The Asian Review of Civil Engineering
ISSN: 2249-6203 (P); 2583-7893(E)
Vol.14 No.2, 2025, pp.1-14

DOI: https://doi.org/10.70112/tarce-2025.14.2.4270

Groundwater Quality and Assessments of Heavy Metals and Bacteriological Parameters in Orumba North Local Government Area, Anambra State, South-East Nigeria

Uche Osoagba Chukwura[1*], Eric Nnamdi Chukwura[2] and Maryrose Ebere Anyalogbu[3]

[1*]Department of Geology, Faculty of Physical Sciences, University of Calabar, Calabar, Cross River State, Nigeria
[2&3]Department of Microbiology, Faculty of Natural Sciences, Chukwuemeka Odumegwu Ojukwu University, Uli, Anambra State, Nigeria
E-mail: en.chukwura@coou.edu.ng, maryroseebere47@gmail.com
*Corresponding Author: ucheosoagba@unical.edu.ng
(Received 12 July 2025; Revised 10 August 2025; Accepted 2 September 2025; Available online 10 September 2025)

Abstract - **Groundwater pollution is an environmental concern that affects life. There is little information on the nature or quality of groundwater in communities in Anambra State, South-East Nigeria. This study therefore assessed the nature and quality of groundwater for drinking and other related domestic uses in Orumba North Local Government Area, Nigeria. Eighty water samples were collected from ten selected groundwater sources (boreholes)-forty samples each during the dry and wet seasons-from Nanka, Oko, Amaokpala, Ufuma, and Ajali. Heavy metals and bacteriological parameters were determined using standard methods, and water quality indices (WQI) were evaluated. Data were analyzed using descriptive statistics. The groundwater samples were slightly acidic during the dry (4.82–6.57) and wet (5.12–6.87) seasons. Groundwater hardness (expressed as $CaCO_3$ in mg/L) ranged from 4.0 to 160.32 (dry season) and 3.07 to 149.30 (wet season). The water was moderately hard in one community (Nanka, BH1) in both seasons and soft in other locations (Oko, Amaokpala, Ufuma, and Ajali). Heavy-metal concentrations (mg/L) ranged from 0.030 to 0.126 (iron), 0.111 to 0.530 (manganese), and 0.001 to 0.060 (lead) during the dry season, and from 0.049 to 0.380 (iron), 0.109 to 0.471 (manganese), and 0.001 to 0.040 (lead) during the wet season. Total coliform counts recorded in the dry season (<2 MPN/100 mL at BH1–BH4) were below the WHO allowable limit, whereas values slightly above the limit (140 MPN/100 mL at BH10) were recorded in non-chlorinated borehole samples during the wet season. The WQI values of the borehole samples were classified as poor at BH1 (Nanka), good at BH2 (Oko), and very poor and unsuitable for drinking at other locations (Amaokpala, Ufuma, and Ajali). Confirmatory analyses of chlorinated (chlorine-treated) groundwater revealed that both physicochemical and bacteriological parameters were within regulatory standards for drinking water. Significant correlations ($p < 0.05$) were observed between total dissolved solids, calcium, magnesium, sodium, and total hardness, among other parameters. The findings reveal the presence of physical, chemical, and microbial contaminants associated with health risks and with the potential to degrade groundwater quality. The use of chlorine as a low-cost treatment method for groundwater was therefore recommended.**

Keywords: **Groundwater Quality, Heavy Metals, Water Quality Index (WQI), Bacteriological Contamination, Nigeria**

I. INTRODUCTION

Water is a natural resource vital for life. Nevertheless, increased anthropogenic (human) activities-such as informal e-waste and automobile scrap assemblages, improper disposal of municipal waste, poorly sited dumpsites arising from inadequate waste handling and management, and other pollutants-have resulted in the contamination and depletion of the environment and hydrological systems [8], [53]–[55]. Globally, contamination of water bodies due to anthropogenic activities has been widely reported in several countries. Man-made activities, particularly industrial operations such as the discharge of solid wastes (industrial and municipal) and mining activities, have significantly contributed to the contamination of water resources in many regions worldwide, including parts of Europe such as the United Kingdom [1]–[3], Nigeria [4]–[8], [53], as well as groundwater quality issues related to nitrate contamination in Iran [9], Morocco [10], and Iraq [11].

Several studies have reported the impacts of mine discharges on aquatic environments [12]; some mining impacts were found to be controlled by environmental pollution [13], while others led to the formation of acid rock drainage from the oxidation of iron sulfide minerals [14] or to circum-neutral mine waters [3]. These sources significantly contribute to groundwater contamination and pose threats to the wider environment.

Generally, most human diseases (about 80%) in developing countries are caused by unsafe water and inadequate sanitation, according to reports from the World Health Organization. The provision of good and potable drinking water is vital for population wellbeing and for socioeconomic development. In Nigeria, water supplies are exposed to chemicals from agricultural activities, including fertilizers and herbicides, as well as industrial wastes from urban and rural settings and hydroelectric power usage. The increasing demand for potable and affordable water for various purposes may further exacerbate pollution of existing water supplies.

Water pollution, particularly groundwater pollution, usually occurs when contaminated surface water carrying organic and inorganic pollutants infiltrates subsurface systems, thereby deteriorating groundwater quality. Once contaminated, groundwater is extremely difficult to restore, even after the cessation of pollutant discharge [16]. Continuous monitoring of groundwater for pollutants is therefore necessary to maintain good-quality and potable water resources [24], [25]. It is essential to ensure that permissible limits for chemical constituents and metals are not exceeded.

Accordingly, protecting water resources requires the establishment of routine and regular monitoring systems. Studies investigating groundwater pollution from anthropogenic activities associated with poor or improper solid waste management and other activities-such as industrial operations [17]–[19], waste generation from cassava processing mills [20], [21], and solid waste disposal sites (dumpsites) [22]-have received considerable attention.

In Orumba North communities of Anambra State, groundwater resources are threatened by contamination resulting from poor solid waste management practices, posing significant health risks to the population. Farming is the predominant activity in the area, with cassava, yam, rice, and maize cultivation relying heavily on herbicides, fertilizers, and pesticides, which may deteriorate groundwater quality through infiltration processes.

This situation is of concern because local residents consume the water without treatment, compounded by limited awareness of the health risks associated with waterborne diseases such as dysentery, infectious hepatitis, typhoid fever, and others. A major challenge faced by residents of Orumba North is the lack of access to adequate and potable water supplies.

Environmental pollution resulting from improper disposal of municipal waste, untreated sewage, poorly sited soakaway pits near boreholes, and automobile repair activities is prevalent in the area and may adversely affect groundwater systems. Furthermore, policies and strategies for groundwater protection, management, and sustainable use are largely absent.

Potable water scarcity has been a persistent problem in Orumba North Local Government Area (LGA), with some residents relying on hand-dug wells for domestic activities such as washing. This study assessed the seasonal effects of contaminant release, including heavy metals and bacterial coliforms, and the associated health impacts on residents consuming borehole water in Orumba North LGA. The outcomes of this research contribute to the understanding and control of heavy metal pollution [23]. The study also serves as a follow-up to a previously published investigation conducted in Orumba South LGA of Anambra State, South-East Nigeria [15].

The study aimed to evaluate seasonal variations in heavy metal concentrations and bacterial accumulation, as well as to identify sources influencing groundwater quality in Orumba North LGA for domestic (e.g., drinking), irrigation, and industrial uses. The data generated from this study were used to formulate pollution abatement guidelines and to provide practical environmental management solutions.

II. LITERATURE REVIEW

A. Location, Climate/Relief and Geology

The following areas-Nanka, Oko, Amaokpala, Ufuma, and Ajali-located in Orumba North Local Government Area (LGA) of Anambra State, South-East Nigeria, were used for this study. Orumba North lies between latitudes 5°58′0″N and 6°15′0″N and longitudes 6°59′30″E and 7°18′0″E in the south-eastern region of Nigeria (Figure. 1). Two seasons are observed in the study area, namely the wet season (April to October) and the dry, dusty Harmattan season (November to March).

Figure.1 shows the study area, Orumba North, in Anambra State, South-East Nigeria. Orumba North is located within the Benue Trough (Anambra Basin) (Figure. 2) and is predominantly composed of clastic sedimentary rocks with an estimated thickness of about 2500 m, comprising different lithostratigraphic units and formations ranging in age from the Upper Campanian to the Recent [26]–[28].

Boreholes constitute the dominant source of water supply in the area. Other water sources include hand-dug wells, streams, rivers, and rainwater; however, local residents rely primarily on boreholes. The average annual rainfall in the area is approximately 2000 mm. Most of the rainfall occurs during the rainy season, which lasts for about six to seven months (April to October).

