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Solid Earth Sciences 4 (2019) 102–112

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Integrated groundwater potentials studies, aquifer hydraulic characterisation and vulnerability investigations of parts of Ndokwa, Niger Delta Basin, Nigeria

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Received 3 April 2019; revised 3 June 2019; accepted 23 June 2019
Available online 6 July 2019

Abstract

Field geological and geophysical (Vertical Electrical Sounding VES) survey data were used in investigating groundwater potentials, aquifer characteristics and vulnerability in parts of Ndokwa area, Niger Delta, Nigeria. Data from twenty-one (21) representative VES survey points using Schlumberger configuration were acquired, processed and interpreted. Pumping test data and litho-log data from existing boreholes in the area were used to constrain interpretation and correlation of the VES results. The results revealed five to six geo-electric layers/units across the study area. The subsurface lithology is predominantly sandstone intercalated, in some cases, with clay, sandy clay, and clayey sand. Results also revealed the average depth to aquifer as 71.91 m (10.33–173.97 m); average aquifer thickness as 42.52 m (4.7–149.7 m) and average aquifer resistivity value as 1289 Ωm (470.84–2697.7 Ωm). Average overburden thickness was estimated to be 28.53 m (4.28–62.44 m). Aquifer characteristics derived from the VES results gave average calculated aquifer transmissivity value as 1162.31 m^2/day (129.54–4181.31 m^2/day), and average calculated aquifer hydraulic conductivity as 27.28 m/day (25.69–28.92 m/day). Longitudinal conductance values range of 0.006–0.137 were recorded from geo-electric field survey data in the area, indicating dominance of sand and sparse distribution of clay; and suggesting that the Aquifer Protective Capacity APC of the overburden above the aquifers in the study area is mostly poor to weak and prone to contamination from infiltration. The DRASTIC model was applied to ascertain the DRASTIC Index and compute aquifer vulnerability distribution of the area; and it revealed that the study area is characterised by low – moderate – high vulnerability at different locations. Topsoil corrosivity studies showed that topsoil in the area is practically non-corrosive to slightly corrosive. The results of this study have implications for groundwater resources development and management in the study area.

Keywords: Groundwater development; Aquifer vulnerability; Hydraulic characterisation; Geo-electric survey; Niger Delta

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1. Introduction

Water is among the natural resources of utmost important to man all over the world, and groundwater is a major source of water to man especially in developing nation and rural communities where availability of requisite public infrastructure for surface water treatment, reticulation and supply are inadequate or non-existent. This inadequacy in public water supply drives the reliance of locals on groundwater resources which are usually exploited through boreholes and relatively shallow hand-dug wells. The availability of groundwater depends on the presence and hydraulic properties of aquiferous (groundwater bearing) units; and its portability depends on its hydrogeochemical properties and vulnerability to contamination/pollution (Obiadi et al., 2012, 2016; Ozoemenam et al., 2018; Okolo et al., 2017; 2018). Aquifer vulnerability refers to the degree of protection against contamination offered by the overlying strata and the potential for purification of

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Peer review under responsibility of Guangzhou Institute of Geochemistry.

https://doi.org/10.1016/j.sesci.2019.06.002

2451-912X/

contaminated water in the aquifer (Mohammadi et al., 2009; Mundel et al., 2003; Foster, 1987; Fritch et al., 2000). Sustainable management of groundwater resources such as exploration and exploitation, the prediction of the pollution risk and the protection of these resources are very crucial and important. Groundwater contamination can be minimized by delineating and monitoring vulnerable areas for sustainable management.

Ndokwa, Delta State, Southeast Nigeria, can be regards as a fast developing town characterised by relatively high population density occasioned by the large number of industries, commercial centres and civil service institutions. It is located in the oil rich Niger Delta Basin of Nigeria. Public water resources management infrastructures are almost non-existent and where they exist cannot meet the needs of the growing population. Many private individuals and communities have resorted to exploiting groundwater resources by constructing boreholes and hand-dug wells targeting confined and unconfined aquifers mainly in the sand members of the Benin Formation and the Sombreiro-Warri Deltaic Plain deposits. The exploration and exploitation of portable water within these geologic units has attracted much attention in recent time.

This study will therefore employ geological and geophysical strategies to study and understand the nature of aquifers and aquifer hydraulic characteristics in the study area to ensure a better success rate of groundwater exploration schemes; as well as characterize the susceptibility/vulnerability of the aquifer to contamination/pollution using the geoelectrical methods and the DRASTIC Model, and hence delineate areas susceptible to groundwater contamination/pollution from infiltration. Aquifer vulnerability assessment map that will be produced from this study will inform policies on groundwater resources management and waste disposal management in the study area.

2. Methodology

Geological and geophysical field surveys were conducted to obtain data which were analysed and interpreted in this research. Geological field mapping, by surface traversing, contact identification and detailed outcrop studies, was done done to identify the lithologies outcropping in the study area and their spatial distribution, which are input parameters for constraining geophysical field survey data interpretations and modelling, as well as groundwater vulnerability assessment studies.

Geophysical field survey done involved the use of the Resistivity Method (Vertical Electrical Sounding VES). Several VES locations on representative grid points (Fig. 1) were conducted to investigate the vertical and lateral distribution of lithologies; presence, nature and depth to aquifer unit(s); and the nature of overburden. The Schlumberger array

