



Integrated approaches to groundwater quality assessment and hydrochemical processes in Lagos, Nigeria

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Abstract

Integrated approaches of water quality indices, multivariate statistical analysis, and geostatistical technique were applied to examine the groundwater quality and hydrochemical processes in Lagos, Nigeria. Fifteen samples each were randomly collected from peri-urban, rural, and urban settlements totaling 45 samples from protected dug wells during dry and wet seasons. Samples were analyzed for physicochemical parameters, anion, and cation using standard method. The result shows that 95.6% of the samples during the dry season had pH below the minimum guideline for drinking water. Factor analysis explained 73.5% and 84.2% of the variance during dry and wet seasons, respectively, and extracted two factors—salinity and weathering of minerals. Gibbs plot indicates rock-weathering process as the mechanism controlling the groundwater system. Drinking water quality index shows excellent quality. Revelle index indicates that 6.6% of the samples are strongly affected by salinity during the wet season. One-quarter of sample indicate very severe corrosion based on the water stability index in both seasons. The Piper's plot delineated four facies with primary hardness and mixed waters being the dominant during the dry and wet seasons, respectively. The study concludes that the groundwater is suitable for drinking. The study contributes to knowledge in the mapping of groundwater salinization and water stability indices and delineation of water types for information dissemination with a view to ensuring effective groundwater quality management. A policy that will ensure adequate protection of groundwater pollution from leachates, salinity, and anthropogenic impacts was recommended for sustainable groundwater use in the region.

Keywords Groundwater quality · Hydrochemical processes · Integrated approach · Lagos—Nigeria

Introduction

Groundwater is one of the vital resources that require adequate protection from anthropogenic pollution sources. Globally, the alarming rate of anthropogenic activities and climate change phenomenon has impacted significantly on the quality of both the surface and groundwater resources (Arian et al. 2008; Bu et al. 2010). Groundwater quality can be influenced by the lithology, water–rock interaction, and changes in space and time (Todd and Larry 2005; Srinivasa-moorthy et al. 2008; Bhattacharya and Bundschuh 2015). The continuous rise in anthropogenic activities, uncoordinated

development, has led to an increase in point source pollutants such as leachates from dumpsite, seepage from the septic tank, and municipal sewage plants among others. Current emerging pollutants from agro-based activities such as nitrate, pesticides, and other heavy metals and persistent organic products (POPs), volatile organic carbon (VOCs) among others pose serious challenges to human health and the sustainability of groundwater (Kumazawa 2002; Jalali and Kolahchi 2008; Balogun and Adegun 2013; Salami and Susu 2013; Ocheri et al. 2014).

Globally, water-related diseases are the leading causes of morbidity and mortality in many parts of the developing world, with about 2–12 million deaths per year (Gleick 2002; WWAP 2003). Due to the present health and environmental challenges resulting from water-related diseases, the assessment of water quality, therefore, becomes very imperative because it serves as a vital tool for sustainable water resources management strategies (Zhou et al. 2007; Bu et al. 2010). The approaches of water quality assessment

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and hydrochemical processes abound in the literature. For instance, the application of water quality indices (WQI) serves as a veritable scientific tool for assessing the suitability of water quality for various uses in an integrated manner (Balogun et al. 2012). The WQIs also helps to reveal the effects of individual groundwater parameters on the overall water quality in a given location (Sarala and Uma Mageswari 2014). The WQIs also show the variation and the possible trends both spatially and temporarily for easy information dissemination to the public (Bharti and Katyal 2011; Akoteyon 2013). Apart from WQI, the applications of water stability index (WSI), such as Langelier saturation index (LSI), Ryznar stability index (RSI), Puckorius scaling index (PSI), and Aggressive index (AI) (Gholizadeh et al. 2017; Choi et al. 2015; Chung et al. 2004; Kurdi et al. 2015), serve as very useful tools to assess corrosion and scaling potential of water resources globally. Studies have shown that LSI is one of the most widely used indicators for determining scale formation potential in water supply and drinking water networks (Gholizadeh et al. 2017; Maeng et al. 2015; Alsaqqar et al. 2014). Beyond the problems of corrosion and scaling, groundwater salinization in coastal areas has continued to be a major concern of water resources management in these regions. This has led to the development of various indices, for example applications of GALDIT index Lobo Ferreira et al. (2005), Revelle index (Revelle 1941), and ionic ratios of electrical conductivity, sodium/chloride, magnesium/calcium (Narany et al. 2014). The use of Revelle index has been proven to be a very veritable tool in evaluating groundwater salinization in both the tropical and arid regions (Aris et al. 2009; Tziritis et al. 2009; Revelle 1941). Other relevant graphical techniques employed in groundwater quality assessment include Gibbs plot (Gibbs 1970), Schoeller (1964), Stiff (1951), Durov (1948), Piper (1944), Collins diagrams (Collins 1923). Piper's diagram has been extensively used in groundwater data set to delineate hydrochemical facies to reveal discernible patterns and trends in water quality for a better understanding of groundwater flow and geochemistry in an aquifer system (Dalton and Upchurch 1978).

Similarly, Gibbs plot has enhanced the interpretation of the effect of hydrogeochemical processes (i.e., precipitation, rock–water interaction, and evaporation) with the aim of providing knowledge on the source of water contamination and the interaction between rock and aquifer (Howladar et al. 2017; Boateng et al. 2016). There is a scanty study on a holistic application of water quality indices, chemometric methods, such as multivariate statistical analysis and geostatistical technique in the study area. This study applied water stability index with drinking water quality index, groundwater salinization with the chemometric method, such as multivariate statistical analysis and geostatistical technique. The methodology provides a reliable technique of data

mining and source apportionment for better interpretation of water quality data which are difficult to evaluate using only elemental concentrations (Machiwal and Jha 2015). The study is also significant because it employed a novel method that delineates the sampling sites into distinct geographical strata, namely peri-urban, rural, and urban settlements beyond administrative boundaries for environmental quality assessment studies in Lagos, Nigeria. This study, therefore, seeks to examine the groundwater quality and hydrochemical processes using integrated approaches in Lagos, Nigeria. The study contributes to knowledge in the mapping of the distributional patterns of groundwater salinization and water stability index. It also identified the major mechanism controlling groundwater chemistry, sources of groundwater pollution and delineation of water types in the study area as baseline information for effective groundwater management.

Study area

The study site is located in the coastal plain sand (CPS) aquifer of Lagos, in parts of Southwestern Nigeria. It lies approximately on latitudes 6°30'N–6°40'N and longitudes 3° 00'E–4°00'E. The area is bounded by Ogun State in the east and north, the Atlantic Ocean in the south, and Benin republic in the west. It occupies about 73.63 km² of land covering peri-urban, rural and urban settlements around Lagos metropolis, Ikorodu, Epe, and Badagry geographical regions (Fig. 1).

The climate of Lagos state is controlled by the tropical and continental air masses, which are associated with north-east and moisture-laden southwest winds, respectively. The movements of the air masses result in the two weather seasons, namely dry and wet seasons (Adepelumi 2009). The average temperature is 30 °C, while the mean annual rainfall is about 1532 mm. The dominant vegetation is comprised of tropical swamp forest (freshwater and mangrove swamp forests and dry lowland rainforest; Akoteyon 2013). The topography of the area is comprised of troughs which are dominated by a system of the Island, sandbars, and lagoons, developed by barrier beaches associated with sand deposition (Adepelumi 2009). It has a lowland territory, very flat in its western portion and somewhat hilly in its eastern zone. The state is bisected and parallel to the ocean by the Lagos lagoon and Badagry creek. The northern section of the state is composed of lowlands in the west, flat hills in the east, and marshland of the Ogun River in the Centre. In the central region lies the Lagos metropolis, characterized by a densely populated settlement (Coode et al. 1997). The area is drained by various river systems, for example Ogun River in the center, the Ona River and Osun in the east, and the Yewa in the west, flowing southwards to join coastal lagoons (Akoteyon et al. 2010). The geology of the area lies solely in the Dahomey sedimentary basin and has no outcrop. The

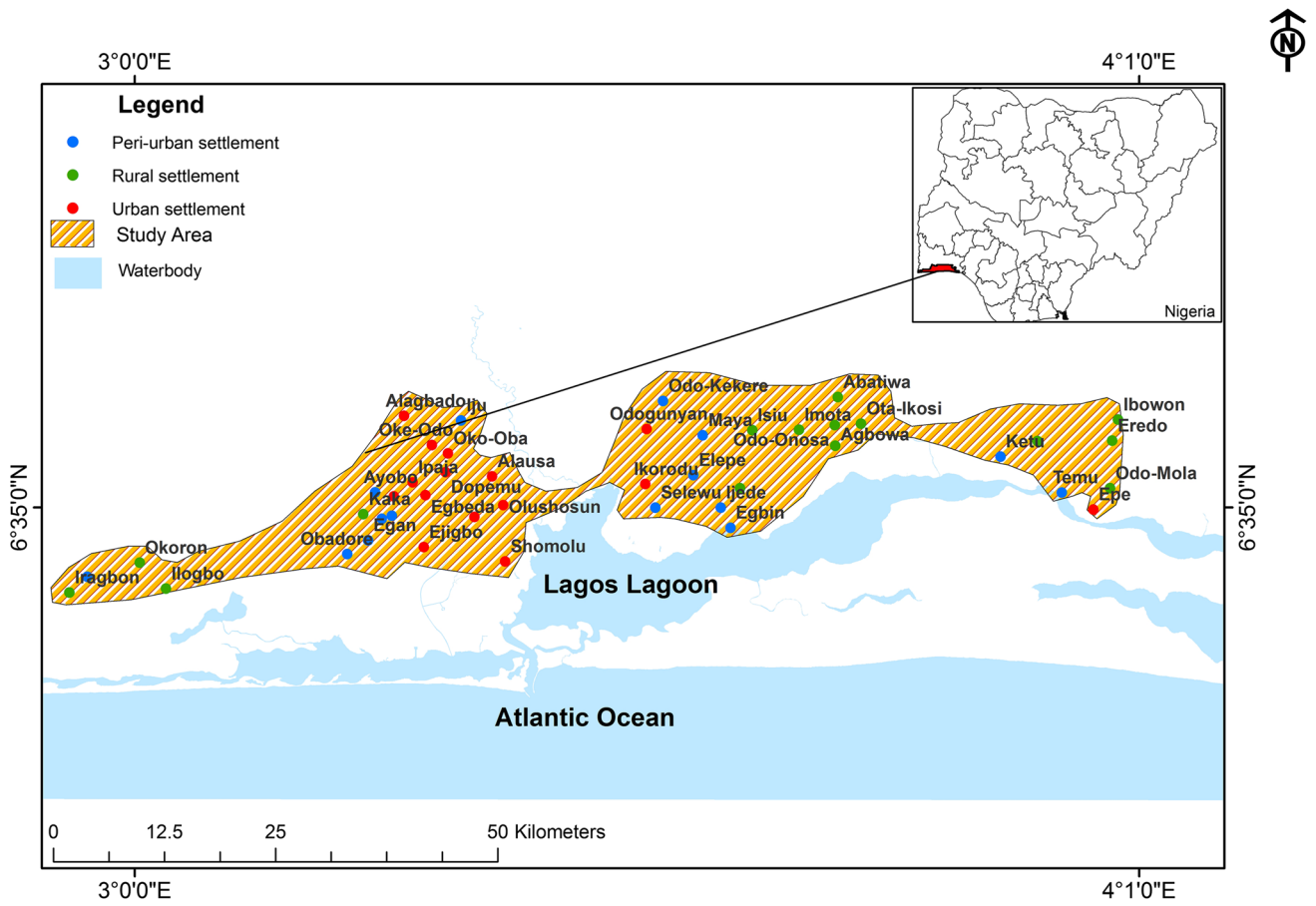


Fig. 1 The study area

geological sequence in the Dahomey basin extends from the Precambrian to recent (Coode et al. 1997). The upper sediments in the Dahomey Basin are underlain by coastal plain sands, also known as the Benin formation of the Quaternary age. Studies have shown that recent sediments occur along the coastal belt in the form of alluvial deposits along the major rivers in the coastal areas (Coode et al. 1997).

