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Determination of Groundwater Quality for Human Consumption using Inferential and Geostatistics Analysis in Enugu, Southeastern Nigeria

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Abstract
Groundwater has been assumed to be naturally clean and needs no purification. This study determined groundwater quality in Enugu, Southeastern Nigeria to determine if it is safe for human consumption. Quasi-experimental design was adopted for the research while inferential and geostatistic tools were used in data analysis. Analysis of Variance (ANOVA) was used to compare the mean values of the water quality, with all parameters significant except two. The Principal Component Analysis (PCA) showed discernible spread pattern of the sampled parameter. The Piper Plot revealed mixed $CaNaHCO_3$ (Calcium-Sodium-Bicarbonate) and $NaHCO_3$ (Sodium-Bicarbonate) types. The Stiff Plot revealed variation in water type showing that 60%, 17% and, 23% are $NaHCO_3$ type, $CaNaHCO_3$ type and other types, respectively. The Gibbs Plot reveals that the groundwater of the study area is influenced by rock weathering and precipitation. The Durov plot reveals a high pH signifying water acidity making it questionable for drinking. The findings reveal that groundwater quality in the study area is mainly influenced by natural factor, and generally unfit for drinking. The study recommends continuous monitoring using software technologies for effective management of groundwater quality and internet based technologies for disseminating water quality status to the public.

Keywords: Groundwater Quality, Hydrogeochemical, Sustainable protection, Rock-water interaction, Mineral dissolution, Enugu

Introduction
Groundwater is a naturally occurring resource beneath the earth. It is a crucial supply of water for many nations around the world because it is frequently used for drinking, bathing, washing, cooking, and irrigation (Ugochukwu and Ojike, 2019). Due to this and the population growth, the resource is under tremendous pressure. An estimated 2.6 billion people lack the means to obtain better sanitation facilities globally, and larger populations still lack access to safe drinking water (WHO/UNICEF, 2010). A sizeable portion of these people (42%) live in Sub-Sahara Africa and Asia (20%) (WHO/UNICEF, 2000). As a result, 90.2% of children under the age of five in underdeveloped nations pass away each year from illnesses brought on by a lack of access to safe drinking water and standardized public health services (WHO/UNICEF, 2005). Unquestionably, everyone has the right to adequate water supply, yet, most developing nations have significant challenges in meeting this vital human need (Mokadem et al., 2018).

Growing worry about unsafe drinking water has garnered international attention (WHO and UNICEF, 2014). This is due to the fact that the development of high-quality water resources has been connected to the socioeconomic position and health assessments of many countries (Akoto et al., 2017; Karikari and Ansa-Asare 2006). As supported by the Millennium Development Goals (Ogunniyi et al., 2011) and now evaluated in the current Sustainable Development Goals (Emenike et al., 2017), world leaders have demonstrated a readiness and commitment to make adequate clean water accessible. Adoption of this review is essential due to the rise in water-borne diseases in poor nations, such as cholera, diarrhoea, and other gastrointestinal ailments (Forstinus et al., 2016; Oguntoke et al., 2009). The proper identification of water contamination problems and the development of effective preventative and mitigation methods depend on the monitoring and assessment of groundwater quality (Aisien et al., 2010; Eletta, 2012).

According to several studies (Coomar et al., 2019; Emenike et al., 2017; Jampani et al., 2020; Shi et al., 2018; Wang et al., 2015), the quality of groundwater is influenced by a variety of factors, including soil type, geology, grade of chemical weathering of various rock types, water-rock interface, climate precipitation, evaporation, and water-rock interactions. With this in mind, determining the quality of the groundwater should not be the exclusive objective of research projects. Thus, in-depth understanding of groundwater quality and the factors influencing its evolution is necessary for sustainable groundwater development.

Due to carelessness and bad government policies throughout the years, inhabitants in different portions of the study area do not have access to a reliable public pipe-borne water supply. The most trustworthy source of water supply for the locals is groundwater. The majority of residents use affordable groundwater in their properties, which mostly recharges during the rainy season. For many low-income residents in the region, groundwater from hand-dug wells provides a cheap supply of water; it is mostly utilized for bathing, cooking, drinking, and washing. Although the region's groundwater contamination makes it dangerous to use for these essential household uses, low-income residents nevertheless unknowingly use the contaminated water, putting their health at risk (Ugochukwu and Ojike, 2019). This is based on the assumption that groundwater is purified as it stays non- disturbed underneath the earth (Nwobodo et al., 2015). It is commonly acknowledged that geology has an impact on the chemical quality of water (Lester and Birkett, 1999). However, the intricate processes governing the chemical interaction between the soil and water can be attributed to the soil's influence on water quality (Hesterberg, 1998). This has sparked concern about the necessity of ongoing hydrogeological and hydrochemical facies monitoring. In the region, this area of concern has not been extensively studied. The majority of studies focused on groundwater exploration (Okamkpa et al., 2018; Okonkwo et al., 2016) and groundwater quality evaluation (Ajagu and Ajiwe, 2017; Aniebone, 2014; Ayogu et al., 2021; Ugochukwu & Ojike, 2019).

Thus, this study concentrated on the hydrogeological and hydrogeochemical aspects of the aquifer in light of the aforementioned concern. The findings would help to better understand the hydrogeochemical processes occurring in the region in relationship to groundwater quality, and if it is fit for human consumption. It would also serve as a helpful resource for long-term groundwater protection, management, and monitoring.

Materials and Methods

Study Area

Enugu State comprises 17 Local Government Areas (LGAs), and shares borders with six States which include; Abia, Imo, Ebonyi, Anambra, Kogi and Benue States. Abia and Imo to the south, Ebonyi to the east, Benue to the northeast, Kogi to the northwest and Anambra to the west. The study area comprises Enugu East, Enugu North and Enugu South LGAs that were purposively chosen because of the prevalence of boreholes. It is located within latitudes 06^{o} 24’N and 06^{o} 30’N of the Equator and longitudes07^{o} 27’E and 07^{o} 32’E of the Prime Meridian (Figures 1 and 2). Enugu city is underlain by the Enugu Shale and Nkpolo shale (Onwuka et al., 2013). These Shales are known to be aquicludes (Offodile, 2002). Water table of the geological location is controlled by the seasons of the year. The Shales are fractured and weathered to a lateritic regolith which is highly porous and permeable that suggests localized saturated conditions. The permeable laterite rests on the impermeable shale bedrock, and thus, a perched aquifer is developed constituting the only known aquifer directly beneath the metropolis. The perched aquifer of the Enugu Shale is thin and most times becomes reduced in thickness especially during dry season (Onwuka et al., 2013). The climate of the study area is in the humid tropical rain forest belt of Southeastern Nigeria. It experiences only two seasons (rainy and dry seasons). The rainy season lasts from April to October while the dry season lasts from November to March. It has annual rainfall of about 1500-1830mm. (Okagbue and Ifedigbo, 1995). In terms of land use types, the residential area is classified into three which includes; high, medium and low density areas. However, mixed densities exist as a result of spread effects. This mixed density is due to high demand of residential accommodation.

