IJESKA
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www.ijeska.com
ISSN: 2687-5993

International Journal of Earth Sciences Knowledge and Applications

RESEARCH ARTICLE

Groundwater Vulnerability Mapping and Quality Assessment around Coastal Environment of Ilaje Local Government Area, Southwestern Nigeria

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INFORMATION

Article history
Received 05 May 2020
Revised 17 June 2020
Accepted 19 June 2020
Available 01 August 2020

Keywords
Aquifer vulnerability
Longitudinal conductance
Water quality index
Protective capacity
Physicochemical analysis

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ABSTRACT

Aquifer vulnerability study assists in the implementation of groundwater management strategies to prevent degradation of groundwater quality. The study was focused on the determination of groundwater quality and vulnerability potential of material overlying the aquifer units in Ilaje area of Ondo State, southwestern Nigeria using geo-electrical method, aquifer vulnerability index (AVI), GOD index, and Dar Zarrouk longitudinal conductance. This was complemented by physicochemical analysis of 25 water samples, randomly taken from boreholes within depths range of 1 to 50 m. All the tested samples have values within the World Health Organization (WH) except nitrate which shows relatively high values higher than maximum contaminant level of 10 mg/l recommended by WHO in southern part. The range of nitrate concentration (0.25 – 15.4 mg/l) was as a result of high anthropogenic discharge of domestic and municipal waste into drainages especially during the wet season. Also, some degree of contamination by lead, cyanide, arsenic, ammonia, and mineral oil from petroleum exploitation by major oil companies was also observed in the samples. The average calculated water quality index is 121 which falls within poor/unfit water for drinking due to high level of contamination. The GOD vulnerability and AVI maps show that the aquifer units in the area are vulnerable by 60% and 55%, respectively. The longitudinal conductance index indicates that 53.3% of the area have poor/weak protective capacity. All the vulnerability maps and indices used corroborate very well as they show little variations. Therefore, appropriate water treatment should be conducted on the water before drinking, and also government should enact laws that would discourage indiscriminate dumping of refuse, waste water etc., enhanced containment for storage of wastes and chemicals on vulnerable soils. Also, the activities of the oil companies should be regulated to reduce the heavy metal/mineral oil contamination.

1. Introduction

The need for groundwater vulnerability assessments and water-management programs have become an important tool in groundwater management at federal, state, and local levels in Nigeria. This must include the identification and location of sustainable sources of drinking water, ground-water disinfection, pesticide management plans, underground injection of waste, and confined animal feeding operations. The quality of water we drink and used for agricultural activities is a critical parameter in determining the overall quality of our lives (Foster, 1987; Tesoriero et al., 1998). Water quality is determined by the solutes and gases dissolved in the water, as well as the matter suspended in and floating on the water. One of the most important aspects of groundwater management is the protection of the water quality in an aquifer (Atakpo and Ayolabi, 2009).

There are a number of artificial sources of potential groundwater contamination. Pollution from such sources as septic tanks; sanitary landfills; land-treatment systems for municipal wastewater; waste injection wells; toxic chemical disposal sites; cemeteries; mine tailings; acid mine drainage; water softener regeneration salt; highway deicing salt; oil field brines; agricultural chemicals, fertilizers, and accidental oil; gasoline; and chemical spills (El-Naqa and Al-Shayeb, 2009; Aller et al., 1987; Plymale and Angle, 2002).

Groundwater contamination can occur also when water of poor quality is drawn into a well field that originally has been developed in high quality water, especially when there is salt water intrusion in coastal areas (Akpan et al., 2018).

The unsaturated zone overlying an aquifer can act as a waste treatment system. However, the unsaturated zone can do much more than act as a physical filter to remove bacteria, viruses, metals (including heavy metals) (Akpan et al., 2018). Groundwater contamination is not an irreversible process. There are natural conditions that act to remove contaminants. Attenuation mechanisms include dilution, dispersion, mechanical filtration, volatilization, biological activities, ion exchange and adsorption on soil particle surfaces, chemical reactions and radioactive decay, although the decay products may also be toxic (Khrisat and Al-Bakri, 2019; Vrba and Zaporozec, 1994).

One of the most common pollution are septic tanks, landfills, chemical spills and leaking of underground tanks. Septic tank effluents contain viruses and bacteria. The most important factor that influences the development of ground water contamination from the septic tanks is the density of septic tank systems in the area. Several cases of infectious disease outbreaks due to septic tanks have been reported in the study area, due to high density of homes with septic tanks; the soil layer over permeable bedrock is thin, the soil is extremely permeable, the water table is within a couple of feet of the land surface. Burial in a landfill is the most common means of disposing of municipal refuse, ashes, garbage, leaves, demolition debris, and sludge from municipal and industrial waste water treatment facilities. Leachate can move these materials downward from the landfill into the water table and cause groundwater contamination (Akpan et al., 2018; Lima et al., 1995).

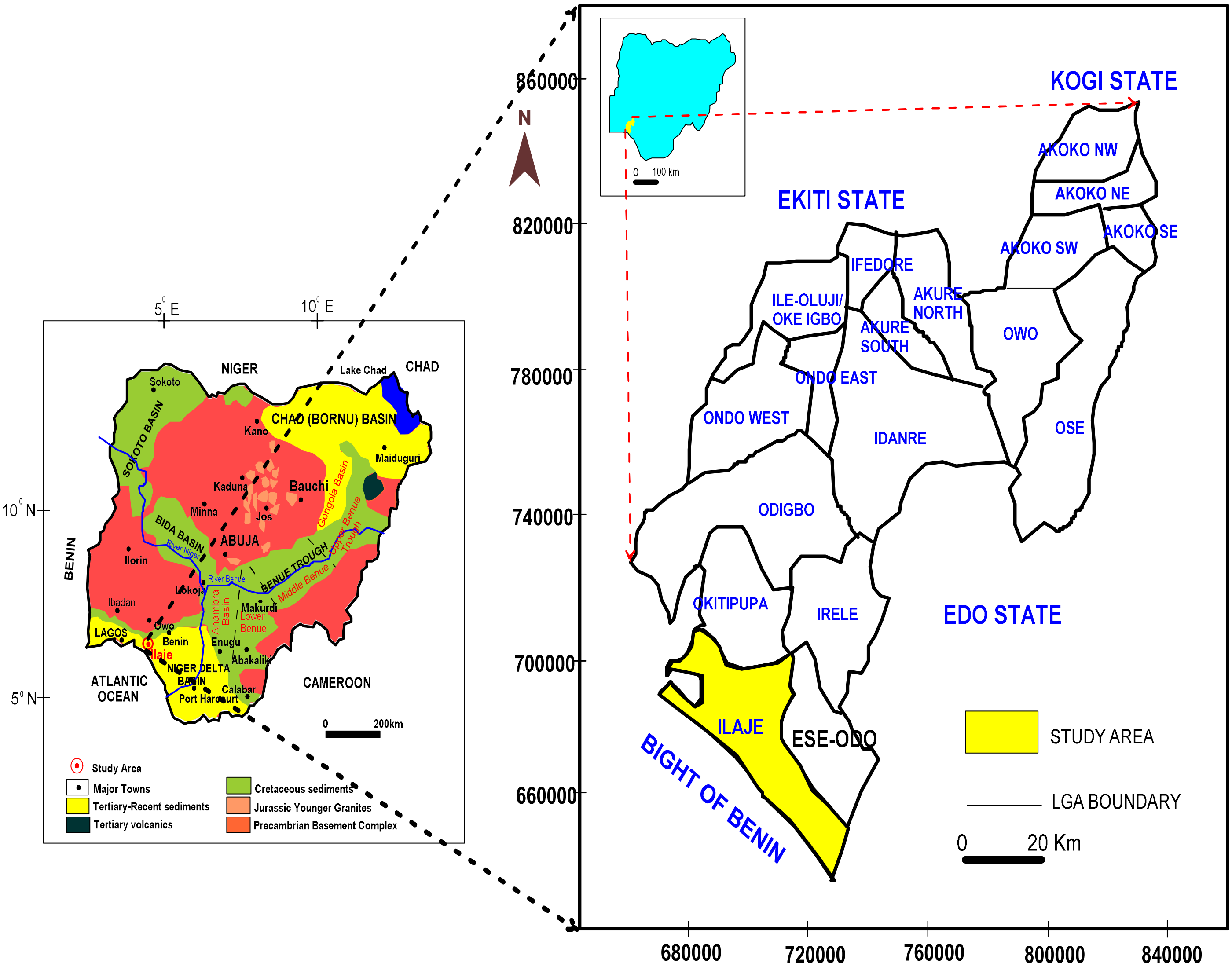

Fig. 1. Location map of the Study Area and Geological map of Nigeria showing the Study Area on Tertiary - Recent sediments (Modified after Obaje, 2009)