The hydrogeology of the CPS aquifer is composed of lenticular unconsolidated yellowish (ferruginous) to whitish sands with shale, clay, and sandy clay intercalations. The CPS formations consist of multi-aquifer systems arising from the alternation of sands and clay. The sand has artesian or sub-artesian characteristics. The sources of groundwater recharge in the CPS are through surface runoff and percolation from precipitation. More than 30% of groundwater supply in Lagos State taps water from the CPS to meet domestic, municipal, and industrial water demands (Akoteyon 2013). The aquifer is tapped for groundwater supply in Lagos through the establishment of the micro- and mini water works (Balogun et al. 2012). Lateral variations exist in the CPS aquifer due to its lithology and water quality. The CPS aquifer in Lagos

is subdivided into four, namely recent sediment, upper CPS, lower CPS and the Abeokuta formation (Coode et al. 1997). The water table of the CPS ranged between 0.4–21 m with an annual fluctuation of less than 5 m (Akoteyon 2013).

Variation in the thickness of the recent and lower CPS aquifer ranged between 200 m and 250 m, respectively, with mean groundwater storage of the first CPS aquifer estimated at $2.87 \times 10^3 \text{ m}^3$ (Akoteyon 2013). The recent sediment is water table aquifer usually found along the coast and in the alluvial plains of the river valleys. The water table is shallow and has higher total dissolved solids (TDS), conductivity compared to the upper coastal plain sand (UCPS) and the lower coastal plain sand (LCPS). The shallow nature of the water table makes it vulnerable to contamination from sewage and waste disposal (Coode et al. 1997). Groundwater salinity in the aquifer varies from north to south (Akoteyon et al. 2010). Saltwater intrusion occurs into this aquifer with the second aquifer being fresh water-bearing in the northern and central parts of the state, while the southern coastal belt is characterized by saltwater (Akoteyon et al. 2010).

Materials and methods

A total of fifteen groundwater samples each were collected from peri-urban labeled (P₁–P₁₅), rural (R₁–R₁₅) and urban (U₁–U₁₅) settlements totaling 45 samples from protected dug wells (PDW) using random sampling technique during March 2012—dry season—and July 2012—wet season—to assess the quality, characterize the water type, and identify the hydrogeochemical processes operating within the groundwater system in the study (Fig. 2).

The groundwater samples were collected in one-liter polyethylene bottles. Prior to the sample collections, the bottles were washed with distilled water and thereafter rinsed with water to be sampled (APHA 1998). The groundwater samples were preserved in ice chests to minimize error during transit and taken to the Chemistry Department, University of Lagos for laboratory analyses, using standard procedure after APHA (1998). The parameters examined include pH, electrical conductivity (EC), total dissolved solids (TDS), sodium (Na⁺), potassium (K⁺), calcium (Ca²⁺), magnesium (Mg²⁺), chloride (Cl⁻), bicarbonate (HCO₃⁻), carbonate

(CO₃⁻), and sulfate (SO₄²⁻). Total hardness (TH) was evaluated based on Fournier (1981) method as indicated in Eq. 1.

$$TH = 2.5 Ca (mg/L) + 4.1 Mg(mg/L) \tag{1}$$

where Ca—calcium, Mg—magnesium.

Groundwater pH, TDS, and EC were measured in situ using pHep and DiST EC HANNA single-parameter probe (HI7007 and HI98303), respectively. The TDS was measured using TDS-3 m HM Digital multi-parameter probe. The major ions were determined based on standard procedures after APHA (1998). Titration method was employed to determine calcium and magnesium based on standard EDTA (0.01 M) solution. Chloride was determined by titration using standard silver nitrate. Bicarbonate and carbonates were evaluated titrimetrically using standard hydrochloric acid (0.01 N) solution. Flame photometer was employed to analyze potassium and sodium, and sulfate by spectrophotometer. The reliability test of the laboratory analyses of the major ions was subjected to internal consistency to identify inconsistencies using charge balance error (CBE) formula by Apello and Postma (2005) as indicated in Eq. 2. Generally, all the samples are within ± 5%.

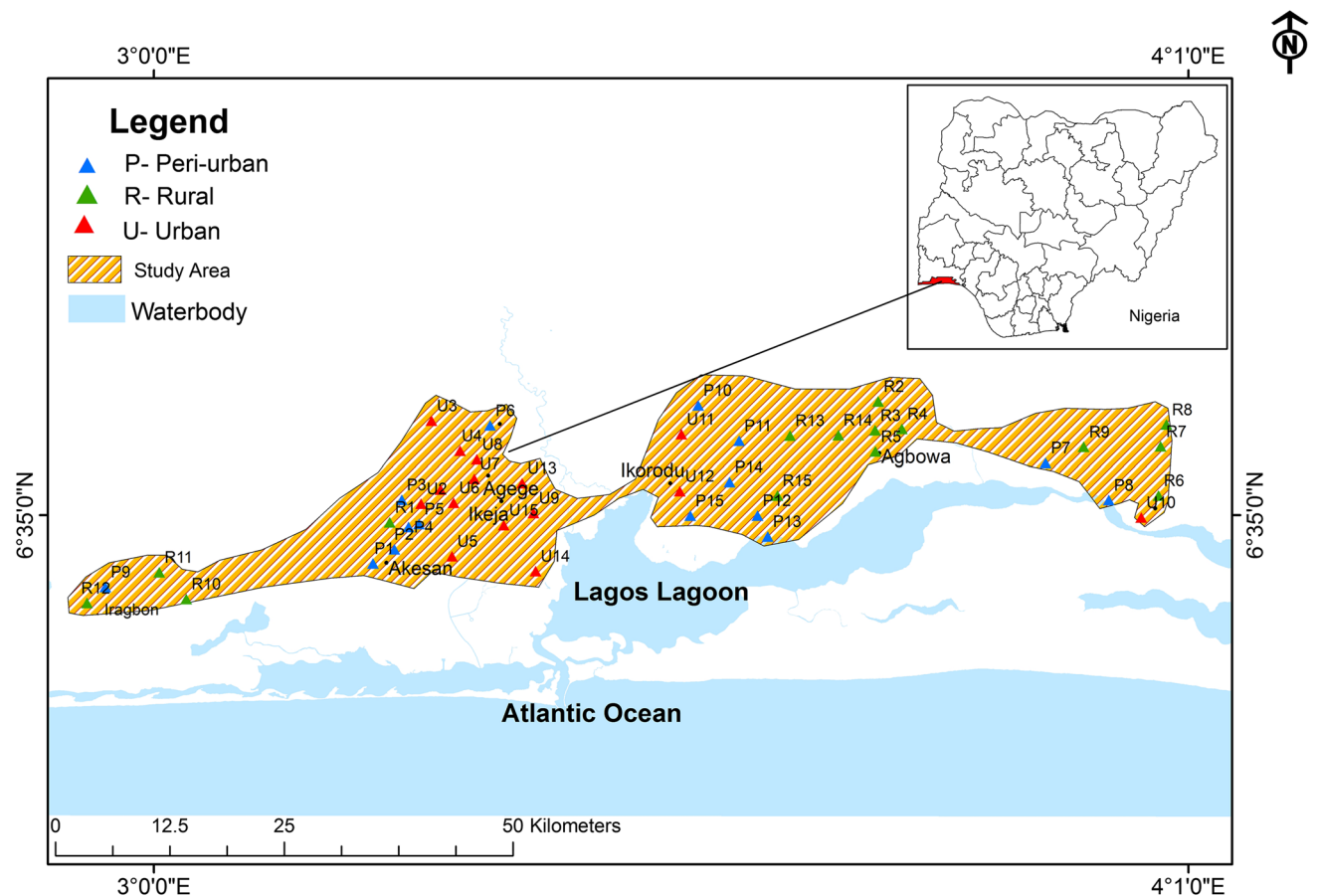


Fig. 2 The sampling sites

$$CBE = \left(\sum \text{cations} - \sum \text{anions} \right) / \left(\sum \text{cations} + \sum \text{anions} \right) \times 100\% \tag{2}$$

Descriptive, inferential, and multivariate statistical techniques were employed for data analyses using Statistical Package for Social Sciences (SPSS) 22.0 version.

Water quality indices

Drinking water quality index

The WQI of the study area was computed using 11 parameters, namely pH, TDS, EC, Ca²⁺, Mg²⁺, TH, Na⁺, K⁺, Cl⁻, HCO₃⁻, and SO₄²⁻, to determine the suitability of the water for human consumption using the method proposed by Sahu and Sikdar (2008). The computation involved four stages as follows:

1. Allocation of weight to each parameter according to their relative importance in line with WHO (2011) guideline for drinking purpose (Table 1)
2. Computation of relative weight (Wi) based on Eq. 3.

$$Wi = wi / \sum_i^n = 1 \quad wi \tag{3}$$

where Wi=relative weight, wi=weight of each parameter, and n=number of parameters.

