

Water Quality Index (WQI) in Parts of Okene and Adavi Area, Wet Season, North Central Nigeria

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Abstract: Groundwater Quality Index (WQI) was used in evaluating the water qualities of shallow groundwater of Okene and Adavi areas, North central Nigeria for drinking, domestic, agricultural and industrial purpose. Water Quality Index (WQI) simply converts and integrates large numbers of complicated datasets of the physicochemical elements with the hydrogeological parameters into quantitative and qualitative data for better understanding of water quality. Thirty-two shallow groundwater samples were sampled (fifteen from boreholes and seventeen from hand dug wells). Physico-chemical parameters like pH, EC, TDS, temperature, Na^+ , Ca^{2+} , K^+ , Mg^{2+} , Fe^{2+} , Cl^- , HCO_3^- , NO_3^- , SO_4^{2-} and faecal coliform count were analyzed and the groundwater classified. Physical parameters show that, the average pH of water is 5.54 (slightly acidic), Total dissolved solids (TDS) 326.47mg/l, Electrical Conductivity (EC) 599.12 $\mu\text{S}/\text{cm}$, temperature (T) 29.32 $^\circ\text{C}$, Dissolved oxygen (DO) 8.32mg/l. The order of mean concentration of cations was $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{Na}^+ > \text{K}^+$ with Ca constituting 55% in most cases. The anions had an abundant distribution of $\text{Cl}^- > \text{HCO}_3^- > \text{SO}_4^{2-} > \text{NO}_3^- > \text{PO}_4^{3-}$. The Gibbs plot revealed all of the samples fall within the rock-water interaction dominance. The Piper's plot classified the groundwater as Ca–Mg– HCO_3^- (60%) and mixed Ca–Na– HCO_3^- (27%). water type. Total viable count ranged between 7.10×10^1 - 1.20×10^6 and total coliform ranged between 0.00 - 3.00×10^3 respectively. It was evident that only four (4) shallow groundwater samples (representing 12.5%) are within the NSDWQ, and WHO guidelines of 0 CFU/100 ml. The result of the WQI of the shallow groundwaters in Okene and environs indicates that 62.5% fall under the excellent water category, 25% fall in the good category, and 12.5% are in poor category. With adequate and proper treatment, the poor category can be used for drinking and groundwater sources are suitable for agricultural purposes based on the SAR, %Na, MH, KR, TDS, EC and Wilcox classifications.

Keywords: WQI, Cations, Anions, Okene, Groundwater.

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I. INTRODUCTION

Groundwater is an essential natural resource that supports domestic, agricultural, and industrial activities across both rural and urban communities worldwide. In many developing countries, including Nigeria, groundwater serves as the primary source of potable water because it is generally protected from direct contamination through natural filtration within permeable geological formations (Lapworth et al., 2020). The quality of groundwater is commonly evaluated using physical, chemical, and biological parameters such as pH, temperature, total dissolved solids (TDS), hardness, major ions, trace elements, and coliform bacteria, all of which are regulated by standards established by the World Health Organization (WHO) and the Nigerian Standard for Drinking Water Quality (NSDWQ) (World Health Organization

[WHO], 2022; Standards Organisation of Nigeria [SON], 2021). Variations in these parameters are influenced by hydrogeological conditions, climatic factors, and geochemical interactions between groundwater and aquifer materials.

Despite its importance, groundwater quality has increasingly deteriorated due to both geogenic and anthropogenic influences. Natural processes such as mineral dissolution, ion exchange, and rock weathering alter groundwater chemistry, while anthropogenic activities including poor waste disposal, septic tank seepage, agricultural runoff, and industrial discharges contribute significantly to groundwater contamination (Adelana & MacDonald, 2021; Emenike et al., 2022). These contaminants may affect aquifer properties and reduce the suitability of

groundwater for drinking and other uses. In rapidly urbanizing areas such as Okene and Adavi in Kogi State, increasing population growth, urban expansion, and inadequate sanitation systems have intensified pressure on groundwater resources, which can increase the risk of contamination from domestic and environmental pollutants.

To effectively assess groundwater suitability, researchers commonly employ the Water Quality Index (WQI), which integrates multiple physicochemical and biological parameters into a single numerical value representing overall water quality status (Atta et al., 2022). In addition, multivariate statistical methods such as Principal Component Analysis (PCA), Cluster Analysis (CA), and Geographic Information Systems (GIS) have become important tools for identifying pollution sources, hydrogeochemical processes, and spatial variations in groundwater quality (Noori et al., 2023; Saqib et al., 2023). These techniques simplify complex hydrochemical datasets and improve understanding of groundwater evolution, contamination pathways, and seasonal variations, thereby enhancing groundwater management and environmental monitoring.

Several recent studies have applied WQI, GIS, and hydrogeochemical approaches to evaluate groundwater quality in Nigeria and other parts of the world. Saadu et al. (2020) classified groundwater quality in the Kaduna Basin using physicochemical parameters and WQI, while Alimi et al., (2021) assessed groundwater quality in northwestern Nigeria. Similarly, Akakuru et al., (2022) investigated hydrogeochemical evolution and pollution indices in the eastern Niger Delta, whereas Erhan et al. (2022) evaluated groundwater quality and associated health risks in Turkey. Studies by Arjun et al., (2021), Noori et al., (2023), and Saqib et al., (2023) further demonstrated the effectiveness of WQI and GIS techniques in groundwater assessment for drinking and irrigation purposes. In view of the growing environmental pressures within Okene and Adavi, this study evaluates the groundwater quality of the area using WQI and hydrogeochemical approaches to determine its suitability for domestic use and sustainable groundwater management.

► The Study Area

The study area is situated between latitudes $7^{\circ}32'$ and $7^{\circ}38'N$ and longitudes $6^{\circ}10'$ and $6^{\circ}18'E$ (Fig. 1). It encompasses approximately 35 km² and includes Okene, Adavi, and parts of Okehi Local Government Areas in north-central Nigeria.

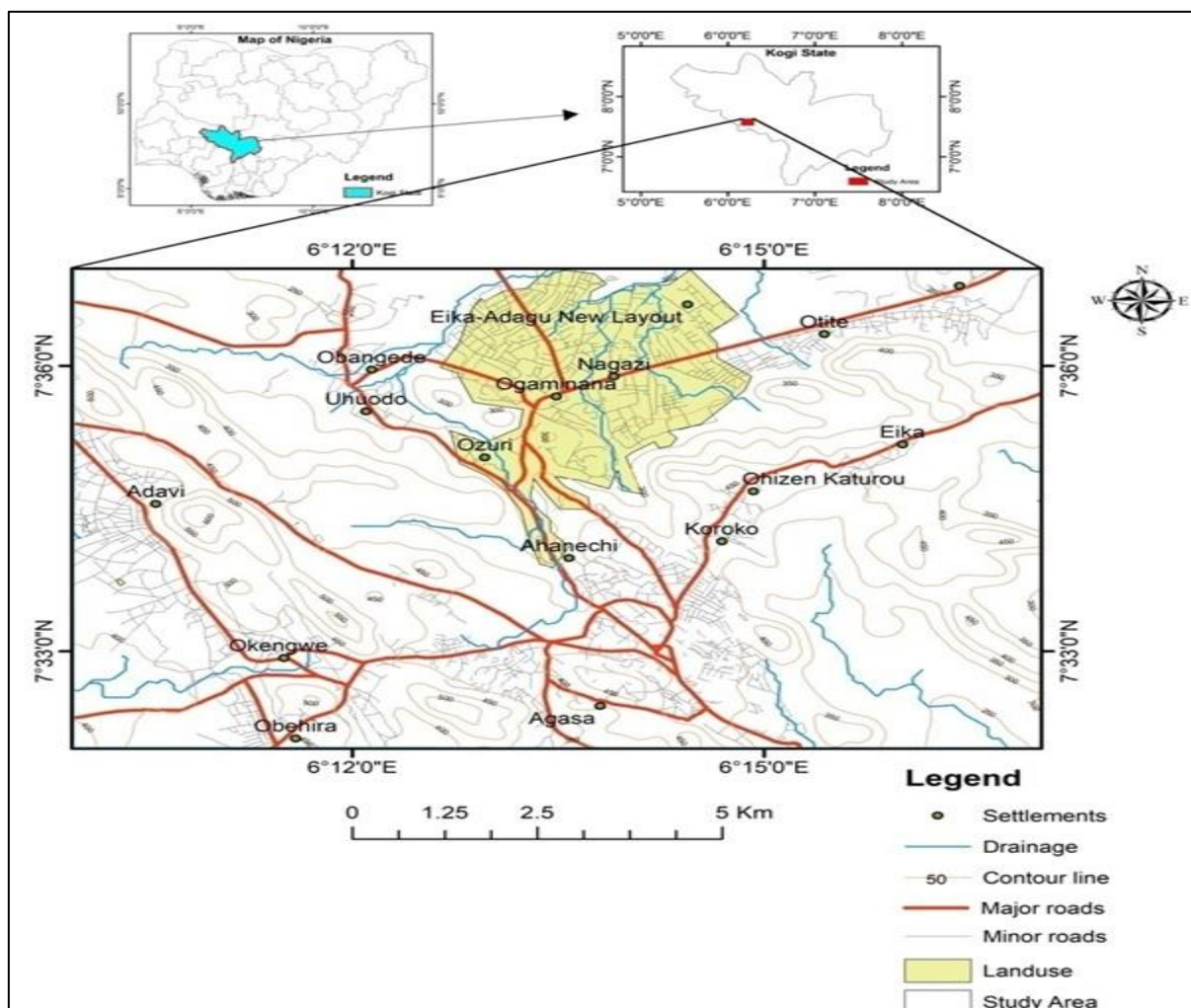


Fig 1 Location Map of the Study Area

This region features a climate typical of the tropical woodland and tall grass savannah zone due to its geographical location. It is characterized by two distinct seasons: the rainy season and the dry season. The temperature ranges from 18.4°C to 36.9°C, with an annual rainfall of about 1500 mm (Ogbonna et al., 2006). Relative humidity is low during the dry season and high during the wet season, which begins around March and ends in October. The dry season commences in November and lasts until early March of the following year (Aremu et al., 2014). Heavy rainfall usually occurs in June and July, followed by a short break in August and another downpour in September, leading to two distinct peaks of rainfall in the area.

II. GEOLOGY OF THE STUDY AREA

The study area Okene, is part of the Southern Basement Complex of Nigeria (sub division of the Nigeria Basement Complex) which is a component of the Pan- African belt that is located to the east and southwest of the West African and Congo cratons respectively (Ajibade, et al., 1987). The terrain is structurally complex, reflecting a long polycyclic tectonothermal history associated with the Pan-African orogeny. The local geology of Okene includes major rocks such as Migmatite gneiss and granite (attached geological map of the study area) and minor rocks such as quartzofeldspathic intrusions (quartz veins and dykes).

