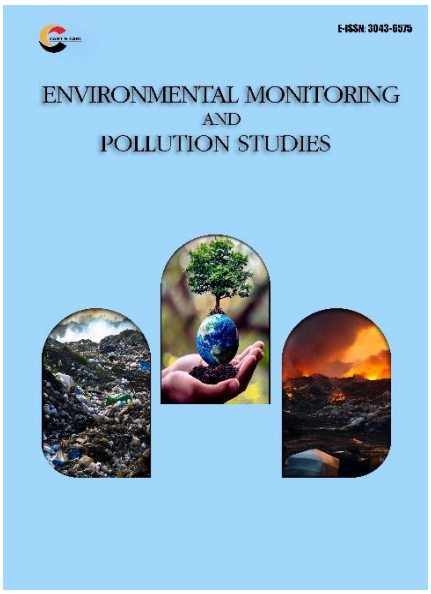
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Hydrochemical Evaluation of Saltwater Intrusion in Some Coastal Areas in Rivers State, Nigeria

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Abstract
This study evaluates the hydrochemical characteristics and extent of saltwater intrusion in selected coastal communities of Rivers State, Niger Delta, Nigeria, with particular emphasis on groundwater vulnerability, salinity distribution and suitability for domestic and agricultural applications. Groundwater samples were collected from six (6) boreholes and six(6) hand-dug wells across Sama, Tema, Abalama, Buguma, Ido and Obuama communities and analysed for physicochemical parameters, major ions and selected heavy metals using standard laboratory procedures. The results revealed considerable spatial variability in groundwater quality, with electrical conductivity (EC) ranging from 77 to 7,490 µS/cm and total dissolved solids (TDS) varying between 40 and 3,750 mg/L. Salinity concentrations were exceptionally elevated at Tema (3,810 mg/L), Sama (3,310 mg/L) and Ido (2,712 mg/L), exceeding the recommended drinking water threshold. Sodium concentrations also exceeded permissible limits at selected sampling locations, while elevated sodium adsorption ratios indicated potential irrigation constraints. Chloride-bicarbonate ratios ranged from 0.229 to 1.552, suggesting variable saline influence and localized hydrochemical modification. Spatial distribution maps further revealed heterogeneous salinization, reflecting interactions between coastal hydrodynamics, aquifer characteristics and anthropogenic activities. The findings establish that saltwater intrusion constitutes a significant threat to groundwater sustainability, necessitating continuous hydrochemical monitoring, regulated groundwater abstraction and appropriate aquifer protection strategies to safeguard potable water resources in the coastal Niger Delta.

Keywords: Groundwater Vulnerability, Hydrochemical, Salinity, Saltwater Intrusion, Niger Delta, Rivers State

Introduction

Groundwater remains the most reliable source of potable water in many coastal communities of Rivers State, Nigeria. With increasing population growth, urbanization, and industrial activities, the demand for groundwater has intensified, placing immense pressure on aquifer systems. Coastal aquifers, however, are inherently vulnerable to saltwater intrusion due to their proximity to tidal rivers and the Atlantic Ocean. The delicate balance between freshwater and saline water, is easily disrupted when groundwater extraction exceeds natural recharge or when sea level rise alters hydraulic gradients. Empirical studies using electrical resistivity methods have provided clear evidence of this vulnerability. In Bakana, resistivity surveys revealed freshwater aquifers at depths of 13-200m, overlain by clay and silty clay units, while shallow horizons exhibited low resistivity values indicative of saltwater intrusion and possible hydrocarbon contamination (Oghonyon et al., 2024). Similarly, investigations in Tombia, Degema LGA, confirmed saline encroachment at depths of 20-40m and 82-95m, with freshwater aquifers identified at deeper horizons of 140-175m (Dickenson et al., 2022).

These findings highlight a recurring pattern: shallow aquifers are highly susceptible to saline intrusion, while deeper aquifers, often confined by clay layers, remain relatively fresh and suitable for potable water supply. The implications of saltwater intrusion extend beyond hydrogeology to

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public health and socio-economic development. Communities that rely on shallow wells and boreholes face increasing risks of consuming saline or contaminated water, which can lead to health challenges and reduced agricultural productivity. The situation is further compounded by anthropogenic activities such as poor waste disposal and industrial effluent discharge, which introduce additional contaminants into groundwater systems. The present study is focus on the salinity and contamination using hydrochemical parameters with selected metals and infer the degree of seawater mixing and contaminant loading in screened intervals and assess aquifer vulnerability and the risk to community water supplies by integrating hydrogeological setting, patterns, and contaminant distribution.

Materials and Methods

Study Area and Its Geology

The study area is in Asari-Toru and Degema Local Government Area of Rivers State, Niger Delta Southern Nigeria, which is located between latitudes 4˚ 46'21"N and 4˚22'00"N, and longitudes 4˚2'39"E and 7˚10'27"E. It is marked by two distinct seasons, the dry season and the rainy season (Figure 1).

The dry season lasts from about November to April and while the rainy season spans May to October with a brief dry spell in August. The study area has characteristic tropical equatorial climate with mean annual temperature of 32.8^{0}C and annual rainfall of 2673.8 mm. Located in Benin Formation, Asari-Toru and Degema is typically riverine and has a large number of outlets through which her tributes from River Niger empty their water into the Atlantic Ocean. It is predominantly sandy with a few intercalations of shale beds. The sands are always unconsolidated, granular in texture and characteristically fine to coarse grained size and described as fresh water bearing. At various depths in the formation, both confined and unconfined aquifers are encountered (Figure 1).

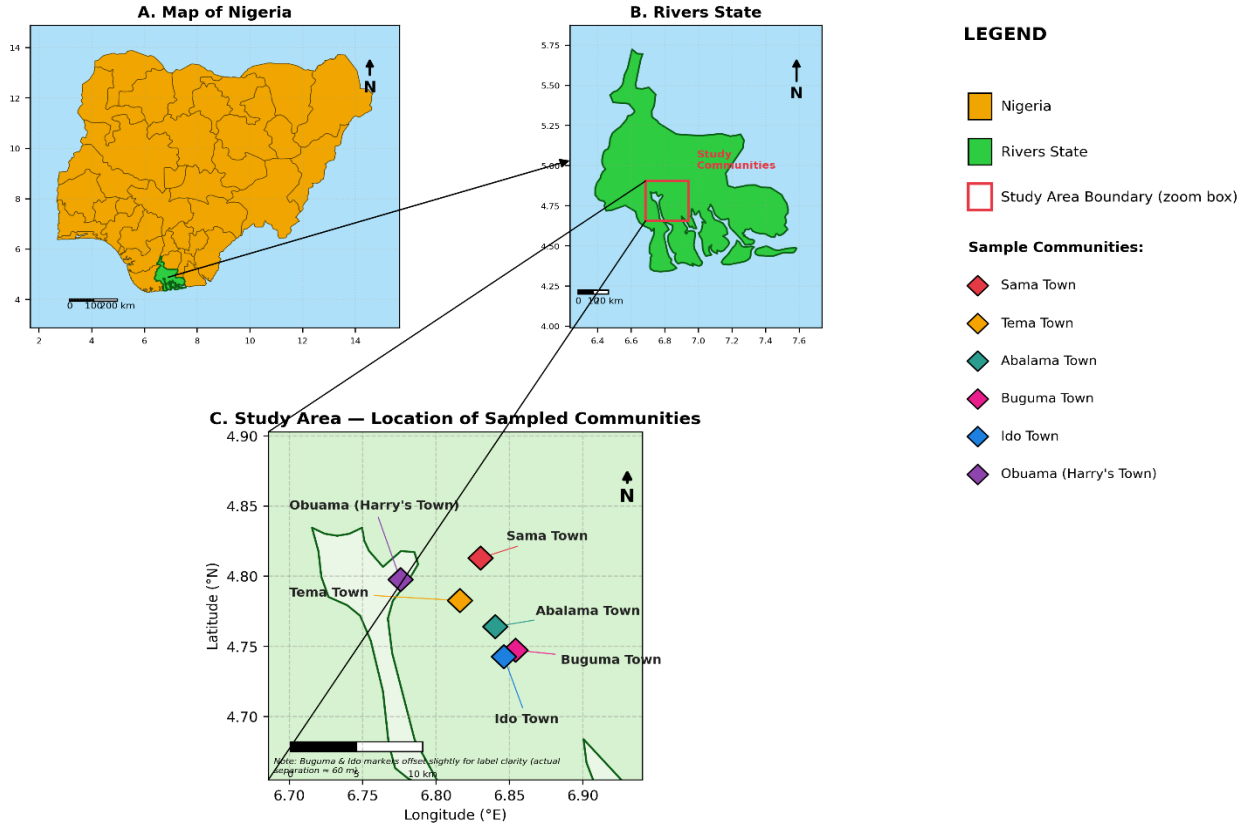


Figure 1: Map showing the study area

Geology and Hydro-geological Setting

In Rivers State, southern Nigeria, the hydrogeology of the study area is located within 4˚ 46'21"N and 4˚22'00"N, and longitudes 4˚2'39"E and 7˚10'27"E. (Figure.1)., which includes Sama Town, Tema Town, Abalama Community, Buguma Town, Ido Town, and Obuama Town, is fundamentally controlled by the geologic framework, lithologic characteristics, climatic conditions, and geomorphic setting of the eastern Niger Delta coastal plain. This study area encompasses all of

