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Geophysical Appraisal of the Aquifer Geomaterials of Ugep and Environs, Southeastern, Nigeria Using Resistivity Data

Inyang Godwin Edet[1], Opara Alexander Ifeanyichukwu[1*], Ibechu Bridget Odochi[1], Nwachukwu Helen Gloria[1], Eluwa Ndidiamaka[2], Amadi Chinyere Caroline[1], Emberga Theophilus Terhemba[3] and Eke Daberechi Richmond[1]

[1]Department of Geology, Federal University of Technology, Owerri, Nigeria.
[2]Department of Geology and Geophysics, Federal University Ndufu Alike-Ikwo, Abakaliki, Ebonyi State, Nigeria.
[3]Department of Physics and Electronics, Federal Polytechnic, Nekede, Nigeria.

Authors' contributions

This work was carried out in collaboration between all the listed authors. Authors IGE and OAI designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors IBO, NHG, EN, ACC, ETT and EDR participated in the data acquisition and managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

Hydrogeophysical characterization of the aquifers of Ugep and environs, Southeastern Nigeria was carried out to delineate the aquifers of the study area, evaluate their geometrical potentials and to assess their level of vulnerability to pollution from surface contaminants. Forty (40) Schlumberger Vertical Electrical Soundings (VES) were acquired within the various parts of the study area with a maximum half current electrode separation (AB/2) of 500 metres using the digital terrameter, SAS

**Corresponding author: E-mail: oparazanda2001@yahoo.com;*

4000 model. Seven (7) out of these soundings were parametric soundings carried out at the exact positions of existing boreholes for the purpose of correlation and comparison. The VES data were processed using a combination of curve matching and computer iterative modeling techniques. Layer parameters interpreted from the VES data together with the available well data were used to assess the vulnerability of the shallow aquifers using the DRASTIC model. Results of the study revealed the presence of 3-8 geoelectric layers with the KH curve type being dominant. Information extracted from iso-resistivity models of the study area revealed a distinct hydrogeological divide in line with the geology of the study area. Depth to the water table ranges from 12.4 m to 147 m with a mean value of 67.96 m. The aquifers of the study area are variable in thickness with values ranging from 5.7 m to 123 m with a mean value of 47.3 m.The Dar Zarrouk parameters which gave insights into the hydrogeological condition of the study area revealed that longitudinal conductance values varies from 0.0053 Sm (VES 28) to 0.0053 Sm (VES 40), with a mean value of 0.2848 Sm while the transverse resistance ranges from 1106.33 Ωm^2 to 84992 Ωm^2 with a mean value of 19819.3 Ωm^2. Result of the groundwater vulnerability assessment revealed that 2.5% of the study area falls within the low vulnerability zone, whereas about 55% of the study area is of moderate vulnerability to groundwater contamination with aquifer vulnerability index ranges of 108 to 133. The pattern of spatial variation of vulnerability is believed to be as the result of the variation in depth to water table from east to west. It was also revealed that about 42.5% of the study area falls within the high aquifer vulnerability zone with the DRASTIC index value ranging from 141 to 161.

Keywords: Hydrogeophysical; Dar-zarrock parameters; aquifer vulnerability; geomaterials; vertical electrical sounding; Ugep; Nigeria.

1. INTRODUCTION

Groundwater is a major source of potable water in Ugep and its environs Southeastern Nigeria, with hundreds of boreholes drilled over the past few decades by private firms and individuals to provide the teaming populace with potable water. Most of these wells were sited and drilled without proper hydrogeological and hydrogeophysical investigations. This practice has therefore led to a very high rate of borehole failures in the study area thus making the supply of good quality water in the area grossly inadequate. This problem is more pronounced in parts of the study area mainly around Nko, Idomi and parts of Ugep town. Some of these wells are associated with very high drawdown during the dry season resulting in outright failure of wells thereby leading to inadequate water supply in the areas. There is therefore a need to carry out detailed hydrogeophysical studies of the study area to determine its aquifer geometric, hydraulic and vulnerability characteristics.

Ugep area geologically belongs to the Calabar Flank of Southeastern Nigeria but geomorphologically, it is classified as part of the Cross River hydrogeological province [1]. Ugep area which is part of the Calabar Flank has good hydrogeological potentials [2]. Ugep area is underlain by the sedimentary rocks of the Calabar Flank, and is drained mainly by the Cross River. Sedimentary basins worldwide have been shown to generally possess enormous hydrological and hydrogeological potentials due to their good porosity, permeability and hydraulic conductivity [2-6]. Earlier scholars have therefore delineated these aquifers and estimated their characteristics using surface geophysical methods in different parts of the world [7-17], and results have shown how geophysical data can be used to improve aquifer optimization and proper management of the hydrogeological potentials of such basins in order to enhance safe discharge of the groundwater resources and for appropriately safeguarding the quality status of the groundwater resources. [18] identified three potential aquiferous units in the study area as lenticular sandstone beds in shale and siltstone, fractured sedimentary rocks at contact zones between the sediments and intrusives and finally fractures and joints in the intrusives. The major hydrogeologic group in the area is the shale-siltstone-sandstone group. Yields of 1-2.0 litres/second are common in most parts of the study area [18]. Areas like Mkpani are covered and underlain by cretaceous indurated sediments of sandstone, siltstones, shale and doleritic/granodioritic rocks [18]. The aquiferous bodies include regolith, and fractures of sediments/igneous rocks; and interstices of poorly compacted sands. Fractures of small apertures are the major aquiferous structures identified within the subsurface of the area. Groundwater yield is small, and will only sustain low–moderate scale groundwater schemes. Aquiferous properties are low to moderate in rating with drawdown from pumped wells being gentle with abstraction/discharge rate lower or equal to 1.0 litres/second. [19] in the study to determine the potential groundwater sites using geological and geophysical techniques identified the following hydrogeological units; in the crystalline basement complex, the water bearing units include the decomposed zone, the partially decomposed zone (overburden) and the fractured bedrock. The water table in this zone is highly variable. Much of the wells drilled in these areas have become abortive or dried up due to poor or lack of scientific investigation. These wells are associated with very high drawdown during the dry season resulting in outright failure of wells and consequent inadequate water supply in the areas.