The lithological assemblages are dominated by older granites, metasedimentary schist belts, and extensive migmatite–gneiss complexes (fig 2).

➤ Hydrogeology of the Study Area

Okene is situated within the Nigerian Precambrian Basement Complex, where groundwater occurs mainly within weathered and fractured crystalline rocks. Groundwater storage and movement are controlled by the thickness of the weathered overburden and the intensity of fractures within the bedrock, with productive aquifers commonly associated with deeply weathered and highly fractured zones (Adelana & MacDonald, 2021; Emenike et al., 2022). The area is underlain by granite, migmatite, gneiss, and schist, whose weathering and structural deformation have produced secondary porosity that enhances groundwater occurrence and recharge. Consequently, groundwater yield and quality in the area are strongly influenced by lithology, fracture systems, mineral composition, and water–rock interaction processes (Akinsanola et al., 2022; Oyebamiji et al., 2023).

In addition, Quaternary alluvial deposits consisting mainly of clay, silt, sand, and gravel are developed along drainage channels, serving as local shallow aquifers (Offodile, 2002).

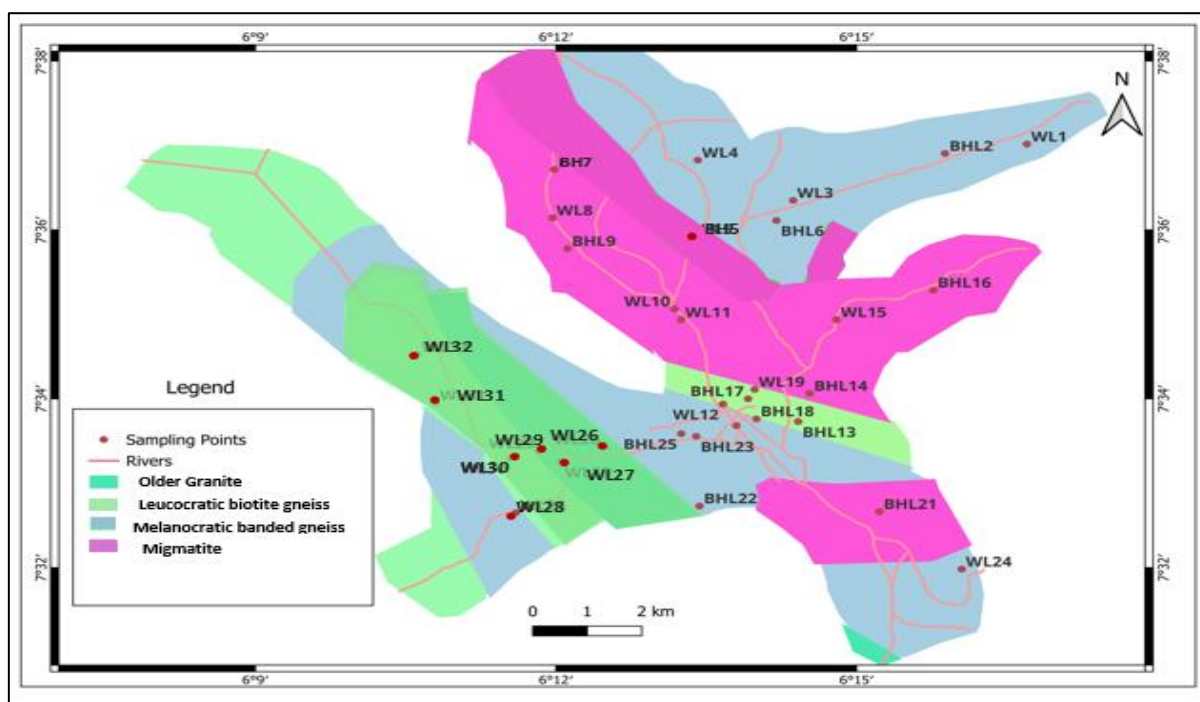


Fig 2 Geologic Map of the Study Area Showing Sampling Points.

III. MATERIALS AND METHODS

Thirty-two (32) groundwater samples obtained from boreholes and hand-dug wells were collected using clean 250 ml polythene containers and bailers, while the coordinates and elevations of each sampling location were recorded with a Global Positioning System (GPS). The samples were filtered in situ using UNICEF standard filters to eliminate

suspended particles before preservation. Samples intended for cation and anion analyses were completely filled to minimize oxidation and air entrapment, whereas those meant for bacteriological analysis were partially filled to permit microbial activity. In addition, samples for cation analysis were acidified with nitric acid to maintain dissolved ions in solution and prevent adsorption onto the container walls. Field measurements of temperature, pH, electrical

conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), and bicarbonate alkalinity were conducted using standard digital meters and titration procedures. Thereafter, the samples were transferred into sterilized plastic bottles, preserved in ice-packed coolers, and transported to the laboratory for detailed hydrochemical and microbiological analyses. Major cations and trace elements were determined using Atomic Absorption Spectrophotometry (AAS), chloride and bicarbonate concentrations were analyzed by titration, sulfate, nitrate, and phosphate were determined using Flame Spectrophotometry, while bacteriological examination was carried out using the membrane filtration method.

➤ Data Evaluation and Statistical Treatment

The hydrochemical data obtained in this study were subjected to comprehensive evaluation using a combination of statistical and analytical techniques. The specific methods employed are outlined below.

➤ Water Quality Index (WQI)

A water quality index is a means of summarizing large complex amounts of water quality data into more simple terms for reporting to management and the public in a consistent manner. It can tell us the overall quality of water bodies and suitability for drinking and other use like for irrigation, habitat for aquatic life, recreation and aesthetics (Akakuru et al., 2021b). This index allows for a general analysis of water quality on many levels that affects a stream's ability to host life. The WQI is determined in three phases. the quality rating scale (qi) for each boundary gotten by partitioning the sample value (Ci) in each water test by its standard Si. Ci is the mean value of the parameter under consideration while Si is the water quality standard by WHO. The outcome is then multiplied by 100 (Akakuru and Akudinobi, 2018; Gopinath et al., 2016)

$$Q_i = \frac{C_i}{S_i} \times \frac{100}{1} \dots\dots\dots (1)$$

The relative weight Wi is

$$W_i = \frac{1}{S_i} \dots\dots\dots (2)$$

$$WQI = \sum q_i W_i \dots\dots\dots (3)$$

Where qi = ith parameter quality, Wi = weight of the unit ith parameter

➤ Contamination Factor (Cf)

The contamination factor (Cf) is the ratio obtained by dividing the concentration of each metal in the water/sediment by the upper permissible value of its background value (concentration in uncontaminated water/sediment) Akakuru et al., 2022; Hakanson, 1980). Cf values were interpreted as: Cf < 1 = low contamination; 1 < Cf < 3 = moderate contamination; 3 < Cf < 6 = considerable contamination and Cf > 6 = very high contamination. The

contamination factor was determined following the method proposed by Hakanson (1980)

$$CF = C_n / B_n$$

Where Cn = concentration of metal in the study area.
Bn = background value of concentration in the region (SON, 2021)

➤ Sodium Adsorption Ratio (SAR)

The sodium adsorption ratio (SAR) is used to evaluate water suitability for agricultural irrigation purpose. This is done to check the water for high SAR can result in a reduction in the permeability and structure of soil (Ahmed et al., 2020). Also, under arid climatic conditions, this may cause a lot of problems such as soil salinization which affects the capacity of plants through the roots and poor drainage conditions (Akakuru et al., 2022). SAR takes in consideration of the presence of calcium and magnesium ion in natural waters been responsible for high sodium concentration.

Therefore, when SAR value is less than 10, the water is excellent for irrigation and has no effect on the soil; if the value rises above 18 but less than 26, serious physical soil problems occur and plants have difficulty absorbing water (Eyankware et al., 2020). SAR is calculated from the relationship from (Richards, 1954).

$$SAR = \frac{Na}{\sqrt{(Ca + Mg) / 2}}$$

Cation concentration is in meq /L

➤ Magnesium Hazard (MH)

MH is an important parameter for assessing the suitability of water quality for irrigation. High level of magnesium is caused by exchangeable Na in irrigated soils. MH is calculated using equation below. High concentration of magnesium in water has negative influence on crop yields as the soil becomes more alkaline (Eyankware et al., 2020). MH was computed using the equation by Szabolcs and Darad (1964).

$$MH = \frac{(Mg^{2+})}{Ca^{2+} + Mg^{2+}} \times 100$$

➤ Percent Sodium (%Na)

Sodium percentage is a crucial criterion for defining irrigation water quality, as it influences soil structure and plant health. High sodium concentrations in irrigation water cause sodium ions to replace calcium (Ca²⁺) and magnesium (Mg²⁺) ions in the soil. This ion exchange can lead to soil dispersion, reducing soil permeability and water flow, and ultimately causing soil hardening and compacting when dry. Such changes impair water infiltration and aeration, which can negatively affect plant growth. It is generally advised not to use irrigation water with a sodium percentage exceeding 60%, as it can severely damage soil structure. The sodium

percentage in water is calculated using specific equations, such as those proposed by Karma & NakoMan (2010).

$$\%Na = \left[\frac{Na^{+} + K^{+}}{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}} \right] \times 100$$

Kelly's ratio (KR) or Kelly's Index

Kelly's ratio is a parameter introduced to evaluate water quality for irrigation based on the level of sodium ion measured against calcium and magnesium ions (Kelly, 1963). Water with $KR < 1$ is suitable for irrigation, whereas water with $KR > 1$ is unsuitable for agricultural purpose due to alkali hazards (Akakuru et al., 2021b; Eyankware et al., 2020). KR is computed using Kelly (1963) equation.

$$KR = \frac{(Na^{2+})}{Ca^{2+} + Mg^{2+}}$$

➤ Total Hardness (TH)

Water is termed hard when there is high concentration of dissolved calcium and magnesium ions in the solution of their salts (Eyankware et al., 2020). Hardness is determined by the calcium and magnesium content of water. Since calcium and magnesium are essential plant nutrients, moderate levels of hardness of 100- 150mg/l are considered ideal for plant growth. These levels of hardness also inhibit plumbing systems corrosion but are not high enough to cause serious clogging from scale formation (Akakuru et al., 2017a, 2017b, 2022; Eyankware et al., 2022; Todd, 1980). High concentration of hardness above 150mg/l will build up on contact surfaces, plug pipes and irrigation lines and damage water heaters. These levels can also cause foliar deposits of scale. Removal of hardness using a water softener is necessary only if the water is causing problems. Extremely soft water below 50 mg/l may require fertilization with calcium and magnesium. The total hardness is calculated using the equation described by Todd (1980).

$$TH = 2.5 \times Ca^{2+} + 4.1 \times Mg^{2+}$$

➤ Total Dissolved Solids (TDS)

The TDS in groundwater gives a comprehension into the amount of proportion of split up inorganic salts in a given water (Adimalla and Venkatayogi, 2018; Urom et al., 2021). Geochemical measures and other anthropogenic activities are critical records that impacts the TDS in groundwater (Akakuru et al., 2021b; Raju et al., 2011; Yetis et al., 2019). Centralization of separated salt in a given volume of water are pungency (WHO, 2017).