these towns. This region is located within the Niger Delta Basin, which is a prolific sedimentary province that is distinguished by thick accumulations of unconsolidated Quaternary to Recent sediments. These sediments are responsible for the existence of large and valuable groundwater systems. The intimate interplay between fluvial, deltaic, and marine processes has a significant impact on the formation of aquifers, groundwater flow regimes, and the distribution of water quality throughout the region (Short and Stauble, 1967; Reijers *et al*., 1997). It is the Benin Formation that serves as the primary aquifer system that supports the towns of Sama, Tema, Abalama, Buguma, Ido, and Obuama. The majority of this formation is made up of fine to coarse grained sands and gravels that are either unconsolidated or weakly consolidated, and it also contains clay and silt interbeds that are subordinate. These interbeds were deposited in fluvial, floodplain, and upper delta plain settings (Short and Stauble, 1967; Doust and Omatsola, 1990). In most cases, the sandy units are well sorted, have a high concentration of quartz, and are extremely porous. This results in a high groundwater storage capacity and transmissivity. Studies conducted in the eastern part of the Niger Delta have shown that the transmissivity values are typically high. This is a reflection of the fact that the Benin Formation is dominated by permeable sandy lithologies (Onuoha and Mbazi, 1988; Nwankwoala and Ngah, 2014).

Both unconfined and semi-confined circumstances contribute to the presence of groundwater in the region under investigation. In most cases, the shallow aquifer system is unconfined. This is particularly true in the cities of Sama, Tema, Buguma, and Ido, where sandy units stretch from the surface and the clay cover is either thin or discontinuous. In contrast, the villages of Abalama and Obuama, which are located closer to mangrove swamps and tidal creeks, display localised semi-confined conditions as a result of the existence of peat layers, organic-rich mud, and silty clay with a high concentration of organic matter. Perched or semi-confined aquifer systems are created as a result of these layers, which function as semi-constricting horizons that locally impede the transport of groundwater into the vertical direction. A heterogeneity of this kind is typical of deltaic aquifers, and it has been extensively described in hydrogeological investigations that have been conducted in the Niger Delta in recent years (Nwankwoala *et al*., 2020).

Recharge to the groundwater system is predominantly received from the direct penetration of rainwater, which is copious due to the humid tropical environment of the region. This is the primary source of recharge. In addition to the high average annual rainfall, the combination of a flat terrain, sandy soils that are permeable, and a short depth to the water table makes it easier to effectively replenish the water table. Additional recharge takes place as a result of the interaction between surface water and groundwater, notably from rivers, tidal creeks, and plains that are inundated yearly during high water stages. Reijers *et al*., (1997) and Oteri (2019) found that in locations that are prone to flooding, protracted inundation and clayey surface layers might potentially impair infiltration efficiency locally, even when there is a significant quantity of rainfall.

Regional hydraulic gradients, lithologic heterogeneity, and the dense network of surface water bodies all have a role in determining the flow of groundwater within the area under scientific investigation. It is common for groundwater to flow from interior recharge zones toward coastal discharge regions, such as estuaries, tidal creeks, and the Atlantic Ocean, when seen on a regional scale. As a result of the effect of tidal variations, channel architecture, and heterogeneity within the aquifer system, flow directions are extremely varied on a local level. Onuoha and Mbazi (1988) and Oteri (2019) found that periodic tidal forcing can cause short-term reversals in hydraulic gradients in coastal and estuarine zones, which in turn promotes mixing between freshwater and saltwater water.

The depth of the water table in the towns of Sama, Tema, Abalama, Buguma, Ido, and Obuama is often shallow, typically ranging from less than one meter to a few meters below the surface of the earth. This is especially true during the rainy season. There is a significant amount of variation in groundwater levels throughout the year, with water tables being recorded to be higher during times of extreme rainfall and flooding, and seeing considerable drops during the dry season. Nwankwoala and Udom (2011) found that oscillations like these have an effect on the mechanisms of contaminant transport, the availability of groundwater, and the susceptibility of aquifers to pollutants that are derived from the surface.

One of the most significant hydrogeological challenges that the study region faces is the presence of saline water incursion. Because of their proximity to the coast, low elevation, and the strong hydraulic link that exists between aquifers and tidal water bodies, freshwater aquifers are extremely vulnerable to the incursion of saltwater. When protective clay layers are weak, fractured, or missing, saline intrusion can occur laterally from tidal streams and estuaries or vertically from deeper saline zones. This is especially true in situations when the clay layers protect the soil. By decreasing freshwater heads and enabling salty water to move

inland, excessive groundwater extraction for residential and industrial use might further worsen this problem (Oteri, 2019; Nwankwoala *et al*., 2020). This problem can be further exacerbated by the depletion of freshwater heads.

Recent research conducted in the eastern Niger Delta has shed light on the growing effect of saline intrusion and groundwater pollution, which are linked to fast population increase, urbanisation, and activities connected to oil extraction (Etu-Efeotor and Odigi, 2013; Nwankwoala *et al*., 2020). Because the aquifer system in many sections of the study region is shallow and unconfined, groundwater is especially susceptible to pollution from a variety of sources, including the discharge of household waste, septic systems, hydrocarbon spills, and runoff from agricultural land. According to Nwankwoala and Amadi (2013) and Adeoti *et al*., (2021), investigations that are based on electrical resistivity have been shown to be successful in identifying polluted zones, mapping saline-freshwater interfaces, and characterising aquifer geometry in coastal Niger Delta environments that are comparable.

Both natural and manmade variables have an impact on the hydrogeochemical conditions that are present in the vicinity of the research region. The chemistry of groundwater naturally reflects the interaction of water and rocks inside sandy aquifers, the ion exchange processes that include clay minerals, and the mixing of freshwater and saltwater. An additional modification to the quality of groundwater is caused by human activities, which leads to increased concentrations of dissolved solids, chloride, and other toxins in some areas. (Adeoti *et al*., 2021) Recent hydrogeochemical investigations in the state of Rivers have shown evidence of geographic heterogeneity in groundwater quality. This variability is connected to the closeness of the groundwater to streams, land use patterns, and the depth of the aquifer.

Within the Benin Formation, the hydrogeology of Sama Town, Tema Town, Abalama Community, Buguma Town, Ido Town, and Obuama Town is characterised by groundwater systems that are abundant but extremely susceptible. These groundwater systems are home to the Benin Formation. The hydrogeological regime is characterised by high permeability, shallow water tables, active interaction between surface water and groundwater, and close proximity to the shore. Groundwater resources are normally abundant and easily accessible; nevertheless, they are increasingly being endangered by saline intrusion and pollution than they were previously. When it comes to protecting coastal aquifers in the eastern Niger Delta area, these features highlight the need of conducting integrated hydrogeological and geophysical research, continuously monitoring groundwater, and managing water resources in a sustainable manner. Lithostratigraphically, these rocks are divided into the oldest Akata Formation (Paleocene), the Agbada Formation (Eocene) and the Youngest Benin Formation (Miocene to Recent). Generally, the present knowledge of the geology of the Niger Delta was derived from the works of the following researchers (Reyment, 1965; Short & Stauble, 1967; Murat, 1970; Merki, 1970) as well as the exploration activities of the oil and gas companies in Nigeria. The formation of the so called proto-Niger Delta occurred during the second depositional cycle (Campanian-Maastrichtian) of the southern Nigerian basin. However, the modern Niger Delta was formed during the third and last depositional cycle of the southern Nigerian basin which started in the Paleocene. The geologic sequence of the Niger Delta consists of three main Tertiary subsurface lithostratigraphic units (Short & Stauble, 1967) which are overlain by various types of Quaternary deposits (Table 1).