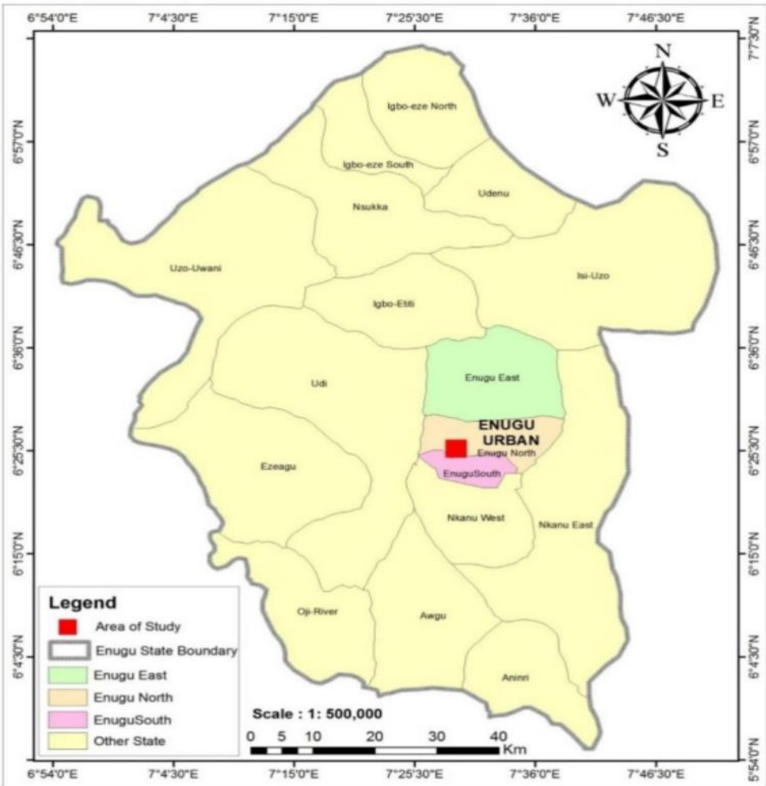


Figure 1: Map of Enugu State Showing Enugu Urban
Source: Space Consult and Mapping Enugu

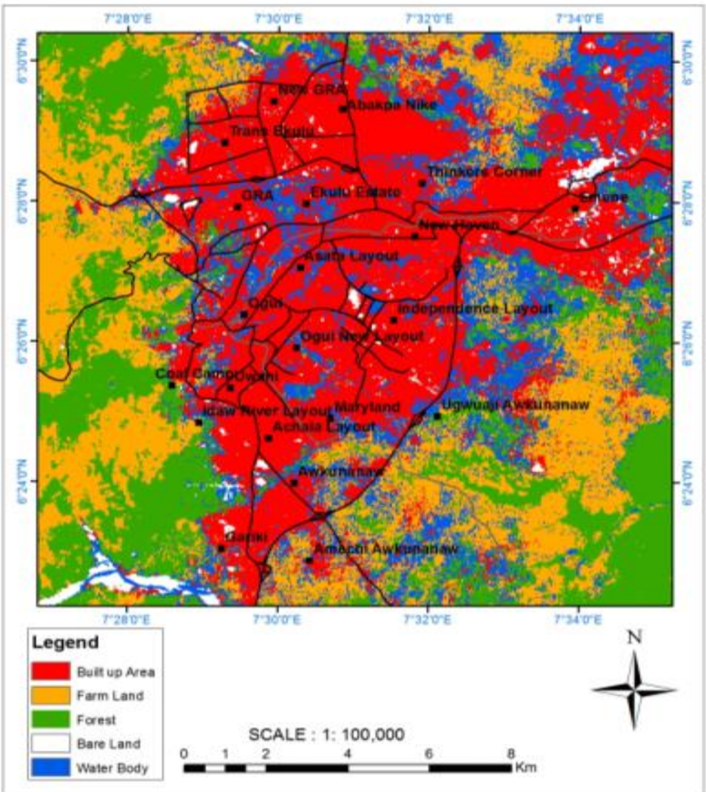


Figure 2: Land use and land cover map of the study area
Source: Space Consult and Mapping Enugu

Data Collection

Reconnaissance survey of the area was carried out prior to the actual samples collection. This facilitated a better understanding of the spatial distribution of the hand-dug wells within the study area. The groundwater samples were collected in March 2021, at seventeen different sampling sites in the study area. Groundwater samples were collected in triplicates from each sampling site. The twenty-one (21) parameters analysed were; pH, Electrical Conductivity (EC), Turbidity, Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Total hardness, Chlorides (Cl^-), Sulphates (SO_4^{2-}), Nitrate (NO_3^-), Total Alkalinity, Calcium Hardness, Magnesium Hardness, Iron, Calcium Ion Ca^{2+}), Magnesium Ion (Mg^{2+}), Total Coliform (TC), Sodium (Na^+), Potassium (K^+), Bicarbonate (HCO_3^-), Fluoride (F^-), Carbonate (CO_3^-). An *in-situ* test was carried out using portable digital meter for pH, Total Dissolved Solids and Electrical conductivity. pHep tester was used in measuring pH and H196301 used in measuring Electrical conductivity and Total Dissolved Solids. The coordinates were recorded using Global Positioning System (GPS) Garmin etrex 10. The water samples were collected in clean 1.5 litre plastic jars with screw caps and packed in a cooler and transported to the laboratory immediately. The groundwater samples were stored in the refrigerator at 4°C until analysis was completed. All the twenty-one parameters were analysed according to the standard methods of APHA-AWWA-WEF (2012).

Method of Data Analysis

The study used Analysis of Variance (ANOVA) to compare the mean of the sampled parameters across the study area. The Duncan multiple comparisons was further used to identify the specific places where significance exists. Principal Component Analysis (PCA) was employed to examine discernible pattern in the sample parameters were original variables of the data set were transformed into new, uncorrelated variables or axes, known as the principal components (PCs) which are linear combinations of the original variables. PCA was performed to extract principal components (PCs) from the sampling points and to evaluate spatial variations and possible source of pollution in groundwater. Prior to the analysis, Kaiser-Meyer-Olkin Measure of Sampling Adequacy (KMO) and Barlett's test were conducted to determine the data suitability. The KMO is a statistic that indicates the proportion of variance in the variables that might be caused by underlying factors. The extracted principal components were subjected to Varimax rotation to distinguish the factor loadings on the parameters. In addition, a hydrochemical classification of the water samples was conducted by generating the Piper trilinear diagram.

The Principal components (PCs)according to Singh et al. (2005) is expressed as ;

$$Z_{ij} = a_{i1} x_{1j} + a_{i2} x_{2j} + \ldots \; a_{im} x_{mj} \quad (1)$$

where, Z stands for the component score, a, i, j, m and x are the component loading, component number, sample number, total number of variables and the measured values of variables, respectively.