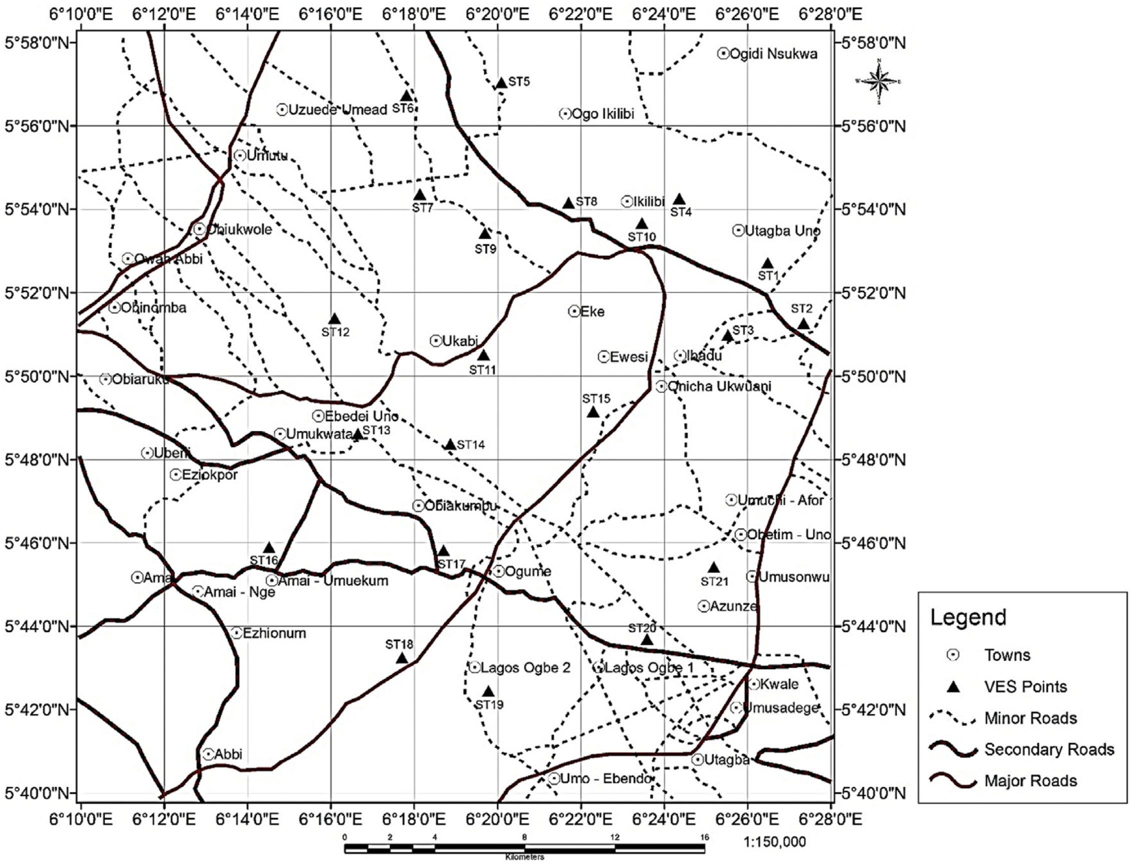

Fig. 1. Base map of the study area illustrating VES point locations.

configuration was used in the VES data acquisition, with a maximum half current electrode spacing (AB/2) of 350 m. The OMEGA 48 resistivity meter was used to measure the apparent resistivity distribution, and the data recorded and stored in a computer laptop. The apparent resistivity distribution data was analysed and modelled using the Interpex 1D inversion and RES1DIV inversion softwares to produce the geo-electric sections of the surveyed points with layer thicknesses and depths. Subsurface geologic models and interpretations derived were constrained by borehole logs and data obtained within the study area especially those close to the VES points, as well as the knowledge of the general geology of the study area. The geo-electric sections were then correlated to determine the vertical and horizontal distribution, and lateral continuity of lithologic units (aquifer and overburden) of interest.

Data obtained from the modelling and interpretation of the VES survey (layer apparent resistivities, thicknesses and depth; vertical and horizontal distribution) were used to produce aquifer distribution/thickness and potentials (in terms of transmissivity and hydraulic conductivity) maps of the study area. The VES data, together with the longitudinal conductance and transverse resistance data obtained over a unit square cross-sectional area within the study area was then used to model the hydraulic characteristics (transmissivity and hydraulic conductivity) of the aquiferous units using the following relations (Niwas and Singhal, 1981):

$$T = K\,\sigma R = \frac{KS}{\sigma} = Kh \tag{1}$$

Where T is the transmissivity, K is the hydraulic conductivity, R is the transverse resistance of the aquifer (computed as the product of aquifer resistivity and aquifer thickness), S is the longitudinal conductance, σ is the aquifer electrical conductivity (inverse of resistivity) and h is aquifer thickness. The parameters R and S are commonly called the Dar Zarrouk parameters. The numeric value of K obtained from pumping test conducted in the study area is given as 26.8 m/day, and was used in this analysis. All other parameter was obtained from the analysis of the field resistivity survey.

The Aquifer Protective Capacity APC, which is dependent on the aquifer thickness, nature and protective capacity of aquifer overburden materials, was estimated from the longitudinal conductance, and its protective capacity analysed and rated according to Golam et al. (2016); Henriet (1976); Oladapo et al. (2004); Ogungbemi et al. (2013) which rated longitudinal conductance (in mhos) value ranges of >10, 5–10, 0.7–4.9, 0.2–0.69, 0.1–0.19 and < 0.1 as indicative of excellent, very good, good, moderate, weak and poor aquifer protective capacity, respectively. Excellent and good APC are characterised by relatively high longitudinal conductance while weak and poor APC are characterised by relatively low longitudinal conductance. A map of the APC distribution in the study area was then produced.

The DRASTIC Model of the Overlay and Index method, which is best suited for large/regional studies, was used for aquifer vulnerability assessment in this research. DRASTIC is a model that estimates groundwater contamination vulnerability of the aquifer systems based on the hydrogeological parameters and settings of the area. DRASTIC represents acronym for seven factors analysed in the method, and they are; Depth to water table [D], net Recharge [R], Aquifer media [A], Soil media [S], Topography [T], Impact of the vadose zone [I], and hydraulic conductivity [C]. With the DRASTIC model, each factor is assigned a rating (from 1 to 10) and weight (from 1 to 5) based on its comparative significance with regards to aquifer contamination/pollution potential (Table 1) (Aller et al., 1987; Navulur, 1996). Contamination/pollution potential is estimated by the DRASTIC Index [DI] which is computed by summation of the products of factors ratings and weights (2):

$$DI = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \tag{2}$$

The subscripts r and w denote the rating and the weight of the factor being considered, respectively. Higher DI values connote higher vulnerability/pollution potential of the aquifer.

Table 1
The DRASTIC weights and rating systems (Aller et al., 1987).