The major aquiferous formation in the study area is the Benin Formation. It is about 2100m thick at the basin centre and consists of coarse-medium grained sandstones, thick shales and gravels. The upper section of the Benin Formation is the quaternary deposits which is about 40 – 150m thick and comprises of sand and silt/clay with the later becoming increasingly more prominent seawards (Etu-Efeotor & Akpokodje, 1990). The formation consists of predominantly freshwater continental, friable sands and gravel that have excellent aquifer properties with occasional intercalations of claystone/shales (Olobaniyi & Oweyemi, 2006). According to Etu-Efeotor (1981), Etu-Efeotor & Akpokodje (1990), Offodile (2002), Udom *et al*., (2002), the main source of recharge is through direct precipitation where annual rainfall is as high as 2000 – 2400mm. The water infiltrates through the highly permeable sands of the Benin Formation to recharge the aquifers. Groundwater in the study area occurs principally under water table conditions. Multi-aquifer systems occur in the study area and the upper aquifers are generally unconfined (EtuEfeotor, 1981; Offodile, 2002; Amadi, 2004; and Udom, 2004).

Table 1: Quaternary deposits of the Niger Delta (after Etu-Efeotor & Akpokodje, 1990)

Geologic Unit	Lithology Age	Age
Alluvium Gravel	Sand, clay, silt	
Freshwater Backswamp, meander	Sand, clay, some silt, gravel	
Saltwater Mangrove Swamp and backswamp	Medium-fine sands, clay and some silt	Quaternary
Active/abandoned beach ridges	Sand, clay, and some silt	
Sombreiro-warri deltaic plain	Sand, clay, and some silt	

Data Collection Procedure

Groundwater samples were collected from 6 (six) boreholes and 6(six) hand dug well after 5 minutes of pumping to ensure the samples were true representative from the aquifer. The samples were stored in sterilized two-litre containers with tightly fitting covers wrapped in a black polyethylene plastic bag and put in a cooler to ensure constant temperature. The containers were first washed with de-ionized water, and then several times with the sample water before collection in order to avoid any contamination. Parameters like pH and temperature and electrical conductivity were determined in the field due to their unstable nature. The pH of the water sample was measured with a pH meter. The glass tube in the kit was sterilized before been filled to its mark with water sample. The tube was then placed in the space provided in the equipment and a knob adjusted for colour matching, the pH was then read and recorded. The temperature was read using a mercury thermometer. The electrical conductivity was measured using a Mark electronic switchgear conductivity meter. After sampling, the lids of the containers were immediately replaced to minimize contamination and escape of gases. The samples were then stored in an ice-packed cooler for analysis within 24 hours. All analyses were carried out at a standardized laboratory using national and international regulatory methods. The evaluation of water quality was in accordance with regulatory standard. The approach ensures that the samples collected were tested in accordance with agreed requirements using competent personnel as well as appropriate equipment and materials. Figure.1, is the map showing sampling locations.

Analysing saltwater intrusion in coastal area involved hydrogeological and geochemical at various locations (see Figure 1) around the study area. Water samples were collected and analysed for (i) pH, (ii) Electrical Conductivity, (iii) Chlorides, (iv) Bicarbonates, (v) Calcium, (vi) Sodium, (vii) Magnesium, (viii) Sulphates, (ix) Total Hardness and (x) Total Dissolved Solids, using standard water quality assessment (APHA, 1989) methods. argentometric titration using standard silver nitrate solution. Sulphate (SO_4^{2-}) was analysed by the turbidimetric method using a UV–Visible spectrophotometer, while bicarbonate (HCO_3^-) was determined by acid titration Nitrate (NO_3^-) concentrations were measured spectrophotometrically following Standard Methods for the Examination of Water and Wastewater.

Heavy Metal Analysis

Groundwater samples were digested using concentrated nitric acid according to APHA standard procedures. Iron (Fe), manganese (Mn), lead (Pb), cadmium (Cd), chromium (Cr), nickel (Ni), copper (Cu), and zinc (Zn) were quantified using Flame Atomic Absorption Spectrophotometry. Calibration curves were prepared from certified standard solutions, while reagent blanks, duplicate samples, and certified reference materials were analysed simultaneously to ensure analytical accuracy and precision.

Results and Discussion

Physico-Chemical Parameters of the Study Area

The analytical results for groundwater samples from study area are presented in Table 2. reveal a dataset dominated by strong positive skewness, reflecting the coexistence of minimally impacted wells and heavily mineralized boreholes within the same coastal corridor. Temperature was essentially invariant (mean 28.18 ± 0.45 °C; CV = 1.6%), There is no standard value recommended for groundwater temperature by the WHO (2006), consistent with equatorial shallow aquifer conditions, whereas EC and TDS exhibited the highest dispersion in the dataset (EC: 77-7,490 µS/cm, CV = 132%; TDS: 40-3,750 mg/L, CV = 148%), confirming the spatially heterogeneous salinization documented for the Niger Delta coastal belt (Eyankware *et al*., 2021; Udota *et al*., 2022). Mean pH (6.57 ± 0.49) was marginally acidic and within the 6.5-8.5 window recommended for irrigation (Ayers & Westcot, 1985), although BH5 (Ido, 5.37) fell below it. Sodium (121.12 ± 110.95 mg/L; CV = 92%) and chloride (96.70 ± 42.20 mg/L) displayed wide ranges with three Na exceedances of the NSDWQ (2007) limit.

Table 2:The Physico-Chemical parameters

S/N	Parameter	BH1 Sama	WELL1 Sama	BH2 Sama	WELL2 Tema	BH3 Tema	WELL3 Abalama	BH4 Abalama	WELL4 Buguma	BH5 Buguma	WELL5 Ido	BH6 Ido	WELL6 Obuama	WHO (2000)	NSDWQ (2007)
	Latitude	4°48'46 "N	4°48'46 "N	4°48'46 "N	4°46'57 "N	4°46'57 "N	4°45'50 "N	4°45'50 "N	4°44'41 "N	4°44'41 "N	4°44'42 "N	4°44'42 "N	4°47'51 "N		
	Longitude	6°49'49 "E	6°49'49 "E	6°49'49 "E	6°48'59 "E	6°48'59 "E	6°50'25 "E	6°50'25 "E	6°51'02 "E	6°51'02 "E	6°50'59 "E	6°50'59 "E	6°46'33 "E		
	Elevation	20m	20m	20m	13m	13m	10m	10m	0m	0m	0m	0m	10m		
1	Temp.	28.3	28.5	28.4	27.8	29.2	27.8	28.3	28.1	28.3	27.7	27.5	28.2	NS	NS
2	EC	6530	229	77	7490	529	596	1120	428	985.8	897.6	3763	596	NS	<1000
3	pH	6.39	6.65	6.26	6.44	7.09	6.92	7.01	6.99	5.37	6.17	6.66	6.92	6.5â€“8.5	
4	TDS	3270	114	40	3750	50	296	559	214	50	43	2733	296	<1000	<500
5	Salinity	3310	114	40	3810	50	298	556	215	50	44	2712	298	NS	<500
6	Sodium	242.7	36.3	24.75	365	88.6	97.3	189.8	78.8	20.5	55.7	232	22	<200	<200
7	Calcium	6.07	3.84	6.75	6.88	5.54	2.03	9.33	8.63	6.87	5.73	4.78	8.45	NS	<75
8	Magnesium	2.24	6.65	5.76	4.62	4.64	8.63	6.87	6.92	5.77	5.76	7.32	4.42	NS	<50
9	Sulphate	23.74	67.77	26.72	8.98	23.22	24.03	91.33	84.63	60.87	65.73	53.77	72.78	<250	<100
10	Nitrate	2.03	9.33	8.63	6.87	5.73	9.76	8.23	7.34	4.66	6.74	5.76	4.43	<50	<50
11	Chloride	147.63	86.68	103.87	146.85	25.7	56.33	103.5	50.67	112.7	127.9	145.4	53.22	<250	<250
12	Bicarbonate	103.36	88.8	84.22	121.58	112.02	238.7	123.5	98.2	83.9	89.8	93.7	66.7	NS	NS
13	Iron	0.22	0.46	0.42	0.19	0.44	0.32	0.29	0.3	0.42	0.53	0.31	0.44	<0.3	<0.3
14	Nickel	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	<0.02	<0.02
15	Cadmium	0.001	0.0001	0.0001	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	<0.003	
16	Copper	BDL	0.32	0.65	0.32	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	<1.0	<1.0
17	Potassium	5.03	6.21	4.74	7.73	6.22	6.65	5.34	6.33	3.23	2.43	3.67	3.44	NS	<12
18	Lead	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	BDL	<0.01	<0.01
19	BOD	5.12	1.43	0.87	6.22	2.7	2.91	3.24	1.23	0.65	1.72	4.67	0.23	NS	NS
20	COD	10.3	2.5	1.72	13	6.3	3.3	5.93	3.22	1.12	3.44	9.98	2.23	NS	<10
â€	SAR	21.38	2.6	1.69	26.38	6.71	6.64	11.49	4.84	1.39	3.93	15.56	1.53	<10	NS