Aquifer vulnerability assessment to delineate areas that are more susceptible to contamination from anthropogenic sources has therefore become an integral and important element for sensible water resource management and land use planning. This concept was first introduced in France by the end of the 1960’s to create awareness to groundwater contamination [20]. The concept of vulnerability assessment is based on the assumption that the system, involving soil, rock, and groundwater, can offer a degree of protection against contamination of the groundwater by natural attenuation. There are numerous approaches for assessing groundwater vulnerability, however the most widely used and well known is DRASTIC; a qualitative rating model [21]. It is an index model designed to produce vulnerability scores for different locations by combining several thematic layers. The model was developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential for the entire United States [22,23]. The DRASTIC model rates relative sensitivity of land units by integrating information on depth to groundwater, impact of vadose zone, soils, recharge, hydraulic conductivity, topography (slope), and aquifer media in determining a ranking of groundwater sensitivity. Recent studies have further improved upon this method, evolving the method beyond a simple rating of sensitivity, to a descriptive approach identifying areas with similar hydro-geologic characteristics (i.e. hydrologic setting) and assessing individually these areas for groundwater susceptibility to potential contamination [24]. The DRASTIC method has been used for vulnerability mapping projects in the United States and discussed as a possible tool for such assessments [23-26]. Recently DRASTIC has been used as a screening tool to investigate broad geographic areas for susceptibility to groundwater contamination by pesticides using existing hydrogeologic parameters in geographic information systems [27-29].

The present study therefore summarizes the hydrogeophysical assessment of the aquifer system of Ugep area. It assesses the nature of the aquifers, their distribution, characteristics and thus, provides data to assess the productivity of the aquifers. This study is also geared towards the evaluation of vulnerability indices of these aquifers with the intent of proffering suggestions to water resource planners and developers for more efficient and safe utilization of groundwater.It is hoped that results of this study will help to appraise aquifer geometrical parameters, their distribution, characteristics and thus, provides data to assess the productivity of the aquifers.

1.1 Description of the Study Area

1.1.1 Location, climate and physiography

The study area is Ugep and environs with an estimated landmass of 87.8 km^2 (Fig. 1). It is located within the southeastern part of Cross River State, Nigeria and lies within latitudes 5° 42^1 N to 5° 59^1 N and longitudes 8° 00^1E to 8°25 ^{1} E. The area is part of the Cross River plain and covers a large area with undulating topography.Its highest relief is about 350 ft (170 m) and a low of approximately 100 ft (30.48 m) especially in the northeast, which is the direction of slope. The study area is characterized by an equatorial climate with a mean annual rainfall of between 2000 and 2500 mm per year. This abundant rainfall feed an extensive hydrogeological system. The temperature ranges from 24.5℃ to 34.5℃. The relative humidity is usually high throughout the year with values above 70% recorded for places like Nko, while Ijiman, Idomi and Ntankpo have values less than 70% [1,18]. The area is drained by the Cross River and its tributaries which include Okwo, which drains from east to west, the Uhuru which runs north through south of the mapped area and the Lokpoi which trends in the northeast direction (Fig. 1). The drainage density in the area is 0.53 with a frequency of 0.87. The drainage pattern in the study area is generally dendritic [1,18].

1.2 Geology of the Study Area

The study area is part of the Calabar Flank which is characterized by crustal block faulting and is bounded by the Oban Massif to the north and the Calabar hinge line delineating the Niger Delta basin in the south. It is also separated from the Ikpe platform to the west by a NE-SW trending fault. In the east, it extends up to the Cameroon volcanic ridge. The initial rifting of the southern Nigerian margin produced two principal sets of faults, a NE-SW and NW-SE system. The former set of faults bound the Benue depression while the later sets were more prominent and active in Calabar Flank. The basement structures of the Calabar Flank are aligned parallel to those of the coastal basins of Gabon, Congo and Angola. These structures were produced during the opening of the South Atlantic Ocean [30,31].

The study area is part of the Calabar Flank and consists of a Precambrian crystalline basement and a sedimentary cover ranging in age from Cretaceous to Tertiary. The total sediment thickness of the Calabar Flank is about 3.5 km with the ages of the sedimentary facies in the Calabar Flank ranging from Aptian to Campanian-Maastrichtian. Santonian and early Campanian sedimentary rocks have not been reported in the Calabar Flank, probably representing a period of non deposition and/or erosion. The basement complex consists predominantly of migmatites, and banded granitic gneisses. Relics of the meta-sedimentary and meta-volcanic rocks are widely distributed within the migmatite - gneiss complex [32]. Generally, the basement complex rocks have been extensively intruded by volcanic, granitic and charnockitic rocks of Pan-African age in most part of the study area. Sedimentary rocks cover more than ninety (90) percent of the study area, while igneous intrusive rocks are found in about 10 percent of the total area under investigation (Fig. 2).