➤ Correlation Matrix

The correlation matrix based on the Pearson's correlation coefficient was utilized for displaying relationship between two variables. The correlation coefficient is usually between -1 and + 1. If the r value is close to -1, the relationship

is said to have a negative slope or anti- correlated. When the value r is close to +1 the relationship is said to have a positive slope or considered to be correlated. If the value is zero, the points are said to be uncorrelated (Srivastava et al., 2014). High correlation coefficient between pair of element or groups of elements may be indicative of similar geochemical processes, factor and reactions which may have influenced metal distribution whereas, marked differences in the element correlations may indicate dissimilar source materials, leaching or physicochemical depositional characteristics (Kronberge et al., 1979).

➤ Principal Component Analysis (PCA)

PCA has been a vital statistical tool utilized to ascertain the relationship with some process that controls the water quality (Subba Rao, 2007). PCA is a technique for reducing the dimensionality of such data set, increasing interpretability but at the sametime minimizing information loss (Ahmad et al., 2020; Yahaya et al., 2021). It explains the relationship that exist between parameters to identify the likely sources of contamination of groundwater.

➤ Hierarchical Cluster Analysis

Cluster analysis is a series of multivariate methods used to define true groups of data (Harikumar and Jisha, 2010). Objects are grouped such that similar objects fall into the same class. Hierarchical clustering which joins the most similar observations and successively the most similar observations was employed. The levels of similarity at which observations are merged are used to construct a dendrogram. The squared Euclidean distance method is used to construct dendrogram. Low distance shows that the two objects are similar or close together whereas a large distance indicates dissimilarity (Praveen et al., 2007; Sekabira et al., 2010; Harikumar and Jisha, 2010).

IV. RESULTS AND DISCUSSIONS

Physical parameters show that, the average pH of water is 5.54 (slightly acidic), Total dissolved solids (TDS) 326.47mg/l, Electrical Conductivity (EC) 599.12µs/cm, temperature (T) 29.32°C, Dissolved oxygen (DO) 8.32mg/l. The order of mean concentration of cations was $Ca^{2+} > Mg^{2+} > Na^{+} > K^{+}$ with Ca constituting 55% in most cases. Ca concentration ranged between 14.1 and 210 mg/l and a mean value of 46.82mg/l (table 1). Mg values ranged between 19.2 and 105.6mg/l and a mean value of 45mg/l. Na values ranged between 7 and 200.1 mg/l with mean of 58.13mg/l. K value ranged between 0 and 23 mg/l with mean of 3.92mg/l, and mean total hardness (TH) 302.21. The alkaline earth metals had higher concentration compared to alkali metals. Also, the anions had an abundant distribution of $Cl^{-} > HCO_3^{-} > SO_4^{2-} > NO_3^{-} > PO_4^{3-}$ with the values of 26 – 250 mg/L and mean of 92.91 mg/L, 38mg/l – 165mg/l (83.29mg/l), 5mg/l – 170mg/l (33.44 mg/l), 1 – 15mg/l (6.91mg/l), 0 – 2mg/l (0.32mg/l) respectively. The elevated concentration of Cl (although within WHO permissible limits) could be from rocks containing minerals rich in chloride (Gideon et al., 2022).

Table1 Physicochemical Results

S/no	pH	TDS	EC	Temp	DO	Na	K	Ca	Mg2	Cl	HCO3	SO4	NO3	PO4
WL1	6.0	277	500	31	9	25.4	0.9	43.6	57.6	154	63.5	40.7	1.9	0.2
BHL2	5.5	355	661	29	8	63.9	0.8	24.7	48.0	50	126.9	18.0	5.9	0.2
WL3	6.5	294	558	28	8	41.4	4.1	63.3	38.4	56	38.1	27.0	7.7	0.1
BHL4	5.7	308	521	30	9	106.8	1.1	22.9	28.8	38	114.2	14.0	3.8	0.3
BHL5	5.5	650	1200	30	6	171.3	4.5	29.0	105.6	180	126.9	67.0	8.8	0.5
BHL6	5.9	193	395	29	7	35.5	1.2	21.0	38.4	78	50.8	21.0	7.7	0.2
BHL7	5.6	413	770	31	9	64.9	1.5	44.9	57.6	90	114.2	36.0	10.2	0.3
WL8	5.2	421	790	30	8	113.0	2.4	51.2	48.0	74	63.5	49.0	8.1	0.2
BHL9	5.7	433	800	28	10	120.8	3.4	40.6	57.6	144	101.5	33.0	2.8	0.1
WL10	4.9	423	798	30	6	178.7	22.5	103.5	28.8	66	88.8	49.3	11.2	0.5
WL11	5.3	186	350	28	8	25.3	4.5	17.3	19.2	26	63.5	9.0	2.3	0.1
WL12	5.0	215	375	28	10	30.1	3.6	22.1	28.8	54	63.5	18.0	2.2	0.2
BHL13	5.8	530	970	28	11	103.2	5.3	192.0	38.4	210	114.2	62.3	5.6	0.3
BHL14	6.0	701	1300	29	9	200.1	20.7	210.0	67.2	250	88.8	65.0	11.5	0.5
WL15	5.4	221	400	29	8	36.0	6.4	22.4	19.2	58	63.5	12.0	5.4	1.0
BHL16	5.6	220	395	28	11	27.1	1.5	29.7	28.8	42	76.2	10.7	1.3	0.2
BHL17	5.4	180	345	30	6	31.1	0.5	26.2	48.0	54	50.8	23.0	4.9	0.1
BHL18	5.4	371	650	30	7	34.3	4.7	42.9	38.4	70	101.5	24.3	15.3	2.5
WL19	5.2	183	348	29	9	18.3	0.4	15.5	28.8	42	76.2	20.0	2.1	0.1
BHL20	5.7	500	940	30	6	53.2	1.3	156.0	86.4	246	114.2	170.0	15.3	0.1
BHL21	5.6	330	600	30	8	44.3	2.2	22.8	57.6	124	88.8	40.0	5.1	0.2
BHL22	6.2	363	635	30	10	103.8	1.0	30.6	48.0	130	126.9	52.0	6.1	0.1
BHL23	5.3	300	550	31	7	25.5	0.2	16.7	38.4	52	165.0	15.0	1.5	0.2
WL24	4.6	157	280	29	9	19.0	1.5	18.6	28.8	68	88.8	27.0	9.2	0.4
BHL25	6.2	380	665	29	7	29.7	0.4	37.2	57.6	146	50.8	47.0	9.2	0.2
WL26	5.4	137	250	28	12	6.8	0.3	14.1	19.2	30	76.2	5.0	2.7	0.1
WL27	5.5	300	548	31	6	28.5	6.1	31.7	57.6	84	38.1	30.7	13.9	0.3
WL28	5.6	265	430	31	8	24.0	0.2	28.1	38.4	53	38.1	28.0	5.1	0.1
WL29	5.3	168	329	30	11	12.7	2.8	20.7	28.8	54	50.8	5.0	5.2	0.5
WL30	5.4	401	750	30	7	54.2	11.1	38.3	67.2	156	101.5	34.0	14.5	0.1
WL31	5.5	390	726	30	9	22.4	5.6	41.7	48.0	58	63.5	10.0	9.3	0.1
WL32	5.4	182	345	30	8	8.7	2.8	18.8	38.4	36	76.2	7.0	5.3	0.2
MAX	6.5	701	1300	31	12	200.1	22.5	210.0	105.6	250	165.0	170.0	15.3	2.5
MIN	4.6	137	250	28	6	6.8	0.2	14.1	19.2	26	38.1	5.0	1.3	0.1
MEAN	5.5	332	610	29	8	60.8	4.4	50.7	46.0	96	84.4	36.6	7.0	0.4

Table 2 Trace Elements

S/no	Ba	TH	Cd	Pb	Mn	As	Ni	Fe	Cr	Cu	Zn
WL1	3.90	346.07	0.00	0.02	0.04	0.04	0.01	0.01	0.04	0.04	0.06
BHL2	0.60	259.34	0.00	0.03	0.03	0.02	0.01	0.05	0.08	0.03	0.05
WL3	15.20	316.19	0.00	0.03	0.01	0.01	0.01	0.06	0.07	0.02	0.02
BHL4	6.60	175.78	0.01	0.02	0.06	0.08	0.01	0.05	0.07	0.02	0.01
BHL5	15.40	507.27	0.00	0.08	0.05	0.00	0.01	0.06	0.05	0.01	0.02
BHL6	6.50	210.57	0.00	0.11	0.06	0.01	0.01	0.08	0.05	0.01	0.04
BHL7	9.60	349.31	0.00	0.10	0.04	0.00	0.02	0.07	0.05	0.02	0.08
WL8	15.70	325.51	0.00	0.04	0.05	0.05	0.00	0.08	0.05	0.00	0.05
BHL9	19.20	338.58	0.00	0.02	0.08	0.04	0.00	0.09	0.05	0.02	0.03
WL10	50.20	377.04	0.00	0.04	0.04	0.03	0.02	0.08	0.06	0.06	0.04
WL11	21.00	122.26	0.00	0.02	0.07	0.05	0.02	0.11	0.07	0.08	0.05
WL12	18.60	173.78	0.00	0.02	0.06	0.06	0.02	0.09	0.05	0.08	0.03
BHL13	23.30	637.56	0.00	0.02	0.05	0.09	0.02	0.10	0.05	0.08	0.03
BHL14	47.90	801.1	0.00	0.03	0.01	0.01	0.02	0.10	0.04	0.07	0.01
WL15	25.40	135	0.00	0.03	0.01	0.01	0.01	0.11	0.04	0.06	0.03
BHL16	11.30	192.76	0.00	0.05	0.00	0.02	0.02	0.11	0.06	0.09	0.08
BHL17	6.70	263.09	0.00	0.07	0.03	0.03	0.03	0.13	0.04	0.07	0.04
BHL18	20.70	265.25	0.00	0.10	0.05	0.00	0.03	0.10	0.05	0.07	0.03