3. Allocation of quality rating scale (qi) for each parameter (Eq. 4).

$$qi = \left(\frac{Ci}{Si} \right) \times 100 \tag{4}$$

Table 1 Relative weight of groundwater parameters

Parameter	WHO guideline (2011)	Weight (wi)	Relative weight (Wi)
pH	6.5–8.5	4	0.11
TDS	500 mg/L	5	0.14
EC μS/cm	500 mg/L	4	0.11
Ca ²⁺	75 mg/L	2	0.06
Mg ²⁺	30 mg/L	2	0.06
TH	200 mg/L	2	0.06
Na ⁺	200 mg/L	4	0.11
K ⁺	200 mg/L	2	0.06
Cl ⁻	250 mg/L	3	0.09
HCO ₃ ⁻	500 mg/L	3	0.09
SO ₄ ²⁻	250 mg/L	4	0.11
		$\sum wi = 35$	$\sum Wi = 1.00$

where qi=quality rating, Ci=concentration of each parameter, and Si=WHO (2011) drinking water guideline for each parameter.

4. The final WQI is calculated based on Eqs. 5 and 6.

$$Sli = Wi \times qi \tag{5}$$

$$WQI = \sum_{i=1}^n Sli \tag{6}$$

where Sli is the sub-index of ith parameter, while qi is the rating according to the concentration of ith parameter, and n is number of parameters. The computed WQI values are classified into five categories according to Sahu and Sikdar (2008) as follows:

- < 50 Excellent water
- 50–100 Good water
- 100–200 Poor water
- 200–300 Very poor water
- > 300 Water unfit for drinking

Groundwater salinization

The degree of groundwater salinization was determined using Revelle index (RI) (Revelle 1941) as indicated in Eq. 7.

$$RI = rCl^- / (rHCO_3^- + rCO_3^-) \tag{7}$$

where r=meq/L, Cl⁻—chloride, HCO₃⁻—bicarbonate, CO₃⁻—carbonate.

The computed RI values are classified into three categories according to Revelle (1941) as follows:

- < 0.5 meq/L unaffected
- 0.5–6.6 meq/L slightly affected
- > 6.6 meq/L strongly affected

Water stability index

The prediction of the tendency of scaling or corrosion of water was determined based on Langelier saturation index (LSI) proposed by Langelier and Ludwig (1942) and Gupta et al. (2011) using AquaChem software 2012.1 version. The LSI is defined using Eq. 8.

$$LSI = pH - pHs \tag{8}$$

where pH=measured water pH and pHs=pH at saturation in calcite or calcium carbonate and is calculated using Eq. 9.

$$pHs = (9.3 + A + B) - (C + D) \tag{9}$$

where notations A to D are obtained using Eqs. 10 to 13.

$$A = (\log 10[TDS] - 1)/10 \tag{10}$$

$$B = -13.12 \times \log 10(OC + 273) + 34.55 \tag{11}$$

$$C = \log 10[CaH \text{ as } CaCO_3] - 0.4 \tag{12}$$

$$D = \log 10[\text{total alkalinity as } CaCO_3] \tag{13}$$

The LSI values are classified into eleven categories according to Langelier and Ludwig (1942) as follows:

1	-4.0	Very severe corrosion
2	-3.0	Severe corrosion
3	-2.0	Moderate corrosion
4	-1.0	Mild corrosion
5	-0.5	Slight corrosion
6	0.0	Balanced
7	0.5	Faint scale coating
8	1.0	Slight scale/ encrustation
9	2.0	Mild scale/encrustation
10	3.0	Moderate scale/encrustation
11	4.0	Severe scale/encrustation

Graphical techniques of water quality assessment

Gibbs plot

Gibbs ratio (GR) was employed to determine the dominant mechanism controlling groundwater chemistry and the sources of dissolved ions to understand the interaction between rock and water (Gibbs 1970). GR - I was used to plot the anions ($Cl^- / Cl^- + HCO_3^-$), while GR-II was employed for the cations ($Na^+ + K^+ / (Na^+ + K^+ + Ca^{2+})$) as a function of TDS. See Eqs. 14 and 15.

$$\text{Gibb Ratio I} = Cl / (Cl + HCO_3) \tag{14}$$

$$\text{Gibb Ratio II} = (Na + K) / (Na + K + Ca) \tag{15}$$

Piper's plot

The hydrochemical facies of the groundwater were characterized based on the classification scheme for the subdivisions of Piper's diagram suggested by Back and Hanshaw (1965) (See Fig. 3). The facies were plotted using Rockware Aq.QA software version 1.1.1[1.1.5.1] 2006 edition.

Results and discussion

Physicochemical parameters of groundwater

The physicochemical parameters of groundwater of the three geographical settlements during the dry season are presented in Table 2. The groundwater pH in the peri-urban varied between 3.13 and 7.3 indicating acidic to a slightly alkaline condition. The observed low pH in groundwater of the study area may be linked to dissolved carbon dioxide or increase in groundwater temperature (Robinson et al. 2009). The groundwater parameters in all the sites show a low to moderate variation except at Igando with EC, TDS, Mg^{2+} , Na^+ , Cl^- , HCO_3^- , and SO_4^{2-} in the peri-urban. High sulfate recorded in groundwater can be attributed to leaching from municipal waste and sewage water pollutants (Singh 1994). The dominant cation is Na^+ , and the concentration ranged between 1.9 and 1350 mg/L while Cl^- is the dominant anion and ranged between 4 and 2, 800 mg/L. The high values of these parameters at Igando can be attributed to infiltration of leachates from the dump sites in the area. In the

Fig. 3 Classification of hydro-chemical facies

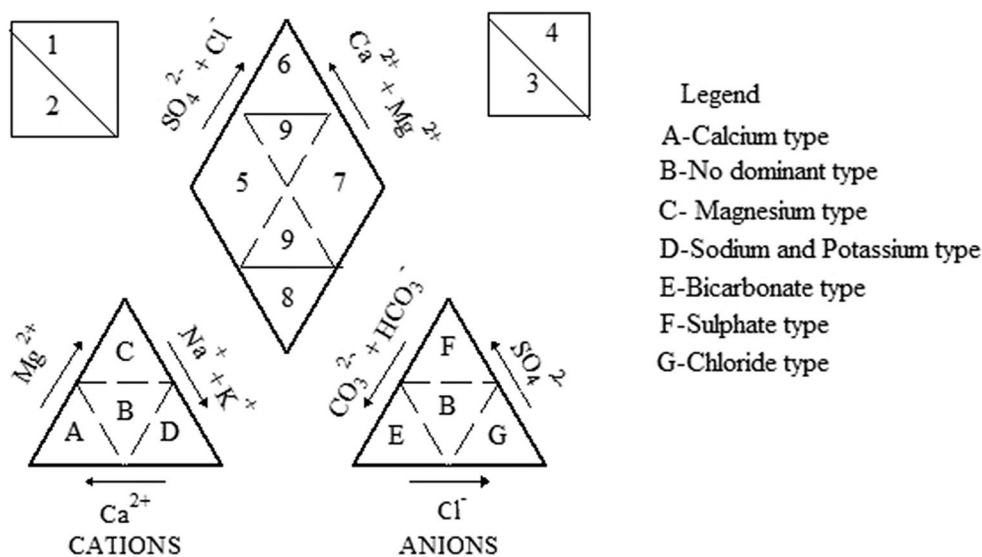


Table 2 Physicochemical parameters of groundwater in the dry season

Sample code	Site	pH	EC	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	HCO ₃ ⁻	SO ₄ ²⁻	CO ₃ ⁻
<i>Peri-urban settlement</i>												
P1	Obadore	5.14	58	42	8	2	5.11	1.35	18	78.4	3	ND
P2	Egan	5.95	135	90	52	24	4.98	1.07	18	178.8	5	ND
P3	Ayobo	5.14	39	28	16	4	3.72	0.86	16	96.2	3	ND
P4	Igando	7.3	9778	4890	52	222	1350	5.62	2800	286.6	82	ND
P5	Ogbomoso	5.32	124	85	41	11	5.88	1.53	22	57.9	5	ND
P6	Iju	4.55	73	55	16	4	6.95	1.35	22	20	3	ND
P7	Ketu	3.13	117	82	20	4	2.59	0.52	8	30	3	ND
P8	Temu	5.22	13	10	10	ND	7.97	1.46	28	67.8	2	ND
P9	Ikoga-Zebbe	4.86	17	12	0.77	0.26	1.87	0	4	66	6	ND
P10	Odo-Kekere	5.54	33	23	25	9	6.98	1.48	12	170	3	ND
P11	Maya	5.73	23	17	17	5	5.62	1.86	10	110	2	ND
P12	Ijede	5.67	91	69	32	6	4.04	1.44	12	80	4	ND
P13	Egbin	4.73	158	112	41	11	9.49	2.11	36	127.6	6	ND
P14	Elepe	5.9	22	23	12	6	3.88	0.73	12	138	2	ND
P15	Selewu	5.32	27	20	11	7	3.72	0.77	12	120	2	ND
<i>Rural settlement</i>												
R1	Kaka	5.37	38	27	13	5	4.26	0.9	16	115.2	3	ND
R2	Abatiwa	5.62	39	27	18	6	5.04	1.82	16	90	2	ND
R3	Odo-Onosa	5.21	113	79	74	26	4.59	1.22	14	159.8	3	ND
R4	Ota-Ikosi	3.9	18	13	13	3	3.98	1.02	12	140	2	ND
R5	Agbowa	6.18	172	115	90	36	2.86	0.54	8	10	4	ND
R6	Odo-Mola	4.83	33	24	4	4	7.56	1.47	24	40	2	ND
R7	Eredo	5.24	25	17	2	2	6.32	0.82	16	20	2	ND
R8	Ibowon	5.38	75	57	20	10	2.16	0.49	6	48.2	3	ND
R9	Igbodu	5.16	59	43	31	5	5.84	1.36	20	60	3	ND
R10	Ilogbo	5.21	349	226	2.8	0.58	53.37	51.69	144	46	4	ND
R11	Okoron	5.92	22	16	1.52	0.44	2.86	4.42	10	93.3	8	ND
R12	Iragbon	4.77	48	36	1.19	0.297	5.62	2.82	18	66	7	ND
R13	Isiu	5.14	85	63	20	6	5.99	1.92	20	86.4	4	ND
R14	Imota	5.01	105	74	19	7	5.68	1.38	22	79	4	ND
R15	Gberigbe	5.88	30	22	21	9	6.58	1.57	12	120	2	ND
<i>Urban settlement</i>												
U1	Ipaja	3.3	227	154	30	8	13.29	2.55	40	18.6	7	ND
U2	Baruwa	5.89	135	94	55	15	2.96	0.62	14	156	6	ND
U3	Alagbado	4.5	77	57	18	2	6.07	1.29	28	40	4	ND
U4	Oke-Odo	4.3	27	18	10	4	3.02	1.05	14	30	2	ND
U5	Ejigbo	5.02	93	64	13	5	7.12	2.08	22	60	4	ND
U6	Egbeda	4.33	119	84	9	3	9.86	2.29	34	18.4	5	ND
U7	Dopemu	5.12	409	274	30	8	30.21	5.81	98	80	9	ND
U8	Oko-Oba	4.99	598	391	50	10	45.3	10.27	146	40	8	ND
U9	Olushosun	3.02	426	289	61	11	41.54	9.79	128.8	10	9	ND
U10	Epe	3.76	191	129	28	8	13.55	2.98	44	30	4	ND
U11	Odogunyan	5.7	151	101	50	12	12.45	2.31	38	114.6	5	ND
U12	Ikorodu	4.4	120	88	14	4	4.02	0.89	36	140	4	ND
U13	Alausa	7.2	102	53	38	2	3.8	0.08	12	181.5	1.2	ND
U14	Shomolu	5.95	362	189	36	24	25.48	15.24	56	42	4	ND
U15	Shogunle	5.85	515	261	24	16	21.26	10.22	52	38	5	ND