All parameters are in mg/L except Temp-^{o}C and Electrical Conductivity (EC)- µS/cm

Table 2 shows the hydrochemical characteristics of groundwater samples indicate direct geochemical interpretation of contamination of the coastal environment. The analyzed parameters show that the groundwater chemistry is dominated by high ionic concentrations typical for saline or under the influence of contamination sudden mineralized water conditions, electrical conductivity and total dissolved solids are more in line with conditions of the mineralized water than pure fresh water. The relative abundance of major cations and anions is indicated in active water sediment interaction among unconsolidated coastal sediments and indicates more influx of saline and anthropogenic influences. Elevated chloride concentrations with respect to bicarbonate are certainly notable, being indicative of marine- or saline contaminating processes with water, rather than only meteoric recharge, whilst equivalent sodium enrichment is indicative of ion exchange processes, commonly found in coastal aquifer system cases of contamination or salinization. The pH values for Table 2 range from slightly acidic to near-neutral, which is in the general range of water which has passed through clayey and silty coastal deposits and agrees with the geoelectrical identification of conductive horizons interpreted as contamination or saline fronts. One can see the presence and relative calcium and magnesium content is also providing evidence for dissolution of sedimentary material and the possible mixing of fresh and salty water, which further supports the interpretation of a disturbed hydrochemical regime. Where nitrate and sulphate are elevated, their occurrence is consistent with surface derived sources of contamination such as domestic waste, agricultural runoff or lagoonal backflow, which are common in low lying coastal communities of the ground water is affected by contamination or saline intrusion. Table 2 confirms the fact that the quality of ground water in the study area is highly affected by the coastal processes and contamination pathways, thus confirming that saline intrusion and anthropogenic contamination is a major threat to ground water sustainability in the area.

The spatial distribution of groundwater salinity across the study area reveals a markedly heterogeneous contamination regime, with discrete thermal like hotspots of extreme ionic enrichment that substantially transgress the Nigerian Standard for Drinking Water Quality (NSDWQ, 2007) threshold of <500 mg/L. The most pronounced salinity anomalies are concentrated at Tema (Well 2: 3,810 mg/L), Sama (BH1: 3,310 mg/L), and Ido (BH6: 2,712 mg/L), which collectively define a bifocal plume architecture exceeding the regulatory limit by factors of 5.4 to 7.6 (Figure 2). These extreme values are diagnostic of active saltwater intrusion or anthropogenic saline loading, consistent with regional findings that coastal aquifers of the Niger Delta Benin Formation exhibit low longitudinal conductance and high vulnerability to salinization due to permeable overburden and proximity to marine interfaces (Nkpoidet *et al*., 2025). By contrast, samples from Sama (BH2: 40 mg/L; Well 1: 114 mg/L), Tema (BH3: 50 mg/L), and Buguma (BH5: 50 mg/L) register salinity well within the NSDWQ potable envelope, underscoring extreme spatial heterogeneity at the intra community scale (Table 2 and 3).

The spatial gradient manifests a distinct NW-SE vector of increasing salinity, with the highest conductometric signatures clustering around low-elevation coastal settlements (Buguma and Ido at 0 m elevation) and extending inland toward Tema and Sama. This topographically controlled distribution corroborates time-lapse electrical resistivity investigations that document active lateral salinity changes rapidly intruding freshwater aquifers in southeastern Niger Delta coastal environments (Inim *et al*., 2020). Notably, the elevated salinity values coincide with high electrical conductivity and total dissolved solids, forming a coherent hydrochemical facies indicative of Na-Cl dominance driven by seawater mixing or evaporite dissolution (Omajene *et al*., 2024). The NSDWQ (2007) threshold, although not exceeded in all sampling points, is breached at four distinct locations, signifying that approximately one third of the monitored aquifer units are already compromised. The concentration map thus captures a transitional hydrogeological state wherein fragmented freshwater lenses are progressively assimilated by encroaching conductive fronts, necessitating immediate aquifer vulnerability assessment and regulated extraction to avert total potable collapse (Nkpoidet *et al*., 2025).

Table 3: Key Observations from the Map

Zone	**Salinity Range**	**Status**
Tema (Well 2)	~3,810 mg/L	Severely contaminated — exceeds NSDWQ limit by 7×
Sama (BH1)	~3,310 mg/L	Severely contaminated — exceeds NSDWQ limit by 6.6×
Ido (BH6)	~2,712 mg/L	Highly contaminated— exceeds NSDWQ limit by 5.4×
Abalama (BH4)	~556 mg/L	Marginally above NSDWQ (<500 mg/L)
Obuama, Buguma, Abalama (Well)	<300 mg/L	Within acceptable range
Sama (BH2, Well 1), Tema (BH3)	40–114 mg/L	Pristine/fresh

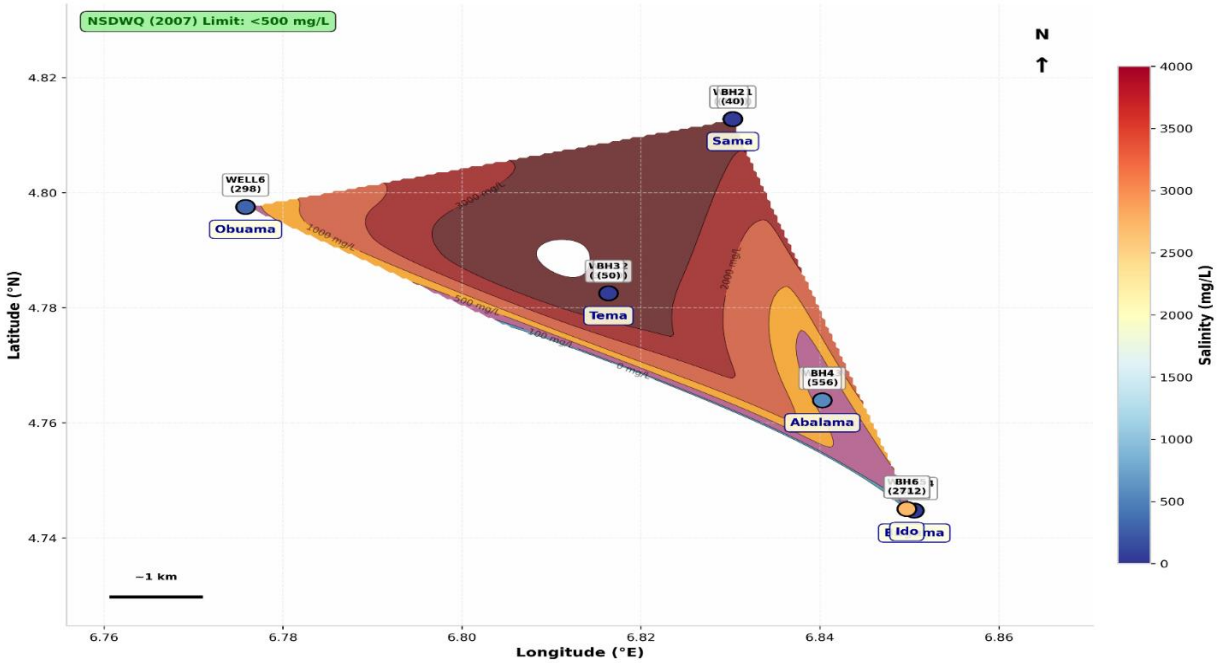


Figure 2: Spatial distribution of Groundwater Salinity Concentration Map

The spatial distribution of hydrochemical parameters across the study area reveals a tripartite zonation reflecting differential contamination vectors and aquifer vulnerability within the Niger Delta Benin Formation (Figure 3). The Northwest cluster (Obuama) registers consistently moderate signatures, with Well 6 exhibiting electrical conductivity (596 µS/cm), total dissolved solids (296 mg/L), and salinity (298 mg/L) within or marginally approaching potable thresholds, alongside a low sodium adsorption ratio (SAR = 1.53), indicating minimal sodium hazard. This cluster represents the least compromised hydrogeological regime, likely benefiting from greater topographic elevation (10 m) and distance from saline intrusion fronts.