WL19	6.70	157.3	0.01	0.15	0.01	0.02	0.02	0.12	0.05	0.05	0.06
BHL20	10.00	745.33	0.00	0.13	0.02	0.01	0.02	0.13	0.04	0.08	0.05
BHL21	13.70	294.13	0.00	0.15	0.01	0.02	0.02	0.16	0.06	0.10	0.00
BHL22	9.80	274.07	0.00	0.10	0.01	0.00	0.02	0.18	0.03	0.09	0.02
BHL23	8.00	199.83	0.00	0.07	0.02	0.01	0.02	0.19	0.03	0.08	0.00
WL24	12.00	165.04	0.00	0.13	0.04	0.01	0.03	0.22	0.02	0.09	0.00
BHL25	9.00	330.09	0.00	0.14	0.03	0.01	0.04	0.20	0.01	0.08	0.02
WL26	8.90	114.27	0.00	0.19	0.05	0.01	0.07	0.22	0.02	0.11	0.03
WL27	25.70	316.35	0.00	0.14	0.02	0.01	0.05	0.26	0.03	0.12	0.04
WL28	8.00	228.3	0.00	0.09	0.02	0.01	0.02	0.24	0.02	0.13	0.01
WL29	16.70	170.29	0.00	0.06	0.08	0.03	0.02	0.32	0.03	0.11	0.03
WL30	39.10	372.36	0.00	0.14	0.02	0.01	0.02	0.35	0.02	0.12	0.04
WL31	24.00	301.79	0.00	0.17	0.03	0.01	0.02	0.35	0.01	0.11	0.05
WL32	16.10	205.07	0.01	0.15	0.02	0.02	0.02	0.36	0.02	0.13	0.02
MAX	50.20	801.10	0.01	0.19	0.08	0.09	0.07	0.36	0.08	0.13	0.08
MIN	0.60	114.27	0.00	0.02	0.00	0.00	0.00	0.01	0.01	0.00	0.00
MEAN	16.95	311.35	0.00	0.08	0.04	0.02	0.02	0.15	0.04	0.07	0.03

The order for trace element is Ba > Fe > Cr > Mn > Zn > Cu > Pb > As > Ni > Cd.

Based on the results of the contamination factor (CF). The CF for Ba, apart from sample BHL2 with low contamination of 0.857, all the remaining 31 water samples range from impressive defilement to extremely high pollution. Cd; all samples range between low to moderate contamination except for sample WL32 which shows impressive defilement. For Pb, samples WL1, BHL4, BHL9, WL11, WL12, BHL13, BHL14, WL15, show low to moderate contamination, BHL2, WL8, WL10, BHL16 show impressive defilement, BHL5, BHL6, BHL17, BHL18, WL19, BHL20, BHL21, BHL22, BHL23, WL24, BHL25, WL26, WL27, WL28, WL29, WL30, WL31, WL32 show extremely high pollution. As; but for BHL4 and BHL13 with CF 7.927 and 8.867 respectively which are extremely high pollution, all the remaining 30 shallow groundwater samples are within low to moderate contamination. Fe is low to moderate in all samples. Cr is low to moderate in all samples; Cu, Zn, Ni, and Mn were all low in contamination.

➤ Correlation Matrix

The correlations between anions (Cl^- , SO_4^{2-} , NO_3^-) and salinity indicators were slightly stronger. Cl^- – SO_4^{2-} showed a very strong association ($r \approx 0.80$) in the wet season pointing to enhanced flushing and mobilization of soluble salts during recharge. Similarly, the relationship between NO_3^- and TDS/EC strengthened slightly in the wet season ($r \approx 0.50$) which reflects increased leaching of nitrate from agricultural soils and other anthropogenic sources following rainfall infiltration.

NO_3^- showed positive correlations with K ($r = 0.45$) and Na ($r = 0.26$). This is a signature of leaching and agricultural runoff. Phosphate, however, displayed weak or inconsistent correlations. During rainfall recharge, it is more influenced by soil inputs, adsorption, and dilution processes than by mineralization. Wet season chemistry is influenced by recharge-driven leaching of anions, water–rock interaction and anthropogenic contaminants.

Table 3 Pearson's Correlations in Groundwater (Okene) for Wet Season

	pH	TDS	EC	Temp	DO	Na	K	Ca	Mg	Cl	HC	SO	NO	PO	Ba	Cd	Pb	Mn	As	Ni	Fe	Cr	Cu	Zn
pH	1.00																							
TDS	0.31	1.00																						
EC	0.30	1.00	1.00																					
Temp	0.15	0.06	0.05	1.00																				
DO	0.0	0.0	0.0	-	1.0																			

	0 5	21	2 2	0.4 1	0 0																			
Na	0. 1 3	0. 81	0. 8 1	- 0.0 3	0. 1 3	1. 0 0																		
K	- 0. 1 1	0. 49	0. 5 1	- 0.0 4	0. 2 1	0. 6 3	1. 0 0																	
Ca	0. 2 8	0. 70	0. 7 1	- 0.1 6	0. 0 2	0. 5 7	0. 5 7	1. 0 0																
Mg 2	0. 3 3	0. 74	0. 7 4	0.3 0	0. 4 2	0. 4 3	0. 0 9	0. 3 2	1. 00															
Cl	0. 4 2	0. 79	0. 7 9	0.0 2	0. 1 0	0. 5 3	0. 3 1	0. 7 4	0. 75	1. 0 0														
HC O3	- 0. 0 7	0. 45	0. 4 5	0.1 7	0. 0 1	0. 4 0	0. 0 1	0. 1 8	0. 30	0. 3 1	1.0 0													
SO 4	0. 2 4	0. 65	0. 6 5	0.1 4	0. 3 0	0. 4 2	0. 1 6	0. 6 7	0. 68	0. 8 0	0.2 9	1. 00												
NO 3	0. 0 3	0. 50	0. 5 1	0.2 7	0. 5 3	0. 2 6	0. 4 5	0. 4 0	0. 50	0. 4 4	0.0 4	0. 51	1. 00											
PO 4	- 0. 1 4	0. 10	0. 0 9	0.0 6	0. 1 5	0. 0 3	0. 1 8	0. 0 4	- 0. 09	- 0. 03	0.1 0	- 0. 07	0. 38	1. 00										
Ba	- 0. 1 7	0. 44	0. 4 6	- 0.0 7	0. 1 5	0. 5 2	0. 9 5	0. 5 1	0. 06	0. 2 9	- 0.0 4	0. 11	0. 47	0. 21	1. 0 0									
Cd	- 0. 0 2	- 0. 01	- 0. 0 1	0.1 2	0. 0 3	0. 0 6	0. 0 4	0. 0 4	0. 04	0. 1 5	0.0 4	- 0. 08	0. 06	0. 01	0. 0 5	1. 0 0								
Pb	- 0. 1 0	- 0. 18	- 0. 1 7	0.3 3	0. 1 1	0. 4 3	0. 2 2	0. 2 4	0. 17	0. 0 3	- 0.0 8	0. 05	0. 32	0. 07	0. 1 3	0. 0 1	1. 0 0							
Mn	- 0. 2 7	- 0. 08	- 0. 0 7	- 0.1 6	0. 1 6	0. 0 5	0. 0 1	0. 1 4	0. 13	0. 1 2	- 0.0 1	- 0. 17	0. 16	0. 11	0. 0 7	0. 0 3	0. 0 0	1. 0 0						
As	- 0. 0 9	- 0. 01	- 0. 0 2	- 0.3 1	0. 2 9	0. 1 7	0. 0 2	0. 2 0	0. 30	0. 0 2	0.0 1	0. 08	0. 43	0. 19	0. 0 1	0. 1 2	0. 6 0	0. 4 8	1. 0 0					
Ni	- 0. 1	- 0. 29	- 0. 3	0.0 3	0. 1	0. 4	0. 1	0. 1	0. 15	0. 1	- 0.1	0. 12	0. 13	0. 06	0. 0	0. 3	0. 6	0. 1	0. 2	1. 0				

	4		1		1	1	0	4		5	7				3	7	0	6	7	0				
Fe	-	-	-	0.3	0.	-	0.	-	-	-	-	-	0.	0.	0.	0.	0.	-	-	0.	1.			
	0.	0.	0.	1	0	0	0	0.	0.	0.	0.1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0			
	2	24	2		5	1	0	0	05	4	9	21	19	12	1	1	6	1	3	4	0			
	1		3												8	7	7	5	1	4	0			
Cr	0.	0.	0.	-	0.	0.	0.	0.	0.	0.	0.1	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.		
	0	12	1	0.3	0	3	1	1	08	0	4	05	16	06	0	1	6	1	3	5	7	0		
	9		4	2	9	4	0	4		8					3	5	3	4	9	0	7	0		
Cu	-	-	-	0.2	0.	0.	0.	0.	0.	0.	-	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	
	0.	0.	0.	0	1	4	0	0	18	0	0.2	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
	2	28	3		2	5	6	6		9	1	14	08	04	2	0	5	3	2	6	8	6		
	1		0												1	2	2	0	2	1	3	5		
Zn	-	-	-	-	0.	0.	0.	0.	0.	0.	-	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	1.	
	0.	0.	0.	0.0	0	1	1	0	06	0	0.0	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.	0.		
	3		0	1	6	2	0	1		7	9	06	04	08	1	0	0	0	0	2	2	2	0	
															3	9	5	5	1	8	6	8		

Table 4 Principal Component Analysis (PCA) Wet Season

Parameter	PC1	PC2	PC3	PC4	PC5	PC6	PC7
pH	0.12034	-0.02578	-0.27425	0.29984	-0.11531	-0.39397	-0.26139
TDS	0.36816	0.04764	-0.01756	0.04769	0.07807	0.07153	-0.04531
EC	0.37102	0.04554	-0.01536	0.03845	0.07017	0.05864	-0.01028
Temp	0.00952	0.22808	-0.15876	-0.35064	0.27399	0.03478	0.12981
DO	-0.11545	-0.136	0.09545	0.47722	0.0814	0.16444	-0.06023
Na	0.32593	-0.09813	0.13895	-0.02506	0.1343	0.02005	-0.08225
K	0.22323	0.07014	0.46513	-0.07242	-0.09382	-0.15037	0.03878
Mg2	0.26891	0.16315	-0.31151	-0.03346	0.08918	0.02938	0.12081
Cl	0.31846	0.10959	-0.11789	0.25805	0.02504	0.09091	0.03492
HCO3	0.15777	-0.02808	-0.12884	-0.0777	0.3368	0.38978	-0.31481
SO4	0.28423	0.10883	-0.21347	0.09766	-0.03329	0.07709	0.18286
NO3	0.20742	0.28037	0.05061	-0.23741	-0.23284	0.03468	0.10569
PO4	0.04287	0.03323	0.17202	-0.3492	-0.23517	0.26377	-0.42422
Ba	0.18921	0.11486	0.50954	-0.03296	-0.06368	-0.10382	0.08586
Cd	-0.0031	-0.046	0.07746	-0.19124	0.5012	-0.40034	0.09539
Pb	-0.11384	0.38576	-0.15016	-0.00231	0.01561	0.03805	0.08141
Mn	-0.0316	-0.21172	0.10179	-0.083	0.14103	0.49337	0.30141
As	0.01199	-0.3174	0.17381	0.20306	0.20937	0.15204	0.26851
Ni	-0.15169	0.27449	0.0546	0.18309	-0.27026	0.28295	-0.05702
Fe	-0.14654	0.36362	0.15078	0.08851	0.26967	-0.04983	0.14639
Cr	0.10635	-0.36604	-0.01566	-0.1829	-0.15129	-0.15768	-0.01706
Cu	-0.14873	0.34074	0.20909	0.20797	0.09553	-0.01449	0.02238
Ca	0.30121	0.02114	0.14833	0.27298	-0.08848	-0.02331	0.09153
Zn	0.00387	-0.10568	-0.16907	-0.09914	-0.3601	0.0026	0.58428

79.32% (wet season) of the total variance. Based on Kaiser criterion, the number of significant PCs for the interpretation was selected with an Eigen value higher than one and a total described percentage variation equal to or greater than 70 %. Table 5 presents the factor loading, latent root, Eigen value and percentage variation in PC.