Depth to water (ft)	Net recharge (inches)	Aquifer media characteristic	Soil media	Topography (Slope %)	Impact of the vadose zone	Hydraulic conductivity (gpd/ft^2)
DRASTIC	DRASTIC	DRASTIC	DRASTIC	DRASTIC	DRASTIC	DRASTIC
Weight: 5	Weight: 4	Weight: 3	Weight: 2	Weight: 1	Weight: 5	Weight: 3
Range rating	**Range rating**	**Range rating**	**Range rating**	**Range rating**	**Range rating**	Range rating
100 + 1	0–2 1	Shale 1	Clay 1	>18 1	Clay 1	1–100 1
75–100 2	2–4 3	Till 3	Loamy clay 4	16–18 2	Shale 2	100–300 2
50–75 3	4–7 6	Silt 3	Clayey loam 5	14–16 3	Silt 3	300–700 4
30–50 5	7–10 8	Schist 4	Loam 7	12–14 4	Schist 4	700–1000 6
15–30 7	>10 9	Sandstone 5	Sandy loam 8	10–12 5	Till 4	1000–2000 8
5–15 9		Limestone 6	Loamy sand 9	8–10 6	Green rocks 5	2000 + 10
0 − 5 10		Green rocks 6	Sand/gravel 10	6–8 7	Sandstone 5	
		Sand 8		4–6 8	Limestone 6	
		Sand & gravel 9		2–4 9	Sand 8	
		Gravel 10		0–2 10	Sand & gravel 9	
					Gravel 10	

The ***depth to the water table*** was estimated from interpreted geo-electric section. The ***Net recharge*** represents the amount of water per unit area of land, which penetrates the land and reaches the water table, and it is taken to be about 12% of the average annual rainfall (Navulur, 1996) of the study area (Ndokwa West, Delta State, Nigeria). The ***aquifer media***, which influences the contamination/pollution attenuation capacity of the system, was determined from geophysical data and the hydrogeology of the study area. The ***soil media***, considered as the uppermost weathered zone of the earth, an average depth of one meter or less from the ground surface, was determined from the geological field mapping data and soil map of the study area. ***Topography***, a representation of the variability of slope of the land surface, which influences/controls the likelihood that a pollutant will run off or pool and remain on the surface in one area long enough to infiltrate, was determined from the topographic map of the study area. The ***impact of the vadose zone*** (unsaturated/discontinuously saturated zone above the water table) was determined from the lithological/strata description of the VES data analysis and geologic field mapping data. ***Hydraulic Conductivity*** was estimated from the analysis of the resistivity data. The hydraulic conductivities were converted from m/day to gpd/ft^2 before application in finding the DRASTIC Index (1 gal/day/ft^2 = 0.0408m/day). The aquifer vulnerability of the study area was assessed and classified according to Navulur (1996) and a map of aquifer vulnerability distribution produced. According to Navulur (1996), DRASTIC Index ranges of 1–100, 101–140, 141–200 and 141–200 are indicative of low, moderate, high and very high aquifer vulnerability, respectively.

Top soil corrosivity, which impact water reticulation infrastructures, was also assessed from the top soil resistivity data and classified according to Oladapo et al. (2004) and Akintorinwa and Abiola (2011) which gave soil resistivity ranges of <10, 10–60, 60–180 and > 180 as indicative of very strongly corrosive, moderately corrosive, slightly corrosive and practically non-corrosive, respectively.

3. Results and interpretation

3.1. VES analysis and aquifer characterisation

Raw field resistance data (in ohms) for all the VES point locations were converted to apparent resistivity (in ohm-meter) by multiplying it with the appropriate geometric factor. The apparent resistivity data were plotted against current electrode spacing (Fig. 2) and interpreted using the iterative modules of Interpex 1D™ and RES1DIV™ inversion, and constrained by data obtained from partial curve matching of master curves and auxiliary point charts (Obiadi et al., 2013; Koefoed, 1979; Orellana and Mooney, 1966). The results, which gave RMS error of <5%, revealed five to six geo-electric layers/units with their corresponding thicknesses

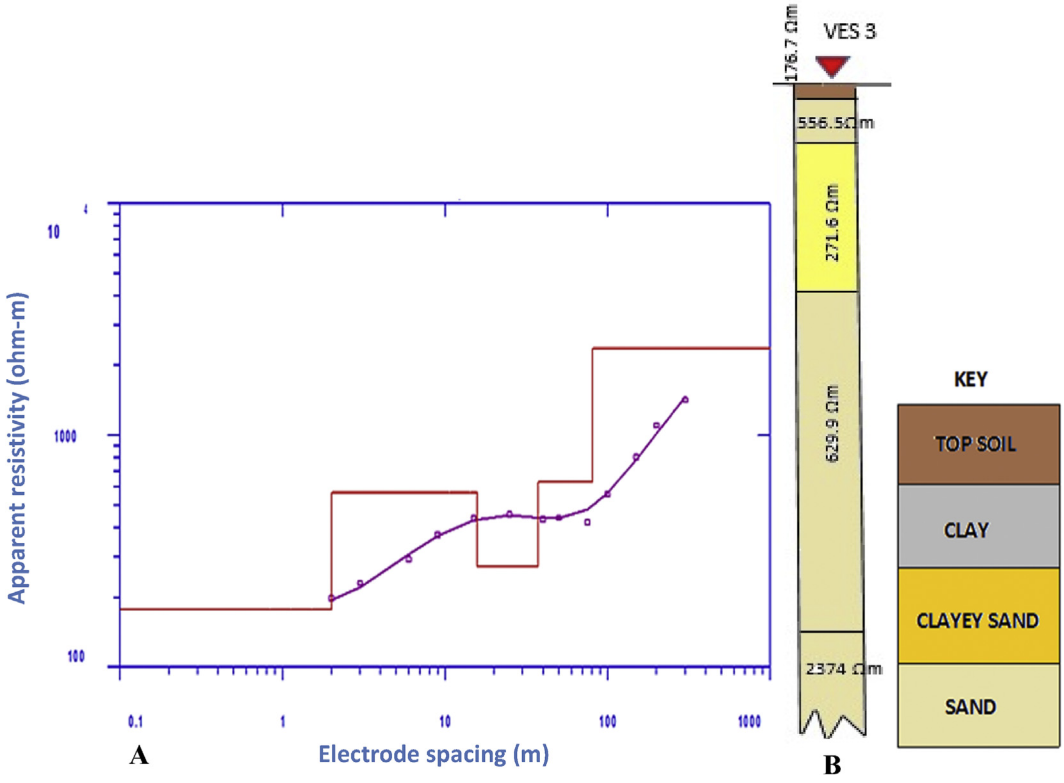

Fig. 2. (A) Representative computer software plot of apparent resistivity data from VES survey. The purple curve represent the field apparent resistivity vs current electrodes spacing plot, while the step-wise red lines represents the software interpreted geo-electric section layers thickness and apparent resistivity. (B) Geologic section inferred from the interpretation of the geo-electric section.

