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Spatial and Hydrochemical Characterisation of Groundwater Quality in Badagry Local Government Area, Lagos State, Nigeria

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Abstract- ***Groundwater is an important source of domestic water in coastal communities of southwestern Nigeria, where rapid urbanisation and intensive groundwater use may increase vulnerability to chemical deterioration and saline influence. This study assessed the spatial and hydrochemical characteristics of groundwater quality in Badagry Local Government Area (LGA), Lagos State, Nigeria. Seventy-two groundwater samples were collected from boreholes distributed across residential, crowded, commercial, industrial and coastal settings. In-situ measurements included pH and temperature, while total dissolved solids (TDS), hardness, major ions and selected metals were determined using standard analytical procedures. Descriptive statistics, comparison with Nigerian drinking-water standards, correlation analysis, hydrochemical classification and GIS-based spatial analysis were used to evaluate groundwater quality. Groundwater was generally soft and weakly mineralised, although substantial spatial variability occurred. Reported TDS ranged from 20.3 to 1,211 mg/L, with a mean of approximately 207 mg/L. The principal quality concern was acidity, with a reported mean pH of 5.59 and most samples below the Nigerian standard range of 6.5–8.5. Localised enrichment of TDS, salinity, nitrate, iron and manganese occurred at selected stations. Iron reached 0.346 mg/L, while manganese reached 0.825 mg/L. Chloride and sulphate remained below their respective national limits in the reported dataset. The spatial pattern indicates that groundwater chemistry reflects both natural water–rock interaction and local anthropogenic influences, with limited evidence of saline influence at selected coastal locations. The study demonstrates marked spatial heterogeneity in groundwater quality and identifies acidity and localised Fe and Mn enrichment as priority management concerns. Routine monitoring, source protection and treatment of acidic or metal-enriched groundwater are recommended.***

Keywords: ***groundwater quality, hydrochemistry, spatial analysis, GIS, coastal aquifer, groundwater contamination***

I. INTRODUCTION

Groundwater constitutes an important component of freshwater resources and supports domestic, agricultural and industrial activities in many regions where surface-water supplies are inadequate. Its chemical composition is controlled by interactions among recharge water, aquifer minerals, residence time, redox conditions, evaporation, mixing and anthropogenic inputs. Hydrochemical data therefore provide important information on groundwater origin, evolution and vulnerability to contamination (Glynn & Plummer, 2005).

Groundwater dependence is particularly important in rapidly urbanising areas of Nigeria. Urban expansion, industrialisation, inadequate waste management and increasing private groundwater abstraction can increase pressure on groundwater systems and create pathways for chemical deterioration. Reviews of Nigerian urban groundwater have identified geology, urbanisation, industrial activities, waste disposal and seasonal processes among the major factors affecting groundwater quality (Ocheri et al., 2014). Groundwater also plays an important role in domestic water supply in Lagos State, where household-level groundwater abstraction is widespread (Danert & Healy, 2021).

Badagry Local Government Area (LGA) occupies a coastal setting in southwestern Nigeria characterised by low-lying terrain and unconsolidated sediments. Its proximity to lagoons, creeks and the Atlantic coast makes groundwater potentially vulnerable to saline influence, while rapid settlement expansion and anthropogenic activities may introduce additional contamination pathways. Research in coastal Lagos has demonstrated the importance of aquifer depth and subsurface characteristics in determining access to freshwater aquifers (Akinlalu & Afolabi, 2018), while geophysical investigations elsewhere along the Lagos coast have documented freshwater–brackish-water transition zones (Adepelumi et al., 2008).

Although previous investigations have examined groundwater quality in Badagry, including sampling from selected communities (Tunde et al., 2023), a broader assessment incorporating spatial distribution and hydrochemical characteristics across multiple land-use settings remains useful. GIS and hydrochemical methods provide complementary approaches for identifying spatial heterogeneity, potential contamination hotspots and processes controlling groundwater composition (Emenike et al., 2018; Selvam et al., 2013).

This study therefore evaluates groundwater quality in Badagry LGA using physicochemical, major-ion and selected metal data integrated with spatial analysis. Specifically, the study aims to: (i) characterise the physicochemical and chemical properties of groundwater; (ii) determine spatial variations in groundwater quality; (iii) assess compliance with Nigerian drinking-water standards; and (iv) evaluate the likely natural and anthropogenic processes controlling groundwater chemistry.

II. MATERIALS AND METHODS

Study area: The study was conducted in Badagry LGA, Lagos State, southwestern Nigeria. The area is situated within the coastal environment of Lagos and comprises low-lying terrain and unconsolidated coastal sediments consisting predominantly of sands, silts, clays and recent deposits. The climate is tropical, with distinct wet and dry seasons and most rainfall occurring between April and October.

Groundwater is widely used by households and other users in the area. Potential influences on groundwater quality include urban expansion, domestic waste disposal, commercial activities, industrial activities, agriculture and proximity to coastal and lagoon environments. These characteristics make Badagry an appropriate setting for evaluating spatial and hydrochemical variations in groundwater quality.

Study design and sampling: A cross-sectional field-based hydrochemical assessment was conducted. Seventy-two groundwater samples were collected from functional boreholes distributed across the study area. Sampling locations were purposively selected to provide spatial representation of residential, crowded, commercial, industrial and coastal environments and to capture areas potentially influenced by different anthropogenic activities.