PCA 1(27.61%) had strong positive loadings on TDS (0.37), EC (0.37), Na (0.33), Cl (0.32), SO₄ (0.28), Ca (0.30), Mg (0.27). Both components reflect mineralization from water-rock interaction. The grouping of Na⁺, K⁺, Cl⁻, SO₄²⁻, HCO₃⁻, Mg²⁺, TH, and Fe suggests contributions from silicate weathering (feldspar, biotite), carbonate dissolution, and

sulphide oxidation with chloride and sulfate pointing to evaporite or anthropogenic contributions.

PC 2 with 17.97% had high positive loadings for Pb (0.39), Fe (0.36), Cu (0.34), Ni (0.27), NO₃ (0.28), and moderate negative loadings for Mn (-0.21), As (-0.32), Cr (-0.37) suggesting increased ionic concentration, redox and anthropogenic influence, especially the mobilization of trace/heavy metals under variable groundwater redox conditions. PC 3 and PC 4 showed 10.02 % and 7.80 % respectively of the total variance. PC 3 had loading for K (0.47), and Ba (0.51), while PC 4 had loading for DO (0.48) and pH (0.30), geogenic, biogeochemical processes and dilution, while PC 5 with 6.17% of the total variance had

loadings for Cd (0.50), As (0.21), Fe (0.27) indicating toxic trace element control, partly geogenic (As, Pb from basement rocks) and partly anthropogenic (Cd, Zn from agrochemicals, waste) in line with findings of (Abimbola et al., 2002). PC6 with 5.28% of the total variance showed loadings of HCO_3^- (0.39), Mn (0.49), Ni (0.28) indicative of geogenic control

(Fe/Cr mobilization) with seasonal oxidation influences and carbonate weathering plus redox metals. while in the wet season, PC 7 with 4.47% of the total variance showed Zn (0.58), isolated zinc contamination, possibly from galvanized pipes.

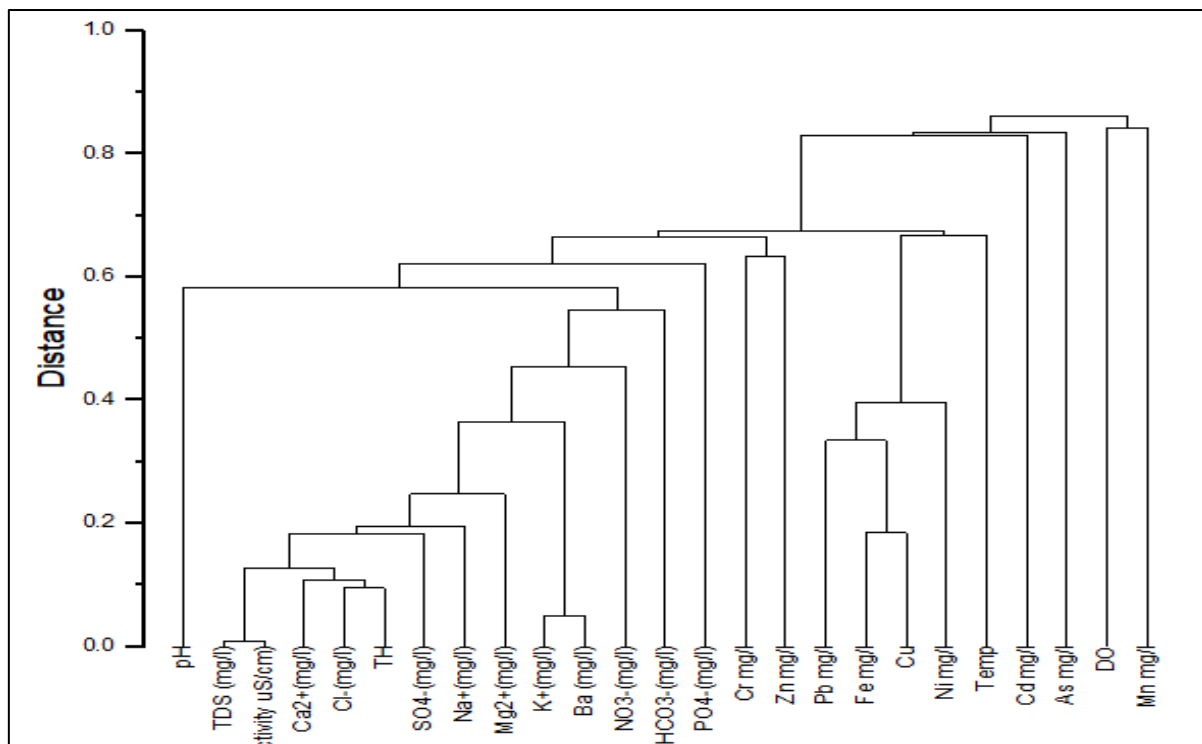


Fig 3 Dendrogram for Groundwater in Okene

The wet season dendrogram of shallow groundwater in Okene indicates that groundwater chemistry is mainly controlled by hydrogeochemical processes driven by seasonal recharge, mineral weathering, and rock–water interaction within the basement complex aquifer. A major cluster of pH, TDS, EC, Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , SO_4^{2-} , and total hardness suggests a shared geogenic origin, mainly from silicate and carbonate mineral dissolution and ion exchange processes.

A second cluster (K^+ , Ba, NO_3^- , HCO_3^- , PO_4^{3-} , Cr, Zn) reflects mixed geogenic and anthropogenic influences, with nutrients (nitrate and phosphate) likely linked to agricultural runoff and waste infiltration enhanced by wet-season recharge, while trace metals indicate both natural mineral sources and human activities.

A third cluster (Pb, Fe, Ni, Cd, As, Mn, dissolved oxygen, temperature) points to redox-controlled mobilization of trace metals, especially Fe–Mn reduction processes, alongside possible contamination from urban waste and weathering of metal-bearing rocks. Seasonal conditions further enhance metal mobility through increased infiltration and changing redox environments. The groundwater quality in Okene during the wet season is primarily governed by natural geochemical processes, with secondary but significant influence from anthropogenic inputs and seasonal hydrological effects.

➤ Contamination Factor (CF) and Pollution Index (PI)

The wet season (Table 6) was characterized by higher mobilization and leaching: Ba showed extremely high CF values (up to 71.7 in WL10), Cd increased moderately (0.8–3.9) with very high contamination at WL32 (CF ~3.97), and Pb reached even higher CF values (up to 18.6 in WL26), highlighting enhanced solubility during infiltration. Similarly, As recorded significantly elevated CF values (7.9 in BHL4; 8.9 in BHL13), suggesting strong natural mobilization under recharge conditions. Other trace metals, including Ni, Fe, and Cr, remained largely low to moderate, with Mn showing negligible contamination (<0.2), while Cu and Zn were consistently very low except for isolated agrochemical contributions. Wet-season PLI values were also <1 in most locations but slightly higher (0.55–0.65 in WL10 and WL32) than in the dry season, signifying moderate but localized pollution risks in recharge zones. Groundwater quality in Okene is generally within acceptable thresholds, enhanced leaching and anthropogenic inputs during the wet season significantly elevate CF and PLI values for Ba, Pb, Cd, and As, posing potential health risks and aligning with findings from similar basement terrains in Nigeria (Adeyeye et al., 2019; Ocheri et al., 2014) and globally (Chakraborti et al., 2017; Ravindra & Garg, 2020).

Table 5 Interpretation of Contamination Factor (CF) for Trace Elements and Pollution Load Index (PLI) for Wet Season