Table 2
Aquifer parameter and characteristics obtained and estimated at various VES point locations in the study area.

VES number and location	Northing	Easting	Aquifer resistivity ρ (Ωm)	Depth to aquifer (m)	Aquifer thickness (m)	Overburden thickness (m)	T_C (m2/day)	K_C (m/day)
1 Utagba-Uno	5.879037	6.441965	2085.1	132.25	83.9	48.32	2345.3	27.95
2 Obiukpo	5.846247	6.460085	1475.7	131.68	84.5	47.19	2339.1	27.68
3 Ibabu	5.846947	6.425615	629.99	80.52	43.2	37.35	1166.0	26.99
4 Ikilibi	5.903315	6.392352	918.47	38.83	11.31	27.52	305.95	27.08
5 Farm Settlement 1	5.949447	6.335112	598.41	51.14	25.7	25.46	699.99	27.24
6 Farm settlement 2	5.945878	6.299153	1738.3	42.86	22.1	20.71	618.91	28.00
7 Akakpani	5.905647	6.30254	1131.9	10.33	6.05	4.28	165.07	27.28
8 Akpuofor	5.901968	6.361833	470.84	98.84	62.3	36.55	1650.51	26.49
9 Obi-Igbo	5.891535	6.329073	2697.7	33.40	21.5	11.89	621.85	28.92
10 Umusam Uno	5.894255	6.387855	1158.4	173.97	149.7	25.31	4181.31	27.93
11 Ukabi 1	5.846042	6.32682	1477.3	41.45	22.98	18.46	636.93	27.72
12 Ukabi 2	5.856077	6.26901	786.8	39.69	27.7	12.01	758.69	27.39
13 Ebedei	5.808425	6.278227	1276.4	24.85	4.7	20.12	129.54	27.56
14 Obiakumbu	5.805117	6.314028	1064.4	75.89	67.9	7.96	1744.02	25.69
15 Onicha	5.819	6.372017	1158.4	90.33	19.9	51.31	556.13	27.95
16 Umu-okum	5.764247	6.242238	1672.4	62.85	34.2	28.60	921.03	26.93
17 Ogume 1	5.763067	6.311667	1200.0	72.98	10.5	62.44	271.04	25.81
18 Ogume 2	5.720333	6.29554	2109.3	110.60	56.0	54.63	1582.14	28.25
19 Lagos Ogbe 2	5.706692	6.330553	1672.4	111.63	95.5	16.07	2569.3	26.90
20 Lagos Ogbe 1	5.723333	6.399157	1087.9	35.19	25.2	9.98	661.59	26.25
21 Azunze	5.730067	6.423235	667.83	50.86	18.04	32.86	484.21	26.84

*T_c = Calculates aquifer transmissivity; K_c = calculated aquifer hydraulic conductivity.

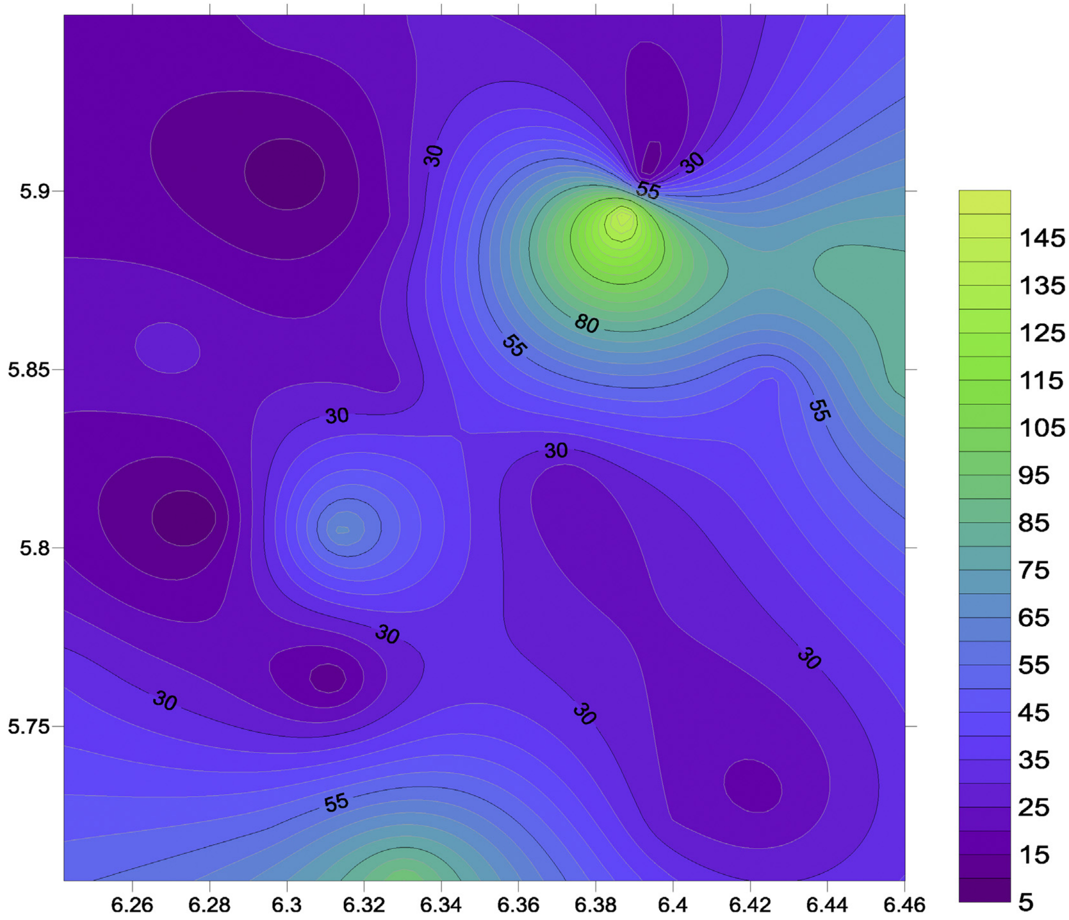

Fig. 3. Aquifer thickness (Isopach) map of the study area. (Contour in meters).

and apparent resistivities at variable depths across the study area. The geology (lithology) of the geo-electric layers was interpreted and inferred from the apparent resistivity distribution pattern and general geology of the study area, and constrained using borehole data (logs) obtained from the study area especially close to the VES points. The lithologies are topsoil at the surface and clays, sandstone and clayey sandstone units of variable thicknesses at variable depth horizons.