Geostatistics tools were also employed to determine hydrochemical facies using the Piper, Durov, Gibbs and Stiff Plots. The hydrochemical facies represents a diagnostic chemical aspect of groundwater solution occurring in hydrological systems. The facies reflect the interaction of chemical processes within the lithologic framework and pattern of flow of the groundwater. However, The Piper-trilinear plot (Piper, 1944) reflects the chemical character of the water samples in our study area using the dominant cation and anion to show the differences and similarities of the groundwater samples. Similarly, Durov Plot displays possible geochemical processes that aid the knowledge of groundwater evaluation and quality. A Gibbs Plot is useful in analysing major natural factors governing groundwater formation mechanisms (Marghade et al., 2012; Naseem et al., 2010). Moreover, Gibbs Plot was used to grouped groundwater formation mechanisms into three types which include rock dominance, evaporation dominance, and precipitation dominance (Gibbs, 1970; Li et al., 2015). Finally, Stiff plot was used to display ion concentration in water, soil and rock samples, and the greater the distance from the central 0 axis, the greater the ionic concentration.

Results

Water Quality Characteristics

Tables 1, 2 and 3 show the comparison of mean of the physico-chemical parameters across the study area.

Table 1: Comparison of mean of the physico-chemical parameters across the study area

Sampling site	pH	Turbidity	EC	TDS	TSS	Chloride	Total Alkalinity
Abakpa Nike	3.93*	4.56*	70.67	46.10	.01	72.98$^{\#}$	3.00*
Achara Layout	5.76^{a}	6.10*	107.00	70.10	.01	133.96	5.00*
Asata	6.39^{b}	9.41^{a}	80.60^{c}	52.60^{c}	.01	36.99*	17.00
Awkunanaw	7.04^{c}	52.10	51.80	33.60	.01	61.48	3.93*
Coal camp	5.88^{a}	25.00	27.90*	18.10*	.01	21.49	8.00^{a}
Emene	5.12$^{\#}$	1.31*	30.00*	19.50*	.01	11.50	27.00
GRA	4.16*	682.00	122.20	78.50	.01	77.98	2.00
Idaw River	5.79^{a}	10.20^{a}	59.07^{b}	38.60^{b}	.00	69.48^{c}	11.00
Ind. Layout	6.65^{b}	0.37	64.40	41.80^{b}	.01	53.98^{b}	8.00^{a}
Iva valley	6.67^{b}	35.90	43.30^{a}	28.20^{a}	.01	4.50	4.10*
Mary Land	6.60^{b}	11.20	80.80^{c}	53.70^{c}	.01	72.98$^{\#}$	3.80*
New haven	5.74^{a}	3.31*	60.40^{b}	39.30^{b}	.01	68.98^{c}	8.00^{a}
New Layout	4.93$^{\#}$	2.19*	69.20	45.10	.01	31.49	5.00*
Trans Ekulu	5.57^{a}	1.43*	41.50^{a}	26.90^{a}	.01	37.99*	4.50*
Ugbo Odogwu	4.01*	2.22*	45.60^{a}	29.40^{a}	.01	53.93^{b}	4.00*
Ugwu Aaron	7.30^{c}	164.00	157.40	101.60	.01	112.93	146.00
Uwani	6.40^{b}	155.00	26.00*	16.90*	.01	26.49	5.00*
F	66.982	12224.011	566.319	285.448	0.043	797.024	3669.964
P value	< 0.001	< 0.001	< 0.001	< 0.001	1.000	< 0.001	< 0.001

*$^{abc\#}$ *Duncan multiple comparisons indicating means not significantly different*
Source: Author's Fieldwork, 2021

Table 2: Comparison of mean physico-chemical parameters across study area Contd.

Sampling site	Total Hardness	Calcium Hardness	Magnesium Hardness	Ca^{+}	Mg^{2+}	Fe^{2+}	$S04^{2-}$
Abakpa Nike	32.00^{a}	27.00*	5.00^{c}	0.24*	11.13^{a}	1.50	28.00^{b}
Achara Layout	23.00*	18.67*	4.00^{a}	0.20*	7.60*	1.20	6.00*
Asata	57.00	51.00*	6.00	0.67*	20.40	1.80	27.00^{b}
Awkunanaw	16.00*	13.00*	3.00*	1.17^{b}	5.20*	0.90	2.90*
Coal camp	22.00*	18.00*	4.00^{a}	0.43*	7.20*	1.20	4.00*
Emene	75.00	68.00*	7.00	0.01^{c}	27.20	2.10	.00
GRA	223.00	212.00*	11.00	28.60	84.80	3.30	30.00
Idaw River	9.00	6.00*	3.00*	0.62*	2.40	.90	12.00^{a}
Independence layout	27.00*	24.00*	3.00*	0.07^{c}	9.60	.90	14.00^{a}
Iva valley	25.00*	21.00*	4.00^{a}	1.60	8.40	1.20	28.00^{b}
Mary Land	40.00^{b}	35.00*	5.00^{c}	1.01^{b}	14.00^{b}	1.44	3.00*
New haven	21.00*	17.00*	4.00^{a}	0.32*	6.80*	37.50	12.00^{a}
New Layout	131.00	484.00^{b}	10.00	0.12*	48.40	3.00	90.00
Trans Ekulu	40.00^{b}	36.00*	4.00^{a}	0.06^{c}	14.40^{b}	1.20	5.00*
Ugbo Odogwu	39.00^{b}	35.00*	4.00^{a}	0.35*	14.00^{b}	1.20	43.00
Ugwu Aaron	545.00	533.00^{b}	12.00	18.20	213.20	3.60	26.00^{b}
Uwani	35.00^{a}	30.00*	5.00^{c}	20.80	12.00^{a}	1.50	34.00
F	903.485	3.402	92553	967.482	3932.273	0.985	401.371
P value	< 0.001	0.001	< 0.001	< 0.001	< 0.001	0.493	< 0.001

*$^{abc\#}$ *Duncan multiple comparisons indicating means not significantly different*
Source: Author's Fieldwork, 2021

Table 3: Comparison of mean physico-chemical parameters across study area Contd.