Rainfall is typically associated with high-intensity storms that often result in flooding, erosion, and gully formation [29]. The study area lies within the humid rainforest belt [29], [30]. High temperatures ranging from 27.2 °C to 35.0 °C are commonly experienced between January and February, while lower temperatures (18.2 °C to 23.0 °C) occur between August and September [15]. The study area is characterized by an undulating terrain and extensive alluvial plains [29].

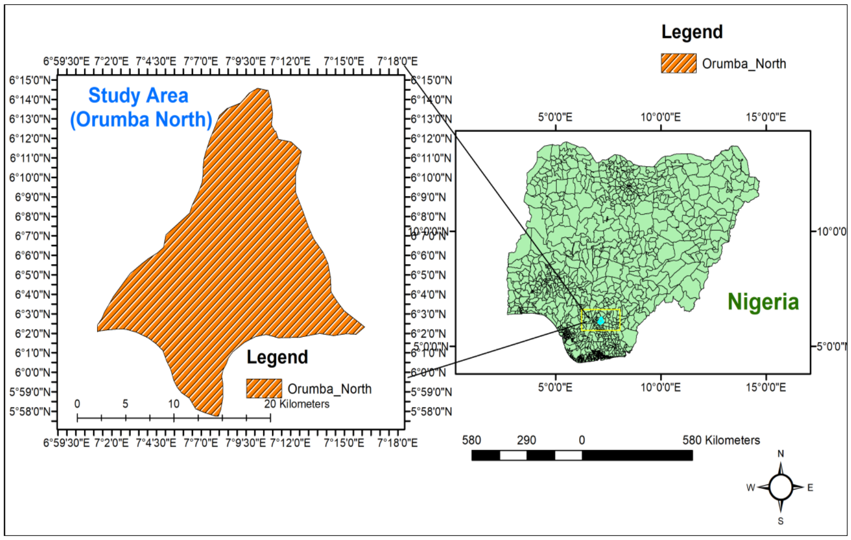

Fig.1 Map of Orumba North (Study Area) Within Anambra State, Nigeria

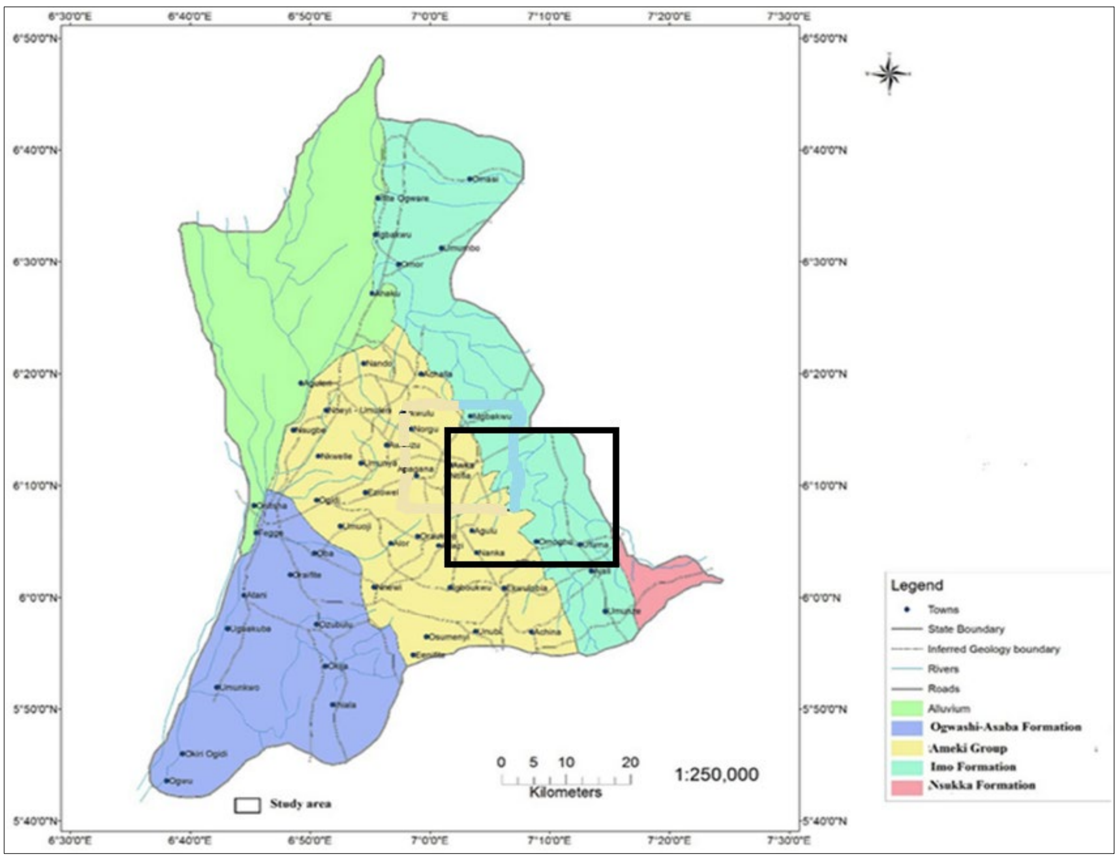

Fig.2 Geology Map of the Study Area Orumba North in Anambra State Displaying the Basin and Formations (After [27])

III. MATERIALS AND METHODS

A. Sampling and Analytical Procedures of Water

Eighty (80) groundwater samples were collected from ten (10) selected boreholes located within five towns-Nanka, Oko, Amaokpala, Ufuma, and Ajali (BH1–BH10)-in Orumba North Local Government Area, southern Anambra State, Nigeria. Prior to sampling, water from each borehole was allowed to flow for approximately five (5) min before filling the sample bottles; thereafter, the flow rate was reduced to prevent splashing.

A gas removal technique was employed before sample collection by repeatedly filling and emptying the sample bottles. Sampling was conducted seasonally, with forty (40) samples collected during both the dry and wet seasons: December, January, and February (dry season) and May, June, and July (wet season) of 2019. Samples were collected in sterilized 1-L high-density polyethylene terephthalate

(PET) screw-capped bottles. The sample bottles were properly labeled and stored overnight in ice coolers at 4 °C, transported to the laboratory, refrigerated, and subsequently analyzed for physicochemical and bacteriological parameters. Standard methods prescribed by the American Public Health Association (APHA) were adopted for physicochemical analysis of the groundwater samples [20], [31]. Eighteen (18) physicochemical parameters were analyzed, including temperature, turbidity, pH, total dissolved solids (TDS), biochemical oxygen demand (BOD_5), dissolved oxygen (DO), total alkalinity, total hardness (TH), phosphate, chloride, nitrate, nitrite, sulphate, sodium, potassium, iron (Fe), manganese (Mn), and lead (Pb). pH was measured using a pH meter, while temperature was determined with a mercury-in-glass thermometer.

Turbidity was measured using a turbidimeter and reported in nephelometric turbidity units (NTU). Total hardness, total dissolved solids, chloride, and nitrate concentrations were determined using APHA standard methods [32]. Dissolved oxygen was measured using a DO meter, while BOD_5 was determined after a 5-day incubation period. Phosphate, sulphate, and nitrite concentrations were measured using standard titrimetric and colorimetric methods [33]. Total alkalinity, sodium, and potassium were determined following the procedures described in [34] using flame photometric methods. Heavy metal concentrations were determined using standard analytical techniques. Lead (Pb) was analyzed using the dithizone spectrophotometric method, while iron (Fe) and manganese (Mn) were determined using methods described in [33] and [4], respectively.

B. Bacteriological Analyses

Several analyses were conducted for bacteriological assessment of the water samples. These included the Most Probable Number (MPN), total viable count, isolation and purification of isolates, identification and characterization of isolates, molecular identification, and microscopic characterization of isolates (Gram staining). The Most Probable Number (MPN) method involves the use of three basic tests to detect coliform bacteria, as described by Cappuccino and Sherman [35]. These tests include the presumptive, confirmatory, and completed tests. Lactose Fermentation Broth (LFB) was used for the presumptive test, while Levine’s Eosin Methylene Blue (EMB) agar was used for the confirmatory and completed tests.