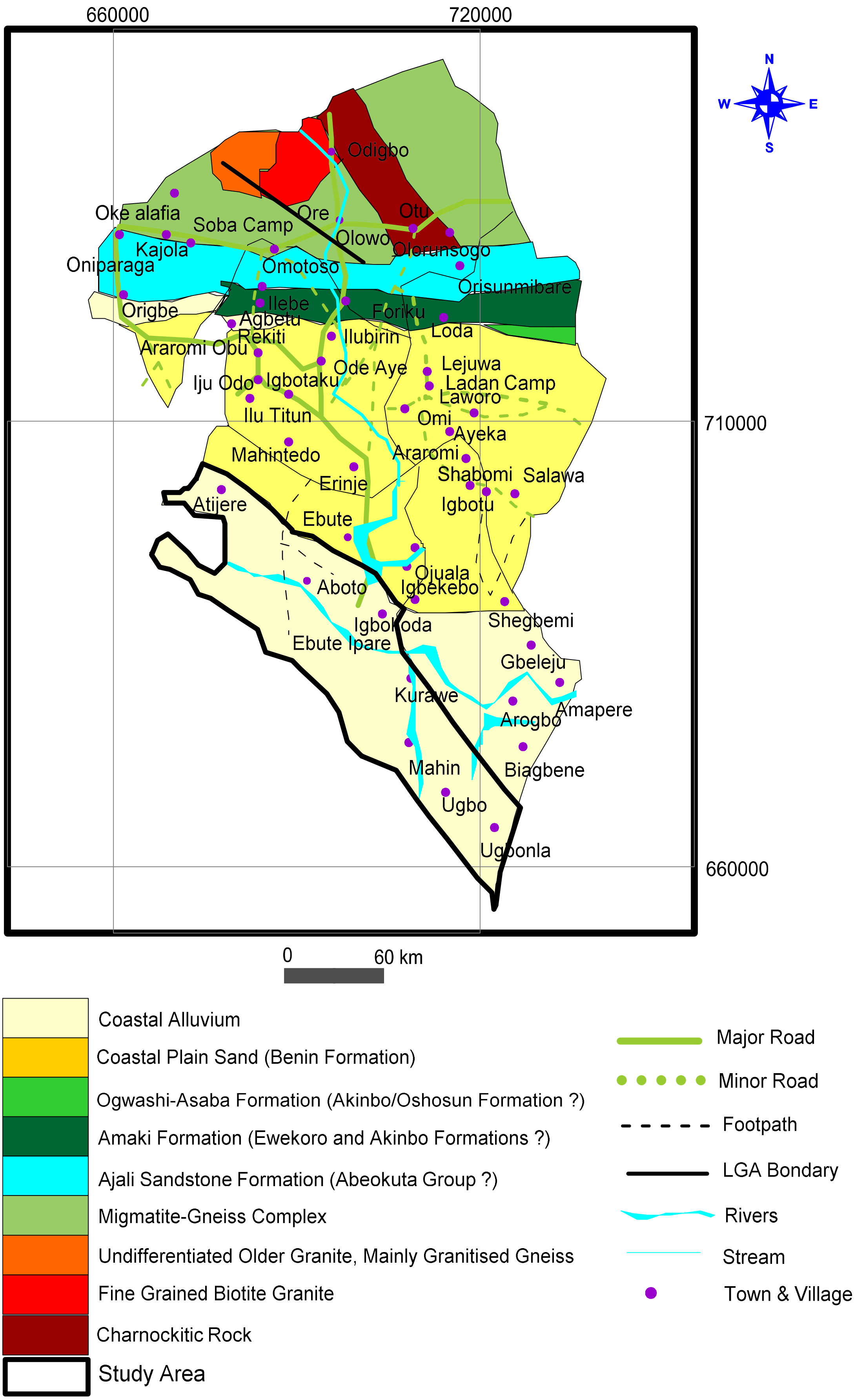

Fig. 2. Local geology map of the area with predominant alluvium sand

Aquifer's intrinsic susceptibility is a measure of the ease with which water enters and moves through an aquifer; it is a characteristic of the aquifer and overlying material and hydrologic conditions, and is independent of the chemical characteristics of the contaminant and its sources. An analogous definition to "aquifer sensitivity" is "intrinsic vulnerability" (Aller at al., 1987; Al-Zabet, 2002; Spizzico et al., 2004) defined by the time of travel of water from the point of contaminant entry to the reference location in the ground-water system. It is also sensitivity plus intensity, where 'intensity' is a measure of the source of contamination. Clearly, groundwater vulnerability is a function not only of the properties of the ground-water-flow system (intrinsic susceptibility) but also of the proximity of contaminant sources, characteristics of the contaminant, and other factors that could potentially increase loads of specified contaminants to the aquifer and (or) their eventual delivery to a ground-water resource (National Research Council, 1993).

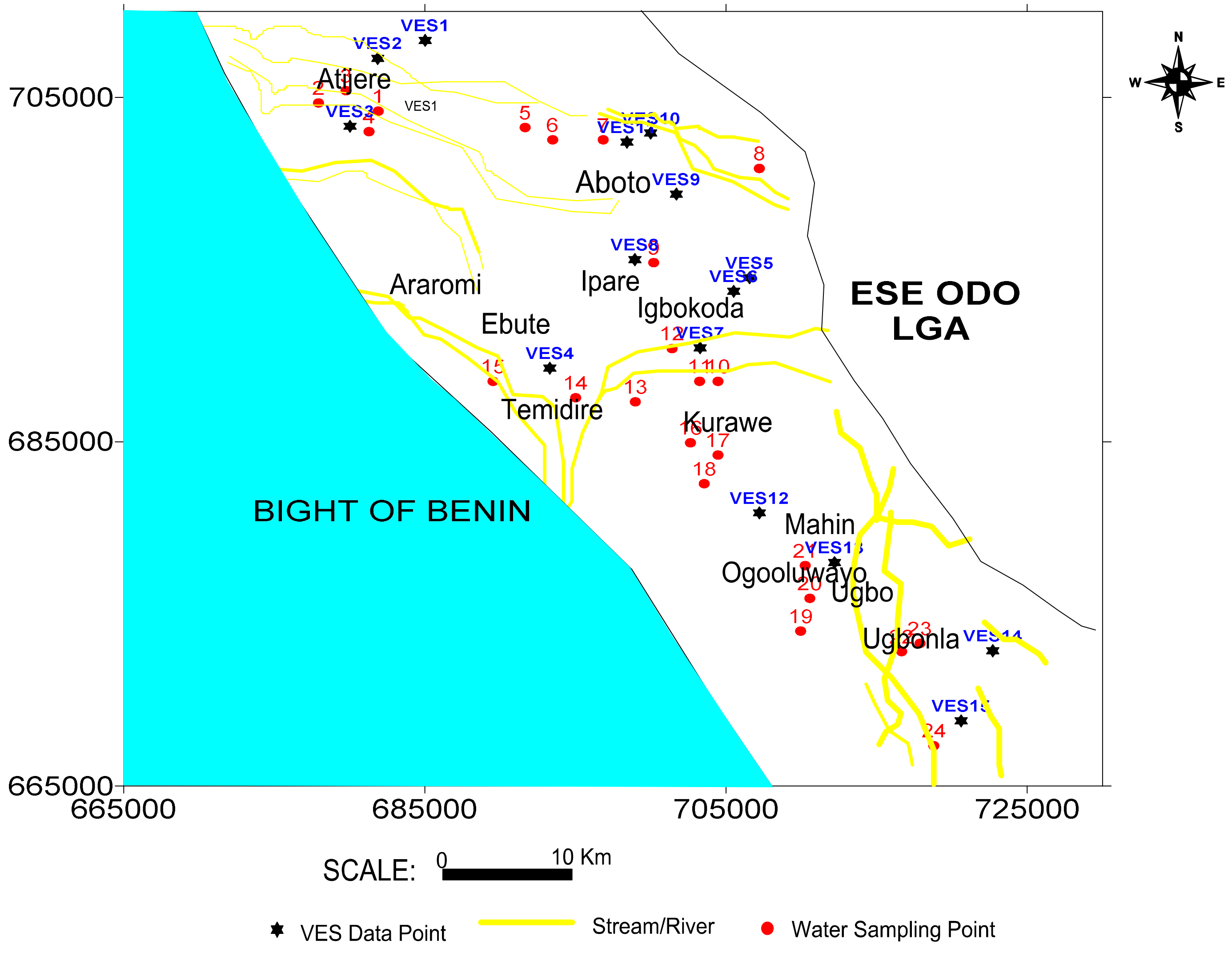

Fig. 3. Data acquisition map for the study

The vulnerability of a ground-water resource to contamination depends on intrinsic susceptibility as well as the locations and types of sources of naturally occurring and anthropogenic contamination, relative locations of wells, and the fate and transport of the contaminant(s). Water-resource decision makers are often faced with a choice of deciding whether to manage a resource based on knowledge of intrinsic susceptibility or to target more comprehensive and contaminant-specific assessments of vulnerability. Several methods of aquifer vulnerability have been proposed; among these methods, index methods are the most popular (Samia-Haque et al., 2017). There are many of such models but the most useful are DRASTIC, GOD, SINTAX, SI, IRISH, AVI (Napolitano and Fabbri, 1996; Al-Hallaq and Elaish, 2012; Albinet and Margat, 1970; Al-Adamat et al., 2003). For example, an assessment of groundwater vulnerability in Azraq catchment in Fuhais-Jordan using DRASTIC model was carried out by Khrisat and Al-Bakri (2019), and generated spatial map of vulnerability showed 5 classes with different percent for each. These were: very low (5%), low

(16%), moderate (11%), high (34%) and very high (34%). In terms of area, the high and very high vulnerability classes distributed over 7.75 km^2, while the low vulnerability distributed over 1.10 km^2.