Sampling Site	NO_3^{2-}	Total Coliform	Na^+	K^+	HCO_3^-	CO_3^-	F^-
Abakpa Nike	17.70[b]	11.00*	182.32[c]	10.01	314.53[#]	17.05[b]	1.20
Achara Layout	20.00[c]	14.00[c]	177.86[c]	8.10[a]	285.30	15.53[b]	0.84*
Asata	16.10[a]	12.00[a]	176.75[c]	10.55[b]	244.02[c]	16.25[b]	0.82*
Awkunanaw	17.80[b]	12.00[a]	129.68[a]	7.18[a]	206.70[a]	11.23[a]	0.70*
Coal camp	12.40	14.00[c]	124.53[a]	6.82[a]	202.57*	10.37*	0.55
Emene	7.90*	12.00[a]	117.69*	3.80*	202.42*	9.40*	0.72*
GRA	18.80	11.00*	195.81[#]	12.87	355.15	26.58[#]	1.42
Idaw River	9.80	12.00[a]	124.64[a]	9.06	213.57	11.80[a]	0.94[a]
Independence layout	21.20	12.33[a]	115.60*	3.77*	208.65[a]	10.24*	0.77*
Iva valley	5.30	12.00[a]	140.97[a]	8.43	212.23[b]	11.63[a]	0.86*
Mary Land	14.80[a]	11.00*	150.07[b]	10.48[b]	247.93[c]	13.00[a]	1.07[b]
New haven	14.80[a]	12.00[a]	160.94[a]	8.75	254.20	16.37[b]	0.91[a]
New Layout	19.50[c]	13.00	175.38[c]	10.07	348.12	20.97[c]	1.09[b]
Trans Ekulu	19.90[c]	12.00[a]	133.20	7.93[a]	212.72[b]	10.36*	1.06[b]
Ugbo Odogwu	8.20*	12.00[a]	197.93[#]	11.27	316.22[#]	19.93[c]	1.11
Ugwu Aaron	17.80[b]	11.00*	470.20	16.02	517.03	28.06[#]	1.80
Uwani	7.30*	11.00*	150.53[b]	10.47[b]	201.13*	11.33[a]	0.83*
F	62.178	3.188	1281.542	20.907	1594.433	46.897	9.054
P value	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

*[abc#] *Duncan multiple comparisons indicating means not significantly different*

Source: Author's Fieldwork, 2021

A Kaiser-Meyer-Olkin Measure of Sampling Adequacy value of 0.753 generally indicates that the factor analysis is appropriate for the data. Bartlett's test of sphericity indicates that the correlation matrix is not an identity matrix (P < 0.001), which means that the variables are related and therefore suitable for structure detection (Table 4). Thus, the realized values indicate data suitability.

Table 4: Analysis of KMO and Bartlett's Test

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.753
Bartlett's Test of Sphericity	Approx. Chi-Square	1730.649
	Df	210
	Sig.	.000

The eigenvalue, or percentage of variance in the original variables accounted for by each component, is displayed in the Total column (Table 5). The % of Variance column displays the percentage of variance that each component contributes to the overall variance of all the variables. As a result, factor 1 accounts for 48.9% of the total variation, factor 2 for 10.1%, factor 3 for 8.1%, factor 4 for 7.4%, factor 5 for 5.6%, and factor 6 for 4.9%. The first component explains a greater proportion of the variance, but the other ones only account for a smaller proportion. Retaining all components that met the Kaiser criterion, there was an average communality of 0.6. Consequently, all elements have eigenvalues higher than one. In the columns labelled Extraction Sums of Squared Loadings, the eigenvalues related to these components are once more shown, along with the proportion of variation that is explained. For all six components together, the percentage is 85%. By employing these components, we can significantly reduce the complexity of the data set while only losing 15% of the information because they account for 85% of the variability in the original 21 variables. Table 6 shows the rotated component matrix of all the parameters.

Table 5: PCA Analysis Presentation

Total Variance Explained

Comp-onent	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumula-tive %	Total	% of Variance	Cumula-tive %	Total	% of Variance	Cumula-tive %
1	10.272	48.915	48.915	10.272	48.915	48.915	8.100	38.572	38.572
2	2.141	10.195	59.111	2.141	10.195	59.111	2.942	14.010	52.583
3	1.698	8.086	67.197	1.698	8.086	67.197	2.543	12.108	64.691
4	1.546	7.360	74.556	1.546	7.360	74.556	1.943	9.253	73.944
5	1.184	5.636	80.192	1.184	5.636	80.192	1.235	5.882	79.826
6	1.025	4.879	85.071	1.025	4.879	85.071	1.102	5.245	85.071
7	.841	4.004	89.075						
8	.627	2.987	92.061						
9	.550	2.621	94.682						
10	.365	1.739	96.421						
11	.236	1.125	97.546						
12	.185	.879	98.425						
13	.140	.666	99.091						
14	.097	.462	99.553						
15	.032	.153	99.707						
16	.031	.148	99.854						
17	.019	.092	99.946						
18	.006	.028	99.974						
19	.003	.015	99.989						
20	.002	.008	99.997						
21	.001	.003	100.000						

Extraction Method: Principal Component Analysis.

Table 6: Rotated Component Matrix Presentation

Rotated Component Matrix[a]

	Component					
	1	2	3	4	5	6
Total Hardness	.925					
Mg^+	.924					
Na^+	.923					
$S04^{2-}$	.775					
HCO_3^-	.855					
$N0_3^2$	.796					
Magnesium Hardness	.778					
Calcium Hardness	.764					
Ca^+	.855					
F^-	.722					
CO_3^-	.715					
K^+	.673					
Chloride		.863				
EC		.689				
Turbidity			.921			
pH				-.804		
Total Alkalinity				.889		
Iron					.753	
Total Coliform					-.572	
TDS						.694
TSS						.923

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 7 iterations.

Determination of Hydrochemical facies

The Piper, Durov, Gibbs and Stiff Plots show the results of the hydrochemical facies in the study are as illustrated in Figures 3, 4, 5 and 6.