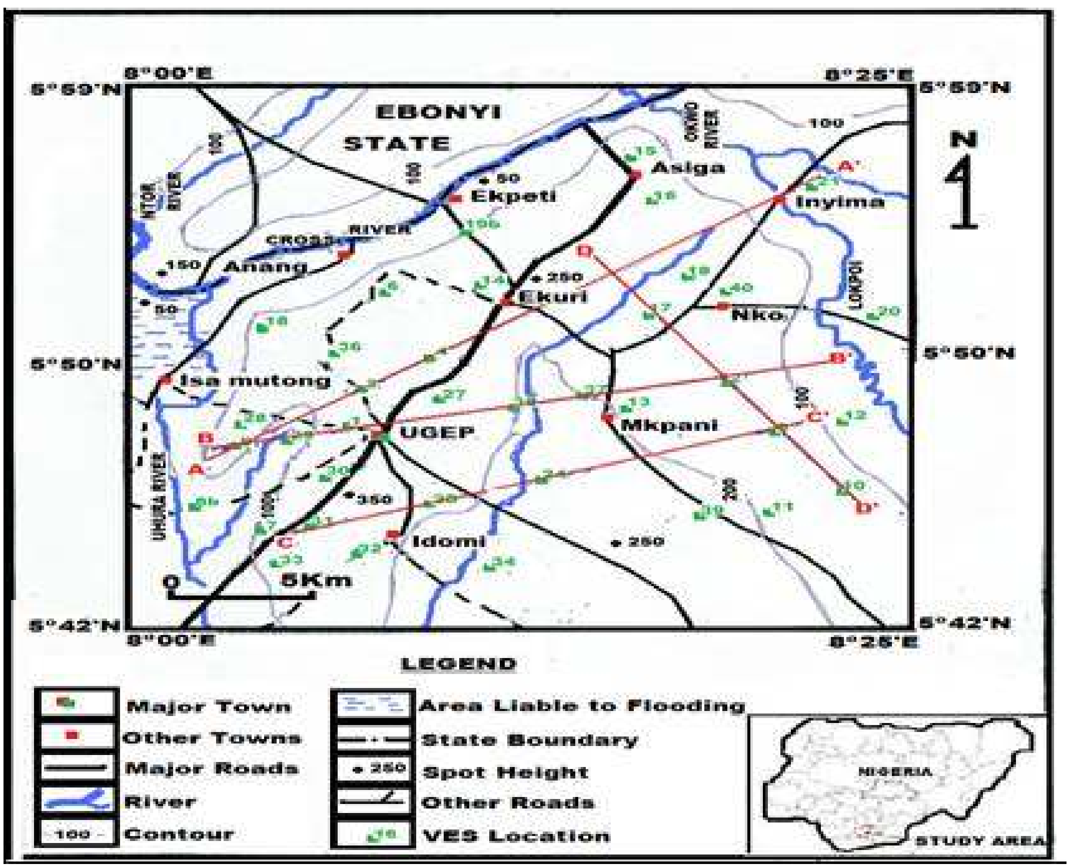


Fig. 1. Location map of study area

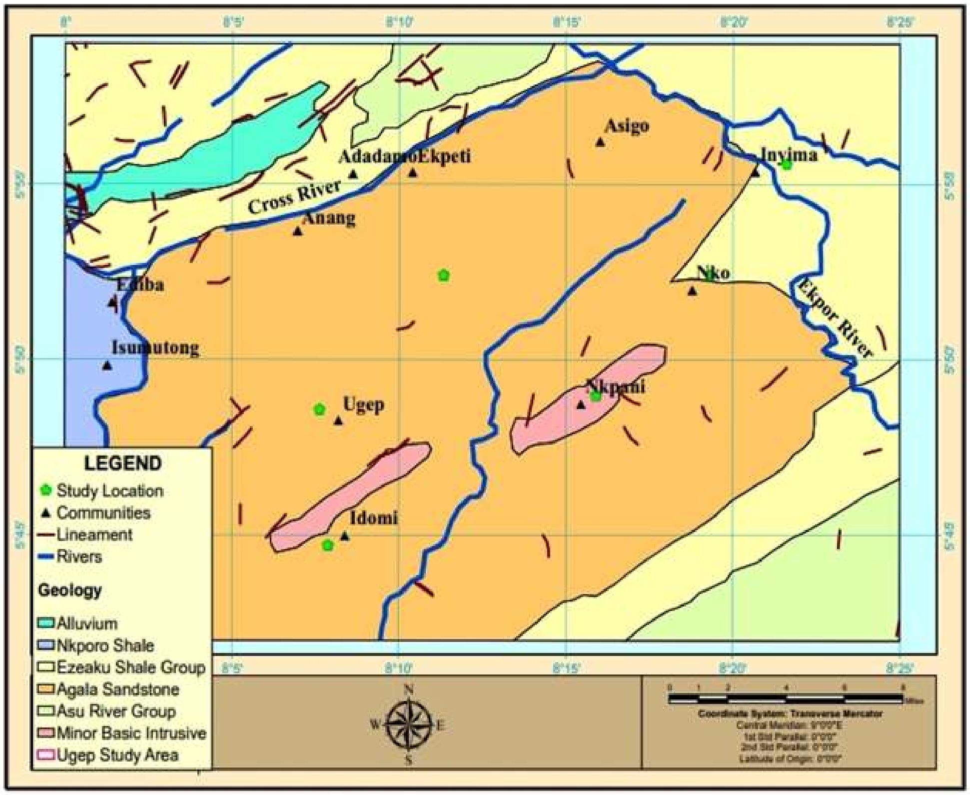


Fig. 2. Geological map of Ugep and its environs

The area is underlain by three main sedimentary facies which include the Asu River Group, Nkporo shale and the Ezeaku Formation. Asu River Group (Albian-cenomanian) consists of alternating sequence of shales and siltstones with occurrences of sandstone having its maximum thickness as 1500 m. It represents the first and oldest cycle of shallow marine to brackish water sediments deposited on the basement complex. There has been reported presence of Cenomanian sediments and Santonian intrustives of dykes and sills extrusives. Ezeaku Formation (Turonian-coniacian) consists of flaggy calcareous shale with thin sandy or shaley limestone and calcareous siltstone. Eze-Aku Formation overlies the Asu River Group with the formation deposited as a result of renewed transgression in the second depositional cycle of the Benue Trough. The thickness of the Ezeaku Formation is highly variable and may get to a thickness of 1200 m [2,18]. The Nkporo Shale Formation (late Campanian – Maastrichtian) was deposited in various environmental settings including shallow open marine paralic and continental regimes [31]. It consists of dark grey and highly fissile shale with interbeds of sandy shale, siltstone and mudstone. The Nkporo Shale is spread across the Lower Benue Trough and consists of dark grey, fissile shale, brown silty and sandy shale, mudstone and fine-grained sandstone. In the Calabar flank, lateral persistent black shales facies can be identified in both outcrops and subcrops.

The major hydrogeological units are the crystalline basement rocks (mainly the fractured basement), sandstone / siltstone units, fractured shales and the sandstone members of the Nkporo and Ezeaku Formations (which consists of its sand members which include the Agala and Afikpo sandstones respectively) [18,19]. The broad and thick shale facies reduces the groundwater potential in the study area as they separate the hydrogeological units into distinct hydraulically unconnected units. However, the intercalation and interfingering of sandstone – siltstone family leeads to increased permeability within the group. [18] identified three potential aquifer groups in the study area namely: lenticular sandstone bed in shale and siltstone; fractured sedimentary rocks at contact zones between the sediments and intrusive fractures; and joints within the intrusive bodies.

2. MATERIALS AND METHODS

Geoelectric data was collected across the study area using the Vertical Electrical Sounding (VES) technique. A total of 40 VES data with a maximum electrode spacing of 1000 m was acquired at various stations across study area using the schlumberger array. Seven of the VES data were acquired at the positions of existing borehole locations where borehole data was available for correlative purposes. The ABEM 4000 SAS Terameter was used for data collection. The observed field data was converted to apparent resistivity values by multiplying with the schlumberger geometric factor (K) such that:

$$\rho_a = KR \quad (1)$$

where ρ_a= apparent resistivity, R = resistance, K is therefore obtained thus:

$$K = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right) \quad (2)$$

a and b being half current electrode spacing and potential electrode spacing respectively.

$$\text{Hence} \qquad \rho_a = \pi\left(\frac{a^2}{b} - \frac{b}{4}\right)R \quad (3)$$

