African Journal of Environment and Natural Science Research
ISSN: 2689-9434
Volume 9, Issue 1, 2026 (pp. 12-22)
www.abjournals.org

CHARACTERIZATION OF HYDROCHEMICAL FACIES OF GROUNDWATER IN TOMBIA COMMUNITY IN BAYELSA STATE, NIGERIA

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Cite this article:

Otobo, I. T., Inengite, A. K. (2026), Characterization of Hydrochemical Facies of Groundwater in Tombia Community in Bayelsa State, Nigeria. African Journal of Environment and Natural Science Research 9(1), 12-22. DOI: 10.52589/AJENSR-XVHFDRAG

Manuscript History

Received: 6 Dec 2025

Accepted: 6 Jan 2026

Published: 19 Jan 2026

ABSTRACT: *The study of hydrochemical facies is particularly relevant in coastal and deltaic environments, where aquifers are shallow, hydraulically connected to surface water systems, and vulnerable to contamination. The absence of a comprehensive facies-based assessment for the study area represents a critical knowledge gap. This study investigated the geochemical characteristics and determined the hydrochemical facies of groundwater in Tombia, Bayelsa State, Nigeria, with the aim of assessing water quality, identifying dominant geochemical processes, and evaluating potential contamination risks. Five groundwater samples were collected from boreholes across the community and analyzed for physicochemical properties, major cations, and anions using standard analytical techniques and the results were subjected to statistical analysis. Piper's trilinear diagram was employed for the hydrochemical facies classification. Results show pH values (6.35–6.95), indicating slightly acidic conditions, likely influenced by organic matter decomposition and acid sulphate soils. Major ion chemistry is dominated by* Ca^{2+} *(0.391–1.657 mg/L) and* HCO_3^- *(40.0–90.0 mg/L), with ionic dominance sequences of* $Ca^{2+} > Na^+ > Mg^{2+} > K^+$ *and* $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$ *for cations and anions respectively, reflecting carbonate weathering and rainfall recharge as primary geochemical controls. Piper's trilinear diagram revealed that 80% of samples fall within the Ca–Mg–*HCO_3 *facies, characteristic of recently recharged, fresh groundwater, while 20% lie in the mixed Ca–Mg–Cl field, indicating minor ion-exchange processes. The study concludes that while groundwater in the study area remains geochemically fresh and suitable for agriculture and domestic use based on major ion chemistry, slightly acidic groundwater conditions may enhance contaminant mobility. These findings underscore the need for regular monitoring, improved waste management, water treatment interventions, and policy actions to ensure safe and sustainable groundwater use in the Niger Delta region.*

KEYWORDS: Geochemical analysis, Groundwater, Hydrochemical facies, Water quality.

Article DOI: 10.52589/AJENSR-XVHFDRAG
DOI URL: https://doi.org/10.52589/AJENSR-XVHFDRAG

INTRODUCTION

Groundwater remains one of the most critical natural resources supporting human survival and ecosystem sustainability (Van Der Gun, 2021). It accounts for nearly 99% of the Earth's accessible liquid freshwater and provides potable water for almost half of the world's population. Its importance is magnified in developing regions, where surface water resources are often unreliable due to seasonal variability, contamination, or inadequate infrastructure (Scanlon et al., 2023). However, groundwater is far from chemically uniform. Its composition is the product of complex interactions among aquifer lithology, climate, recharge sources, and anthropogenic influences, which collectively determine its chemical character, quality, and suitability for specific uses (Van Der Gun, 2021; Ravindiran et al., 2023).

Abugu et al. (2024) stated that one of the most widely applied approaches to understanding groundwater chemistry is the characterization of hydrochemical facies, distinct water types defined by the relative abundance of major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^{-}, SO_4^{2-}, Cl^{-}, NO_3^{-}). Hydrochemical facies serve as diagnostic indicators of groundwater evolution and provide insight into the dominant geochemical processes, including silicate weathering, carbonate dissolution, cation exchange, and saline intrusion (Islam, 2023). They also reveal the potential impacts of human activities such as agriculture, waste disposal, and industrial discharges. Piper's trilinear diagram, along with derivative plots such as Durov and Chadha diagrams, is commonly used to classify these facies and assess groundwater suitability for domestic and agricultural purposes (Sunkari et al., 2025; Kitaro et al., 2025)