The Central cluster (Tema-Abalama) manifests extreme spatial bifurcation, a hallmark of point-source contamination superimposed on regional salinization. Tema Well 2 registers the most severe deterioration across all parameters (EC 7,490 µS/cm; TDS 3,750 mg/L; salinity 3,810 mg/L; Na^+ 365 mg/L; SAR 26.38), exceeding NSDWQ (2007) limits by an order of magnitude, whereas adjacent BH3 maintains pristine conditions (EC 529 µS/cm; TDS 50 mg/L). This intra community disparity is consistent with hydrochemical investigations documenting that Na-Cl facies in the Niger Delta arise from both saltwater intrusion and anthropogenic effluent discharge, with spatial heterogeneity driven by preferential flow pathways and differential aquifer confinement (Odesa 2024). Abalama exhibits intermediate degradation (BH4: EC 1,120 µS/cm; salinity 556 mg/L), suggesting progressive plume encroachment (Table 3).

The Southeast cluster (Buguma-Ido) at 0 m elevation demonstrates coastal aquifer vulnerability, with Ido BH6 registering elevated TDS (2,733 mg/L), salinity (2,712 mg/L), and SAR (15.56), indicative of density-driven saltwater intrusion. Buguma remains comparatively moderate, though BH5 exhibits anomalous EC (985.8 µS/cm) despite low TDS, possibly reflecting conductive ionic species from surficial contamination. The collective spatial gradient intensifying from northwest to southeast corroborates regional models attributing coastal groundwater degradation to marine intrusion exacerbated by low topographic relief and excessive extraction (Hagage *et al*., 2024). The tripartite zonation thus captures a continuum from relatively protected inland reserves to actively salinizing coastal aquifers.

The spatial distribution of the Irrigation Water Quality Index (IWQI) across the study area delineates a pronounced hydrogeochemical mosaic, reflecting differential aquifer vulnerability and anthropogenic loading within the Niger Delta coastal Formation. The severely compromised zones are concentrated at Tema (Well 2: IWQI 38.0 Very Poor) and Sama (BH1: IWQI 45.4 Poor), where extreme electrical conductivity (>6,500 µS/cm) and sodium adsorption ratios exceeding 20 collectively indicate acute salinity and sodium hazards (Figure 4). These parameters exceed the critical thresholds where SAR >10 and EC >3,000 µS/cm trigger severe soil permeability degradation and osmotic stress, rendering the water unsuitable for most crop types

(Agidi *et al.*, 2026). The elevated Na^+ percentages (>94%) at these points suggest reverse ion exchange processes, wherein sodium displaces calcium and magnesium on clay matrices, a phenomenon well documented in coastal aquifers subjected to saltwater intrusion and anthropogenic effluent discharge (Egbueri *et al.*, 2025). Conversely, pristine zones are identified at Sama (BH2: IWQI 90.4; Well 1: IWQI 88.6) and Obuama (Well 6: IWQI 87.8), all classified as Excellent. These samples register SAR values <3, EC <250 µS/cm, and Na% <70, satisfying the stringent criteria for unrestricted irrigation use where water can be applied to sensitive crops without soil structural deterioration. (Meireles *et al.*, 2024). The spatial gradient manifests a northwest to southeast deterioration vector, with inland elevated communities (Sama at 20 m, Obuama at 10 m) maintaining superior quality, while coastal low-elevation towns (Buguma, Ido at 0 m) exhibit intermediate to fair classifications. This pattern corroborates regional hydrogeochemical models attributing coastal groundwater degradation to marine intrusion exacerbated by topographic relief and excessive extraction. (Sylvester, 2023).

Most critically, intra community disparity is starkly evident within Sama, where BH1 (Poor) and BH2 (Excellent) exhibit a 45point IWQI differential over minimal spatial separation. This bifurcation indicates highl contamination vectors likely artisanal drilling conduits or fracture driven preferential flow rather than diffuse regional salinization, necessitating borehole specific remediation strategies rather than blanket administrative interventions.

The geospatial distribution of sodium and chloride across the six coastal communities delineates a salinization gradient that is strongly conditioned by proximity to tidal conduits and shoreline position. Sodium concentrations exceed the NSDWQ (2007) permissible limit of 200 mg/L at BH1 (Sama, 242.7 mg/L), BH2 (Tema, 365 mg/L) and Well 6 (Ido, 232 mg/L), with the two former sites occupying the western, ocean-facing and river-channel axis through which Atlantic water propagates during tidal flooding. This spatial correspondence is consistent with the landward salt influx mechanism documented for the Niger Delta by Abam (2001) and empirically imaged at Okrika and Bonny by Abija *et al.*, (2021) and Udota *et al.*, (2022). Chloride, although below the 250 mg/L threshold at all stations, exhibits a coherent eastward elevating band (112-148 mg/L) tracking the tidal creek system, while the most inland station (Obuama) records the lowest values a distance decay pattern diagnostic of marine influence.

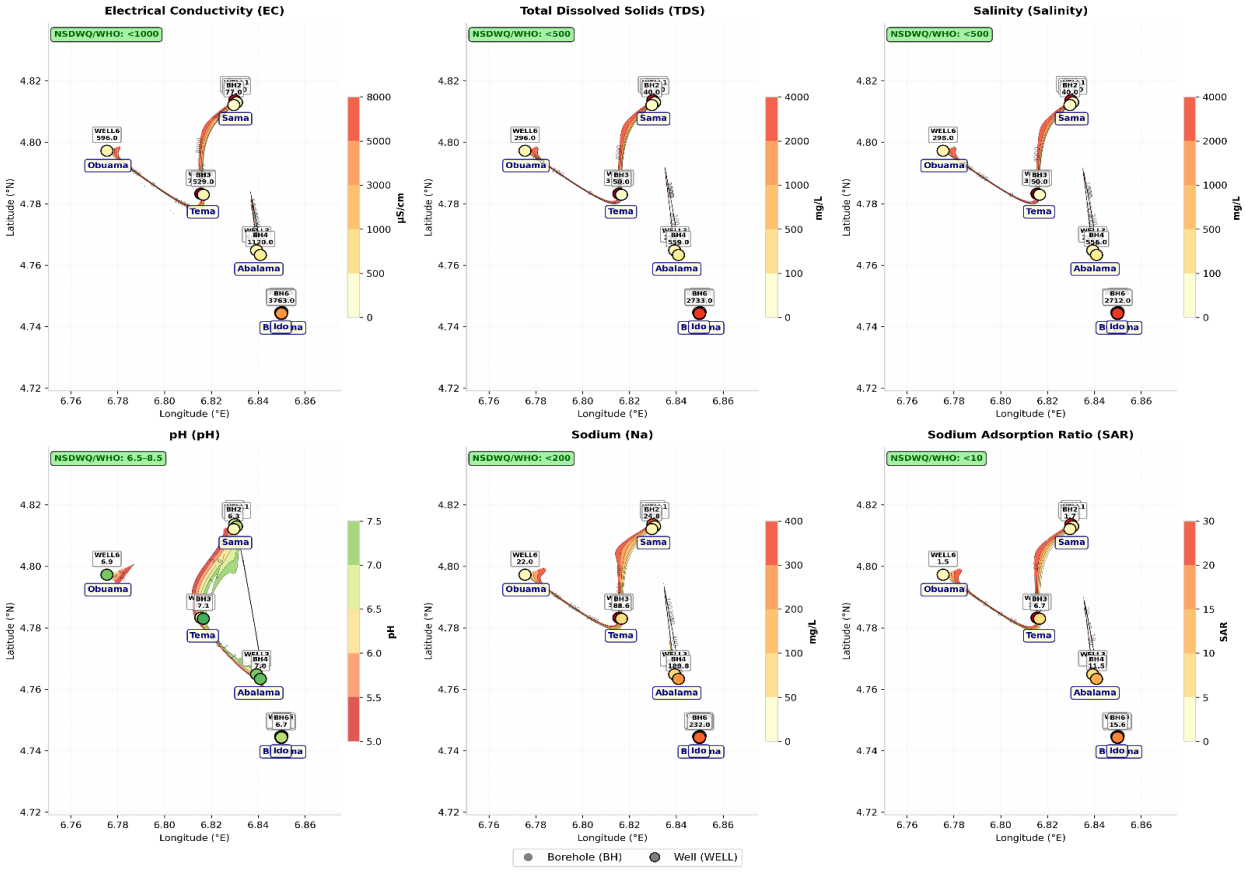


Figure 3: Comprehensive Spatial Distribution Map **of hydrochemical parameters across the study area**

