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Hydrogeochemical Characteristics of Surface and Groundwater from Eleme Communities in Rivers State

Ideriah, T. J. [a], Boisa, N. [a], Oyor, O. N. [a], Bull, O. S. [a] and Ibirinde, A. O. [b*]

[a] Rivers State University, Port Harcourt, Rivers State, Nigeria.
[b] University of Port Harcourt, Port Harcourt, Rivers State, Nigeria.

Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Surface and groundwater are critical sources of fresh water globally, essential for drinking and agricultural purposes. However, both sources are increasingly affected by pollution from industrial activities and urban runoff, which introduces toxic metals and contaminants. This study focuses on Eleme Local Government Area in Rivers State, Nigeria, where water sources are heavily contaminated by chemical and petrochemical products from major local industries. The analysis reveals that groundwater pH is consistently acidic (4.1-6.1), falling below WHO permissible limits, indicating a need for treatment before usage. Seasonal variations affect temperature, conductivity, and TDS, with increased levels during the dry season. Total solids concentration in surface water in the area is high and above WHO limits with TDS level of Aleto River (5970.40-11454mg/L) and Agbonchia River (89.8-91.20 mg/L), and TSS level of Aleto River (89.8-91.20mg/L) and Agbonchia

**Corresponding author: Email: ibirinde2000@yahoo.com;*

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River (81.0 mg/L). Also, turbidity in the area surface water was found to be elevated and exceeding WHO limit with Aleto River (74.44-89.0 NTU) and Agbonchia River (31-71 NTU). Elevated chloride, calcium, and magnesium levels, along with high oil/grease concentrations during the dry season, signal the need for remediation. Cadmium (Aleto Rivers:0.004mg/L, Agbonchia River: 0.004-0.005mg/L) and Iron (Aleto Rivers:1.98-2.35mg/L, Agbonchia River: 1.05-1.695mg/L), concentrations in surface water also surpass WHO limits, highlighting significant contamination issues. This study provides essential data on water quality in Eleme, underscoring the importance of addressing contamination to protect human health and ensure access to safe drinking water.

Keywords: Groundwater; surface water; eleme communities.

1. INTRODUCTION

Surface water and groundwater are essential sources of fresh water for human populations worldwide, serving as primary sources for drinking water [1]. Surface water is further categorized into running bodies like brooks, streams, and rivers, and stationary bodies like lakes and ponds [1]. Both surface and groundwater are increasingly polluted by human activities, including industrial waste and urban run-off, leading to contamination with toxic metals [1]. Groundwater contamination poses a significant threat to water resources, especially as groundwater constitutes a substantial portion of global fresh water and is a vital source of drinking water [2]. Various studies focus on assessing groundwater contamination, such as through vulnerability mapping [3] risk assessment based on pollution loading [4] and identifying contamination sources using advanced techniques like principal component analysis and geostatistics [2]. Groundwater contamination can result from various sources, including agricultural activities like irrigation [5] industrial processes [6] and landfill leachate [7]. On the other hand, surface water pollution is a pressing issue that requires attention to protect ecosystems and human health [8].

Just like everywhere in the world, communities in Eleme Local Government Area, Rivers State heavily rely on surface and groundwater for domestic and agricultural purposes. Unfortunately, these water sources have been significantly contaminated by chemical and petrochemical products from the activities of oil and gas companies in the region [9]. Industries such as the Port Harcourt Refinery Company, Alesa Eleme, Indorama Eleme Petrochemical Company Limited, Notore Chemicals Limited, and Indorama Fertilizer Chemicals Limited have been identified as major contributors to the pollution of water sources in Eleme and neighboring communities in Khana, Gokana, Ogu/Bolo, and Okrika local governments [10,9]. This contamination has made the groundwater in the area unsafe for human consumption [11]. The residents of Eleme Local Government Area, Rivers State, are exposed to contaminated surface and groundwater, increasing their susceptibility to various diseases and infections. This issue is exacerbated by the fact that these water sources serve as the primary sources of drinking water in the region, contributing to approximately 80% of infections in countries like Nigeria due to poor water quality and unhygienic conditions. The study provided the crucial data for understanding the water quality in Eleme Local Government Area, Rivers State, and assessing the associated health risks of consuming water from these sources. Understanding the hydrogeochemical characteristics of the water sources is vital for implementing effective water management strategies and ensuring access to safe drinking water for communities in Eleme.

2. MATERIALS AND METHODS

2.1 Study Area

Eleme Local Government Area is one of the twenty-three local government areas of Rivers State. Located geographical on latitude 4°44' N and longitude 7°15'E. It consists of ten communities namely; Ogale, Alode, Aleto, Agbonchia, Akpajo, Ebubu, Alesa, Onne, Ekporo and Eteo. However, nine communities, Ogale, Alode, Aleto, Agbonchia, Akpajo, Ebubu, Alesa, Onne, and Eteo, were sampled in this study as Ekporo had communal crisis during the study period hence was excluded in the study. It is a crude oil producing local government with presence of oil and gas, petrochemical, and fertilizer industries. Apart from major oil companies like SPDC, Mobil etc., the local government also host Port Harcourt refinery company, Alesa Eleme; Indorama Eleme Petrochemical Company Limited; Notore Chemicals Limited; and Indorama Fertilizer Chemicals Ltd.

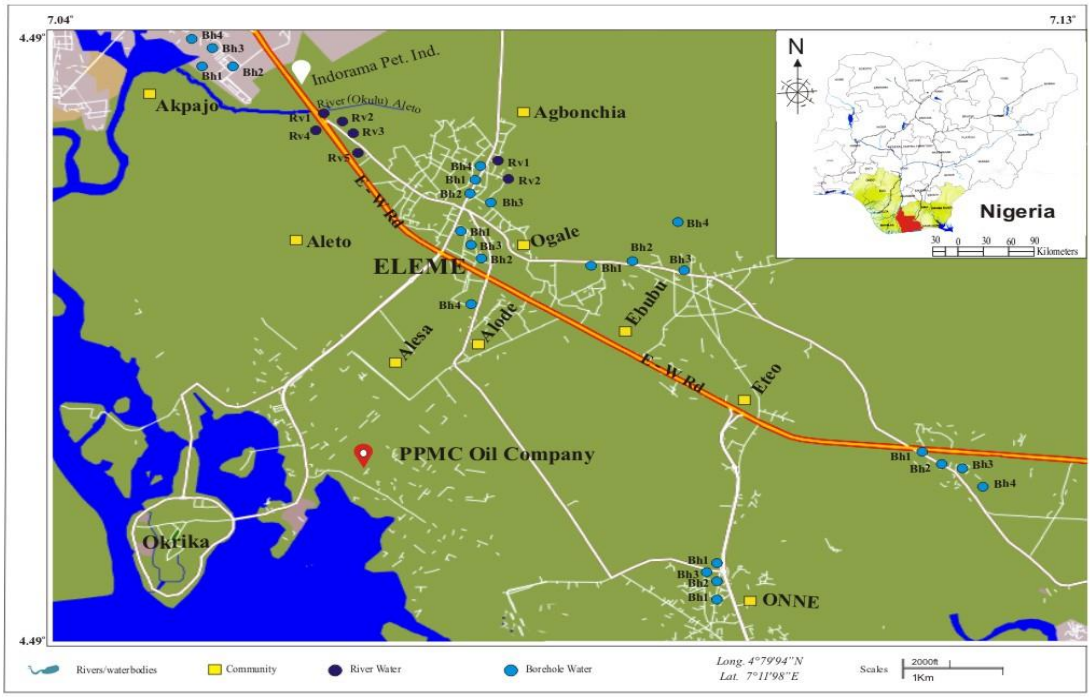

Fig. 1. Map of Eleme communities showing the sampling locations

2.2 Sample Collection and Processing

The procedure for sample collection began with a survey of the communities in the study area. The survey identified functional streams, wells and boreholes frequently used by the people, before sample collection. All plastic bottles were washed thrice with the sample water before the samples were taken.

