Assessment and mapping of the spatial trend in groundwater quality in Abeokuta, Nigeria

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The growth and development of a city is no doubt one of the factors that could affect the quality of water sources. Nevertheless, the level of water contamination arising from increasing population and urbanization is expected to vary from one region to the other depending on the measures taken to prevent the pollution. This study assessed groundwater quality in Abeokuta city towards the identification of major contaminants in nine (north, north-east, east, south-east, south, south-west, west, north-west and core-central) specific areas of the city. Available groundwater quality data for Abeokuta city over a period of fifteen years (2001- 2015) was acquired from archive and used to establish the spatial variation of groundwater quality across the highlighted categorized nine sections of the city. The Data was analyzed using descriptive (mean and standard deviation) statistics and spatial (geo-statistical analysis) assessment. Results show that the core central part of the city are the recent bank for high values of parameters such as pH, EC, TDS, Na, SO_4^{2-} and Fe. Parameters such as Ca, Mg and K are currently more pronounced in the northern areas; whereas HCO_3^-, Zn, and Cu have more concentrations in the southern parts of the city. Also, lately concentrations of Cl, NO_3^- and Pb are increasing in the southwestern section, while Cd majorly occurs in the western part of the city. Chloride – nitrate ratio shows that similar sources of chloride and nitrate introduction into groundwater only exist in the northern, southwestern and western sections. The paper concluded that there is an accumulated increase in the values of all the listed parameters within year 2006 to 2010, which can be associated to major road rehabilitation/construction in most parts of Abeokuta city in that period.

Key words: Abeokuta, developing city, groundwater, groundwater quality, mapping, spatial trend analysis.

INTRODUCTION

The quality of water and its quantity is a vital concern to mankind since water is directly linked with human welfare (Balakrishnan et al., 2011). The rate of urbanization in Nigeria is mounting as major cities are growing at rates between 10 to 15% yearly (Olukayode et al., 2011). Consequently, the rate of development affects both the quality and quantity of water through the resulting increase in waste generation and subsequent discharges into water bodies, which leads to water contamination and eventually reduces the volume of consumable water. Generally, the human population in Abeokuta depends on groundwater (via hand-dug wells and boreholes) for domestic uses. Hand-dug wells, which account for the largest percentage are mostly semi-protected and are prone to contamination owing to the mode of construction and hygiene practices of water users with contamination risk as high as 39% (Oluwasanya et al., 2016). Over the years, many studies (Ufoegbune et al., 2009; Orebiyi et al., 2010; Adejuwon and Adeniyi, 2011; Adekunle et al., 2013; Amori et al., 2013; Moroof and Gabriel, 2014; Oluwasanya et al., 2016) reported and established the groundwater quality status in Abeokuta city. The studies inferred that most of the groundwater sources in Abeokuta are contaminated with one or combination of parameters such as nitrate, iron, lead, nickel, zinc and faecal pollution. The contamination of some of these sources have been traced to, but not limited to, proximity to sewage systems, solid waste dumps and exposure to unwanted materials from the environments through runoff (Oluwasanya, 2013; Oluwasanya et al., 2016). The present study assesses the spatial trend of groundwater contaminants, generates trend mapping to highlight spatial variability of groundwater contamination across Abeokuta metropolis and associated rock types. It also reviews the appropriate measures for reducing water quality parameters of concern (that is those above World Health Organisation (WHO, 2011) permissible limits).

Abeokuta is the capital of Ogun State. The city is located in the sub-humid tropical region of Southwestern Nigeria. It lies between Latitudes 7° 5' N to 7° 20' N and Longitudes 3°17' E to 3° 27' E (Figure 1).

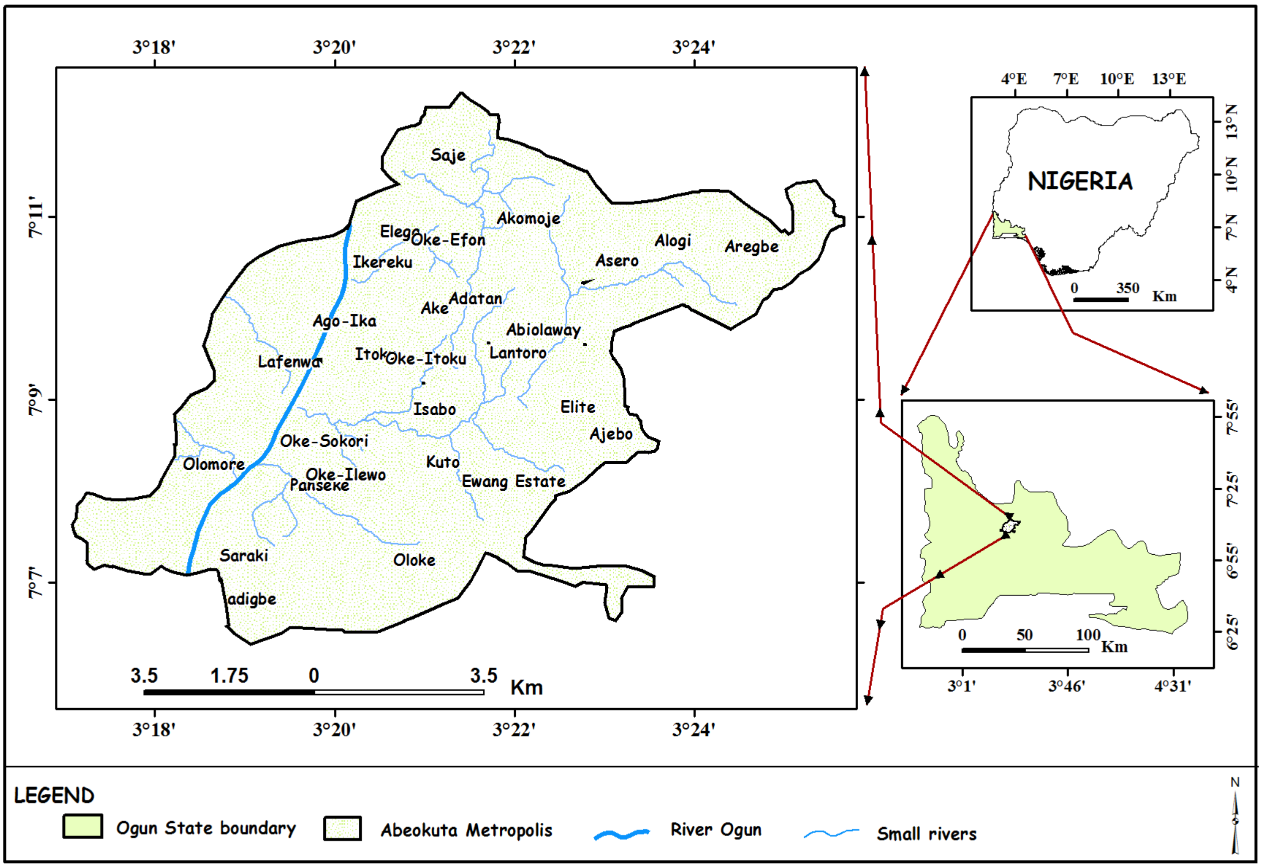

Figure 1. Map of Ogun State, Nigeria showing Abeokuta city.

Abeokuta covers a geographical land area of 879 square kilometers and has human population of about 451,607 with an annual growth rate of 3.03% referenced to 2006 census (NPC, 2010). The human population is projected to be 646,138 in 2018. The boundary of Abeokuta metropolis, which covers Abeokuta South and parts of Abeokuta North, Obafemi Owode and Odeda Local Government Areas of Ogun State is delineated and shown in Figure 1. Large part of Abeokuta has been deforested to give way to various human activities such as schools, banks, public and private institutions. Only small pockets of the ancient forests exist, mainly, scattered forest reserves and those found along river valleys (Orebiyi, 2009). Abeokuta is drained by one major river (River Ogun), which passes through and divides the city into two parts to form a dendritic drainage pattern. On the outskirts, upstream of Ogun river is another main river (Oyan river), which discharges its flow into the river Ogun at Oyan and takes its name from this point. Rivulets as well as annual and perennial streams in the neighborhood of Ogun River empty their waters with eroded materials at both upstream and downstream entry points. Thus, River Ogun acts as drainage channel for all the streams in the area. The streams are distributed on both sides of Ogun River, take their source from flow areas of high altitude and flow through the city to discharge their content into Ogun River. The city is characterized by an undulating topography with elevation ranging from 100 to 400 m above mean sea level. The topography is rugged with distinctly pronounced domed and boulder strewn hills. The hills are developed over the basement complex with their summits ranging between 300m to 600m above mean sea level. The most popular of the hills is "Olumo" rock (Orebiyi, 2009), one of the Nation's tourist attractions. Also, Abeokuta is composed of granite and associated metamorphic rocks of the basement complex. The dominant rock type in Abeokuta city is older granites and gnesis-migmatite complex (Jones and Hockey, 1964), which influences groundwater chemistry through the addition of minerals such feldspars (aluminium silicates with potassium, sodium, or calcium) and quartz (a form of silicon dioxide) (Huggett, 2011). As shown in Figure 2, the coarse-porphyritic-biotite and biotite- muscovite-

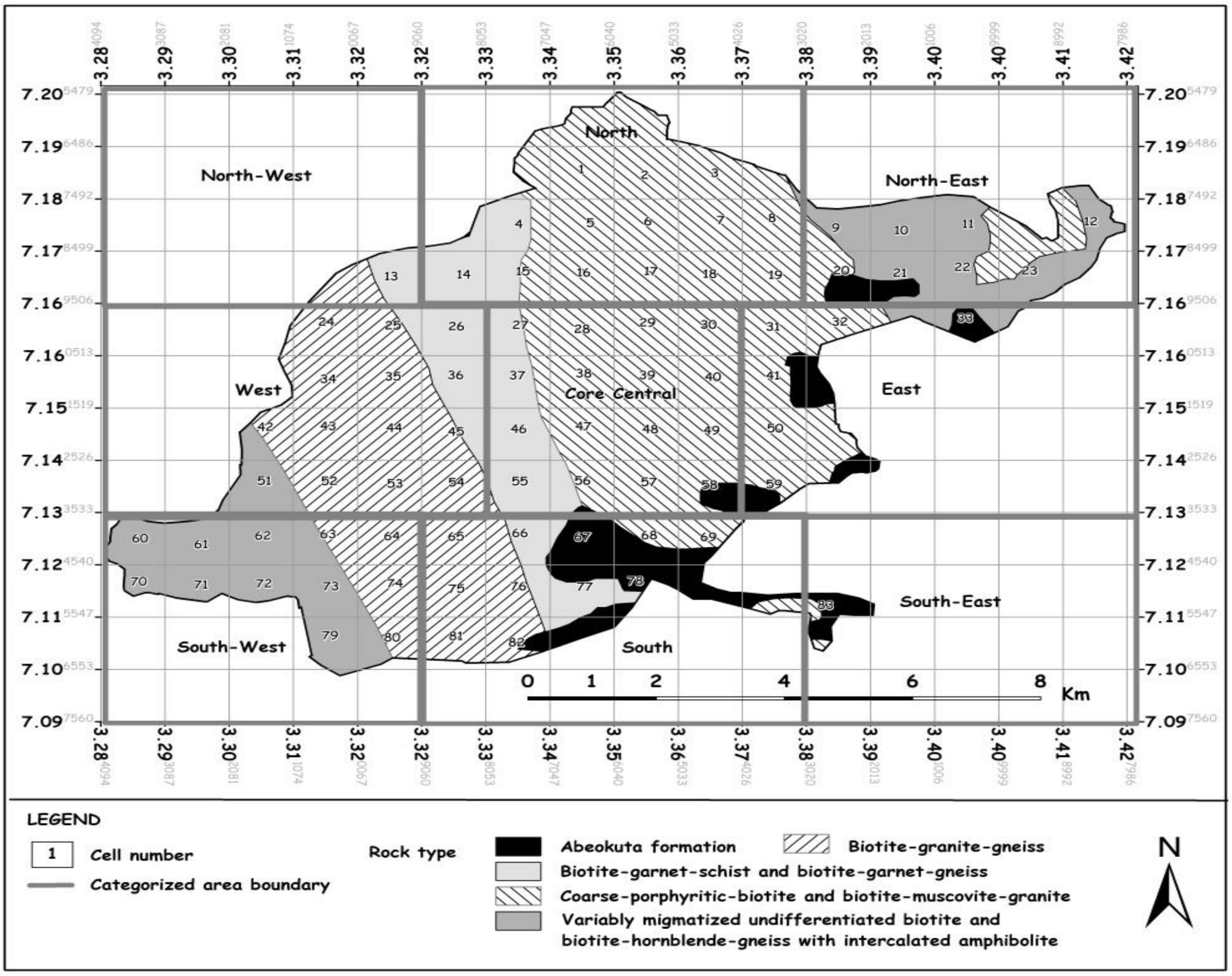

Figure 2. Gridded geology map of Abeokuta city, Nigeria.
Source:(Adapted from Jones and Hockey (1964).

granite (rock type-1) dominate the northern, northeastern, eastern and core-central sections of Abeokuta city; biotite-granite-gneiss (rock type-2) is found in the northwestern, western, southwestern and southern sections of the city; biotite-garnet-schist and biotite-garnet-gneiss (rock type-3) cut across the northern, northwestern, western, core-central and southern sections of the city; Abeokuta formation (rock type-4) scatters across northeastern, eastern, core-central, southern and southeastern sections of the city; while variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite (rock type-5) cut across the northeastern, eastern, western and southwestern sections of the city.