The MPN test determines the presence of coliform bacteria and fecal contamination through lactose fermentation, resulting in acid and gas production after an incubation period of 24 h at 37 °C. The total viable count was determined using the pour plate method in accordance with APHA guidelines [31]. This method involved plating 0.1 mL from a 10^{-3} dilution, in duplicate, into sterile Petri dishes. Subsequently, 20 mL of molten sterile agar was poured into each Petri dish and allowed to solidify before incubation in an inverted position at 37 °C for 24 h. After incubation, colonies on each agar plate were counted, and the mean value was recorded. The total viable count, expressed in colony-forming units per milliliter (cfu/mL), was calculated using the formula below.

$$TVC\ in \frac{cfu}{ml} = Mean\ colony\ count\ X\ reciprocal\ of\ dilution\ factor \quad (1)$$

Isolation and purification of isolates involved tenfold serial dilution, in which 9 mL of distilled water (diluent) was dispensed into separate test tubes to reduce microbial load and enable the isolation of distinct colonies. In the first test tube, 1 mL of the stock water sample was added and vortexed. Subsequently, 1 mL was transferred aseptically to the second test tube using a sterile pipette. This procedure was repeated sequentially until the final test tube, after which 1 mL was discarded. A dilution factor of 10^{-3} was used, and inoculation was performed by aseptically plating 0.1 mL of the diluted sample onto nutrient agar [36]. The pour plate method was employed, and the plates were incubated in an inverted position at 37 °C for 24 h. After incubation, distinct colonies were aseptically subcultured by streaking a single colony onto freshly prepared sterile agar plates, which were further incubated at 37 °C for 24 h to obtain pure cultures. Identification and characterization of isolates were carried out following the procedures described by Bragg [37]. Pure cultures were examined for colonial morphology, including colony color, surface texture, size, optical characteristics, elevation, and colony margins.

Furthermore, isolates were identified using both molecular and phenotypic approaches under the molecular identification process. Microscopic characterization (Gram staining) was conducted to differentiate Gram-positive from Gram-negative bacteria. In this procedure, a pure culture of each isolate was used to prepare a smear on a grease-free glass slide. The smear was allowed to air-dry and then heat-fixed over a Bunsen burner prior to staining.

C. Water /Groundwater Quality Index (WQI)

The water/groundwater quality index (WQI) refers to a numerical evaluation of groundwater to assess its suitability for drinking [8], [16], [20], [38]. In this study, the WQI was calculated because local residents regularly consume groundwater on a daily basis. The index was computed by assigning different weights (wi) to individual parameters based on their relative importance for drinking [8] (Tables V and VI). Using Equation 2, the relative weight (Wi) of the selected parameters was calculated, following methods adopted in previous studies [8], [16], [20], [38].

For the WQI calculation, the following parameters were selected and weighted: pH, total hardness (TH), calcium (Ca^{2+}), sodium (Na^+), magnesium (Mg^{2+}), potassium (K^+), sulphate (SO_4^{2-}), total dissolved solids (TDS), dissolved oxygen (DO), manganese (Mn), lead (Pb), and iron (Fe) [8], [16], [20], [38]. Each parameter was assigned a weight (wi) from 1 to 5 according to its relative significance for drinking water quality [16].

The measured concentrations of the parameters were compared with WHO standards [39] and incorporated into the WQI calculation [8]. The WQI for the water samples was then computed and categorized according to the classification scheme in [8], [16], [38] as follows: below 50 (excellent or suitable), 50–100 (good), 100–200 (poor), 200–300 (very poor), and above 300 (unsuitable). The WQI was calculated using the step-by-step formulas reported in [8].

$$\mathrm{Wi} = wi/\sum^{n} \mathrm{wi} \qquad (2)$$

Where Wi is the relative weight, wi is the weight assigned to an individual parameter, and n is the number of parameters. The water quality rating (Qi) for each individual parameter was calculated using Equation 3 as follows:

$$Qi = \left(\frac{Ci}{Si}\right) X\ 100 \qquad (3)$$

Where Ci is the concentration of the individual parameter, and Si is the WHO [39] standard guideline for drinking water. The calculations for sub-indices (SIi) and WQI, as reported in previous studies [8], were then computed as follows:

$$\mathrm{Si} = Wi * Qi$$

$$\mathrm{WQI} = \sum \mathrm{SIi}$$

D. Data Analysis and Management

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) software, version 20.0, and presented as descriptive statistics in comparison with World Health Organization (WHO) standards [40]. SPSS was also employed for multivariate statistical analysis to evaluate the relationships between elements in the groundwater system. Results from the Pearson correlation analysis, showing significant correlations at the 0.05 level, are presented in Tables III and IV.

IV. RESULTS AND DISCUSSION

A. Chemical Assessment/ Analyses for the Groundwater

Results of the physicochemical analyses of the ten (10) groundwater (borehole) samples obtained from the selected sampling sites during the two seasons (dry and wet) are presented in Tables I and II. In the study area, borehole samples had pH values ranging from 4.82 to 6.57 (slightly acidic to neutral) and hardness values ranging from 4.0 to 160.32 mg/L (moderately hard to soft), with an average hardness of 25.57 mg/L. These values were higher than those reported elsewhere [8], but were comparable to a previous study conducted in Orumba South Local Government Area (LGA) [15].

TABLE I THE PHYSICO-CHEMICAL PARAMETERS AND ANALYSIS FOR THE GROUNDWATER (BOREHOLE) SAMPLES AT ORUMBA NORTH (DRY SEASON)

Site Locations	Depth (m)	Colour	pH	Temperature	Turbidity	TDS	BOD_5	DO	Ca	Mg	Total Hardness	SO_4	Na	K	Pb	Mn	Fe
	(m)			(°C)	(NTU)	(mg/L)											
BH 1	600	29	5.45	21.75	22.00	600	13.70	48.70	78.1	82.01	160.32	0.05	4.15	5.30	0.001	0.11	0.04
BH 2	170	0	6.55	18.10	1.00	26	0	0	8.76	2.47	11.22	0.03	7.60	8.60	0.001	0.21	0.12
BH 3	145	2	6.57	26.50	4.20	26	21.40	38.40	5.84	9.39	15.23	0.08	4.80	5.80	0.01	0.40	0.36
BH 4	160	2	5.90	30.75	4.00	1	1.00	50.60	4.38	6.04	10.42	0.04	3.35	4.35	0.02	0.12	0.08
BH 5	45	24	5.29	24.95	15.00	2	40.20	53.70	4.87	5.55	10.42	0.70	3.70	4.80	0.00	0.53	0.04
BH 6	40	27	5.07	26.10	16.00	6	34.80	48.30	6.81	0.40	7.21	0.06	5.50	6.76	0.00	0.48	0.06
BH 7	75	23	4.82	23.85	14.90	2	2.20	66.70	4.38	1.09	4.01	0.07	3.70	4.30	0.00	0.31	0.08
BH 8	70	23	5.35	23.20	14.00	3	24.70	44.20	5.35	5.87	11.22	0.05	4.65	5.25	0.001	0.50	0.06
BH 9	45	25	5.19	29.95	15.50	7	28.00	52.60	7.30	7.13	14.42	0.04	6.40	7.25	0.02	0.48	0.03
BH 10	50	26	5.52	36.50	15.00	7	47.80	75.40	6.32	4.90	11.22	0.06	5.55	6.27	0.06	0.5	0.05
Mean	140	18.1	5.57	26.17	12.16	68	23.76	53.18	13.21	12.49	25.57	0.118	4.94	5.86	0.01	0.36	0.09
S.D	169.3	11.72	0.59	5.19	6.70	187.16	16.11	11.32	22.84	24.58	47.45	0.20	1.34	1.37	0.01	0.16	0.09
WHO (2006)	-	15	6.5 – 8.5	26.6	5 - 25	1000	5	5	75	50	100	250	200	12	0.05	0.4	0.3

TABLE II THE PHYSICO-CHEMICAL PARAMETERS AND ANALYSIS FOR THE GROUNDWATER (BOREHOLE) SAMPLES AT ORUMBA NORTH (WET/RAINY SEASON)