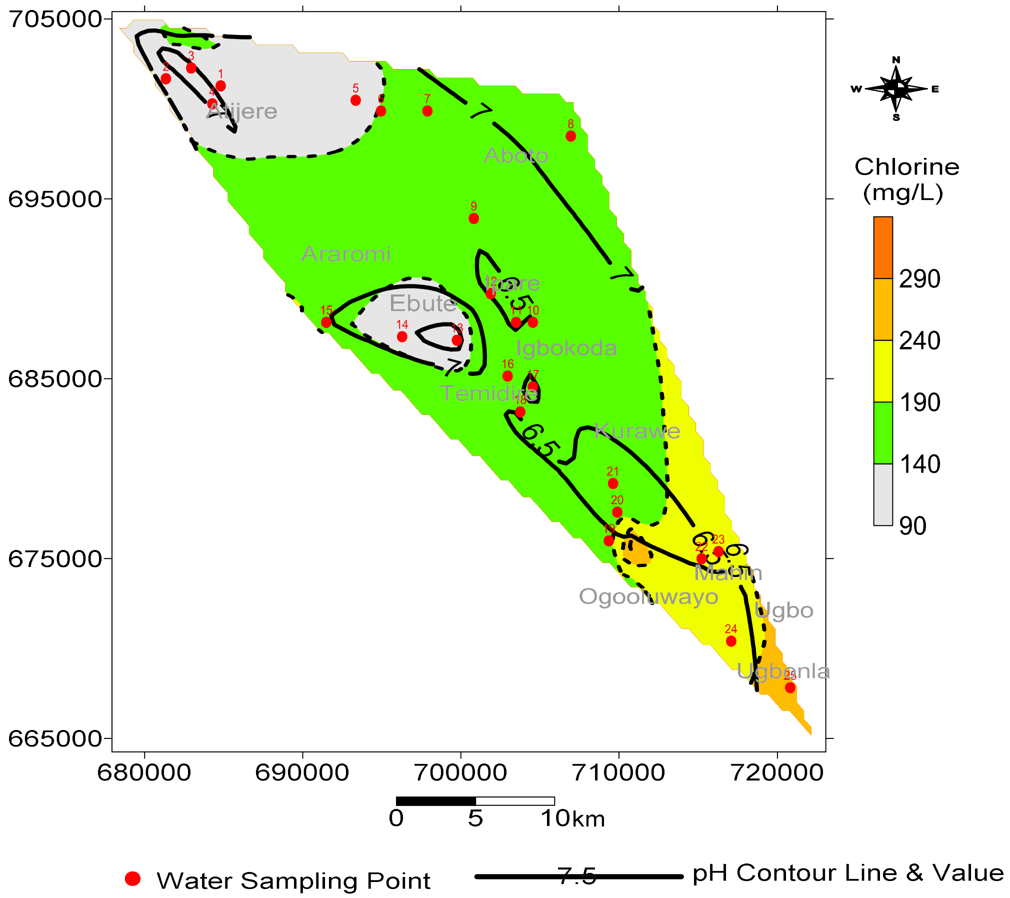

Fig. 4. Spatial distribution of chloride and pH

Aquifer vulnerability assessment by S-model is a cheaper alternative to index models (Atakpo and Ayolabi, 2009; Braga, 2008). In S-model the protective capacity of vadose zone is assessed by determining lithological composition and thickness through electrical resistivity sounding and remote sensing methods (Mishra et al., 1990; Mosuro et al., 2016). Longitudinal conductance (S) values are grouped into different vulnerability zones (Braga and Francisco, 2014).

The resistivities of earth material depend on soil type, porosity and fluid present in pore spaces and can be determined by electrical resistivity surveying, a geophysical technique used for the determination of such resistivities variations. There are different geophysical methods used for groundwater development through determination of formation resistivity, properties of a fluid inside pores and protective capacities of material above the saturated zone (Falowo et al., 2017a; Hammour and El-Naqa, 2008; Mosuro et al., 2016).

Geophysical surveys have been used in exploring the shallow subsurface for groundwater. A number of different techniques are used, the most common of which are direct current resistivity, seismic refraction, gravity and magnetic method. Geophysical methods may be used to determine indirectly the extent and nature of the geologic materials beneath the surface. The thickness of unconsolidated surficial materials, the depth to the water table, the location of subsurface faults, and the depth of the basement rocks (Kelly and Stanislav, 1993; Sonkamole, 2014; Anomohanran, 2013).

ERS has proved a non-distractive and appropriate method for determination of various subsurface geologic strata and groundwater quality (Patil et al., 2015; Al-Dulaymi et al., 2012). ERS has also been used in various groundwater studies for the achievement of multiple objectives in numerous hydrogeological conditions (Sikandar et al., 2010; Ugwu et al., 2016). This technique, VES with Schlumberger electrode configuration is very famous for the groundwater studies. Eniola et al. (2016) carried geophysical survey, involving schlumberger depth soundings, were conducted at Alade, Ondo State, Nigeria to assess the aquifer vulnerability to contamination.

The results revealed that the topsoil layer has a resistivity mostly within the range of 1-100 ohm-m across the area. Resistivity values within the bracket indicate clay sequence;

which suggests that aquifers within the unconsolidated overburden are mostly capped by semi - pervious materials, geologically protecting the aquifer from near -surface contamination. Also, Akpan et al. (2018) carried out geoelectric evaluation of groundwater potential and vulnerability of overburden aquifers at Onibu-Eja active open dumpsite, Osogbo, southwestern Nigeria. The present study aimed at determining the pollution vulnerability potential of the unsaturated/saturated aquifer layer and groundwater quality from twenty-five water samples taken from streams and borehole which are the major water sources in Ilaje area of Ondo State Nigeria. Also, GOD, AVI, and S-model were incorporated to characterize the area into different vulnerability zones.

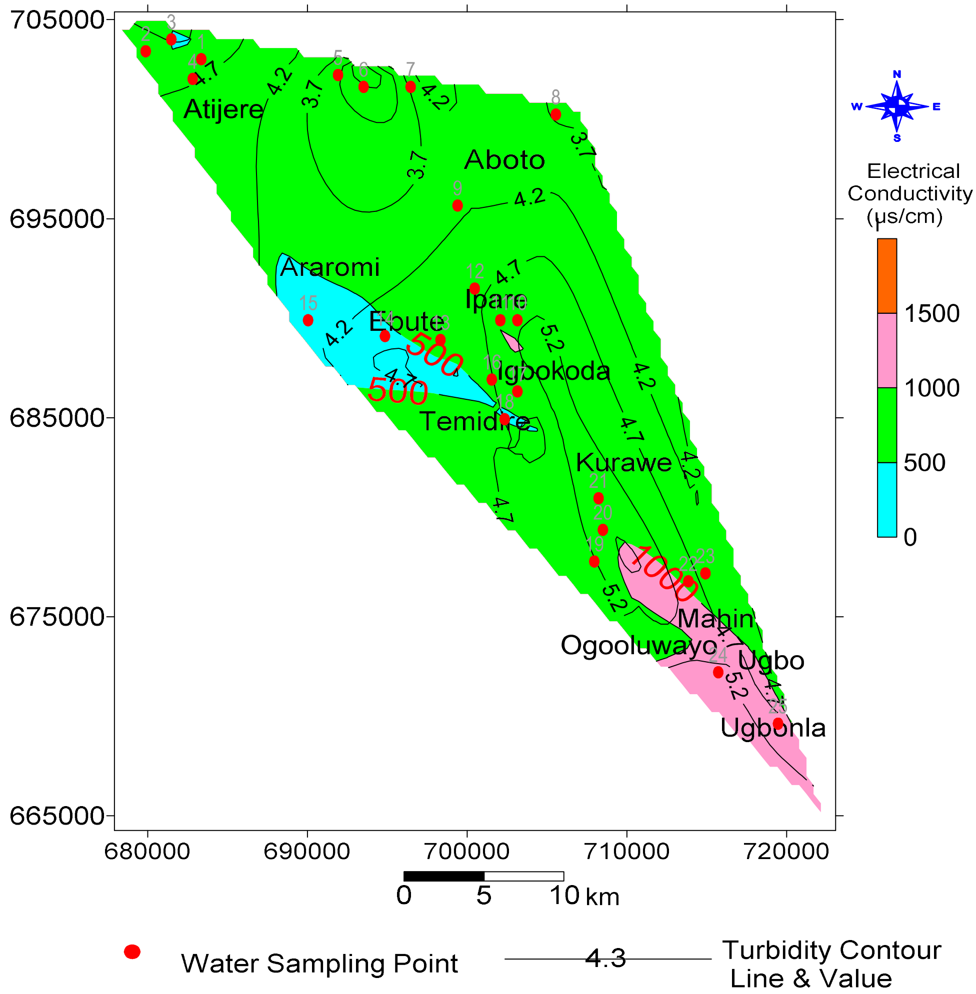

Fig. 5. Areal distribution of electrical conductivity and turbidity

2. Materials and Methods

2.1. Description of the study area

The study area is Ilaje local government area of Ondo State, which falls within southwestern Nigeria (Fig. 1) between 670000 and 740000 mE and 630000 and 720000 mN. Major part of the study area is devoted to fishing activities. Also, oil exploration and exploitation are presently carried out onshore in the study area. The people of the area depend on government boreholes and streams for drinking and other domestic uses. The area is within the tropical rain forest region of Nigeria characterized by wet and dry seasonal variations, with a mean annual rainfall of 180 cm, mean temperature of 24 °C, and mean humidity of 80% (Iloeje, 1981). The study area is generally characterized by flat and gently undulating topography. Topographic elevations vary from about 2 to 10 m above sea level. The area is drained by many perennial streams and rivers such as Ominla, Akeun, Ufara, Okomu, Ofara and others, which form a network of dendritic drainage pattern and empty their waters into the Atlantic Ocean to the south (Omosuyi, 2001). The rivers and streams in the area are being fed by several lagoons, ponds, canals, creeks and small streams scattered across the study area.

The area is characterized by heavy annual rainfall averaging about 2,000 mm. Rainfall is distributed virtually over all the months of the year with the minima occurring between November and March. Plant type is generally mangrove in the costal part of the study area, typical of swamp forest, while the mainland area is characterized by oil palm, rubber plantation and other broadleaved species, typical of rainforest vegetation. The different ethnic groups that live in the area are the Egbados, Ikales, Ilajes and Ijaws. They live in hamlets, villages and towns which are closely separated from each other although mostly connected by fairly-good to poor roads.

