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HYDROGEOCHEMICAL FACIES AND DRINKING-WATER SUITABILITY OF GROUNDWATER IN OIL-IMPACTED NIGER DELTA COMMUNITIES: A PIPER DIAGRAM AND WHO COMPLIANCE ASSESSMENT OF OKERENKOKO, KURUTIE, AND KUNUKUNUMA, DELTA STATE, NIGERIA

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ABSTRACT

The assumption that petroleum contamination is the primary source of hydrochemical character in coastal Niger Delta aquifers is widely accepted but can be tested directly through facies-level analysis. This study characterised the hydrogeochemistry of groundwater from three communities (Okerenkoko, Kurutie and Kunukunuma) in the Gbaramatu Kingdom of Warri South-West, Delta State, using 30 sampling points and Piper trilinear diagram classification. Groundwater was consistently acidic (pH 4.34–5.76, mean 4.96 ± 0.73), with total dissolved solids (80.6–212.75 mg/L) and salinity (92.8–109.9 mg/L) within WHO (2022) limits, but chloride (319.78–360.2 mg/L) and fluoride (2.47–2.98 mg/L) exceeded permissible thresholds. Piper classification identified a near-uniform Mg^{2+}–Cl^- hydrochemical facies across all sites, attributed to marine influence rather than to petroleum contamination. A simple mixing estimate using Cl^- suggests approximately 2% seawater mixing in the shallow aquifer. A combination of high chloride and low alkalinity suggests corrosive water quality and irrigation suitability is rated C3–S2 to C4–S3 (salt-tolerant crops only). The study establishes a baseline for the hydrogeochemistry that supports the fact that groundwater throughout the region is impacted by regional controls and not local controls, therefore necessitating regionally coordinated water-treatment intervention.

Keywords: Water Chemistry, Piper Diagram, Mg–Cl Water Type, Groundwater Quality, Niger Delta And Suitability For Irrigation.

1.0 Introduction

In the rural and peri-urban Niger Delta where the prevalence of piped municipal supply is low (Nwankwoala & Ngah, 2014; Beka et al., 2015), groundwater is vital to any aspect of domestic and agricultural activities. In the coastal deltaic environment like Warri South-West of Delta State, this dependence is coupled with a hydrogeological environment that is heavily influenced by marine processes, silicate-rich deltaic sediments and in many communities, high-intensity petroleum exploration activity. It is not just a matter of semantics to distinguish the significance of these influences and identify what aspects of this work drive the dominant ionic nature of the local groundwater because that choice of focus dictates whether the check is applied to industrial discharge, sanitation infrastructure or the far more intractable nature of the problem where geochemistry is emanating from the sea and conditions are naturally very saline.

Understandably, petroleum contamination is blamed for higher ionic loading and lower groundwater qualities as water from the Niger Delta region continues to be historically used in oil exploration, which is the usual default approach in groundwater literature from the region (Udom et al., 2018; Nwankwoala & Udom, 2011). This geochemical default does not seem like an unreasonable one where the hydrocarbon indicator occurs simultaneously with the hydrochemical signal; however it may overshadow another significant and often stonger, geochemical signature in coastal environments – marine influence. The Piper problem is unique in that it shows a groundwater facies, or the specific ground-water ionic makeup, and is a direct test of the process that really describes the observed ionic makeup (Olobaniyi & Owoyemi, 2006).

Okerenkoko, Kurutie, and Kunukunuma, three communities within the Gbaramatu Kingdom directly exposed to oil-exploration infrastructure, had not previously been the subject of a facies-level hydrogeochemical assessment prior to the source study on which this article draws. Existing Niger Delta hydrogeochemical literature has concentrated disproportionately on Port Harcourt and other urban centres (Nwankwoala & Udom, 2011; Udom & Esu, 2004), leaving this specific, oil-exposed community cluster without a site-specific hydrochemical baseline against which future change, whether from further industrial activity, sea-level rise, or remediation, could be measured. This absence constitutes the research gap this study addresses: the lack of a quantitative, Piper-diagram-anchored hydrogeochemical baseline capable of distinguishing marine-driven from anthropogenically driven ionic loading in a community cluster where both processes plausibly operate.

This study therefore aims to (i) characterise the major-ion chemistry of groundwater across the three communities, (ii) classify the dominant hydrochemical facies using Piper trilinear diagram analysis, (iii) identify the geochemical processes responsible for that facies, and (iv) evaluate the resulting implications for drinking-water potability and irrigation suitability. In doing so, it establishes the first hydrogeochemical baseline for this specific community cluster and directly tests the assumption that Niger Delta groundwater chemistry near oil-exploration sites is necessarily petroleum-dominated.

2. Literature Review

2.1 Groundwater Chemistry Evolution in Deltaic Settings

Changing the residence time, pH, and matrix- and scenario flow dynamics of the groundwater causes the chemical composition of water to vary continuously as described by Appelo & Postma (2005), Nwankwoala & Udom (2011), Afolabi et al. (2023), and Gbadebo et al. (2026). Water–rock interaction and ion exchange can cause the gradual change of groundwater towards different more evolved geochemical facies as residence time increases, and as meteoric water passes through more developed geochemical environments in coastal or marine influenced systems, continued water–rock interaction, ion exchange and mixing can result in groundwater becoming more evolved and saline (Na–Cl or mixed facies) (Nwankwoala & Udom, 2011; Owoyemi et al., 2019). Coastal aquifers can then experience hydrochemical alteration processes from seawater mixing, tidal flushing, mineral dissolution, and/or other local/coastal hydrogeochemical processes.