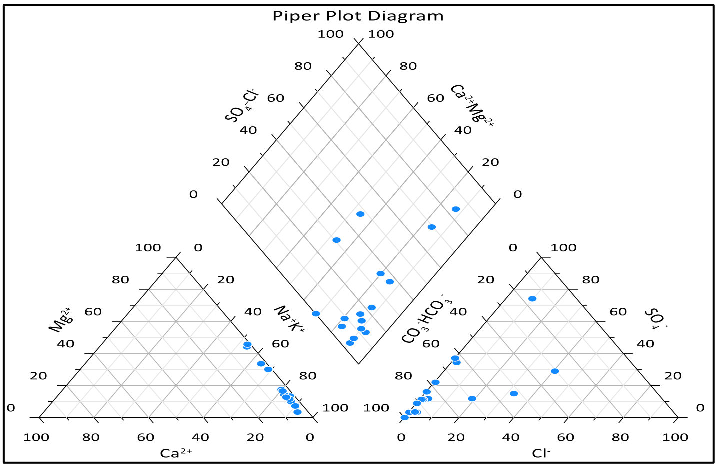


Figure 3: Piper (Trilinear) Plot of the study area

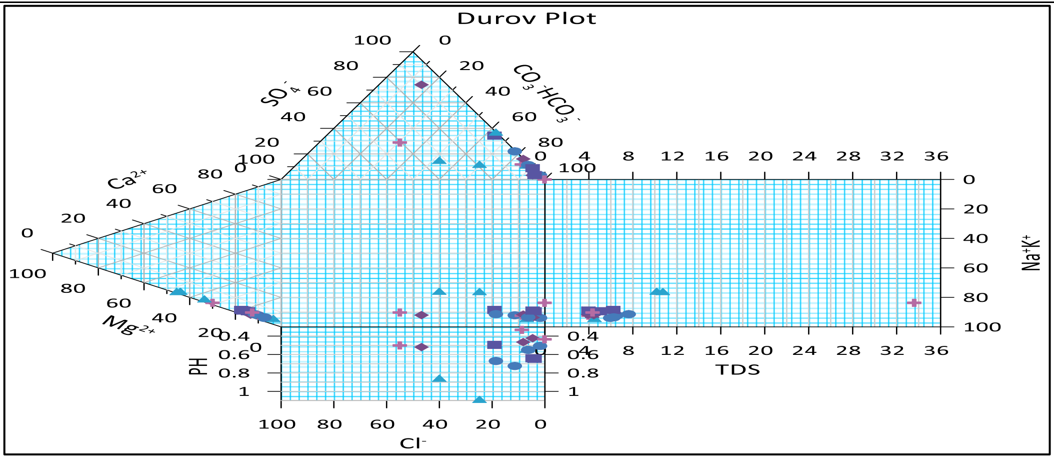


Figure 4: Durov Plot of the study area

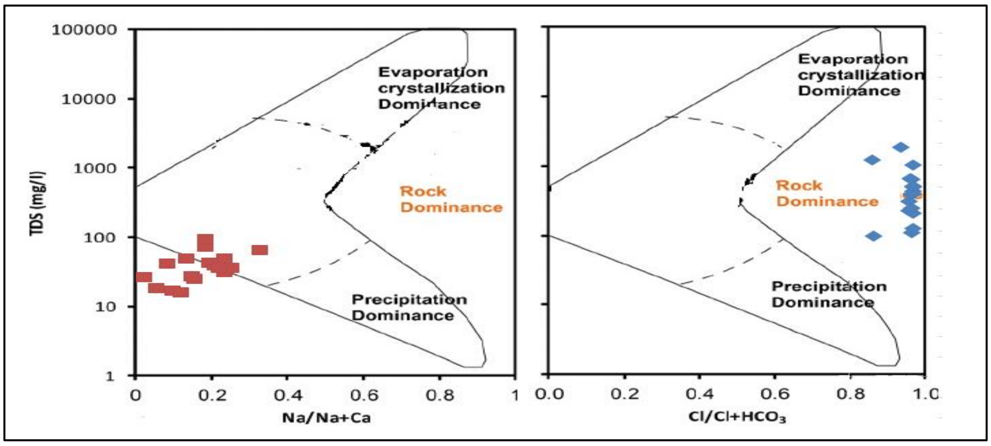
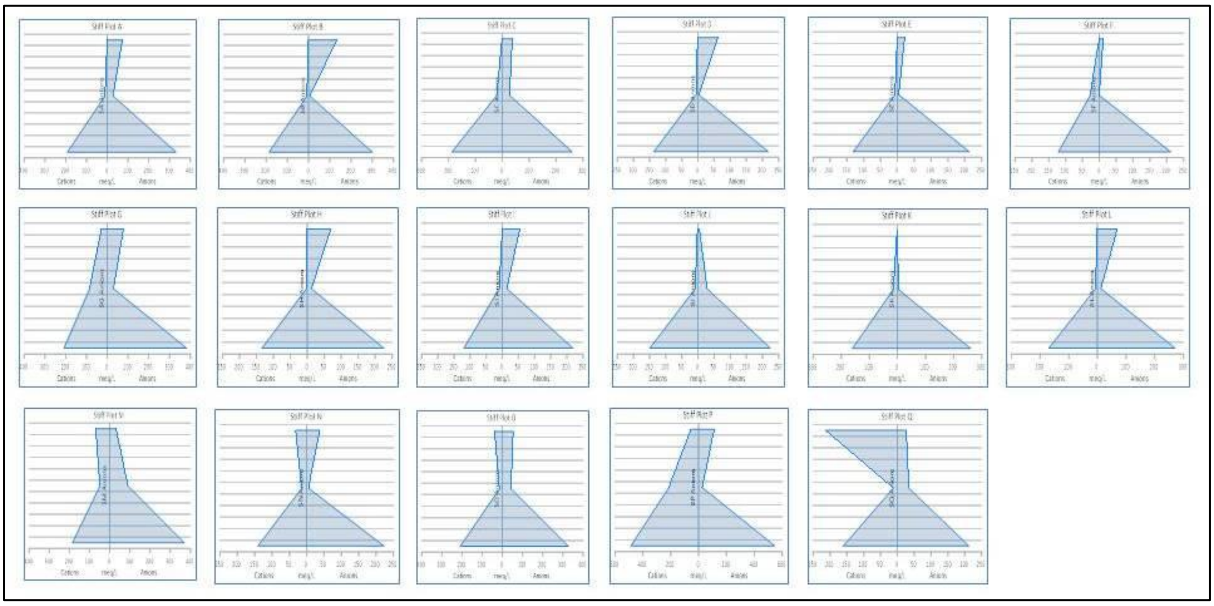


Figure 5: Gibbs Diagram of the study area



Figures 6: Stiff Diagram of the sampled locations.

Discussion

As shown in Tables 1, 2 and 3, the parameters were significantly different across various locations in the region ($p < 0.05$) except TSS and Iron. The Duncan multiple comparison indicates means of parameters not significantly different. It indicated that pH was the same in locations such as Abakpa Nike (A), GRA (G) and Ugbo-Odogwu (O) with mean range of 3.93–4.16. Emene (F) and New Layout (M) with mean range of 4.93–5.12. Achara Layout (B), Coal camp (E), Idaw River (H), New Haven (L) and Trans-Ekulu (N) with mean range of 5.57–5.88. Asata (C), Independence Layout (I), Iva Valley (J), Maryland (K) and Uwani (Q) with mean range of 6.39–6.67. Awkunanaw (D) and Ugwu-Aaron (P) with mean range of 7.04–7.30. This is an implication that those locations have similar components in terms of alkalinity or acidity. However, Awkunanaw (D) and Ugwu-Aaron showed neutrality in pH, which is a quantitative measure of the acidity or basicity of aqueous or other liquid solutions on a logarithmic scale.

Turbidity is the state of cloudiness of water, usually because of suspended matter. Table 1 showed that the parameter was same in Abakpa Nike (A), Achara Layout (B), Emene (F), New Haven (L), New Layout (M), Ugbo-Odogwu (O) with mean range of 0.37NTU–6.10NTU. Asata (C) and Idaw River (H) with mean range of 9.41NTU–10.20NTU. The result revealed that 60% of the locations exceeded the permissible limit of 5NTU according to WHO standard (WHO, 2017).

Electrical Conductivity (EC) is a measure of the electrical current conduction of water. The higher the concentration of dissolved charged chemicals, the greater the electrical current that can be conducted. Table 1 showed that the parameter was the same in Coal Camp (E), Emene (F) and Uwani (Q) with mean range of 26.00 µS/cm–30.00 µS/cm. Iva Valley (J), Trans-Ekulu (N) and Ugbo-Odogwu (O) with mean range of 41.50 µS/cm–45.60 µS/cm. Idaw River (H) and New Haven (L) with mean range of 59.07 µS/cm–60.40µS/cm . Asata (C) and Mary Land (K) with mean range of 80.60 µS/cm–80.80 µS/cm. This revealed that the entire sampled locations were within the permissible limit of 1000 µS/cm (WHO, 2017).