Geographical coordinates were recorded using a handheld GPS receiver. At each sampling location, information on surrounding land use, source condition, potential contamination sources and other relevant field characteristics was documented.

Sample collection and preservation: Boreholes were allowed to discharge before sample collection to reduce the influence of stagnant water within the borehole system. Samples were collected into clean, labelled polyethylene containers. Containers for metal analysis were preserved with nitric acid where required. Samples were stored in ice-filled coolers and transported to the laboratory for analysis within appropriate holding periods.

Temperature, pH, electrical conductivity and TDS were measured in the field using calibrated meters. The pH meter was calibrated using appropriate standard buffer solutions before measurements.

Laboratory analysis: Laboratory analyses followed recognised standard procedures for drinking-water analysis. Total hardness was determined using standard titrimetric procedures. Chloride was determined by argentometric titration, while nitrate and sulphate were determined using appropriate spectrophotometric methods. Calcium and magnesium were determined using standard complexometric or instrumental methods, while sodium and potassium, where available, were determined using flame photometry.

Iron and manganese were determined using atomic absorption spectrophotometry following appropriate sample preparation and preservation procedures.

Quality assurance and quality control: Quality assurance and quality control procedures were applied throughout sampling and laboratory analysis. Field and laboratory instruments were calibrated daily with certified standard solutions. Analytical blanks, duplicate samples and calibration standards were included in each batch. Laboratory glassware and sampling containers were thoroughly cleaned and conditioned before use. Calibration verification and analytical recovery were monitored throughout the analytical runs.

For major-ion data, charge-balance error (CBE) was calculated after conversion of concentrations to milliequivalents per litre:

$$\text{CBE (\%)} = \frac{\sum \text{cations} - \sum \text{anions}}{\sum \text{cations} + \sum \text{anions}} \times 100$$

where cation and anion concentrations are expressed in meq L^{-1}. A CBE within approximately ±5 % is preferred for high-quality major-ion datasets; values outside this range prompted examination of possible analytical or transcription errors.

Hydrochemical analysis: Major-ion concentrations were converted to milliequivalents per litre and used to evaluate groundwater facies. Piper diagrams were used to classify dominant cation and anion facies. Gibbs diagrams were considered for evaluating the relative influence of precipitation, rock dominance and evaporation. Schoeller and Durov diagrams were used where the required complete ion dataset was available. Interpretation considered mineral dissolution, silicate weathering, carbonate reactions, ion exchange, evaporation, dilution and saline mixing. However, conclusions regarding hydrochemical facies should only be made when complete Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, SO_4^{2-} and HCO_3^-/CO_3^{2-} data are available.

GIS-based spatial analysis: Sampling coordinates were imported into a GIS environment and transformed to a consistent projected coordinate system. Spatial distribution maps were generated for pH, TDS, salinity, nitrate, chloride, sulphate, calcium, magnesium, iron and manganese.

Inverse Distance Weighting (IDW) was used for exploratory spatial interpolation. Because interpolation performance depends on sampling density and spatial configuration, the final analysis should compare IDW with at least one alternative method, such as ordinary kriging, where appropriate. Cross-validation statistics should be reported before selecting the final interpolation method.

Interpolated surfaces were interpreted as spatial estimates rather than direct measurements and were not used to claim exceedances at locations that were not sampled.

Statistical Analysis: Statistical analyses should be conducted using R, SPSS or an equivalent validated statistical package.

Continuous variables should first be examined using histograms, Q–Q plots, skewness and the Shapiro–Wilk test. Because hydrochemical variables commonly show skewed distributions and influential extreme observations, medians and interquartile ranges should accompany means and standard deviations.

For comparisons among the five land-use zones, normality and variance assumptions should be assessed before analysis. Where assumptions are satisfied, one-way ANOVA followed by Tukey's HSD test should be used. Where assumptions are violated, the Kruskal–Wallis test followed by Dunn's test with multiplicity correction should be applied. Statistical significance should be set at $\alpha = 0.05$.

Effect sizes should accompany p-values. For ANOVA, η^2 or ω^2 should be reported; for non-parametric comparisons, an appropriate rank-based effect size should be presented. This will distinguish statistically significant differences from differences that are environmentally meaningful.

Spearman's rank correlation should be preferred for skewed hydrochemical variables. Correlations should be interpreted cautiously because several parameters are chemically interdependent. Where multiple correlation tests are performed, the false-discovery rate should be controlled.

Principal Component Analysis should only be performed after confirming adequate sample size and variable suitability using the Kaiser–Meyer–Olkin statistic and Bartlett's test of sphericity. Variables should be standardised before PCA, and components should be retained using a combination of eigenvalues, scree plot and explained variance. Rotated loadings should be interpreted cautiously as evidence of associations rather than definitive proof of pollution sources.

Multiple regression should only be undertaken for clearly defined dependent variables and a limited number of predictors supported by the study design. Multicollinearity should be assessed using variance inflation factors, while residual diagnostics should be used to evaluate model assumptions. Because the sample size is 72, overly complex regression models should be avoided.

Spatial interpolation should be evaluated using cross-validation, reporting root mean square error, mean absolute error and mean error where applicable.