In the Niger Delta in particular, there had been many studies showing that spatiotemporal variations in the chemistry of the Benin Formation aquifer system exists between inland and coastal area (Nwankwoala & Udom, 2011; Olobaniyi & Owoyemi, 2010; Owoyemi et al., 2019). Nwankwoala and Udom (2011) recorded the existing variable groundwater chemistry and hydrochemical facies of Port Harcourt, whereas Olobaniyi and Owoyemi (2010) noted the groundwater chemistry and facies that is typical of deltaic plain sands of Warri. Later, Owoyemi et al. (2019) derived several hydrochemical facies found in Delta State and these hydrochemical facies are Ca – HCO3, Na – HCO3, Na – Cl, and Ca – Mg – Cl – SO4. Seawater tidal flushing and ion exchange processes along the coast and silicate weathering and ion exchange processes in the inland influenced coastal and inland groundwaters, respectively (Owoyemi et al., 2019). The

spatial distribution of this pattern underscores the hydrochemical facies effects of marine influence and shows that other anthropogenic influences are not be excluded such as industrial influences.

This image has been reaffirmed and elaborated on in more recent studies. According to Afolabi et al. (2023) the groundwater of the communities along the southern axis of the Atlantic Ocean, in Bayelsa State was dominated by Ca–Mg–HCO3, Na–HCO3, and Ca–Mg–SO4/Cl water–rock interaction and carbonate weathering were identified as important. Meanwhile, Aleku et al. (2024) also showed the complexity of the geochemistry of groundwater in the eastern Niger Delta region where Na–Cl groundwater predominated in the shallow aquifers, but there is no evidence of intrusion of saltwater in the ground; and that anthropogenic sources including sewage were indeed significant in influencing the groundwater geochemistry. Similar results were also reported by Ojo et al. (2025) for borehole water samples from Effurun, Delta State on the diverse hydrochemical characteristics of the borehole water, which showed Ca–HCO3 and Na–Cl water types and also showing both natural and anthropogenic influences. Recent studies by Gbadebo et al. (2026) revealed mixed hydrochemical facies and manifestation of carbonate weathering, reverse ion exchange, rock–water interaction and anthropogenic influences in selected communities within the Niger Delta. The results show that hydrochemical facies in the Niger Delta is not exclusive to marine influence hence should be interpreted in relation to the geological, hydrological and anthropogenic characteristics of each study area.

2.2 The Piper Trilinear Diagram as a Diagnostic Tool

One of the most widely used graphical techniques for identification of groundwater hydrochemical facies is the Piper trilinear diagram as it enables the plotting of cation percentage, anion percentage on paired triangle plots along with plotting of percentage cation-anion percentage on the central diamond field that defines the groundwater water-type (Piper, 1944; Nwankwoala & Udom, 2011; Aleku et al., 2024). To identify hydrochemical types, Nwankwoala and Udom (2011) applied Piper trilinear diagram and ionic ratios to groundwater in Port Harcourt City where saline infiltration of groundwater is suspected. The results revealed a variable range of water types characterized by variable major ion concentrations and dominance by chloride, which reflected the importance of Piper classification in identification of hydrochemical variability in Niger Delta coastal environment. In a coastal setting with geologic and hydrologic characteristics similar to the present

study area, the Keta Basin in Ghana, Yidana et al. (2010) used Piper classification along with multivariate statistical analysis to classify the waters as low-salinity Ca–HCO3 and higher-salinity Na–Cl waters. The authors concluded that groundwater salinification was due to weathering of minerals and sea water intrusion. Methodologically this yields insight into the fact that a coastal African setting, where onshore conditions are similar, is equally suitable for separating marine-ionized facies from the other possible sources of degraded groundwater quality by hydrochemical classification as it is elsewhere. These suggest that it is not wise to treat Piper classification separately from other studies from the Niger Delta. Aleku et al. (2024) found shallow groundwater that was Na–Cl dominated in the eastern Niger Delta, but their other findings were not robust enough to conclude saltwater intrusion as the main cause anthropogenic sources such as sewage played an important part in causing the water chemistry observed. Therefore, Piper facies are used as a useful diagnostic tool, and the classification of the type of water from these facies should be correlated with other hydrochemical measurements of the water and, if feasible, accompanying geochemical or isotopic data.

2.3 Hydrogeochemical Studies in the Niger Delta

Nwankwoala and Udom (2011) reported on hydrogeochemical studies in the groundwater of Port Harcourt City, which revealed different major-ion concentrations and hydrochemical facies of groundwater with evidence of chloride dominance and possible saline-water influence. They showed the utility of major-ion chemistry, ratios of major ions and Piper trilinear diagrams in assessing the hydrogeochemical processes and groundwater vulnerabilities in the Niger Delta. Similarly, Olobaniyi and Owoyemi (2010) described the hydrochemical zonation of groundwater in the deltaic plain sands aquifer in Warri, and suggested some site specific evidence of hydrochemical heterogeneity in the western Niger Delta. Although they highlighted a general hydrochemical facies of the groundwater in Delta State, the authors stated that there was significant spatial variation in groundwater dominant hydrochemical facies and the groundwater chemistry processes across the region and that characterisation of each site like this should be maintained. This was then followed by the identification of various hydrochemical facies and natural water–rock interaction processes by Afolabi et al. (2023) in coastal Bayelsa, and the ability of Na–Cl groundwater in the eastern Niger Delta to be formed from non-salty waters and having anthropogenic signatures by Aleku et al. (2024). Injefere and his colleagues (2025) presented various hydrochemical muddy that also indicated the presence of both natural and anthropogenic