Modeling of the VES data was done using the OFFIX software. Analysis of the resulting apparent resistivity versus half current electrode separation yielded model curves composed of individual layers of specified thickness and apparent resistivity. Both the resistivity (ρ) and the thickness (h) of these layers were obtained from the quantitative interpretation of the VES data. The concept of Dar-zarrouk parameters (Longitudinal conductance, S and transverse resistance, T_r) was first introduced by [33] to explain the problem of non-uniqueness in the interpretation of resistivity depth sounding curves. For a sequence of n horizontal, homogeneous and isotropic layers of resistivity ρ_i and thickness h_i, Dar-zarrouk parameters are defined respectively as: The longitudinal conductance (S) is a parameter used to define target areas of groundwater potential. High S values usually indicate relatively thick sediment succession and should be accorded the highest priority in terms of groundwater potential and vice - versa.The longitudinal conductance (S_i) is mathematically represented as:

$$S_i = \sigma_i h_i \quad (4)$$

where σ_i is the layer conductivity which is analogous to the layer transmissivity. Similarly, the transverse resistance (T_r) is one of the parameters used to define target areas of good groundwater potential. It has a direct relationship with transmissivity and the highest T_r values generally reflect the highest transmissivity values of the aquifers or aquiferous zones and vice versa. Similarly, the transverse resistance (T_r) is given as:

$$T_r = h_i \rho_i \quad (5)$$

2.1 Aquifer Vulnerability Assessment

Groundwater vulnerability defines the tendency of an aquifer to receive contaminants introduced at or near the earth‘s surface. This depends on the intrinsic properties of the aquifer system and their sensitivity to human and natural activities. Groundwater vulnerability is a function of not only the properties of the groundwater flow system but also of its nearness to contaminant sources, the character of the contaminant, and other factors that could cause the potential contaminants to reach the groundwater resource [34]. The DRASTIC model was adopted for the purpose of groundwater vulnerability assessment. The model was developed by the US Environmental Protection Agency (EPA) to evaluate groundwater pollution potential [22]. The model is based on the concept of the hydrogeological setting that is defined as a composite description of all the major geologic and hydrogeologic factors that affect and control groundwater movement into, through and out of an area [22]. The significant media type of each of these parameters is assigned a subjective rating varying from 1 to 10 based on their relative effect on the aquifer vulnerability. Every parameter in the model has affixed weight multiplier indicating the relative influence of the parameter to contaminant transport [22]. The final DRASTIC index (D_i) is the weighted sum overlay of the seven parameters using the following equation:

$$D_i = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w \quad (6)$$

where D, R, A, S, T, I, C are the seven parameters, and the subscripts r and w are the corresponding ratings and weights respectively. The weights and ratings are assigned according to [22]. Table 1 shows the aquifer vulnerability rating based on the DRASTIC Index.

Table 1. Aquifer vulnerability rating based on the final DRASTIC index [22,35]

DRASTIC index (D_i)	1-100	101-140	141-200	>200
Vulnerability category	Low	Moderate	high	Very high

3. RESULTS INTERPRETATION AND DISCUSSION

3.1 Geoelectric Curves

Typical geoelectric curve types generated from the study area are presented in Figs. 3a and 3b. Results of the curve matching was studied in details. Results of the study revealed the presence of 3-8 geoelectric layers (Table 2). Similarly, ten (10) geoelectric curve types were encountered in the study area with the KH-type being prevalent. The shape of the geoelectric curve for each sounding gave an insight into the character of the beds or layers between the surface and the maximum depth of penetration. This is because the shape of a VES curve depends on the number of layers in the subsurface, the thickness of each layer, and the ratio of the resistivity of the layers [34,35]. It should be noted that the shape of curves obtained from geo-electric sounding over a horizontally stratified medium is a function of the resistivities and thicknesses of the layers as well as the electrode configuration [36,37].

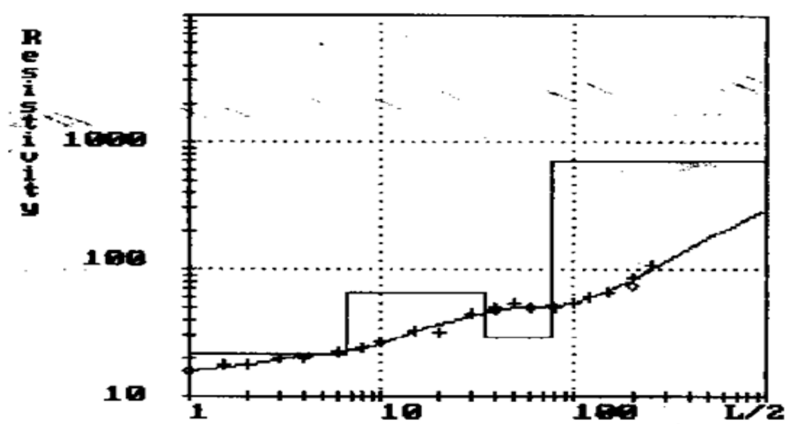


Fig. 3a. Typical geoelectric curve types in the study area at VES 13 (Okpirike Afaben Mkpani)

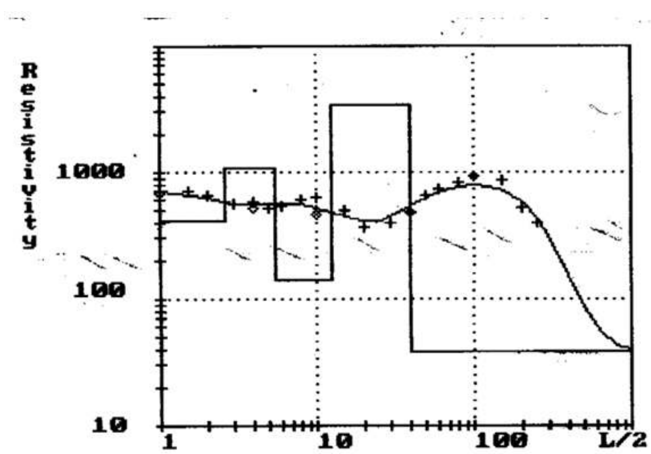


Fig. 3b. Typical geoelectric curve types in the study area at VES 13 (Nko II)

3.2 Aquifer Resistivity, Depth and Thickness of the Study Area

The contour map of the various measured parameters were gridded using kriging interpolation technique. This was done using the gridding module in Golden Software Surfer 12. An interpolation technique in which measured values are weighted to derive a predicted value for an unmeasured location. Kriging is the surrounding unique among the interpolation methods because it provides an excellent method that guarantees accuracy of the interpolation process. Kriging is based on regionalized variable theory, which assumes that the spatial variation in the data being modeled is homogeneous across the surface. Aquifer resistivity across the study area ranges from a value of 34.9 Ωm at Idomi Road 2 (VES 32) to 3920 Ωm at Ugep (VES 1), with a mean value of 629.63 Ωm (Table 3). The resistivity contour map in Fig. 4 shows that resistivity is high towards the southern region of the study area, while the resistivity value is low towards the northern part of the map. The depth to water table in the study area varies between 12.4 m (VES 3) to 147 m (VES 16) with a mean value of 67.96 m. Fig. 5 shows that the areas with blue and purple colours corresponds to regions having low depth to water table (0- 40 m), while deeper water table are shown with red colours (50-150 m). Similarly, aquifer thicknesses across the study area ranges from 5.7 m at Lokpoi (VES 20) to 123 m at Itigidi Road 4 (VES 8b) with a mean thickness of 47.3 m. The isopach map shown in figure 6 revealed that areas with blue and purple colours corresponded to regions of low aquifer thickness (0-40 m), while areas with high aquifer thickness are shown in red colours (50-150 m).