Site Locations	Depth	Colour	pH	Temperature	Turbidity	TDS	BOD_5	DO	Ca	Mg	Total Hardness	SO_4	Na	K	Pb	Mn	Fe
	(m)			(°C)	(NTU)	(mg/L)											
BH 1	60	31	5.75	19.70	20.00	550	16.70	45.70	77.16	80.89	149.30	0.07	3.15	3.25	0.001	0.109	0.06
BH 2	170	0	6.75	16.05	2.00	22	0	0	7.65	1.47	10.22	0.05	6.60	6.55	0.001	0.209	0.128
BH 3	145	3.50	6.87	22.40	4.70	23	24.40	35.40	4.83	8.35	12.23	0.10	3.75	2.80	0.001	0.403	0.38
BH 4	160	3.00	6.10	27.70	4.50	0.6	3.00	48.60	3.40	5.02	7.42	0.06	2.35	2.30	0.01	0.116	0.083
BH 5	45	25	5.59	22.95	16.00	1.80	42.10	51.80	3.75	4.45	8.42	0.90	2.65	1.80	0.001	0.41	0.049
BH 6	40	29	5.29	24.05	18.00	0.70	36.60	46.50	5.55	0.20	5.21	0.08	4.50	4.76	0.001	0.471	0.065
BH 7	75	23	5.12	21.75	15.00	1.90	4.10	64.8	3.85	1.06	3.01	0.09	2.70	2.30	0.001	0.309	0.083
BH 8	70	24	5.55	22.15	15.50	2.50	26.50	42.40	4.75	4.85	10.22	0.07	3.65	3.30	0.001	0.40	0.08
BH 9	45	27	5.49	27.90	17.00	4	30.00	50.60	6.40	6.12	12.42	0.06	5.40	5.25	0.01	0.471	0.05
BH 10	50	28	5.72	29.45	18.00	5	50.80	72.40	5.65	3.85	7.22	0.08	4.55	4.20	0.04	0.40	0.059
Mean	86	19.35	5.823	23.41	13.07	61.15	26.02	50.91	12.29	11.63	22.57	0.156	3.93	3.651	0.007	0.329	0.104
S.D	51.46	12.11	0.58	4.068	6.63	171.9	16.20	11.29	22.82	24.46	44.62	0.261	1.348	1.512	0.012	0.137	0.099
WHO (2006)	-	15	6.5 – 8.5	26.6	5 - 25	1000	5	5	75	50	100	250	200	12	0.05	0.4	0.3

B. pH

pH measures the concentration of hydrogen or hydroxide ions in a solution [52]. During the dry season, pH values ranged from 4.82 to 6.57, with an average of 5.57, where BH3 recorded the highest value and BH7 the lowest (Figure.3).

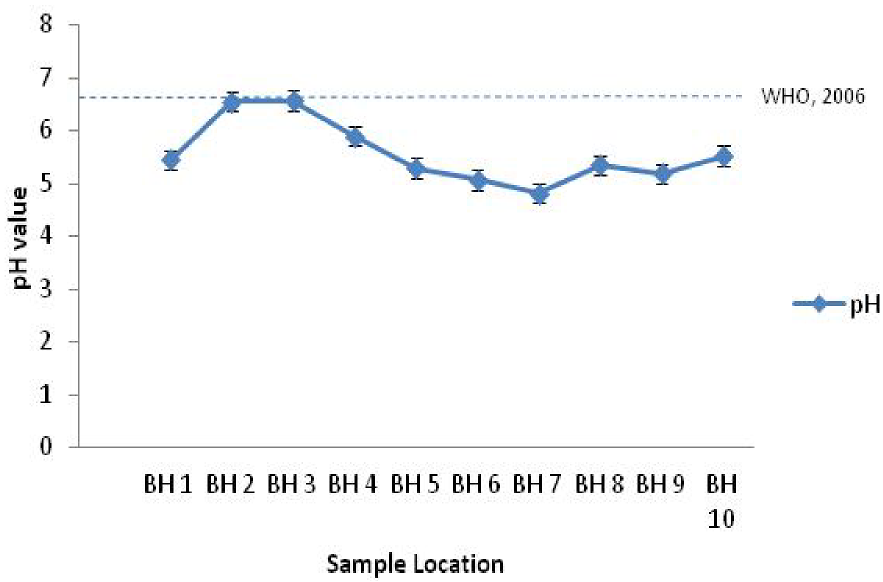

Fig.3 pH Value of the Groundwater Sample Locations at Orumba North in Anambra State (Dry Season)

The pH during the wet season ranged from 5.12 to 6.87, with an average value of 5.82, where BH3 recorded the highest value and BH7 the lowest (Figure.4).The pH values in both seasons were low and below the WHO maximum allowable limits for drinking water. According to the WHO guideline for drinking water, pH values ranging from 6.5 to 8.5 are considered suitable for consumption [39], [40]. Lower pH values can corrode water, while higher values may adversely affect the eyes and skin, as well as alter taste [8], [41]. The pH was significantly correlated with iron (Fe) at 0.717. Furthermore, pH was not significantly correlated with some other parameters (Tables III and IV).

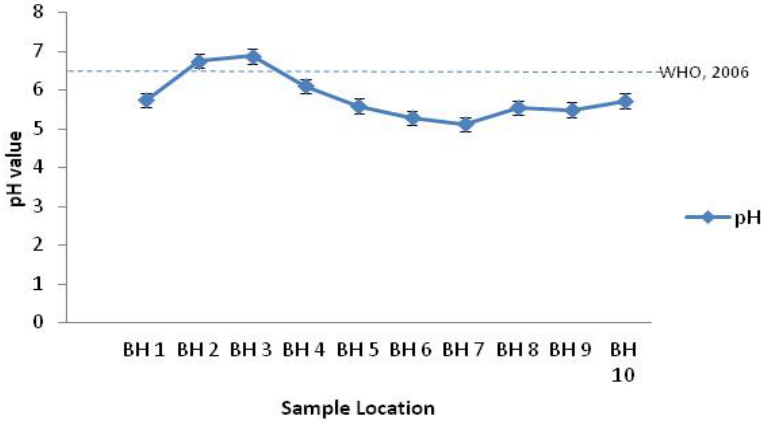

Fig.4 pH Value of the Groundwater Sample Locations at Orumba North in Anambra State (Wet/Rainy Season)

C. Total Hardness (TH)

Total hardness (TH, as $CaCO_3$) measures the dissolved Ca^{2+} and Mg^{2+} content in water [8], [52]. In the dry season, TH ranged from 4.0 to 160.32 mg/L, with an average value of 25.57 mg/L, where the highest value was recorded at BH1 and the lowest at BH7 (Table I). In the wet season, TH ranged from 3.07 to 149.30 mg/L, with an average value of 22.57 mg/L, the highest at BH1 and the lowest at BH7 (Table II). This suggests that calcium in the groundwater may originate from the dissolution of carbonate-rich sedimentary rocks or minerals such as calcite and limestone [1]. Additionally, calcium and magnesium may be further released through weathering of silicate minerals and hydrolysis in agricultural settings [42].

Ca^{2+} was significantly correlated with TH at 0.997, and Mg^{2+} was significantly correlated with TH at 0.998. Sodium (Na^+) was significantly correlated with potassium (K^+) at 0.986 (Tables III and IV). According to WHO classification [43], water hardness can be categorized as: below 60 mg/L (soft), 61–120 mg/L (moderately hard), 121–180 mg/L (hard), and above 180 mg/L (extremely hard). Based on this classification, groundwater in the study area is soft to moderately hard and may be suitable for irrigation [44], [45].

D. Total Dissolved Solids (TDS)

TDS in the dry season ranged from 1 to 600 mg/L, with an average value of 68 mg/L; BH1 recorded the highest value, while BH4 had the lowest (Table I). In the wet season, TDS ranged from 0.6 to 550 mg/L, with an average of 61.15 mg/L; BH1 had the highest value and BH4 the lowest (Table II). According to [16], [46], high TDS in groundwater is generally not harmful for drinking; however, elevated concentrations may cause constipation or laxative effects and may affect individuals with heart or kidney conditions. TDS was significantly correlated with Ca^{2+} at 0.999, as well as with Mg^{2+} and TH (Tables III and IV). Higher TDS values in the groundwater are associated with noticeable taste, color, and odor, reflecting strong correlations with total hardness and other parameters, consistent with previous reports [8].

E. Dissolved Oxygen (DO)

DO in the dry season ranged from 38.40 to 75.40 mg/L, with an average value of 53.18 mg/L; the highest value was recorded at BH10 and the lowest at BH3 (Table I). In the wet season, DO ranged from 35.40 to 72.40 mg/L, with an average of 50.91 mg/L; BH10 had the highest value and BH3 the lowest (Table II). These DO values are above the WHO maximum allowable limit of 5.0 mg/L [40].

F. Biochemical Oxygen Demand (BOD_5)

BOD_5 in the dry season ranged from 1.00 to 47.80 mg/L, with an average of 23.76 mg/L; BH10 recorded the highest value and BH4 the lowest (Table I). In the wet season, BOD_5 ranged from 3.00 to 50.80 mg/L, with an average of 26.02 mg/L; BH10 had the highest value and BH4 the lowest (Table II). BOD_5 was significantly correlated with manganese (Mn) at 0.826 (Tables III and IV). Higher BOD_5 values indicate abundant organic matter deposition in some groundwater samples, as reported elsewhere [28].