interactions in Efura in Delta State, which showed a combination of both Ca–HCO3 and Na–Cl water types. Moore et al. (2016) also observed mixed hydrochemical facies and the effects of man and nature on the geochemical parameters in the selected communities of the Niger Delta area.Gbadebo et al. (2026) also reported mixed hydrochemical facies and the combined effect of both nature and anthropogenic activities in selected communities of the Niger Delta area. These studies show the importance of interpretation of a hydrochemical facies in an integrated sense, rather than assigning each water type a specific source, without evidence.

2.4 Research Gap

Although well developed and able to delineate marine versus anthropogenic (human) origin of ionic sources in coastal African environments, as documented in the literature, such a capability has never been applied to Okerenkoko, Kurutie, or Kunukunuma communities whose location close to the coastline and also in the vicinity of oil-exploration infrastructure would make marine versus anthropogenic distinction particularly relevant. This study aims to fill this gap by compiling the hydrogeochemical baseline of these individual community clusters for the first time using a Piper diagram based approach.

3. Study Area and Geological Setting

The study area is located in mangrove and freshwater swamp areas of the western part of Niger Delta located in the Okerenkoko, Kurutie and Kunukunuma villages of Gbaramatu kingdom in the Warri South-West local government area (LGA) of the Delta state. The near surface hydrostratigraphic unit is the Benin Formation, which is made up from unconsolidated to poorly consolidated sands with interbedded clay layers. Hydrogeological conditions are generally well suited for marine ionic influence on shallow ground water in the area: low relief, shallow water table, high proportion of small tidal creeks and close proximity to the coastal environment.The hydrogeological conditions are optimum to study marine ionic influence of shallow ground water, in this area.

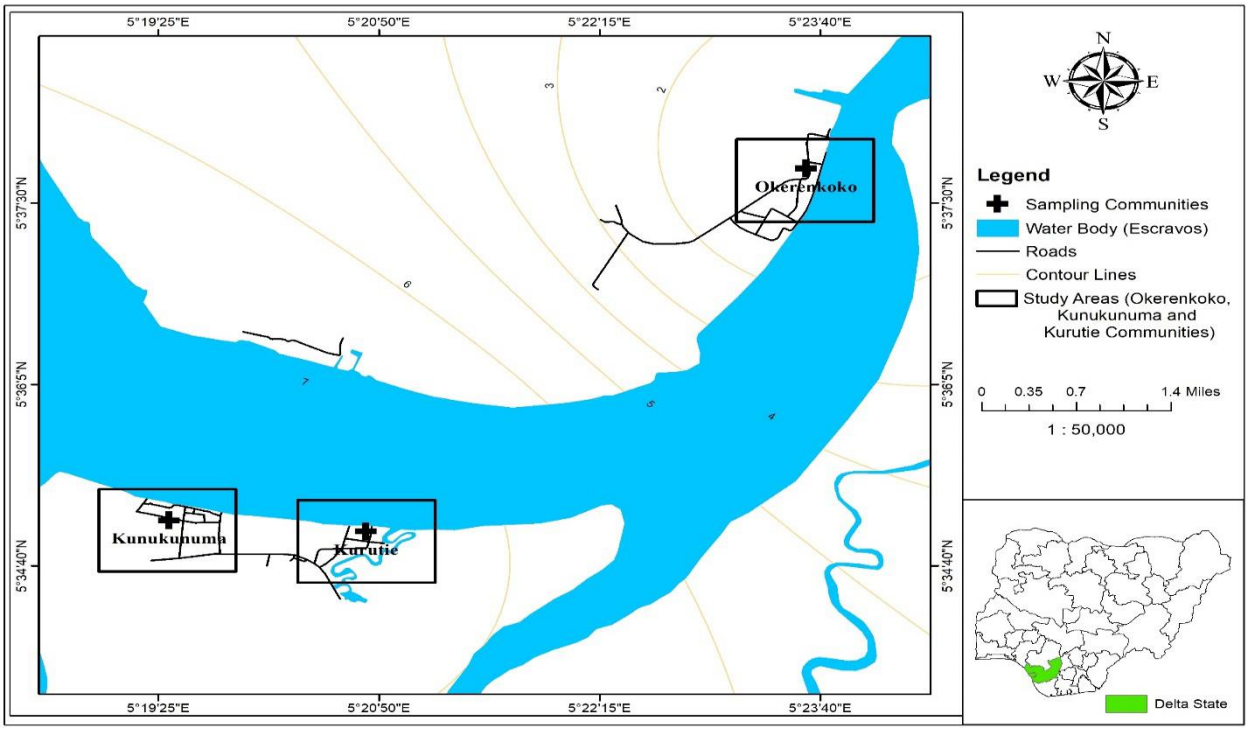


Figure 1. Location map of Okerenkoko, Kurutie and Kunukunuma, Gbaramatu Kingdom, Warri South-West LGA, Delta State, Nigeria. (Source: Author)

4. Materials and Methods

4.1 Sample Collection

Thirty groundwater samples were collected from hand-dug wells and boreholes systematically distributed across the three communities, using pre-cleaned high-density polyethylene (HDPE) bottles to minimise contamination during sampling and transport, following standard protocols recommended by the American Public Health Association (APHA, AWWA & WEF, 2023). Samples were analysed for pH, total dissolved solids (TDS), salinity, hardness, alkalinity, and major ions (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, Cl^{-}, $SO4^{2-}$, $NO3^{-}$, $HCO3^{-}$, $PO4^{3-}$) using standard analytical methods.