The study of hydrochemical facies is particularly relevant in coastal and deltaic environments, where aquifers are shallow, hydraulically connected to surface water systems, and vulnerable to contamination. In such areas, salinity, acidity, and heavy metal mobilization can compromise groundwater quality, threatening both public health and agricultural productivity (Greggio et al., 2020). The Niger Delta in southern Nigeria exemplifies this context. As one of the world's largest wetlands, the delta is a mosaic of river channels, mangrove swamps, floodplains, and sandy aquifers (Elegbede et al., 2025). Millions of inhabitants depend on groundwater as their primary source of drinking water, yet the region is subject to widespread environmental pressures, including oil and gas exploitation, industrial effluents, urban expansion, and agricultural runoff. These pressures, coupled with natural processes such as ion exchange and carbonate dissolution, make hydrochemical characterization essential for groundwater management (Owoyemi et al., 2019).

The study area is located in the Yenagoa Local Government Area of Bayelsa State and is a typical Niger Delta community where reliance on groundwater is high. Most residents obtain water from boreholes and shallow wells for drinking, domestic use, and irrigation. However, safe drinking water remains scarce in rural settlements, with previous studies reporting contamination from heavy metals, hydrocarbons, and nutrients (Adeloju et al., 2021). Rapid urbanization and poorly regulated industrial and agricultural activities further exacerbate risks to groundwater integrity (Raghavendra, 2024). While earlier research has assessed water quality in parts of Bayelsa State (Peterside et al., 2022; Nwankwoala et al., 2023; Nicholas, 2023; Egbo & Ikele, 2023), detailed hydrochemical facies characterization specific to the study area remains limited.

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Volume 9, Issue 1, 2026 (pp. 12-22)

The absence of a comprehensive facies-based assessment for Tombia represents a critical knowledge gap. Such a study is necessary to distinguish between natural geochemical controls and anthropogenic impacts, to understand the hydrochemical evolution of the aquifers, and to provide a scientific basis for groundwater management and public health protection. Moreover, characterizing hydrochemical facies will contribute to ongoing discussions on water sustainability in the Niger Delta, where population growth, climate variability, and increasing competition for freshwater resources intensify pressures on aquifer systems.

The study seeks to advance understanding of groundwater quality in Tombia and provide evidence to support sustainable water resource management, safeguard public health, and guide environmental policy in Bayelsa State and beyond.

Study Area

The study area is located within the Yenagoa Local Government Area of Bayelsa State, Nigeria, situated between latitudes 4°59′58″N and 4°59′51″N and longitudes 6°15′52″E and 6°15′46″E. It lies in the central Niger Delta, a region dominated by extensive river networks, swamps, and floodplains. The settlement is representative of many Niger Delta communities, where rural populations depend heavily on shallow aquifers for water supply.

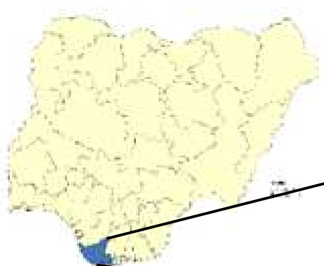

Figure 1a. Map of Nigeria Showing Bayelsa State

Figure 1b. Map of Bayelsa State Showing Yenagoa L.G.A

Physiography and Climate

Bayelsa State occupies a low-lying terrain, with elevations rarely exceeding a few meters above sea level. The study area experiences a humid tropical climate, marked by two distinct seasons: a rainy season from about April to October and a dry season from November to March. Annual rainfall averages 2,500–3,000 mm, with relative humidity consistently above 70%. The high rainfall contributes to substantial aquifer recharge but also increases the risk of flooding and leaching of contaminants into groundwater. Surface water bodies, including tributaries of the Nun River, influence both the hydrology and water quality of the area (Okoro & Ofordu, 2025).

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Geology and Hydrogeology

The Niger Delta basin consists of thick sequences of unconsolidated Quaternary sediments underlain by the Benin Formation, which is predominantly sandy and highly permeable (Wali et al., 2021). The aquifers are shallow, unconfined, and composed largely of sand and gravel interbedded with clay lenses. These characteristics favor high infiltration rates but also make the aquifers vulnerable to contamination from surface activities. Groundwater flow is largely controlled by rainfall recharge and the hydraulic connection to nearby rivers. Water levels fluctuate seasonally, with higher levels during the rainy season and lower levels during the dry season (Tijani, 2023).