3.3 Iso-resistivity Map of the Study Area

The iso- resistivity map (resistivity depth slices) was estimated across the study area (Table 3). The iso- resistivity models were generated at depth intervals of AB/2 = 10 m, 20 m, 30 m, 60 m, 75 m, 100 m, 150 m, 200 m, and 300 m (Table 3). The iso-resistivity map (Fig. 7) revealed a continuous decrease of resistivity with depth indicating a resistive overburden overlying a conductive base. The iso-resistivity map showed that the western and central axes are underlain by relatively low resistive materials at a depth of AB/2 = 60 m down to AB/2 = 300 m. The Southeastern part on the other hand is underlain by relatively less conductive materials at these spacing. The resistivity values in this area ranges from 110 Ωm near VES 25 to 493 Ωm near VES 35 with a mean of 212.48 Ωm at AB/2 = 75 m.

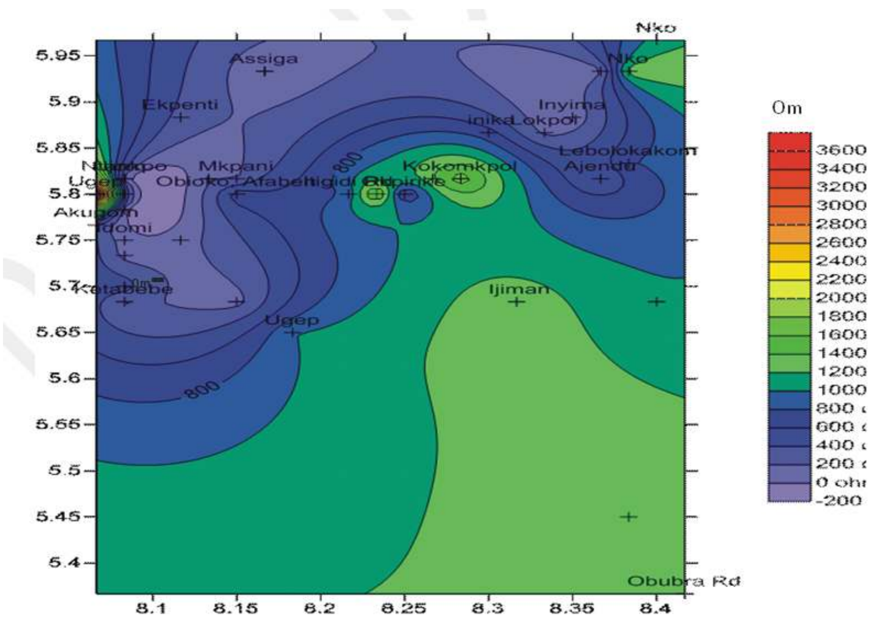


Fig. 4. Map of aquifer resistivity of Ugep and environs(Ωm)

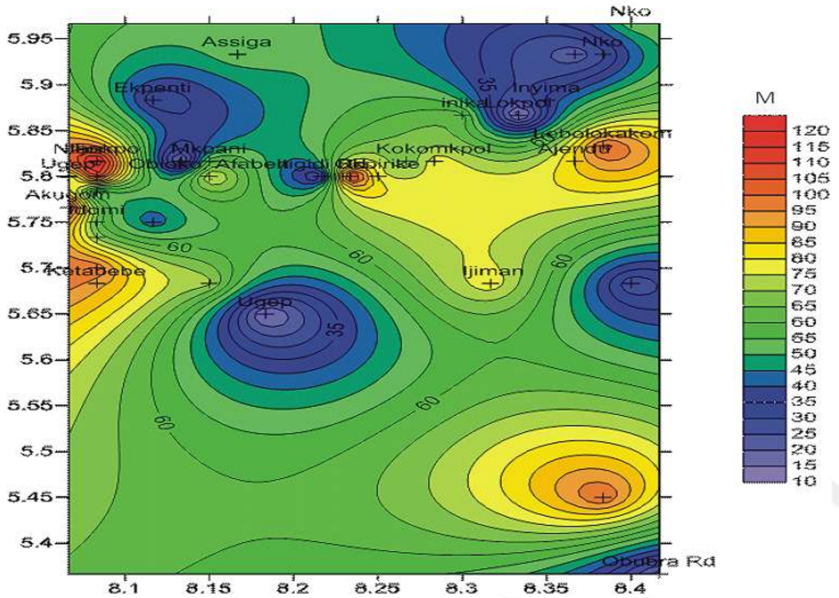


Fig. 5. Contour map of aquifer depth of Ugep and environs

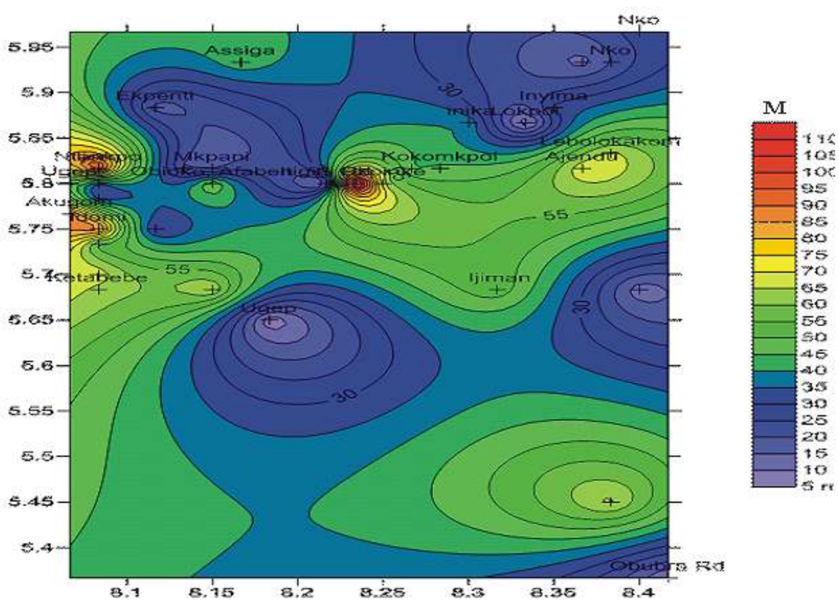


Fig. 6. Isopach map of the aquifers of Ugep and environs

3.4 Spatial Variation of Dar-zarrock Parameters

Longitudinal conductance varies from 0.0053 Sm (VES 28) to 0.005 Sm (VES 40), with a mean value of 0.2848 Sm (Table 4). Longitudinal conductance (S) values decreases from the northwestern region of the study area towards the south and eastern parts of the study area. This is shown with purple to blue colours in the map. The study area reveals an increase in longitudinal conductance, towards the northwestern flank while the southeastern, northeastern and the entire southern part of the study area revealed low conductive materials. The map of the aquifer longitudinal conductance

(S) is shown in Fig. 8. The southeastern half of the study area and other zones of high S values are probably underlain by thick layers of conducting sediments. These could either be fully saturated zones or areas with high percentage of conducting clays or both. Although the aquifer thickness is higher in the central part of the study area, underlain by the Ezeaku Formation, the relatively medium to high resistivity values for the aquiferous zones could account for the lower values of S in these areas.