G. Sulphate (SO_4^{2-})

Sulphate values in the dry season ranged from 0.03 to 0.70 mg/L, with an average of 0.118 mg/L; BH5 had the highest value and BH2 the lowest (Table I). In the wet season, values ranged from 0.05 to 0.90 mg/L, with an average of 0.156 mg/L; BH5 had the highest value and BH2 the lowest (Table II). Sulphate levels in both seasons were below the WHO maximum allowable limit [40] and likely originated from the weathering of sulfate- and gypsum-rich sedimentary rocks ($CaSO_4 \cdot 2H_2O$) [8], [47], [48].

TABLE III STATISTICAL REPRESENTATION OF CORRELATION (PEARSON) OF GROUNDWATER PHYSICOCHEMICAL PARAMETERS (DRY SEASON)

	pH	TDS	BOD	DO	Ca	Mg	TH	SO4	Na	K	Pb	Mn	Fe
pH	1												
TDS	-.030	1											
BOD	-.319	-.170	1										
DO	-.695*	-.021	.481	1									
Ca	-.049	.999**	-.156	-.023	1								
Mg	-.023	.994**	-.139	.018	.991**	1							
TH	-.031	.998**	-.143	-.005	.997**	.998**	1						
SO4	-.176	-.129	.410	.137	-.136	-.104	-.118	1					
Na	.350	-.176	.070	-.567	-.148	-.220	-.183	-.353	1				
K	.382	-.114	.079	-.611	-.086	-.161	-.121	-.303	.986**	1			
Pb	.050	-.203	.454	.501	-.195	-.169	-.180	-.195	.142	.089	1		
Mn	-.349	-.557	.826**	.338	-.546	-.531	-.538	.376	.155	.113	.215	1	
Fe	.717*	-.160	-.173	-.337	-.195	-.145	-.169	-.132	.053	.067	-.080	-.037	1
*. Correlation is significant at the 0.05 level (2-tailed).													
**. Correlation is significant at the 0.01 level (2-tailed).													

TABLE IV STATISTICAL REPRESENTATION OF CORRELATION (PEARSON) OF GROUNDWATER PHYSICOCHEMICAL PARAMETERS (WET SEASON)

	pH	TDS	BOD	DO	Ca	Mg	TH	SO4	Na	K	Pb	Mn	Fe
pH	1												
TDS	.000	1											
BOD	-.324	-.150	1										
DO	-.701*	-.038	.501	1									
Ca	-.026	.999**	-.135	-.035	1								
Mg	.000	.995**	-.117	.003	.992**	1							
TH	-.005	.998**	-.130	-.034	.998**	.998**	1						
SO4	-.146	-.125	.395	.135	-.137	-.106	-.117	1					
Na	.323	-.178	.038	-.559	-.147	-.221	-.175	-.356	1				
K	.220	-.074	-.033	-.534	-.038	-.124	-.073	-.458	.970**	1			
Pb	-.070	-.171	.492	.518	-.156	-.152	-.167	-.162	.156	.141	1		
Mn	-.319	-.568	.724*	.279	-.554	-.549	-.552	.227	.245	.128	.137	1	
Fe	.737*	-.115	-.152	-.355	-.153	-.099	-.125	-.162	.046	-.099	-.219	.077	1
*. Correlation is significant at the 0.05 level (2-tailed).													
**. Correlation is significant at the 0.01 level (2-tailed).													

V. HEAVY METAL ANALYSES OF THE GROUNDWATER

A. Lead (Pb)

The lead (Pb) concentration in the dry season ranged from 0.001 to 0.06 mg/L, with an average value of 0.012 mg/L. BH10 recorded the highest value, while BH1–BH7 had the lowest values. The highest concentration was slightly above the WHO maximum allowable limit of 0.05 mg/L [39], [40] (Table I, Figure.5). Pb values in the wet season ranged from 0.001 to 0.04 mg/L, with an average value of 0.007 mg/L. BH10 recorded the highest value, while BH1–3 and BH5–8 had the lowest values, all below the WHO regulatory standard [40] (Table II , Figure.6).

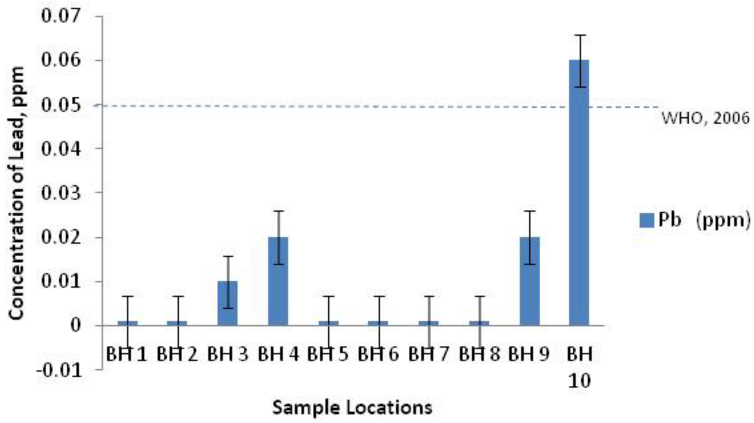

Fig.5 Graphical Representation of the Concentration of Lead in the Sampling Sites at Orumba North and in Comparison with WHO (Dry Season)

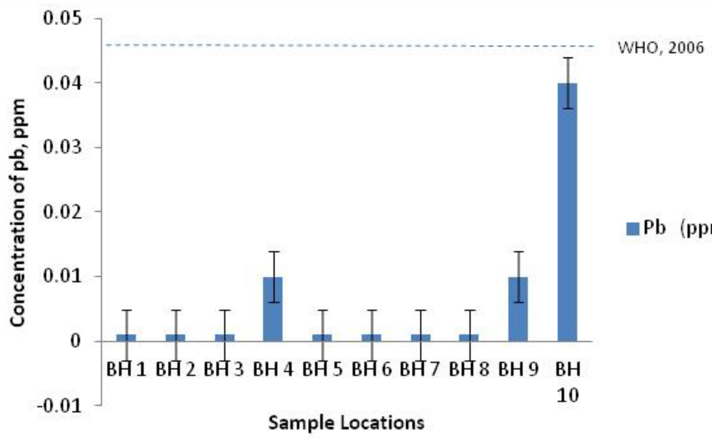

Fig.6 Graphical Representation of the Concentration of Lead in the Sampling Sites at Orumba North and in Comparison with WHO (Wet/Rainy Season)

B. Manganese (Mn)

The manganese (Mn) concentration in the dry season ranged from 0.111 to 0.53 mg/L, with an average value of 0.366 mg/L. BH5 recorded the highest value, while BH1 had the lowest value. The highest concentration exceeded the WHO maximum allowable limit of 0.4 mg/L [39], [40] (Table I, Figure.7).

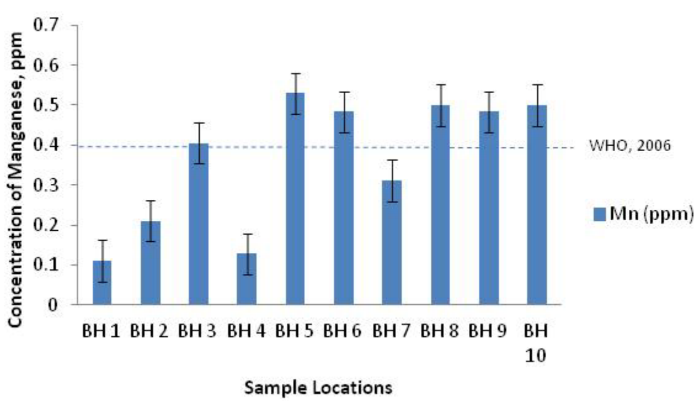

Fig.7 Graphical Representation of the Concentration of Manganese in the Sampling Sites at Orumba North and in Comparison with WHO (Dry Season)

Mn values in the wet season ranged from 0.109 to 0.471 mg/L, with an average value of 0.329 mg/L. BH6 and BH9 recorded the highest values, while BH1 had the lowest value. The highest concentrations were slightly above the WHO regulatory standard of 0.4 mg/L [40] (Table II, Figure.8). Some studies elsewhere reveal the presence of manganese affinity, scavenged by certain heavy metals [17], [28], [49].