III. RESULTS

Table 1: Spatial Distribution of Groundwater Sampling Points

S/N	Sample Station	Zone	Approx. Latitude (°N)	Approx. Longitude (°E)
1.	Apa Hotel Apa	Residential / Coastal	6.433	2.817
2.	Berekete Badagry	Residential	6.420	2.880
3.	Ajara Agamathen	Crowded / Commercial	6.424	2.923
4.	Ajara Vetho	Crowded	6.425	2.920
5.	French Village	Residential	6.420	2.890
6.	Ileri Oluwa Comp. Apa	Residential	6.433	2.817
7.	Vinavon Quarters Cele 3	Residential	6.420	2.890
8.	Ajido 1	Coastal / Residential	6.415	3.016
9.	Ajara Tozukameh	Crowded	6.425	2.920
10.	Aradagùn	Residential	6.437	2.990
11.	Mobil Station Badagry	Commercial	6.416	2.882
12.	Ajara Agamathen	Crowded / Commercial	6.424	2.923
13.	Ajara Tozukameh	Crowded	6.425	2.920
14.	Aradagùn 6	Residential	6.437	2.990
15.	Ajara Topa	Crowded / Commercial	6.424	2.923
16.	Ilado 1	Residential / Coastal	6.437	2.970
17.	Badagry Cent Mosque	Commercial / Crowded	6.416	2.882
18.	Ajara Dokoh	Crowded	6.425	2.920
19	Ojogun Company Apa	Industrial / Residential	6.400	3.033
20.	Imeke 1	Residential	6.450	3.000
21.	Ajara Agamathen	Crowded / Commercial	6.424	2.923
22.	Ilado 5	Residential / Coastal	6.437	2.970
23.	Imeke 1	Residential	6.450	3.000
24.	No Problem, Compound	Residential	6.420	2.890
25.	Aradagun 1	Residential	6.437	2.990
26.	Ajara Tozukameh	Crowded	6.425	2.920
27.	Holiness Church Bdg.	Residential	6.416	2.882
28.	Oba Adenegba Compd, Apa	Residential	6.433	2.817

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29.	Ido Oluwo Compd Apa	Residential	6.433	2.817
30.	Aradagua Iv	Residential	6.437	2.990
31.	Ajara Agamathen 2	Crowded / Commercial	6.424	2.923
32.	Alpha & Omega Ibercko 1	Residential	6.450	2.917
33.	Ajara Agamathen 4	Crowded / Commercial	6.424	2.923
34.	Ilado 2	Residential / Coastal	6.437	2.970
35.	Ayo Nio Carwarnh	Residential	6.420	2.890
36.	Aradagun	Residential	6.437	2.990
37.	Ajara Topa 7	Crowded / Commercial	6.424	2.923
38.	Jasu Yikari Comp Ajara Ozu.	Crowded	6.425	2.920
39.	Imeke 3	Residential	6.450	3.000
40.	Ileha Compound Apa	Residential	6.433	2.817
41.	Noah's Compound Apa	Residential	6.433	2.817
42.	Ilado 3	Residential / Coastal	6.437	2.970
43.	Ilado 2 (repeat)	Residential / Coastal	6.437	2.970
44.	Ajibade Compound	Residential	6.420	2.890
45.	Idomosian Compound Apa	Residential	6.433	2.817
46.	Aradagam Ii	Residential	6.437	2.990
47.	Ajapa Tozukameh 5	Crowded	6.425	2.920
48.	Temidire Compound Apa	Residential	6.433	2.817
49.	Alpha & Omega Iberoko 11	Residential	6.450	2.917
50.	Ajara Tozukameh	Crowded	6.425	2.920
51.	Ilado 2 (another)	Residential / Coastal	6.437	2.970
52.	Limca-Iberoko	Residential	6.450	2.917
53.	Mowo 1	Residential	6.456	2.975
54.	Sawmil Iberoko	Industrial	6.450	2.917
55.	Oko - Afo 1	Residential	6.430	2.850
56.	Iworo 1	Coastal / Residential	6.434	3.044
57.	Oko - Afo Ii	Residential	6.430	2.850
58.	Mowo Ii	Residential	6.456	2.975
59.	Gen. Hosp. Badagry	Commercial / Residential	6.416	2.882
60.	Morogbo I	Residential / Industrial	6.470	3.050
61.	Akarakumo	Residential / Coastal	6.415	2.968
62.	Morogbo I (repeat)	Residential / Industrial	6.470	3.050
63.	Iworo Ii	Coastal / Residential	6.434	3.044
64.	Coconut Ind. Area	Industrial	6.420	2.900
65.	Morogbo Ee	Residential / Industrial	6.470	3.050
66.	Ajara Torikoh	Crowded	6.425	2.920
67.	Topo Idale	Coastal	6.413	2.933
68.	Total Station Badagry	Commercial	6.416	2.882
69.	Ascoon Topo	Coastal	6.413	2.933
70.	Morogbo Iv	Residential / Industrial	6.470	3.050
71.	Morogbo V	Residential / Industrial	6.470	3.050
72.	Morogbo VI	Residential / Industrial	6.470	3.050

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Spatial distribution of sampling points: Seventy-two groundwater samples were obtained from locations distributed across Badagry LGA. Sampling covered residential, crowded, commercial, industrial and coastal environments, including Apa, Ajara, Aradagun, Ajido, Ilado, Imeke, Mowo, Morogbo, Iworo, Oko-Afo and other settlements. The sampling design provided broad geographical coverage and included areas representing contrasting anthropogenic settings. However, several coordinates in the supplied station table are repeated for multiple samples. This suggests that some samples were collected from different sources within the same locality, but the final manuscript should distinguish sampling station, source identifier and geographic location to avoid implying that all 72 samples represent 72 spatially independent locations.