The lineaments of the study were super-imposed on the maps of the longitudinal conductance and transverse resistance of the study area. Analysis of these maps revealed that lineaments and faults have limited effect on the Dar-zarrouk parameters. These parameters are mainly dependent on the lithological compositions of the various formations.

Transverse resistance across the study area varies from 1106.33 Ωm^2 at Idomi Road 2 (VES 32) to 84992 Ωm^2 at Obubra Road 3 (VES 6) with a mean value of 19819.3 Ωm^2 (Table 4). The transverse resistance (T_r) values increases from the northwestern region to the southeastern region(areas with red colours) with values ranging from 25,000 - 85,000 Ωm^2. However, low values of T_r were recorded at Idomi Road 2 (areas with purple and blue colours) with values between 25,000 - 30000 Ωm^2. The transverse unit resistance (T_r) map is considered a unique map for hydrological classification of an environment with a thick sedimentary sequence, as is the case under study. This is because the transverse unit resistance (T_r) which is a product of aquifer thickness (h) and resistivity (ρ), is closely related to transmissivity (T) which is a product of aquifer thickness and hydraulic conductivity (K). Thus the southeastern part of the study area (Fig. 9) where the transverse unit resistance values are high, are expected to correlate well with areas having the highest hydraulic transmissivity (T) and storage coefficient, whereas the northwestern part of the study area with low values of transverse resistance (T_r) are expected to have the least transmissivity (T) and storativity values. High T_r values but low S values were obtained for the aquiferous unit of the Agala sandstone (Ezeaku Group) within the central part of the study area whereas high S values and low T_r values were noticed at the fringes especially within the Asu River Group. The high S values obtained in part of the study area can be attributed to higher salinity of the groundwater or high clay content or both. Sufficiently high T_r coupled with good aquifer thickness is necessary for water well exploitation. Consequently the most prospective areas for the drilling of productive boreholes can be delineated in the vicinities of Ijiman and environs.

3.5 Geo-electric Correlation in the Study Area

Geo-electric correlation was carried out along four interpretative geologic cross sections as shown in Fig. 2 to correlate various aquifer geomaterials and to relate them to the geology of the study area. Variation of aquifer depth, thickness, resistivity, etc were correlated along the four interpretative profiles in the study area which include A-A^1, B-B^1, C-C^1, and D-D^1 (Fig. 10).

3.5.1 Profile A-A^1

Profile A-A^1 has a northeast – southwest (NE-SW) trend and is about 25.6 km in length. The profile cuts across VES stations 5,3,4 and 21. Along this profile, the depth to the water table varies from 12.4 m at Afaben Community (VES 3) to 36.8 m around Inyima (VES 21) with a mean value of 22.9 m. Similarly, the aquifer thickness ranges from 5.9 m to 31.4 m with a mean aquifer thickness of 14.6 m. The spatial variation in the depth and thickness values of the aquifers along the profile is in line with the geology and topography of the area. Similarly, seven geoelectric layers were encountered along this profile (Fig. 10a), and are interpreted as lateritic top soil, shale, siltstone, silty sands with some intercalation of shale, shaly sands, and sandstone in that sequence.

3.5.2 Profile B-B^1

Profile B-B^1 is an E-W trending 21.3 m profile cutting through VES stations 29, 1, 37, and 2 (Fig. 10b). Six lithological sequences were interpreted along the profile which includes lateritic top soil, siltstone, shaly siltstone, medium sand and finally sandstones which is believed to be the aquifer geomaterial. The aquifer depth varies from about 59.6 m at Ijom 2 (VES 37) to 87 m at VES 29 with a mean depth of 74.4 m along the profile. Similarly, the aquifer thickness ranges from 49.2 m to 63 m along the profile with a mean thickness of 56.8 m.