MATERIALS AND METHODS

Data collection procedures

The available groundwater quality and rainfall data for a fifteen year period (2001 - 2015) were collected from the research archive of Department of Water Resources Management and Agro-meteorology at the Federal University of Agriculture, Abeokuta, Nigeria and Nigeria Meteorological Agency (NIMET), respectively. Sensitivity assessment of the collected data was conducted using Microsoft excel to test for consistency. The data was then analyzed using descriptive statistics (mean and standard deviation) and spatial distribution assessment. Subsequently, the values of the selected parameters were compared with the World Health Organization standards (WHO, 2011). Also, annual rainfall data for Abeokuta was used to further explain the annual trend of nitrate-NO_3 within the study area.

Geo-statistical mapping/analysis of groundwater quality

Using geo-statistics tools, a continuous surface can be created when the sample points at different locations are given. Geo-statistics methods depend on both statistical and mathematical functions that include autocorrelation (Sajil et al., 2011). Interpolations are made for areas with unknown values through mathematical functions that are directly based on the surroundings of measured values. The most common methods are Kriging and Inverse-distance weighting. The two methods are similar except that the weights in Kriging method are based not only on the distance between the measured sampling points but also on the overall spatial arrangement among the sampling points. This research adopts the Kriging weighting method, which have a basic assumption that the sampling points that are close to each other are similar than those that are away (Sajil et al., 2011). As the first step in geo-statistics modeling, the above mentioned assumption is verified using empirical semi-variogram. Then the best fit is provided by the line that represents points in the empirical semi-variogram cloud graph, which quantifies the spatial autocorrelation. Based on the spatial autocorrelation among the measured and predicted locations, Kriging weights that are assigned to each measured parameter were determined. Once the Kriging weights were derived, the values of the parameter for all unknown locations were then calculated. According to Sajil et al. (2011), the predicted value for any location is given by Equation 1.

$$\hat{Z}(S_0) = \sum_{i=1}^{N} \lambda_i Z\,(S_i) \qquad (1)$$

Where, $\hat{Z}(S_0)$ is the location to be predicted,
λ_i is the unknown weight for the measured sample location,
$Z(S_i)$ is the measured value at the ith location,
N is the number of sample locations

The geo-statistical analysis was done with ArcMap 10.1 software package. The Kriging weighting method, which was integrated in the interphase of ArcMap 10.1, enabled it plot the empirical semivariogram and executed all the required geo-statistical investigations. The outcome of the analysis provided the spatial distribution of the selected groundwater quality parameters. The data used for the geo-statistical analysis include the co-ordinates (latitude and longitude) of the sampling locations and the corresponding mean concentration values of the selected parameters.

The delineated map of the study area was divided into grids of 1000 m by 1000 m (Figure 2), which were further categorized into nine; northern, northeastern, eastern, southeastern, southern, southwestern, western, northwestern and core-central areas of Abeokuta. The gridded map was overlaid on Google earth and the areas that fall within each of the cells were extracted and documented (Appendix Table 1). The average of the measured values for each of the selected parameters in the areas that falls in each of the cells was computed and used as the mean concentration values for each of the gridded cells. The computation involved an initial grouping of the 15 years data into 3 'five years interval' groupings, that is, 2001 – 2005, 2006 – 2010 and 2011 – 2015. The outcomes of the geo-statistical analysis are maps showing the spatial spread of five-yearly mean concentration of selected water quality parameters within the study area and the extent of groundwater contamination.

The selected water quality parameters are pH, electrical conductivity (EC), total dissolved solids (TDS), sodium ion (Na^+), potassium ion ($K^{+)}$, calcium ion (Ca^{2+}), magnesium ion (Mg^{2+}), chloride (Cl^-), nitrate (NO_3^-) sulphate (SO_4^{2-}), bi-carbonate (HCO_3^-), cadmium (Cd), copper (Cu), iron (Fe), lead (Pb) and zinc (Zn). The unique selection criteria were availability and consistency across the 15- year period of investigation.

RESULTS AND DISCUSSION

Distribution of physico-chemical water quality parameters across Abeokuta Metropolis

The spatial trend of pH for 2001- 2005 in the study area (Figure 3) shows that the mean pH value of groundwater is within the WHO permissible range (6.5- 8.5) for drinking water in most parts of the city, although a lower mean value is shown for towns in the north towards the eastern part and most locations in the southern parts of the city. However, the spatial trend for 2006-2010 and 2011 – 2015 shows that the whole city maintains a pH value range of 6.50 – 8.50. The computed mean pH values in groundwater of Abeokuta city is seen to be highest in the western part of the city (6.98) in year 2001- 2005, while the eastern part of the city has the highest value (7.36) in the period 2006 – 2010 and the core central part of the city has the highest value (7.19) in the period 2011 – 2015 (Table 1). In relation to rock types, result showed that groundwater of areas dominated by rock type-1, 2 and 3 have slightly alkaline mean pH values while rock type-4 and 5 are characterized by slightly acidic mean pH values (Table 2).

Across 2001 – 2005, the spatial trend of EC and TDS values (Figures 4 and 5) show that the mean EC and TDS values of groundwater are within the permissible range in all parts of the city. Although most parts of the metropolis still maintains a mean EC value within the permissible limit (1000 µS/cm) in 2006 – 2010, some parts of the city such as locations found in the north towards the western region like Oke-efon, Ake and Ago-Ika, have mean EC values above the permissible limit. The spatial trend for 2011 – 2015 further shows a high (> 100 µS/cm and > 500 mg/L) mean EC and TDS values for Ago-Ika, which implies that some activities (such as high rate of industrial and household wastes discharge) are happening in locations around Ago-Ika causing the observed unacceptable limit of EC. Other parts of the city with very high conductivity and total dissolved solids in the third spatial map are Lafenwa and Itoku (Figure 4). There is an indication that water from these parts of the city requires some forms of treatment before they can be considered consumable. Itoku, which is not very far from Ago-Ika, is the location of traditional textile tie and dye cottage industry while one of the oldest and biggest open food market, which is also not very far from Ago-Ika is located in Lafenwa.

The observed anthropogenic activities in Itoku and Lafenwa can be regarded as the major sources of high EC in the city. The core central part of Abeokuta have the highest mean TDS and EC values (257.82 mg/L and 458.57 mg/L; 497.65 µS/cm and 895.92 µS/cm) in periods 2001 – 2005 and 2011 – 2015, respectively (Table 1). Whereas across 2006 – 2010, the southeastern part of the city has the highest mean TDS value (451.20 mg/L) and the northern part of the city has the highest mean EC value (781.73 µS/cm) (Table 1). The core central part of the city is again found to have the highest TDS and EC values (458.57 mg/L and 895.92 µS/cm) for 2011 – 2015 (Table 1). Results further showed that groundwater of areas dominated by rock type-1 have higher concentration of dissolved solids

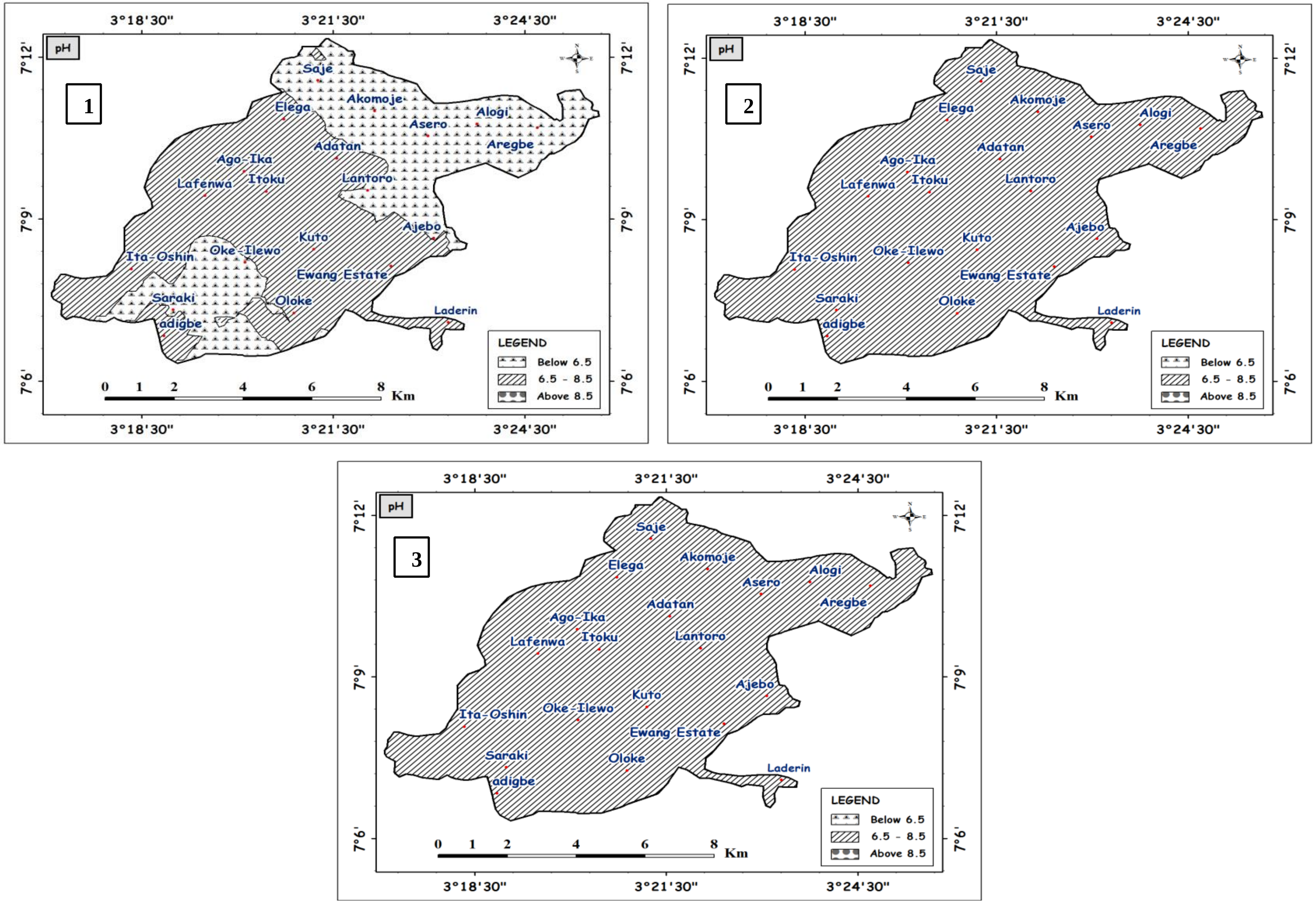

Figure 3. Spatial trend of Groundwater pH in Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

Table 1. Descriptive statistics: Physico-chemical groundwater quality parameters across Abeokuta city, Nigeria.

Parameter	Period of observation	Areas (Mean ± SD)							
		North	**Northeast**	**East**	**Southeast**	**South**	**Southwest**	**West**	**Core central**
Temp (ºC)	2001 - 2005	32.15 ± 1.63	32.8	30.0	-	-	31.27 ± 1.17	32.36 ± 0.91	32 ± 1.13
	2006 - 2010	29.48 ± 2.1	29.85 ± 2.18	27.63 ± 0.93	30.94 ± 2.88	-	27.32 ± 2.01	27.67 ± 2.12	30.58 ± 1.91
	2011 - 2015	29.07 ± 2.12	26.88 ± 1.22	27.07 ± 4.1	-	-	30.03 ± 1.49	29.68 ± 2.07	29.48 ± 2.25
pH	2001 - 2005	5.95 ± 0.46	5.67 ± 0.19	6.43 ± 0.33	-	-	6 ± 0.35	6.98 ± 0.49	6.62 ± 0.58
	2006 - 2010	7.25 ± 0.19	6.74 ± 0.38	7.36 ± 0.85	7.02 ± 0.18	-	6.67 ± 0.84	7.32 ± 0.93	7.34 ± 0.56
	2011 - 2015	7.19 ± 0.23	6.64 ± 0.61	6.04 ± 0.73	-	-	7.16 ± 0.26	7.18 ± 0.34	7.19 ± 0.35
EC @ 25ºC (µS/cm)	2001 - 2005	370.92 ± 130.04	341.82	148.5	-	-	-	432 ± 237.97	497.65 ± 217.06
	2006 - 2010	781.73 ± 431.36	416.08 ± 475.07	459.21 ± 362.51	-	-	433.82 ± 243.94	743.55 ± 358.19	651.29 ± 373.5
	2011 - 2015	805.93 ± 357.74	338.75 ± 268.45	288.58 ± 259.59	-	-	427.38 ± 150.58	650.35 ± 452.91	895.92 ± 396.1
TDS (mg/L)	2001 - 2005	201.17 ± 66.26	156.5 ± 65.76	198.13 ± 178.04	-	-	103.23 ± 12.54	228.96 ± 104.42	257.82 ± 138.31
	2006 - 2010	405.33 ± 212.1	211.05 ± 186.13	223.33 ± 193.45	451.2 ± 327.45	-	196 ± 147.01	322.05 ± 187.08	338.32 ± 194.02
	2011 - 2015	322.66 ± 117.56	191.71 ± 147.87	177.53 ± 160.38	-	-	371.08 ± 199.52	614.83 ± 463.43	458.57 ± 265.51

NB: SD = Standard deviation; ‘ - ‘: Not available.

Table 2. Descriptive statistics: Physico-chemical groundwater quality parameters across rock types.

Parameter	Rock type (mean ± SD)				
	1	**2**	**3**	**4**	**5**
Temp (ºC)	29.45 ± 1.77	28.31 ± 3.01	28.18 ± 2.56	30.1 ± 0	29.7 ± 2.34
pH	7.13 ± 0.49	7.17 ± 0.68	7.1 ± 0.74	6.98 ± 0.19	6.74 ± 0.55
EC @ 25 ºC (µS/cm)	759.21 ± 419.86	542.84 ± 320.89	659.33 ± 396.34	38.23 ± 0	391.43 ± 305.02
TDS (mg/L)	360.67 ± 215.46	340.38 ± 294.23	345.69 ± 234.79	379.55 ± 0341.44	215.03 ± 166.7

NB: 1 = coarse-porphyritic-biotite and biotite-muscovite-granite, 2 = biotite-granite-gneiss, 3 = biotite-garnet-schist and biotite-garnet-gneiss, 4 = abeokuta formation, 5 = variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite.