Physicochemical characteristics

Table 2: Station-by-station physicochemical results

Sample Station	pH	Temp (°C)	TDS (mg/L)	TH (mg/L)	Salinity	CO_3^{2-} (mg/L)	NO_3^- (mg/L)	SO_4^{2-} (mg/L)	Cl^- (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Fe (mg/L)	Mn (mg/L)
Apa Hotel Apa	5.6	32.2	28.7	12.45	23	0.63	2.34	10	3.83	2.1	0.007	0.017	—
Berekete Badagry	6.8	32.1	376.6	52.69	99	1.4	14.11	60	13.41	9.58	0.317	0.018	—
Ajara Agamathen	4.2	32.4	555.8	47.9	90	2.1	19.06	60	7.66	9.81	0.075	0.129	—
Ajara Vetho	5.6	32.4	326.9	45.98	82.5	1.79	8.15	50	6.89	9.53	0.014	0.032	—
French Village	6.5	32.6	39.2	22.03	16.5	0.34	0.8	10	3.06	4.62	0.012	0.013	—
Ileri Oluwa Comp. Apa	5.7	32.3	93.1	23.95	66	0.37	0.16	40	3.06	5.09	0.346	0.054	—
Vinavon Quarters Cele 3	6.5	32.6	39.9	22.03	16.5	0.23	<0.02	10	3.06	4.62	0.013	0.008	—
Ajido 1	6.8	32.6	385.7	43.11	99	2.44	7.9	60	7.66	8.64	0.007	0.002	—
Ajara Tozukameh	6.8	32.3	235.2	45.98	41.3	2.66	0.24	25	8.81	9.06	0.013	0.191	—
Aradagùn	5.2	32.5	137.2	38.32	49.5	2.49	0.08	30	7.66	7.48	0.033	0.048	—
Mobil Station Badagry	6.9	32.4	251.3	41.19	66	0.28	0.08	40	7.66	7.9	0.021	0.006	—
Ajara Agamathen	4.8	32.5	436.8	52.69	66	1.28	12.72	40	8.81	10.05	0.021	0.067	—

Ajara Tozukameh	4.9	32.0	426.3	62.27	82.5	1.09	22.23	50	11.49	12.57	0.106	0.825	—
Aradagùn 6	6.6	32.0	1211	19.01	255.8	2.06	0.96	155	10.72	13.97	0.022	0.008	—
Ajara Topa	4.6	32.0	236.6	38.32	49.5	0.76	39.1	30	33.72	8.13	0.05	0.114	—
Ilado 1	5.0	32.4	51.8	14.37	16.5	0.71	7.9	10	4.98	2.57	0.033	0.027	—
Badagry Cent Mosque	6.9	32.2	396.2	43.11	66	0.37	0.56	40	3.83	6.96	0.043	0.004	—
Ajara Dokoh	6.6	32.3	84.7	23.95	33	0.14	18.55	20	14.56	4.9	0.032	0.003	—
Ojogun Company Apa	6.2	32.3	136.5	28.74	33	0.41	0.96	20	3.83	6.07	0.018	0.005	—
Imeke 1	6.4	32.6	99.4	28.74	16.5	24	1.72	3.03	10	3.83	4.86	0.038	0.012
Ajara Agamathen	4.7	32.7	387.1	52.69	90.8	26	1.83	0.8	55	8.81	11.45	0.045	0.067
Ilado 5	5.3	32.2	45.5	17.24	16.5	23	0.4	13.6	10	5.74	2.99	0.014	0.047
Imeke 1	5.9	32.4	94.5	19.16	33	28	0.73	0.8	20	4.98	2.52	0.036	0.011
No Problem Compound	6.4	32.6	102.2	23.95	16.5	47	0.25	1.99	10	8.81	4.44	0.047	0.008
Aradagun 1	6.5	32.2	57.4	26.82	16.5	36	0.35	2.79	10	5.74	5.32	0.077	0.008
Ajara Tozukameh	4.9	30.0	165.2	26.82	33	18	0.87	0.48	20	4.98	5.79	0.025	0.307
Holiness Church Bdg.	6.4	29.8	153.3	22.03	49.5	64	0.24	4.06	30	3.06	4.62	0.068	0.003
Oba Adenegba Compd, Apa	5.9	29.8	186.9	19.16	49.5	42	0.87	7.89	30	4.98	3.45	0.045	0.015
Ido Oluwo Compd Apa	4.8	29.8	99.4	14.37	16.5	20	0.92	3.75	10	3.06	2.75	0.043	0.026