Field parameters were determined in situ at each sampling point immediately upon collection, before any change in temperature or dissolved-gas content could occur: temperature and pH were measured with a calibrated portable pH/temperature meter, and electrical conductivity, total dissolved solids and salinity with a calibrated portable conductivity meter. Meters were calibrated at the start of each sampling day against standard buffer solutions (pH 4.00 and 7.00) and a standard KCl conductivity solution, and the calibration was re-checked at the close of each day.

Wells were purged before sampling until field parameters stabilised, so that the water sampled was representative of the aquifer rather than of the standing column in the well. Samples were preserved in accordance with APHA, AWWA and WEF (2023). Aliquots reserved for cation determination were acidified in the field to pH < 2 with concentrated nitric acid, while aliquots reserved for anion determination were left unacidified. All samples were stored in insulated cool boxes at approximately 4 °C, transported to the laboratory on the day of collection, and analysed within the holding times prescribed for each determinand.

Chain-of-custody procedures were maintained throughout. Every bottle was labelled at the point of collection with a unique sample code, community, coordinates, date and time of collection, and preservation status; a chain-of-custody form accompanied each batch and was signed at every transfer between field team, transport and laboratory, so that custody of each sample is traceable from collection to analysis. Quality assurance and quality control comprised field blanks and duplicate samples collected at a rate of approximately one in ten, laboratory reagent blanks, and analysis of certified reference solutions alongside the sample batches; results were accepted where duplicate agreement was within 10%, and blanks returned concentrations below the method detection limit.

4.2 Piper Trilinear Diagram Construction

Major-ion concentrations were converted to milliequivalents per litre (meq/L) and expressed as percentages of total cations and total anions respectively, then plotted on cation and anion trilinear triangles and projected into the central diamond field to derive the dominant hydrochemical facies for each community, following the standard Piper (1944) convention as applied in comparable Niger Delta and West African coastal studies (Olobaniyi & Owoyemi, 2006; Yidana et al., 2010). The plotting was done in Python 3.11 with the use of Matplotlib library, the boundaries of different facies fields in hydrochemical fields were created in a custom Python script, which performs the trilinear coordinate transform.

For each ion, conversion from mass concentration to equivalent concentration was done.

$$meq/L = C\ (mg/L) \div [M\ (g/mol) \div |z|]$$

Divisor is the equivalent weight of the ion, where C is its measured concentration, M is the formula weight of the ion and |z| is the absolute value of its charge. It was then possible to express each ion as a percentage of the total cations, or total anions (as appropriate); these percentages were plotted

on the trilinear fields instead of the absolute concentrations. The charge-balance error was calculated for each sample as a check on the analytical data and was plotted along with it:

$$CBE\ (\%) = [(\Sigma\ cations - \Sigma\ anions) \div (\Sigma\ cations + \Sigma\ anions)] \times 100$$

Samples that returned a charge-balance error of more than ±5% was re-sampled and, if subsequent sampling failed to correct the error, were not included in the facies classification. In this study descriptive statistics used are means and standard deviations; the limitations for formal inter-community comparison of these statistics are discussed at Section 8.

4.3 Seawater-Mixing Estimation

To assess the likelihood of marine influences on the observed dominance of Cl^-, a simple conservative-mixing calculation was performed by assuming that representative local rainwater Cl^- concentration (approx. 5–10 mg/l) and the standard seawater Cl^- concentration (approx. 19,400 mg/l) are end-members, applied following the mixing-ratio logic which is generally followed in coastal hydrogeochemistry (Appelo & Postma, 2005). It is clearly a qualitative approach that was designed to test the physical plausibility of the interpretation of marine influence rather than to precisely quantify the proportion of seafarming to an estimate of the seawater fraction; more precise estimates would be obtained with the use of stable-isotope or additional conservative-tracer data, as indicated in Section 8.

Two-end-member mixing by chloride was used conservatively to estimate the amount of seawater present in the mixture, f.

$$f = (Cl^-sample - Cl^-rain) \div (Cl^-seawater - Cl^-rain)$$

Cl^- sample is the chloride concentration measured in the groundwater sample, Cl^- rain is the chloride concentration of the local meteoric recharges (which is assumed to be 5–10 mg/L), and Cl^- seawater is the chloride concentration of standard seawater (19,400 mg/L). As a worked example, the mean chloride concentration of Kunukunuma is 360.2 mg/L and a rainwater end-member is 7.5 mg/L:

$$f = (360.2 - 7.5) \div (19{,}400 - 7.5) = 352.7 \div 19{,}392.5 = 0.018,\ i.e.\ approximately\ 1.8\%\ seawater$$

When the three community means are included in the calculation, as is the default, and the full 5-10 mg/L range for the rainwater end-member are used, the same calculation will yield marine fractions of 1.60-1.83% (1.77-1.80% at Okerenkoko, 1.60-1.62% at Kurutie, 1.81-1.83% at

Kunukunuma). This shallow aquifer contribution from the sea water is approximately 2% and is used consistently throughout.