Total Dissolved Solids (TDS) concentration describes inorganic salts and small amounts of organic matter present in water solution. The principal constituents are mainly sodium, magnesium, calcium, chloride, carbonate, sulphate, nitrate anions, potassium cations and hydrogen carbonate. TDS can be used as a first-hand assessment of the potability of water (Sharma et al., 2016). It has been established that high levels of TDS can lead to gastrointestinal irritations and laxative effects (Selvakumar et al. 2014). The result (Table 1) showed that TDS was same in the following locations; Coal Camp (E), Emene (F) and Uwani (Q) with mean range of 16.90mg/l–19.50mg/l. Ugbo-Odogwu (O), Trans-Ekulu (N) and Iva Valley (J) with mean range of 26.90mg/l–29.40mg/l. Similarly, the same in New Haven (L), Independence Layout (I) and Idaw River (H) with mean range of 38.60mg/l–41.80mg/l. Asata (C) and Mary Land (K) with mean range of 52.60mg/l–53.70mg/l. Total Suspended Solids (TSS) concentration is a measure of the total weight of solid residuals contained in the water source. It can be trapped by a filter. The result revealed that all the sampled locations were within the standard limit of 1500mg/l (WHO, 2017). Though, this contradicts the findings of Emenike et al. (2018) where 95% of their sampled area in Southwestern Nigeria, exceeded the standard limit.

Chloride is an inorganic compound highly soluble in groundwater. High concentration is caused due to leaching from industrial and household activities (Adimalla and Venkatayogi, 2018; Sunitha and Sudharshan, 2019). Table 1 showed that the parameter was the same in Asata (C) and Trans-Ekulu (N) with mean range of 36.99mg/l–37.99mg/l; Independence Layout (I) and Ugbo-Odogwu (O) with mean range of 53.93mg/l–53.98mg/l; Idaw River (H) and New Haven (L) with mean range of 68.98mg/l–69.48mg/l; Abakpa Nike (A) and Mary Land (K) with mean values of 72.98mg/l. The standard limit for chloride in drinking water is 250 mg/L (WHO, 2011). The result revealed that all the sampled locations were below the permissible limit.

Total Alkalinity (TA) is a measure of water's ability to neutralize acids. The presence of hydroxides and carbonates compounds in alkaline water eliminates hydrogen ion H+ from water. This lowers the acidity of the water and results to higher pH. Table 1 showed that the parameter was same in Abakpa Nike (A), Achara Layout (B), Awkunanaw (D), Iva Valley (J), Mary Land (K), New Layout (M), Trans-Ekulu (N), Ugbo-Odogwu (O) and Uwani (Q) with mean range of 3.00mg/l–5.00mg/l. Coal Camp (E), Independence Layout (I) and New Haven (L) with mean values of 8.00mg/l. All the sampled locations were within the permissible limit of 100mg/l (WHO, 2011) except location P (146.00mg/l). This may be due to the recharge zone, solubility of the aquifer materials or anthropogenic activities at the sampling site as stated by Emenike et al., 2018.

Total Hardness (TH) is the sum of temporary and permanent hardness in water. Although it showed significance different (< 0.05) further analysis indicated that TH was same in Achara Layout (B), Awkunanaw (D), Coal Camp (E), Independence Layout (I), Iva Valley (J), New Haven (L) with mean values ranging from 16.00mg/l to 27.00mg/l. Abakpa Nike (A) and Uwani (Q) had mean range of 32mg/l to 35.00mg/l. Trans-Ekulu (N) and Ugbo-Odogwu (O) had mean range of 39mg/l to 40.00mg/l. The TH varied from 16mg/l–101.60mg/l (Table 2), which is within the acceptable limit of 500mg/l (WHO, 2017). According to Sawyer et al. (2003), groundwater is considered as safe at <75, moderate to hard from 75–150, hard from 150–300 and very hard at >300. Most of the locations (88%) were safe and 12% of the sample locations fell within moderate to hard.

Calcium and magnesium hardness were significantly different across the areas. The result (Table 2) showed calcium hardness was same in all the sampled locations except New Layout (M) and Ugwu-Aaron (P) which were also same with mean values between 484.00mg/l and 533.00mg/l. Table 2 shows that magnesium hardness was same in Awkunanaw (D), Idaw River (H) and Independence Layout (I) with mean values of 3.00mg/l. The same in Achara Layout (B), Coal Camp (E), Iva Valley (J), New Haven (L), Trans-Ekulu (N) and Ugbo-Odogwu (O) with mean values of 4.00mg/l . Abakpa Nike (A), Mary Land (K) and Uwani (Q) had the mean values of 5.00mg/l. However, all the sampled locations exceeded the permissible limit for magnesium hardness (1.0mg/l). The result also revealed that 29% of the sampled locations exceeded the permissible limit for calcium hardness for drinking water of 200mg/l according to WHO (2017) standard.

Calcium (Ca^{2+}) and magnesium (Mg^{2+}) ions contribute significantly to the hardness of groundwater. Table 2 shows that calcium ion was the same in Emene (F), Independence Layout (I) and Trans-Ekulu (N) with mean values ranging from 0.01–0.07mg/l. Abakpa Nike (A), Achara Layout (B), Asata (C), Coal Camp (E), Idaw River (H), New Haven (L), New Layout (M) and Ugbo-Odogwu (O) with mean values ranging from 0.12mg/l–0.35mg/l. Awkunanaw (D) and Mary Land (K) had the same with mean values of 1.17mg/l and 1.01mg/l. It also shows that magnesium ion was the same in Achara Layout (B), Awkunanaw (D), Coal Camp (E) and New Haven (L) with mean values ranging from 5.20mg/l–7.60mg/l. Abakpa Nike (A) and Uwani (Q) had the same with mean range of 11.13mg/l–12.00mg/l. Similarly, the same in Mary Land (K), Trans-Ekulu (N) and Ugbo-Odogwu (O) with mean values of 14.00mg/l. The permissible limit of Ca^{2+} and Mg^{2+} were 200mg/l and 150mg/l respectively (WHO, 2017). This reveals that Mg^{2+} concentrations in the sampled locations exceeded permissible limit for drinking water. The high Mg^{2+} concentrations found in the study area may be due to the dissolution of carbonate rocks and alkaline intrusive rocks, which may be attributed to the cations exchange between iron and magnesium minerals in the rocks of the study area.