Aradagua Iv	5.6	30.0	67.2	14.37	16.5	29	1.12	0.24	10	3.06	2.75	0.041	0.018
Ajara Agamathen 2	4.8	30.1	270.2	28.74	49.5	19	1.26	1.12	30	5.74	5.61	0.05	0.052
Alpha & Omega Ibercko 1	5.4	30.1	24.5	14.37	16.5	24	0.58	0.72	10	5.74	2.1	0.045	0.011
Ajara Agamathen 4	6.7	30.1	791	91.01	148.5	106	1.19	38.34	90	27.97	15.38	0.034	0.004
Ilado 2	4.6	30.1	189	23.95	33	19	1	1.59	20	3.83	4.9	0.041	0.01
Ayo Nio Carwarnh	6.7	30.3	209.3	31.61	66	88	0.37	6.14	40	8.81	5.56	0.067	0.059
Aradagun	5.9	30.3	168	19.16	49.5	29	1.6	3.75	30	3.06	2.52	0.047	0.048
Ajara Topa 7	4.5	30.3	241.5	17.24	66	23	1.59	1.59	40	5.74	2.8	0.085	0.034
Jasu Yikari Comp Ajara Ozu.	5.2	29.8	31.5	12.45	16.5	25	0.19	2.07	10	3.06	2.29	0.054	0.056
Imeke 3	5.2	29.8	24.5	7.66	16.5	23	0.02	0.56	10	3.06	1.4	0.037	0.03
Ileha Compound Apa	5.7	29.9	96.6	17.24	16.5	66	0.2	5.5	10	3.83	3.27	0.043	0.002
Noah's Compound Apa	5.7	29.9	20.3	7.66	16.5	32	0.14	0.64	10	1.91	1.4	0.019	0.101
Ilado 3	5.3	30.0	55.3	19.16	16.5	0.13	0.4	10	1.91	4.2	0.014	0.093	—
Ilado 2	6.2	29.9	244.3	36.4	66	0.41	8.76	40	9.58	6.54	0.047	0.008	—
Ajibade Compound	5.4	30.1	55.3	7.66	66	30	0.14	3.27	40	1.91	1.4	0.05	0.149
Idomosian Compound Apa	5.5	30.2	130.2	12.45	33	29	0.66	5.66	20	3.06	2.29	0.056	0.01
Aradagam Ii	4.1	30.1	196.7	19.16	49.5	16	1.54	0.4	30	3.06	3.92	0.014	0.033

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Ajapa Tozukameh 5	5.0	30.2	42.7	22.03	16.5	18	0.84	1.75	10	3.06	4.62	0.013	0.037
Temidire Compound Apa	4.0	30.0	151.2	19.16	33	18	0.96	3.11	20	4.98	3.45	0.02	0.05
Alpha & Omega Iberoko 11	5.7	30.0	128.1	23.95	33	47	0.48	6.37	20	5.74	4.44	0.016	0.008
Ajara Tozukameh	5.6	30.0	164.5	23.95	41.3	24	1.61	1.67	25	3.83	4.9	0.039	0.002
Ilado 2	4.2	30.2	332.5	36.4	82.5	19	2.15	7.65	50	10.7	6.26	0.056	0.18
Limca-Iberoko	5.88	29.4	310	44.66	110.28	48.35	0.14	9.34	66.9	13.23	8.16	0.099	0.205
Mowo 1	6.336	31.9	471	4.266	22.002	29.336	1.32	1.59	13.3	8.042	6.576	0.134	0.272
Sawmil Iberoko	5.0	33.1	37.9	22.64	14.814	40	1.95	5.39	1	2.999	2.32	0.049	0.1223
Oko-Afo 1	4.3	30.0	73.5	42.5	44.5	80	55.4	32.4	10	31.84	5.45	0.042	0.01
Iworo 1	6.9	32.3	221	36.4	41.3	95	1.5	5.45	25	8.81	8.4	0.06	0.058
Oko-Afo Ii	5.2	32.0	140	36.32	45.5	17	0.16	0.4	30	5.45	6.75	0.05	0.008
Mowo Ii	4.1	30.1	24.4	45.55	66	28	0.72	17.47	30	9.45	3.45	0.021	0.125
Gen. Hosp. Badagry	5.6	32.6	32.5	7.66	16.5	23	0.14	1.59	10	3.83	9.55	0.05	0.014
Morogbo I	6.6	30.1	165.4	14.37	16.4	40	2.15	0.9	10	3.04	2.15	0.043	0.049
Akarakumo	4.4	32.2	375	23.95	66	47	0.37	0.05	40	3.06	4.44	0.047	0.008
Morogbo I	4.8	30.0	67.8	19.16	15.6	22	0.85	2.45	10	3.06	2.75	0.014	0.038
Iworo Ii	5.7	30.0	60	43.11	16.5	24	0.24	1.85	10	7.66	4.62	0.013	0.002
Coconut Ind. Area	4.4	32.4	436.7	23.74	49.4	13	1.19	1.05	30	5.65	3.55	0.033	0.0121
Morogbo Ee	5.0	29.8	25.3	16.45	30.5	0.62	5.45	20	11.5	11.42	0.076	0.096	—
Ajara Torikoh	5.9	32.4	59.1	52.69	82.5	19	0.45	7.9	50	3.06	4.62	0.013	0.016

Topo Idale	5.8	30.2	25.1	18.43	68.7	35	1.25	18.5	125	9.45	7.26	0.042	0.04
Total Station Badagry	6.7	32.6	135	22.03	33	18	2.35	9.5	20	3.83	6.75	0.023	0.004
Ascoon Topo	6.0	32.0	102	20.55	210.5	67	0.25	3.35	40	3.52	8.45	0.054	0.003
Morogbo Iv	6.4	29.8	277	19.16	49.5	31	1.18	0.8	40	4.98	2.52	0.037	0.019
Morogbo V	6.4	30.1	80.3	24.54	16.8	34	0.14	0.35	20	1.75	4.54	0.022	0.018
Morogbo VI	4.7	30.3	160	22.03	33	53	1.6	3.47	20	1.91	1.4	0.075	0.034

Groundwater was generally soft and weakly mineralised, although considerable spatial variability occurred.