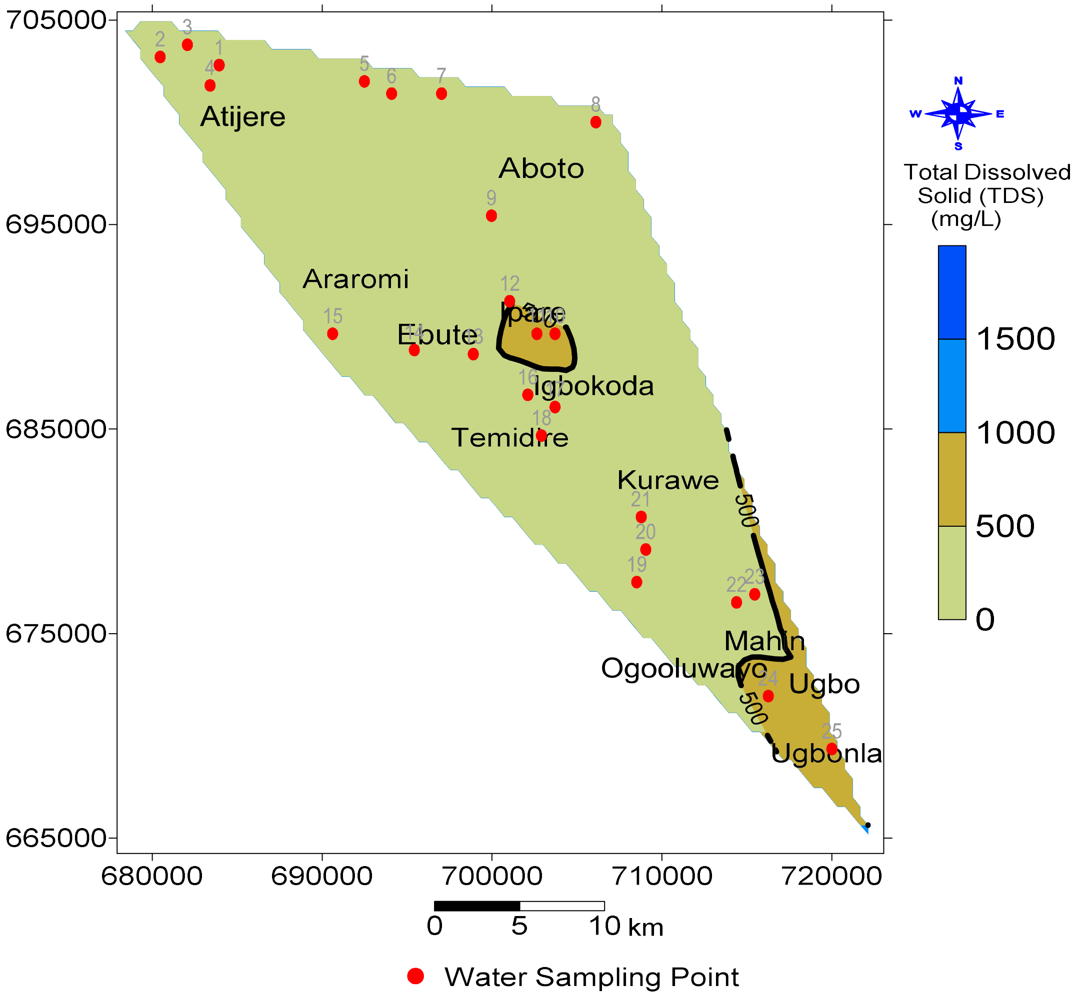

Fig. 6. Spatial variation of total dissolved solids

2.2. Geology
The eastern Dahomey basin, geologically where the study area located, as beginning with the Abeokuta Group (Omosuyi et al., 2007), made up of three Formations from oldest to the youngest namely; the Ise, Afowo and Araromi Formations (Fig. 1 and Fig 2). The Ise Formation unconformably overlies the basement complex of southwestern Nigeria and consists of conglomerates and grits at base and in turn overlain by coarse-to-medium grained sands with interbedded Kaolinite.

The conglomerates are unimbricated and at some locations ironstones occur (Nton, 2001). The age is Neocomian to Albian. Overlying the Ise Formation is the Afowo Formation, which composed of coarse to medium grained sandstones with variable but thick interbedded shales, siltstones and claystones. The sandy facies are tar-bearing while the shales are organic-rich (Enu, 1990).

The lower part of this Formation is transitional with mixed brackish to marginal horizons that alternate with well sorted, sub-rounded sands indicating a littoral or estuarine near-shore environment of deposition. Using palynological assemblage, Billman (1992) assigned a Turonian age to the lower part of this Formation, while the upper part ranges into the Maastritchian. Araromi Formation overlies the Afowo Formation (Fig. 2) and has been described as the youngest cretaceous sediment in the eastern Dahomey basin (Omatsola and Adegoke, 1981).

It is composed of fine to medium grained sandstone at the base, overlain by shales, siltstone with interbedded limestone, marl and lignite. This Formation is highly fossiliferous containing abundant planktonic foraminifera, Ostracods, pollen and spores. Omatsola and Adegoke (1981) assigned a Maastritchian to Paleocence age to this Formation based on faunal content.

2.3. Field mapping, water sampling and analysis

Therefore, in order to evaluate the vulnerability of the aquifers/water bearing units to contamination or pollution, longitudinal conductance using geophysical method (vertical electrical sounding), GOD and Aquifer Vulnerability Index (AVI) (Stempvoort et al., 1993) were used.

Fifteen (15) Schlumberger vertical electrical soundings (VES) were conducted across the study area using a maximum current electrode separation (AB) of 750 m. Fig. 3 shows the VES locations. Resistivity measurements were made with an Ohmega digital resistivity meter which allows for read out of current and voltage.

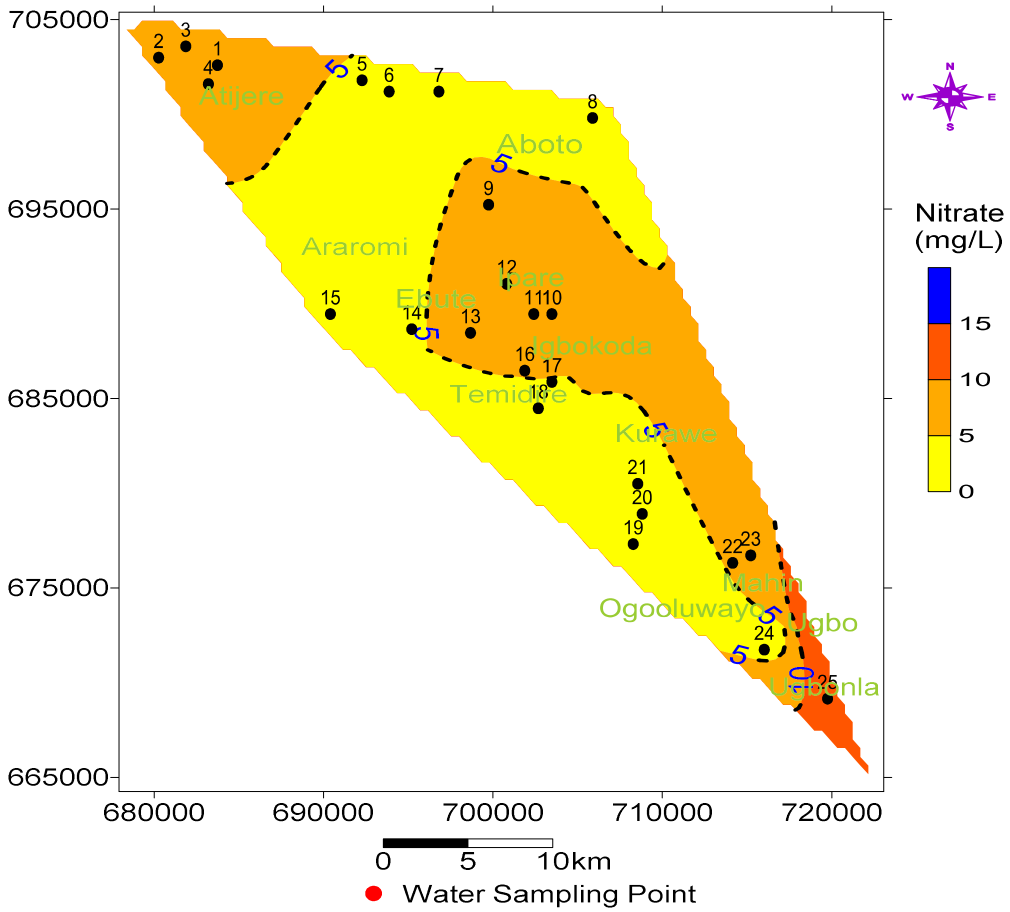

Fig. 7. Spatial distribution of nitrate

The location of each sounding stations in both geographic and Universal Traverse Mercator coordinates was recorded with the aid of the GARMIN 12 channel personal navigator-geographic positioning system unit. The field curves were interpreted through partial curve matching with the help of master curves and auxiliary point charts. From the preliminary interpretation, initial estimates of the resistivity and thickness of the various geoelectric layers at each VES location were obtained. These geoelectric parameters were later used as starting model for a fast computer-assisted interpretation.

The program takes the manually derived parameter as a starting geoelectric model, successively improved on it until the error is minimized to an acceptable level. The interpreted result was considered satisfactory where a good fit of the field curves and computer-generated curves is less than 10%. The total longitudinal layer conductance (S) of the overburden at each station was calculated (Atakpo and Ayolabi, 2009; Braga and Francisco, 2014; Braga, 2008).