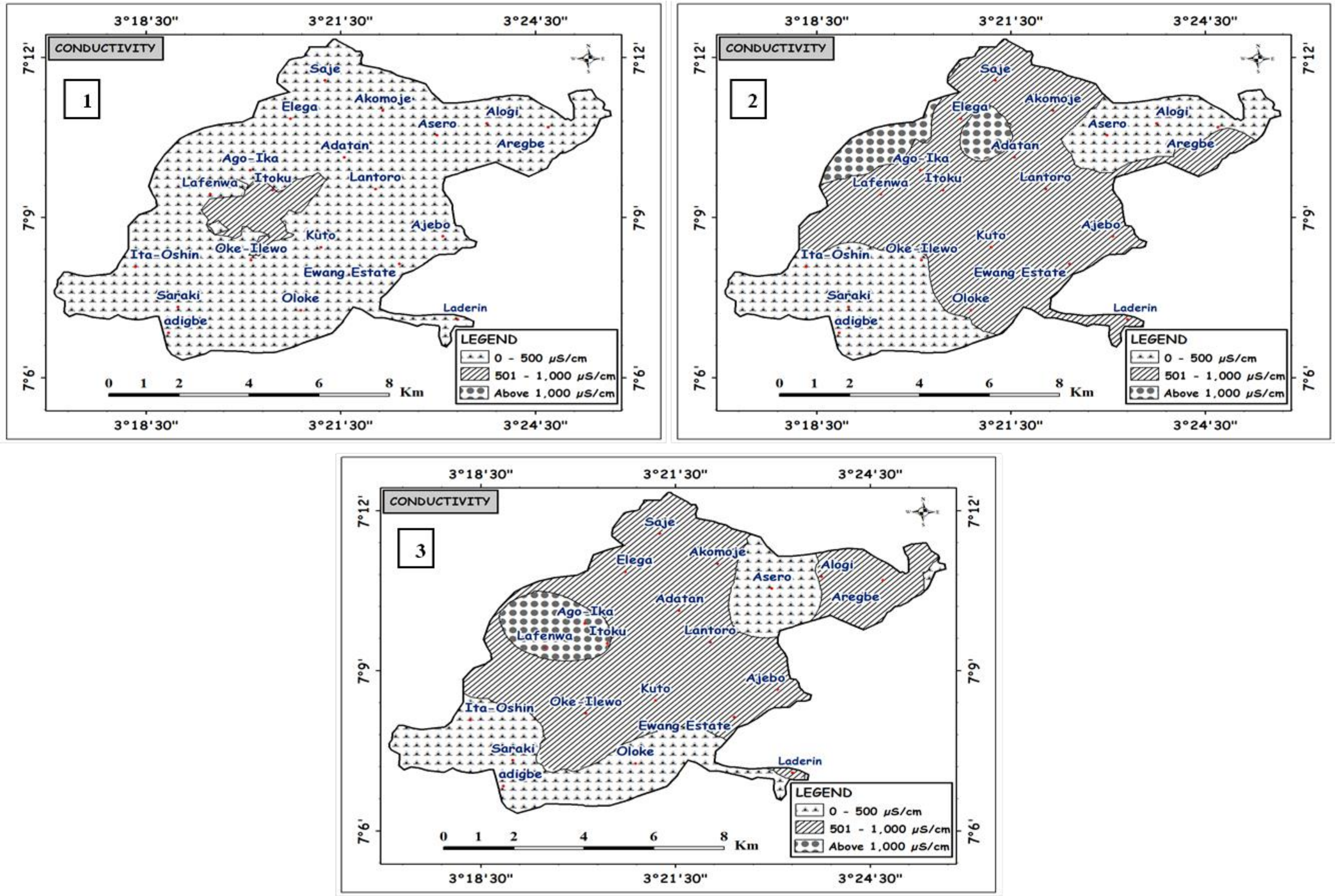

Figure 4. Spatial trend: Electrical conductivity (µS/cm) of Groundwater in Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

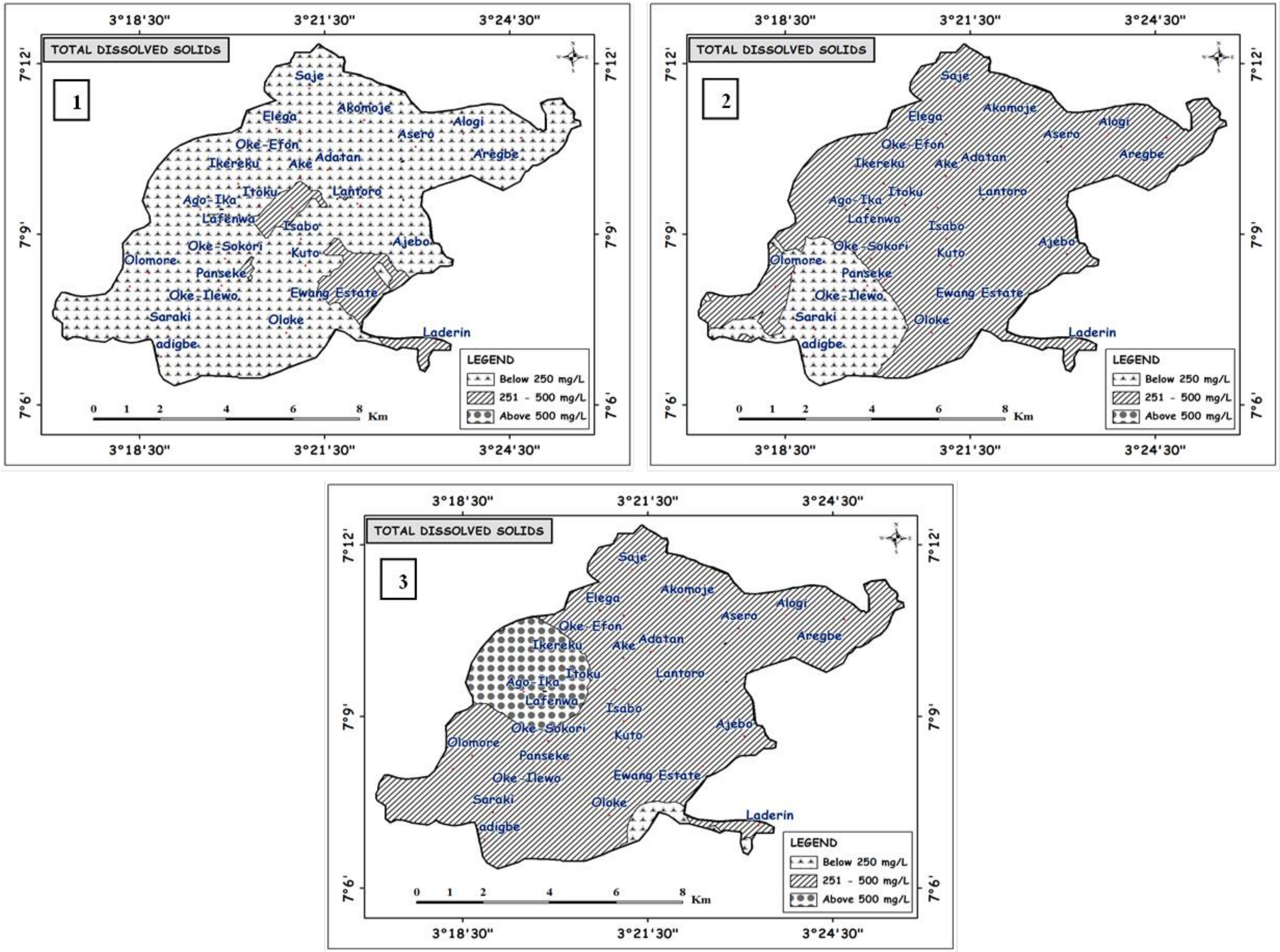

Figure 5. Spread of Total Dissolved Solids (mg/L) in Groundwater, Abeokuta city, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

than other rock types, especially, rock type-5.

Distribution of chemical groundwater quality parameters across Abeokuta metropolis

Major cations

Calcium is often associated with magnesium in all kinds of water (Chandra et al., 2012) and can enter the water bodies through dissolution of rocks such as gneiss and schist (Elango and Kannan, 2007; Simerjit and Promila, 2012). Across 2001 – 2005, the highest mean Ca and Mg concentrations (42.65 and 18.20 mg/L) are recorded in the core central and northern parts of the city, respectively, while the western and southern areas of the metropolis have the highest mean concentrations (59.94 and 45.20 mg/L) for Ca and Mg, respectively, during 2006 – 2010. However, the trend changed such that in 2011 – 2015, the northern part of the city has the highest values (122.07 and 70.56 mg/L) for the two parameters (Table 3). Results for calcium ion for 2001 – 2005 further show that a higher percentage of Abeokuta maintains an average concentration from bdl – 50 mg/L with a small percent of the city in the eastern region having an average concentration of 51 – 100 mg/L (Figure 6). For magnesium ion, a larger percentage of the city have an average concentration of bdl – 15 mg/L while other parts of the city (mostly in the southern and western part of the city) have an average concentration of 16 – 50 mg/L (Figure 7). But, there is an alteration in the average concentration of calcium for 2006 – 2010; the average level around the southern part towards the west, increased from a range of bdl – 50 mg/L to 51 – 100 mg/L while a decrease from 51 – 100 mg/L to bdl – 50 mg/L around the eastern region is observed. On the other hand, an increase in the average concentration of magnesium in the city is observed, with all parts of the city maintaining an average range of 16 – 50 mg/L. The third spatial trend (2011 – 2015) shows an increase in the average concentration of calcium except for few areas in the eastern part, which maintains a range of bdl – 51 mg/L. Also, for magnesium, the third spatial spread shows a further increase in the concentration range of magnesium ion from 16 – 50 mg/L to 51 – 100 mg/L in some parts of the northwestern, northeastern and western part of the city. However, a decrease in the concentration range is observed in some parts of the central region towards the west, while the remaining parts of the city maintain a concentration range of 16 – 50 mg/L. In all, the geo-statistical analyses indicate that the city maintains average concentrations of calcium and magnesium ion within the permissible limit (200 and 150 mg/L, respectively) for drinking-water. Meanwhile, lowest concentrations of calcium and magnesium are found in the groundwater of areas underlain by rock type-5 and 2, respectively, while highest concentrations of calcium and magnesium are found in areas underlain by rock type-3 (Table 4).

Sodium occurs widely in water and many igneous rocks. It is an essential component of most groundwater. In compound form, sodium is readily soluble in water. Generally, in the period 2001 – 2005, the mean concentration of Na is highest in the northern part of the city (46.00 mg/L), while K is highest in the western part of the city (6.77 mg/L) (Table 3). The core central part of the city has the highest mean concentration of Na (101.83 mg/L and 24.55 mg/L) for 2006 – 2010 and 2011 – 2015, while the southwestern part of the city has the highest mean value of K (28.44 mg/L) in 2006 – 2010 and the northern part has the highest K concentration (20.10 mg/L) for 2011 – 2015 (Table 3). The spatial trend of sodium ion in the study area for 2001 – 2005 shows that the city maintains an average concentration of bdl – 50 mg/L, while the spread of potassium ion in the study area shows that a larger part of the city have an average concentration of bdl – 5 mg/L and the other areas (majorly western and southwestern region) have an average concentration of 6 – 10 mg/L (Figures 8 and 9). However, the spatial trend for 2006 – 2010 shows that there is an increase in the average concentration of sodium ion from a range of bdl – 50 to 51 – 100 mg/L in most parts of the city except the northern region and some parts of the southwestern region, which maintains the concentration range of bdl – 50 mg/L. Also, there is a high alteration in the average concentration of potassium ion in the city. As at 2006 – 2010, the average concentration of potassium ion in most parts of Abeokuta increased above the prescribed limit of 20 mg/L, with only few areas maintain a

Table 3. Descriptive statistics: Major cations in groundwater across Abeokuta metropolis, Nigeria.

Parameter	Period of observation	Areas (Mean ± SD)							
		North	Northeast	East	Southeast	South	Southwest	West	Core central
	2001 - 2005	35.53 ± 20.74	14.75 ± 14.5	-	-	34.65 ± 32.17	17.53 ± 2.16	16.18 ± 21.36	42.65 ± 31.7
Ca^{2+}(mg/L)	2006 - 2010	35.22 ± 19.2	43.40 ± 15.5	-	-	50.5 ± 16.97	47 ± 11.77	59.94 ± 38.12	40.88 ± 18.24
	2011 - 2015	122.07 ± 80.38	99.56 ± 76.92	-	-	59.18 ± 59.32	105.63 ± 22.99	73.77 ± 73.57	86.38 ± 74.47
	2001 - 2005	18.2 ± 4.53	13.45 ± 2.19	-	-	12.87 ± 8.23	3.43 ± 1.25	3.98 ± 6.93	14.46 ± 10.21
Mg^{2+} (mg/L)	2006 - 2010	30.56 ± 18.09	37.50 ± 14.29	-	-	45.2 ± 31.57	41.38 ± 12.99	35.75 ± 36.05	40.44 ± 41.94
	2011 - 2015	70.56 ± 50.75	65.33 ± 44.33	-	-	23.18 ± 18.66	53.75 ± 10.68	49.79 ± 26.55	26.85 ± 31.89
	2001 - 2005	46.00	5.80	-	-	14.87 ± 3.19	6.43 ± 3.41	39.35 ± 24.88	28.45 ± 22.41
Na^{+} (mg/L)	2006 - 2010	24.58 ± 17.55	21.54 ± 15.77	-	-	73.38 ± 168.93	22.88 ± 10.29	80.38 ± 129.91	101.83 ± 145.32
	2011 - 2015	23.00 ± 16.76	10.00 ± 2.28	-	-	11.67 ± 1.37	-	-	24.55 ± 10.78
	2001 - 2005	3.92 ± 4.04	2.10 ± 0.14	-	-	5.74 ± 3.57	1.90 ± 0.36	6.77 ± 7.24	4.76 ± 4.8
K^{+} (mg/L)	2006 - 2010	15.70 ± 7.69	21.53 ± 13.42	-	-	20.68 ± 11.81	28.44 ± 10.99	18.49 ± 28.27	25.09 ± 28.64
	2011 - 2015	20.10 ± 10.71	6.00 ± 3.22	-	-	7.17 ± 2.71	-	-	19.05 ± 7.26

SD: Standard deviation, ‘ - ‘: Not available.