Analysis of the interpreted geo-electric layers based on the resistivity distribution, borehole data and geology of the study area revealed that water saturated sandstones, which are the typical aquifers in the study area, were encountered at average depth of 71.91 m (10.33–173.97 m); with average aquifer thickness of 42.52 m (4.7–149.7 m) and average aquifer resistivity value of 1289.43 Ωm (470.84–2697.7 Ωm). The result also shows that the average overburden thickness is 28.53 m (4.28–62.44 m) (Table 2). The geology of the overburden varies from topsoil to clay, clayey-sandstone and sandstone.

Results of the analysis of the resistivity data using the Dar Zarrouk parameters and Eq. (1) gave the average calculated aquifer transmissivity value as 1162.31 m^2/day (129.54–4181.31 m^2/day), and average calculated aquifer hydraulic conductivity as 27.28 m/day (25.69–28.92 m/day) (Table 2).

Distribution and depth to aquifer, aquifer thickness and potentials (in terms of transmissivity and hydraulic conductivity) in the study area were correlated and plotted (Figs. 3–5). The maps show that aquifer thickness and potentials are highest in the northeast and southwest parts of the study area (see also Table 3).

4. Aquifer protective capacity and aquifer vulnerability

The longitudinal conductance S, which is one of the Dar Zarrouk parameters, and was estimated from the aquifer thickness and resistivity (Eq. (1)), was referenced against standards (according to Golam et al., 2016; Henriet, 1976; Oladapo et al., 2004; Ogungbemi et al., 2013) to evaluate the Aquifer Protective Capacity APC and rate its distribution. Results of the rating showed that the study area is generally characterised by poor to weak Aquifer Protective Capacity APC which has implications for aquifer vulnerability (Table 3). APC map of the study area was produced from the plotting of the values of the longitudinal conductance and presented as Fig. 6.

Aquifer vulnerability was modelled and estimated using the DRASTIC Model. The input factors (see methodology) estimated from the resistivity survey data, geologic field survey data, topographic and soil map and annual rainfall data of the study area were weighted and rated, and applied to the

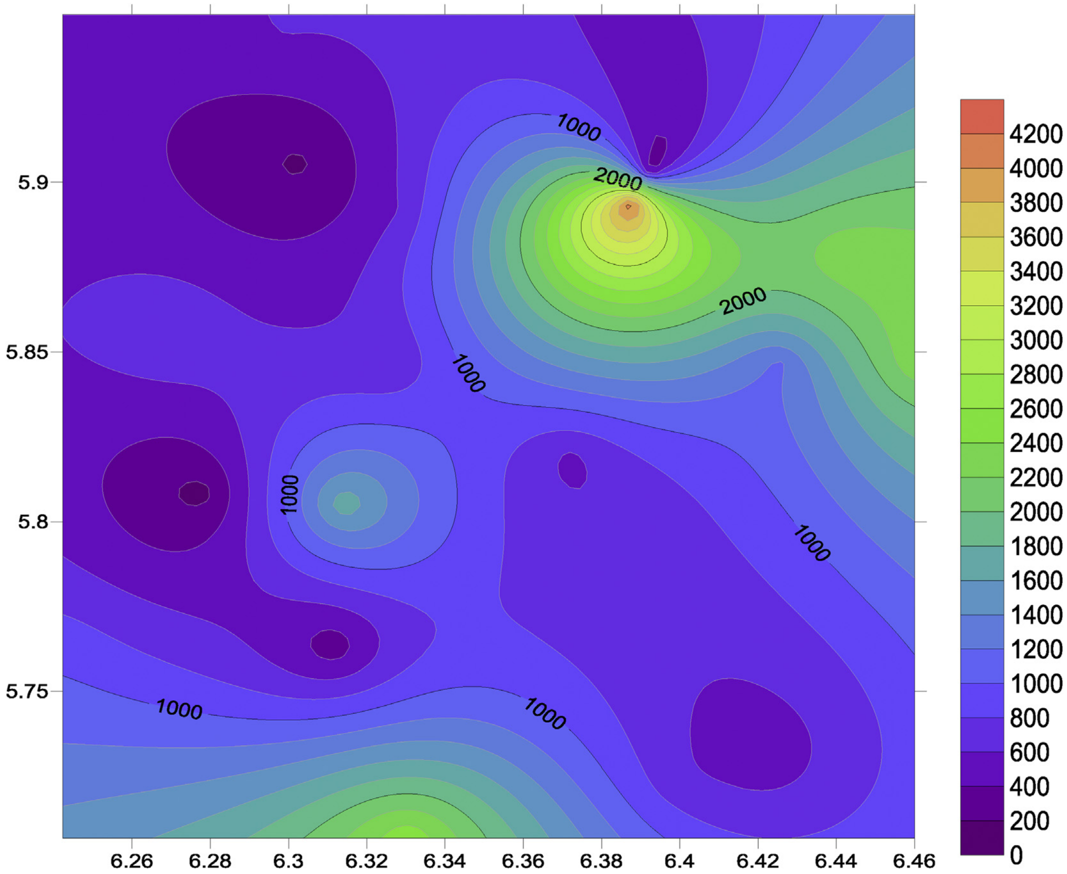

Fig. 4. Aquifer transmissivity/Potential Rating Map of the study area (contour in m^2day^{-1}). Values > 500 m^2day^{-1} corresponds to high potentials, while values of 50–500 m^2day^{-1} correspond to moderate potentials (contours in m^2day^{-1}) (see Table 5).