Table 1. Aquifer protective rating using longitudinal conductance values

Longitudinal conductance (mhos)	Protective capacity rating
>10	Excellent
5-10	Very Good
0.7-4.9	Good
0.2-0.69	Moderate
0.1-0.19	Weak
<0.1	Poor

Total longitudinal layer conductance (S) is one of the Dar Zarrouk parameters. Summary of the VES number/GPS coordinates, geoelectric parameters, total longitudinal conductivity of protective layers, and the aquifer protective capacity rating of the study area were determined. A standard used in assessing longitudinal conductance/aquifer protective capacity of an area is presented in Table 1. It is on the basis of this classification that the aquifer protective capacity of the area was characterized (Akpan et al., 2018).

In addition, ground water samples were collected from twenty-five borehole locations (Fig. 3) which are functional and continuously in use for drinking and domestic purposes, in the month of November (2018)-February (2019). Samples were collected in polythene bottles, pre-cleaned by washing with non-ionic detergents, rinsed with water, 1:1 hydrochloric acid and finally with de-ionized water. Before sampling, the bottles were rinsed three times with sample water. Tube wells were operated at least five minutes before collection of the water samples.

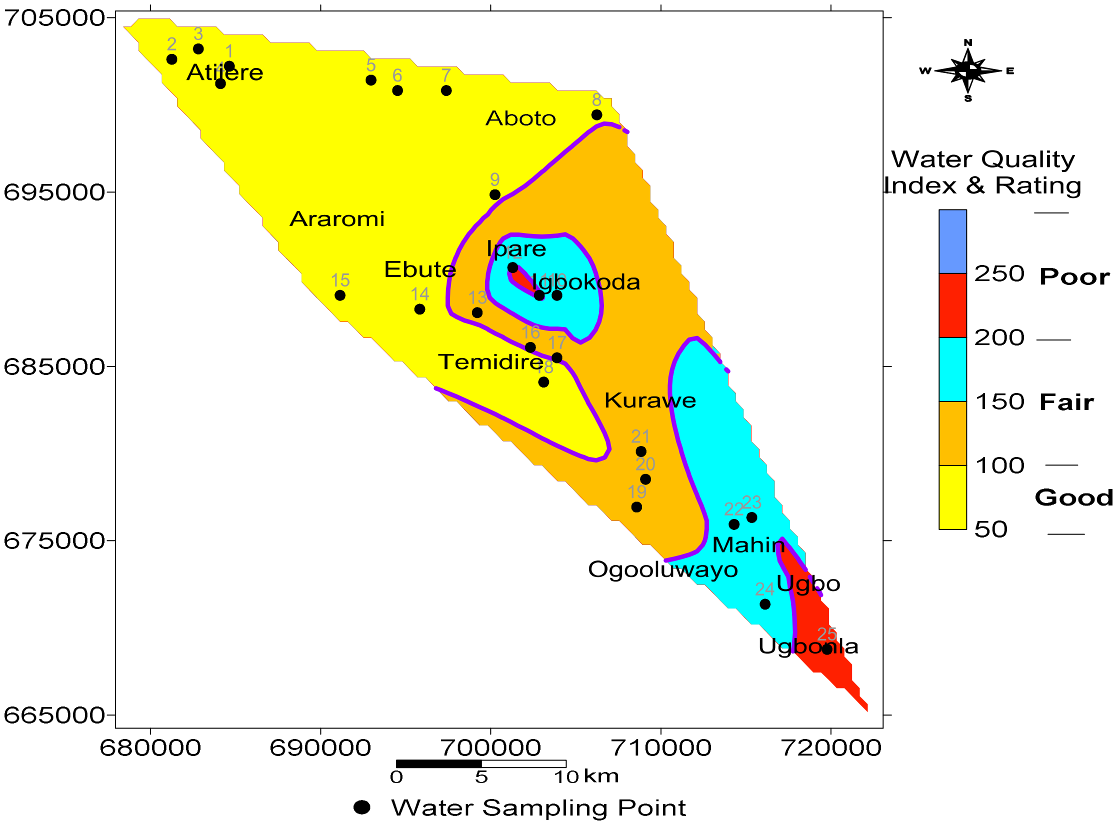

Fig. 8. Spatial variation of Water Quality Index

2.4. Aquifer vulnerability assessment

The aquifer vulnerability index method (Stempvoort et al., 1993) is a measure of groundwater vulnerability based on two physical parameters: (a) thickness of layer above the uppermost aquifer surface, and (b) estimated hydraulic conductivity of each of the (sedimentary) layers. The thickness (d) of sedimentary layers (e.g. sand, clay, silt, gravel) was obtained from the geoelectric sections. Since hydraulic conductivity (K) determinations may not be available for each geologic unit, a table of estimated values (Tables 1 and 2) was used accordingly to Freeze and Cherry (1979). Based on the two physical parameters, d and K, the hydraulic resistance "c" can be calculated (Table 3), where:

$$C = \sum \frac{d_i}{K_i} \text{ .... (2) for layers 1 to i} \quad (1)$$

The parameter "c" is a theoretical factor used to describe the resistance of an aquitard to vertical flow (Kruseman and de Ridder, 1990). Thus, the weighting of the two factors, thickness and hydraulic conductivity of each sediment layer above the uppermost saturated aquifer surface, is not arbitrary, but is based on physical theory. Hydraulic resistance (c) has dimension "Time", which indicates the approximate travel time for water to move by advection downward through the various porous media above the upper most saturated aquifer surface.

However, it should be noted that, in a strict sense, c is not a travel time for water or contaminants. Factors such as hydraulic gradient, diffusion, and sorption are not considered. The calculated c or log (c) values can be used directly to generate iso-resistance contour maps. The AVI method takes into account indirectly the various factors or parameters used by DRASTIC (Aller et al., 1987), with the exception of topography, and aquifer media (i.e. type of sediment or rock serving as aquifer media, hydraulic conductivity of aquifer).

Table 2. Hydraulic conductivity (*K*) estimates (mean values) for various sediments

Sediment type	Standard code	Hydraulic conductivity
Gravel	A	1000 m/d
Sand	B	10 m/d
Silty sand	C	1 m/d
Silt	D	10^{-1}m/d
Fracture till, clay or shale (0 to 5 m from ground surface)	E	10^{-3}m/d
Fracture till, clay or shale (0 to 5 m from ground surface)	F	10^{-4}m/d
Fracture till, clay or shale (10 m from ground surface, but weathered based on color: brown or yellow)	F	10^{-4}m/d
Massive till or mixed sand-silt-clay	G	10^{-5}m/d
Massive clay or shale	H	10^{-6}m/d

Table 3. Relationship of aquifer vulnerability index to hydraulic resistance

Hydraulic resistance	Log (c)	Vulnerability (AV)
0 to 10 y	<1	Extremely High
10 to 100 y	1 to 2	High
100 to 1, 000 y	2 to 3	Moderate
1, 000 to 10, 000 y	3 to 4	Low
>10, 000 y	>4	Extremely Low

Table 4. Interval values of the GOD index and corresponding classes (Modified after Murat et al., 2003)

Index	Vulnerability class
0 - 0.1	Very Low
0.1 – 0.3	Low
0.3 – 0.5	Moderate
0.5 - 0.7	High
0.7 – 1.0	Very High

Table 5. Attribution of notes for GOD model parameters (Modified after Khemiri et al., 2013)

Aquifer Type	Note	Depth to aquifer/water bearing unit	Note	Lithology (Ω-m)	Note
Non-Aquifer	0	< 2	1	< 60	0.4
Artesian	0.1	2- 5	0.9	60-100	0.5
Confined	0.2-0.4	5-10	0.8	100-300	0.7
Unconfined	0.5-1	10-20	0.7	300-600	0.8
		20-50	0.6	> 600	0.6
		50-100	0.5		

The GOD method is characterized by a rapid assessment of the aquifer vulnerability; it was developed by Foster (1987) for studying the vulnerability of the aquifer against the vertical percolation of pollutants through the unsaturated zone, without considering their lateral migration in the saturated zone. The approach used in this model takes in consideration three parameters: groundwater occurrence (confinement of the aquifer); overall aquifer class (lithology overlying the aquifer), and depth to aquifer/water bearing unit.

The GOD index which is used to evaluate and map the aquifer vulnerability caused by pollution, was calculated by multiplication of the influence of the three parameters using the equation 2:

$$\text{GOD Index} = Cl \times Ca \times Cd \quad (2)$$

Where: Ca is the type of aquifer, Cl is the lithology of the unsaturated zone and Cd is the depth to aquifer. These GOD parameters were interpreted from the geoelectric sections. The intervals values of GOD Index and corresponding classes (Table 4), attribution of notes for GOD Model parameters was modified after Murat et al. (2003) (Table 5). The corresponding classes of vulnerability used, which were derived from GOD Index used is presented in Table 4.

3. Results and Discussion

3.1. Physical and chemical parameters

The results of the physical, chemical, and heavy metals/toxic contaminants are presented in Tables 6 and 7. The pH of the water samples ranges from 6.0 to 7.9 with an average (av.) of 6.71. This result is similar to investigation carried out (6.5-9.5) near the study area by Ojo et al. (2014) and Adeyemo et al. (2015) which recorded pH of 6.0-7.1.

From Fig. 4, the study is generally characterized by slightly acidic to neutral water. EC measured in the study area ranges from 400 to 1200 µs/cm (av. 781.44 µs/cm). The southern part is characterized by high EC, but generally EC in the range of 500-1000 accounts for 85% of the area (Fig. 5). Although the range of values obtained is far below the permissible limit of 1500 µs/cm (WHO, 2011). The TDS values vary from 101.5-1109.5 mg/l with a mean of 335.3 mg/l. The maximum permissible limit of 1500 mg/l is the recommended limit for TDS (WHO, 2011).