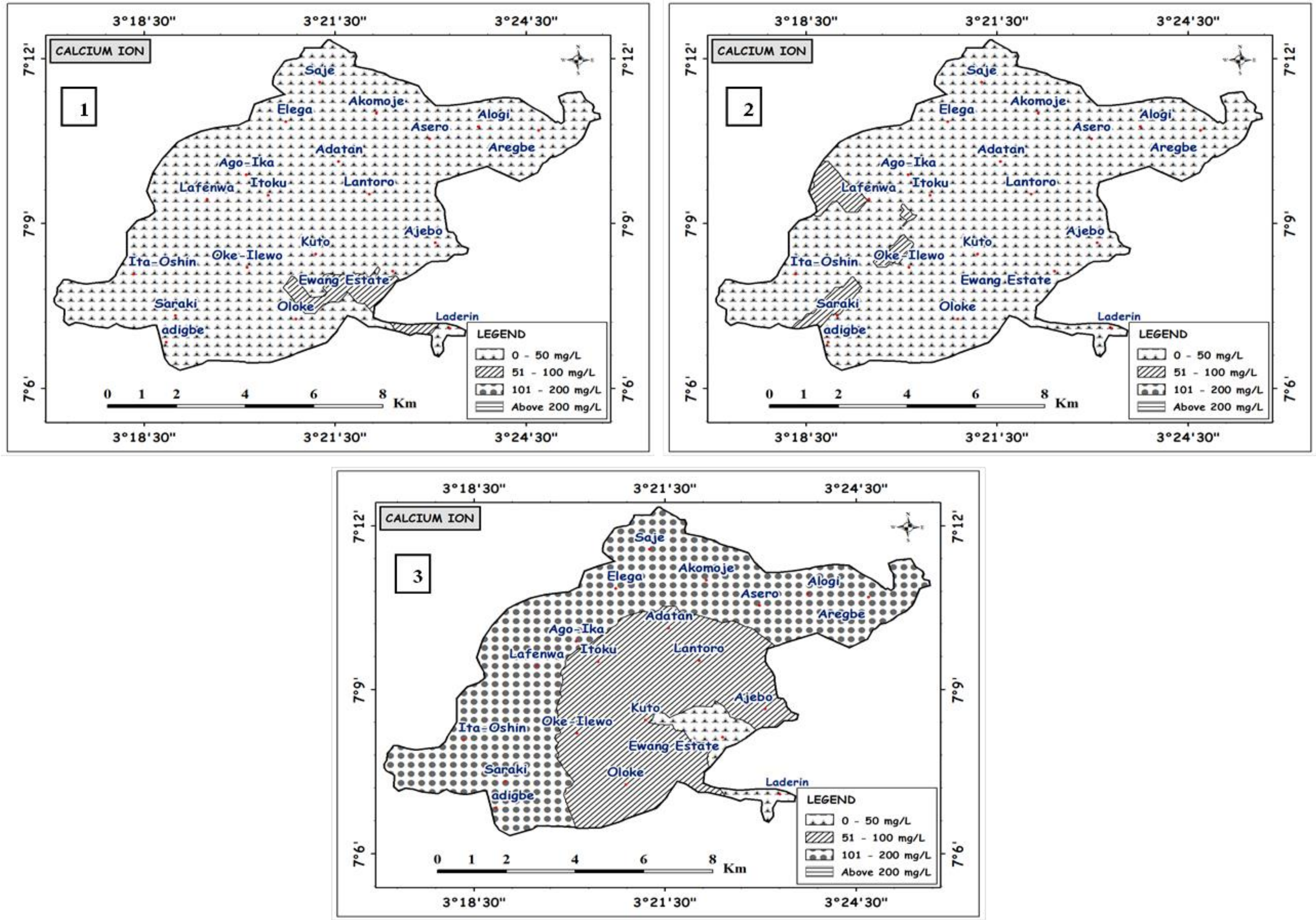

Figure 6. Spatial trend of Calcium ion (mg/L) in Groundwater, Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

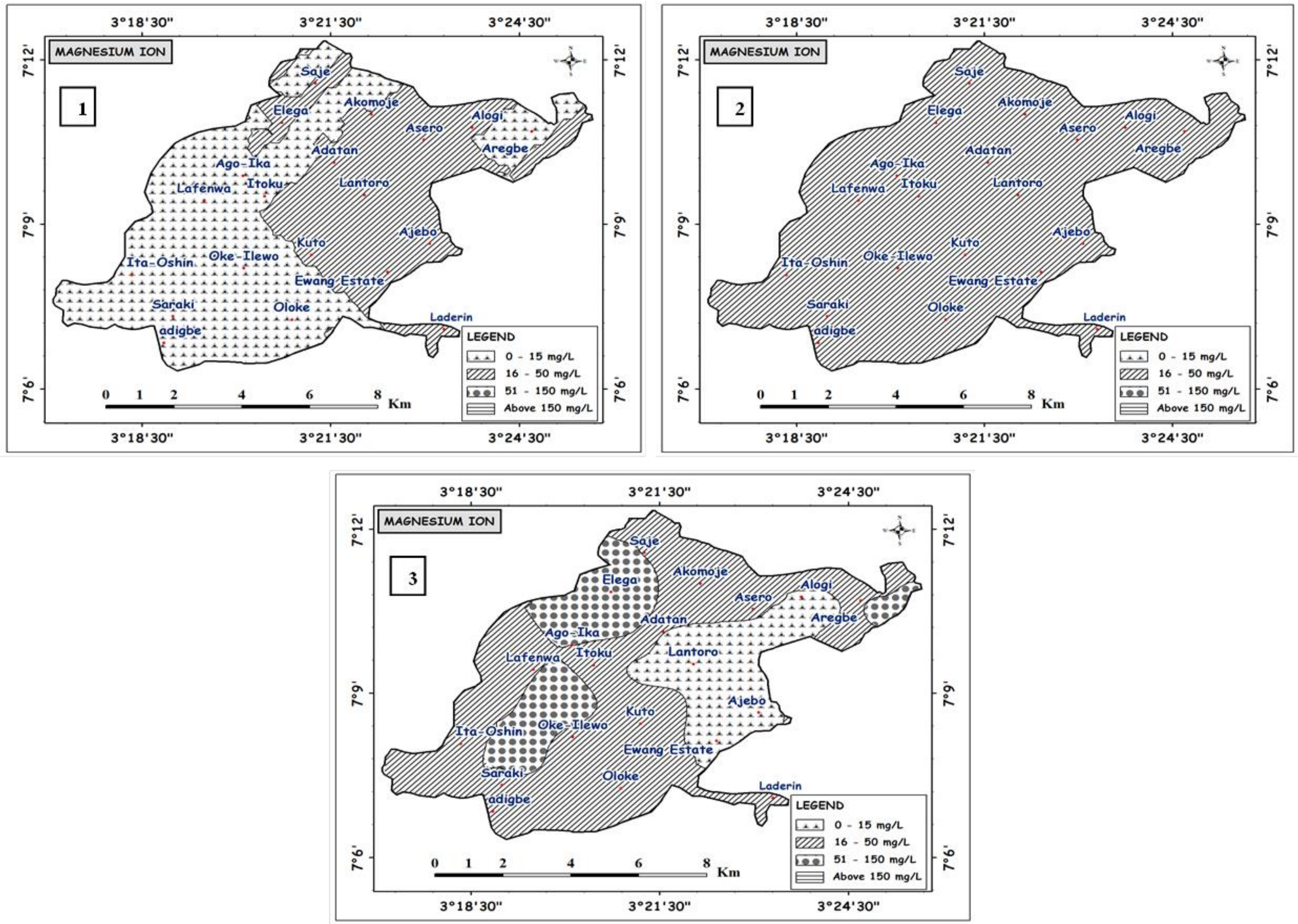

Figure 7. Spatial trend of Magnesium ion (mg/L) in Groundwater, Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

Table 4. Descriptive statistics: Major cations in groundwater across rock types.

Parameter	Rock type (mean ± SD)				
	1	2	3	4	5
Ca^{2+} (mg/L)	56.84 ± 47.91	42.4 ± 48.92	68.39 ± 66.12	-	40.2 ± 48.07
$Mg2^{+}$ (mg/L)	26.06 ± 31.14	20.09 ± 27.52	37.91 ± 38.14	-	27.14 ± 30.67
Na^{+} (mg/L)	33.15 ± 27.13	46.65 ± 69.52	72.31 ± 131.15	-	25.3 ± 19.71
K^{+} (mg/L)	15.94 ± 10.3	13.47 ± 19.99	19.88 ± 23.77	-	16.37 ± 14.17

NB: 1 = coarse-porphyritic-biotite and biotite-muscovite-granite, 2 = biotite-granite-gneiss, 3 = biotite-garnet-schist and biotite-garnet-gneiss, 4 = abeokuta formation, 5 = variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite.

concentration range of 11 - 20 mg/L. The third spatial trend (2011 – 2015) shows that the average concentration of sodium ion in the city reduced back to a range of bdl – 51 mg/L (Figure 8) and that the concentration of potassium in most parts of the city has also been normalized to the range of 11 – 20 mg/L with only few sections of the northwestern region having a concentration range above the prescribed limit of 20 mg/L (Figure 9). The mean concentrations of sodium and potassium in groundwater underlain by rock type-3 are generally higher than other rock types. Rock type-5 has the lowest concentration of sodium, while rock type-2 has the lowest concentration of potassium (Table 4).

Major anions

The mean concentration of HCO_3^- is highest in the southwestern part of Abeokuta (147.00 mg/L) during 2001 – 2005, whereas the western area has the highest value (191.13 mg/L) in the period 2006 – 2010, and the southern part has the highest mean concentration (190.75 mg/L) in 2011 – 2015 (Table 5). The number of captured data (160) is, however, insufficient to compute the mean concentration value for an adequate number of cells required to perform the geo-statistical analysis for the generation of spatial trend of bi-carbonate in the study area. Groundwater of areas underlain by rock type-5 has the highest mean concentration of bicarbonate than other rock types in the city (Table 6). According to Oke and Tijani (2012), migmatite gneiss rock type has bicarbonate as most dominant anion.

In general, chloride in groundwater originates from natural sources (e.g. rocks), sewage and industrial effluents, urban runoff in regions where de-icing salt is used, and saline intrusion (WHO, 1993; Balakrishnan et al., 2011) while the main source of nitrate (NO_3^-) in water is from the atmosphere, legumes, plant debris and animal excreta (WHO, 1993). Water containing more than 45 mg/L of nitrate, when consumed, causes methemoglobinemia, the so called blue baby syndrome in humans (Logeswari and Kumaraguru, 2015). Result shows that the southern and western parts of Abeokuta metropolis have the highest mean Cl^- and NO_3^{2-} concentrations (47.88 and 2.89 mg/L), respectively, in 2001 – 2005. Within 2006 – 2010, the concentration of Cl^- (230.67 mg/L) is found to be highest in the northern section of the city, while the western section of the city still had the highest concentration for NO_3^- (9.15 mg/L). However, the highest mean concentrations of Cl^- and NO_3^{2-} (133.75 and 5.24 mg/L) for 2011 – 2015 are recorded in the southwestern district (Table 5). The spread of chloride in the study area (Figure 10) shows that the mean level of chloride content in the groundwater is higher at the north-western part of the city, which may be the main source of chloride pollution in the groundwater system of Abeokuta apart from sources such as intrusion from sanitary facilities. The very high chloride content in groundwater sources