Sulphates easily dissolve in groundwater. It is commonly found as gypsum (CaSO4.2H2O), barite (BaSO4), and epsomite (Mg SO4.7H2O) minerals (Greenwood and Earnshaw, 1985). Sulphates concentration beyond permissible limit cause laxative effects on humans as well as give unpleasant taste to drinking water. The result (Table 2) showed that the parameter was same in Abakpa Nike (A), Asata (C), Iva Valley (J) and Ugwu-Aaron (P) with the mean range of 26.00mg/l–28.00mg/l. Similar in Achara Layout (B), Awkunanaw (D), Coal Camp (E), Mary Land (K) and Trans-Ekulu (N) with mean values ranging from 2.90mg/l–6.00mg/l. The same in Idaw River (H), Independence Layout (I) and New Haven (L) with the mean range of 12.00mg/l–14.00mg/l. However, all of the groundwater samples were below the permissible limit of sulphate in the study area.

Nitrate in groundwater is majorly caused by the unrestricted use of nitrogen fertilizers, animal manure and the inability to use established water and soil management methods, septic tanks, and improper disposal of domestic waste (Canter, 1996). These activities can elevate NO^{3-} concentrations in drinking water and cause gastric cancer in adults, which is blue baby syndrome in infants (Bao et al., 2017). Nitrate concentration in the area showed significant different (Table 3). It was indicated that the parameter was the same in Emene (F), Ugbo-Odogwu (O) and Uwani (Q) with mean range of 7.30mg/l–8.20mg/l. Asata (C), Mary Land (K) and New Haven (L) were the same with the mean range of 14.80mg/l–16.10mg/l. It was also the same for Abakpa Nike (A), Awkunanaw (D) and Ugwu-Aaron (P) with the mean range of 17.70mg/l -17.80mg/l. In Achara Layout (B), New Layout (M) and Trans-Ekulu (N), the calcium ion was the same with mean range of 19.50mg/l–20.00mg/l. However, all the sampled locations were within the permissible limit of 50mg/l (WHO, 2011).

Presence of Total Coliform (TC) in water indicates bacterial contamination either with faeces or sewage. It has the potential to cause diseases such as fever, vomiting, stomach upset, diarrhoea and even death. The parameter was the same in Abakpa Nike (A), G.R.A (G), Mary Land (K), Ugbo-Odogwu (O) and Uwani (Q) with mean values of 11.00mg/l. Asata (C), Awkunanaw (D), Emene (F), Idaw River (H), Independence Layout (I), Iva Valley (J) New Haven (L) ,Trans-Ekulu (N) and Ugbo-Odogwu (O) were the same with mean range of 12.00mg/l–12.33mg/l. Similarly, Tc was the same for Achara Layout (B) and Coal Camp (E) with mean values of 14.00mg/l. The result (Table 3) revealed that permissible limit of 3cu/ml (WHO, 2011) was exceeded in all the locations. This is of great concern and requires prompt intervention.

Sodium (Na^+) and potassium (K^+) ions are mainly found in rock and soils and are easily dissolved in groundwater. It does not pose any threat at allowable limit. However, may pose risk of heart disease, kidney issues or hypertension to human health beyond permissible limits (Yenugu et al., 2020). It can also lead to the deterioration of soil structure and reduced crop yield if the water is used for irrigation (Islam et al., 2017). The result (Table 3) indicated that 94% of the locations were within the permissible limit of sodium (200mg/l). It also shows that the parameter was same in Emene (F) and Independence Layout (I) with mean range of 115.60mg/l -117.69mg/l; Awkunanaw (D), Coal Camp (E), Idaw River (H), Iva Valley (J) and New Haven (L) with mean range of 124.53mg/l–140.97mg/. In addition, the parameter is the same for Mary Land (K) and Uwani (Q) with mean range of 150.07mg/l–150.53mg/;. Abakpa Nike (A), Achara Layout (B) and Asata (C) with mean of 176.75mg/l–182.32mg/l; G.R.A (G) and Ugbo-Odogwu (O) with mean range of 195.81mg/l–197.93mg/l.

Table 2 also shows that potassium is same in Emene (F) and Independence Layout (I) with mean range of 3.77mg/l–3.80mg/l. The same in Achara Layout (B), Awkunanaw (D), Coal Camp (E), and Trans-Ekulu (N) with mean range of 6.82mg/l–8.10mg/l. It was the same in Asata (C), Mary Land (K) and Uwani (Q) with mean range of 10.47mg/l–10.55mg/l. Only 6% of the location indicated higher concentration of Na^+ and K^+ exceeding permissible limit (Table 3). This may be due to agricultural practices, sewage effluent and leaching of potassium through soil profile into groundwater. Sewage effluent and agricultural activities are common practices at Ugwu Aaron; an informal settlement of low income earners with little or no proper toilet system.

Table 3 shows that bicarbonate (HCO_3^-) was same in Coal Camp (E), Emene (F) and Uwani (Q) with mean range of 201.13mg/l–202.57mg/l. Awkunanaw (D) and Independence Layout (I) were similar with mean range of 206.70mg/l–208.65mg/l. In addition, it is similar in Iva Valley (J) and Trans-Ekulu (N) with mean range of 212.23mg/l–212.72mg/l. Asata (C) and Mary Land (K) were the same with mean range of 244.02mg/l-247.93mg/l. HCO_3^- was the same for Abakpa Nike (A) and Ugbo-Odogwu (O) with mean range of 314.53mg/l–316.22mg/l. Carbonate (CO_3^{2-}) was also same in Coal Camp (E), Emene (F), Independence Layout (I) and Trans-Ekulu (N) with mean range of 9.40mg/l–10.37mg/l. Awkunanaw (D), Idaw River (H), Iva Valley (J), Mary Land (K) and Uwani (Q) were similar with mean range of 11.23mg/l–13.00mg/l. Similarly, Abakpa Nike (A), Achara Layout (B), Asata (C) and New Haven (L) were the same with mean range of 15.53mg/l–17.05mg/l. finally, New Layout (M) and Ugbo-Odogwu (O) were similar with mean range of 19.93mg/l–20.97mg/l. G.R.A (G) and Ugwu-Aaron (P) recorded the similar values with mean range of 26.58mg/l–28.06mg/l. The HCO_3^- groundwater content is relatively high in few locations (29%). This may be due to carbonated rich sedimentary formations which contribute to carbonate and bicarbonate to the groundwater in the study area. However, it has no direct adverse health effects on humans. Most of the groundwater samples fell within the permissible limit of 300mg/l (WHO, 2011).

Flouride is one of the major anions. Table 3 showed that the parameter was the same in Abakpa Nike (A), Achara Layout (B), Asata (C), Emene (F), Independence Layout (I), Iva Valley (J) and Uwani (Q) with mean range of 0.70mg/l–0.86mg/l; the same in Idaw River (H) and New Haven (L) with mean range of 0.91mg/l–0.94mg/l; the same in Mary Land (K), New Layout (M) and Trans-Ekulu (N) with mean range of 1.06mg/l–1.09mg/l. The result revealed that 94% of the sampled area was below the permissible limit of 1.5mg/l (WHO, 2011). Only 6% (1.8mg/l) was above the permissible limit. Higher fluoride concentration might be derived from basic flows, geogenic sources and carbonate minerals in the area (Brindha and Elango, 2013; Sudharshan et al., 2020). High fluoride concentration was observed in the study area. This may be as a result of increased alkalinity as also observed in the findings of Muralidhara et al. (2019), who found that fluoride bearing water is usually high in alkalinity and low in hardness, chloride and sulfate. However, the study shows contrast in chloride and sulphate. Consequently, consumption of these high fluoride containing water may lead to dental and skeletal fluorosis (Adimalla and Taloor, 2019).