However, some places in the south like Ugbonla/Ugbo and Igbokoda show relatively higher values greater than 500 mg/l (Fig. 6). This corroborates high TDS values recorded by Adeyemo et al. (2015) in Ugbonla, Ugbo, Orioke, Asisa, etc. Turbidity ranges between 2-5.9 NTU (av. 4.06 NTU) with relatively high values occur in the south. This result is a little bit higher than the values (0.07-0.6 NTU) recorded by Oshoma et al. (2018) in Benin City, which is still within the same sedimentary environment.

The chloride varies from 93-321 mg/l with a mean of 173.15 mg/l. The southern area is characterized by relatively high chloride values (Fig. 4) which could be as a result of high anthropogenic activities (contamination from sewage, and other domestic wastes) and also closeness of the area to major rivers. However, the dominant range is in between 140-190 mg/l, and account for 65% of the area.

Table 6. Result obtained from the physical parameters measured/examined

Location	EAST	NORTH	Sample No	EC (µS/cm)	Turbidity NTU
ATIJERE	681896	704211	1	410	5.4
	677932	704687	2	1050	4.9
	679761	705400	3	730	5.6
	681286	703022	4	558	4.8
EBUTE	691654	703260	5	920	3.9
	693483	702546	6	445	2.0
	696838	702546	7	1015	4.4
	707206	700882	8	508	3.5
ABOTO	700192	695411	9	801	4.2
IGBOKODA	704461	688514	10	750	5.5
	703242	688514	11	1080	5.2
	701412	690417	12	1010	4.8
IPARE	698972	687325	13	410	4.1
	695008	687563	14	400	4.9
	689519	688514	15	430	4.0
	702632	684946	16	450	4.8
IGBOKODA	704461	684233	17	490	4.5
UGBONLA	703547	682568	18	780	4.7
	709950	674006	19	952	5.1
	710560	675909	20	1000	5.2
	710255	677811	21	1050	5.9
MAHIN	716659	672817	22	1010	5.2
	717879	673292	23	1000	4.2
UGBONLA	718794	667346	24	1200	5.5
	723063	664254	25	1050	5.5
Min.	-	-	-	400	2.0
Max.	-	-	-	1200	5.9
Average	-	-	-	781.44	4.66

Hard waters can thus consume excessive quantities of soap, and cause damaging scale in water heaters, boilers, pipes, and turbines. Many of the problems associated with hard water, however, can be mitigated by using water-softening equipment. Ca-hardness and Mg-hardness vary from 8 – 132 mg/l (av. 39.89 mg/l) and 11-210 mg/l (av. 79 mg/l). The Mg-hardness in the water samples is more than Ca-hardness. Sulphate, an anion formed by oxidation of the element sulfur, is commonly found in groundwater. The concentration of sulphate in the study area varies from 12.5-68.1 mg/l and a mean of 32.82 mg/l.

Generally, the area has low concentration of sulphate. The concentration of bicarbonate is a little bit higher than the recommended standard of 120 mg/l, as it ranges from 65 and 251 mg/l (av. 144.26 mg/l). High concentrations of nitrate are undesirable in drinking waters because of possible health effects. The maximum contaminant level, for nitrate is 10 mg/l (WHO, 2011). The range of nitrate in the study area is in between 0.25 and 15.4 mg/l (av. 5.64 mg/l).

Fig. 7 shows that nitrate in the range of 5-15 mg/l is the most dominant account for about 55% of the area. This could be as a result of high anthropogenic discharge. The concentration of calcium and magnesium varies from 6.9-120.8 mg/l (av. 43.88 mg/l), 1.52-39.5 mg/l (av. 15.89 mg/l) respectively. The obtained values are within the WHO (2011) of 75 mg/l for drinking water, respectively.

3.2. Toxic metal contamination

Iron and manganese recorded values in the range of 0.01 to 0.29 mg/l and 0.024 to 0.01 mg/l, respectively. However, no indication of traces of lead (0.0012-0.0099 mg/l), cyanide (0.0001-0.0054 mg/l), arsenic (0.0001-0.0019 mg/l), mineral oil (0.0001-0.0002 mg/l) and ammonia (0.0001-0.0025) in some of the groundwater samples. These values are less than 0.1 mg/l standard recommended by WHO (2011). These results are relatively lower than what was obtained by Igbemi et al. (2019) in Eastern Obolo Local Government Area of Akwa Ibom State, which is located at the eastern fringe of the Niger Delta between Imo and Qua Iboe River estuaries: lead (0.24 mg/l), iron (1.40 mg/l) and cadmium (0.68 mg/l).

However, caution must be taken to keep this value low to prevent serious health challenges (Hussain et al., 2016). The values of water quality index vary from 55 to 212 with an average of 121 (Fig. 8). This range of values is lower to what was obtained (22.7 – 88.6) in northern part of Ondo State (Falowo et al., 2017a; Falowo et al., 2017b). Using the mean value of 121, the area is generally or falls within poor/unfit water type. However poor water is associated with southern part (Ugbonla, Mahin) and some part of Igbokoda; while fair/good water type is observed in the northern part.

3.3. Vulnerability indices/maps

The generated GOD map (Fig. 9) shows that high to very high vulnerability areas account for 60% of the area, while moderate accounts for 40%. The map divides the area into two distinct vulnerability zones of (moderate) in the north and (high/very high) in the south. In addition, small closure of high vulnerability is observed in north east (Aboto community). The AVI map (Fig. 10) shows that the area is generally of high vulnerability except some areas around Ebute and some part of Igbokoda which are characterized by low vulnerability values.

The low/moderate vulnerability area constitute about 45% of the area while high vulnerability accounts for 55% of the area. In addition, the AVI map corroborates the GOD map which distinctly divides the area into north and south vulnerability zones. The depth to the aquifer delineated in the area varies from 0.7 to 38.3 m. This shows that most of the aquifers are at shallow depth and would be vulnerable to contamination or pollution arising from anthropogenic, geogenic, oil spillage contamination. Typical curve types are shown in Fig. 11.

The total longitudinal conductance of the study area is moderate, ranging from 0.011 mhos (at VES 8; Ipare) to 3.2075 mhos (at VES 10; Aboto), with an average of 0.7757 mhos, which falls within the “good protective rating”. By implication, the aquifer protective capacity of the area is good. The overburden units show that the topsoil and subsoil layers at all the VES points are mostly sandy. The low resistivity values recorded in the overburden units of VES 11, 13, 14 and 15 is due to high saturation of the overburden units in these locations (Aboto, Kurawe, Ugbo, and Ugbonla respectively) with resistivity range of 6 - 1327 Ωm.

Table 7. Summary of the analyzed chemical parameters

Well No	pH	Cl^-	Mg Hardness	Ca Hardness	SO_4^{2-}	NO_3^-	Mn	TDS	HCO_3^-	Mg^{2+}	Ca^{2+}	Fe^{2+}	WQI (%)
1	6.4	189	65	15	23.4	7.85	ND	550.5	114	2.45	39.2	0.15	28
2	6.0	104	75	25	12.9	6.96	0.014	236.5	221	1.52	26.5	0.12	30
3	6.1	93	19	14	28.8	6.47	0.022	120.2	142	1.98	17.4	0.14	24
4	7.2	98	25	8	19.4	6.88	0.009	133.5	180	16.54	15.5	0.11	28
5	6.7	102	45	10	32.5	5.11	0.009	115.1	74	12.25	18.9	NIL	28
6	6.9	112	65	15	33.6	3.56	0.011	120.3	65	8.59	6.9	0.09	24
7	7.0	184	60	12	48.5	3.55	ND	110.4	125	6.80	8.8	0.01	30
8	7.4	156	88	19	52.2	2.36	0.010	116.8	133	9.92	10.1	ND	29
9	6.6	165	84	18	12.6	5.87	0.015	119.5	85	2.27	8.5	0.18	27
10	6.5	147	102	68	41.1	9.25	ND	550.2	180	30.20	95.2	0.23	46
11	6.4	185	105	36	65.9	9.25	0.021	580.5	175	33.42	102.3	0.14	50
12	6.4	180	210	37	29.3	8.22	0.024	584.2	105	32.40	120.8	0.28	52
13	7.9	102	18	44	24.2	6.35	0.018	420.1	102	10.22	98.5	0.19	31
14	7.2	105	15	18	45.8	4.52	ND	105.2	95	8.54	88.1	0.20	26
15	6.9	198	25	26	68.1	3.15	ND	120.2	88	6.29	65.2	0.14	27
16	6.6	190	45	14	43.2	3.28	0.011	101.5	98	4.44	44.2	0.18	26
17	7.2	155	52	16	32.2	1.12	0.008	225.5	102	8.57	18.7	NIL	26
18	6.4	178	94	18	30.5	1.45	0.009	120.2	111	3.25	12.4	NIL	28
19	6.8	172	102	102	12.5	1.56	0.016	198.5	141	25.62	7.5	0.11	40
20	6.6	321	110	123	14.5	0.25	0.018	188.2	189	12.23	25.9	0.15	41
21	6.2	159	109	132	16.8	0.81	0.015	145.5	120	14.25	21.2	0.25	39
22	6.8	215	78	44	20.5	0.85	0.009	689.1	245	30.25	32.8	0.29	45
23	6.5	223	98	25	16.0	10.55	0.011	510.1	223	39.50	44.5	0.25	48
24	6.5	245	105	46	32.2	11.98	0.014	569.5	215	35.23	25.8	0.23	51
25	6.0	283	115	52	48.9	15.40	0.008	1109.5	251	31.25	102.2	0.18	56
Min.	6	93	15	8	12.5	0.25	0.008	101.5	65	1.52	6.9	0.01	28
Max.	7.9	321	210	132	68.1	15.4	0.024	1109.5	251	39.5	120.8	0.29	30
Mean	6.71	173.15	79.04	39.89	32.82	5.64	0.01	335.25	144.26	15.89	43.88	0.17	24