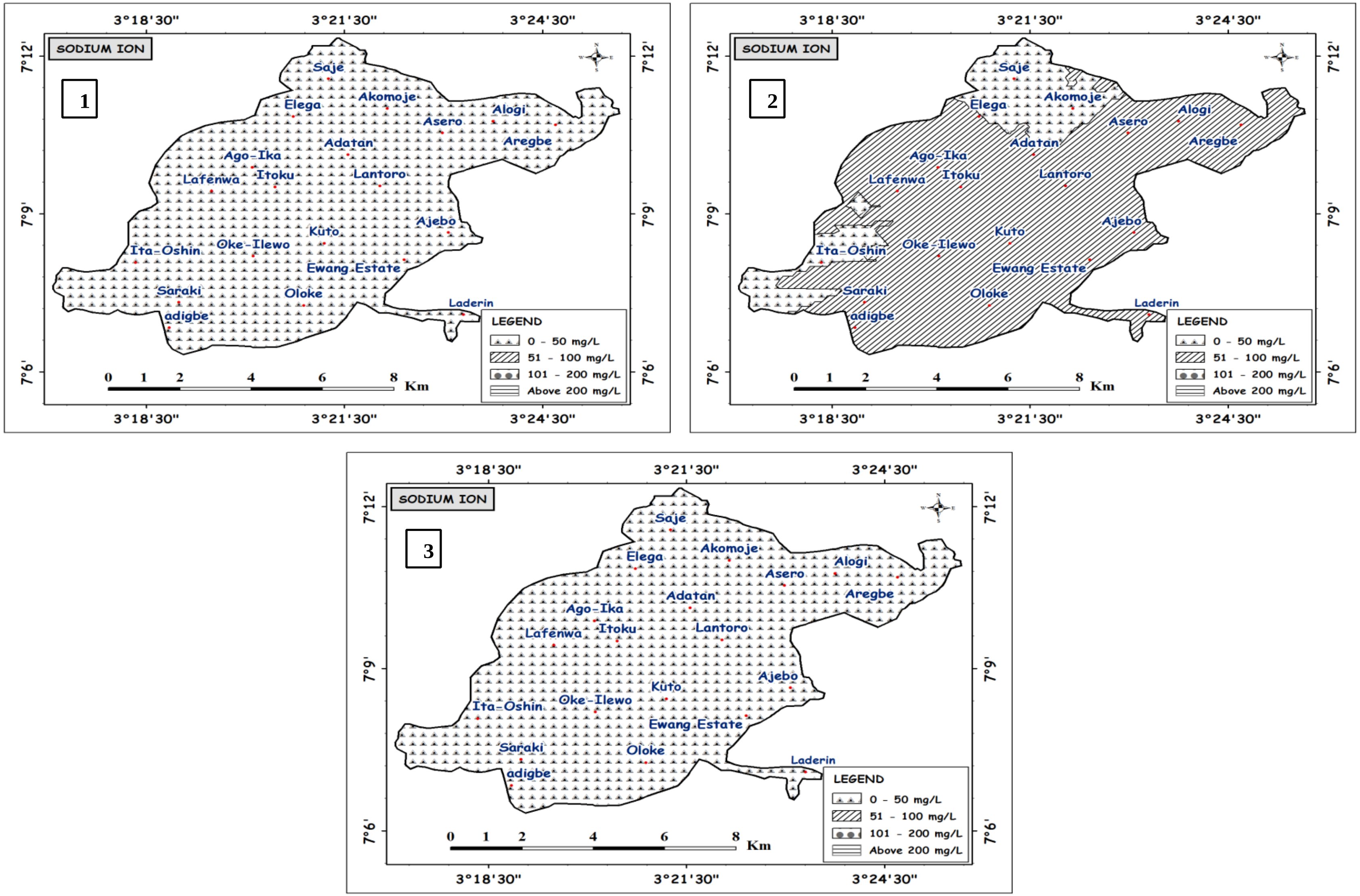

Figure 8. Spatial spread of Sodium ion (mg/L) in Groundwater, in Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

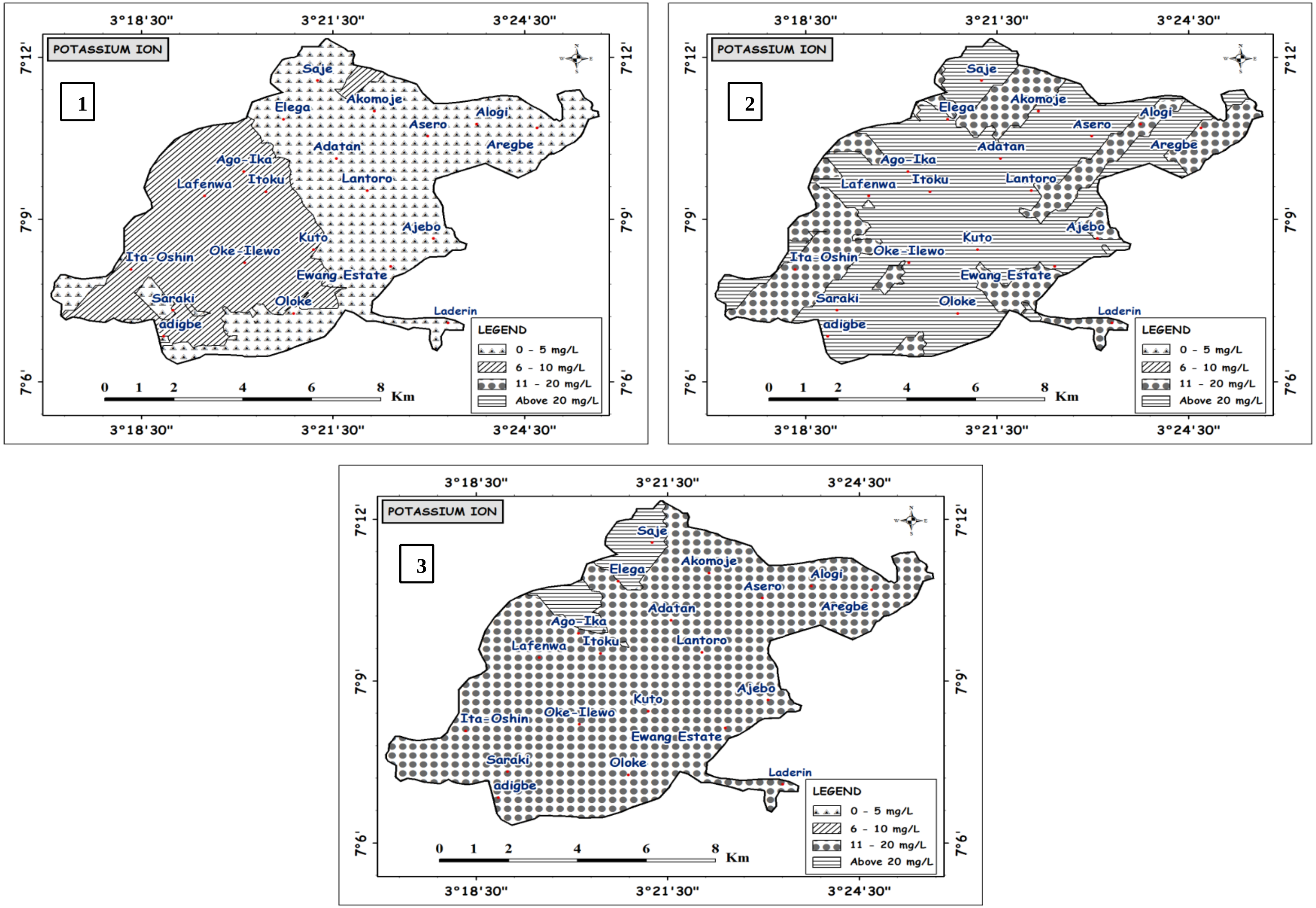

Figure 9. Spatial trend of Potassium ion (mg/L) in Groundwater, Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

Table 5. Descriptive statistics: Major anions in groundwater across Abeokuta city Nigeria.

Parameter	Period of observation	Areas (Mean ± SD)							
		North	**Northeast**	**East**	**Southeast**	**South**	**Southwest**	**West**	**Core central**
	2001 - 2005	-	111.00	-	-	83.75 ± 12.37	147 ± 96.01	123.77 ± 62.24	83.67 ± 11.41
HCO^{3-} (mg/L)	2006 - 2010	-	79.30 ± 47.41	-	-	111.33 ± 30.89	140.3 ± 107.12	191.13 ± 149.15	130.74 ± 151.43
	2011 - 2015	39.33 ± 28.65	168.22 ± 115.65	-	-	190.75 ± 143.62	-	72.25 ± 29.78	116.9 ± 158.51
$S0_4^{2-}$ (mg/L)	2001 - 2005	49.5 ± 6.36	23.00 ± 31.11	-	-	16.67 ± 24.58	2.00 ± 3.46	4.78 ± 14.93	40.6 ± 29.38
	2006 - 2010	19.71 ± 14.2	22.30 ± 13.35	-	-	35.44 ± 19.36	23.7 ± 12.59	27.81 ± 22.69	25.63 ± 19.76
	2011 - 2015	93.58 ± 23.72	23.33 ± 10.8	-	-	31.5 ± 11.93	-	-	93.61 ± 24.53
Cl^- (mg/L)	2001 - 2005	23.67 ± 22.05	18.50 ± 6.36	-	-	47.88 ± 68.5	17.00 ± 6.08	44.78 ± 33.83	25.65 ± 31.02
	2006 - 2010	230.67 ± 181.54	141.10 ± 254.95	-	-	47.37 ± 70.64	32.04 ± 31.84	105.88 ± 133.08	99.65 ± 105.87
	2011 - 2015	77.37 ± 79.71	92.86 ± 72.03	-	-	64.34 ± 49.53	133.75 ± 61.86	62.35 ± 31.14	121.37 ± 122.63
	2001 - 2005	bdl	bdl	-	-	bdl	-	2.89 ± 2.53	bdl
NO_3^{2-} (mg/L)	2006 - 2010	5.45 ± 2.44	5.80 ± 3.7	-	-	3.51 ± 1.32	2.85 ± 1.64	9.15 ± 8.09	7.09 ± 5.16
	2011 - 2015	1.86 ± 0.91	1.79 ± 0.48	-	-	2.48 ± 0.9	5.24 ± 2.57	2.68 ± 1.78	3.24 ± 2.33

SD: Standard deviation, ‘ - ‘: Not available, bdl: below detection limit.

Table 6. Descriptive statistics: Major anions in groundwater across rock types.

Parameter	Rock type (mean ± SD)				
	1	**2**	**3**	**4**	**5**
HCO_3^- (mg/L)	115.44 ± 161.54	125.39 ± 88.17	119.3 ± 134.65	-	133.52 ± 95.17
$S0_4^{2-}$ (mg/L)	55.94 ± 40.2	10.78 ± 19.71	49.84 ± 37.64	-	8.53 ± 13.68
Cl^- (mg/L)	109.24 ± 129.97	60.91 ± 67.34	96 ± 99.91	21.6 ± 0	63.16 ± 111.65
NO_3^{2-}	3.08 ± 2.61	3.9 ± 4.63	6.1 ± 5.48	2.93 ± 0	3.98 ± 2.87

NB: 1 = coarse-porphyritic-biotite and biotite-muscovite-granite, 2 = biotite-granite-gneiss, 3 = biotite-garnet-schist and biotite-garnet-gneiss, 4 = abeokuta formation, 5 = variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite.

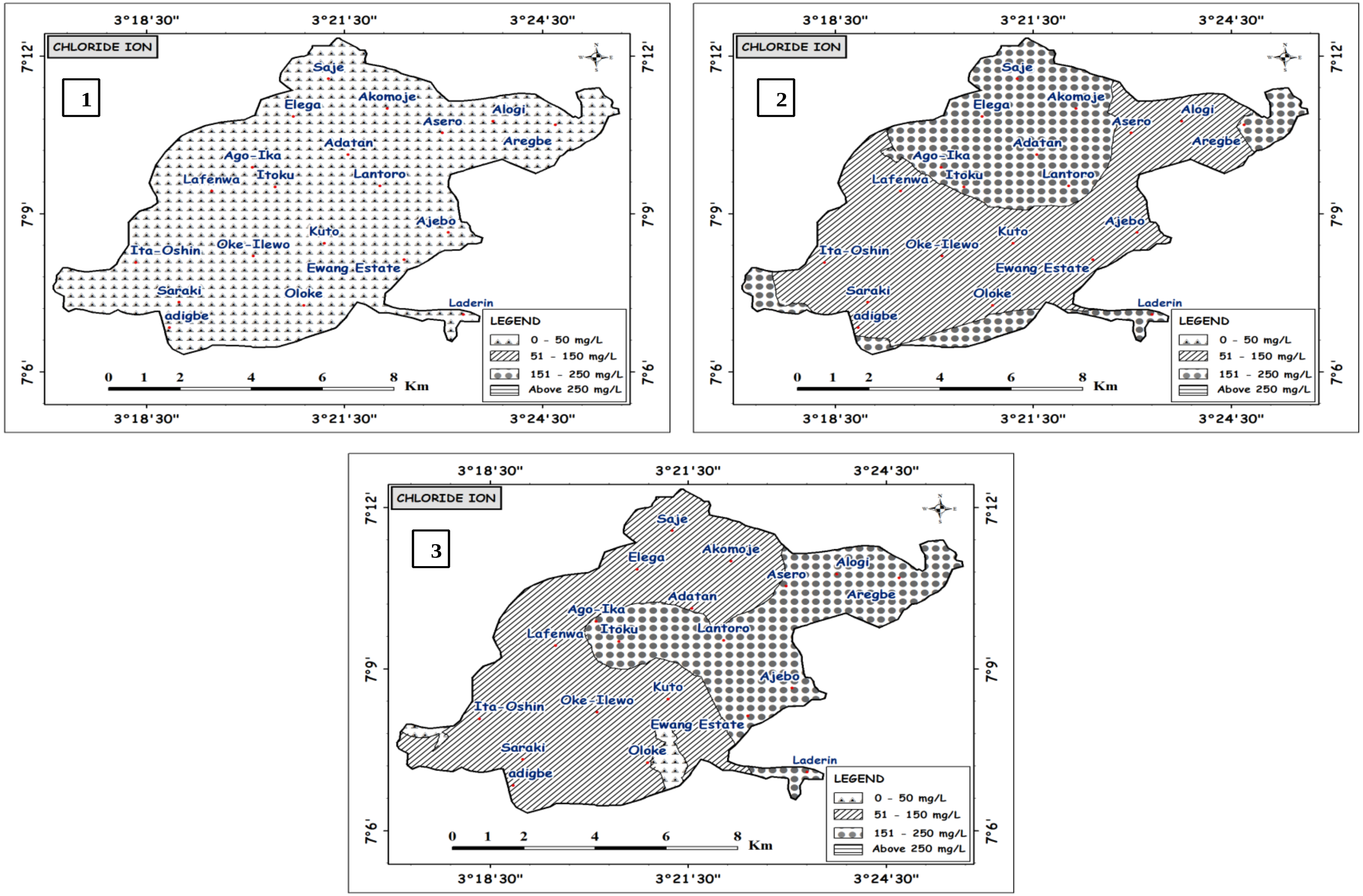

Figure 10. Groundwater Chloride content (mg/L) in Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

in the identified section of the city can be attributed to the textile industry, where tie and dye are produced in the part of the city. One of the areas in the affected cells found in the north-western section is Itoku, the residents engage in tie and dye of textiles with a big market for the product. In the tie and dye industry, one of the most important reagent is sodium chloride. This reagent is usually discharged with the untreated effluents generated during production into nearby water bodies and drainage channels, which may eventually find its way into the groundwater system.