For groundwater samples, boreholes with depth of 100-150 meters frequently used by inhabitants of the communities were identified and sampled for the study. Four boreholes from each community were selected for sampling, a total of 36 boreholes were sampled for the study. The selected boreholes from each community were selected in a manner that every part of the community was adequately represented in the sampling. Samples were collected from the boreholes at the borehole heads. The boreholes were allowed to pump for 15 minutes in order to achieve an approximate constant temperature and pH before samples were taken. Water samples were collected in 1 litre plastic bottles. For surface water samples, samples from the rivers (Aleto and Agbonchia) were collected in the morning (when minimum activity was taking place). Samples were collected from Aleto and Agbonchia at the top depth of 10metres and 20 metres respectively. All samples were collected in June (rainy season) and November (Dry season) of 2021. After sampling, the containers were tightly covered and appropriately labelled and transported to the laboratory.

2.3 Analytical Methods

Collected samples were investigated as per standard methods recommended by American Society for Testing and Materials (ASTM, 2010) and American Public Health Association (APHA, 1995). The study analysed twenty-eight physico-chemical parameters of both surface and groundwater present in the study area. The twenty-eight parameters are: pH, conductivity, temperature, total dissolved solid, total suspended solid, turbidity, electrical conductivity, nitrite ion concentration, calcium ion concentration, magnesium ion concentration, total hydrocarbon concentration, sodium ion concentration, chloride ion concentration, Polycyclic Aromatic Hydrocarbons (PAHs), phosphate ion concentration, total hardness, oil/grease concentration, biochemical oxygen demand, chemical oxygen demand, carbonate ion concentration, salinity, cadmium ion concentration, lead ion concentration, iron ion concentration, nickel ion concentration, copper ion concentration, manganese ion concentration and arsenic ion concentration.

3. RESULTS AND DISCUSSION

3.1 Physico-chemical Parameters

3.1.1 pH

The groundwater pH in Eleme ranges from 4.1-6.1 during the rainy season, with Onne having the lowest (4.1±0.18) and Akpajo the highest (6.1±0.58) (see Table 1). In the dry season, pH ranges from 5.2-6.4, with Alesa and Aleto at the low end (5.2±0.34) and Ogale and Alode at the high end (6.4±0.33) (see Table 2). The pH increases slightly during the dry season, but the seasonal difference is not statistically significant at the 0.05 level (see Tables 4 and 5). The groundwater is acidic, typical of tropical regions. Comparisons with other studies [12,10,13] performed in the study area show similar pH levels. Surface water pH ranges from 6.4-6.7 in the rainy season and 6.6-6.9 in the dry season (see Table 3), indicating it is less acidic than groundwater. Seasonal variations in pH are influenced by changes in aquifer and river levels, as well as photosynthesis, respiration, and organic decomposition, which affect CO_2 levels (Hakanson, 2005). The groundwater's acidity makes it unsuitable for consumption according to WHO standards (6.5-8.5), necessitating treatment before use.

3.1.2 Temperature

The groundwater temperature in Eleme ranges from 28.3-31.1°C during the rainy season, with Ebubu being the lowest (28.3±1.14°C) and Onne the highest (31.1±0.05°C) (see Table 1). In the dry season, it ranges from 30.5-31.7°C, with Eteo at the low end (30.5±0.27°C) and Ogale at the high end (31.3±0.34°C) (see Table 2). For surface water, Aleto River has a temperature of 29.6±0.23°C and Agbonchia River 30.2±0.36°C in the rainy season, while in the dry season, Aleto River is 30.9±0.93°C and Agbonchia River 30.3±0.42°C (see Table 3). Seasonal temperature variations are more pronounced in surface water than in groundwater, with significant differences at the 0.05 level (see Tables 4 and 5). The groundwater temperature during the rainy season aligns with Akuro [13] who reported 25.88°C in Eleme.

3.1.3 Conductivity

Conductivity measures the conductance of an electric current in water, closely related to the total dissolved solids (minerals). In Eleme, groundwater conductivity ranges from 33.75±2.22 to 128.3±63.4 µS/cm during the rainy season, with Ebubu having the lowest and Akpajo the highest values (see Table 1). During the dry season, it ranges from 72±13.14 to 242.25±38.4 µS/cm, with Akpajo at the low end and Aleto at the high end (see Table 2). Conductivity is higher in the dry season due to less dilution from the water table rise during the rainy season. Ebubu's conductivity (33.75±2.22 µS/cm) is lower compared to other studies, such as Sokpuwu [12]. and Akuro [13].

For surface water, Aleto River shows 19904±1155 µS/cm and Agbonchia River 620±0.000 µS/cm during the rainy season, and Aleto River 9270.8±8847.70 µS/cm and Agbonchia River 620±0.000 µS/cm in the dry season (see Table 3). While groundwater conductivity is within WHO permissible limits (1000 µS/cm), surface water, especially from Aleto River, exceeds these limits and is unsuitable for human consumption and aquatic life. Seasonal differences in conductivity for both groundwater and surface water are not statistically significant at the 0.05 level (see Tables 4 and 5).

3.2 Total Dissolved Solids Concentration

The groundwater total dissolved solids (TDS) in Eleme range from 14.50±14.15 to 93.8±43.8 mg/L during the rainy season, with Agbonchia having the lowest and Akpajo the highest values (see Table 1). During the dry season, TDS ranges from 49.25±27.32 to 168.75±26.55 mg/L, with Akpajo at the low end and Aleto at the high end (see Table 2). TDS is higher in the dry season due to reduced dilution from the water table rise during the rainy season. Ebubu's rainy season TDS (51.25±26.29 mg/L) is higher than previous reports by Sokpuwu [12] and Akuro [13]. Similarly, Ogale's TDS (63.75±98.50 mg/L) exceeds the findings of Oyor et al. [10]. For surface water, Aleto River shows 11454±725 mg/L and Agbonchia River 174.5±7.78 mg/L during the rainy season, and Aleto River 5970.40±5553.77 mg/L and Agbonchia River 20.5±6.36 mg/L in the dry season (see Table 3). Groundwater TDS levels are within the permissible limit of 2000 mg/L. However, Aleto River's TDS exceeds WHO limits in both seasons, making it unsuitable for human consumption and aquatic life. Seasonal differences in groundwater TDS are significant at the 0.05 level, while surface water variations are not (see Tables 4 and 5).