Table 8. Summary of the analyzed toxic chemicals and contaminants

Well No	Toxic Chemicals						Contaminants					
	Lead	Cyanide	Cadmium	Arsenic	Barium	Mercury	Pesticide	Mineral oil	Ammonia	Phenol	Detergent	Radionuclides (Bq/L)
1	ND	0.0018	NIL	0.0015	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
2	ND	0.0015	NIL	0.0015	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
3	ND	0.0025	NIL	0.0012	ND	ND	NIL	NIL	0.0025	NIL	NIL	NIL
4	ND	0.0014	NIL	0.0012	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
5	ND	NIL	NIL	0.0012	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
6	ND	NIL	NIL	0.0013	ND	ND	NIL	NIL	0.0011	NIL	NIL	NIL
7	0.0080	NIL	NIL	0.0012	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
8	ND	0.0044	NIL	0.0001	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
9	ND	NIL	NIL	ND	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
10	0.0077	0.0041	NIL	0.0004	ND	ND	NIL	0.0002	0.0111	NIL	NIL	NIL
11	0.0056	0.0021	NIL	00001	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
12	0.0099	NIL	NIL	ND	ND	ND	NIL	0.0001	0.0020	NIL	NIL	NIL
13	0.0012	0.0015	NIL	ND	ND	ND	NIL	NIL	0.0011	NIL	NIL	NIL
14	NIL	NIL	NIL	0.0011	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
15	NIL	0.0011	NIL	0.0011	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
16	NIL	0.0001	NIL	0.0011	ND	ND	NIL	0.0002	ND	NIL	NIL	NIL
17	0.0078	NIL	NIL	NIL	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
18	0.0065	0.0001	NIL	0.0001	ND	ND	NIL	NIL	ND	NIL	NIL	NIL
19	0.0022	0.0054	NIL	NIL	ND	ND	NIL	0.0001	0.0012	NIL	NIL	NIL
20	0.0090	0.0011	NIL	NIL	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
21	0.0065	0.0023	NIL	0.0011	ND	ND	NIL	0.0001	ND	NIL	NIL	NIL
22	0.0013	ND	NIL	0.0019	ND	ND	NIL	0.0002	ND	NIL	NIL	NIL
23	0.0025	0.0020	NIL	0.0017	ND	ND	NIL	0.0002	0.0001	NIL	NIL	NIL
24	0.0085	0.0052	NIL	0.0018	ND	ND	NIL	0.0002	ND	NIL	NIL	NIL
25	0.0011	0.0044	NIL	0.0001	ND	ND	NIL	0.0001	0.0001	NIL	NIL	NIL

Table 9. The results of the VES, layer longitudinal conductivity, total longitudinal conductivity and aquifer protective capacity rating

VES No	Coordinate East/North	Location	Resistivity ρ (Ωm)	Thickness (m)	Depth (m)	Curve Type	Layer Longitudinal Conductivity (S)	Longitudinal Conductivity of Protective Layers (mhos)	Aquifer protective capacity rating
1	685018/708326	Atijere	3294/ 15874/ 3163/ 173/ 125	1.0/1.0/9.1/175.9	1.0/ 2.0/ 11.0/ 186.9	KQQ	0.0003/0.00001/0.0029/1.0167	0.2550	Moderate
2	681866/707276	Atijere	3567/ 1730/ 2666/ 168/ 408	0.8/ 0.8/ 6.0/ 80.4	0.8/ 1.6/ 7.6/ 88	HKH	0.0002/0.0005/0.0023/0.4786	0.1204	Weak
3	680027/703336	Atijere	1034/ 1462/ 179/ 203/ 271	0.7/ 1.9/ 2.6/ 68.3	0.7/ 2.6/ 5.1/ 73.4	KHA	0.0007/0.0013/0.0145/0.3365	0.0882	Poor
4	693292/689283	Ebute	660/ 1011/ 685/ 9035	0.5/ 1.2/ 45.0	0.5/ 1.7/ 46.7	KH	0.0008/0.0012/0.0657	0.0226	Poor
5	706557/694537	Igbokoda	1269/ 1257/ 190/ 142/ 165	1.1/ 2.9/ 16.5/ 55.1	1.1/ 4.0/ 20.5/ 75.6	QQH	0.0009/0.0023/0.0868/0.3880	0.1195	Weak
6	705506/693749	Igbokoda	1175/ 1245/ 114/ 213/ 34	0.9/ 4.2/ 8.8/ 63.8	0.9/ 5.0/ 13.8/ 77.6	KHK	0.0008/0.0034/0.0772/0.2995	0.0952	Poor
7	703274/690465	Igbokoda	5776/ 22267/ 223/ 14280	0.4/ 0.7/ 188	0.4/ 1.2/ 189.2	KH	0.00007/0.00003/0.8431	0.2811	Moderate
8	698940/695587	Ipare	1652/ 1540/ 603/ 1854/ 39055	5.6/ 12.2/5.0/44.9	5.6/ 17.8/ 22.8/ 67.7	QHA	0.0034/0.0079/0.0083/0.0242	0.0110	Poor
9	701698/699396	Aboto	179/ 1535/ 944/ 666/ 37788	0.8/ 2.9/ 15.3/ 56.1	0.8/ 3.7/ 19.0/ 75.1	HQH	0.0045/0.0019/0.0162/0.0842	0.0267	Poor
10	699990/702942	Aboto	849/ 1000/ 373/ 39/ 11/ 66	0.8/ 2.4/ 5.9/ 38.3/ 165.4	0.8/ 3.2/ 9.1/ 47.4/ 212.8	KQQH	0.0009/0.0024/0.0158/0.9821/15.0363	3.2075	Good
11	698415/702417	Aboto	458/ 1327/ 224/ 99/ 64	0.7/ 0.8/ 6.1/ 93.1	0.7/ 1.5/ 7.6/ 100.7	KQQ	0.0015/0.0006/0.0272/0.9404	0.2424	Moderate
12	707214/680878	Kurawe	957/ 573/ 666/ 142/ 28	0.6/ 9.6/ 25.3/ 90.5	0.6/ 10.2/ 35.5/ 126.0	HKQ	0.0006/0.0168/0.0380/0.6373	0.1732	Weak
13	712204/677989	Ugbo	60/ 24/ 7/ 21/ 260	0.7/ 2.8/ 26/ 88.6	0.7/ 3.6/ 29.6/ 118.2	QHA	0.0117/0.1167/3.7143/4.2191	2.0154	Good
14	722711/672866	Ugbo	35/ 15/ 10/ 89/ 271	0.8/ 1.6/ 32.7/ 55.9	0.8/ 2.4/ 35.1/ 91.0	QHA	0.0229/0.1067/3.27/0.6281	1.0069	Good
15	720610/668795	Ugbonla	27/ 6/ 530/ 21/ 4	1.4/ 1.8/ 5.9/ 185.9	1.4/ 3.2/ 9.1/ 195	HKQ	0.0519/0.3/0.0111/8.8524	2.3038	Good