Meanwhile, the spatial trend of NO_3^- in the study area for 2001 - 2005 (Figure 11) shows that the mean concentration of nitrate in groundwater is higher than the maximum limit of 10 mg/L prescribed for drinking-water (WHO, 2011) at the central part towards the upper part of the city. However, places around the southeastern and southwestern parts maintain a lower mean content range of 5 – 10 mg/L, which is within the prescribed value. Other places in the city found around the southern part maintain a much lower mean concentration range of 2.51 – 5.00 mg/L with few places having a mean concentration range of bdl – 2.50 mg/L. The second spatial trend (2006 – 2010) shows that majority of the places in the city have mean NO_3^- content within the permissible limit, except for places around Lafenwa, Itoku, Isabo, Lantoro, Abiola way, Adigbe and Oloke. The third spatial trend; 2011 – 2015, shows that the spread of high NO_3^- concentration in groundwater cut across a larger (63.3%) percentage of the city. Only few places (Lafenwa, Oke-Sokori, Olomore, Ita-Oshin, Saraki, Adigbe, Oloke and Oke-Efon) are seen to have mean NO_3^- concentration within the permissible limit. The high NO_3^- content of groundwater in most parts of Abeokuta can be traced to the high number of burial sites and sanitation facilities constructed close to water wells in most residential areas across the city, especially, the core central district. In relation to the annual rainfall of the city over the years of consideration, the reduced concentration of NO_3^- within 2006 – 2010 may be attributed to the sharp reduction in the annual rainfall recorded in between the years 2005 and 2008 (Figure 12). Furthermore, areas underlain by rock type-2 have higher mean concentration of chloride compared to others (Table 6). A similar research (Oke and Tijani, 2012) showed that porphyritic biotite granite rock type is rich in chloride. Also, mean concentrations of nitrate are generally low (2.93 – 6.10 mg/L) across all the rock types. Rock type-3 is, however, discovered to have the highest mean concentration (Table 6). Oke and Tijani (2012) also noted that Abeokuta groundwater is under saturated with respect to nitrates.

The chloride – nitrate ratio is further computed to ascertain the pollution level of groundwater in the various areas of Abeokuta city. A ratio value of 0.453 (r^2 = 0.2049) is recorded for the northern part of the city, with a ratio value of -0.032 (r^2 = 0.001) recorded for the northeast region, -0.306 (r^2 = 0.0936) for the southern part, 0.445 (r^2 = 0.1978) for the southwestern area, 0.377 (r^2 = 0.1419) for the western part and 0.132 (r^2 = 0.0175) for the core central district (Figure 13). The ratio values 0.453, 0.445 and 0.377 recorded in the northern, southwestern and western parts of the city, respectively, is an indication that the groundwater in the highlighted sections of the city may have similar sources of chloride and nitrate content.

On the other hand, the negative ratio values of -0.032 and -0.306 recorded in the northeastern and southern parts of the city, respectively, may be an indication that chloride and nitrate in these two parts of the city have distinct sources of entry into the groundwater of the identified areas. However, there is no clear relationship between the sources of chloride and nitrate in the core central district. The overview is that, only few parts of the city, the northern, southwestern and western parts may have groundwater systems polluted by similar sources of chloride and nitrate. There is an indication that chloride and nitrate pollution can be attributed to localized pollution rather than regional.

Water with a high sulphate concentration has medicinal taste and a pronounced laxative effect on those not accustomed to it. Also, sulphate occurs naturally, in soluble form, in earth materials (James, 1973). Also, man-made sources similar to those for chlorides can contribute to sulphate concentrations locally. In

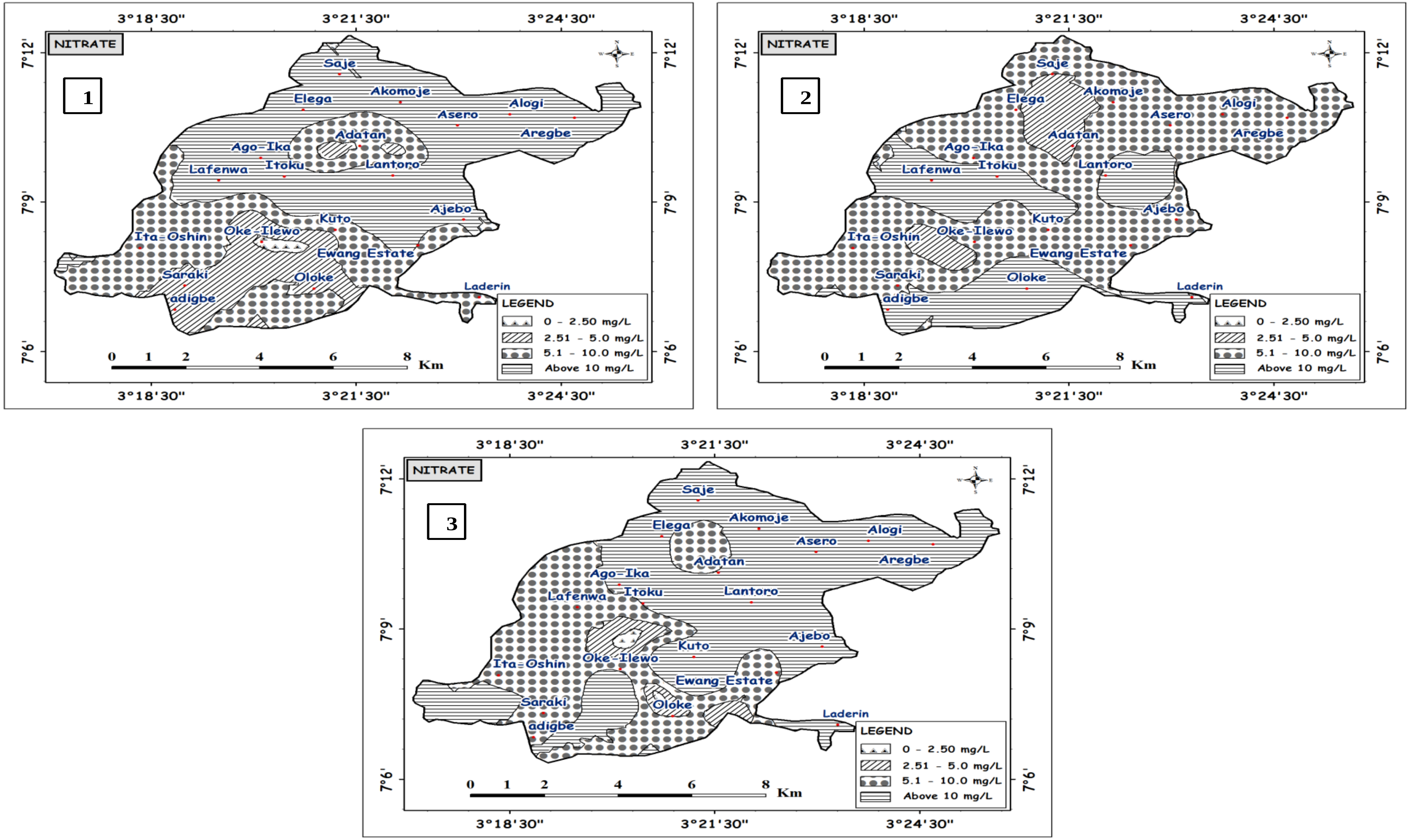

Figure 11. Nitrate-NO_3 (mg/L) in Groundwater, Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

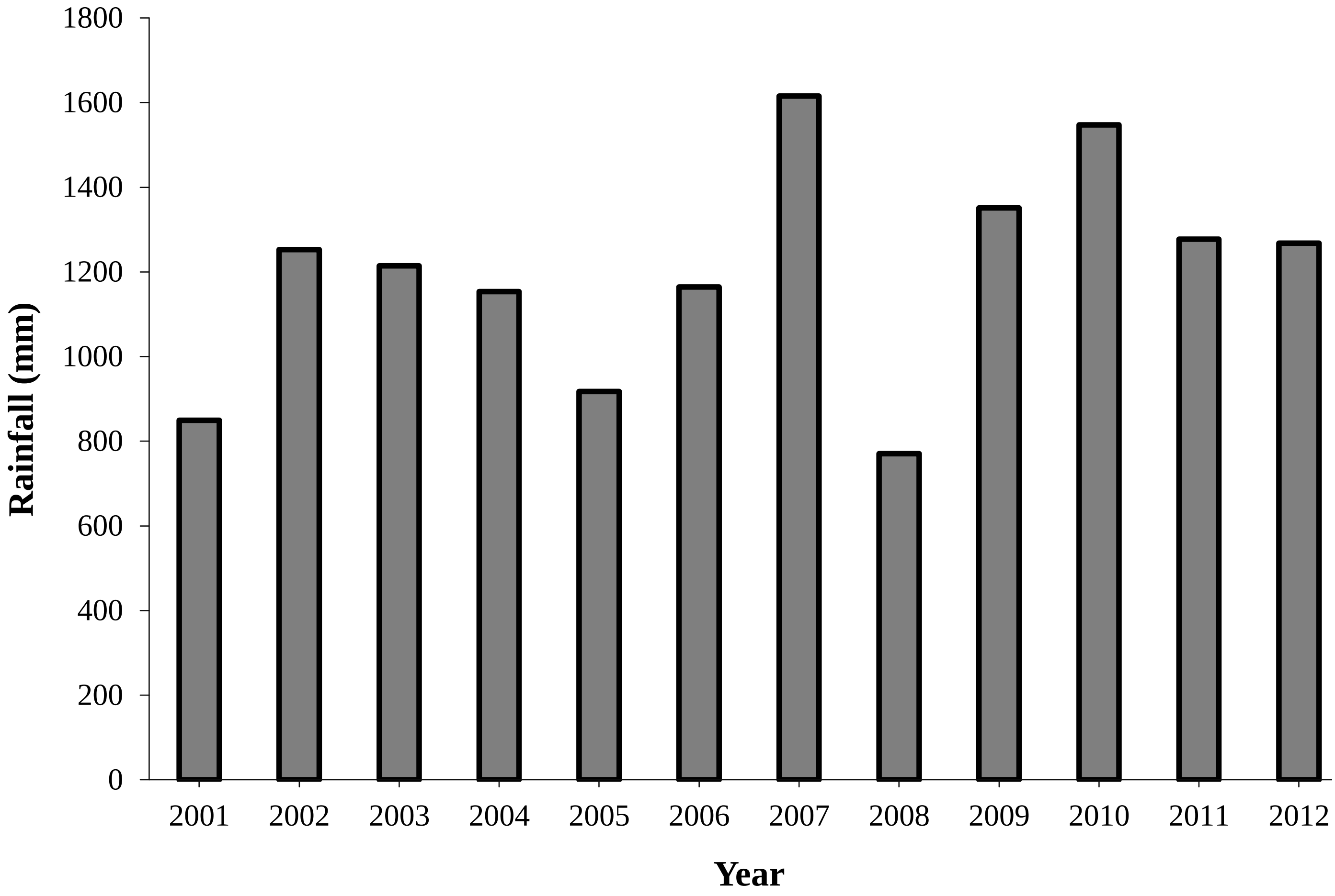

Figure 12. Rainfall Trend (2001 - 2012) in Abeokuta, Nigeria.

general, the mean concentration of $S0_4^{2-}$ is highest in the northern part of the city (49.5 mg/L) during 2001 – 2005, but highest in the southern part with a mean concentration of 35.44 mg/L in 2006 – 2010. However, for 2011 – 2015, the core central area has the highest $S0_4^{2-}$ concentration of 93.61 mg/L (Table 5). The spatial trend of sulphate in the study area for 2001 – 2005 shows that all parts of the city, except places around Kuto and Isabo with a concentration value between 51 and 100 mg/L, maintains a mean sulphate concentration of 0 – 50 mg/L (Figure 14). The spatial trend for 2006 – 2010 further shows that the entire city maintains a mean sulphate range of 0 – 50 mg/L. However, the mean concentration is seen to have increased across all parts of the city to a range of 51 – 100 mg/L, with exceptions in places around Kuto, Isabo, Oke-sokori and Panseke where concentration rose to a mean range of 101 – 250 mg/L. The rise in sulphate content implies that an activity (such as runoff from food markets or sewage intrusion) is ongoing in places around Kuto, Isabo, Panseke and Oke-sokori (Figure 14). In general, groundwater of areas underlain by rock type-2 has higher mean concentration of sulphate than other rock types in the city (Table 6).