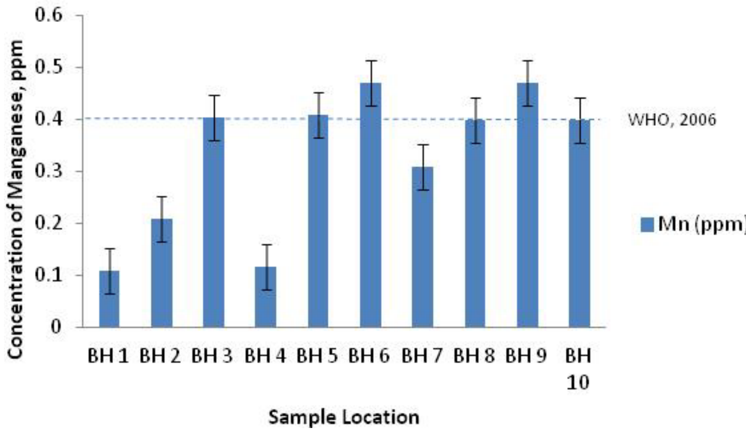

Fig.8 Graphical Representation of the Concentration of Manganese in the Sampling Sites at Orumba North and in Comparison with WHO (Wet/Rainy Season)

C. Iron (Fe)

The iron (Fe) concentration in the dry season ranged from 0.03 to 0.126 mg/L, with an average value of 0.095 mg/L. BH2 recorded the highest value, while BH9 had the lowest value. All values were below the WHO maximum allowable limit of 0.3 mg/L [40] (Table I, Figure.9).

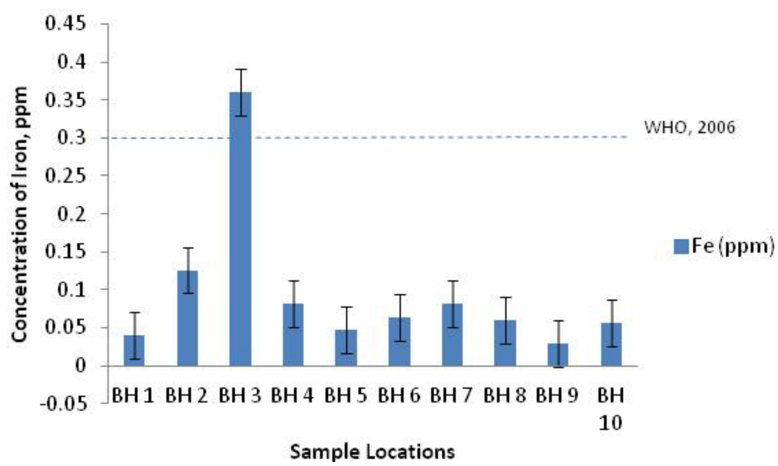

Fig.9 Graphical Representation of the Concentration of Iron in the Sampling Sites at Orumba North and in Comparison with WHO (Dry Season)

Fe values in the wet season ranged from 0.049 to 0.38 mg/L, with an average value of 0.104 mg/L. BH3 recorded the highest value, while BH5 had the lowest value (Table II, Figure.10). The low concentration of Fe in the groundwater systems could be attributed to rock dissolution and geochemical processes [28].

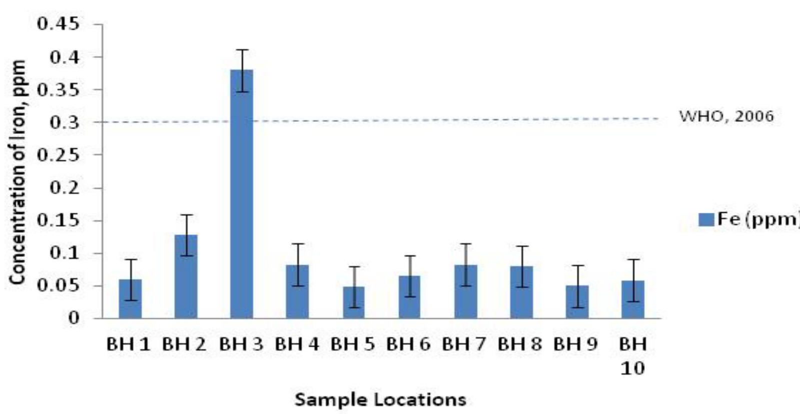

Fig.10 Graphical Representation of the Concentration of Iron in the Sampling Sites at Orumba North and in Comparison with WHO (Wet/Rainy Season)

D. Groundwater Quality Assessment Adopting Water Quality Index (Wqi) Method

The quality of the groundwater was assessed using the water quality index (WQI) method. Following the WQI classification scheme [16], [38], values below 50 are considered suitable/excellent, between 50 and 100 are good, between 100 and 200 are poor, between 200 and 300 are very poor, and above 300 are unsuitable for drinking. The computed WQI classifies the groundwater systems for drinking as poor at BH1 (Nanka), good at BH2 (Oko), and very poor and unsuitable at other locations (Amaokpala, Ufuma, and Ajali) (Table V and VI).

TABLE V WATER QUALITY PARAMETERS, STANDARD (WHO, 2017), ASSIGNED WEIGHT (W_I), AND RELATIVE WEIGHT (W_I)

Parameters	WHO [39] Standard	Assigned Weight (w_i)	Relative weight (W_i)
pH	8.5	4	0.1026
DO (mg/L)	5	4	0.1026
TDS (mg/L)	500	4	0.1026
Ca^{2+} (mg/L)	75	2	0.0513
Mg^{2+} (mg/L)	50	1	0.0256
Total hardness (mg/L)	120	2	0.0513
SO_4 (mg/L)	250	4	0.1026
Na^+ (mg/L)	200	3	0.0769
K^+ (mg/L)	30	3	0.0769
Mn (mg/L)	0.04	4	0.1026
Pb (mg/L)	0.05	4	0.1026
Fe (mg/L)	0.1	4	0.1026
Total		39	1

TABLE VI WATER QUALITY INDEX (WQI)

Sample	Sample/Location ID	WQI Calc. Values	Groundwater Type
Borehole (groundwater)	BH1	169.26	Poor water
	BH2	79.397	Good water
	BH3	233.34	Very poor water
	BH4	158.52	Poor water
	BH5	260.06	Very poor water
	BH6	238.65	Very poor water
	BH7	232.79	Very poor water
	BH8	234.50	Very poor water
	BH9	249.00	Very poor water
	BH10	310.92	Water unsuitable for drinking

E. Total Coliform Count of Water Samples

Total coliform counts (TCC) across the borehole water samples for both seasons (dry and wet/rainy) and the corresponding Most Probable Numbers (MPN) are shown in Tables VII and VIII. The highest TCC was 140 MPN/100 mL, recorded in borehole sample BH10 during the wet/rainy season. The lowest TCC was <2 MPN/100 mL, recorded in borehole samples BH1, BH2, BH3, and BH4 during both seasons. TCC values were generally higher in the wet/rainy season across the study area. Recorded TCC in the dry season were within the WHO [50] permissible limit of <2.2 MPN/100 mL. Higher TCC values (110 and 140 MPN/100 mL), along with total viable counts, were observed in chlorine- and calcium hypochlorite-treated borehole water samples. These values slightly exceeded the WHO [50], [51] regulatory limit of <2.2 MPN/100 mL (and total viable counts of 1.0×10^2 CFU/mL) in the wet season. The values were higher than total coliform counts of 1.0×10^2 to 2.5×10^3 reported elsewhere [4]. This requires low-cost, safe, environmentally friendly, and robust purification strategies, such as the use of calcium hypochlorite solution and chlorine (i.e., chlorination), to reduce the health risks posed by certain waterborne diseases, including cholera, dysentery, and typhoid. In addition, it ensures the availability of potable drinking water for domestic and industrial activities, especially during the wet/rainy season.

TABLE VII TOTAL COLIFORM COUNT OF BOREHOLE WATER SAMPLES IN ORUMBA NORTH IN THE DRY SEASON

Sample Locations	**LB2X-10**	**LB1X-1**	**LB1X-0.1**	**Reading**	**MPN / 100ml**	**Range 95% Probability**
	Tubes	Tubes	Tubes			
BH1	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH2	- - - - -	- - - - -	- - - - -	000	<2	<1.2 – 7.0
BH3	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH4	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH5	- - - - -	- + - - -	- - - - -	010	2	<1.0 – 7.0
BH6	+ - - - -	- - + - -	- - - - -	110	4	<1.0 – 7.0
BH7	+ - - - -	- - + - -	- - - - -	110	4	<1.0 – 7.0
BH8	+ - - - -	- - - - -	- - - - -	100	2	<1.0 – 7.0
BH9	+ + + + +	- + + + -	- - - - -	530	79	25.0 – 190.0
BH10	+ + + + +	+ + + - -	- - + + -	532	94	28 – 220
WHO					0.00	