S/no	Contamination factor										PLI
	Ba	Cd	Pb	Mn	As	Ni	Fe	Cr	Cu	Zn	
WL1	5.571	0.3933 33	2.351	0.1114 75	3.58 2	0.163	0.0289 33	0.784 6	0.0186 65	0.0199 53	0.2787 76
BHL2	0.857	1.0266 67	3.109	0.0809 75	2.02 4	0.1414 29	0.1647 33	1.54	0.0137 2	0.0175 73	0.2876 55
WL3	21.716	1.57	2.958	0.0294 75	1.27	0.1254 29	0.1914 67	1.427 8	0.0122 6	0.0071 97	0.3204 56
BHL4	9.428	1.77	1.535	0.1414	7.92 7	0.1745 71	0.1583	1.444 8	0.0079 6	0.0048 27	0.3667 67
BHL5	22	1.3866 67	7.932	0.1259 25	0.08	0.1494 29	0.2065 33	0.935	0.0062 9	0.0082 87	0.2860 39
BHL6	9.285	1.02	10.77	0.1456	0.51 3	0.0745 71	0.2504 33	1.058 4	0.0056 35	0.0141 1	0.3219 77
BHL7	13.714	1.0333 33	10.03 4	0.1046 75	0.47 2	0.3551 43	0.2361	1.015 2	0.0098 6	0.0281 77	0.4188 41
WL8	22.428	1.0233 33	4.302	0.1215 5	4.57 7	0.0015 71	0.2818 67	1.021 6	0.0021 05	0.0172 67	0.2486 51
BHL9	27.428	1.1666 67	2.071	0.1960 5	4.48 6	0.0358 57	0.3161 67	1.004 4	0.0090 4	0.0098 67	0.3777 72
WL1 0	71.714	1.1366 67	3.751	0.0996 5	2.71 8	0.2631 43	0.2779 33	1.214 8	0.0298 9	0.0119	0.5518 01
WL1 1	30	1.0133 33	1.752	0.1761	4.85 5	0.2351 43	0.3524 33	1.379 6	0.0376 95	0.0151 5	0.5588 84
WL1 2	26.571	1.1966 67	1.746	0.1508 5	5.88 3	0.355	0.2952	1.009	0.0406 3	0.0097 57	0.5388 85
BHL1 3	33.285	1.0866 67	2.298	0.1235 5	8.86 7	0.255	0.3443 67	1.016 4	0.0377 4	0.0116 53	0.5692 72
BHL1 4	68.428	0.8	3.022	0.0158 75	1.19	0.249	0.3470 67	0.895 4	0.0357 85	0.0034 37	0.3526 43
WL1 5	36.285	1.0266 67	2.832	0.0229 5	1.38 7	0.178	0.3594 67	0.781 6	0.0279 3	0.0095 8	0.3675 04
BHL1 6	16.14	0.1833 33	5.396	0.0023	1.57 2	0.3474 29	0.3681 33	1.144 4	0.0462 2	0.0252 73	0.3158 21
BHL1 7	9.5714	0.3533 33	7.209	0.0756 5	3.42 2	0.4442 86	0.4222	0.869 6	0.0336 9	0.0143 8	0.4675 07
BHL1 8	29.571	1.0166 67	9.612	0.1252 8	0.13 8	0.4425 71	0.3410 33	0.992 8	0.0343 45	0.0115 5	0.4438 57
WL1 9	9.571	1.9	14.76	0.0299	1.83 7	0.289	0.4156 33	1.004 2	0.0238 05	0.0194 53	0.4915 51
BHL2 0	14.285	1.02	13.39 2	0.0552 75	0.82 7	0.3107 14	0.4402	0.894	0.0379 05	0.0172 97	0.4846 62
BHL2 1	19.571	1.0266 67	14.60 7	0.0255	1.60 3	0.2971 43	0.5199 33	1.203 8	0.0488 55	0.0009 1	0.3977 87
BHL2 2	14	1.0433 33	9.73	0.0137 25	0.13 8	0.2995 71	0.609	0.535 6	0.0428 65	0.0053 5	0.3006 4
BHL2 3	11.428	0.3933 33	7.244	0.0582 25	1.36 4	0.2998 57	0.6192	0.565 6	0.0423 45	0.0009 57	0.3192 62
WL2 4	17.142	0.2933 33	12.72	0.1006	0.98 8	0.4311 43	0.72	0.348	0.0468 15	0.0008 53	0.3498 1
BHL2 5	12.857	0.05	13.90 8	0.074	1.37 4	0.6091 43	0.6665 33	0.219	0.0420 8	0.0055 93	0.3372 35
WL2 6	12.714	0.0733 33	18.64 1	0.1217	1.06 1	0.9937 14	0.7266	0.378 2	0.0546 35	0.0095 6	0.4472 27
WL2 7	36.714	0.1866 67	14.00 7	0.0387 75	0.78 8	0.7457 14	0.8742 33	0.668 2	0.0621 3	0.0139 73	0.5064 11

WL2 8	11.428	1.27	9.378	0.0540 75	1.4	0.2961 43	0.8163	0.413 2	0.0668	0.0043 97	0.4446 77
WL2 9	23.857	1.17	6.402	0.1940 5	2.52 7	0.2964 29	1.0614	0.565 8	0.0557 35	0.0084 93	0.6121 12
WL3 0	55.857	1.0066 67	14.31 8	0.06	1.08 3	0.2934 29	1.1608 33	0.396 4	0.0590 85	0.0134 47	0.5955 42
WL3 1	34.285	1.1966 67	16.75	0.0843 25	1.25	0.296	1.1615 33	0.217 6	0.0548 45	0.0151 07	0.5824 06
WL3 2	23	3.9666 67	15.12 3	0.0611 75	1.65 6	0.3555 71	1.2003 67	0.477 2	0.0662 65	0.0073 07	0.6515 34

➤ Hydrogeochemical Characterization

• Piper Plots

The wet season Piper plot (fig. 4), revealed the dominant facies as Ca–Mg–HCO₃ (60%) and mixed Ca–Na–HCO₃ (27%). A significant proportion falls within Ca–Na–

HCO₃ facies, suggesting contributions from silicate weathering and cation exchange. Fewer samples trend toward Na–Cl (5%) and mixed Ca–Mg–Cl (5%) facies and very few plots in the Ca–Cl/SO₄ (3%) field showing dilution by rainfall recharge, limited evaporative or anthropogenic inputs during the wet season.

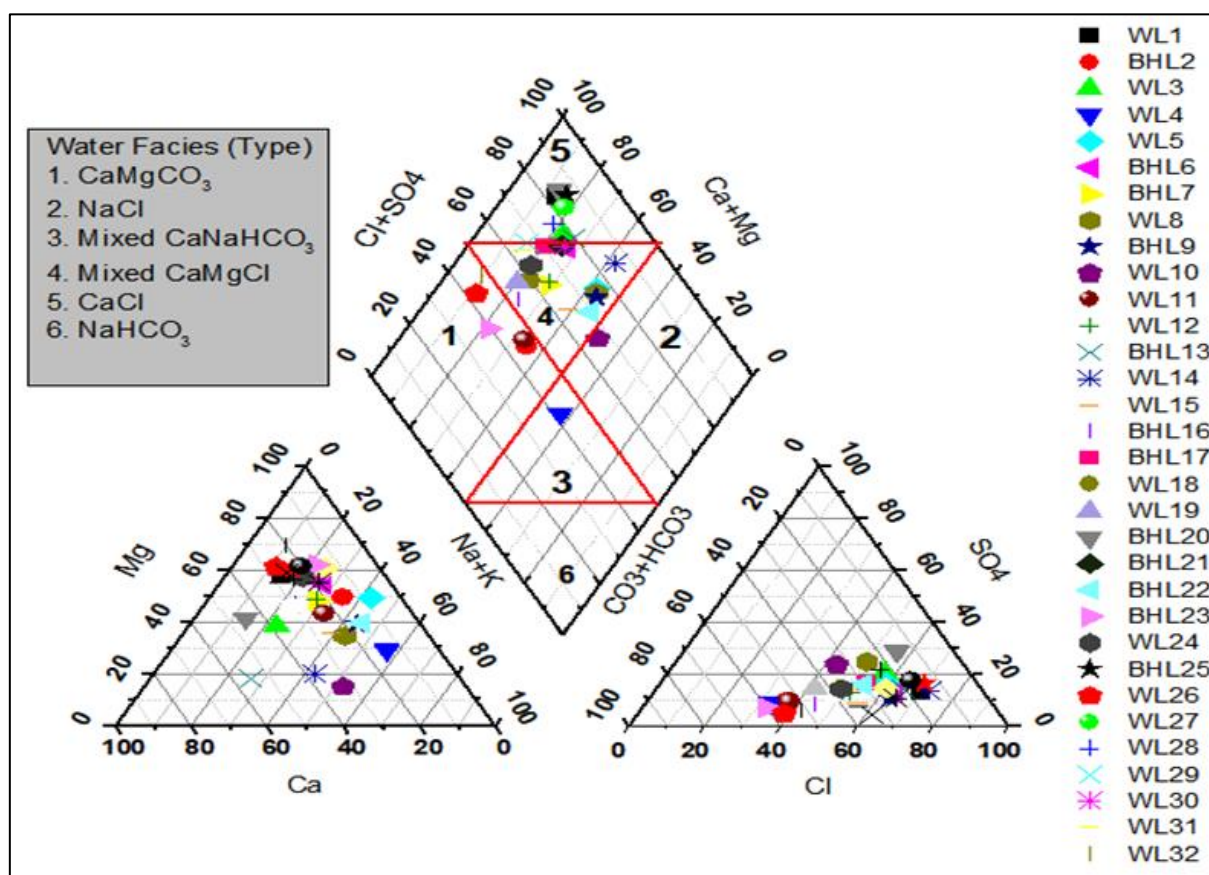


Fig 4 Piper Plot for Wet Season for Groundwater in Okene

• Gibbs Plot

In the wet season (fig 5), almost all the groundwater samples plot within the rock–water interaction (weathering)

field. The Na⁺/(Na⁺+Ca²⁺) ratios fall mostly between 0.3 and 0.6, while TDS values remain relatively low to moderate (< 1000 mg/L), reflecting the diluting effect of rainfall recharge.

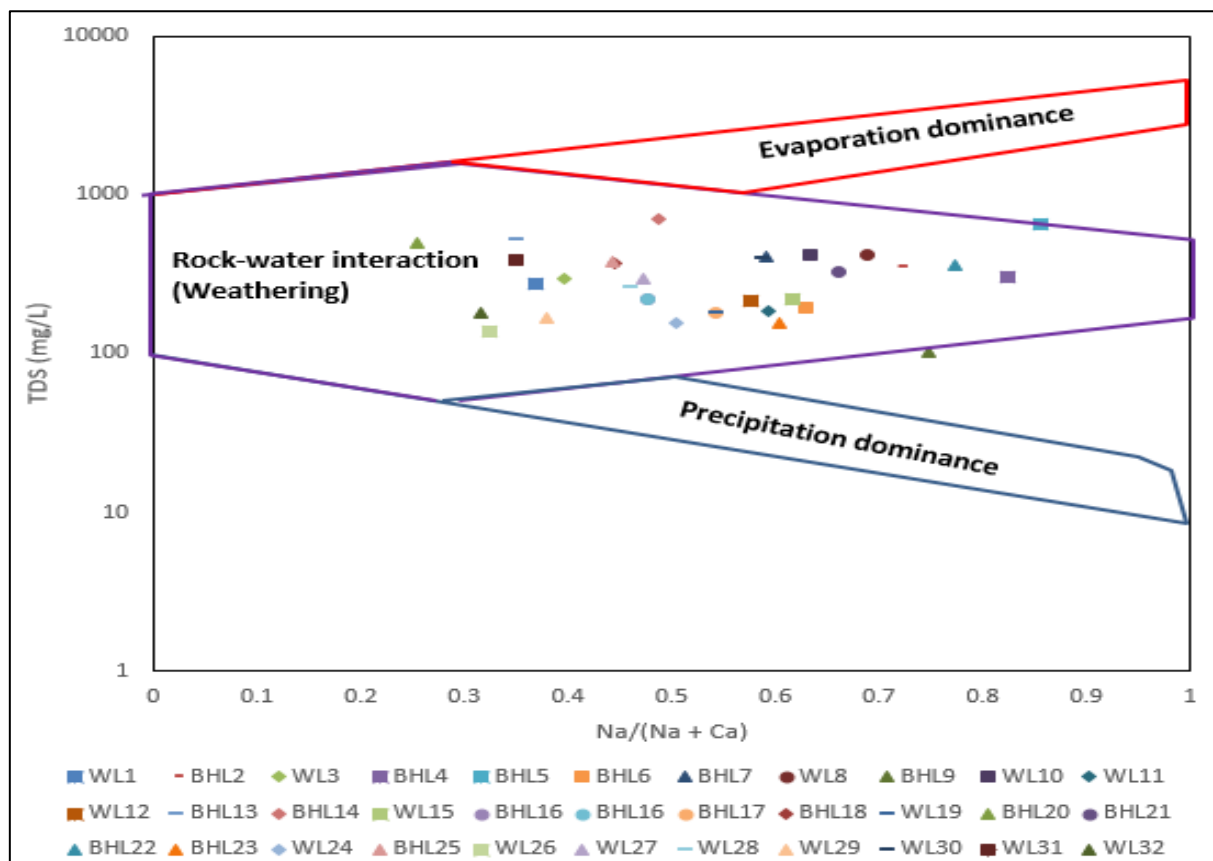


Fig 5 Wet Season – Gibb's Diagram (TDS vs (Na/(Na + Ca)))

The dominance of rock–water interaction suggests that mineral weathering and dissolution of silicate/carbonate minerals remain the primary controls on groundwater chemistry. Similar rock–water interaction dominance has been reported for basement aquifers in southwestern Nigeria and north-central Nigeria (Tijani, 2004; Oladipo et al., 2018).