Land Use and Socio-Economic Setting

The study area and its environs are characterized by rural and peri-urban settlements, with agriculture, fishing, and small-scale trade as the dominant economic activities. Irrigation is increasingly practiced, reflecting national efforts to improve food security through all-season farming (Owota & Michael-Olomu, 2023). However, potable water remains inadequate, and most households depend on boreholes and hand-dug wells. Rapid population growth, coupled with poor waste management, exacerbates stress on water resources. Untreated sewage, refuse disposal, agricultural runoff, and industrial effluents are common in the wider Yenagoa area, contributing to environmental degradation and posing risks to groundwater (Ayanlade & Howard, 2017; Sapere-Obi, 2024).

Environmental Challenges

The hydrogeological setting makes the study area particularly sensitive to groundwater quality issues. Shallow aquifers are easily affected by natural and anthropogenic factors, including acidification, heavy metal mobilization, and nutrient loading. Oil exploration activities in Bayelsa State further contribute to hydrocarbon contamination risks, while saline intrusion from brackish swamps poses an additional concern for groundwater chemistry. These challenges highlight the importance of characterizing hydrochemical facies to disentangle natural geochemical processes from human-induced impacts (Odochi et al., 2024).

MATERIALS AND METHODS

Sampling Design

Groundwater samples were collected from five boreholes distributed across the study area. The sites were selected to provide spatial coverage of the community. Geo referencing of sampling sites was conducted, and sampling sites lay between latitude 04° 00' 05.3'' and 04° 59' 58.5" and longitude 006° 15’ 32.7" and 006° 15' 50.0". Table 1 shows the geographical positions of all the borehole sampling sites, while Figure 2 shows the satellite imagery with sampling location points.

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Table 1: Geographic References of the Sampling Site

Borehole	Northings	Eastings
BH 1	04° 59’ 49.20’’	006°15'32.70’’
BH 2	04° 59' 55.4‘	006° 15'50.0’’
BH 3	05° 0'3.42"	006° 15' 87.45’’
BH 4	05° 0'4.97"	006°16'2.23"
BH 5	04°59'47.03"	006°15'56.26"

Figure 2: Satellite imagery of the study area showing sampling locations

Sampling was carried out during the late dry season to minimize dilution effects from rainfall and to reflect groundwater conditions under relatively stable recharge. At each site, water was allowed to flow for several minutes prior to collection to ensure representative aquifer samples. All samples were collected in pre-cleaned polyethylene bottles, rinsed with borehole water before final filling, and transported in ice-cooled containers to the laboratory. Temperature and pH were measured in situ using a portable digital meter.

Laboratory Analysis

Laboratory analyses focused on major cations and anions. Standard procedures outlined by the American Public Health Association (APHA, 2017) were followed.

Table 2: Methods of Laboratory Analysis

S/no	Parameter	Symbol	Units	Type	Method/Instrument
1	Calcium	Ca^{2+}	mg/L	Cation	EDTA titrimetric
2	Magnesium	Mg^{2+}	mg/L	Cation	EDTA titrimetric
3	Sodium	Na^{+}	mg/L	Cation	Flame photometer
4	Potassium	K^{+}	mg/L	Cation	Flame photometer
5	Bicarbonate	HCO_3^{-}	mg/L	Anion	Acid titration
6	Carbonate	CO_3^{2-}	mg/L	Anion	Acid titration

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7	Chloride	Cl^-	mg/L	Anion	Argentometric titration
8	Sulphate	SO_4^{2-}	mg/L	Anion	Spectrophotometry
9	Nitrate	NO_3^-	mg/L	Anion	Spectrophotometry

To enable hydrochemical facies classification, ion concentrations were converted to milliequivalents per liter (meq/L).

Data Quality Control

To ensure reliability of the analytical results, quality assurance and quality control (QA/QC) measures were implemented. Duplicate samples were collected and standard solutions were run at regular intervals during instrumental analyses. The ionic balance error (IBE) was computed for each sample using the equation. Acceptable results were restricted to an error of ±5%.

$$IBE\ (\%) = \frac{\sum cations\ (meq/L) - \sum anions\ (meq/L)}{\sum cations\ (meq/L) + \sum anions\ (meq/L)} \times 100\%$$

Hydrochemical Facies Classification

The characterization of groundwater hydrochemical facies was carried out using Piper's trilinear diagram (Piper, 1944). This graphical method plots relative percentages of major cations (Ca^{2+}, Mg^{2+}, $Na^+ + K^+$) and anions ($HCO_3^- + CO_3^{2-}$, Cl^-, SO_4^{2-}) in two triangular fields, which are then projected into a central diamond-shaped field to reveal the overall hydrochemical facies. The Piper plots were generated using AquaChem software.