Nonetheless, the first principal component (PC1) explained 48.92% of the total variance (Table 5) and has a high positive loading on TH (0.93), Mg^{2+} (0.92), Na^+ (0.92), SO_4^{2-} (0.76), NO_3^2 (0.80) (0.77), F^- (0.72), HCO^{3-}(0.86), CO^{3-} (0.0.72) Calcium hardness (0.76), magnesium hardness (0.79), Ca^+ (0.86) and K^+ (0.67) as shown in Table 6. Clearly, PC1 represents the influence of mineral dissolution from geological formations on the hydrochemistry of groundwater. This implies that the quality of water in the study area is greatly dependent on the aquifer material which is in agreement with the findings of Emenike et al. (2018). Similarly, it has been revealed that weathering effect assisted by abundant rainfall leads to continuous leaching of minerals into groundwater (Oke and Tijani, 2012). Therefore, this finding shows that mineral dissolution has more effect on the hydrochemistry of region than anthropogenic activities.

The second principal component (PC2) explained 10.20% of the total variance (Table 5) with high loadings on EC (0.69) and Cl^- (0.86) (Table 6). EC requires charged chemicals in water known as salt for electrical current to be conducted. EC and Cl^- can enter groundwater through rocks weathering, solid waste leachate, industrial effluent which is an attribute of poor waste management. However, PC2 showed that the groundwater chemistry of the area is not influenced negatively by these activities. The third principal component (PC3) explained 8.09% of the total variance (Table 5) with high loadings on turbidity (0.92) (Table 6). This component is as a result of leaching of elements from the rocks which was as a result of chemical interaction with surfaces and physical movement of water. The fourth principal component (PC4) explained 7.36% of the total variance with (Table 5) high loadings on alkalinity (0.89) and pH (0.80) (Table 6). This represents the influence of the natural environment such as soil on the chemistry of groundwater. The fifth principal component (PC4) explained 5.64% of the total variance (Table 5) with high loadings on iron (0.75) and total coliform (0.57) (Table 6). This component obviously represents the impact of natural environment and human activities on groundwater quality. As noted by Barzegar et al. (2017) and Sharma et al. (2016), sewage sludge used for agricultural purposes, and organic matter and leachate from dump sites are major source of coliform bacteria. Finally, the sixth principal component (PC6) explained 4.88% of the total variance (Table 5) with high loadings on TDS

(0.69) and TSS (0.92) (Table 6). This represents the influence of mineral dissolution, as well as transport of chemical compounds like decomposing plant materials and microbes. Although the TSS was very low in all the sampled locations.

Piper diagram (Fig. 3) shows that the groundwater of the sampled area consists majorly of NaCl (Sodium-Chloride), mixed $CaNaHCO_3$ (Calcium-Sodium-Bicarbonate) and $NaHCO_3$ (Sodium-Bicarbonate) types. Among cations Sodium is dominant, and among anions bicarbonate is dominant. Ca–Na–HCO_3 water type which has low rock-water interaction is found in northern highland and in central part of the study area. This is attributed to the influence of hydrolysis of silicate minerals into the groundwater. The result is in agreement with findings of Mechal et al. (2017) in Ethiopia groundwater rift where hydrolysis of silicate materials resulted in the release of HCO_3. Na-Ca-HCO_3 water type is characterized by intermediate rock-water interaction and mixed cations. Na-HCO_3 water types are highly mineralized and undergone significant rock-water interaction, and are from fractured basalt, rhyolites, and ignimbrite as noted by Kebede et al. (2008) and Furi et al. (2012). However, the results of this study reveals groundwater quality evolution is from low rock-water interaction Ca–Na–HCO_3 water type to high rock-water interaction Na–HCO_3 water type along ground flow from north to south. This concludes that weathering of silicate minerals and cation exchange along groundwater flow path are responsible for the current characteristics of hydrogeochemical facies.

Moreover, the Durov plot reveals that pH in the study area was acidic which is questionable for drinking (Fig. 4). The total dissolve solid for all of the groundwater samples lies in the range of drinking water standards. The Gibbs Plot shows most of the samples were clustered in the middle part of the diagrams as shown in Fig. 5, indicating that rock weathering is the most important natural factor governing groundwater evolution, and is in tandem of the study of Wu et al. (2008). A large amount of dissolvable minerals occur in the sediments and these sediments were the results of parent rock weathering. It may also be attributed to groundwater abstraction which lower groundwater level, and may alter the hydraulic relationships of adjacent aquifers and/or enhance the water–rock interactions within the aquifers. A study by Li et al. (2016) showed that some samples were influenced to some degree by evaporation which was due to level of depth of the shallow groundwater (<3m) in alluvial plain whereas in this study it was mainly rock dominance.

Finally, the result of the Stiff graph shows that the water type varies from NaHCO3, CaNaHCO3, NaHCO3Cl, NaMgHCO3, NaHCO3Cl (Fig. 6). It reveals that 59% are NaHCO3 type, 17% are CaNaHCO3 while 23% are other types. This shows that the type dominant in piper plot (NaHCO3 and CaNaHCO3) which was as a result of rock weathering and mineral dissolution.

Given the results of the hydrochemical facies of the study area, it is questionable if the water quality is fit for human consumption, thus the water is not safe for drinking. Although, hand-dug wells and boreholes serve as an alternative to inadequate pipe-borne availability and supply in Enugu, it is highly recommended that the water be treated before drinking to avoid some health consequences. Recommendations such as awareness creation through media dialogues, workshops, Tik Tok, and stakeholders' consultative meetings are made to help change the assumption of the people that groundwater is naturally clean and needs no purification. It is also recommended that the Enugu State Government should monitor groundwater quality to alert residents of potential contamination.

Conclusion

Groundwater constitutes a major source of water for residents in Enugu due to inadequate supply and distribution of pipe-borne water by the Enugu State Water Corporation. The study determined the quality of groundwater in Enugu to investigate whether groundwater is fit for human consumption. The results revealed that the physio-chemical properties of groundwater vary significantly across the area, with rock water interaction and mineral dissolution being the major factors indicating that mineral dissolution has more effect on the hydrochemistry of Enugu than anthropogenic activities. This implies that the quality of water in Enugu is greatly dependent on the aquifer material. The hydrochemical facies were determined using the Piper, Durov, Gibbs and Stiff analyses and the results indicate that the groundwater quality in the study area is questionable, thus the water is unsafe for drinking except when treated. Recommendations such as awareness creation about groundwater pollution and purification to change their assumption that groundwater is naturally clean, and measures for effective management of groundwater quality through sustainable protection and monitoring have been made.

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