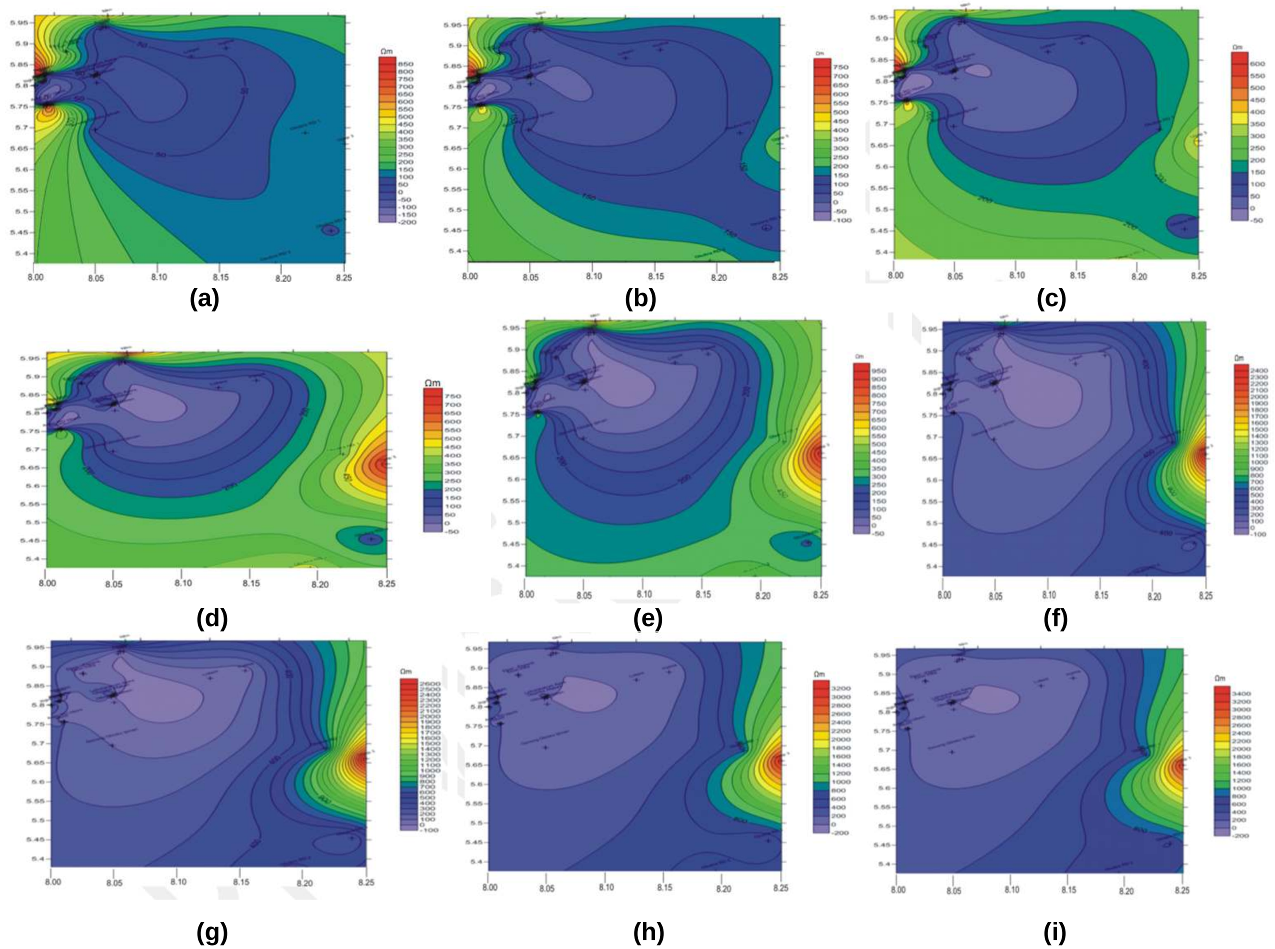


Fig. 7. Iso-resistivity maps of the study area: (a) AB/2=10 m (b) AB/2=20 m (c) AB/2=30 m (d) AB/2=60 m (e) AB/2=75 (f) AB/2=100 m (g) AB/2=150 m (h) AB/2=200 m (i) AB/2=300 m

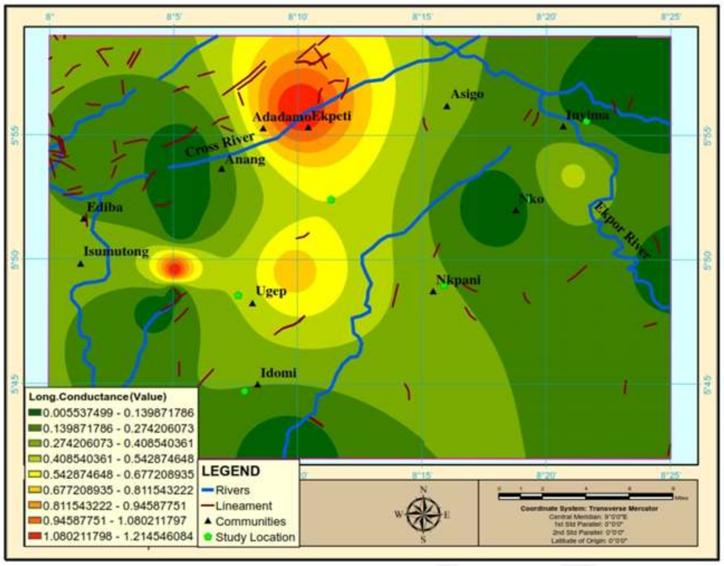


Fig. 8. Longitudinal conductance (Sm) map with lineament overlay

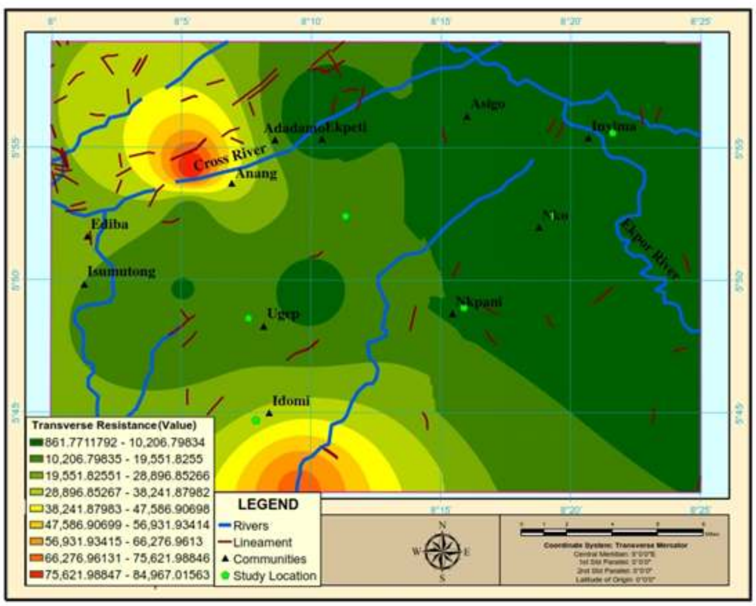


Fig. 9. Transverse resistance (T_r) variation map of Ugep with lineament overlay (Ωm^2)

3.5.3 Profile C-C^1

Profile C-C^1 is a 17 km profile taken along the east-west (E-W) direction and cuts across VES stations 9, 25, 24 and 35 (Fig. 10c). The depth to the water table ranges from 62 m at VES 31 to 103 m at VES 9. Similarly, the aquifer thickness ranges from 62.9 m to 89.4 m. There is a pronounced variations of lithology across the profile. Lithological sequences encountered along the profile include top lateritic soil, fine grained sands with siltstone, shale, silty sand, and medium to coarse grain sandstone. The sands/sandstones are the interpreted aquifer geomaterials and are believed to be of good potentials.