Table 3: Spatial interpolation of critical hydrochemical parameters

Panel	Parameter	NSDWQ/WHO Threshold	Key Observations
(a)	Electrical Conductivity (EC)	<1000 µS/cm	Extreme hotspots at Tema Well 2 (7,490) and Sama BH1 (6,530), indicating severe ionic enrichment
(b)	Total Dissolved Solids (TDS)	<500 mg/L	Sama BH1 (3,270, Tema Well 2 (3,750), and Ido BH6 (2,733) exceed limits by 5–7.5
(c)	Salinity	<500 mg/L	Same hotspots as TDS; Buguma BH5 (50) and Sama BH2 (40) remain pristine
(d)	pH	6.5–8.5	Buguma BH5 (5.37) is strongly acidic; most other samples fall within acceptable range
(e)	Sodium (Na^+)	<200 mg/L	Tema Well 2 (365) and Sama BH1 (242.7) breach the threshold, consistent with Na-Cl facies
(f)	Sodium Adsorption Ratio (SAR)	<10	Sama BH1 (21.38 Tema Well 2 (26.38), and Ido BH6 (15.56) indicate high sodium hazard for irrigation

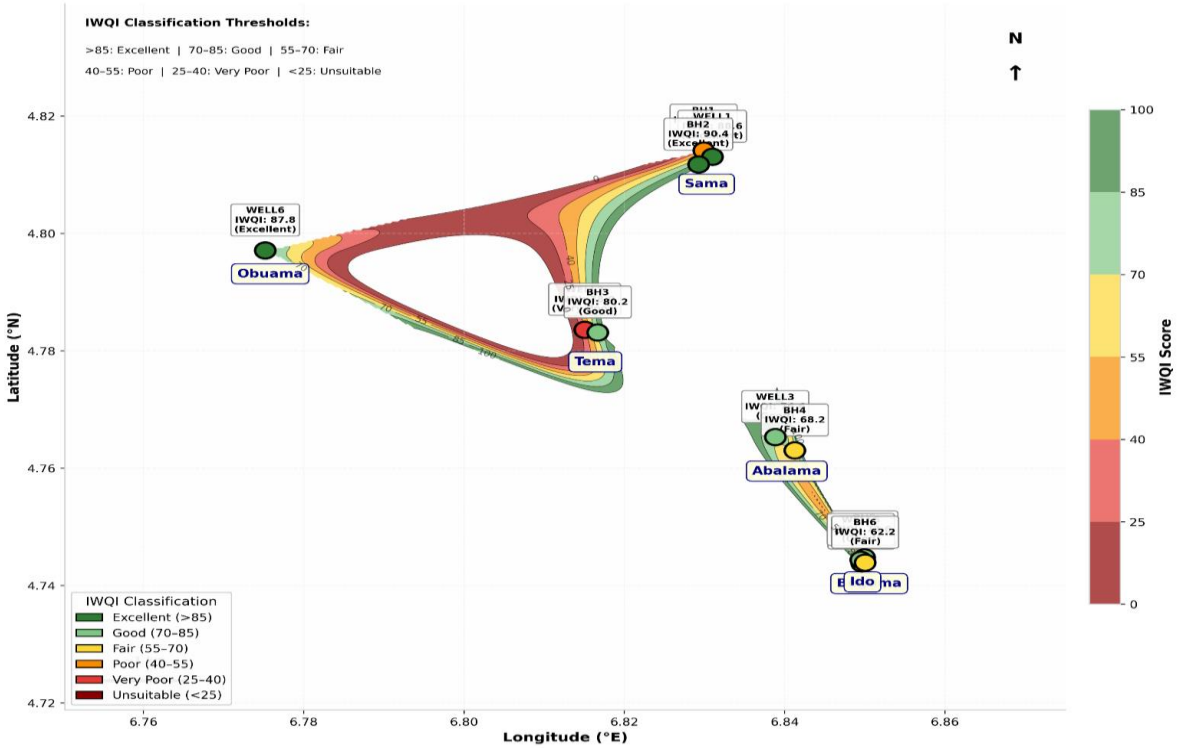


Figure 4: Spatial Distribution Map of Irrigation Water Quality Index (IWQI)

Critically, the decoupled high-chloride/low-sodium signature at BH4 (Buguma; Cl = 112.7 mg/L, Na = 20.5 mg/L) departs from the coupled Na-Cl enrichment expected of seawater mixing (Na^+/Cl^- ≈ 0.86), implying a non-marine chloride source such as connate brackish water, mineral leaching, or anthropogenic input (Giadom *et al.*, 2022). The anomously high sodium at Well 6 relatives to its paired borehole (BH5) further suggests localized well specific contamination rather than regional intrusion. Collectively, the dataset indicates spatially heterogeneous salinization in which active tidal intrusion, paleo-saline beds and point source pollution interact, underscoring the necessity of ionic ratio and isotopic verification before ascribing salinity to seawater intrusion alone (Figure 5).

Geochemical Interpretation of Saltwater Intrusion

Chloride is the dominant ion in seawater and it is only available in small quantities in groundwater. While Bicarbonate which is available in large quantities in groundwater occurs only in very small quantities in seawater (Raghunath, 1990). It has been found that a chloride/bicarbonate ratio greater than 2 is indicative of saltwater intrusion (Revelle, 1941).

The following equation is used to evaluate the degree of salinization:

x/35.46 > 2 indicates intrusion

y/61.02
Where x is chloride concentration in mg/l
y is bicarbonate concentration in mg/l
35.46 molecular mass of chlorine
61.02 molecular mass of bicarbonate

From Figure 6-8, delineates the spatial distribution of electrical conductivity (EC) across Sama, Tema, Abalama, Buguma, Ido and Obuama, using 1000 µS/cm as the threshold separating freshwater from saline-influenced groundwater (Standard Organisation of Nigeria, 2015). Sama and Tema plot within the saline domain, with EC values reaching 6530 and 7490 µS/cm respectively, indicating pronounced marine influence consistent with seawater intrusion (Werner, 2013). Paired boreholes and wells at these locations differ markedly, for instance Tema, where values range from 77 to 7490 µS/cm, signifying vertical heterogeneity in salinity within the aquifer (Todd and Mays, 2005). Abalama records 428 and 1120 µS/cm, placing it near the provisional transition line, whereas the Ido and Buguma cluster, close to 988.8 µS/cm, straddles the boundary. Obuama, positioned westward, remains below the threshold. Collectively, the pattern shows that salinity is controlled by proximity to saline sources and local hydrogeological conditions rather than by simple lateral gradients across the delta (Appelo and Postma, 2005).

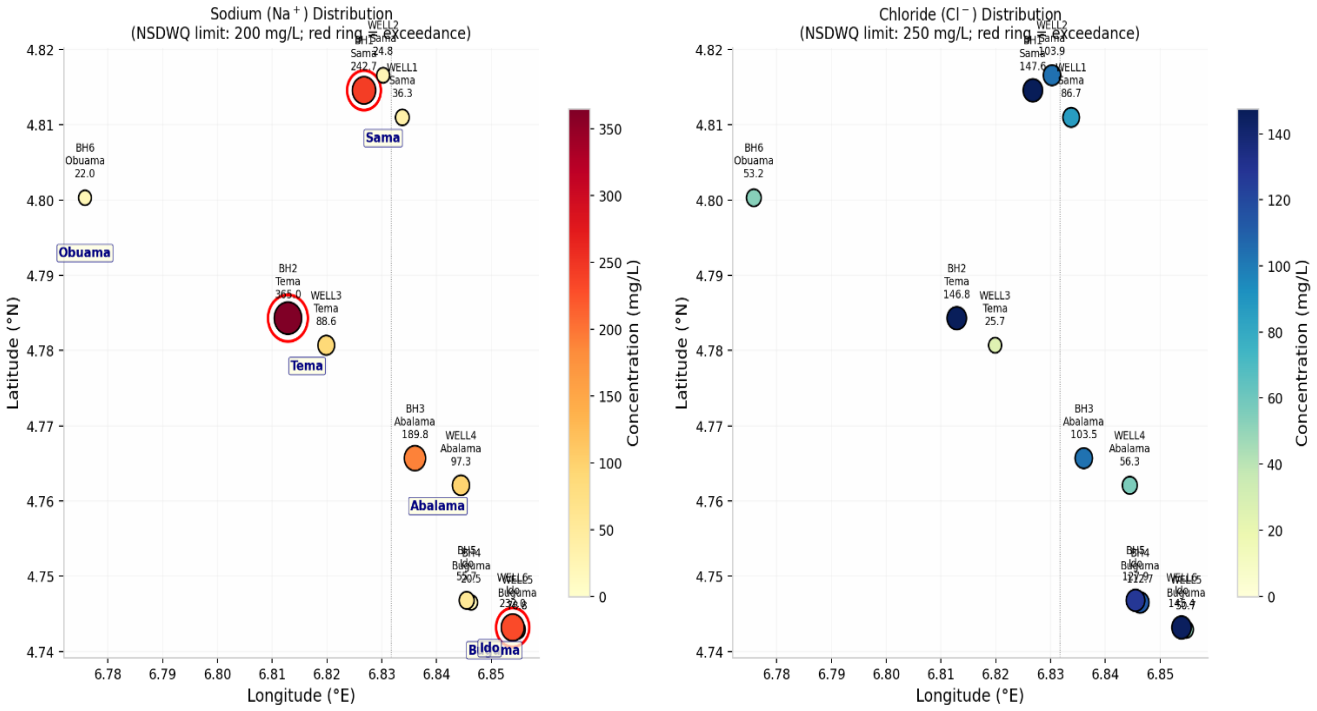


Figure 5: Geospatial distribution of sodium and Chlorine

Table 4: Showing location of monitoring wells, Chloride/Bicarbonate Ratio and Distance from Shoreline