It should be clearly acknowledged that this is a limit of this estimate. It is a qualitative plausibility check, rather than quantitative determination, which assumes conservative behavior of chloride throughout the flow path, a single contribution from only two end-members, and a representative but assumed chloride concentration for each end-member. It is incapable of differentiating between active seawater intrusion and water from the past present (paleoconnate water) or from accumulation of sea-salt aerosol deposition, both of which would generate the signal of chloride. For a stable-isotope ($\delta^{18}O$, $\delta^{2}H$) or other, preferably conservative-tracer, data, a defensible quantitative estimate of the amount of water would be needed as described in Section 8.

4.4 Irrigation Suitability Assessment

The suitability for irrigation, based on the parameters of the sodicity problem, was evaluated qualitatively in terms of the sodium adsorption ratio (SAR) concept and the salinity-sodium classification framework of the United States Department of Agriculture (USDA).The suitability for irrigation was evaluated qualitatively, using the concept of sodium adsorption ratio (SAR) and the salinity-sodium classification framework of the United States Department of Agriculture (USDA), which considers the electrical-conductivity-derived salinity hazard (C-class) combined with the sodium hazard (S-class) to consider appropriate crop and soil management constraints (Todd & Mays, 2005).

5. Results

5.1 Physicochemical Characteristics

At all sites, the groundwater pH in the three communities was found to be below the range (6.5 - 8.5) allowed by WHO (2022); the pH in Kurutie was consistently below 6.5, while in Okerenkoko and Bakhuwana, pH was consistently below 8.5. Groundwater was generally fresh, with low mineralisation, as evidenced by the low Total Dissolved Solids (TDS) (80.6–212.75 mg/L) and Salinity (92.8–109.9 mg/L) across all three communities, which is below the WHO limits. The hardness (19.8 - 22.25 mg/L) and alkalinity (39.6 - 44.4 mg/L) are both lower than typical guideline ranges, indicating that the water is soft and has low acid buffering capacity, which is consistent

with the observed low pH. Nitrate and sulphate concentrations remained well within safe limits at all locations, while phosphate slightly exceeded the WHO range at some sites. Chloride (319.78–360.2 mg/L) and fluoride (2.47–2.98 mg/L) exceeded WHO permissible limits at all three communities without exception (Table 1).

Table 1. Mean physicochemical parameters across the three study communities, compared against WHO (2022) drinking-water guidelines.

Parameter	**Okerenkoko (Mean ± SD)**	**Kurutie (Mean ± SD)**	**Kunukunuma (Mean ± SD)**	**WHO (2022) Limit**
pH	5.76 ± 0.34	4.34 ± 0.28	4.78 ± 0.31	6.5–8.5
TDS (mg/L)	212.75 ± 45.3	151.4 ± 38.7	80.6 ± 22.5	500
Salinity (mg/L)	109.9 ± 15.6	92.8 ± 12.4	105.2 ± 14.8	<200
Hardness (mg/L)	22.25 ± 5.6	21.0 ± 4.8	19.8 ± 4.3	100–500
Alkalinity (mg/L)	43.35 ± 8.7	39.6 ± 7.9	44.4 ± 9.1	200–500
Nitrate (mg/L)	0.361 ± 0.12	0.403 ± 0.14	0.326 ± 0.11	50
Phosphate (mg/L)	0.487 ± 0.15	0.471 ± 0.13	0.541 ± 0.17	0.1–0.5
Sulphate (mg/L)	0.34 ± 0.09	0.38 ± 0.10	0.43 ± 0.11	250
Chloride (mg/L)	353.83 ± 78.5	319.78 ± 65.4	360.2 ± 72.8	250
Fluoride (mg/L)	2.47 ± 0.56	2.98 ± 0.62	2.86 ± 0.58	1.5