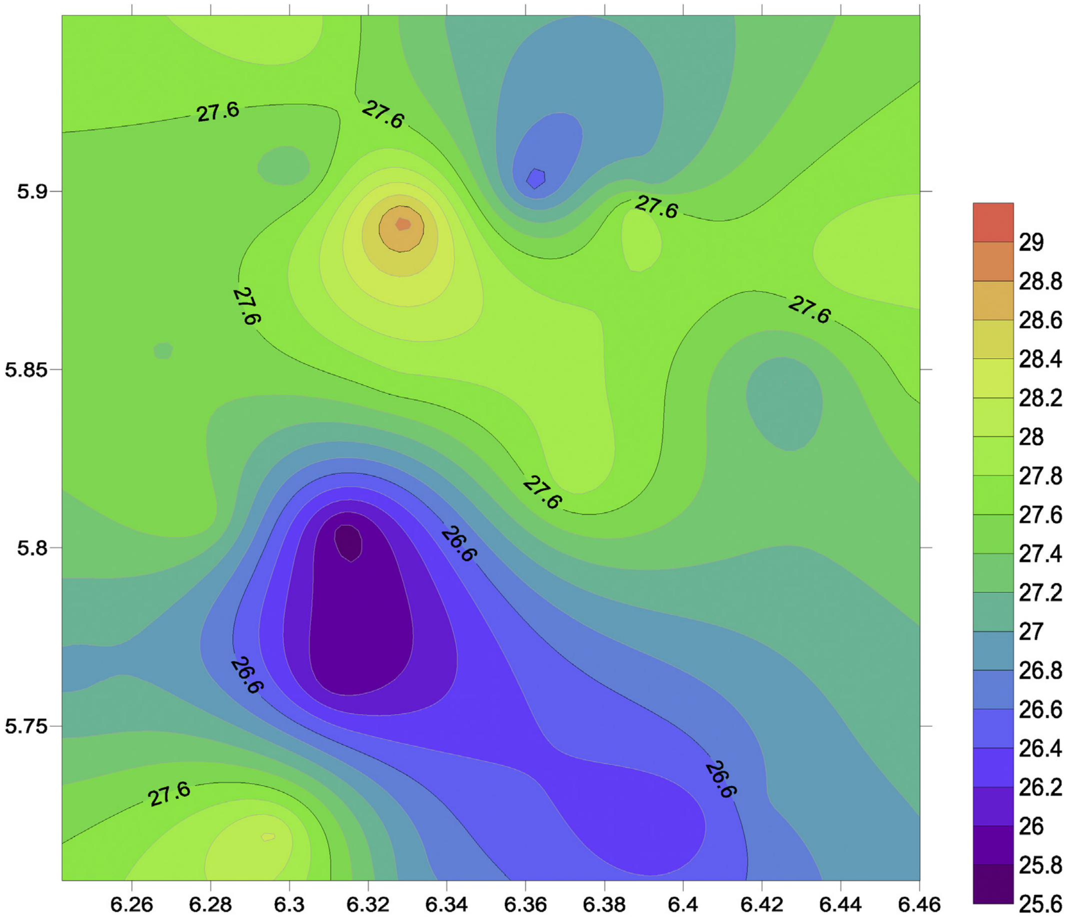

Fig. 5. Aquifer hydraulic conductivity map of the study area (contour in m/day).

Table 3
APC rating and Aquifer potentials distribution in the study area.

VES number and location	Transverse resistance R (Ωm^2)	Longitudinal conductance S (mhos)	APC rating	T_C (m2/day)	Aquifer potentials
1 Utagba-Uno	174939.89	0.403	Moderate	2345.3	High potential
2 Obiukpo	124696.65	0.057	Poor	2339.1	High potential
3 Ibabu	27215.56	0.069	Poor	1166.0	High potential
4 Ikilibi	10387.89	0.012	Poor	305.95	Moderate potential
5 Farm Settlement 1	15379.13	0.043	Poor	699.99	High potential
6 Farm settlement 2	38416.43	0.013	Poor	618.91	High potential
7 Akakpani	6847.99	0.005	Poor	165.07	Moderate potential
8 Akpuofor	29333.33	0.132	Weak	1650.51	High potential
9 Obi-Igbo	58000.55	0.008	Poor	621.85	High potential
10 Umusam Uno	173412.48	0.129	Weak	4181.31	High potential
11 Ukabi 1	33948.35	0.016	Poor	636.93	High potential
12 Ukabi 2	21794.36	0.035	Poor	758.69	High potential
13 Ebedei	5999.08	0.004	Poor	129.54	Moderate potential
14 Obiakumbu	72272.76	0.064	Poor	1744.02	High potential
15 Onicha	23052.16	0.017	Poor	556.13	High potential
16 Umu-okum	57196.08	0.021	Poor	921.03	High potential
17 Ogume 1	12600	0.009	Poor	271.04	Moderate potential
18 Ogume 2	118120.8	0.027	Poor	1582.14	High potential
19 Lagos Ogbe 2	159714.2	0.057	Poor	2569.3	High potential
20 Lagos Ogbe 1	27415.08	0.023	Poor	661.59	High potential
21 Azunze	12047.65	0.027	Poor	484.21	Moderate potential

*Transverse resistance R = aquifer resistivity x aquifer thickness.