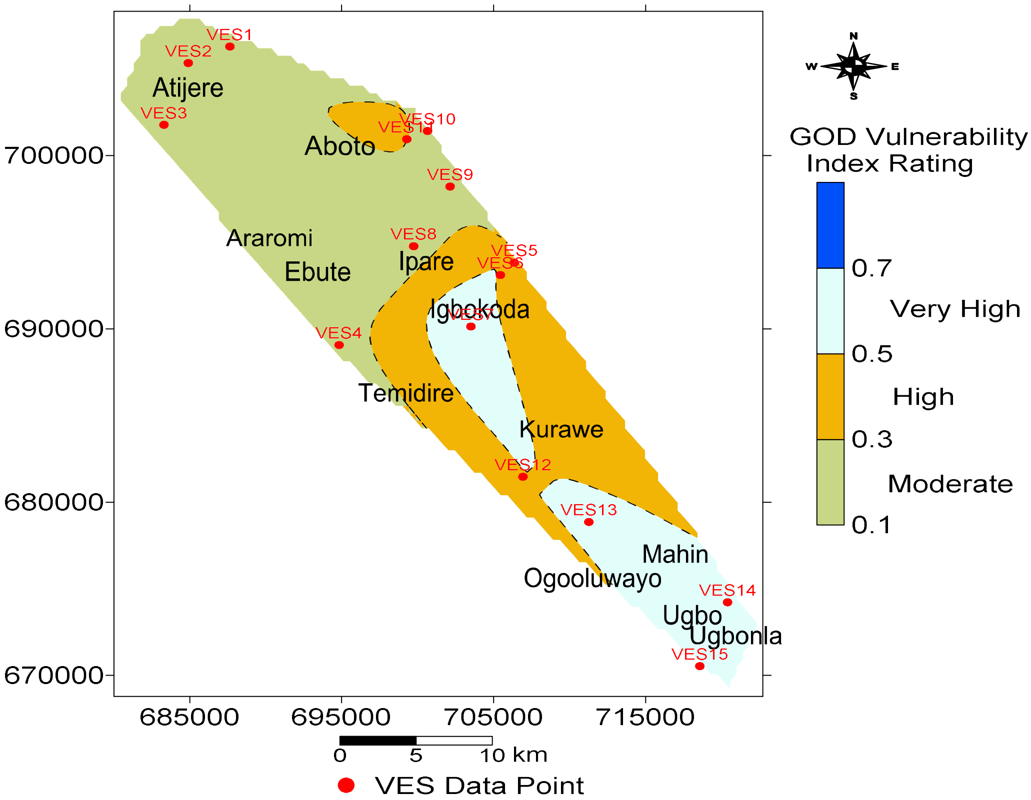

Fig. 9. GOD Vulnerability map of the study area

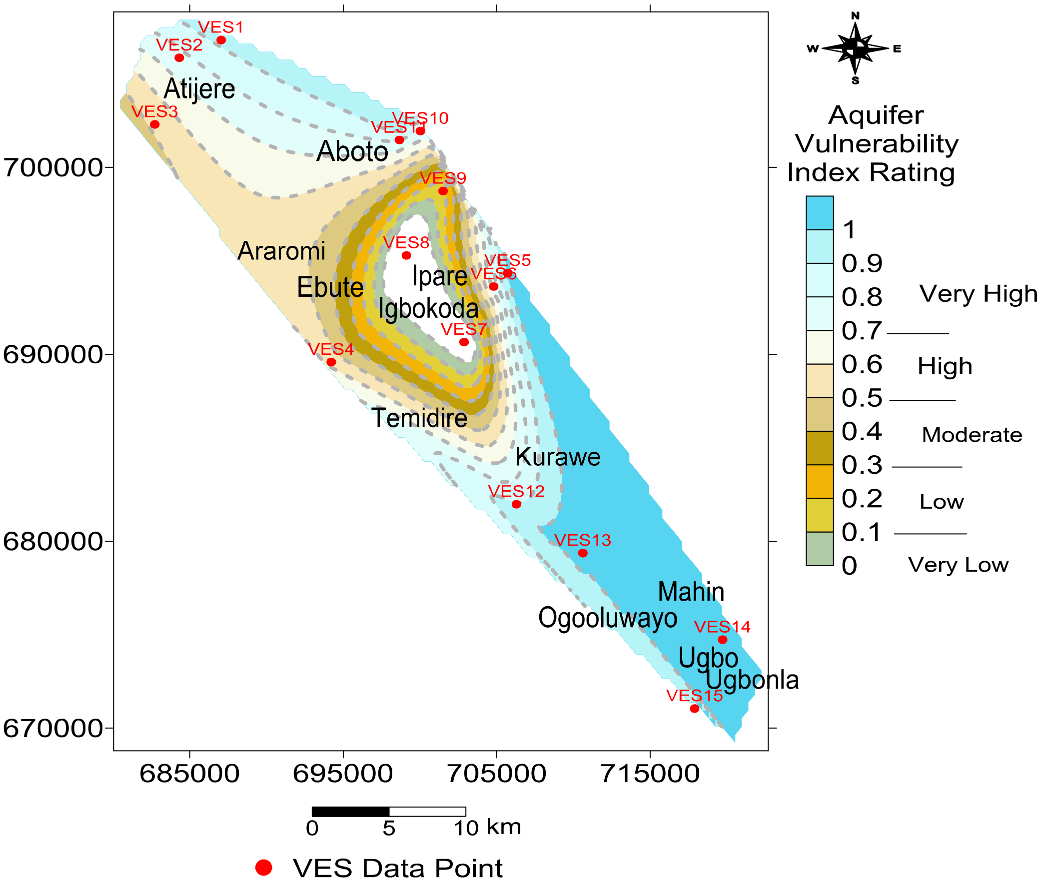

Fig. 10. Aquifer vulnerability Index Rating Map for the study area

In addition, these areas are characterized by thick overburden units with sand/clay intercalation which could be responsible for the relatively high longitudinal conductance calculated. In geological terms, clayey overburden which is characterized by relatively high longitudinal unit conductance offers protection to the underlying aquifer (Akpan et al., 2018). It has been reported that materials such as sand and gravel have low longitudinal conductance resulting from their higher resistivity values as a result of having low aquifer protective capacity. The low value of the protective capacity is as a result of the absence or insignificant amount of clay (in term of thickness) as an impermeable material in VES 3, 4, 6, 8, and 9. This condition enhances the percolation of contaminants into the aquifer.

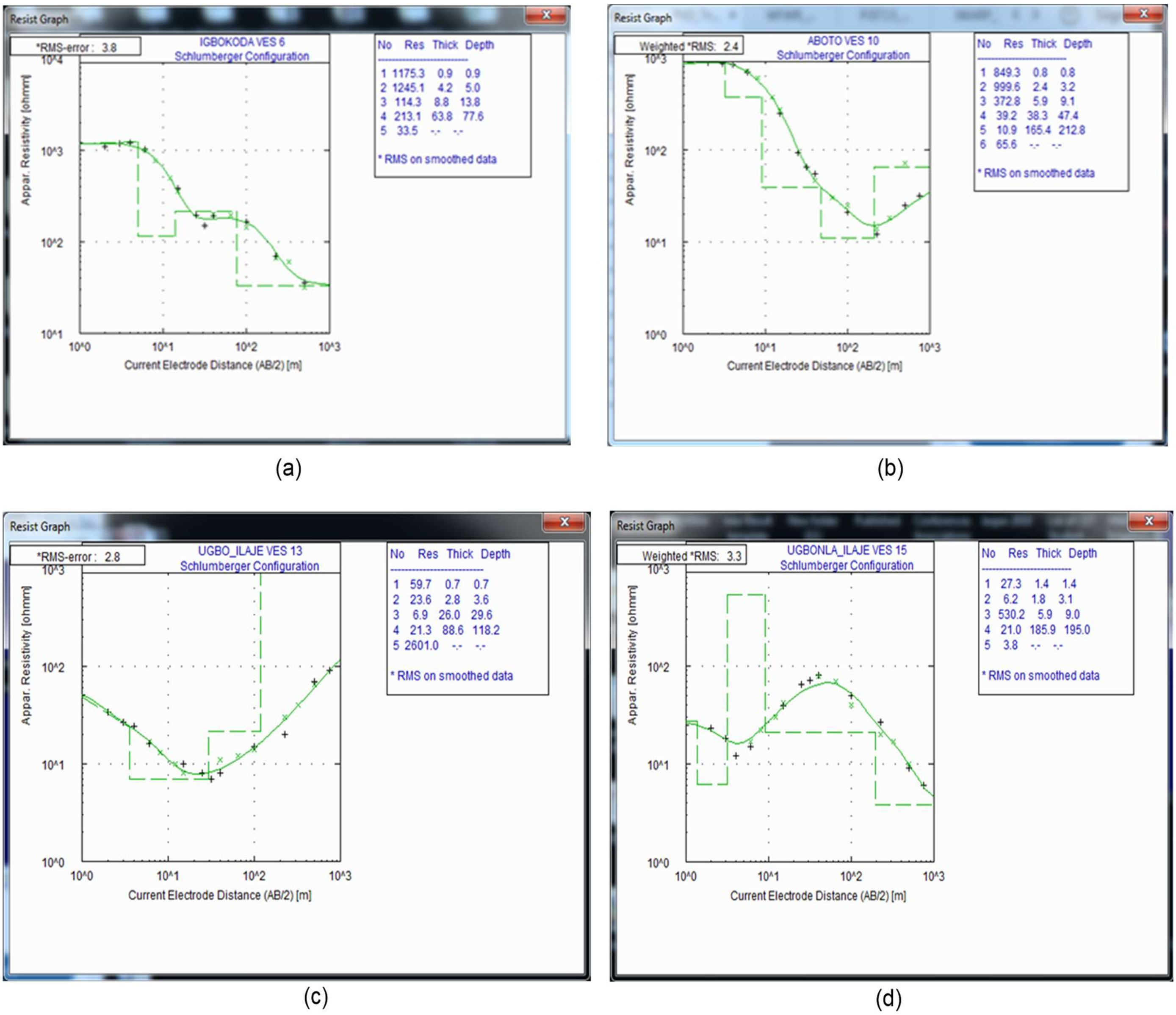

Fig. 11. Typical VES-Types obtained from the study area: (a) KHK, (b) KQQH, (c) QHA and (d) HKQ

Consequently, it can say that the aquifer (shallow) in the study area is prone to pollution by contaminated surface runoff water in the area. Summarily, using Table 1, the protective rating of the longitudinal conductance calculated for all the VES points, 26.67% of the area falls within good protective rating, 20% for weak and moderate ratings, while 33.33% accounts for poor protective rating.

Conclusion

The vulnerability maps are useful in identifying areas where certain activities may pose a higher risk to groundwater quality, but they do not replace the need for site-specific investigations. All the tested samples have values within the WHO except nitrate which shows relatively high values higher than maximum contaminant level of 10 mg/l recommended by WHO. The relatively high concentration of nitrate could be as a result of high anthropogenic discharge, which is common especially in the raining season when people discharge all kinds of domestic and municipal waste into drainages, for it to be washed away by rainfall runoff. Also, poor sanitary practices are very common. Also, some degree of contamination by lead, cyanide, arsenic, ammonia, and mineral oil (from petroleum exploitation by major oil companies) are evident in the water samples. The average calculated water quality index is 121 which fall within poor/unfit water for drinking, which implies high level of contamination. The GOD vulnerability map shows that, very highly vulnerable areas account for 60%, and 55% for AVI. Using longitudinal conductance index, poor/weak protective areas accounts for 53.33%. All the vulnerability maps and index used correlate effectively as they show little variation in their assessment outputs.

Acknowledgement
We are very grateful to Federal Ministry of Water Resources Alagbaka, Akure, Ondo State for assisting in water analysis of this study.

Conflict of Interest
The authors declare no conflict of interest exist in this publication.

Abbreviation/Specific Terms/Acronym Used in Text

DRASTIC	Groundwater vulnerability Index using parameters: Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone media, and hydraulic Conductivity of the aquifer
SINTAX	Groundwater vulnerability Index using different factors such as geological setting, hydro-geological characteristics, underground discharge behavior, amount of rainfall and protection provided by overburden and other factors
GOD	Groundwater vulnerability Index using parameters: groundwater occurrence, overall aquifer class, and depth to aquifer
AVI	Aquifer vulnerability Index
SI	Susceptibility Index
S-model	Susceptibility model
ESR	Electrical resistivity sounding
IRISH	Groundwater vulnerability Index method in the Republic of Ireland

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