Site	Chloride mgL	Bicarbonate mgL	Cl-HCO3ratio	Distance from Obuama km
Sama BH1	147.63	103.36	1.428	6.274
Sama Well 1	86.68	88.8	0.976	6.274
Sama BH2	103.87	84.22	1.233	6.274
Tema Well 2	146.85	121.58	1.208	4.799
Tema BH3	25.7	112.02	0.229	4.799
Abalama Well 3	56.33	238.7	0.236	8.069
Abalama BH4	103.5	123.5	0.838	8.069
Buguma Well 4	50.67	98.2	0.516	10.16
Buguma BH5	112.7	83.9	1.343	10.16
Ido Well 5	127.9	89.8	1.424	10.067
Ido BH6	145.4	93.7	1.552	10.067
Obuama	53.22	66.7	0.798	0

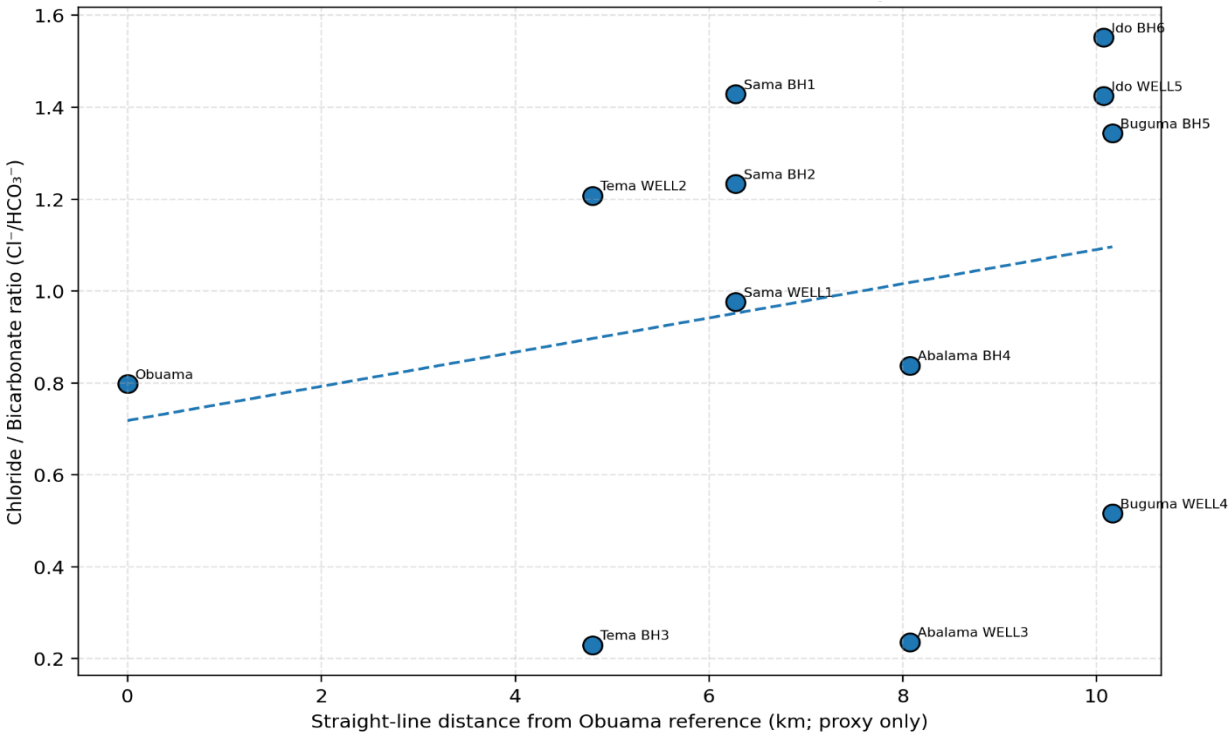


Figure 6 Shows decreasing Chloride-Bicarbonate ratio with increasing distance from shoreline indicating high salinization near the shore.

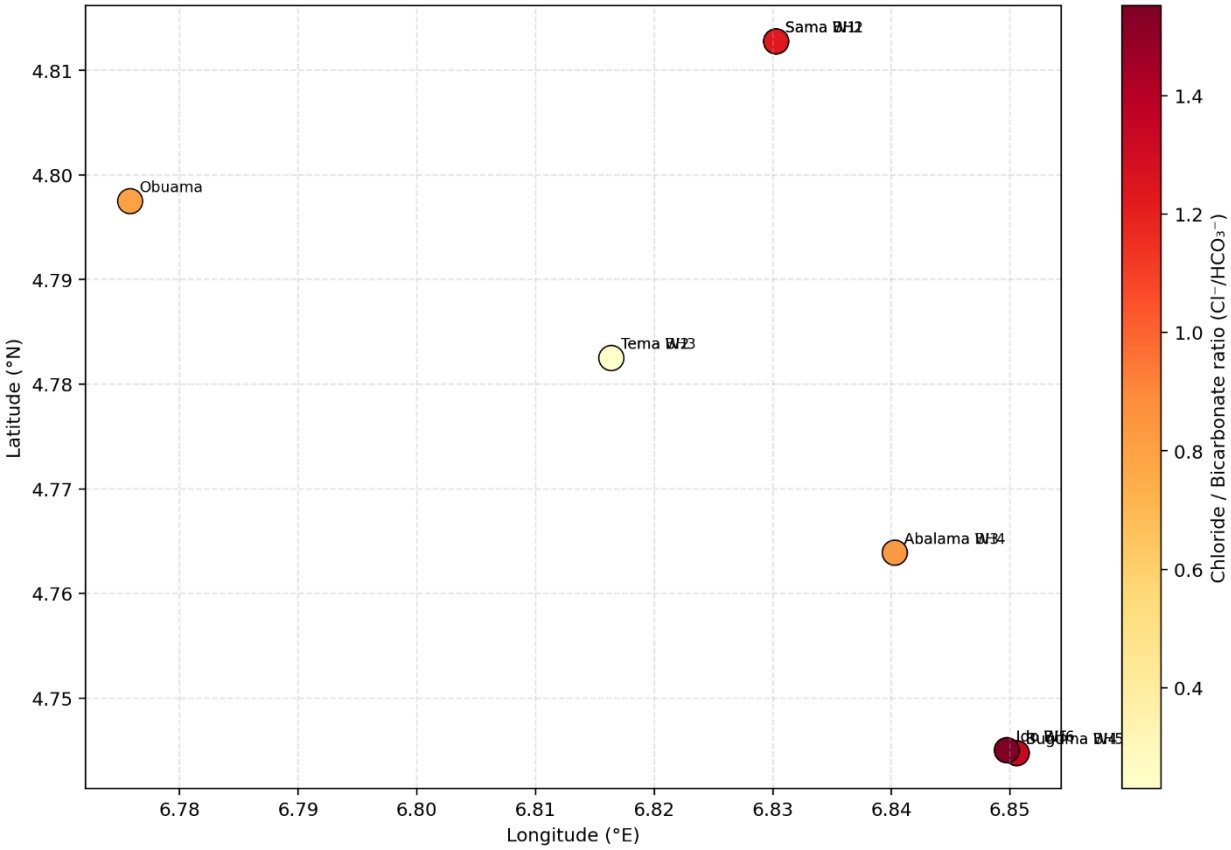


Figure 7: Spatial distribution of Chloride-Biocarbonate Ratio hydrochemical salinization indicator