The dilution by rainfall reduces overall TDS, but enhanced recharge increases the dissolution of carbonates under acidic pH conditions ($\text{pH} < 6.5$, observed in wet season). This explains why Ca^{2+} and Mg^{2+} concentrations are sometimes higher in the rainy season despite lower TDS.

Table 6 Bacteriological results wet season

Sample	TVB (Cfu/mL)	TCB (Cfu/mL)	Bacteria Present
1	$1.20 \pm 1.20 \times 10^6$	$1.10 \pm 0.60 \times 10^3$	B, G
2	$2.00 \pm 2.20 \times 10^2$	$3.00 \pm 1.30 \times 10^1$	B, F
3	$2.30 \pm 1.52 \times 10^2$	$9.00 \pm 0.66 \times 10^1$	F, G
4	$4.50 \pm 0.28 \times 10^2$	NC	B, F
5	$5.40 \pm 1.24 \times 10^5$	$2.10 \pm 1.61 \times 10^3$	B, E
6	$4.70 \pm 0.88 \times 10^2$	$1.06 \pm 0.66 \times 10^1$	A, B
7	$1.70 \pm 1.33 \times 10^2$	$4.00 \pm 0.33 \times 10^1$	B, E
8	$2.10 \pm 1.08 \times 10^3$	$2.30 \pm 1.20 \times 10^2$	C, D
9	$3.10 \pm 1.22 \times 10^2$	NC	A, E
10	$2.40 \pm 1.22 \times 10^4$	$2.30 \pm 2.60 \times 10^2$	B, C, G
11	$1.70 \pm 0.66 \times 10^2$	$2.00 \pm 1.33 \times 10^1$	B, E
12	$3.70 \pm 1.36 \times 10^4$	$2.00 \pm 0.66 \times 10^3$	A, B, C
13	$1.60 \pm 1.80 \times 10^2$	$7.00 \pm 0.39 \times 10^1$	F, G
14	$1.50 \pm 0.96 \times 10^2$	$1.20 \pm 1.43 \times 10^1$	B, D
15	$7.10 \pm 2.27 \times 10^1$	NC	A, E
16	$1.30 \pm 1.28 \times 10^4$	$2.40 \pm 1.62 \times 10^3$	C, D
17	$1.70 \pm 1.48 \times 10^2$	$1.20 \pm 0.66 \times 10^2$	A, D, E
18	$2.20 \pm 2.20 \times 10^3$	$6.00 \pm 2.66 \times 10^1$	B, C
19	$2.60 \pm 1.66 \times 10^3$	$4.00 \pm 2.33 \times 10^1$	D, E
20	$3.00 \pm 1.90 \times 10^4$	$1.40 \pm 1.60 \times 10^2$	B, C

21	$3.10 \pm 0.93 \times 10^5$	$4.10 \pm 2.33 \times 10^3$	A, B
22	$1.50 \pm 0.96 \times 10^2$	$2.00 \pm 1.60 \times 10^1$	A, C, D
23	$8.00 \pm 1.33 \times 10^2$	$4.00 \pm 1.33 \times 10^1$	A, B
24	$2.60 \pm 1.63 \times 10^3$	$8.00 \pm 0.66 \times 10^1$	D, E
25	$7.20 \pm 1.26 \times 10^5$	$3.00 \pm 2.43 \times 10^3$	F, G
26	$2.30 \pm 0.66 \times 10^4$	$1.10 \pm 0.66 \times 10^2$	B, C
27	$2.00 \pm 1.33 \times 10^4$	$7.00 \pm 2.30 \times 10^1$	B, F
28	$1.20 \pm 0.66 \times 10^3$	$1.40 \pm 0.63 \times 10^2$	A, B
29	$8.00 \pm 2.40 \times 10^2$	NC	C, D
30	$1.00 \pm 1.42 \times 10^2$	$2.00 \pm 1.33 \times 10^1$	D, E
31	$1.40 \pm 1.22 \times 10^3$	$1.60 \pm 0.33 \times 10^2$	E, F
32	$2.50 \pm 1.20 \times 10^4$	$1.00 \pm 0.66 \times 10^2$	G, E

TVC – Total Viable Bacteria TCB–Total Coliform Bacteria NC – No Count A– *Staphylococcus aureus*-E. *Coli* C-*Proteus* spp D-*Salmonella* spp E-*Streptococcus* spp F-*Pseudomonasaeruginosa*G –*Shigella* spp

For the wet season only four (4) shallow groundwater samples (representing 12.5%); WL4, BHL9, WL15 and WL29 are within (SON,2021) and (WHO,2022) guidelines suitable for drinking based on faecal coliform count(0 CFU/100 ml) and 28 water sample (representing 87.5%) for wet season have varying amounts of faecal coliform counts. the rainy season represents acute microbiological risk with

12.5% no coliform count. reflects the high permeability of the weathered basement aquifers and the absence of effective sanitary barriers around wells. The rainy season presents a higher risk of outbreaks of waterborne diseases such as diarrhea, cholera, and typhoid.

- **Water Quality Index**

Water Quality Index WQI using the physico-chemical parameters were determined for the analysed groundwater samples. WQI calculation for Sample 1 is shown in Table 7.

Table 7 Wet Season WQI for Sample 1

Parameters	Relative weight	Standard	Concentration	$qi = (C_i/S_i) \times 100$	$Si = W_i \times qi$
Ph	0.0338022	8.5	6	33.33333	1.12674
TDS (mg/l)	0.000540835	500	277.23	55.446	0.029987
Conductivity uS/cm)	0.000901392	300	443.12	147.7067	0.133142
DO	0.019315543	14	9	37.5	0.724333
Na+(mg/l)	0.001352088	200	25.4	12.7	0.017172
K+(mg/l)	0.0225348	12	0.9	7.5	0.169011
Ca2+(mg/l)	0.003605568	75	43.6	58.13333	0.209604
Mg2+(mg/l)	0.005408352	50	57.6	115.2	0.623042
Cl-(mg/l)	0.00108167	250	154	61.6	0.066631
HCO3-(mg/l)	0.001352088	200	63.46	31.73	0.042902
SO4-(mg/l)	0.001352088	200	40.67	20.335	0.027495
NO3-(mg/l)	0.00600928	45	1.93	4.288889	0.025773
TH	0.001352088	200	346.07	173.035	0.233959
Fe mg/l	0.901392007	0.3	0.00868	2.893333	2.608028
TCB	0	0	1200001.2	0	0
					6.03

WQI for all other groundwater samples were similarly calculated. The result of the WQI of the entire samples of the shallow groundwater in Okene and environs for the wet

season as shown in (fig 6) , indicates that 20 samples (62.5%) fall under the excellent water category, 8 samples (25%) fall in the good category.

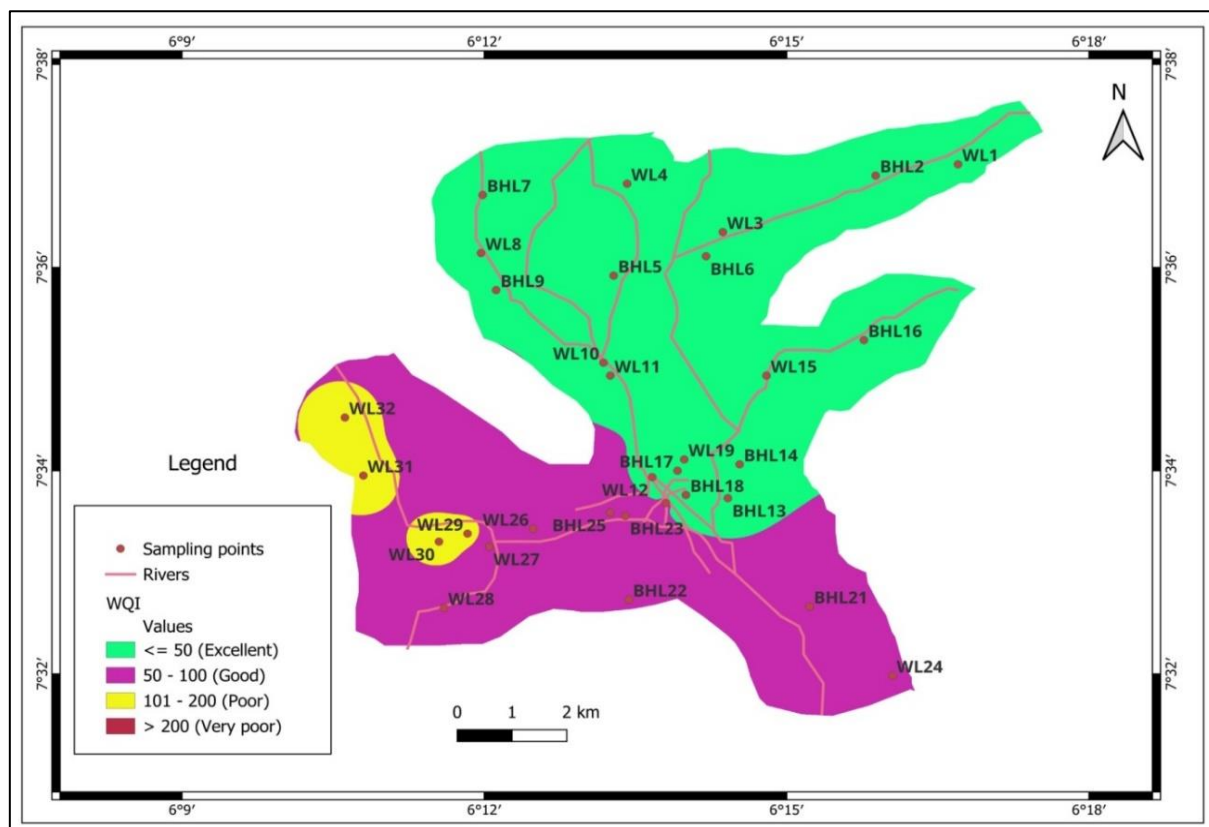


Fig 6 Water Quality Index (WQI) for Wet Season

These can be used for drinking, irrigation and industrial purposes, while only 4 samples (12.5%) are in poor category which can be used for irrigation and industrial purposes. With adequate and proper treatment, it can be used for drinking. The poor water quality status of the shallow groundwater within the affected area (12.5%) is a reflection of poor hygienic practices in this populated area, hence the anthropogenic contamination.