The reported pH ranged from 4.0 to 6.9, with a mean of approximately 5.59 ± 0.84. Based on the 72 station-level pH values supplied, approximately 79% of samples were below the Nigerian standard range of 6.5–8.5. The predominance of acidic groundwater represents the principal widespread quality concern.

Temperature ranged from 29.4 to 33.1°C, with limited overall variation. TDS ranged from 20.3 to 1,211 mg/L, with a reported mean of approximately 207 mg/L. Most samples were therefore characterised by relatively low dissolved-solids concentrations, although the Aradagun 6 sample recorded 1,211 mg/L.

Total hardness ranged from 4.27 to 91.01 mg/L, indicating predominantly soft groundwater. Chloride ranged from 1 to 155 mg/L, while sulphate ranged from 0.05 to 39.1 mg/L. These values were below the corresponding NSDWQ limits of 250 and 100 mg/L, respectively.

Nitrate was generally low but showed localised enrichment. The station-level table contains at least one value above the NSDWQ limit of 50 mg/L; however, the reported descriptive maximum of 76 mg/L does not reconcile with the visible station-level values and should therefore be verified against the original laboratory dataset before publication.

Table 3: Descriptive statistics

Parameter	Unit	n	Mean	SD	Median	IQR	Min	Max
pH	—	72	5.59	0.84	5.6	1.3	4.0	6.9
Temperature	°C	72	31.35	1.20	31.9	2.4	29.4	33.1
TDS	mg/L	72	207	216	137	195	20.3	1211
Total Hardness	mg/L	72	27.7	15.2	23.0	18.5	4.27	91.0
Salinity	—	72	49.6	42.4	41.3	49.5	14.5	255.8
CO_3^{2-}	mg/L	72	39.3	23.7	29	25	0.13	106
NO_3^-	mg/L	72	2.74	10.55	0.87	1.5	0.02	76
SO_4^{2-}	mg/L	72	5.99	8.37	2.8	5.5	0.05	39.1
Cl^-	mg/L	72	30.2	25.6	20	25	1	155
Ca^{2+}	mg/L	72	6.78	5.99	4.98	4.8	1.75	33.72
Mg^{2+}	mg/L	72	5.54	3.12	4.62	3.5	1.4	15.38
Fe	mg/L	72	0.046	0.054	0.041	0.035	0.007	0.346
Mn	mg/L	72	0.059	0.111	0.018	0.05	0.002	0.825

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Major ions and metals

Calcium and magnesium concentrations were generally low, consistent with the predominantly soft nature of the groundwater. Reported calcium concentrations ranged from 1.75 to 33.72 mg/L, while magnesium ranged from 1.40 to 15.38 mg/L.

Iron concentrations ranged from 0.007 to 0.346 mg/L, with a reported mean of 0.046 ± 0.054 mg/L. Most samples were below the NSDWQ limit of 0.3 mg/L, although isolated exceedance occurred.

Manganese ranged from 0.002 to 0.825 mg/L, with a reported mean of 0.059 ± 0.111 mg/L. Several samples exceeded the Nigerian guideline value of 0.2 mg/L, with the highest concentration occurring at Ajara Tozukameh.

The occurrence of Fe and Mn enrichment may reflect natural mobilisation under reducing groundwater conditions, although anthropogenic contributions cannot be excluded without additional hydrochemical, land-use and redox data.

Compliance with drinking-water standards

The Nigerian Standard for Drinking Water Quality (NIS 554:2015) should be used as the primary national benchmark, with WHO guidance used as a supplementary international reference. The national standard specifies pH of 6.5–8.5, TDS of 500 mg/L, chloride of 250 mg/L, sulphate of 100 mg/L, nitrate of 50 mg/L, iron of 0.3 mg/L and manganese of 0.2 mg/L. The most widespread non-compliance involved pH. TDS exceeded the national 500 mg/L limit at the most highly mineralised station (Aradagun 6; 1,211 mg/L). Chloride and sulphate remained below their national limits in the supplied dataset. Nitrate exceedance was localised. Iron and manganese exceedances were similarly spatially restricted, but manganese reached more than four times the national limit at the highest-affected station.

WHO guidance should not be treated as a substitute for the national standard. The current WHO Guidelines emphasise that national authorities establish locally relevant standards and risk-management targets, and the latest WHO edition was updated in 2026.

Table 4: Comparison with drinking-water standards

Parameter	Unit	Standard (WHO / NSDWQ)	Samples exceeding	% exceeding
pH	—	6.5–8.5	Majority (≈55–60)	≈76–83 %
TDS	mg/L	1000 (NSDWQ) / 1500 (WHO)	1–2	≈1–3 %
Total Hardness	mg/L	150 (NSDWQ) / 500 (WHO)	0	0 %
NO_3^-	mg/L	50	1–2	≈1–3 %
SO_4^{2-}	mg/L	100 (NSDWQ) / 400 (WHO)	0	0 %
Cl^-	mg/L	250	0	0 %
Ca^{2+}	mg/L	75–200	0	0 %
Mg^{2+}	mg/L	30–150	0	0 %
Fe	mg/L	0.3	1–3	≈1–4 %
Mn	mg/L	0.1 (preferred) / 0.4	Several (≈8–12)	≈11–17 %

Spatial patterns

GIS analysis indicated pronounced spatial heterogeneity in groundwater chemistry. Low-pH conditions occurred across much of the study area, suggesting that acidity is not confined to a single anthropogenic hotspot.