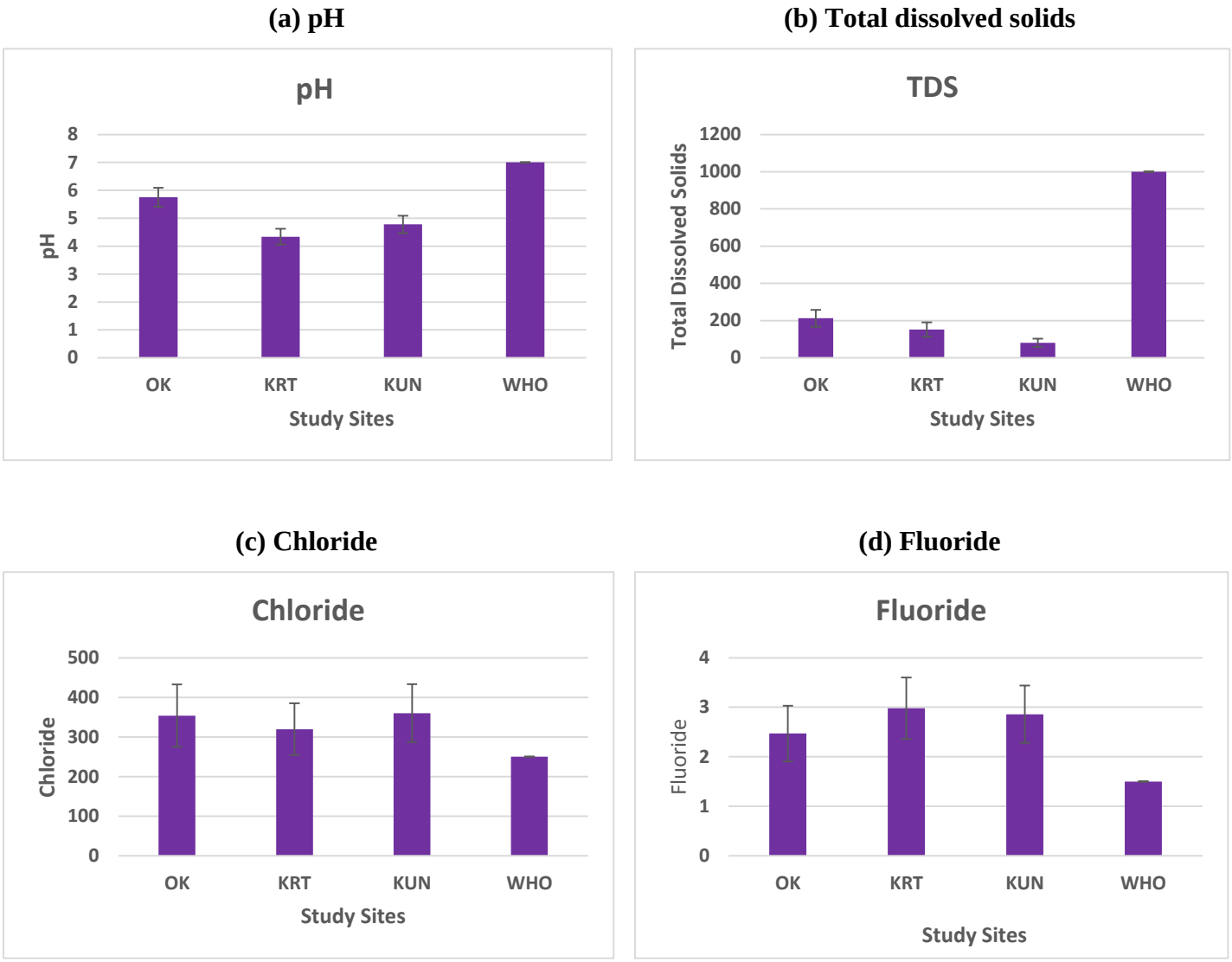


Figure 2. Mean pH, total dissolved solids, chloride and fluoride concentrations at Okerenkoko (OK), Kurutie (KRT) and Kunukunuma (KUN) compared with WHO (2022) drinking-water guideline values. Error bars represent one standard deviation about the mean, as reported in Table 1; no error bar is shown on the WHO column, which is a guideline value rather than a measured mean. (Source: Author).

5.2 Major-Ion Composition and Piper Classification

Cation composition was nearly identical across all three communities, dominated by Mg^{2+} (61–62% meq/L), followed by $Na^{+}+K^{+}$ (33–34% meq/L) and Ca^{2+} (approximately 5% meq/L) (Table

2). Anion composition was overwhelmingly dominated by Cl^- (88–89% meq/L), with $HCO3^-+CO3^{2-}$ contributing only 6–7% and $SO4^{2-}$ approximately 5% (Table 3).

Table 2. Mean cation proportions (% meq/L) across the three communities.

Community	Ca^{2+} (% meq/L)	Mg^{2+} (% meq/L)	$Na^+ + K^+$ (% meq/L)
Okerenkoko	5	61	34
Kurutie	5	62	33
Kunukunuma	5	62	33

Table 3. Mean anion proportions (% meq/L) across the three communities.

Community	$HCO3^-+CO3^{2-}$ (% meq/L)	$SO4^{2-}$ (% meq/L)	Cl^- (% meq/L)
Okerenkoko	7	5	88
Kurutie	6	5	89
Kunukunuma	7	5	88