Table 1. Concentration of physicochemical parameters of eleme communities' groundwater (rainy season)

Parameter	Mean Alesa	Mean Alode	Mean Onne	Mean Ebubu	Mean Ogale	Mean Eteo	Mean Aleto	Mean Akpajo	Mean Agbonchia	WHO Limit
pH	4.9±0.59	5.1±0.13	4.1±0.18	4.9±0.18	5.4±0.5	4.9±0.53	5.3±0.311	6.1±0.580	4.8±0.403	6.5 -8.5
Cond (µS/cm)	50.0±14.14	38.5±6.24	76.5±63.3	33.8±2.22	109.3±44.5	49.5±13.9	59.5±9.3	128.3±63.4	72.3±3.30	1000.0
Temp (ºC)	30.7±0.35	29.5±0.263	31.1±0.05	28.3±1.14	29.2±0.28	30.2±0.13	28.6±0.25	30.1±0.12	30.7±0.47	29 –32
TDS (mg/l)	33.5±3.70	17.3±2.22	56.3±17.75	17.3±2.22	32.5±24.9	35±3.74	36.8±4.57	93.8±43.8	14.5±14.2	2000
TSS (mg/l)	1.0±0.82	3.8±1.71	<DL	2.3±2.22	22.5±21.5	2.0±0.82	3.5±1.29	10.5±2.1	<DL	30
Turb (NTU)	0.3±0.11	0.4±0.50	0.1±0.01	0.3±0.08	6.3±4.43	0.4±0.13	0.5±0.10	0.7±0.40	0.2±0.04	5
NO_3^- (mg/l)	0.02±0.01	0.01±0.003	0.01±0.003	0.1±0.02	0.02±0.01	0.03±0.01	0.03±0.01	0.01±0.003	0.01±0.01	50
Ca^{2+} (mg/l)	1.6±0.62	0.8±0.18	1.0±0.06	0.06±0.02	0.04±0.02	0.07±0.02	0.09±0.01	0.08±0.01	1.2±0.52	100
Mg^{2+} (mg/l)	0.1±0.01	0.03±0.002	0.1±0.04	0.03±0.003	0.1±0.035	0.07±0.01	0.08±0.01	0.05±0.02	0.1±0.06	30
THC (mg/l)	<0.01±0.00	<DL	<DL	<DL	<DL	<0.01 ±0.00	<0.01±0.00	<0.01±0.000	<0.01±0.00	10
Na^+ (mg/l)	3.6±0.16	3.8±0.20	0.5±0.11	2.1±0.71	1.6±0.32	1.5±0.01	2.1±0.80	1.4±0.071	4.0±0.21	200
Cl^- (mg/l)	13.1±0.47	10.5±0.50	15.3±0.29	9.0±0.47	8.2±1.02	13.1±0.46	13.1±1.03	6.1±0.14	6.6±0.36	250
PAHs (µg/l)	<0.01±0.00	<DL	<DL	<DL	<DL	<0.01±0.000	<DL	<0.01±0.000	<0.01±0.00	0.10
PO_4^{3-} (mg/l)	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	5
T/Hardness (mg/l)	1.9±1.05	1.8±0.96	2.3±0.96	0.6±0.48	0.0004±0.0004	0.0012±0.0004	<DL	0.0001±0.001	0.6±0.17	400
Oil/grease (mg/l)	<0.01±0.00	<DL	<DL	<DL	<DL	<0.01±0.000	<DL	<0.01±0.000	<0.01±0.00	10
CO_3^{2-} (mg/l)	1.3±0.74	1.3±0.6	1.6±0.62	0.3±0.28	0.01±0.001	0.04±0.01	0.02±0.003	0.01±0.003	0.8±0.17	120
Salinity (mg/l)	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	<DL	600

Table 2. Concentration of physicochemical parameters of eleme communities' groundwater (dry season)

Parameter	Mean Alesa	Mean Alode	Mean Onne	Mean Ebubu	Mean Ogale	Mean Eteo	Mean Aleto	Mean Akpajo	Mean Agbonchia	WHO Limit
pH	5.2±0.340	6.4±0.495	5.3±0.520	6.2±0.365	6.4±0.333	5.4±.378	5.2±0.082	5.9±0.050	5.8±0.510	6.5 -8.5
Cond(µS/cm)	82.50±6.24	77±0.035	81.25±43.99	69.75±40.26	92.50±143.41	87.25±5.85	242.25±38.4	72±13.14	73.25±40.48	1000.0
Temp (ºC)	30.8±0.265	31.1±0.13	31.65±1.14	30.6±1.053	31.3±0.342	30.5±0.265	30.7±0.275	31.1±0.258	31.0±0.050	29 – 32
TDS (mg/l)	62.25±7.93	54±24.28	65±20.93	51.25±26.29	63.75±98.50	82.75±8.96	168.75±26.55	90.75±9.07	49.25±27.32	2000
TSS (mg/l)	2.50±1.29	7.25±1.71	4.75±2.50	2.75±0.957	26.50±10.85	2±0.817	7.5±1.29	4.75±1.71	0.425±0.250	30
Turb (NTU)	0.523±0.141	0.500±0.082	0.223±0.038	0.625±0.150	1.60±1.81	0.393±0.132	0.600±0.082	0.778±0.364	0.625±0.096	5
NO_3^- (mg/l)	0.030±0.010	1.38±0.498	0.018±0.003	1.03±0.175	1.15±0.669	0.035±0.006	1.72±0.812	1.75±0.510	<DL	50
Ca^{2+} (mg/l)	2.70±1.15	1.06±0.088	1.25±0.234	0.047±0.013	0.051±0.018	0.072±0.016	0.110±0.025	0.074±0.043	1.24±0.518	100
Mg^{2+} (mg/l)	0.741±0.859	0.040±0.009	0.075±0.037	0.021±0.004	0.074±0.018	0.071±0.012	0.093±0.005	0.092±0.011	0.105±0.064	30
THC (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	10
Na^+ (mg/l)	3.52±0.637	3.98±1.04	0.749±0.330	1.97±0.785	1.95±0.328	1.98±0.192	2.28±0.455	1.90±0.084	3.99±0.206	200