Higher TDS and salinity were concentrated at selected locations, including Aradagun and some coastal or near-coastal stations. The highest TDS concentration was 1,211 mg/L. Elevated nitrate occurred at isolated stations, while Fe and Mn enrichment was similarly localised.

The spatial distribution is therefore more consistent with multiple interacting controls than with a single regional contamination source.

Hydrochemical character

The available data indicate predominantly soft and relatively low-mineralised groundwater. The relatively low Ca^{2+} and Mg^{2+} concentrations suggest limited carbonate mineralisation, while the occurrence of higher TDS and chloride at selected locations indicates localised enrichment.

However, definitive assignment of Piper or Durov hydrochemical facies requires complete major-ion data, particularly Na^{+}, K^{+} and HCO_3^{-}. Consequently, claims of specific hydrochemical facies should be restricted until these variables have been verified for all 72 samples.

Water Quality Index and health-risk assessment

A WQI classification cannot responsibly be reported from the information supplied because the final station-specific WQI values, parameter weights and computed sub-indices are absent. Similarly, a quantitative health-risk assessment cannot be reported because exposure assumptions, reference doses, body weights and calculated CDI, HQ and HI values are not provided.

These analyses should therefore be presented only after the calculations have been completed and independently checked.

IV. DISCUSSION

The hydrochemical results indicate that groundwater acidity is one of the most prominent characteristics of the aquifer system in Badagry LGA. The mean pH of approximately 5.59 and the high proportion of samples below the recommended lower limit of 6.5 indicate that acidity is widespread rather than restricted to isolated locations. This finding agrees with previous research in Badagry, where 87.3% of groundwater samples were reported to be slightly acidic, with pH values ranging from 5.0 to 12.28 (Oloruntola et al., 2019). In coastal sedimentary environments, low groundwater pH may result from recharge through acidic soils, organic-matter decomposition, carbon dioxide production, mineral weathering and limited buffering capacity. The generally low calcium and magnesium concentrations and low to moderate hardness further suggest limited carbonate buffering. Similar slightly acidic groundwater has also been reported in coastal aquifers of southwestern Nigeria (Ogbadun et al., 2020).

The widespread acidity has implications for groundwater management. Although low pH is primarily an aesthetic and operational concern rather than a direct health hazard at typical groundwater concentrations, acidic water can increase corrosivity and potentially enhance the mobilisation of metals from geological materials, borehole components and water-distribution infrastructure. Consequently, routine pH monitoring and appropriate treatment should be considered in groundwater management (World Health Organization [WHO], 2022).

Groundwater was generally characterised by low mineralisation, as indicated by predominantly low TDS concentrations. This pattern suggests limited dissolution of soluble minerals and is consistent with recharge and the sandy coastal sedimentary environment. Previous investigation in Badagry similarly reported predominantly fresh groundwater and TDS values ranging from 8 to 520 mg/L (Oloruntola et al., 2019). However, the substantially higher TDS at Aradagun 6 and elevated salinity at selected coastal and near-coastal locations demonstrate spatial hydrochemical variability. Such enrichment may reflect lithological differences, groundwater residence time, evaporation, mineral dissolution or possible freshwater–saline water mixing. Studies of coastal aquifers in southwestern Nigeria have identified mineral dissolution, recharge and saline-water processes as important controls on groundwater chemistry (Ogbadun et al., 2020).

Although saline influence is possible in coastal aquifers, the present results do not provide definitive evidence of seawater intrusion. Elevated TDS or chloride concentrations alone cannot reliably distinguish seawater mixing from other sources of dissolved ions. Confirmation requires integration of hydrochemical indicators with groundwater levels, aquifer characteristics, diagnostic ionic ratios and, where possible, hydrogeophysical or isotopic evidence. This distinction is particularly important in Badagry, where geophysical investigations have previously identified freshwater, brackish and saline-water-bearing layers at different depths and distances from the Atlantic coast (Oloruntola et al., 2019). The observed pattern is therefore more appropriately interpreted as possible local saline influence or hydrochemical enrichment rather than confirmed seawater intrusion.

Nitrate concentrations were generally low, suggesting that widespread nitrate contamination is not a dominant feature of the groundwater system. However, isolated elevated concentrations indicate potential localised anthropogenic enrichment. Possible sources include septic-system and pit-latrine leakage, domestic wastewater, refuse disposal and agricultural activities. Groundwater quality in Nigerian urban environments has been associated with urbanisation, industrialisation, waste disposal, landfill leachates and sanitation-related pressures (Ocheri et al., 2014). Nevertheless, the available data cannot establish a definitive nitrate source. Integration of groundwater depth, well construction, sanitation conditions, land use and, where feasible, nitrogen and oxygen isotope analyses would strengthen source attribution.

Iron and manganese were generally low but showed localised enrichment. The maximum iron concentration of 0.346 mg/L slightly exceeded the applicable Nigerian drinking-water guideline, while manganese reached 0.825 mg/L. Their simultaneous elevation at some locations may reflect geochemical mobilisation under reducing or acidic groundwater conditions, although anthropogenic inputs cannot be excluded. The WHO notes that elevated manganese in groundwater is commonly associated with acidic or reducing conditions, although industrial pollution may also contribute (WHO, 2022). Further assessment incorporating dissolved oxygen, oxidation-reduction potential, alkalinity, bicarbonate, sulphide, groundwater depth and mineralogical information would help clarify the processes controlling Fe and Mn mobility.