Heavy metals

In general, within 2001 – 2005, the highest mean concentrations of Zn and Cd are recorded in the western part of Abeokuta. The northern section has the highest mean Cu content (0.40 mg/L), while the southwestern district has the highest mean value of Pb (0.185 mg/L) and the entire city maintains the same mean concentration of Fe (0.02 mg/L). The core central area has the highest mean concentrations of Fe and Zn (0.33 and 0.278 mg/L) during 2006 – 2010, with the highest mean concentrations of Cd and Cu (0.10 and 0.06 mg/L) in the western part and Pb concentration of 0.085 mg/L in the southern part of the city. Whereas, in the period 2011 – 2015, the highest

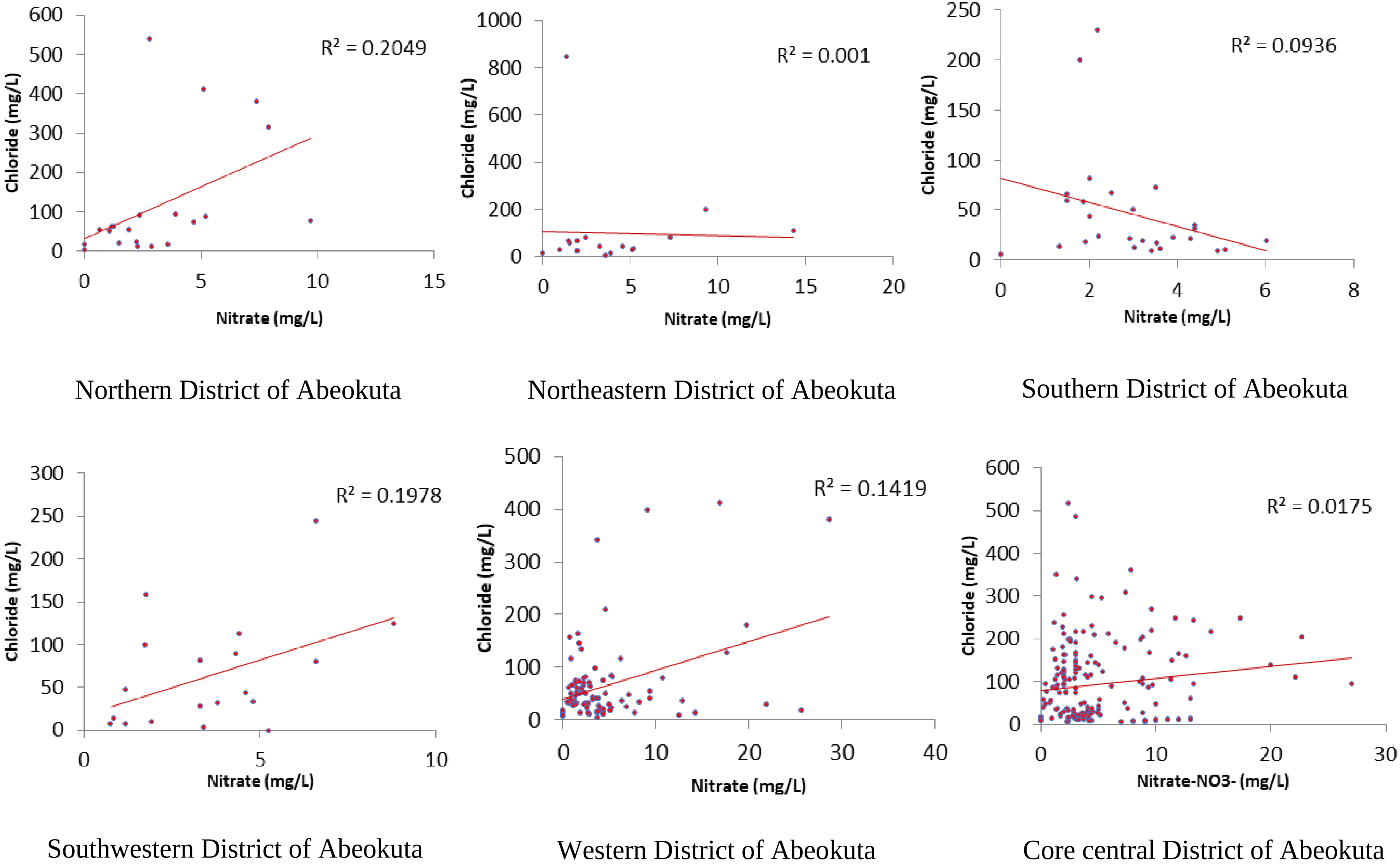

Figure 13. Groundwater Chloride – Nitrate-NO_3 ratio within various districts in Abeokuta metropolis, Nigeria.

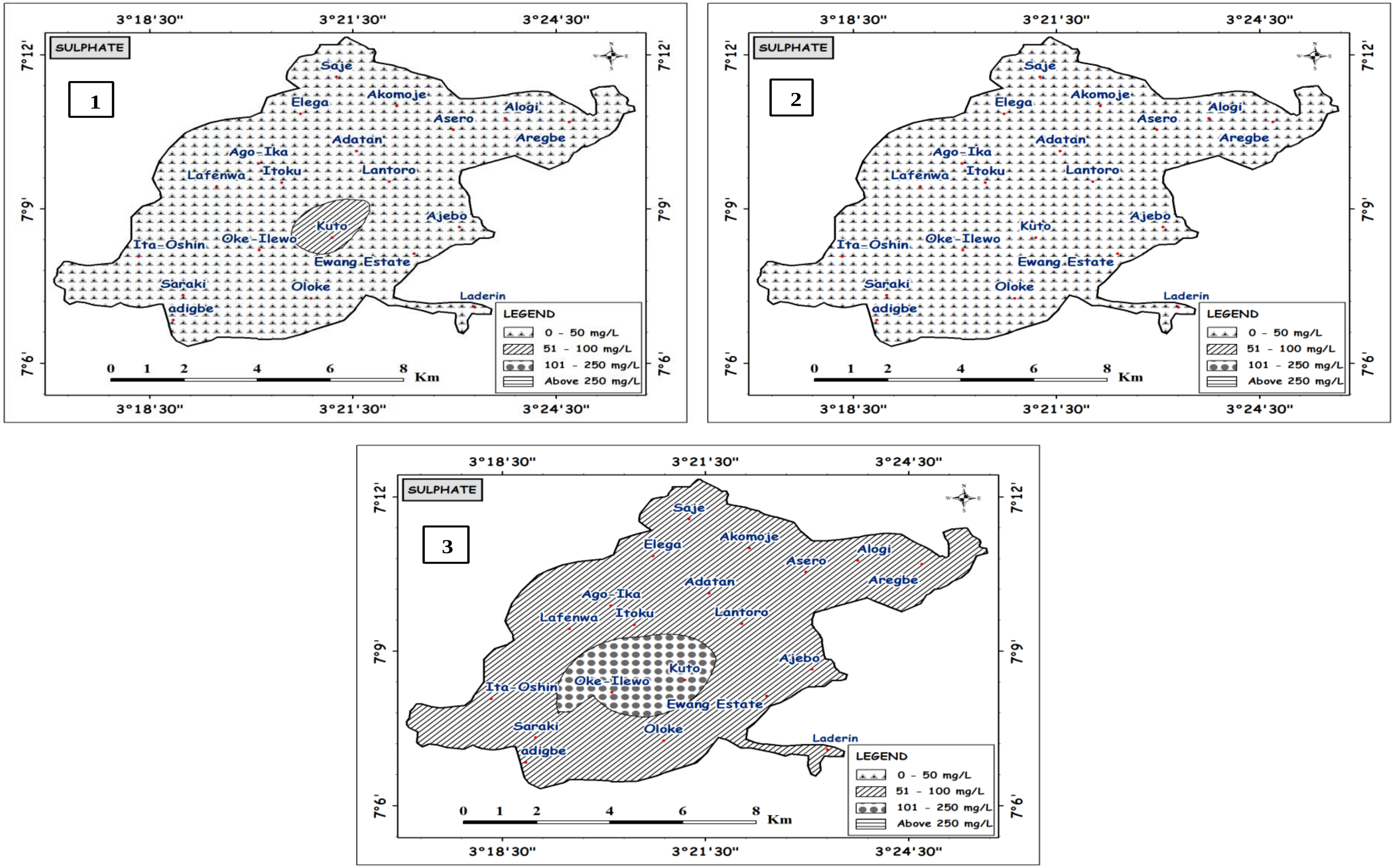

Figure 14. Spatial trend of Sulphate content (mg/L) in Groundwater, Abeokuta metropolis, Nigeria.
NB: 1) 2001 – 2005; 2) 2006 – 2010; 3) 2011 – 2015.

mean concentration Cu and Zn (0.07 and 0.092 mg/L) are recorded in the southern district, highest mean concentration of Fe (0.23 mg/L) is recorded in the city core central, while that of Pb (0.185 mg/L) is recorded in the southwestern part of the city. There is an indication that Cd is more prominent in the western part of the city, while Fe is more prominent in the core central area (Table 7). In comparison with rock types, groundwater in areas underlain by rock type-3 has higher concentration of Zn, Pb, Cd and Cu, while Fe is highest in groundwater of rock type-2. Meanwhile, the number of captured data for the heavy metals (Zn - 216, Pb - 226, Cd - 149, Fe - 88 and Cu - 191) did not cover an adequate number of cells sufficient to perform the geo-statistical analysis for the derivation of spatial trend of heavy metals in the study area.

Spatial trend evaluation of groundwater quality: Implications for health and water safety planning

In general, the spatial trend analysis of groundwater quality parameters in Abeokuta shows that there is an accumulated increase in the concentration of all the parameters within 2006 to 2010. Major road rehabilitation/construction in most parts of Abeokuta city was initiated within this period, leading to the breaking down of soil materials and uprooting of some already decayed/decaying bodies buried along the construction routes of some parts of the city such as a location called Iyana-Mortuary (Mortuary junction), which housed an expansive public burial ground. It is assumed that runoff generated from rainfall during the same period picked up nitrates (generated from organic matter from the decayed/decaying bodies) and some of the construction materials, eventually, finding their way into shallow dug-wells (especially, the semi-protected and unprotected categories) in the city through subsurface flow and, consequently, increasing the amount of dissolved contents in the groundwater. Urban development activities, such as road construction in any city, are inevitable but proper; and adequate drainage networks should be constructed to allow for safe passage of runoff from road construction sites into receiving streams or water bodies to prevent contamination of shallow dug-wells through subsurface flow. Also, handling of burial sites along roads under rehabilitation should be done with utmost care. The parameters found in higher levels above permissible limits prescribed by WHO (2011) in the groundwater system of Abeokuta city are as follows:

Physico-chemical parameters: As displayed by the spatial trend analysis, the electrical conductivity of groundwater systems in the city has increased over the years with some parts of the city having conductivity values above the permissible level of 1000 µS/cm. The affected areas, which include places around Oke-Efon, Ake, Ago-Ika, Lafenwa and Itoku need to be constantly monitored to curtail the increasing conductivity levels. Similar locations were identified to have shallow dug-well water with high conductivity values by Orebiyi (2009) and comparable to the results of previous studies conducted in related aquifers (Adeniyi, 2004; Solabi, 2004) in Abeokuta, and Bello (2004) in Ibadan. The groundwater systems in the highlighted areas, among others, require some form of treatment and water safety intervention before being safe enough for consumption.

Major chemical ions: The mean concentration of sodium, which is regarded as an essential component of groundwater, is found to be above the permissible limit of 200 mg/L for drinking-water in some parts of the city. The outlier water systems were found in cells 19, 37, 40, 47, 53 and 66. Although, the dominant range of sodium ion in the groundwater systems of the city is found to be within 11 – 20 mg/L, intervention is, however, required for sodium pollution in areas within cells 19, 37, 40, 47, 53 and 66. Furthermore, there are indications that the groundwater systems of most townships in the city have high concentration of potassium, with most exceeding the maximum permissible limit of 20 mg/L (WHO, 2011). The high concentration of potassium in the groundwater systems of Abeokuta is well pronounced between 2006 and 2010 (Figure 9). Potassium is an essential element for human nutrient and its intake through drinking-water is well below the level at which adverse health effects may occur (WHO, 2009). However, an

Table 7. Descriptive statistics: Heavy metals in groundwater across Abeokuta metropolis, Nigeria.

Parameter	Period of observation	Areas (Mean ± SD)							
		North	Northeast	East	Southeast	South	Southwest	West	Core central
Zn (mg/L)	2001 - 2005	0.10	-	-	-	0.10	-	0.167 ± 0.058	0.129 ± 0.049
	2006 - 2010	0.081 ± 0.067	0.05 ± 0.017	-	-	0.07 ± 0.004	0.019 ± 0.011	0.049 ± 0.023	0.278 ± 0.192
	2011 - 2015	0.008 ± 0.019	0.028 ± 0.022	-	-	0.092 ± 0.112	-	bdl	0.011 ± 0.013
Pb (mg/L)	2001 - 2005	0.004 ± 0.01	0.018 ± 0.04	-	-	0.08 ± 0.11	0.185 ± 0.18	0.001	0.107 ± 0.08
	2006 - 2010	bdl	0.045 ± 0.09	-	-	0.085 ± 0.08	-	bdl	0.013 ± 0.05
	2011 - 2015	0.003 ± 0.01	0.038 ± 0.08	-	-	0.085 ± 0.08	0.185 ± 0.18	0.001	0.073 ± 0.08
Cd (mg/L)	2001 - 2005	0.08 ± 0.02	0.08 ± 0.02	-	-	bdl	0.04 ± 0.06	0.10 ± 0.04	0.02 ± 0.03
	2006 - 2010	0.03 ± 0.05	bdl	-	-	0.04 ± 0.06	-	0.10 ± 0.04	0.02 ± 0.03
	2011 - 2015	0.05 ± 0.05	-	-	-	-	-	-	-
Fe (mg/L)	2001 - 2005	0.02 ± 0.01	0.02	-	-	0.02	-	0.02 ± 0.02	0.02 ± 0.01
	2006 - 2010	0.01 ± 0.03	0.20 ± 0.46	-	-	0.12 ± 0.17	-	bdl	0.33 ± 0.85
	2011 - 2015	0.02 ± 0.02	0.18 ± 0.43	-	-	0.12 ± 0.17	-	0.02 ± 0.02	0.23 ± 0.71
Cu (mg/L)	2001 - 2005	0.4 ± 0.14	0.10	-	-	bdl	-	0.18 ± 0.19	0.36 ± 0.5
	2006 - 2010	0.05 ± 0.02	0.03 ± 0.01	-	-	0.03 ± 0.03	0.01 ± 0.01	0.06 ± 0.04	0.06 ± 0.1
	2011 - 2015	bdl	0.04 ± 0.09	-	-	0.07 ± 0.07	-	bdl	0.01 ± 0.04

SD: Standard deviation, ‘ - ‘: Not available, bdl: below detection limit.