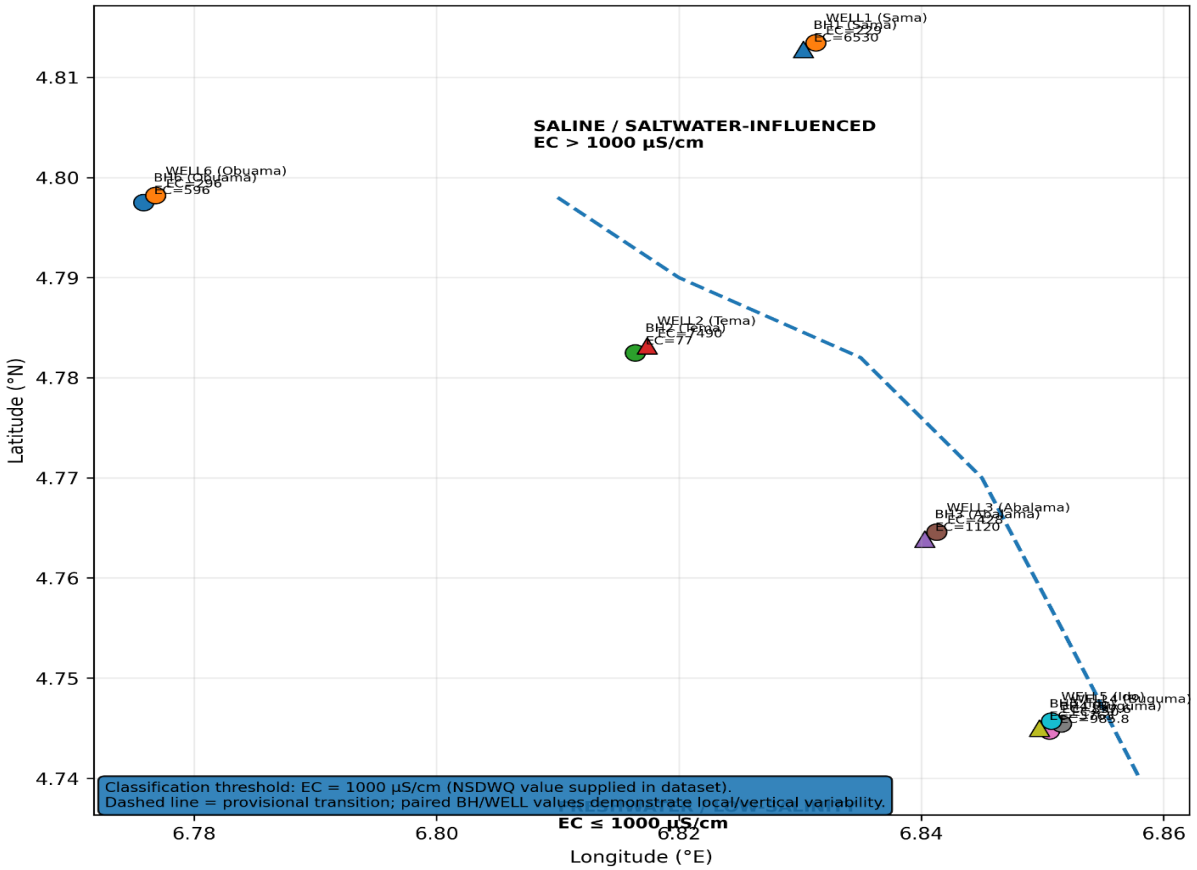


Figure 7: freshwater-saltwater/saline influence boundary map

Irrigation Suitability

Sama BH1 is a typical Na-Cl water with a very high salinity hazard and an extreme sodium adsorption ratio (SAR) of 21.4. This combination renders it unsuitable for irrigation, since excess sodium displaces calcium and magnesium on soil exchange sites, degrading soil structure, while elevated salinity imposes osmotic stress on crops (Richards, 1954; Ayers and Westcot, 1985). Sama Well 1 is also Na-Cl but considerably less hazardous, with low salinity and an SAR of 2.59. However, its high magnesium hazard (74.1%) may promote soil hardening and reduced productivity (Szabolcs and Darab, 1964).

Tema BH2 shares the Na-Cl facies, with low salinity hazard and an SAR of 1.69, although a magnesium hazard above 50% warrants caution. In contrast, Tema Well 2 exhibits very high salinity hazard and an SAR of 26.4, indicating a pronounced sodium hazard and unsuitability for most crops. Abalama BH3 and Well 3, both Na-HCO_3 types, show medium salinity hazard and SAR values of about 6.7. They are therefore borderline, because bicarbonate dominance favours the precipitation of calcium and magnesium carbonates, leaving sodium proportionally more active in the soil solution (Appelo and Postma, 2005). The magnesium hazard of Abalama Well 3 (87.5%) is especially problematic. Buguma BH4 (Na-Cl) combines high salinity hazard with an SAR of 11.5, making it unsuitable for salt-sensitive crops, whereas Buguma Well 4 (Na-SO_4) is milder, with medium salinity hazard and an SAR of 4.84, though its magnesium hazard remains above 50%. Ido BH5 and Well 5 are both Na-Cl waters with high salinity hazard. Their SAR values are low (1.39 and 3.92), but magnesium hazards exceeding 58% sustain the risk of soil alkalinity (Raghunath, 1987). Obuama BH6 is strongly saline, with very high salinity hazard, an SAR of 15.6 and a magnesium hazard of 71.6%, characteristic of brackish water unfit for irrigation. Obuama Well 4 (Na-SO_4) is comparatively moderate, with medium salinity hazard, an SAR of 1.52 and a magnesium hazard below 50%, and is thus relatively safer. Basically, Sama BH1, Tema Well 2 and Obuama BH6 are unsuitable for irrigation because of very high salinity and sodium hazards. The Abalama sources fall in the medium class but are compromised by magnesium hazard, while Buguma and Ido waters pose high hazards and require careful management. Only Sama Well 1, Tema BH2 and Obuama Well 4 show potential for limited irrigation, subject to magnesium related constraints (Ayers and Westcot, 1985).

Hydrochemical Assessment

Evaluation of groundwater chemistry against the WHO (2022) guideline values reveals varying degrees of compliance and exceedance, reflecting the influence of coastal contamination processes. Cadmium, nickel and lead were assessed as priority toxic trace metals because of their public health significance. Where concentrations exceed permissible limits, they suggest anthropogenic inputs such as waste disposal, corrosion of plumbing materials, or salinity driven mobilization from aquifer matrices (Hem, 1985). Even marginal exceedances are of concern because these metals bioaccumulate and pose long-term health risks (WHO, 2022). Magnesium and calcium concentrations generally reflect aquifer mineralogy and water rock interaction. Elevated values indicate prolonged residence time and enhanced dissolution of carbonate and silicate minerals, often intensified by saline mixing (Appelo and Postma, 2005). Potassium normally occurs at low concentrations in natural groundwater; elevated levels therefore point to domestic effluents or agricultural inputs rather than geogenic sources (Hem, 1985). Sodium is a key indicator of coastal contamination. Concentrations approaching or exceeding the WHO (2022) limit of 200 mg/l strongly suggest saline intrusion or cation exchange, in which sodium displaces calcium and magnesium on clay mineral surfaces (Werner 2013). This trend agrees with the dominance of Na-Cl facies in the hydrochemical diagrams.

Finally, pH values largely within the WHO (2022) range indicate near neutral conditions, although slight deviations reflect geochemical reactions such as ion exchange and saline mixing. Electrical conductivity values exceeding recommended limits confirm elevated ionic strength, consistent with saline contamination and supported by the prevalence of sodium and chloride across the study area (Todd and Mays, 2005).

Conclusion

This study has established that groundwater resources within Sama, Tema, Abalama, Buguma, Ido and Obuama communities of Rivers State exhibit considerable hydrochemical variability, reflecting the combined influences of saltwater intrusion, lithological interactions and anthropogenic contamination. The observed electrical conductivity values (77-7,490 µS/cm), total dissolved solids (40-3,750 mg/L) and salinity concentrations demonstrate pronounced spatial heterogeneity in aquifer conditions. Tema, Sama and Ido emerged as the most significantly affected locations, with salinity levels substantially exceeding recommended drinking-water standards, thereby indicating potential deterioration of groundwater quality. Furthermore, elevated sodium concentrations and sodium adsorption ratios at selected sampling points underscore the associated limitations for agricultural utilization. The chloride-bicarbonate ratios provide additional evidence of variable saline influence, although their values suggest that saltwater intrusion cannot be regarded as the sole determinant of groundwater mineralization. The spatial distribution of hydrochemical parameters further demonstrates that localized aquifer characteristics and preferential contaminant migration pathways influence groundwater vulnerability. Consequently, sustainable groundwater management requires systematic hydrochemical surveillance, controlled abstraction, improved waste disposal practices and periodic assessment of coastal aquifer conditions. Ultimately, integrating hydrochemical investigations with geophysical monitoring is essential for identifying saline interfaces, protecting vulnerable freshwater reserves and ensuring the long-term availability of safe groundwater throughout the coastal Niger Delta.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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