All samples are in mg/L except pH and EC ($\mu\text{S cm}^{-1}$)

ND Not detected

rural settlement, pH indicates acidic to moderately alkaline conditions (3.9 to 6.2). The concentration of EC, TDS, K^+ , and Cl^- were relatively high at Ilogbo. These parameters varied between 18 to 349 $\mu S\ cm^{-1}$, 13 to 226 mg/L, 0.5 to 51.7 mg/L, and 6 to 144 mg/L, respectively. High TDS may be due to the impact of anthropogenic sources, such as domestic sewage, septic tanks, and agricultural activities (Logeshkumaran et al. 2015). The observed high EC in groundwater may be linked to nutrient enrichment (Srinivasamoorthy et al. 2014). The concentration of Ca^{2+} and Mg^{2+} was relatively high at Agbowa with a corresponding range of 1.2 and 90 mg/L and between 0.3 and 36 mg/L, respectively. The relatively high concentration of Ca^{2+} and Mg^{2+} can be linked to the water–rock interaction (Todd and Larry 2005). Sodium, K^+ , and Cl^- were low in all the sites except at Ilogbo. High concentration of these parameters can be attributed to seepage and surface /groundwater interaction with the surrounding lagoon. Sodium ranged between 2.2 and 53.4 mg/L, while bicarbonate varied between 10 to 159.8 mg/L. The predominant cation is Ca^{2+} with a mean value of 24.8 mg/L, while HCO_3^- is the dominant anion with an average of 79.0 mg/L. The pH of groundwater in the urban settlement indicates acidic to slightly alkaline conditions (3.0–7.2). A relatively low variation was observed in all the sites except at Oko-Oba which has a relatively high concentration of EC, TDS, and Cl^- with the corresponding mean of 245.7 $\mu S\ cm^{-1}$, 156.2 mg/L, and 54.2 mg/L, respectively. High chloride in groundwater may result from inadequate underground drainage system and poor management of the environment around the abattoir in the area (Logeshkumaran et al. 2015). The concentration of HCO_3^- varied between 10 to 181 mg/L with a mean of 70 mg/L. The dominant cation is Ca^{2+} with an average of 31.5 mg/L, while HCO_3^- is the dominant anion.

Table 3 presents the variations of the physicochemical parameters of groundwater during the wet season in the study area. The result revealed that in the peri-urban, EC, TDS, Na^+ , K^+ , Cl^- , and HCO_3^- were extremely higher at Igando compared to other sites. High bicarbonate in groundwater may result from atmospheric CO_2 and CO_2 released from the organic decomposition in the soil around the dumpsite (Rao 2002). Electrical conductivity ranged between 15 and 6600 $\mu S\ cm^{-1}$, TDS between 13 and 3300 mg/L. Sodium varied between 2 to 1142 mg/L, while potassium ranged between 0.1 and 1102 mg/L. Chloride ranged between 2 and 2280 mg/L, while bicarbonate varied between 14 to 228 mg/L. The groundwater pH indicates moderately acidic to slightly alkaline (4.6–7.4). The variations of Ca^{2+} , Mg^{2+} , SO_4^{2-} , and CO_3^{2-} are low. Sodium and chloride are the dominant cation and anion in the area. There is no significant variation in the groundwater parameters in the rural settlement except for Ilogbo with a relatively high EC, TDS, and Cl^- . The pH is moderately acidic to neutral

(4.8–7.0). The dominant cation is Na^+ with a mean value of 58.4 mg/L, while Cl^- is the dominant anion with an average of 137 mg/L. There are slight variations in the groundwater parameters such as EC, TDS, Na^+ , Cl^- , and HCO_3^- in the urban settlement. Electrical conductivity ranged between 26 and 509 $\mu S\ cm^{-1}$, TDS between 15 and 332 mg/L. Sodium varied between 4.1 to 119.5 mg/L, Cl^- between 6 to 125 mg/L, and HCO_3^- between 8 to 139 mg/L. Sodium and bicarbonate are the dominant cation and anion with an average of 41.9 mg/L and 49.5 mg/L, respectively.

Bivariate analysis of groundwater parameters

The seasonal variations of the physicochemical parameters of groundwater in the study area show that about 95.6% and 60% of the sampling sites had pH values below the minimum guideline for potable water prescribed by WHO (2011). Similarly, only 2.2% of the measured EC fall under high enrichments of salts ($EC > 3000\ \mu S/cm^{-1}$) in both seasons (Rao et al. 2012; Vincy et al. 2015). The classification of TDS revealed that only 2.2% of the samples are moderately saline in both seasons (Carroll 1962). Total hardness of groundwater shows that approximately 51.1, 28.9, 15.6, and 4.4% of the samples in the dry season indicate soft, moderately hard, hard, and very hard, respectively, while 93.3% and 6.97% represent soft and moderately hard water in the wet season, respectively (Todd and Larry 2005). The distribution of chloride in the study area shows that 2.2% indicate extremely fresh/brackish-salt in the dry season, while 11.1% and 2.2% are extremely fresh and brackish-salt, respectively, in the wet season (Stuyfzand 1989). The distribution of bicarbonate shows that 84.4% and 66.7% of the samples fall under poor zone in the wet and dry seasons, respectively (WHO 2011). The result of the seasonal paired sample *T* test shows significant variations between pH, Ca^{2+} , HCO_3^- , and Mg^{2+} in the study area (Table 4). The wet season parameters are in asterisk.

Multivariate analysis of groundwater parameters

The result of the factor analysis (FA) extracted two factors and explained 73.5% of the total variance in the dry season, while three factors were obtained in the wet season, accounting for 84.2% of the total variance (Table 5).

Factor I, in the dry season, accounts for 61.8% of the total variance with high loading on EC, TDS, Ca^{2+} , Mg^{2+} , Na^+ , Cl^- , and SO_4^{2-} . These parameters represent seawater constituents (Lu et al. 2012). Factor II accounts for 11.6% of the total variance and is characterized by medium loadings of Ca^{2+} , K^+ , and HCO_3^- (Table 5). In the wet season, factor I accounts for 59.4% of the total variance, with high loadings on EC, TDS, Na^+ , K^+ , Cl^- , and SO_4^{2-} . The high loading on Cl^- may be attributed to saltwater intrusion,

Table 3 Physicochemical parameters of groundwater in the wet season

Sample code	Site	PH	EC	TDS	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	Cl ⁻	HCO ₃ ⁻	SO ₄ ²⁻	CO ₃ ⁻
<i>Peri-urban settlement</i>												
P1	Obadore	5.8	64	44	1.71	0.1	24.3	0.27	20	60	3	0.01
P2	Egan	6.5	102	69	17.4	0.44	17.12	1.05	4	80	4	0.01
P3	Ayobo	6.1	129	89	4.18	1.62	53.48	0.22	108	49	6	0.01
P4	Igando	6.3	6600	3300	4.84	1.95	1142	1102	2250	228	46	0.1
P5	Ogbomoso	6.1	116	79	28.3	0.39	13.57	1.39	16	42	4	0.03
P6	Iju	5.8	70	48	4.8	4.74	2.89	0.98	7	14	2	0.04
P7	Ketu	4.6	123	87	12.4	0.14	3.17	0.47	4	26	2	0
P8	Temu	6.8	15	19	6.24	0.06	8.05	1.42	21	55	2	0.01
P9	Ikoga-Zebbe	4.9	21	14	0.73	0.21	1.96	0.08	2	31	5	0.02
P10	Odo-Kekere	6.5	29	21	6.68	0.04	12.86	1.94	7	138	2	0.06
P11	Maya	6.2	19	13	1.68	0.07	5.36	0.24	10	85	2	0.01
P12	Ijede	7.4	111	77	14.9	0.92	32.77	4.77	10	72	5	0.01
P13	Egbin	6.6	152	99	16.6	1.46	35.57	5.76	29	105	5	0.08
P14	Elepe	6.5	36	25	4.31	0.09	9.38	0.47	12	100	3	0.03
P15	Selewu	6.7	23	14	4.7	0.32	3.78	0.82	8	94	2	0.01
<i>Rural settlement</i>												
R1	Kaka	6.4	34	22	3.24	2.4	5.23	0.4	4	90	5	0.01
R2	Abatiwa	6.6	26	18	2.72	0.07	8.29	0.15	14	80	2	0.01
R3	Odo-Onosa	6.5	103	70	14.3	0.79	9.18	10.57	16	62	4	0.08
R4	Ota-Ikosi	5.5	15	11	5.28	0.2	3.4	0.8	6	57	2	0.01
R5	Agbowa	6.7	167	106	40.1	0.91	18.15	6.98	5	15	5	0.04
R6	Odo-Mola	5.3	35	38	0.4	1.04	7.8	1.33	18	37	2	0.1
R7	Eredo	6.2	29	18	0.08	0.09	6.91	0.81	12	18	2	0.01
R8	Ibowon	6.7	87	62	10.5	1.07	2.7	0.29	4	40	3	0.04
R9	Igbodu	6.1	72	48	14.6	1.3	5.83	1.33	12	70	2	0.02
R10	Ilogbo	5.6	358	231	2.6	0.44	58.4	49.42	137	37	3	0.01
R11	Okoron	6	26	19	1.42	0.38	3.1	3.68	8	75	6	0.01
R12	Iragbon	4.8	52	42	0.59	0.18	5.84	2.14	15	34	6	0.06
R13	Isiu	6.7	84	58	5.56	0.65	18.87	1.03	16	55	4	0.01
R14	Imota	6.7	110	76	17.1	0.45	23.98	2.46	14	68	5	0.01
R15	Gberigbe	7	31	22	7.08	0.11	3.91	0.47	12	104	3	0.03
<i>Urban settlement</i>												
U1	Ipaja	4.4	243	162	3.31	0.53	82.36	3.09	54	15	6	0
U2	Baruwa	5.8	106	73	27.2	0.35	5.36	1.57	8	139	4	0.02
U3	Alagbado	5.8	65	53	3.8	0.7	8.67	0.6	9	52	3	0.02
U4	Oke-Odo	5.5	26	15	1.82	0.59	5.44	0.3	6	20	2	0.03
U5	Ejigbo	5.1	229	148	14.3	1.34	58.24	4.16	42	25	5	0.01
U6	Egbeda	5.6	157	102	4.92	0.43	55.39	2.76	38	12	5	0.01
U7	Dopemu	5.2	423	275	13.2	0.76	119.5	7.36	106	30	8	0.02
U8	Oko-Oba	5.2	505	332	43.1	1.58	109.9	22.22	125	15	6	0.01
U9	Olushosun	3.6	438	296	32.6	6.8	30.64	8.4	102	8	8	0.06
U10	Epe	4.1	176	158	13.8	0.84	13.87	2.53	31	23	3	0.01
U11	Odogunyan	6.7	149	100	11	0.72	38.62	4.89	38	82	5	0.01
U12	Ikorodu	6.4	117	79	5.36	0.26	4.4	1.2	24	128	3	0.01
U13	Alausa	7.1	98	43	9.24	0.08	4.1	0.42	10	68	1	0.01
U14	Shomolu	6.8	356	174	11.6	4.6	27.64	14.8	43	35	3	0.02
U15	Shogunle	6.6	509	247	10.8	2.8	23.8	10.26	37	43	3	0.01