Table 8. Descriptive statistics: Heavy metals in groundwater across rock types.

Parameter	Rock type (mean ± SD)				
	1	2	3	4	5
Zn (mg/L)	0.03 ± 0.04	0.08 ± 0.07	0.25 ± 0.2	-	0.03 ± 0.02
Pb (mg/L)	0.02 ± 0.05	0.02 ± 0.06	0.09 ± 0.08	-	0.06 ± 0.1
Cd (mg/L)	0.01 ± 0.03	0.02 ± 0.03	0.07 ± 0.04	-	0.05 ± 0.07
Fe (mg/L)	0.27 ± 0.83	0.02 ± 0.02	0.1 ± 0.15	-	0.2 ± 0.47
Cu (mg/L)	0.07 ± 0.19	0.1 ± 0.14	0.08 ± 0.19	-	0.04 ± 0.08

NB: 1 = coarse-porphyritic-biotite and biotite-muscovite-granite, 2 = biotite-granite-gneiss, 3 = biotite-garnet-schist and biotite-garnet-gneiss, 4 = abeokuta formation, 5 = variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite increased exposure to potassium could result in significant health effects in people with kidney disease or other conditions such as heart disease, coronary artery disease, hypertension and diabetes. Similarly, individuals who are taking medications that interfere with the normal handling of potassium in the body, including infants who have been considered to be more vulnerable to high potassium intake may be impacted (WHO, 2009). It is, thus, necessary for most groundwater systems in the city to be considered for potassium reduction before the water abstracted is consumed directly. Potassium and sodium ions should, therefore, be constantly monitored in groundwater assessment for Abeokuta city.

This study shows that the mean concentration of chloride in the groundwater in a lot of places across Abeokuta, though within the permissible limit (WHO, 2011), is mostly higher than 100 mg/L. This high chloride content is an indication that the groundwater system in the city is prone to chloride contamination sources such as weathering of rocks, sewage and runoff (Balakrishnan et al., 2011). A high number of data units with chloride concentration above 100 mg/L in some places around towns like Itoku, Elega, Saje, Ikereku, Ake, Adatan, and Lantoro, is an indication that the water abstracted from groundwater sources in these areas are prone to contaminations from either or combinations of sewage, garbage dumps or industrial effluents and as such should be constantly monitored and treated prior to consumption. Also, mean nitrate-NO_3 concentrations above WHO permissible limit of 10 mg/L recorded in most parts of the city is an indication that water abstracted from groundwater sources in the city should undergo, at least, a treatment process that reduces nitrate-NO_3 concentration before consumption. According to Balakrishnan et al. (2011), water containing more than 10 mg/L of nitrate is bitter to taste and causes physiological distress. However, it will cause methemoglobinemia (blue baby syndrome) in humans when above 45 mg/L (Logeswari and Kumaraguru, 2015). The chloride – nitrate ratios show that the groundwater system in the city is moderately polluted by sanitation facilities, which means that sewage pollution is not the only source of chloride and nitrate pollution within Abeokuta city. However, it can be deduced from the chloride – nitrate ratios that only groundwater systems found in the northern, southwestern and western regions of the city have the same pollution source for chloride and nitrate. Moroof and Gabriel (2014) noted a similar result and suggested that nitrate pollution in Abeokuta city is associated with localized pollution rather than regional. Chloride and Nitrate are, hence, considered necessary in every groundwater quality assessment in Abeokuta.

High sulphate values are found in places around Isabo, Kuto, Oke-Sokori and Panseke. Orebiyi (2009) and Oyawale (2001) confirmed sulphate as the anion with highest concentration in groundwater systems of Abeokuta. Although these high values are within the recommended limit of 250 mg/L for drinking-water, the reported (WHO, 2017) impact (medicinal taste and a pronounced laxative effect on those not accustomed to it) of high sulphate concentration may not be ignored. There is, therefore, a need to carefully monitor the groundwater systems in these areas to curb and manage the increasing concentration of sulphate in the identified parts of the city. Groundwater in the highlighted areas should be treated to reduce the sulphate concentration before consumption.

Heavy metals: Furthermore, this study shows that concentration of heavy metals with values above WHO (2011) permissible limits in the groundwater systems of Abeokuta city is in the order of cadmium > lead > iron > copper > zinc. Cadmium and lead, including iron (in few cells) are found to be above the acceptable limits (0.002, 0.015 and 0.30, respectively), which is an indication that the groundwater systems of the city in places majorly within the core central district (cells 27, 29, 37, 38, 39, 40, 46, 47, 48, 56 and 58) and few places in the southern (cells 76, 77 and 81), northeastern (cell 22) southwestern (cell 34) and western (cell 64) sections, where cadmium, lead and iron are dominant, require necessary treatments to reduce the concentration of the highlighted trace metals before considerations for drinking purposes since the metals are detrimental to human health. The processes causing the dissolution of the highlighted trace metals should also be monitored towards reducing the level at which they are discharged into water bodies. Cadmium accumulates primarily in the kidneys and has a long biological half-life in humans; 10 – 35 years. Although there is evidence that cadmium is carcinogenic by the inhalation route, there is no evidence of carcinogenicity by the oral route and no clear evidence for the genotoxicity of cadmium (WHO, 2017). On the other hand, exposure of human to lead is associated with a wide range of effects, including various neurodevelopmental effects, mortality (mainly due to cardiovascular diseases), impaired renal function, hypertension, impaired fertility and adverse pregnancy outcomes (WHO, 2017).

Conclusion

There is an accumulated increase in the concentration of all the parameters within 2006 to 2010, with the mean pH level of groundwater in Abeokuta changing progressively from slightly acidic (< 6.5) in some parts of the city between 2001 – 2005 to slightly alkaline (6.5 - 8.5) in the recent years. Places around Oke-Efon, Ake, Ago-Ika, Lafenwa and Itoku are found to be the major parts of the city with high EC values. Meanwhile, concentration of heavy metals with values above permissible limits in the groundwater systems of Abeokuta city is in the order of cadmium > lead > iron > copper > zinc. Furthermore, in recent years, Na, SO_4^{2-} and Fe are, generally, highest in the core central parts of the city, the north is considered as the bank for high pH, Ca, Mg and K, and the Southwestern parts of the city for Cl, NO, Pb. Also, there is an indication that Cd is more prominent in the western parts of the city, while HCO_3^-, Zn and Cu are higher in the Southern parts of the city. Results further showed that groundwater of areas dominated by rock type-1 (coarse-porphyritic-biotite and biotite-muscovite-granite) have higher concentration of total dissolved solids, Cl, SO_4^{2-} and Fe, those underlain by rock type-3 (biotite-garnet-schist and biotite-garnet-gneiss) have higher concentrations of Ca, Mg, Na, K, NO_3^-, Zn, Pb, Cd and Cu, while those underlain by rock type-5 (variably migmatized undifferentiated biotite and biotite-hornblende-gneiss with intercalated amphibolite) have the highest mean concentration of HCO_3^-. There are clear indications that water abstracted from groundwater sources in most parts of Abeokuta city are fit for domestic use. The water should, however, be considered for treatment prior direct consumption, particularly for the reduction of parameters such as potassium, sodium, chloride, nitrate, sulphate, cadmium, lead and iron. A household reverse osmosis mechanism, though expensive, is considered efficient for treatment of drinking water.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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APPENDIX

Appendix Table 1. Extracted locations in cells of the gridded map of Abeokuta metropolis, Nigeria.

S/N	Sample Locations	Coordinates	
		Latitude (ºN)	Longitude (ºE)
4	Kugba, Elega	7.18335	3.34269
5	Kugba Road,	7.18358	3.35271
7	Oba-Ademola Road	7.18409	3.37105
8	Ajikunta Street, Alani-Kayode, Sowemimo Way, Abanise, Paragon	7.18442	3.37820
15	Adedotun, Ikija Road, Mokola, Balogun, Parapo, Ilugun, Ita-Ika	7.17525	3.34330
16	Oke-Bode, Sokori Street	7.17502	3.35182
17	Afolabi-Soyinka, Gbesele	7.17526	3.36128
18	Bola Ajibola Street, Alabata Street, Car Wash	7.17482	3.36953
19	Asero, Orita Aare, Ransom Kuti	7.17462	3.37872
20	Alamu Kayode Street, Fajol Hotel, Muda Lawal Stadium, Fajol	7.17537	3.38794
21	Ebenezer, Alogi, Obantoko	7.17496	3.39617
22	Shomorin	7.17597	3.40493
23	Aregbe	7.17534	3.41438
24	Premier Akindele, Oke Sabo, Adebowale Street	7.16653	3.31572
25	Agbo Eran, Omideyi, Iwajowa	7.16593	3.32508
26	Ago-Ika	7.16577	3.33400
27	Sodeke, Kobiti	7.16600	3.34295
28	Ake, Iporo Ake, Itoko, Isabo Road (Itesi Street), Oju-Agemo	7.16531	3.35161
29	Isale Ake, Adatan, Isale Abetu, Kugba	7.16642	3.36076
30	Ilupeju Street, Abiola Way, Oke Abete	7.16607	3.36934
31	Oke-Ibukun	7.16572	3.37838
34	Elemere Street, Ladipo Street, Sokori, Owode	7.15673	3.31599
35	Lafenwa, Ilupeju Street, Omideyi	7.15716	3.32506
36	Olowu Road, Totoro, Gbagura, Adekunle Fajuyi, Bode-Olude	7.15738	3.33386
37	Igbore, Itoku, Ikija, Oke-Ijemo, Idi-Ape, Kemta,Oloko, Sapon	7.15734	3.34255
38	Ijemo, Shokenu, Ijemo-Agbadu	7.15768	3.35185
39	Erinoso, Skido, Igara, Abule-Oloni, Oke-Ejigbo, Akiode	7.15737	3.36074
40	Oke-Yidi, Abiola Way, Lantoro, Olorunsogo, Oke-Lantoro	7.15709	3.36994
41	Salamu-Kaula, Oke-Ayo, Ajayi,Akinosho, Abeni-Adeleye Avenue, Williams Crescent	7.15730	3.37838
42	Mosebolatan Street, Sekoni, Oyetola	7.14847	3.30683
43	Federal Housing Estate, Irepodun Close, Omolade-Odunbaku Close	7.14860	3.31599
44	Akin Olugbade	7.14830	3.32525
45	Totoro, Ogbe, Ita-Eko	7.14765	3.33392
47	Isabo, Ijaye, Shokenu, NUD	7.14857	3.35180
48	Oke-Ejigbo, Olorunsogo, Ijeun-Titun, MKO Abiola Way, Iyana-Mortuary	7.14808	3.36120
49	Iyana Tekobo, Mayegun Avenue, Oluga Street, Adeboye Street, Elite	7.14787	3.36976
50	FMC, Sobola Street	7.14824	3.37869
51	Ita-Oshin	7.13919	3.30704
52	Surulere Street, Oriyanrin Street, Olomore	7.13915	3.31615
53	Akin Olugbade, Quarry, Bella Street	7.13871	3.32537
54	Ita-Iyalode, Ijeja, Omida, Ita-Eko, Ibara, Post Office	7.13893	3.33400
55	Continental Suites, Presidential, Ibara Road, Ibara Baptist Church, Saje	7.13914	3.34289
56	Kuto	7.13925	3.35167
57	Leme, Sam Ewang-Estate, Idi-Aba	7.13901	3.36100
58	Olokuta Street, Ogunsanya Street,Abeo Grammer School, Idi-Aba, Kemta Street	7.13851	3.36950
61	Coker Street	7.12831	3.29819
62	Upright Hotel, Kuforiji Olubi Street	7.12978	3.30686
63	Upright Hotel, Kuforiji Olubi Street	7.13004	3.31601

64	Onikoko, Adigbe, Lipede	7.12968	3.32498
65	Onikolobo, Ibara Housing Estate	7.12963	3.33392
66	Blue Mango Hotel, Okelowo Bus-Stop	7.13023	3.34293
67	Gateway Hotel, Wenby's Suits, Kuto	7.12961	3.35164
68	Abule Olukosi Road, Ijeun-Lukosi Stadium	7.12984	3.36105
70	Idi-Ori, Bola Folaji Street	7.12200	3.29001
71	Surulere Street, Ogunyemi Street, Alaapa Road	7.12188	3.28941
72	Bode-Oriyomi Street, Sanyaolu Street	7.12135	3.29814
73	Saraki, Isokan, Obada, Road	7.12154	3.30700
74	Adigbe, Iyana-Cele, Araromi Street, Redeemed Church Of God, DG Hotel	7.12109	3.31637
75	Anewennu Estate, Diocese Of Egba Bishop's Court, Fawobi Street	7.12157	3.32536
76	Oloke Street, Segun-Anjorin Street, Abule Ojere, Duro Street	7.12066	3.33399
77	Obada Road, Isokan Street	7.12109	3.34268
78	Oke-mosan	7.12200	3.36000
79	Adigbe, Mango, Abule Ojere	7.11262	3.31628
83	Laderin	7.11822	3.38842

Note: Excluded cells were due to lack of information from Google earth.