Data Analysis and Standards

Descriptive statistics (mean, range, and standard deviation) were computed for all measured parameters. Groundwater results were compared against the World Health Organization (WHO, 2017) and the Nigerian Standard for Drinking Water Quality (NSDWQ, 2007) to evaluate compliance with drinking water guidelines. For interpretation, emphasis was placed on identifying ionic dominance, hydrochemical facies distribution, and geochemical processes shaping groundwater chemistry. Comparisons were also made with previous studies in the Niger Delta and other coastal aquifers to place Tombia's groundwater within a broader hydrogeochemical context.

RESULTS AND DISCUSSION

Physicochemical Characteristics of Groundwater

Field measurements indicated that the pH of the groundwater samples ranged from 6.35 to 6.95, with most samples slightly acidic and below the World Health Organization (WHO) recommended pH range of 6.5–8.5 for potable water. The slightly acidic nature is likely attributed to organic matter decomposition, infiltration of humic substances, and possible influences from acid sulfate soils within the shallow aquifer environment.

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Temperature measurements were consistent across boreholes, ranging between 28.3°C and 29.0°C, which is typical for shallow tropical aquifers influenced by ambient temperature. The overall physicochemical results suggest that Tombia groundwater is fresh, slightly acidic, and low in salinity.

Major Ions and Hydrochemical Facies

The chemical composition of groundwater is largely governed by interactions between infiltrating water, soil, and geological formations, which control the dissolution, precipitation, and exchange processes of dissolved ions. The concentrations of the major cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) and anions (HCO_3^{-}, Cl^{-}, SO_4^{2-}, NO_3^{-}) measured from groundwater samples across the five boreholes (BH1–BH5) are presented in Table 5. The results reveal considerable spatial variation in ionic composition across the study area. Among the cations, calcium (Ca^{2+}) was the most abundant, with concentrations ranging from 0.391 mg/L at BH4 to 1.657 mg/L at BH1, and an average of 1.046 mg/L. The high calcium levels observed in BH1 and BH3 reflect enhanced carbonate mineral dissolution, primarily from calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$), indicating active water-rock interaction in these boreholes. (Nwankwaola et al., 2014). Magnesium (Mg^{2+}) concentrations varied between 0.076 mg/L and 0.717 mg/L, with the highest concentration recorded at BH3. Elevated magnesium concentrations in this borehole are likely associated with dolomite weathering and cation exchange reactions within the aquifer matrix (Yu et al., 2025). Sodium (Na^{+}) concentrations ranged from 0.196 mg/L to 1.040 mg/L, with the highest levels recorded at BH3 and BH1. Sodium enrichment in groundwater is commonly attributed to feldspar weathering or cation exchange between Na^{+} and Ca^{2+}/Mg^{2+} on clay minerals. Potassium (K^{+}) concentrations were relatively low across all boreholes, ranging from 0.064 mg/L to 0.617 mg/L, which is typical due to the strong adsorption of potassium onto clay minerals and plant uptake. Similar interpretations have been reported for groundwater systems in the Niger Delta and other parts of southern Nigeria, where elevated K^{+} has been attributed to a combination of natural water–rock interaction and diffuse agricultural activities (Edet & Okereke, 2002). Among the anions, bicarbonate (HCO_3^{-}) was dominant, ranging from 40.0 mg/L at BH4 to 90.0 mg/L at BH1, with a mean concentration of 60.4 mg/L. The predominance of bicarbonate indicates that carbonate weathering and dissolution of soil CO_2 are the primary geochemical processes controlling groundwater chemistry in the area (Nwankwaola et al., 2014). Chloride (Cl^{-}) concentrations ranged from 5.9 mg/L to 20.9 mg/L, which are well below the WHO and NSDWQ permissible limits, suggesting limited influence of saline water intrusion or anthropogenic contamination. Sulphate (SO_4^{2-}) concentrations varied between 3.0 mg/L and 15.0 mg/L, while nitrate (NO_3^{-}) levels were consistently low (0.5–4.3 mg/L), indicating negligible contributions from agricultural runoff or sewage infiltration. The ionic dominance pattern for cations was $Ca^{2+} > Na^{+} > Mg^{2+} > K^{+}$, whereas for anions it was $HCO_3^{-} > Cl^{-} > SO_4^{2-} > NO_3^{-}$. This distribution reflects a water chemistry controlled primarily by carbonate dissolution, with minor influences from silicate weathering, ion exchange processes and atmospheric CO_2 dissolution.