Table 4 Seasonal paired samples *T* test of groundwater parameters

Parameters	Mean	SD	Std. error mean	95% confidence interval		<i>t</i>	<i>Df</i>	<i>p</i> -value
				Lower	Upper			
Pair 1 pH–pH*	– 0.84	0.6	0.1	– 1.01	– 0.7	– 8.9	44	0
Pair 2 EC–EC*	67.4	475.2	70.8	– 75.33	210.2	0.9	44	0.3
Pair 3 TDS–TDS*	34.4	238.0	35.5	– 37.14	105.9	0.9	44	0.3
Pair 4 Ca ²⁺ –Ca ²⁺ *	15.3	13.9	2.01	11.14	19.5	7.4	44	0
Pair 5 Mg ²⁺ –Mg ²⁺ *	11.6	32.6	4.9	1.82	21.4	2.4	44	0.0
Pair 6 Na ⁺ –Na ⁺ *	– 7.8	39.5	5.9	– 19.64	4.1	– 1.3	44	0.2
Pair 7 K ⁺ –K ⁺ *	– 25.0	163.4	24.4	– 74.08	24.1	– 1.0	44	0.3
Pair 8 Cl [–] –Cl [–] *	15.0	83.2	12.4	– 9.97	40.1	1.2	44	0.2
Pair 9 HCO ₃ [–] –HCO ₃ [–] *	24.1	28.2	4.2	15.62	32.6	5.7	44	0
Pair 10 SO ₄ ^{2–} –SO ₄ ^{2–} *	1.1	5.4	0.8	– 0.54	2.7	1.4	44	0.2

Table 5 Factor analysis matrix in the dry and wet seasons

Parameters	Dry season factors		Parameters	Wet season factors		
	<i>F</i> ₁	<i>F</i> ₂		<i>F</i> ₁	<i>F</i> ₂	<i>F</i> ₃
pH	0.4	0.3	pH	– 0.1	0.9	– 0.1
EC	0.9	0.0	EC	0.9	0.1	0.1
TDS	0.9	0.0	TDS	0.9	0.0	0.1
Ca ²⁺	0.2	0.6	Ca ²⁺	– 0.1	0.0	0.8
Mg ²⁺	0.9	0.2	Mg ²⁺	0.2	– 0.3	0.7
Na ⁺	0.9	0.0	Na ⁺	0.9	0.1	0.0
K ⁺	0.1	– 0.6	K ⁺	0.9	0.1	0.0
Cl [–]	0.9	0.0	Cl [–]	0.9	0.1	0.0
HCO ₃ [–]	– 0.0	0.6	HCO ₃ [–]	0.6	0.7	– 0.2
SO ₄ ^{2–}	0.9	0.0	SO ₄ ^{2–}	0.9	0.0	0.1
CO ₃ [–]	ND	ND	CO ₃ [–]	0.5	0.1	0.4
% of variance	61.8	11.6	% of variance	59.4	15.6	9.3
Cumulative %	61.8	73.5	Cumulative %	59.4	74.9	84.2

ND Not detected

pollutions from sewage, and industrial wastewater (Amadi et al. 2012). Similarly, high loading on Ca²⁺ indicates the impact of weathering of minerals such as calcite and feldspar on the aquifer system (Sahu et al. 2016). High loading of EC, TDS, Na⁺, and SO₄^{2–} indicates the influence of salinity on the groundwater system (Abdel Latif and El Kashouty 2010; Lu et al. 2012; Raju et al. 2015). Factor II accounts for 15.6% of the total variance and is characterized by high to medium loading of pH and HCO₃[–]. Factor III accounts for 9.3% of the total variance with high and medium positive loading on Ca²⁺ and Mg²⁺, respectively. The constituents of EC and TDS can be categorized as an anthropogenic source of pollution from leachates, sewage, and wastewater in the area (Lu et al. 2012). The extreme values of EC and TDS from Igando (P₄), a sample site near a dumpsite, are very conspicuous.

Mechanism controlling groundwater

The Gibb's plot revealed the dominance of rock-weathering as the major mechanism controlling groundwater chemistry and the sources of dissolved ions in the study area (Gibbs 1970). The results show that more than 95% and 93% of the anions and cations are dominated by rock-weathering in both seasons (Figs. 4 and 5). Studies by Logeshkumaran et al. (2015) confirm the predominance of the rock–water interaction dominance and evaporation in Chennai based on the Gibbs plot. Narany et al. (2014) indicated that the hydrochemistry of Amol-Babol Plain is influenced by rock dominance, carbonate and silicate rock weathering. The findings of Sahu et al. (2016) show that the enrichment of the major ions in the groundwater of West Bengal is due to rock-weathering. Yidana et al. (2012) and Prasanna et al. (2008) reported the dominance of water–rock interaction as the major factors contributing to solute in the study area.

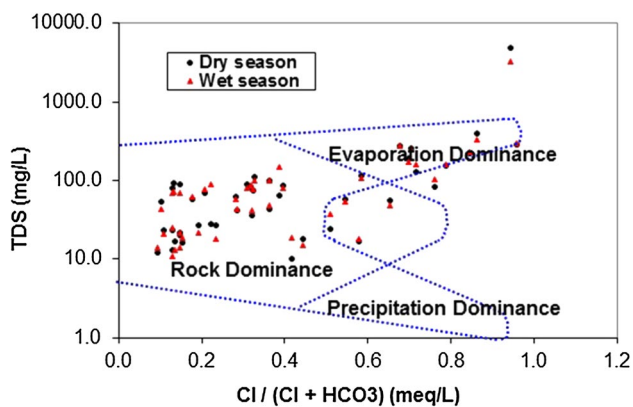


Fig. 4 Gibbs plot of anion

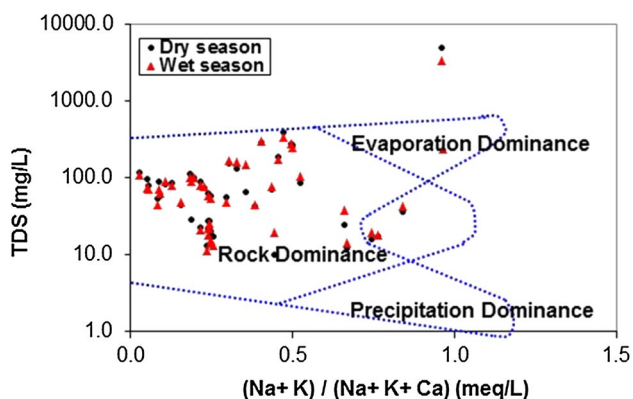


Fig. 5 Gibbs plot of cation

Water quality index

Drinking water quality

The results of the drinking WQI show a broad range between 10 and 573 in the peri-urban. The range is relatively low between 10 and 35 and between 11 and 47, respectively, in the rural and urban settlements during the dry season. The wet season value in peri-urban ranged between 9 and 430, while it varies from 10 to 32 and from 9 to 44 in the rural and urban settlements, respectively. Approximately 95.6% and 2.2% of the sampling sites have excellent/good water quality, while the remaining 2.2% indicates unsuitable water for drinking in the peri-urban settlement during the dry season (Table 6). The computed WQI shows that in the wet season, all the sampling sites have excellent quality except at Igando, a peri-urban settlement indicating unsuitable water for drinking (Table 6). The result of the drinking WQI revealed that the rural settlement has the lowest range in both seasons. This can be attributed to the low level of anthropogenic activities that are capable of degrading

Table 6 Water quality index and classification in the study area

Sample code	Site	WQI dry season		WQI wet season	
		Classification		Classification	
<i>Peri-urban settlement</i>					
P1	Obadore	14	Excellent	14	Excellent
P2	Egan	33	Excellent	18	Excellent
P3	Ayobo	15	Excellent	22	Excellent
P4	Igando	573	Unsuitable	430	Unsuitable
P5	Ogbomoso	51	Good	18	Excellent
P6	Iju	16	Excellent	13	Excellent
P7	Ketu	16	Excellent	15	Excellent
P8	Temu	17	Excellent	15	Excellent
P9	Ikoga-Zebbe	10	Excellent	9	Excellent
P10	Odo-Kekere	18	Excellent	14	Excellent
P11	Maya	15	Excellent	12	Excellent
P12	Ijede	18	Excellent	20	Excellent
P13	Egbin	25	Excellent	23	Excellent
P14	Elepe	19	Excellent	17	Excellent
P15	Selewu	15	Excellent	13	Excellent
<i>Rural settlement</i>					
R1	Kaka	19	Excellent	16	Excellent
R2	Abatiwa	16	Excellent	13	Excellent
R3	Odo-Onosa	35	Excellent	18	Excellent
R4	Ota-Ikosi	12	Excellent	10	Excellent
R5	Agbowa	41	Excellent	24	Excellent
R6	Odo-Mola	13	Excellent	12	Excellent
R7	Eredo	10	Excellent	11	Excellent
R8	Ibowon	18	Excellent	16	Excellent
R9	Igbodu	16	Excellent	15	Excellent
R10	Ilogbo	31	Excellent	32	Excellent
R11	Okoron	14	Excellent	12	Excellent
R12	Iragbon	14	Excellent	12	Excellent
R13	Isiu	16	Excellent	16	Excellent
R14	Imota	16	Excellent	18	Excellent
R15	Gberigbe	15	Excellent	14	Excellent
<i>Urban settlement</i>					
U1	Ipaja	20	Excellent	23	Excellent
U2	Baruwa	29	Excellent	18	Excellent
U3	Alagbado	16	Excellent	13	Excellent
U4	Oke-Odo	11	Excellent	9	Excellent
U5	Ejigbo	17	Excellent	23	Excellent
U6	Egbeda	16	Excellent	20	Excellent
U7	Dopemu	36	Excellent	37	Excellent
U8	Oko-Oba	47	Excellent	44	Excellent
U9	Olushosun	39	Excellent	34	Excellent
U10	Epe	21	Excellent	18	Excellent
U11	Odogunyan	25	Excellent	22	Excellent
U12	Ikorodu	18	Excellent	18	Excellent
U13	Alausa	23	Excellent	16	Excellent
U14	Shomolu	38	Excellent	29	Excellent
U15	Shogunle	38	Excellent	33	Excellent