TABLE VIII TOTAL COLIFORM COUNT OF BOREHOLE WATER SAMPLES IN ORUMBA NORTH IN THE WET/RAINY SEASON

Sample Locations	**LB2X-10**	**LB1X-1**	**LB1X-0.1**	**Reading**	**MPN / 100ml**	**Range 95% Probability**
	Tubes	Tubes	Tubes			
	1 2 3 4 5	1 2 3 4 5	1 2 3 4 5			
BH1	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH2	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH3	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH4	- - - - -	- - - - -	- - - - -	000	<2	<1.0 – 7.0
BH5	- - - - -	- + - - -	- - - - -	010	2	<1.0 – 7.0
BH6	+ - - - -	- - + - -	- - - - -	110	4	<1.0 – 11.0
BH7	+ - - - -	- - + - -	- - - - -	110	4	<1.0 – 11.0
BH8	+ - - - -	- - - - -	- - - - -	100	2	<1.0 – 7.0
BH9	+ + + + +	- + + + -	- + - - -	531	100	34.0 – 250
BH10	+ + + + +	+ + - + +	+ - + + -	532	140	52 – 400
WHO					0.00	

VI. CONCLUSION

The study investigated the seasonal variation in physicochemical and bacteriological qualities of groundwater in the vicinity of the Orumba North Local Government Area, Nigeria. The study revealed that the boreholes/groundwater sources had pH values that were slightly acidic to neutral, and hardness ranging from moderately hard to soft, compared with the WHO acceptable limits for drinking water. Significant differences were observed in the parameter values, which were within the WHO acceptable limits, except for dissolved oxygen, lead, manganese, and total coliforms. Low-cost, safe, environmentally friendly, and robust purification strategies were recommended, such as the use of calcium hypochlorite solution and chlorine (i.e., chlorination), to reduce health risks posed by waterborne diseases, including cholera, dysentery, and typhoid. In addition, these measures ensure the availability of potable drinking water for domestic and industrial activities, especially during the wet/rainy season. This was confirmed by the analysis of chlorinated groundwater, which showed that both physicochemical and bacteriological parameters were within regulatory standards for drinking water. The water was found to be of good quality in the Oko community, whereas it was poor or unsuitable for drinking and domestic purposes at other locations unless properly treated. Therefore, borehole drilling near sewage tanks, dumpsites, or related environments could contribute to groundwater pollution and deterioration through routine leachate release.

ACKNOWLEDGEMENT

The authors express their profound gratitude to postgraduate student Anyalogbu Maryrose Ebere for her assistance in the fieldwork and data collection for the interpretation of the study, as well as for her collaboration in producing this paper. The authors also sincerely thank the editors and reviewers assigned to this manuscript for their constructive

comments, which improved the quality of the paper for readers.

Declaration of Conflicting Interests
The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The authors received no financial support for the research, authorship, and/or publication of this article.

Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation
The authors confirm that no AI-assisted technologies were used in the preparation or writing of the manuscript, and no images were altered using AI.

ORCID
Uche Osoagba Chukwura https://orcid.org/0000-0002-3401-7340
Eric Nnamdi Chukwura https://orcid.org/0009-0009-2427-8158
Maryrose Ebere Anyalogbu https://orcid.org/0009-0009-0529-3643

REFERENCES

[1] U. O. Chukwura and A. S. Hursthouse, "Evaluating controls on potentially toxic element release in circum-neutral mine water: A case study from the abandoned Pb-Zn mines of Leadhills and Wanlockhead, South of Scotland, United Kingdom," *Environ. Earth Sci.*, vol. 79, no. 363, 2020, doi: 10.1007/s12665-020-09108-x.

[2] D. Banks, P. L. Younger, R. T. Arnesen, E. R. Iversen, and S. B. Banks, "Mine-water chemistry: The good, the bad and the ugly," *Environ. Geol.*, vol. 32, no. 3, pp. 157–174, 1997.

[3] D. K. Nordstrom, "Mine waters: Acidic to circumneutral," *Elements*, vol. 7, pp. 393–398, 2011.

[4] U. O. Chukwura and O. Igwe, "Seasonal evaluation of the hydrogeochemical interpretations of groundwater quality: A case study from Automobile Junk Waste in Obosi and Onitsha environs, South-east Nigeria," *Arab. J. Geosci.*, vol. 14, no. 244, 2021, doi: 10.1007/s12517-021-06643-0.

[5] U. O. Chukwura, G. J. Udom, S. J. Cuthbert, and A. S. Hursthouse, "Evaluation of hydrochemical characteristics and flow directions of groundwater quality in Udi Local Government Area Enugu State, Nigeria," *Environ. Earth Sci.*, vol. 73, no. 8, pp. 4541–4555, 2015, doi: 10.1007/s12665-014-3741-4.

[6] E. E. Igonor, A. A. Oko, and M. I. Oden, "An insight into the economics of groundwater exploitation – Southeast Nigeria," *IOSR J. Appl. Geol. Geophys.*, vol. 1, no. 1, pp. 44–48, 2013.

[7] O. D. Omole, "Sustainable groundwater exploitation in Nigeria," *J. Water Resour. Ocean Sci.*, vol. 2, no. 2, pp. 9–14, 2013, doi: 10.11648/j.wros.20130202.11.

[8] U. O. Chukwura-Osoagba, P. C. Igwilo, C. C. Opara, and A. D. Akam, "Investigation of hydrochemical characteristic of groundwater quality of Bogoberi in Calabar Municipality in Cross River State, Southeastern Nigeria," *Discover Environ. J.*, vol. 3, no. 48, 2025, Open Access, doi: 10.1007/s44274-025-00235-5.

[9] V. Amiri, N. Sohrabi, P. Li, and F. Amiri, "Groundwater quality for drinking and non-carcinogenic risk of nitrate in urban and rural areas of Fereidan, Iran," *Expo Health*, vol. 15, pp. 807–823, 2023, doi: 10.1007/s12403-022-00525-w.

[10] O. Boukich, R. Ben-tahar, E. Gharibi, B. El Guerrouj, and Y. Smiri, "Assessment of groundwater quality and nitrate-related risks to human health: A case of Angads Plain, Morocco," *Water Air Soil Pollut.*, vol. 235, no. 787, 2024, doi: 10.1007/s11270-024-07605-4.

[11] J. M. S. Tawfeeq, E. Dişli, and M. H. Hamed, "Hydrogeochemical evolution processes, groundwater quality, and non-carcinogenic risk assessment of nitrate-enriched groundwater to human health in different seasons in the Hawler (Erbil) and Bnaslawa Urbans, Iraq," *Environ. Sci. Pollut. Res.*, vol. 31, pp. 26182–26203, 2024, doi: 10.1007/s11356-024-32715-1.

[12] P. Younger and C. Wolkersdorfer, "Mining impacts on the fresh water environment: Technical and managerial guidelines for catchment scale management," *Mine Water Environ.*, vol. 23, no. 1, pp. 2–80, 2024.

[13] C. Carbone, E. Dinelli, P. Marescotti, G. Gasparotto, and G. Lucchetti, "The role of AMD secondary minerals in controlling environmental pollution: Indications from bulk leaching tests," *J. Geochem. Explor.*, vol. 132, pp. 188–200, 2013.

[14] B. Ohlander, T. Chatwin, and L. Alakangas, "Management of sulfide-bearing waste, a challenge for the mining industry," *Minerals*, vol. 2, pp. 1–10, 2012, doi: 10.3390/min2010001.

[15] M. E. Anyalogbu, E. N. Chukwura, and C. C. Ezemba, "Seasonal variety on bacteriological evaluation of borehole waters in Orumba South Local Government Area in Anambra State," *Microbiol. Res. J. Int.*, vol. 30, no. 12, pp. 31–39, 2020.

[16] C. R. Ramakrishnaiah, C. Sadashivaiah, and G. Ranganna, "Assessment of water quality index for the groundwater in Tumkur Taluk, Karnataka State, India," *J. Chem.*, vol. 6, no. 2, pp. 523–530, 2009.

[17] I. E. Arinze, O. Igwe, and C. O. Una, "Analysis of heavy metals' contamination in soils and water at automobile junk markets in Obosi and Nnewi, Anambra State, Southeastern Nigeria," *Arab. J. Geosci.*, 2015, doi: 10.1007/s12517-015-2001-6.

[18] J. O. Ogbuagu and V. I. E. Ajiwe, "Industrial pollution survey in Anambra State, Nigeria," *Bull. Environ. Contam. Toxicol.*, vol. 61, no. 2, pp. 269–270, 1998.

[19] E. Ekbal and T. A. Khan, "Hydrogeochemical characterization of groundwater quality in parts of Amroha District, Western Uttar Pradesh, India," *J. HydroRes.*, vol. 5, pp. 54–70, 2022.