The sampling design incorporated contrasting anthropogenic settings, including industrial, commercial/crowded and residential areas, providing a basis for evaluating spatial patterns. However, differences among these zones should not be interpreted as evidence of direct contamination from particular land uses without statistical support. Environmental concentration data are frequently non-normally distributed; therefore, the Kruskal–Wallis test with appropriate post-hoc comparisons would be suitable for evaluating zone-specific differences. Effect sizes and confidence intervals should also be reported to demonstrate the magnitude and practical importance of observed differences.

Spatial relationships should also be interpreted cautiously because groundwater quality may be influenced by groundwater-flow direction, borehole depth, well construction, aquifer thickness, recharge and lithological heterogeneity. Consequently, proximity to industrial or densely populated areas alone does not establish causation. The findings are better interpreted as evidence of spatial association and potential vulnerability unless supported by stronger statistical or hydrogeological evidence. This caution is particularly relevant to coastal aquifers, where lithological and hydrogeological conditions can produce substantial spatial variation in groundwater chemistry (Oloruntola et al., 2019).

Overall, groundwater in Badagry LGA is predominantly weakly mineralised but chemically vulnerable, with widespread acidity and localised enrichment of TDS/salinity, nitrate, iron and manganese. The combination of low hardness, generally low TDS, relatively low sulphate and chloride concentrations and variable pH suggests that extensive mineral dissolution is not the dominant control on groundwater chemistry. Instead, groundwater composition appears to reflect recharge, coastal sedimentary aquifer characteristics and limited buffering, with additional local hydrochemical and potentially anthropogenic influences. This interpretation is broadly consistent with previous studies showing that groundwater chemistry in coastal southwestern Nigeria reflects interactions among recharge, lithology, mineral dissolution and saline-water processes (Ogbadun et al., 2020).

The findings demonstrate the importance of spatially targeted groundwater management rather than reliance on area-wide mean concentrations. Routine monitoring should be combined with assessment of land use, groundwater levels, borehole characteristics and aquifer properties. Future investigations should incorporate hydrogeological, redox and geochemical indicators to better resolve the processes controlling groundwater quality and provide a stronger basis for sustainable groundwater management in Badagry LGA.

V. LIMITATIONS

Several limitations should be considered when interpreting the findings. First, inconsistencies were observed between some station-level data and reported summary statistics, particularly for pH and nitrate. The original laboratory dataset should therefore be used to recalculate and reconcile all descriptive statistics before submission. Second, some sampling points have similar or repeated coordinates and locality names, creating uncertainty about whether they represent distinct groundwater sources or multiple sources within the same community. Clear identification of sampling points is necessary for reliable spatial analysis. Third, borehole depth, static water level, screened interval, construction characteristics and aquifer units were not consistently available. Their absence limits interpretation of depth-related hydrochemical variations in the coastal aquifer. Fourth, Na^+, K^+ and HCO_3^- data were incomplete, limiting comprehensive hydrochemical classification using Piper, Durov and Gibbs diagrams. Future studies should include a complete suite of major ions and ionic-balance assessment. Fifth, the WQI and health-risk assessments require verification to ensure reproducible calculations and appropriate application of standards. Analyses that cannot be adequately validated should be revised or excluded. Sixth, the cross-sectional design represents groundwater conditions during a limited sampling period and may not capture seasonal variations in recharge and contaminant mobilisation. Wet- and dry-season sampling would provide stronger evidence of temporal variability. Finally, microbiological parameters were not assessed. Consequently, physicochemical results alone cannot establish drinking-water safety. Future studies should include microbial indicators, particularly total coliforms and *Escherichia coli*, alongside hydrochemical and hydrogeological parameters. Despite these limitations, the study provides useful baseline information on groundwater quality in Badagry LGA. Addressing these data and methodological gaps would strengthen future assessments and support more effective groundwater management.

VI. CONCLUSION

Groundwater in Badagry LGA is predominantly soft and weakly to moderately mineralised, but exhibits considerable spatial variability. The major regional concern is widespread acidity, with many samples falling below the recommended pH range of 6.5–8.5. Localised elevations of TDS, nitrate, iron and manganese indicate additional site-specific groundwater-quality concerns, particularly manganese enrichment.

The generally low chloride and sulphate concentrations do not indicate widespread saline contamination; however, elevated TDS and salinity at selected coastal and near-coastal locations warrant continued monitoring for possible local saline influence. Overall, groundwater chemistry appears to reflect interactions among natural hydrogeochemical processes, aquifer characteristics and local anthropogenic pressures rather than a single contamination source.

Effective groundwater management should prioritise routine monitoring of pH, TDS, chloride, nitrate, iron and manganese, protection of water sources from contamination pathways, and appropriate treatment of acidic or metal-enriched groundwater. Before publication, the raw laboratory dataset should be reconciled with reported statistics. Further studies incorporating groundwater levels, complete major-ion chemistry, redox and microbial parameters, seasonal sampling, hydrochemical facies analysis and GIS-based assessment would strengthen groundwater-quality management in Badagry LGA.

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