Parameter	Mean Alesa	Mean Alode	Mean Onne	Mean Ebubu	Mean Ogale	Mean Eteo	Mean Aleto	Mean Akpajo	Mean Agbonchia	WHO Limit
Cl^- (mg/l)	19.50±1.54	3.95±1.17	15.25±0.293	3.70±1.39	8.68±7.57	27.63±3.11	16.45±6.97	6.08±0.502	4.55±0.810	250
PAHs (µg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.10
PO_4^{3-} (mg/l)	0.225±0.150	0.073±0.013	<DL	0.310±0.305	0.0400±0.00	0.020±0.012	0.040±0.000	0.012±0.005	<DL	5
T/Hardness (mg/l)	2.75±1.06	1.52±0.606	3.0±0.807	0.473±0.424	0.0007±0.0004	0.004±0.003	0.001±0.001	0.004±0.003	4.01±0.096	400
Oil/grease (mg/l)	<0.01	58.96±45.59	1.31±0.586	18.12±7.62	20.20±20.24	<0.01	41.08±41.17	<0.01±0.000	21.72±12.61	10
CO_3^{2-} (mg/l)	1.59±1.11	2.04±0.789	3.04±0.820	0.222±0.226	0.018±0.007	0.048±0.008	0.024±0.004	0.014±0.004	1.09±0.130	120
Salinity (mg/l)	0.045±0.024	0.035±0.017	7.5±3.70	0.035±0.017	0.045±0.064	0.025±0.013	0.115±0.017	0.055±0.027	0.035±0.017	600

Table 3. Concentration of physicochemical parameters in eleme communities' surface water

Parameter	Mean Aleto River		Mean Agbonchia River		WHO Permissible Limit
	Rainy season	Dry season	Rainy season	Dry season	
pH	6.7±042	6.9±0.089	6.4±0.283	6.6±0.071	6.5 – 8.5
Cond (µS/cm)	19904±1155	9270.8±8847.7	620	620	1000.0
Temp (ºC)	29.6±0.228	30.9±0.928	30.3±0.354	30.2±0.424	29 – 32
TDS (mg/l)	11454±725	5970.40±5553.77	174.5±7.78	20.5±6.36	2000
TSS (mg/l)	89.8±5.63	91.20±8.32	81	81	30
Turb (NTU)	89.0±5.57	74.44±99.56	71±4.24	31±38.18	5
NO_3^- (mg/l)	2.9±1.72	1.82±2.02	0.55±0.629	0.96±0.050	50
Ca^{2+} (mg/l)	50.26±6.16	47.14±6.80	15.35±1.63	17.05±0.778	100
Mg^{2+} (mg/l)	16.26±10.33	12.64±3.63	12.5±0.495	12.20±0.849	30
THC (mg/l)	<0.01	<0.01	<0.01	<0.01	10
Na^+ (mg/l)	31.36±6.90	30.06±6.81	31±0.566	32.05±0.919	200
Cl^- (mg/l)	65.30±3.01	912.68±1306.1	27.1±32.60	2.50±2.12	250
PAHs (µg/l)	<0.01	<0.01	<0.01	<0.01	0.10
COD (mg/l)	29.2±2.28	44±12.33	29.5±10.61	39.50±3.54	80
BOD (mg/l)	7.0±0.29	7.30±0.752	6.3±0.212	6.7±0.354	50
PO_4^{3-} (mg/l)	2.1±0.46	0.7±0.447	0.370±0.438	0.060	5
T/Hardness (mg/l)	155.0±32.1	158.44±17.63	145.8±4.38	140.1±3.68	400
Oil/grease (mg/l)	<0.01	60.75±40.76	<0.01	32.05±3.97	10
CO_3^{2-} (mg/l)	6.08±1.52	7.76±3.35	1.4±0.354	1.70±0.141	120
Salinity (%)	4.50±4.29	12.54±0.594	0.015±0.007	6.3±0.919	600

Table 4. Seasonal differences of eleme ground water physicochemical parameters

Parameter	Rainy season versus Dry season
	p-value
pH	.747
Cond (µS/cm)	.073
Temp (°C)	.000*
TDS (mg/l)	.032*
TSS (mg/l)	.936
Turb (NTU)	.012*
NO_3^- (mg/l)	.000*
Ca^{2+} (mg/l)	.071
Mg^{2+} (mg/l)	.033*
Na^+ (mg/l)	.318
Cl^- (mg/l)	.000*
PO_4^{3-} (mg/l)	.000*
T/Hardness (mg/l)	.022*
Oil/grease (mg/l)	.000*
CO_3^{2-} (mg/l)	.010*
FCB (MPN/100ml)	.022*
TCB (MPN/100ml) ppb	.000*
THB (cfu/ml)	.700
Salinity (mg/l)	0.001*

**. Correlation is significant at the 0.05 level*

Table 5. Seasonal differences of Eleme surface water physicochemical parameters

Parameter	Rainy season versus Dry season
	p-value
pH	.085
Cond (µS/cm)	.713
Temp (°C)	.000*
TDS (mg/l)	.963
TSS (mg/l)	.202
Turb (NTU)	.044*
NO_3^- (mg/l)	.616
Ca^{2+} (mg/l)	.678
Mg^{2+} (mg/l)	.177
THC	.959
Na^+ (mg/l)	.003*
Cl^- (mg/l)	.091
PAHs (µg/l)	.108
COD (mg/l)	.117
BOD (mg/l)	.581
PO_4^{3-} (mg/l)	.011*
T/Hardness (mg/l)	.271
Oil/grease (mg/l)	.000*
CO_3^{2-} (mg/l)	.010*
FCB (MPN/100ml)	.362
TCB (MPN/100ml) ppb	.000*
THB (cfu/ml)	.000*
Salinity (mg/l)	.066

**. Correlation is significant at the 0.05 level*

Table 6. Concentration of elements in boreholes from the study area (rainy season)

Parameter	Mean Alesa	Mean Alode	Mean Onne	Mean Ebubu	Mean Eteo	Mean Aleto	Mean Akpajo	Mean Agbonchia	Mean Ogale	WHO Limit
Cd^{2+} (mg/l)	0.0003±0.0001	0.001±0.000	0.0002±0.0001	0.0001±0.0001	0.0003±0.0001	0.0002±0.0001	0.0001±0.0001	0.089±0.008	0.0002±0.0001	0.003
Pb^{2+} (mg/l)	0.051±0.007	0.077±0.046	0.045±0.0049	0.003±0.0017	0.003±0.0008	0.003±0.0011	0.005±0.0049	0.073±0.005	0.004±0.0014	0.010
Fe^{2+} (mg/l)	0.306±0.467	0.066±0.008	0.040±0.0086	0.095±0.0083	0.005±0.0014	0.006±0.0006	0.002±0.0000	0.007±0.002	0.001±0.0004	0.3
Ni^{2+} (mg/l)	0.057±0.014	0.074±0.003	0.078±0.0112	0.083±0.0083	0.004±0.0008	0.004±0.0006	0.002±0.0062	0.0003±0.0001	0.002±0.0010	0.07
Cu^{2+} (mg/l)	0.0003±0.0001	0.0003±0.0001	0.0001±0.0001	0.0007±0.0002	0.0002±0.0001	0.0051±0.0005	0.0001±0.000	0.162±0.033	0.0001±0.000	2
Mn^{2+} (mg/l)	0.042±0.011	0.040±0.033	0.117±0.0760	0.011±0.0021	0.004±0.0006	0.006±0.0024	0.003±0.0006	<0.001±0.000	0.003±0.0015	0.40
As^{3+} (µg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.0010