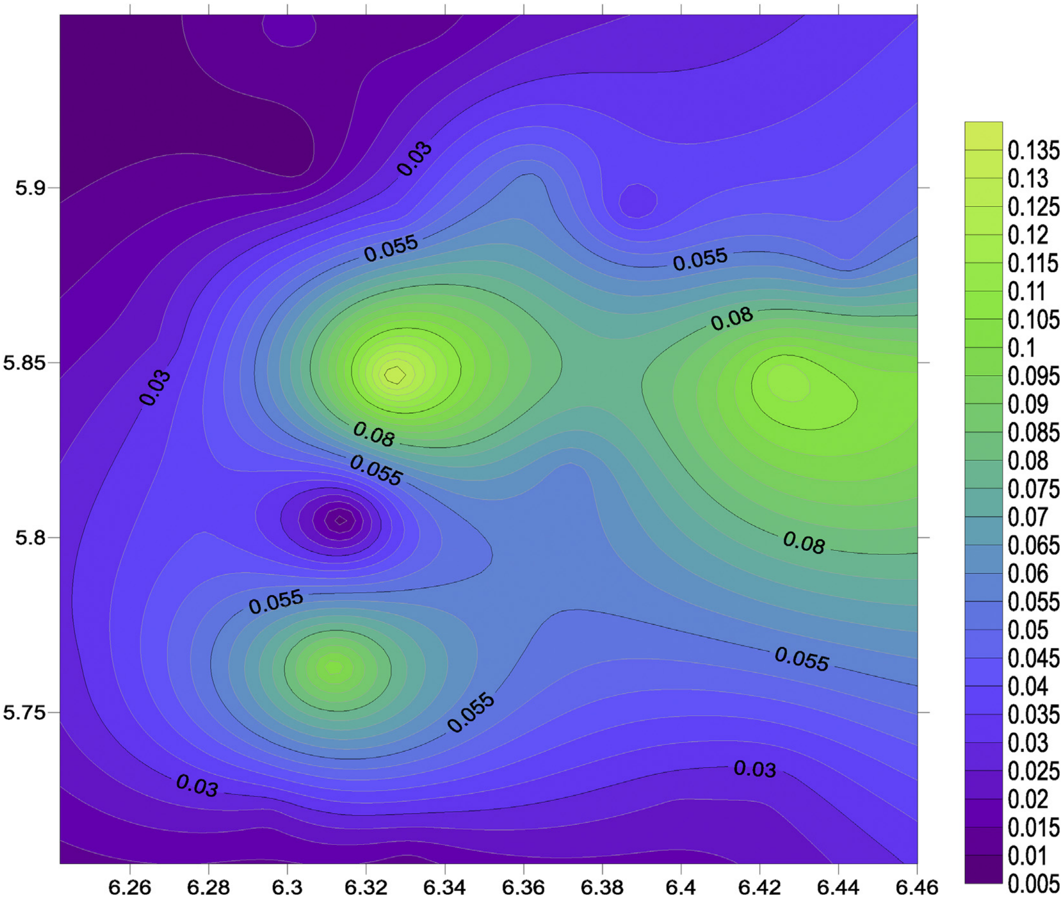

Fig. 6. APC map produced from the 2-D plotting of the longitudinal conductance values (in mhos). Values < 0.1 are classified as poor while values between 0.1 and 0.19 are classified as weak.

Table 4
Calculated DRASTIC Index and DRASTIC Qualitative Category of the sounding locations.

Weights			5	4	3	2	1	5	3		Drastic qualitative category
VES number and location	Northing	Easting	D_r	R_r	A_r	S_r	T_r	I_r	C_r	DI	
1.Utagba-Uno	5.879037	6.441965	1	9	8	4	6	8	4	131	Moderate
2.Obiukpo	5.846247	6.460085	1	9	8	1	6	3	4	100	Low
3.Ibabu	5.846947	6.425615	1	9	3	4	5	2	4	85	Low
4.Ikilibi	5.903315	6.392352	1	9	3	8	5	3	4	98	Low
5.Farm Settlement 1	5.949447	6.335112	2	9	3	5	1	8	4	118	Moderate
6.Farm settlement 2	5.945878	6.299153	1	9	8	8	2	3	4	110	Moderate
7.Akakpani	5.905647	6.30254	7	9	8	5	2	8	4	159	High
8.Akpuofor	5.901968	6.361833	1	9	1	4	4	8	4	108	Moderate
9.Obi-Igbo	5.891535	6.329073	5	9	8	5	5	3	6	133	Moderate
10.Umusam Uno	5.894255	6.387855	1	9	8	5	6	8	4	133	Moderate
11.Ukabi 1	5.846042	6.32682	1	9	8	4	5	1	4	95	Low
12.Ukabi 2	5.856077	6.26901	3	9	3	8	2	2	4	100	Low
13.Ebedei	5.808425	6.278227	1	9	8	5	5	8	4	132	Moderate
14.Obiakumbu	5.805117	6.314028	5	9	8	5	4	8	4	151	High
15.Onicha	5.819	6.372017	1	9	8	5	5	8	4	132	Moderate
16.Umu-okum	5.764247	6.242238	1	9	8	8	5	8	4	138	Moderate
17.Ogume 1	5.763067	6.311667	1	9	8	5	6	3	4	108	Moderate
18.Ogume 2	5.720333	6.29554	1	9	8	5	5	8	4	132	Moderate
19.Lagos Ogbe 2	5.706692	6.330553	2	9	8	7	6	8	4	142	High
20.Lagos Ogbe 1	5.723333	6.399157	3	9	8	4	6	2	4	111	Moderate
21.Azunze	5.730067	6.423235	1	9	3	8	6	3	4	99	Low

* DI = DRASTIC Index.

Table 5
Transmissivity/aquifer potential Scale (after Gheorghe, 1978).

Range	Potential
>500 m^2day^{-1}	High potential
50–500 m^2day^{-1}	Moderate potential
5–50 m^2day^{-1}	Low potential
0.5–5 m^2day^{-1}	Very low potential
˂0.5 m^2day^{-1}	Negligible potential

DRASTIC model empirical equation (Eq. (2)) to compute the DRASTIC Index DI distribution in the study area (Table 4). Aquifer vulnerability was inferred from the DI value distribution and aquifer vulnerability map of the study area was produced by plotting the spatial distribution of the DI values (Fig. 7). The DI values and vulnerability map show that the study area is characterised by low – moderate – high vulnerability.

Topsoil corrosivity evaluated from the topsoil layer resistivity value distribution shows that the study area is characterised by slightly corrosive to practically non-corrosive topsoil.

5. Discussion

Results of the interpretation and modelling of the VES and field geological data showed that the study area is characterised by aquiferous units at variable depth horizons. The aquifer unit thickness appears to follow a trend of highest values (i.e. higher thickness) which runs from the NE parts of the study area through the central parts to the SW parts (Fig. 3). Aquifer transmissivity characteristics also follow this trend, suggesting a good correlation between aquifer thickness and aquifer transmissivity (Figs. 3 and 4). Calculated aquifer hydraulic conductivity map, on the other hand, showed higher values to the north and SW of the study area (Fig. 5). This, perhaps, is a consequence of the porosity and permeability property distribution of the aquifer units. The proximity of hydraulic conductivity values obtained from pumping test (26.8 m/day) and those calculated from VES interpretations (average of 27.28 m/day) is a good indication of the credibility and reliability of the calculated parameters. The presence of aquiferous units at various horizons in the subsurface all through the study area suggests that the study area has good potentials for groundwater development and exploitation. However the occurrence of aquifer of greater thicknesses and transmissivity to the NE, central and SW parts of the study area indicates that these areas have better groundwater potentials relative to other parts.