groundwater quality in the area. Unlike the observed unsuitable water for drinking found at one of the sites at Igando, the deterioration of the groundwater quality can be linked to the infiltration of leachates from the nearby dumpsite into the well. The result of the present study shows that the WQI of the study area is suitable for drinking. Similar studies by Ebong et al (2017) reported the suitability of groundwater quality from Abi, southeastern Nigeria, for drinking and irrigation purposes based on WQI. The findings of Etim et al (2013) also concluded that the water sources from the borehole and pipe-borne water in the Niger-Delta region of Nigeria based on WQI are safe for human consumption and for other domestic purposes. Also, Olatunji et al (2015) reported the suitability of groundwater quality for drinking based on their study in Ilorin metropolis, Nigeria. Balogun and Adegun (2013) reported the high concentration of EC, TDS, Cl, and trace metals in their study around Igando. A similar study by Yidana and Yidana (2010) asserts that the WQI of the Voltaian sedimentary basin in Ghana is suitable for drinking purpose.

Groundwater salinization

The result of the RI ranged between 0.1 and 22.2 meq/L in the dry season and between 0.1 and 21.8 meq/L in the wet season. The distribution of groundwater salinity in the study area shows that approximately 48.9% and 46.7% of the sampling sites in the dry season are unaffected and slightly affected by salinity, respectively. Only 4.4% of the samples sites are strongly affected by salinity (Fig. 6). The RI during the wet season indicates that 46.7% of the sampling sites are unaffected/slightly affected by salinity, while 6.6% are strongly affected by salinity (Fig. 7). The impact of salinity on the groundwater quality around Igando and Oko-Oba is indicative of the land use/ anthropogenic activities resulting from dumpsite and abattoir in the settlement, respectively. The result of the RI in the present study is attributed to land use/anthropogenic activities in the study area. A similar study by Amadi et al (2012) reported groundwater quality deterioration of the coastal aquifers of Eastern Niger-Delta Nigeria, due to salinity and anthropogenic interference.

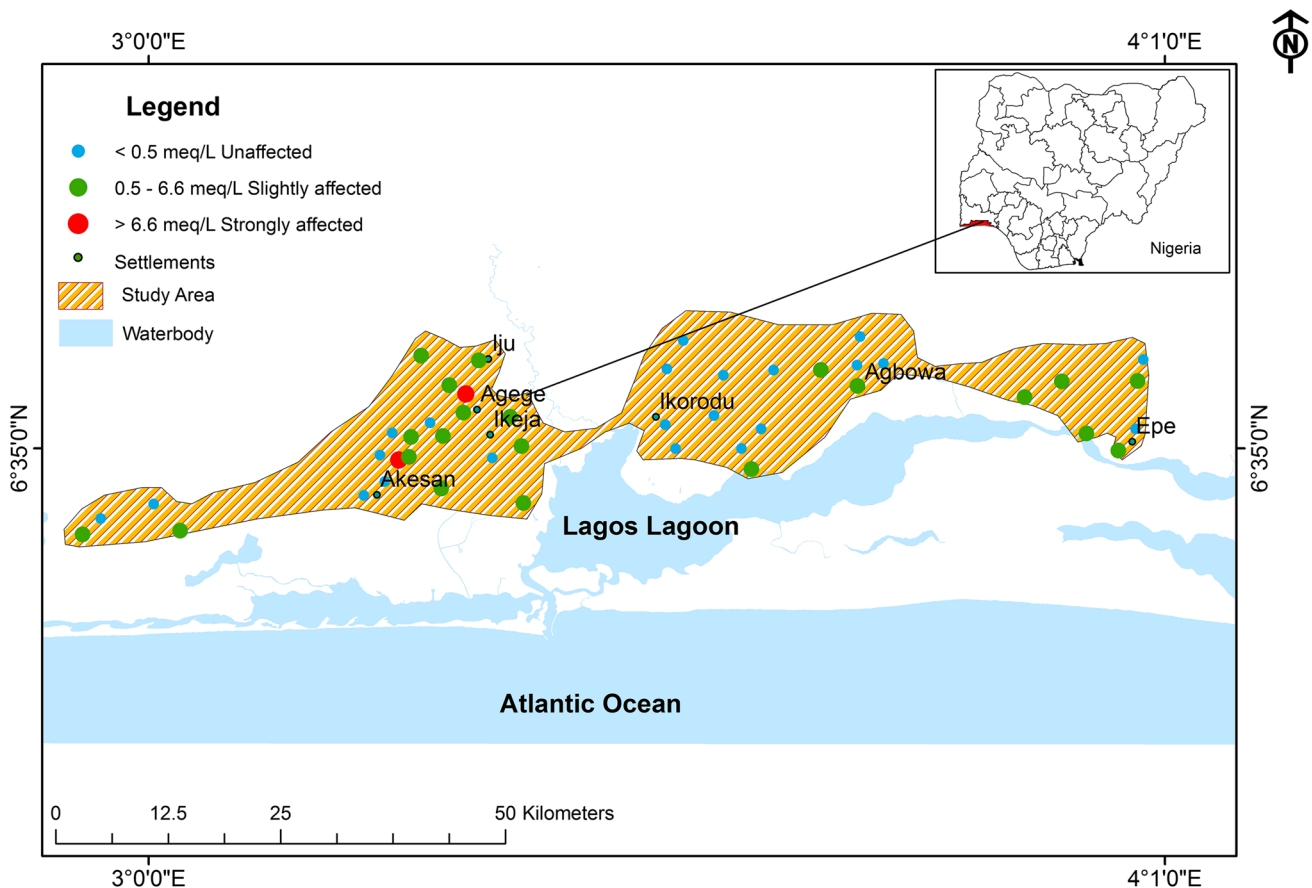


Fig. 6 Distribution of Revelle index in the dry season

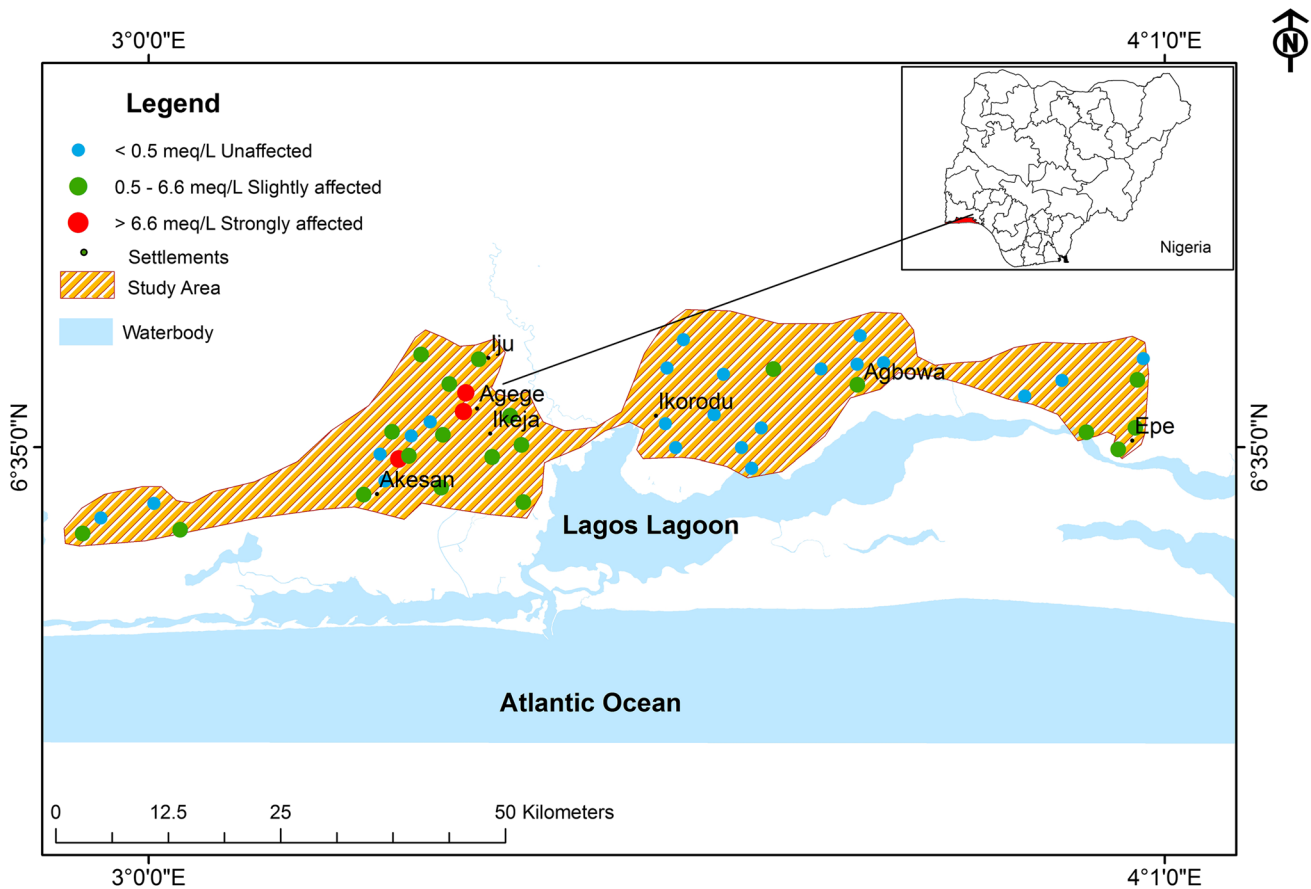


Fig. 7 Distribution of Revelle index in the wet season

Water stability index

Langelier Saturation Index

The results of the LSI varied from -5.81 to -0.16 with an average of -3.28 in the dry season. It varies from -5.52 to -1.06 with an average of -3.05 in the wet season. The dry season value of LSI shows that 31.1% of the samples indicate very severe/ moderate corrosion. About 28.9% of the groundwater samples indicate severe corrosion, while 4.4% shows mild/slight corrosion in the dry season (Fig. 8). During the wet season, 35.6, 24.4, 22.2, and 17.8% of the samples are indicative of moderate, severe, very severe, and mild corrosion, respectively (Fig. 9). The severe cases of corrosion in the study area can be attributed to the high value of pH, TDS, TH, and HCO_3^- in the study sites (Gholizadeh et al. 2017). The results of the LSI show that the groundwater is corrosive due to the high value of pH, TDS, TH, and HCO_3^- in the study area. A study conducted by Ibeneme et al (2013) on the spring water at Ife-Owutu, Southeastern based on LSI, inferred that the water is moderate to severely corrosive. Similarly,

Ozoko (2015) reported that the water sources in Abakaliki, Nigeria, are very corrosive in all the samples.