Generally, the groundwater in Okene is of low to moderately mineralized type with limited migration history. Better water quality is obtained in the dry season due to the absence of leaching and dilution experienced in the wet season.

➤ Irrigation Indices

The irrigation assessment of groundwater in Okene for wet season (fig 8) revealed most samples plot within the “excellent” class for SAR (Richards, 1954), indicating negligible toxicity hazard. However, for sodium percentage only 34.4% were excellent and almost one-fifth was

permissible (Wilcox, 1955). This suggests that recharge-driven dilution in the wet season does not uniformly reduce sodium risk, as bedrock weathering continues to supply Na^+ . A more critical parameter is the magnesium hazard, with 87.5% of samples unsafe, reflecting the dominance of Mg-rich gneisses and granitoids in the study area (Szabolcs & Darab, 1964). Kelly’s Ratio supports the overall suitability of most samples. The Wilcox diagram revealed 34.36% as excellent, 46.89% as good and 18.75% as permissible groundwater for irrigation (fig 7).

Total hardness (TH) and carbonate dissolution are more pronounced during the wet season, where 75% of samples fall in the “very hard” category, (Todd, 1980). This hardening is attributed to enhanced infiltration and leaching of Ca–Mg carbonates under recharge conditions. Conversely, salinity indicators (TDS and EC) point to improved irrigation quality in the wet season, with 87.5% of samples suitable (TDS < 450 mg/L) and 84% classed as “good” under EC (Davis & De Wiest, 1966; Wilcox, 1955). Wet season recharge produces fresher but harder and magnesium-rich waters.

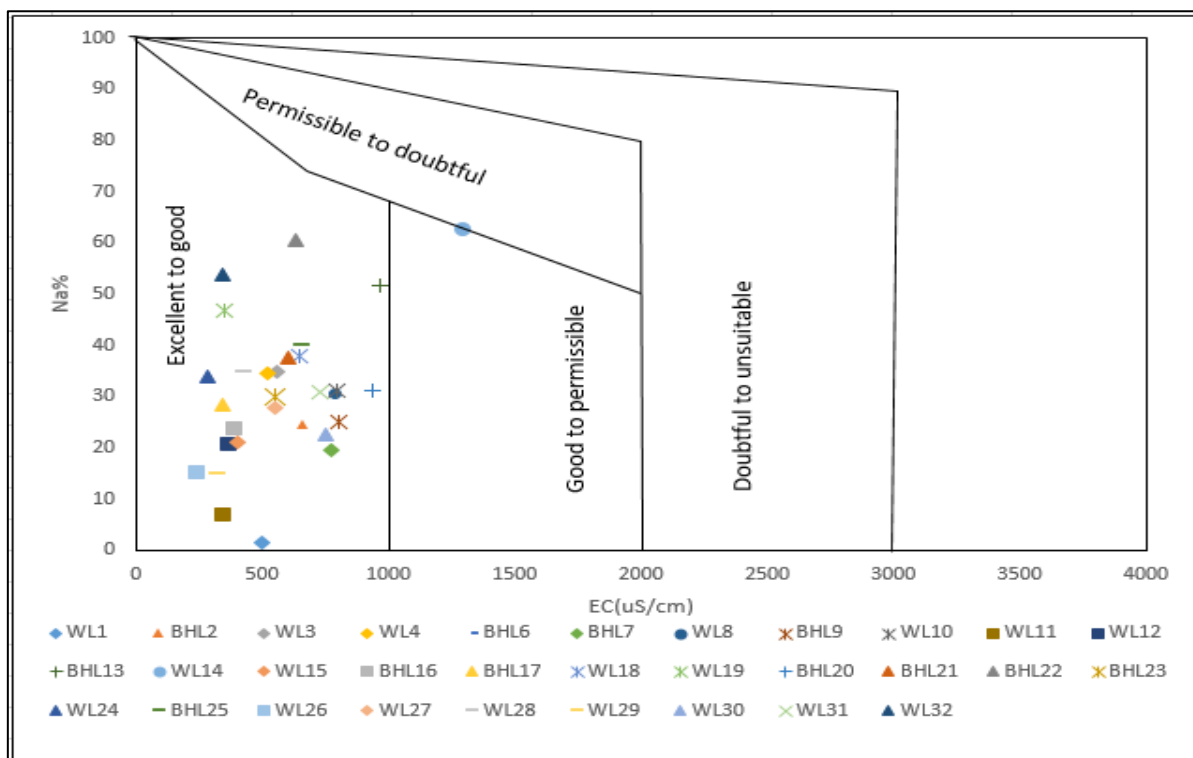


Fig 7 Wilcox Plot for Wet Season

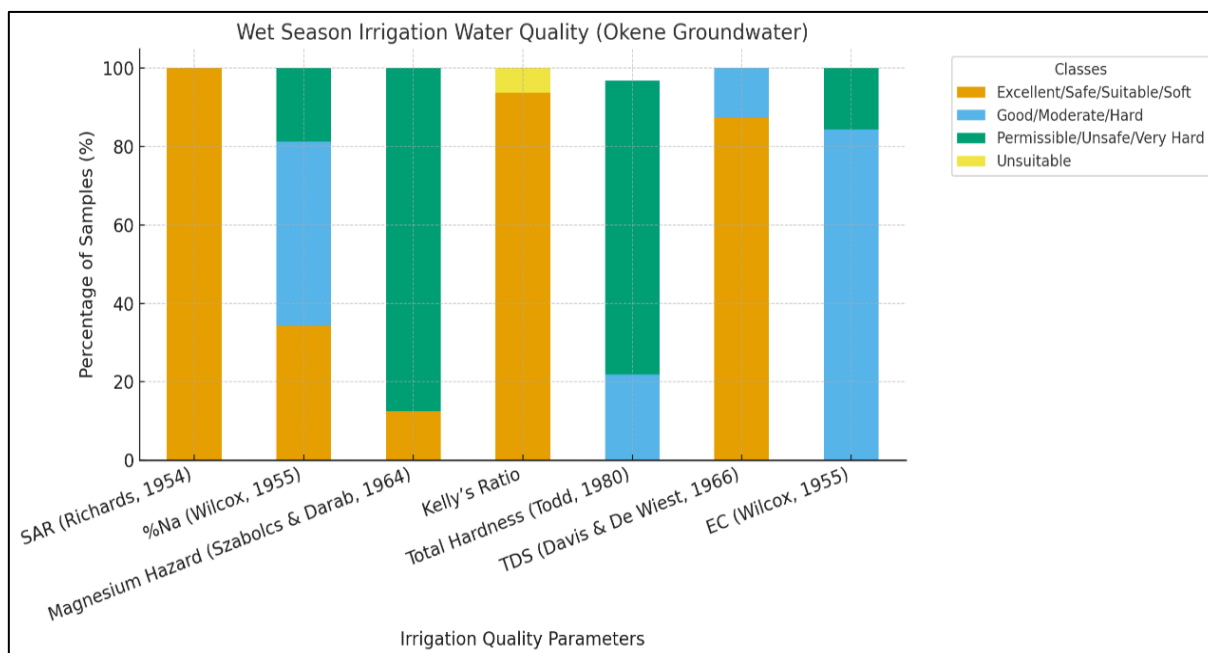


Fig 8 Summary of Wet Season Irrigation Indices

V. CONCLUSION

The hydrogeochemical assesment of shallow groundwater in Okene and environs reveals the major cations are predominantly Ca^{2+} , Mg^{2+} , Na^{+} , and K^{+} and the principal anions comprise Cl^{-} , HCO_3^{-} , SO_4^{2-} , NO_3^{-} , and PO_4^{3-} . This ionic composition suggest that groundwater chemistry is largely influenced by water - rock interaction, mineral dissolution and weathering of basement complex rocks. Contamination Factor (CF) results indicates that most groundwater samples exhibit insignificant contamination

although a few locations record low to high contamination associated with elevated concentrations of Ca^{2+} , Mg^{2+} , TDS, EC, and total hardness. Nevertheless, Pollution Load Index (PLI) values below unity across all sampling locations suggest generally low cumulative pollution levels.

Piper diagram classification identifies Ca–Mg– HCO_3 and mixed Ca–Na– HCO_3 as the dominant hydro chemical facies, further confirming the influence of silicate weathering and rock-water interaction on groundwater evolution, as supported by Gibbs plots. Microbiological analysis records

total counts ranging from 7.10×10^1 to 1.20×10^6 , while total coliform counts vary from 0 to 3.00×10^3 CFU/100 ml. Only 12.5% of the groundwater samples comply with WHO and NSDWQ microbiological standards for drinking water consumption, indicating that the majority require appropriate treatment to address microbial contamination.

Water Quality Index (WQI) assessment classifies 62.5% of the samples as excellent, 25% as good, and 12.5% as poor for drinking purposes. Irrigation assessment further reveals that most groundwater samples are suitable for irrigation based on SAR, %Na, Kelly's Ratio, EC, and Wilcox classifications. However, elevated magnesium hazard values in some locations may affect long term soil quality.

Overall, the findings demonstrate that shallow groundwater quality in Token and its environs is primarily governed by natural geochemical processes, particularly mineral weathering and rock-water interaction, with localized influences from contamination. Although the groundwater exhibits generally favourable photochemical characteristics and is largely suitable for irrigation, microbiological contamination remains a significant limitation to its direct consumption. Consequently, appropriate water treatment and routine quality monitoring are recommended to ensure the safety and sustainable utilization of groundwater for domestic and agricultural purposes.

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