Table 7. Concentration of measured elements in Eleme communities' groundwater (dry season)

Parameter	Mean Alesa	Mean Alode	Mean Onne	Mean Ebubu	Mean Ogale	Mean Eteo	Mean Aleto	Mean Akpajo	Mean Agbonchia	WHO Limit
Cd^{2+} (mg/l)	0.0001±0.000	0.0001±0.000	0.0006±0.0002	0.0001±0.0001	0.0003±0.0001	0.0002±0.0001	0.0006±0.0009	0.0002±0.0001	<DL	0.003
Pb^{2+} (mg/l)	0.055±0.009	0.114±0.006	0.048±0.0052	0.003±0.0012	0.004±0.0010	0.002±0.001	0.002±0.0004	0.005±0.0050	0.088±0.0120	0.010
Fe^{2+} (mg/l)	0.065±0.014	0.079±0.009	0.045±0.0106	0.294±0.4324	0.002±0.0008	0.004±0.001	0.006±0.001	0.003±0.0010	0.071±0.0076	0.3
Ni^{2+} (mg/l)	0.055±0.011	0.074±0.003	0.086±0.0151	0.073±0.0076	0.003±0.0012	0.003±0.001	0.003±0.001	0.002±0.0009	0.006±0.0022	0.07
Cu^{2+} (mg/l)	0.0001±0.000	0.0001±0.000	0.0003±0.0002	0.0005±0.0001	0.0002±0.0001	0.0001±0.000	0.0057±0.002	0.0003±0.0001	0.0001±0.0000	2
Mn^{2+} (mg/l)	0.029±0.011	0.021±0.004	0.122±0.0912	0.011±0.0011	0.004±0.0014	0.004±0.002	0.004±0.001	0.004±0.0004	0.172±0.0135	0.40
As^{3+} (µg/l)	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001

DL=Detectable limit

Table 8. Seasonal differences of Eleme ground water heavy metals parameters

	Rainy season versus Dry season
Parameter	**p-value**
Cd^{2+} (mg/l)	.992
Pb^{2+} (mg/l)	.338
Fe^{2+} (mg/l)	.895
Ni^{2+} (mg/l)	.834
Cu^{2+} (mg/l)	.746
Mn^{2+} (mg/l)	.923

**. Correlation is significant at the 0.05 level*

Table 9. Concentration of measured elements in eleme communities' surface water

Parameter	Aleto River		Agbonchia River		WHO Permissible Limit
	Rainy season	Dry season	Rainy season	Dry season	
Cd^{2+} (mg/l)	0.004±0.0015	0.004±0.001	0.004±0.0004	0.005±0.001	0.003
Pb^{2+} (mg/l)	0.002±0.0003	0.002±0.0002	0.002±0.0004	0.002±0.0001	0.010
Fe^{2+} (mg/l)	1.98±0.438	2.35±1.31	1.05±0.0141	1.695±0.233	0.3
Ni^{2+} (mg/l)	0.001±0.0005	0.002±0.0006	0.005±0.0003	0.002±0.0003	0.07
Cu^{2+} (mg/l)	0.152±0.143	0.175±0.201	0.861±0.057	0.851±0.018	2
Mn^{2+} (mg/l)	0.734±0.224	1.01±0.389	0.647±0.050	0.650±0.010	0.40
As^{3+} (µg/l)	<0.001	<0.001	<0.001	<0.001	0.0010

Table 10. Seasonal differences of Eleme surface water heavy metals parameters

Parameter	Rainy season versus Dry season
	p-value
Cd^{2+} (mg/l)	.821
Pb^{2+} (mg/l)	.141
Fe^{2+} (mg/l)	.144
Ni^{2+} (mg/l)	.488
Cu^{2+} (mg/l)	.490
Mn^{2+} (mg/l)	.055

**. Correlation is significant at the 0.05 level*

3.3 Total Suspended Solids Concentration

The groundwater total suspended solids (TSS) in Eleme range from 0-22.5±21.5 mg/L during the rainy season, with Onne and Agbonchia having the lowest (ND) and Ogale the highest values (see Table 1). In the dry season, TSS ranges from 0.425±0.250 to 7.5±1.29 mg/L, with Agbonchia at the low end and Aleto at the high end (see Table 2). Ebubu's rainy season TSS (2.25±2.22 mg/L) is higher than Sokpuwu's [12] findings (<0.0001 mg/L), while Ogale's TSS (26.50±10.85 mg/L) is comparable to Oyor et al. [10]. (25.3±0.77 mg/L). For surface water, Aleto River has TSS values of 89.8±5.63 mg/L in the rainy season and 91.20±8.32 mg/L in the dry season (see Table 3). Agbonchia River shows 81±0.000 mg/L for both seasons (see Table 3). Seasonal differences in TSS for both groundwater and surface water are not significant at the 0.05 level (see Table 4 and 5). Groundwater TSS levels in all communities are within WHO permissible limits (30 mg/L), indicating no need for treatment. However, TSS levels in Aleto and Agbonchia Rivers exceed permissible limits, making them unsuitable for human consumption and aquatic life without treatment.

3.3.1 Turbidity

Groundwater turbidity in Eleme ranges from 0.14±0.009 to 6.25±4.43 NTU during the rainy season, with Onne having the lowest and Ogale the highest values (see Table 1). In the dry season, turbidity ranges from 0.223±0.038 to 1.60±1.81 NTU, with Onne at the low end and Ogale at the high end (see Table 2). Ebubu's rainy season turbidity (0.27±0.075 NTU) is higher

than that reported by Sokpuwu [12] (<0.0001 NTU), while Ogale's turbidity (1.60±1.81 NTU) is lower than that reported by Oyor et al. [10] (25±0.6 NTU) during the dry season. For surface water, Aleto River has turbidity values of 89.0±5.57 NTU during the rainy season and 74.44±99.56 NTU in the dry season (see Table 3). Agbonchia River shows 71±4.24 NTU for the rainy season and 31±38.18 NTU for the dry season (see Table 3). Seasonal differences in turbidity for both groundwater and surface water are significant at the 0.05 level (see Table 4 and 5). Groundwater turbidity in all communities is within WHO permissible limits (5 NTU), indicating no need for treatment. However, turbidity levels in Aleto and Agbonchia Rivers exceed permissible limits, making them unsuitable for human consumption and aquatic life without treatment.