Pipers plot

Characterization of Hydrochemical facies of groundwater

The hydrochemical facies of the study area can be classified into four major categories based on the section of the diamond shape according to the classification scheme by Walton (1962). The first group is primary hardness and consists of calcium, magnesium, and bicarbonate. This water type falls within the section designated as 5 in Piper’s plot. The classification shows that primary hardness accounted for 59.9% and 31.8% of the samples in the dry and wet seasons, respectively. The second class is secondary hardness and comprised of sulfate, chloride, magnesium, and calcium (Back and Hanshaw 1965; Walton 1962; Tay and Kortatsi 2008). This category is designated as 6 in Piper’s plot and represents 20% and 4.5% in the dry and wet seasons,

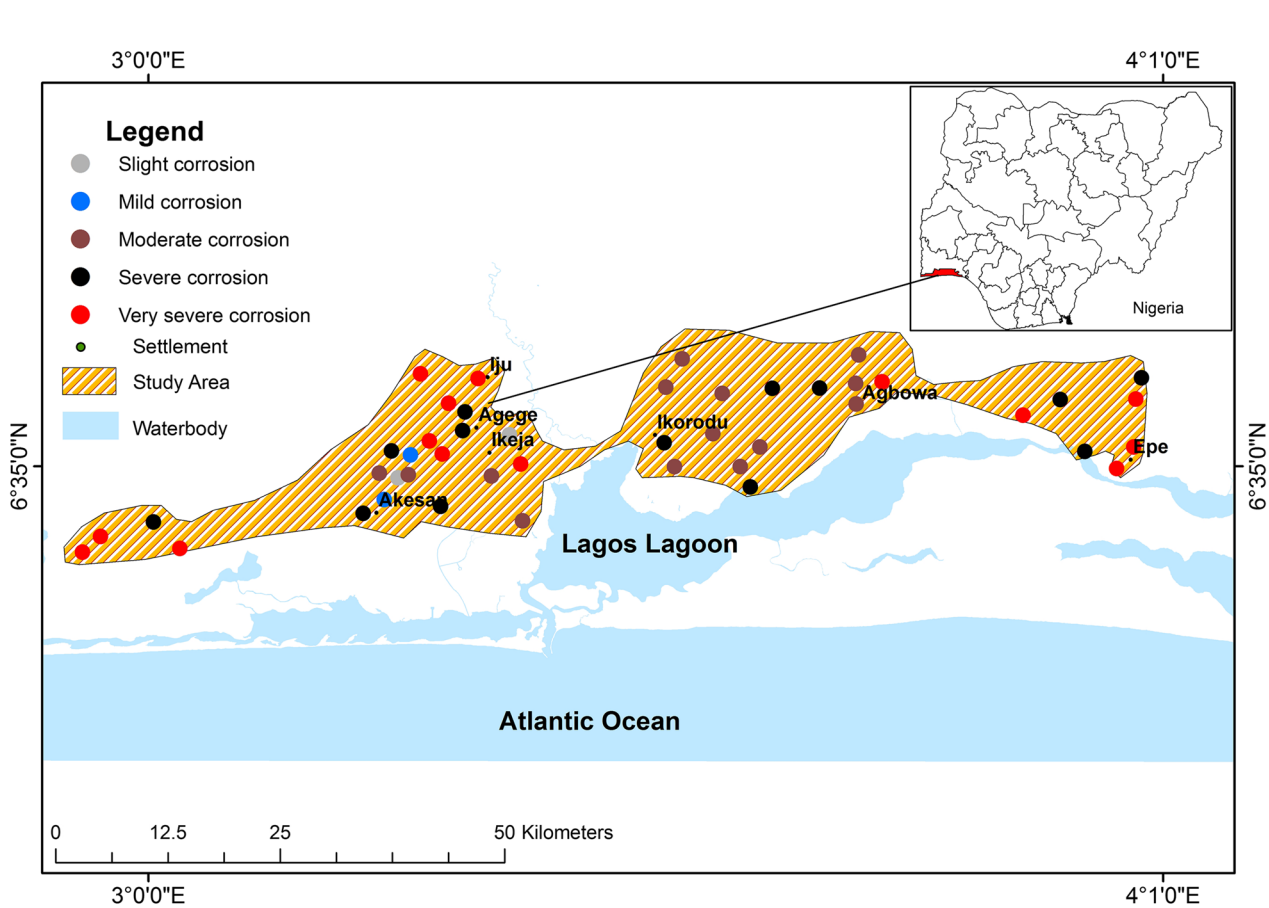


Fig. 8 Distribution of Langelier index in the dry season

respectively. The third class is known as primary salinity and comprised of alkali metals, sulfate, and chloride. This category is regarded as brackish or extreme saline water. It occupies the portion designated as 7 in Piper's plot and accounts for 22.7% and 6.7% in the wet and dry seasons, respectively. The fourth class is mixed waters which usually result from multiple mineral dissolution or mixing of chemically distinct water types (Walton 1962; Sahu et al. 2016). This group occupies the portion designated 9 in Piper's diagram. Mixed waters account for 41% and 13.4% of the samples in the wet and dry seasons, respectively (Back and Hanshaw 1965; Walton 1962; Tay and Kortatsi 2008). Based on Table 7, the four classes of the hydrochemical facies can be grouped into two major facies. The first group is the concentration of cation which is dominated by Ca–Na type representing 87% of the samples in the dry season and 62% during the wet seasons. HCO_3^- water type is the second group and predominated in the dry season with 69% sample and with 67% during the wet season (Figs. 10 and 11).

A study conducted by Sahu et al. (2016) identified three major water types, namely fresh, mixed, and brackish. They inferred that the freshwater type is dominated by sodium which is indicative of active flushing of the aquifer. They concluded that chloride-rich 'brackish' represents freshening of modified connate water why the 'mixed' type evolved due to the hydraulic mixing of 'fresh' and 'brackish' waters. Ansari et al. (2015) reported the dominance of Ca–Mg– HCO_3^- and Ca–Mg– HCO_3^- – SO_4 waters in the Himalayas, India. In a similar study, Narany et al. (2014) reported that the groundwater indicates low mineralized Ca– HCO_3^- , Ca–Na– HCO_3^- , and Ca–Cl water types to high mineralized Na–Cl water type. The findings of Logeshkumaran et al. (2015) indicated that the groundwater samples are dominated by Na–Cl and mixed Ca–Mg–Cl type. Jamshidzadeh and Mirbagheri (2011) reported the dominance of Na–Cl water type. A study by Sadashivaiah et al. (2008) also shows the predominance of Ca–Mg– HCO_3^- water type during the pre- and post-monsoon seasons in Taluk.

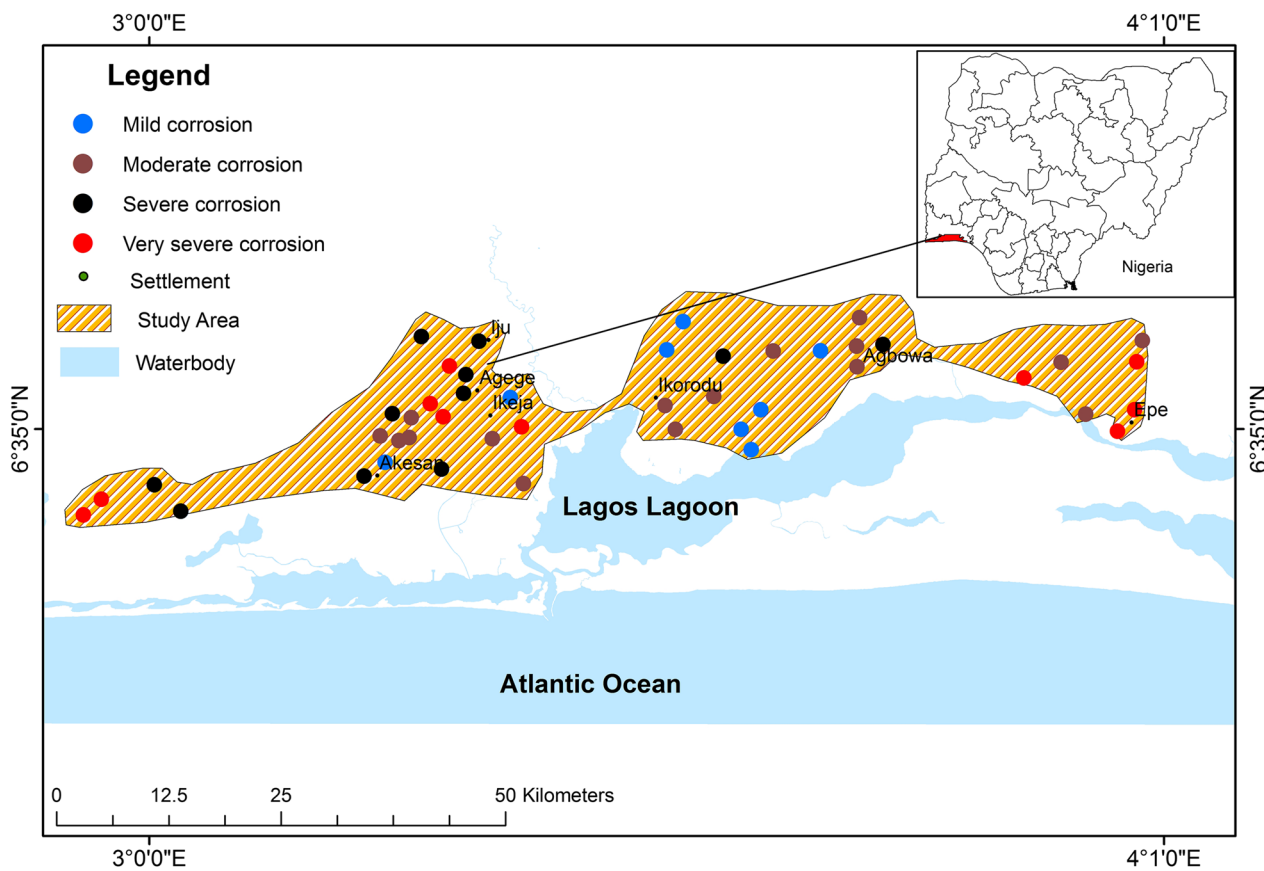


Fig. 9 Distribution of Langelier index in the wet season

Table 7 Characterization of groundwater of the study area on Piper’s plot

Subdivision of the diamond	Characteristics of the subdivision of the diamond fields	Percentage of the samples/season	
		Dry season	Wet season
1	Alkaline earth(Ca + Mg) exceeds alkalies (Na + K)	87	38
2	Alkalies exceeds alkaline earths	13	62
3	Weak acids(CO ₃ + HCO ₃) exceed strong acids(SO ₄ + Cl)	67	69
4	Strong acids exceed weak acids	33	31
5	Magnesium bicarbonate type	60	31.1
6	Calcium chloride type	6.7	2.2
7	Sodium chloride type	6.7	24.4
8	Sodium bicarbonate type	0	6.7
9	Mixed type (no cation–anion exceed 50%)	26.6	35.6