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Table 5: Parameters Concentrations in Groundwater Samples (mg/L)

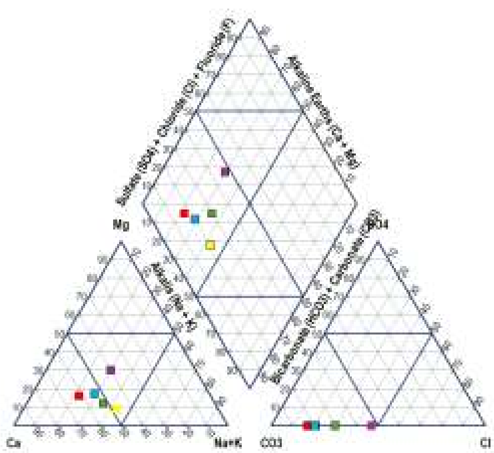
S/No	Parameter	Symbol	Minimum	Maximum	Mean±St.Dev.	NSDWQ*
1	Temperature	°C	28.3	29.0	28.5±0.3	Ambient
2	pH		6.95	6.35	6.6±2.4	6.5 – 8.5
3	Calcium	Ca^{2+}	0.391	1.657	1.046±0.357	75
4	Magnesium	Mg^{2+}	0.076	0.717	0.249±0.269	20
5	Sodium	Na^{+}	0.196	1.040	0.610±0.383	200
6	Potassium	K^{+}	0.064	0.617	0.364±0.273	12
7	Bicarbonate	HCO_3^{-}	40.0	90.0	60.4±19.7	250
8	Chloride	Cl^{-}	5.9	20.9	10.5±5.6	250
9	Carbonate	CO_3^{-}	0.005	0.005	0.005±0	
10	Sulphate	SO_4^{2-}	0.058	0.132	0.086±0.02	100
11	Nitrate	NO_3^{-}	0.086	0.825	0.379±0.30	50

**Permissible limits*

Hydrochemical Facies and Geochemical Processes

Hydrochemical facies classification using Piper's trilinear diagram provides a graphical representation of the dominant ion types and the hydrogeochemical processes influencing groundwater chemistry.

Figure 3. Pipers Trilinear plot for the five Boreholes



The analysis revealed that 80% of groundwater samples plotted within the Ca–Mg–HCO_3 facies, characteristic of recently recharged, fresh groundwater dominated by carbonate weathering. The remaining 20% plotted in the mixed Ca–Mg–Cl field, suggesting minor mixing with other water types or geochemical evolution due to cation exchange processes. The overall observed ionic pattern suggests limited mixing with other groundwater types or progressive geochemical

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evolution along the flow path, controlled by cation exchange reactions between groundwater and clay-rich sediments common within the deltaic aquifer system (Olobaniyi & Owoyemi, 2006). The absence of samples plotting in the Na–Cl facies indicate negligible saline intrusion or evaporite dissolution, further confirming the fresh nature of the groundwater (Piper, 1944). The dominance of bicarbonate and alkaline earth metals over alkali metals indicates low salinity and minimal anthropogenic influence, pointing to a well-buffered hydrochemical system with limited geochemical alteration.

CONCLUSION

The hydrochemical characterization of groundwater in the study area reveals a freshwater system predominantly controlled by natural geochemical processes. Physicochemical analysis shows that the groundwater is generally fresh and low in salinity, while the pH values indicate slightly acidic (<7) conditions, though the values were within guideline limits. Acidic conditions can enhance metal mobility, increasing human and environmental health risks. Major ion chemistry is dominated by Ca^{2+} and HCO_3^-, indicating carbonate weathering as the principal geochemical process. The ionic dominance order ($Ca^{2+} > Na^+ > Mg^{2+} > K^+$ and $HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-$) further supports this interpretation

The study area groundwater exhibits favorable hydrochemical characteristics, such as dominance of Ca–Mg–HCO_3 facies, and minimal evidence of saline intrusion; however, improved waste management and regular groundwater monitoring are recommended, as this study underscores the dual nature of the aquifer system: geochemically pristine yet increasingly threatened by widespread environmental pressures, including oil and gas exploitation, industrial effluents, urban expansion, and agricultural runoff evident in the Niger Delta region. This necessitates integrated management strategies for sustainable water resource use.

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