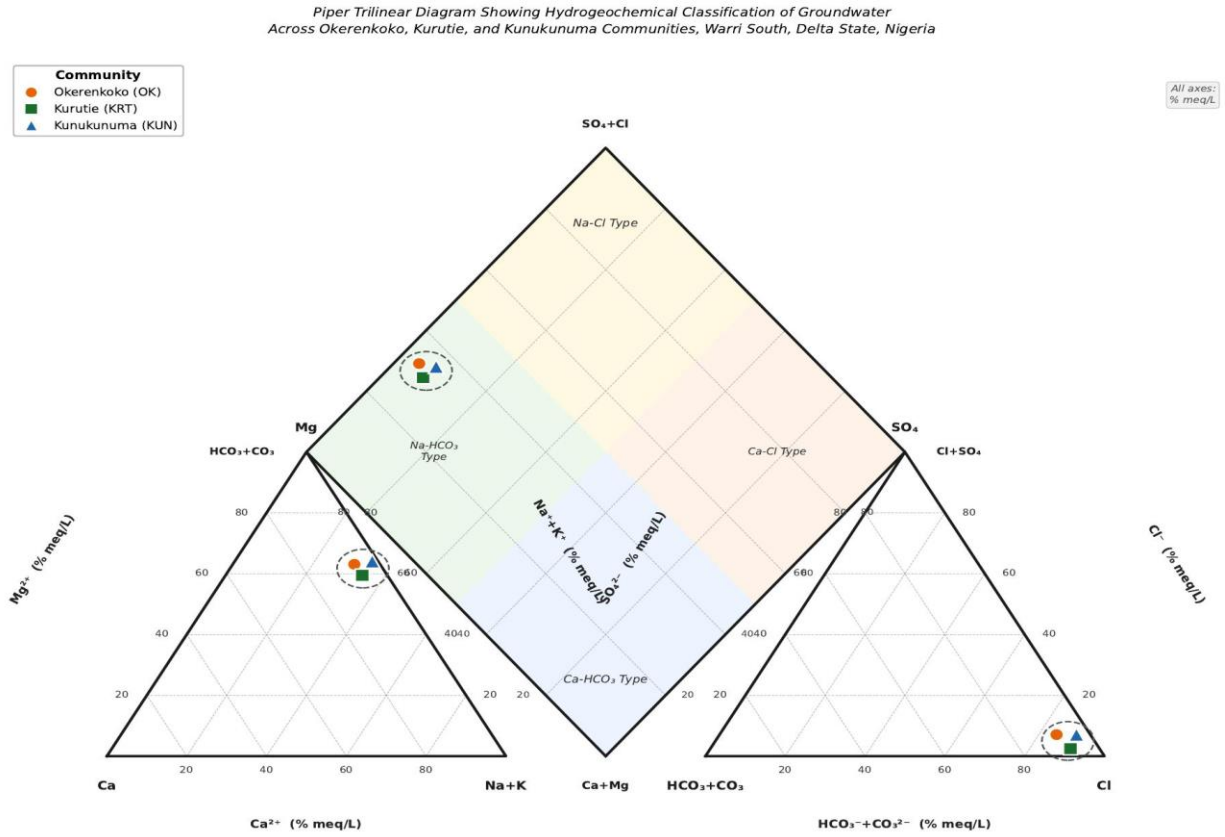


Figure 3. Piper trilinear diagram showing the near-coincident projection of the Okerenkoko, Kurutie and Kunukunuma samples, classifying the groundwater as Mg^{2+}–Cl^{-} type. Source: Author.

Projection into the central diamond field positions all three community samples firmly within the upper-right quadrant, consistent with the joint Mg^{2+} cation dominance and Cl^{-} anion dominance. The resulting hydrochemical facies is magnesium–chloride (Mg^{2+}–Cl^{-}) as the main water type, and it has a second Na^{+}–Cl^{-} water type. The inter-community variabilities by each ion measured was < 1–2% meq/l which suggests a hydrochemically homogeneous regional groundwater system, rather than three hydrochemically separate community level aquifers. A mixing estimate is used to determine the percentage of seawater mixing based on the chloride ion concentration. The Cl^{-}-based mixing estimate (Section 4.3) shows an estimated mixing of seawater in the shallow aquifer of ~2% (1.6–1.8%). This is a minor marine contribution but still is enough to explain the observed dominance in Cl^{-} except it's behaviour is conservative along the flow path.

6. Discussion

The key result of this study is the pervasive near uniformity of hydrochemical composition within the cluster of public supply wells, Okerenkoko, Kurutie, and Kunukunuma, which infers a single regional source influencing the groundwater chemistry of the community cluster - the ocean - rather than one presumably localised to the community of industrial or sanitation impacts. There is no meaningful inter-community variation (0–2% meq/L) between the three communities in any of the measured ions that could be attributable to anthropogenic point source contamination since this would be a direct result of different communities' proximity to the specific pollution sources. This is much more consistent with a common pool or shared aquifer system with uniformity in the regional processes of seawater intrusion, paleo-connate water entrapment from past marine transgressions, and deposition of atmospheric sea-salt by precipitation.

This interpretation has directly addressed, and challenged, the assumption found in the literature of the Niger Delta ground waters, namely, that gas exploration or contaminating events near oil-exploration activity areas inevitably lead to a high ionic loading of the ground water chemistry (Nwankwoala & Udom, 2011). In comparison to the signature of a petroleum contamination, these facies reported here show unequivocal evidence of very high levels of Mg^{2+} and moderately

elevated levels of Cl^- – which may be expected to reach downstream locations – rather than any indication of added total petroleum hydrocarbons and polycyclic aromatic hydrocarbons or any specific enrichment of trace metals. Petroleum contamination is certainly a problem in these communities, as is the evidence for it in the same terrain, based on independent hydrocarbon and heavy metal data, but what does not exclude petroleum contamination is the fact that it should not be interpreted as the major portion of the hydrochemical facies data. The identification of the signature of Mg^{2+}–Cl^- as an indicator of petroleum activity would be misdiagnosing the cause and may lead treatment efforts to focus on industrial source control rather than the geochemical signature indicating that the primary drivers of the signature in this context are marine influence, ferromagnesian silicate weathering, and cation-exchange processes.

This marine-influence explanation is confirmed by the near absence of the anions, $HCO3^-$+$CO3^{2-}$ (6–7%). In freshly recharged, unimpacted meteoric groundwater, bicarbonate typically constitutes 60–80% of total anions, generated through carbonic-acid weathering during infiltration (Appelo & Postma, 2005). Its near-total displacement here indicates that carbonate alkalinity has been diluted or chemically displaced through mixing with a higher-ionic-strength, marine-influenced end-member, a pattern consistent with the coastal hydrogeological setting and with comparable findings from Yidana et al. (2010) in coastal Ghana. Cation-exchange reactions, in which Ca^{2+} is preferentially adsorbed onto clay exchange sites while Mg^{2+} and Na^+ are released into solution, plausibly reinforce the low Ca^{2+} proportion (~5%) observed across all three communities, a process well documented in comparable deltaic clay-sand sequences (Fetter, 2001).