Gheorghe (1978) classified aquifer potentials in terms of aquifer transmissivity (Table 5), and according to this classification, the calculated transmissivity values indicate that the

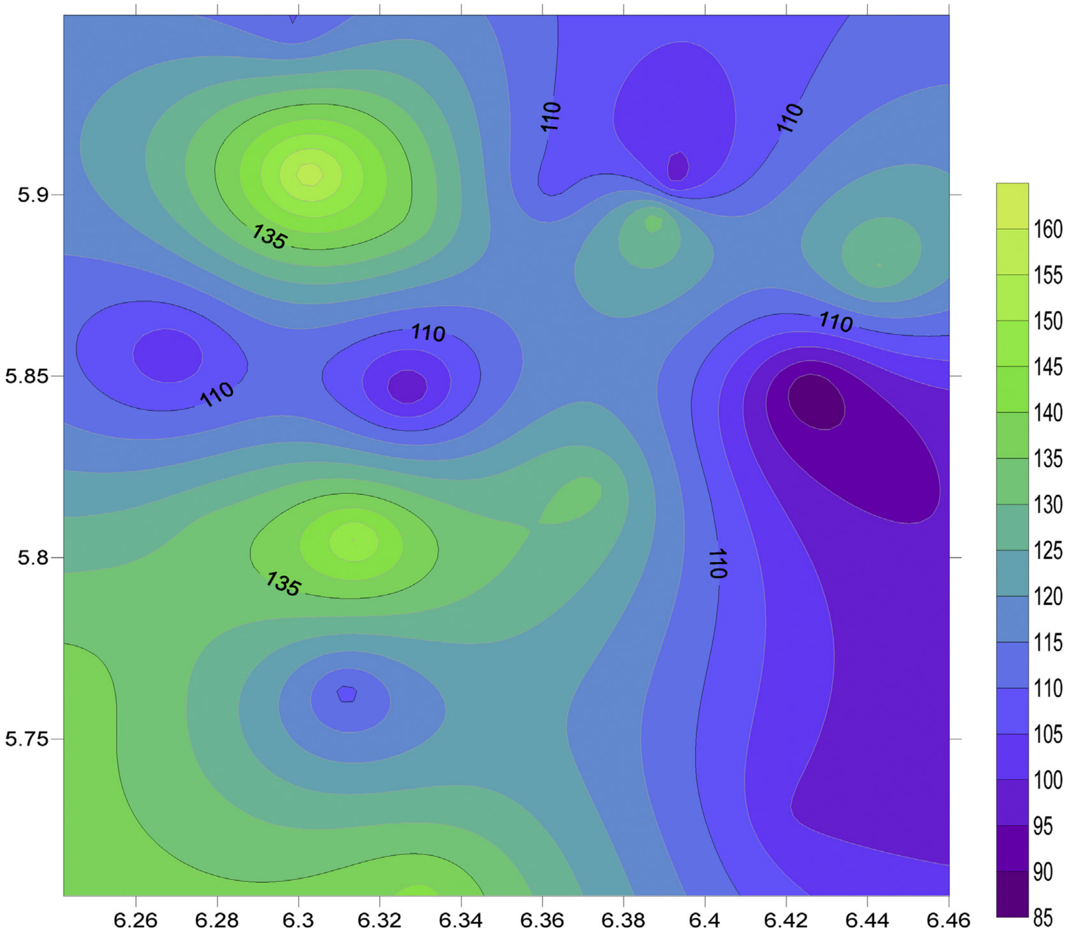

Fig. 7. Aquifer vulnerability map of the study area.

aquifers underlying majority (about 76.2% of total surface area) of the study area are characterised by high yield (Fig. 4, Table 3). This most likely is due to the lithology of the study area which is characterised by highly porous and permeable sandstones amongst other rock types.

Henriet (1976), Oladapo et al., (2004) and Ogungbemi et al. (2013) classified Aquifer Protective Capacity APC of an area from values of Longitudinal Conductance. Values of Longitudinal Conductance obtained from the resistivity survey in the study area showed that the study area is characterised by weak to poor APC (Table 3, Fig. 6). This collaborates well with the Aquifer vulnerability model calculated for the study area using the DRASTIC model which gave DI values distributions of 85−159 and indicative of low − moderate − high aquifer vulnerability (Table 4; Fig. 7). Areas of moderate − high aquifer vulnerability and poor APC are characterised by thin or on shale overburden, resulting in relative ease of contaminant/pollutant transport and infiltration into the aquifer (and hence groundwater body), unlike other areas of low vulnerability which have significant shale rock overburden.

The estimated poor APC and moderate − high aquifer vulnerability, which is a consequence of the local geology, impact the groundwater quality of the study area and its application/suitability for domestic/industrial/aesthetic uses especially where waste are disposed indiscriminately on the land surface/landfills without regards for the underlying geology and resources.

6. Conclusion

Integrated groundwater potentials studies, aquifer hydraulic characterisation and vulnerability investigations were carried out over parts of Ndokwa, Niger Delta Basin, Nigeria from field geological and geophysical survey data. Interpretations of geological and geophysical field data showed that the lithologies underlying the study area at various horizons include topsoil at the surface and clays, sandstone and clayey sandstone units. The results also showed the occurrence of aquiferous units of moderate − high groundwater yield potentials at variable depths in the subsurface all through the study area; however a belt of relatively better/higher aquifer potentials runs from the NE through the central to the SW parts of the study area. Groundwater development and exploitation schemes should target this belt for sustainable management of the groundwater resources of the study area. Aquifer Protective Capacity APC and aquifer vulnerability studies done showed that the study area is characterised by weak to poor APC and low − moderate − high aquifer vulnerability. This has implications on the physico-chemical quality of the groundwater resources as well as its suitability for various uses/applications since the results show that the aquifers/groundwater resources in the study area are prone to contamination/pollution. It is therefore recommended that proper waste disposal schemes/methods that incorporate the nature and effects of the underlying local geology be developed to manage wastes in the study area which have the potentials of polluting groundwater. These waste disposal schemes may be sited in areas characterised by low-moderate aquifer vulnerability instead of areas of high aquifer vulnerability, and should be well managed and monitored to mitigate the effects of groundwater pollution in the area.

Topsoil corrosivity studies showed that the study area is characterised by slightly corrosive to practically non-corrosive topsoil, and hence may not adversely corrode metallic groundwater reticulation infrastructure.

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