Conclusions

Integrated approaches to various water quality indices, chemometric methods, such as multivariate statistical analysis and geostatistical technique, are employed in this study to assess groundwater quality and the hydrochemical

processes in Lagos, Nigeria. The pH of groundwater indicates acidic to slightly alkaline in the peri-urban and urban settlements, while in the rural area it shows acidic to moderately alkaline in the dry season. The dominant cation and anion in the rural and urban settlements are Ca²⁺ and HCO₃⁻, while Na⁺ and Cl⁻ predominate in the peri-urban

Fig. 10 Hydrochemical facies of groundwater in the dry season

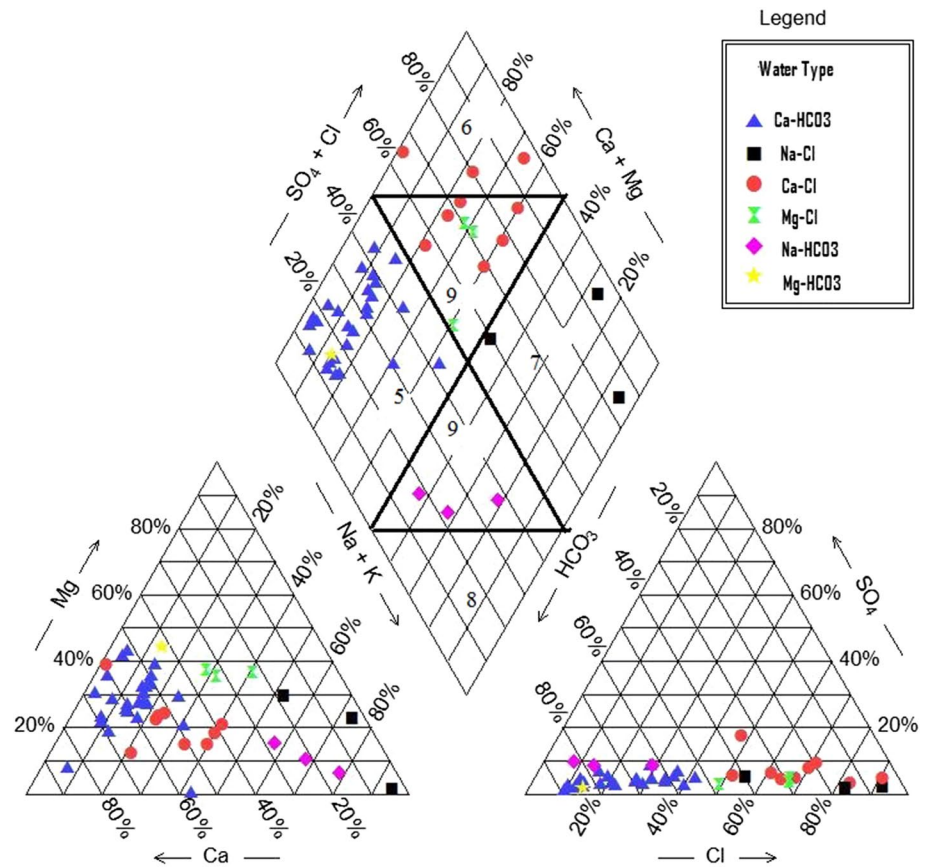
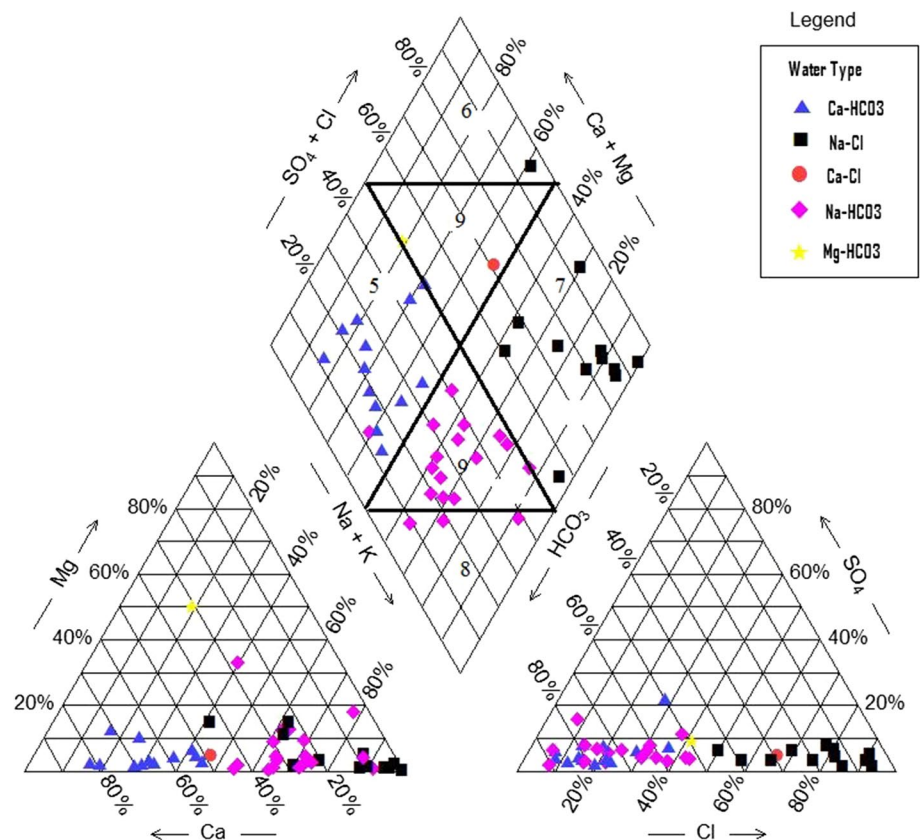


Fig. 11 Hydrochemical facies of groundwater in the wet season



during the dry season. In the wet season, pH indicates moderately acidic to slightly alkaline. Sodium and chloride are the dominant cation and anion in peri-urban. The pH is moderately acidic to neutral in the rural, and the dominant cation and anion are Na^+ and Cl^- . The dominant cation and anion are sodium and bicarbonate in the urban settlement. The seasonal variations of the physicochemical parameters of groundwater in the study area show that about 95.6% and 60% of the sampling sites had pH values below the minimum guideline for drinking water. About 2.2% of the measured EC and TDS fall under high enrichments of salts and moderately saline, respectively, in both seasons. The TH shows that 4.4% and 6.9% of the samples are very hard and moderately hard in the dry and wet seasons, respectively. The distribution of chloride shows that 2.2% of the samples indicate brackish-salt in both seasons, while bicarbonate shows that 84.4% and 66.7% of the samples fall under poor zone in the wet and dry seasons, respectively. The seasonal paired sample *T* test shows significant variations among four parameters including pH, Ca^{2+} , HCO_3^- , and Mg^{2+} . The result of the FA explained 73.5% and 84.2% of the total variance in the dry and wet seasons, respectively. Two major factors were extracted, namely salinity and weathering of minerals. The salinity factors result from EC, TDS Na^+ , K^+ , Cl^- , SO_4^{2-} , and anthropogenic source of pollution from leachates, sewage, and wastewater. The weathering of minerals is due to high loading of Ca^{2+} . The mechanism controlling groundwater chemistry shows that more than 95% and 93% of the anions and cations are dominated by rock-weathering process in both seasons. The results of the drinking WQI in the dry season range between 10 and 573 and between 9 and 430 in the wet season. Approximately 95.6% and 2.2% of the sampling sites have excellent/good water quality, while 2.2% indicates unsuitable water for drinking in the dry season.

The wet season WQI in all the sites has excellent water quality except one site at Igando indicating unsuitable water for drinking. The observed unsuitable water for drinking in the study area is attributed to the land use resulting from dumpsite. The RI ranged between 0.1 and 22.2 meq/L in the dry season and between 0.1 and 21.8 meq/L in the wet season. The distribution of the RI shows that only 4.4% of the samples sites are strongly affected in the dry season. The wet season RI indicates 6.6% of the samples are strongly affected by salinity. The impact of salinity is indicative of the land use/ anthropogenic activities resulting from dumpsite and abattoir in the study area. The results of the LSI varied from -5.81 to -0.16 with an average of -3.28 in the dry season. During the wet season, LSI varies from -5.52 to -1.06 with an average of -3.05 in the wet season. About 31.1% and 28.9% of the samples indicate very severe/severe in the dry season. During the wet season, 22.2% and 24.4%

of the samples are indicative of severe and severe corrosion, respectively. The severe cases of corrosion in the study area can be attributed to the high value of pH, TDS, TH, and HCO_3^- . The cation concentration is dominated by Ca–Mg water type in the dry season, while Na–K type predominates in the wet season. The anion shows that HCO_3^- water type predominated in both seasons. The hydrochemical facies of the study area were grouped into four categories. The primary hardness accounted for 59.9% and 31.8% of the samples in the dry and wet seasons, respectively. Secondary hardness represents 20% and 4.5% in the dry and wet seasons, respectively. Primary salinity accounts for 22.7% and 6.7% in the wet and dry seasons, respectively. Mixed waters account for 41% and 13.4% of the samples in the wet and dry seasons, respectively. The findings revealed that the groundwater quality is suitable for drinking. Leachates, salinity, and land use constitute a major threat to groundwater sustainability in the study area. The study contributes to knowledge in mapping the distributional patterns of groundwater salinization and water stability index. It also identified the major mechanism controlling groundwater chemistry, sources of groundwater pollution and delineation of water types in the study area as baseline information for effective groundwater management.

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Compliance with ethical standards

Conflict of interest We the authors declared that we have no competing interests and that all the authors have seen and approved the revised version of this manuscript.

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