The drinking-water implications of this facies are nonetheless serious, irrespective of its ultimate cause. The combination of high Cl^- and low alkalinity produces water chemistry with a tendency toward negative Langelier Saturation Index behaviour, indicating corrosive potential that could accelerate degradation of water-distribution and well infrastructure and potentially mobilise metals from pipe or casing materials into the water supply. In coastal waters there was an association of elevated levels of Mg2+ with low numerical WHO indications for gastrointestinal effects on osmolarity in sensitive (human) users, however this was not directly measured against the numerical WHO guidance. The higher Cl^- availability and the relatively low Ca^{2+} suggests a higher SAR rating, in this instance in the range of C3–S2 to C4–S3, by the Wilcox water quality

classification, which implies the water would be suitable only for salt tolerant crops, even if unmodified, in well-drained soils for irrigation.

The high chloride content and low alkalinities noted with the marine-influence signature is another conflict of ideas the first sighting, given that seawater is hard and moderately alkaline. The aged, marine end-member is much too weak in hardness or alkalinity to leave a mark on the groundwater when it is mixed at a supposed 2% mixing rate with seawater (Section 5.2), but on the other hand, it is much more concentrated in the relatively unreactive Cl^- fraction, and that is conveyed to the mixed groundwater without undergoing any significant change. The marine signal is, in contrast, more strongly decreased by precipitation, exchange and/or biological uptake of the reactive species of calcium and bicarbonate, compared to Cl^-, even at low mixing fractions. This is the reason for the common occurrence of a marine-influence water type in this setting and why Cl^- is the diagnostic, diagnostic-active, marine-influence tracer in this context—while the concentrations of reactive cations and alkalinity cannot.

7. Implications for Groundwater Resource Management

This was due to the regional uniformity of the dominant hydrochemical facies, rather than the presence of community-specific hydrochemical facies, and because of this, the most effective actions to take at both the water treatment and monitoring level are those that are region-based, and not community-based. Point-of-use treatment technologies that can lower elevated chloride and correct corrosive water chemistry (such as reverse osmosis, or nanofiltration) may be worthy of consideration as a regional-scale "common denominator" solution, not a unique/individual solution for any specific community. Corrosion resistant casing material should be considered as a standard requirement for any new or rehabilitated borehole in this area as the low pH, low alkalinity, high chloride concentration is conducive to corrosion and potential release of metals from well infrastructure. Communities that draw their irrigation water from this groundwater source, for agricultural extension, should be alerted to the use of C3-S2 to C4-S3 type of groundwater and directed towards cultivars and soil management that is well drained.

8. Limitations of the Study

There are four restrictions that need to be clearly stated: First, the estimate of seawater mixing presented in Section 5.2 is a simple application of a two-end-member conservative estimate based

on Cl^- concentration alone; it is a plausibility check rather than a quantitative estimate, and an expanded, more rigorous seawater mixing calculation using stable-isotope (δ18O, δ2H) or additional conservative-tracer analysis would require data that is not in the present dataset. Second, the hydrochemical classification observed in this study was taken during only one hydrological campaign, and Udom et al. (2019) proved that the hydrochemical facies of similar coastal aquifers in the Niger Delta region can change from one period of the year to the next, especially influenced by varying conditions of recharge and tidal intrusion; therefore, the classification reported in this study must not be considered as permanent and stable facies. Third, while this study interprets the observed facies as predominantly marine-influenced rather than petroleum-derived, it does not itself incorporate hydrocarbon or trace-metal data; that evidence is addressed in a companion analysis, and a fully integrated hydrochemical-hydrocarbon dataset would strengthen the marine-versus-anthropogenic attribution made here. Fourth, the dataset comprises 30 samples distributed across three communities and is analysed descriptively, through means and standard deviations, rather than inferentially. A sample of this size is adequate to establish a dominant regional facies, which is the claim advanced here, but it affords limited statistical power for formal inter-community comparison; the hydrochemical homogeneity reported in Section 5.2 should therefore be read as a descriptive observation rather than as a statistically tested result. An enlarged sampling network combined with analysis of variance and inter-ion correlation analysis would allow that homogeneity, and the geochemical processes inferred from it, to be tested formally.

9. Conclusion

This study has established the first Piper-diagram-based hydrogeochemical baseline for Okerenkoko, Kurutie, and Kunukunuma, three oil-exploration-exposed Niger Delta communities previously lacking site-specific facies-level characterisation. Groundwater across all three communities is classified as Mg^{2+}–Cl^- type, with near-identical ionic proportions indicating a single, regionally homogeneous aquifer system governed by marine influence, ferromagnesian silicate weathering, and cation-exchange processes rather than by localised industrial discharge. While total dissolved solids and salinity remain within WHO limits, elevated chloride and fluoride, acidic pH, and the corrosive implications of the low-alkalinity, high-chloride combination mean that this groundwater should not be recommended for direct domestic consumption without treatment, and its use for irrigation should be restricted to salt-tolerant crops under the Wilcox C3–S2 to C4–S3 classification. These findings directly complicate the common assumption that

elevated groundwater ionic loading near Niger Delta oil-exploration sites is necessarily a petroleum-contamination signature, demonstrating instead that regional marine geochemistry is the dominant driver of hydrochemical facies in this specific setting.

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