3.3.2 Nitrate concentration (NO_3^-)

Groundwater nitrate concentration in Eleme ranges from 0.009±0.003 to 0.035±0.006 mg/L during the rainy season, with Ebubu having the lowest and Akpajo the highest values (see Table 1). In the dry season, nitrate concentration ranges from 0 to 1.75±0.510 mg/L, with Agbonchia at the low end and Akpajo at the high end (see Table 2). Nitrate levels are higher in the dry season due to reduced dilution from the water table rise during the rainy season. Ebubu's rainy season nitrate concentration (0.07±0.022 mg/L) is lower than that reported by Sokpuwu[12] (16.01±2.93 mg/L). For surface water, Aleto River has nitrate concentrations of 2.9±1.72 mg/L during the rainy season and 1.82±2.02 mg/L in the dry season. Agbonchia River shows 0.545±0.629 mg/L for the rainy season and 0.955±0.050 mg/L for the dry season (see Table 3). Seasonal differences in groundwater nitrate concentrations are significant at the 0.05 level, while surface water variations are not (see Tables 4 and 5). Both groundwater and surface water nitrate concentrations in all communities are within WHO permissible limits (50 mg/L), indicating no need for treatment.

3.3.3 Calcium ion (Ca^{2+}) concentration

Groundwater calcium ion concentrations in Eleme range from 0.04±0.023 to 1.55±0.620 mg/L during the rainy season, with Onne and Agbonchia having the lowest and Alesa the highest values (see Table 1). In the dry season, concentrations range from 0.047±0.013 to 2.70±1.15 mg/L, with Ebubu at the low end and Alesa at the high end (see Table 2). Ebubu's rainy season calcium ion concentration (2.25±2.22 mg/L) is higher than that reported by Sokpuwu [12] (<0.0001 mg/L). Ogale's concentration (26.50±10.85 mg/L) is comparable to Oyor et al. [10] (25.3±0.77 mg/L). For surface water, Aleto River shows calcium ion concentrations of 47.14±6.80 mg/L during the rainy season and 91.20±8.32 mg/L in the dry season while Agbonchia River shows 17.05±0.778 mg/L for the rainy season and 81±0.000 mg/L for the dry season (see Table 3). Seasonal differences in calcium ion concentrations for both groundwater and surface water are significant at the 0.05 level (see Tables 4 and 5). Groundwater calcium ion concentrations in all communities are within WHO permissible limits (30 mg/L), indicating no need for treatment. However, calcium ion concentrations in both Aleto and Agbonchia Rivers exceed permissible limits in both seasons, making them unsuitable for human consumption and aquatic life without treatment.

3.3.4 Magnesium ion (Mg^{2+}) concentration

Groundwater magnesium ion concentrations in Eleme range from 0.030±0.003 to 0.105±0.064 mg/L during the rainy season, with Ebubu having the lowest and Agbonchia the highest values (see Table 1). During the dry season, concentrations range from 0.021±0.004 to 0.105±0.064 mg/L, with Ebubu at the low end and Agbonchia at the high end (see Table 2). Ebubu's rainy season magnesium ion concentration (0.030±0.003 mg/L) is lower than that reported by Sokpuwu [12] (2.35±0.92 mg/L). The finding for Ogale (2.35±0.92 mg/L) is comparable to Oyor et al. [10] (25.3±0.77 mg/L). For surface water, Aleto River shows magnesium ion concentrations of 16.26±10.33 mg/L during the rainy season and 12.64±3.63 mg/L in the dry season. Agbonchia River has 12.45±0.495 mg/L for the rainy season and 12.20±0.849 mg/L for the dry season (see Table 3). Seasonal differences in groundwater magnesium concentrations are significant at the 0.05 level, while surface water variations are not (see Tables 4 and 5). Groundwater magnesium ion concentrations in all communities are within WHO permissible limits (30 mg/L), so no treatment is needed. However, magnesium ion concentrations in Aleto and Agbonchia Rivers exceed permissible limits, making them unsuitable for human consumption and aquatic life without treatment.

3.3.5 Total hydrocarbon concentration

For surface water, the study reported total hydrocarbon concentration of Aleto River and Agbonchia River to be (<0.01±0.000 mg/l) for both rainy season and dry season (see Table 3). However, the seasonal variation of the surface water hydrocarbon concentration is not significant at 0.05 significance level (see Table 4 and 5). Both groundwater and surface water total hydrocarbon concentration in all the communities in Eleme are within WHO permissible limits (30 mg/l) hence there is no need for treatment.

3.4 Sodium ($Na^{+)}$ Concentration

Groundwater sodium (Na+) concentrations in Eleme range from 0.48±0.11 to 3.99±0.206 mg/L during the rainy season, with Onne having the lowest and Agbonchia the highest values (see Table 1). In the dry season, concentrations range from 0.749±0.330 to 3.99±0.206 mg/L, with Onne at the low end and Agbonchia at the high end (see Table 2). Ebubu's rainy season Na+ concentration (2.11±0.71 mg/L) is higher than that reported by Sokpuwu [12] (10.21±4.66 mg/L). For surface water, Aleto River has Na+ concentrations of 31.36±6.90 mg/L during the rainy season and 30.06±6.81 mg/L in the dry season while Agbonchia River shows 31±0.566 mg/L for the rainy season and 32.05±0.919 mg/L for the dry season (see Table 3). Seasonal differences in sodium ion concentrations are significant for surface water at the 0.05 level, while groundwater differences are not (see Tables 4 and 5). Both groundwater and surface water Na+ concentrations in all communities are within WHO permissible limits (200 mg/L), so no treatment is required.

3.5 Chloride (Cl^-) Concentration

The groundwater chloride (Cl^-) concentrations in Eleme range from 6.11±0.137 to 19.50±1.54 mg/L during the rainy season, with Akpajo having the lowest and Eteo and Aleto the highest values (see Table 1). In the dry season, concentrations range from 3.70±1.39 to 19.50±1.54 mg/L, with Ebubu at the low end and Alesa at the high end (see Table 2). Ebubu's rainy season Cl- concentration (9.0±0.467 mg/L) is lower than that reported by Sokpuwu [12] (42.14±25.22 mg/L). For surface water, Aleto River shows Cl^- concentrations of 65.30±3.01 mg/L during the rainy season and 912.68±1306.06 mg/L in the dry season while Agbonchia River has 27.05±32.60 mg/L for the rainy season and 2.50±2.12 mg/L for the dry season (see Table 3). Seasonal differences in groundwater chloride concentrations are significant at the 0.05 level, while surface water differences are not (see Tables 4 and 5). Groundwater Cl^-concentrations are within WHO permissible limits (250 mg/L), so no treatment is needed. However, surface water Cl^- levels in both Aleto and Agbonchia Rivers exceed WHO permissible limits, making them unsuitable for human consumption and aquatic life without treatment.

3.6 COD Concentration

No COD concentration was found in the groundwater of all the communities in Eleme. For surface water, the study reported COD concentration of Aleto River (29.2±2.28mg/l) and Agbonchia River (39.50±3.54mg/l) for rainy season; and Aleto River (44±12.33mg/l) and Agbonchia River (81±0.000 mg/l) for dry season (see Table 3). Furthermore, the seasonal differences for surface water COD is not significant at 0.05 significance level (see Table 4 and 5). Surface water COD concentration in all the communities in Eleme is within WHO permissible limits (80 mg/l) hence there is no need for treatment.