[20] O. T. Olurin, S. A. Ganiyu, F. O. Ogunsanwo, A. O. Ojo, A. A. Alabi, and O. K. Adegbamigbe, "Groundwater quality assessments around a cassava processing mill on the sedimentary terrain of Ilaro, South-western Nigeria," *J. HydroRes.*, vol. 5, pp. 108–117, 2022.

[21] A. O. Ojo, O. O. Ogunyinka, O. O. Daramola, and F. A. Olaoye, "Hydro-chemical and microbial assessments of water resources around cassava mills in a sedimentary formation of Ilaro, Southwest Nigeria," *Appl. Water Sci.*, vol. 11, no. 62, 2021, doi: 10.1007/s13201-021-01384-7.

[22] A. O. Ojo, O. T. Olurin, S. A. Ganiyu, B. S. Badmus, and O. A. Idowu, "Hydro-geochemical assessment of an open dumpsite in a basement complex of Abeokuta, Ogun State, Southwestern Nigeria," *Arab. J. Geosci.*, vol. 13, no. 620, 2020, doi: 10.1007/s12517-020-05651-w.

[23] G. Machender, R. Dhakate, S. T. M. Rao, B. M. Rao, and L. Prasanna, "Heavy metal contamination in sediments of Balanagar industrial area, Hyderabad, Andhra Pradesh, India," *Arab. J. Geosci.*, vol. 7, pp. 513–525, 2014.

[24] A. C. C. Ezeabasili, O. L. Anike, and B. U. Okoro, "Urban water pollution by heavy metals and health implication in Onitsha, Nigeria," *Afr. J. Environ. Sci. Technol.*, vol. 9, no. 4, pp. 325–331, 2015.

[25] B. N. Nfor, S. B. Olobaniyi, and J. E. Ogala, "Extent and distribution of groundwater resources in parts of Anambra State, Southeastern, Nigeria," *J. Appl. Sci. Environ. Manag.*, vol. 11, no. 2, pp. 215–221, 2007.

[26] R. A. Reyment, *Aspects of the geology of Nigeria*. University of Ibadan, Nigeria Press, 1965, p. 133.

[27] I. I. Obiadi, N. E. Ajaegwu, C. I. Meniru, I. C. Nzeakor, and R. C. Ejike, "Aquifer potentials and vulnerability studies in northern parts of Anambra State, SE Nigeria," *Sustain. Water Resour. Manag.*, vol. 8, no. 177, 2022, doi: 10.1007/s40899-022-00768-0.

[28] O. Igwe and U. O. Chukwura, "Integrated physicochemical and hydrogeochemical assessment to groundwater quality in Obosi and Onitsha provinces, South-eastern Nigeria," *Environ. Earth Sci.*, vol. 77, no. 263, 2018, doi: 10.1007/s12665-018-7433-3.

[29] J. Chukwuma, V. C. Nnodu, A. Okoye, and C. Emmanuel, "Assessment of roof harvested rainwater in parts of Anambra State for environmental pollution monitoring," *Br. Biotechnol. J.*, vol. 4, no. 10, pp. 1105–1114, 2014, doi: 10.9734/BBJ/2014/11876.

[30] N. P. Iloeje, *A new geography of Nigeria*. Longmans of Nigeria, Ikeja, 1965, p. 221.

[31] American Public Health Association (APHA), *Standard methods for the examination of water and wastewater*, 21st ed., 2006.

[32] M. A. H. Franson, *Standard methods for the examination of water and wastewater*. APHA-AWWA-WPCF, 1975.

[33] A. K. De, *Environmental chemistry*, 7th ed., New Age International, India, pp. 234–259, 2010, ISBN: 978-81-224-2617-5.

[34] R. M. Verma, *Analytical chemistry theory and practice*, 3rd ed., CBS Publishers, New Delhi, India, pp. 463–467, 2010.

[35] J. G. Cappuccino and N. Sherman, *Microbiology: A laboratory manual*, 7th ed., Darling Kindersley, India, 2009.

[36] D. R. Arora and B. B. Arora, *Textbook of Microbiology*, 4th ed., CBS Publishers, New Delhi, India, pp. 40–49, 2008.

[37] J. R. Bragg, R. C. Prince, J. B. Wilkinson, and R. M. Atlas, "Bioremediation for shoreline cleanup following 1989 Alaskan oil spill," Exxon Cooperation, Houston, pp. 2–3, 2012.

[38] A. K. Batabyal and S. Chakraborty, "Hydrogeochemistry and water quality index in the assessment of groundwater quality for drinking uses," *J. Water Environ. Res.*, vol. 87, no. 7, pp. 607–617, 2015, doi: 10.2175/106143015X14212658613956.

[39] World Health Organization (WHO), *World Health Organization guidelines for drinking-water quality*, 4th ed., 2017.

[40] World Health Organization (WHO), "Section 1: Managing the quality of drinking water sources," 2006.

[41] P. Ravikumar, M. Aneesul Mehmood, and R. Somashekar, "Water quality index to determine the surface water quality of Sankey Tank and Mallathahalli Lake, Bangalore urban district, Karnataka, India," *Appl. Water Sci.*, vol. 3, pp. 247–261, 2013.

[42] A. O. Alsuhaimi, K. M. Almohaimidi, and K. A. Momani, "Preliminary assessment for physicochemical quality parameters of groundwater in Oqdus Area, Saudi Arabia," *J. Saudi Soc. Agric. Sci.*, vol. 18, no. 1, pp. 22–31, 2019, doi: 10.1016/j.jssas.2016.12.00.

[43] World Health Organization (WHO), *Guidelines for drinking water quality*, Geneva, 2011. [Online]. Available: http://www.who.int/water_sanitation_health/publications/2011/9789241548151_ch08.pdf?ua=1.

[44] L. V. Wilcox, *Classification and use of irrigation waters*, US Dept. Agric., Circular 96919, 1955.

[45] I. Khodapanah, W. N. A. Sulaiman, and N. Khodapanah, "Groundwater quality assessment for different purposes in Eshtehard District, Tehran-Iran," *Eur. J. Sci. Res.*, vol. 36, no. 4, pp. 543–553, 2009.

[46] S. Gupta, A. Kumar, C. K. Ojha, and G. Singh, "Journal of Environmental Science and Engineering," *J. Environ. Sci. Eng.*, vol. 46, no. 1, pp. 74–78, 2004.

[47] L. Elango, R. Kannan, and K. Senthil, "Major ion chemistry and identification of hydrogeochemical process of groundwater in a part of Kancheepuram District, Tamil Nadu, India," *J. Environ. Geosci.*, vol. 10, pp. 157–166, 2003.

[48] A. Jafar Ahamed, K. Loganathan, and R. Jayakumar, "Hydrochemical characteristics and quality assessment of groundwater in Amaravathi river basin of Karur district, Tamil Nadu, South India," *Sustain. Water Resour. Manag.*, vol. 1, pp. 273–291, 2015, doi: 10.1007/s40899-015-0026-3.

[49] T. Wenfeng, L. Fan, F. Xionghan, H. Qiaoyun, and L. Xueyuan, "Adsorption and redox reactions of heavy metals on Fe–Mn nodules from Chinese soils," *J. Colloid Interface Sci.*, vol. 284, pp. 600–605, 2005.

[50] World Health Organization, *Guidelines for drinking water quality*, 2nd ed., vol. 1: Microbiological Methods, Geneva, 2001.

[51] World Health Organization, *Water Quality and Health: Drinking water chlorination – A review of disinfection practices and issues*, 2014.

[52] P. Li, J. Wu, and H. Qian, "Assessment of groundwater quality for irrigation purposes and identification of hydrogeochemical evolution mechanisms in Pengyang County, China," *Environ. Earth Sci.*, vol. 69, pp. 2211–2225, 2013.

[53] N. Ekwe-Testimony and U. Chukwura-Osoagba, "Assessment of the causes and impacts of pollution at the Obosi automobile junk market, Southeastern Nigeria," *Asian Rev. Civ. Eng.*, vol. 14, no. 1, pp. 27–36, 2025, doi: 10.70112/tarce-2025.14.1.4260.

[54] N. Ekwe-Testimony, M. C. Nwachukwu, and U. Chukwura-Osoagba, "An investigation of Nwangene River pollution in Onitsha, Anambra State, Southeastern Nigeria: Causes, effects, and preventive and remedial approaches," *Asian Rev. Civ. Eng.*, vol. 14, no. 1, pp. 9–19, 2025, doi: 10.70112/tarce-2025.14.1.4257.

[55] S. H. Mahmud and K. K. Islam, "Analysis of pollution sources and control measures for the Karatoa River: A comprehensive study on water quality and remediation strategies," *Asian Rev. Civ. Eng.*, vol. 13, no. 1, pp. 16–21, 2024.