3.7 BOD Concentration

No BOD concentration was found in the groundwater of all the communities in Eleme groundwater. For surface water, the study reported BOD concentration of Aleto River (7.0±0.29 mg/l) and Agbonchia River (6.25±0.212 mg/l) for rainy season; and Aleto River (7.30±0.752 mg/l) and Agbonchia River (6.65±0.354 mg/l) for dry season (see Table 3). Furthermore, the seasonal differences for surface water BOD is not significant at 0.05 significance level (see Tables 4 and 5). Surface water BOD concentration in all the communities in Eleme are within WHO permissible limits (50 mg/L) hence there is no need for treatment.

3.8 Phosphate (PO_4^{3-}) Concentration

No PO_4^{3-} concentration was found in the groundwater of all the communities in Eleme during the rainy season (see Table 1) while PO_4^{3-} concentration for dry season ranged from 0-0.225±0.150 (mg/l) with Onne and Agbonchia (ND) with the lowest and Alesa (0.225±0.150mg/l) with the highest (see Table 2). For surface water, the study reported PO_4^{3-} concentration of Aleto River (2.1±0.46 mg/l) and

Agbonchia River (0.370±0.438mg/l) for rainy season; and Aleto River (0.700±0.447mg/l) and Agbonchia River (0.060±0.000 mg/l) for dry season (see Table 3). The study also found variations in the seasonal phosphate concentrations of both groundwater and surface water. Furthermore, the seasonal differences for both surface and groundwater phosphate concentration are significant at 0.05 significance level (see Tables 4 and 5). Surface water and groundwater PO_4^{3-} concentration in all the communities in Eleme are within WHO permissible limits (5 mg/l) hence there is no need for treatment.

3.9 Total Hardness

The groundwater total hardness in Eleme ranges from 0.0001±0.001 to 2.33±0.96 mg/L during the rainy season, with Akpajo having the lowest and Onne the highest values (see Table 1). In the dry season, hardness ranges from 0.0007±0.0004 to 7.5±1.29 mg/L, with Oghale at the low end and Agbonchia at the high end (see Table 2). The study's finding for Ogale (0.473±0.424 mg/L) is lower than Oyor et al. (2017), who reported 5.6±0.5 mg/L during the dry season. For surface water, Aleto River has total hardness of 89.8±5.63 mg/L in the rainy season and 91.20±8.32 mg/L in the dry season while Agbonchia River shows 81±0.000 mg/L for both seasons (see Table 3). Seasonal differences in groundwater total hardness are significant at the 0.05 level, while surface water differences are not (see Tables 4 and 5). Groundwater total hardness across Eleme is within WHO permissible limits (30 mg/L), so no treatment is required. However, the total hardness of surface water in both Aleto and Agbonchia Rivers exceeds WHO limits, making it unsuitable for human consumption and aquatic life without treatment.

3.10 Oil/Grease Concentration

In Eleme, groundwater oil/grease concentrations are <0.01 mg/L in Eteo, Akpajo, Agbonchia, and Alesa during the rainy season, and not detected in other communities (see Table 1). For the dry season, concentrations range from <0.01 to 58.96±45.59 mg/L, with the highest in Ogale and the lowest in Alesa and Eteo (see Table 2). Surface water concentrations are <0.01 mg/L in Aleto and Agbonchia Rivers during the rainy season, rising to 60.75±40.76 mg/L in Aleto River and 32.05±3.97 mg/L in Agbonchia River during the dry season (see Table 3). Seasonal variations in oil/grease concentrations are significant at the 0.05 level for both groundwater and surface water (see Tables 4 and 5). Rainy season groundwater concentrations are within WHO limits (10 mg/L), but during the dry season, only Alesa, Akpajo, and Onne meet the standards, while others exceed it. Surface water concentrations in both rivers exceed WHO limits during the dry season.

3.11 Carbonate (CO_3^{2-}) Concentration

Groundwater CO_3^{2-} concentrations range from 0.010±0.0013 to 1.55±0.62 mg/L in the rainy season, with the lowest in Ogale and the highest in Onne (see Table 1). For the dry season, concentrations range from 0.018±0.007 to 4.01±0.096 mg/L, with the lowest in Agbonchia and the highest in Aleto (see Table 2). The rainy season CO_3^{2-} concentration at Ebubu (0.30±0.28 mg/L) is higher than previously reported values. Surface water CO_3^{2-} concentrations are 6.08±1.52 mg/L in Aleto River and 1.35±0.354 mg/L in Agbonchia River during the rainy season, and 7.76±3.35 mg/L and 1.70±0.141 mg/L, respectively, during the dry season (see Table 3). Seasonal variations in CO_3^{2-} concentrations are significant at the 0.05 level for both groundwater and surface water (see Tables 4 and 5). All groundwater and surface water CO_3^{2-} concentrations in Eleme are within WHO limits (120 mg/L) for both seasons, so no treatment is needed.

3.12 Salinity Concentration

No salinity concentration was detected in the groundwater for rainy season while salinity concentration for dry season ranges from 0.025±0.013-7.5±3.70 (%) with Eteo (0.025±0.013) the lowest and Onne (7.5±3.70) the highest. For surface water, the study reported salinity concentration of Aleto River (12.54±0.594) and Agbonchia River (6.25±0.919) for rainy season; and Aleto River (4.50±4.29) and Agbonchia River (0.015±0.007) for dry season. The study also found variations in the seasonal salinity concentrations of both groundwater and surface water. Furthermore, the seasonal difference for groundwater salinity is significant at 0.05 significance level while that of surface water is not significant at that level. Groundwater and surface water salinity concentration in all the communities in Eleme are within WHO permissible limits (600%) in both rainy and dry seasons.

3.13 Heavy Metal concentrations

3.13.1 cadmium concentration

Groundwater cadmium concentrations ranged from 0 to 0.0006±0.0002 mg/L in the dry season, with Agbonchia at <DL and Onne and Aleto at the highest (see Table 7). During the rainy season, concentrations ranged from 0.089±0.008 mg/L in Alesa and Aleto to 0.089±0.008 mg/L in Ogale and Alode, showing an increase compared to the dry season (see Table 6). The cadmium concentration in Ebubu (0.0003±0.0001 mg/L) is lower than Sokpuwu's (2017) report of 0.361±0.381 mg/L, and Oyor et al.'s (2017) value for Ogale (0.070±0.5 mg/L) is higher than this study's result for Ogale (0.0003±0.0001 mg/L). For surface water, cadmium concentrations were 0.004±0.0015 mg/L in Aleto River and 0.004±0.0004 mg/L in Agbonchia River during the rainy season, and 0.004±0.001 mg/L and 0.005±0.001 mg/L during the dry season, indicating higher levels of cadmium (see Table 9). Seasonal variations in cadmium concentrations in both groundwater and surface water were observed but are not significant at the 0.05 level (see Table 8 and 10). Groundwater cadmium concentrations in Eleme are within WHO limits (0.003 mg/L) during the dry season, but Agbonchia exceeds this limit in the rainy season. Surface water cadmium concentrations in both Aleto River and Agbonchia River exceed WHO limits in both seasons.

3.13.2 Lead concentration

The groundwater lead concentrations ranged from 0 to 0.0006±0.0002 mg/L in the dry season, with Agbonchia at ND and Onne and Aleto at the highest (see Table 7). During the rainy season, lead concentrations were 0.089±0.008 mg/L across Alesa, Aleto, Ogale, and Alode (see Table 6). The lead concentration in Ebubu groundwater (0.003±0.0017 mg/L) is lower than Sokpuwu's [12] report of 0.117±0.056 mg/L and Oyor et al.'s (2017) value of 0.093±0.001 mg/L for Ogale. For surface water, lead concentrations were 0.002±0.0003 mg/L in Aleto River and 0.002±0.0004 mg/L in Agbonchia River during the rainy season, and 0.002±0.0002 mg/L and 0.002±0.0001 mg/L during the dry season (see Table 9). Seasonal variations in lead concentrations were noted but not significant at the 0.05 level (see Tables 8 and 10). Groundwater lead concentrations exceeded WHO limits (0.010 mg/L) in Agbonchia, Alesa, Alode, and Onne during the dry season, and in Agbonchia, Alesa, Alode, and Onne during the rainy season. Surface water lead concentrations in Aleto River and Agbonchia River remained within WHO limits in both seasons.

3.13.3 Iron concentration

The groundwater iron concentrations ranged from 0.002±0.0008 to 0.294±0.4324 mg/L during the dry season, with Ogale having the lowest and Ebubu the highest (see Table 7). In the rainy season, iron concentrations ranged from 0.001±0.0000 to 0.306±0.467 mg/L, with Ogale being the lowest and Alesa the highest (see Table 6). For surface water, iron concentrations were reported as 1.98±0.438 mg/L in Aleto River and 1.05±0.0141 mg/L in Agbonchia River during the rainy season, and 2.35±1.31 mg/L and 1.695±0.233 mg/L respectively during the dry season (see Table 9). These values indicate high iron levels in surface water. Seasonal variations in iron concentrations in both groundwater and surface water were noted but were not significant at the 0.05 level (see Tables 8 and 10). Groundwater iron levels are within WHO limits (0.03 mg/L) for the dry season, but Alesa exceeds the limit during the rainy season. Both Aleto River and Agbonchia River exceed WHO limits for iron concentration in both seasons.

3.13.4 Nickel concentration

Groundwater nickel concentrations ranged from 0.002±0.0009 to 0.083±0.0083 mg/L during the dry season, with Akpajo having the lowest and Onne the highest (see Table 7). During the rainy season, values ranged from 0.002±0.0010 to 0.083±0.0083 mg/L, with Ogale lowest and Ebubu highest (see Table 8). Ebubu's rainy season concentration (0.083±0.0083 mg/L) is higher than Sokpuwu [12] and similar to Oyor et al. [10] for Ogale during the dry season. Surface water concentrations were 0.001±0.0005 mg/L in Aleto River and 0.005±0.0003 mg/L in Agbonchia River for the rainy season, and 0.002±0.0006 and 0.002±0.0003 mg/L for the dry season. Groundwater nickel levels during the dry season were within WHO limits (0.010 mg/L), except in Ebubu, Alesa, Alode, and Onne. During the rainy season, Ebubu and Onne exceeded limits. Surface water nickel concentrations in both Aleto and Agbonchia Rivers were within WHO limits (0.07 mg/L) year-round.

3.13.5 Cooper concentration

The groundwater copper concentrations ranged from 0.0001±0.000 to 0.0006±0.0002 mg/L

during the dry season, with Agbonchia, Eteo, Alode, and Alesa at the lowest and Aleto at the highest (0.0057±0.002 mg/L). During the rainy season, concentrations ranged from 0.0001±0.0001 to 0.089±0.008 mg/L, with Ogale, Akpajo, and Onne at the lowest and Agbonchia at the highest (0.162±0.033 mg/L) [14] . Surface water copper concentrations were 0.152±0.143 mg/L in Aleto River and 0.861±0.057 mg/L in Agbonchia River during the rainy season, and 0.175±0.201 and 0.851±0.018 mg/L during the dry season. Despite seasonal variations, copper concentrations in both groundwater and surface water remain within WHO limits (2 mg/L).

3.13.6 Manganese concentration

The groundwater manganese concentrations ranged from 0.004±0.001 to 0.172±0.0135 mg/L during the dry season, with Eteo, Aleto, and Akpajo having the lowest and Agbonchia the highest. During the rainy season, concentrations ranged from <0.001 to 0.117±0.0760 mg/L, with Agbonchia the lowest and Onne the highest. The manganese concentration reported for Ogale by this study (0.011±0.0021 mg/L) is similar to Oyor et al. (2017) (0.008±0.002 mg/L). Surface water manganese levels were 0.734±0.224 mg/L in Aleto River and 0.647±0.050 mg/L in Agbonchia River during the rainy season, and 1.01±0.389 and 0.650±0.010 mg/L during the dry season. These levels exceed WHO limits (0.40 mg/L) for groundwater but are below the permissible limit for surface water (2 mg/L). Seasonal variations in manganese concentrations are not statistically significant at the 0.05 level.

3.13.7 Arsenic concentration

The arsenic concentration found in the groundwater of all the sampled communities in Eleme in the two seasons are <0.001. For the surface water, this study reported arsenic concentration of Aleto River and Agbonchia River for the rainy and dry seasons to be <0.001. Groundwater arsenic concentration in all the communities in Eleme during the dry season is within WHO and FMEnv permissible limits (0.003 mg/l). Also, the surface water arsenic concentration for both Aleto River and Agbonchia River are below WHO and FMEnv permissible limits (0.001 mg/l) in both the rainy and dry seasons.

4. CONCLUSION

In conclusion, the water quality analysis across Eleme reveals several key findings. Groundwater pH remains acidic throughout both rainy and dry seasons, with values consistently below the WHO permissible limits for drinking water, highlighting a need for treatment. Temperature, conductivity, and TDS levels show seasonal variation, with increased values during the dry season due to reduced dilution. Total suspended solids and turbidity in groundwater are generally within acceptable limits, though surface water, especially from Aleto and Agbonchia Rivers, frequently exceeds permissible levels. Nitrate, calcium, and magnesium concentrations remain within WHO limits, though surface water in the Aleto and Agbonchia Rivers shows elevated levels of chloride, calcium, and magnesium, indicating potential concerns. Oil/grease concentrations in surface water rise significantly during the dry season, necessitating treatment for both groundwater and surface water in several locations. Phosphate and total hydrocarbon concentrations are within acceptable ranges, while cadmium and lead levels in surface water exceed WHO limits, signaling a need for further investigation and remediation. Overall, while groundwater generally meets standards, surface water quality issues persist, warranting targeted interventions to ensure safe and potable water for all communities.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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