Table 2. Summary of results of interpreted layer parameters of the study area

VES No	Location	No of layers	Curve type	Layer resistivity, ρ (ohm-m)								Layer depth, d (m)							Layer thickness (m)						
				ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	ρ7	ρ8	d1	d2	d3	d4	d5	d6	d7	t1	t2	t3	t4	t5	t6	t7
1	Ugep 1	6	KH	2560	779	102	56.1	3970	10300			0.7	1.9	11	24	73.2			0.7	1.2	9.9	13	49.2		
2	Obioko Afaben	5	AK	14.8	21..4	66.7	28.9	720				0.7	6.5	34.6	77.9				0.7	5.8	28.1	43.3			
3	Ugep 3	6	KH	2360	415	60.9	990	62	46			1.4	2.4	6.5	12.4	37.7			1.4	1	4.9	5.9	25.3		
4	Obubra rd 1	6	HA	66800	328	123	44	1030	5090			0.2	1.3	6.7	13.7	25.3	126		0.2	1.1	5.5	5	11.6	100.7	
5	Obubra rd 2	8	HA	1860	440	65.1	624	1200	127	3910	16100	0.7	1.8	5.3	7.6	17.1	41.7	88	0.7	1.1	3.5	2.5	9.5	24.6	46.3
6	Obubra rd 3	7	HKH	8200	181	64.7	337	1280	580	77		0.4	3.6	16.9	34.6	101	155		0.4	3.2	13.3	17.7	66.4	54	
7	Itigidi rd 2	6	KH	4350	136	54	850	4100	3930			0.5	5.3	14	27.6	140			0.5	4.8	8.7	13.6	112.4		
8a	Itigidi rd 3	7	KH	4650	206	107	1380	2110	1310	2860		0.5	1.2	19.9	64.5	135	178		0.5	0.7	18.6	44.6	70.5	43	
8b	Itigidi rd 4	7	KH	4550	267	111	46	75	42	1710		0.5	1.1	25	46.6	73.6	114		0.5	0.6	23.9	21.6	27	40.4	
9	Lebolokakom	6	HK	125	18.2	48.3	148	790	73			0.5	1.5	4.7	36.6	103			0.5	1	3.2	31.9	66.4		
10	Ajendu	6	HA	70.4	29.1	60.6	380	86	47			0.5	3.3	16.2	85.2	162			0.5	2.8	12.9	69	76.8		
11	Afaben	6	HKH	30.8	17.6	125	169	14.7	10.9			0.9	4.8	7.9	12.8	48.4			0.9	3.9	3.1	18.9	21.2		
12	Kokomkpol	7	HKH	338	16.2	357	66	1210	1730	640		0.9	4	8.6	18	32.7	78.8		0.9	3.1	4.6	9.4	14.7	46.1	
13	Okpirike	5	AK	15.2	23	80	27	529				0.9	8.3	30.1	70.6	77	82		0.9	7.4	21.8	40.5	63.2		
14	Ekori -Ekpenti	7	HQ	1410	204	86	336	5.1	9.9	324		0.9	2.2	13.1	30.7	99.3	163		0.9	1.3	10.9	17.6	68.6	63.7	
15	Assiga 1	6	KH	90	31.3	6	66.8	48.7	36.1			0.7	1.9	10.5	54.2	142			0.7	1.2	8.6	43.7	81.7		
16	Assiga 2	6	HKH	57.3	3.6	15.8	43.9	28.4	4.8			0.8	3.3	43	88.7	147			0.8	2.5	39.7	45.7	58.3		
17	Nko 2	6	HKH	760	407	1070	143	84	38.1			1	2.6	5.4	12.7	40			1	1.6	2.8	7.3	27.3		
18	Nko 1	6	HA	543	31	118	9.6	91	80			1.1	8.4	21.6	43.2	73.2			1.1	7.3	13.2	21.6	30		
19a	Ekori inika	6	HQ	188	170	681	116	142	16.3			0.9	2.4	6.3	36.5	82.4			0.9	1.5	3.9	30.2	45.9		
19b	GSS Ugep	6	KQQ	271	36..5	25.5	327	76.2	59.4			0.6	5.7	19.1	58	91.6			0.6	5.1	13.4	38.9	33.6		
20	Lokpoi	6	HKH	398	31.8	151	54	22.4	167			0.4	4.3	10	65.6	170			0.4	3.9	5.7	55.6	104.4		
21	Inyima	6	HKK	129	48	72.7	54.7	66.7	22.4			0.8	5.4	36.8	77	97.6			0.8	4.6	31.4	40.2	20.6		
24	Ketabebe 1	5	HKH	69.66	148.2	128	190.8	37.8				4.27	9.2	29.1	92				4.27	4.93	19.8	62.9			
25	Ketabebe 2	5	KH	202.8	107.9	53.5	505.6	71..4				2.14	9.93	31.4	100				2.14	2.84	37.4	68.6			
26	PCN Ijiman	4	HKH	1524	377.4	467	548.2					1.21	3.84	82.7					1.21	2.47	41.5				
27	Obioko Ijiman 1	6	KH	454.5	70.2	142.1	270	416.4				1.31	2.83	6.09	89.4				1.31	1.52	4.57	83.3			
28	Obioko Ijiman 2	6	KH	910	44.42	129	50.55	52.5	61.5			1.46	3.14	6.77	99.3	101	110	121	1.46	1.68	3.63	26	42.3	99.4	
29	Akugom Ijom	6	KH	96.94	7.55	49.41	54.5	180.8				0.8	4.54	21.8	76.7	87			0.8	3.73	17.3	54.8	63		
30	Ijom 1	6	KH	248.98	55.08	41.8	73.24	127.2				1.4	7.92	21.9	66.4				1.4	6.52	14.0	44.4	65.2		
31`	Ijom 2	4	KH	335.2	33.5	53.01	141.9					0.89	9.83	51.7					0.89	8.94	41.9	89.4			
32	Idomi; 1	4	HKH	259.07	67.65	34.9	18.2					1.47	26.2	46.4	132				1.47	24.7	31.7	100			
33	Idomi; 2	4	QH	288.88	800	136.9	12.9					1.93	15.1	41.4	111				1.93	13.1	28.2	82.4			
34	Adim rd,Idomi	5	KQH	193.6	48.95	142.9	103.1	32.37				1.66	9.34	24.2	68.9	214			1.66	7.68	16.6	52.4	162.6		
35	Kowo st ,Idomi	5	KHK	.727.13	99.9	22.63	44.1	79.0.8				0,97	4.02	18.12	44.7	135			0.97	3.05	14.2	30.5	94.5		
36	Ntankpo 1	3	HA	53.07	125.4	74.32						4.6	67.7						4.6	63.1					

VES No	Location	No of layers	Curve type	Layer resistivity, ρ (ohm-m)								Layer depth, d (m)							Layer thickness (m)						
				ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	ρ7	ρ8	d1	d2	d3	d4	d5	d6	d7	t1	t2	t3	t4	t5	t6	t7
37	Ntankpo 2	4	HA	52.33	35.52	183.3	107.6					1.46	27.7	59.6					1.46	1.68	18.2				
38	Afaben rd,Mkpani	5	HKH	370.66	35.59	108.2	130.9	52.71				1.16	5.38	24.97	79				1.16	4.22	19.5	53.5			
39	GPS Mkpani	4	HKH	34.5	27.76	34.21	82.78					2.62	26.2	82.78					2.62	23.6	56.6				
40	Nko	6	KH	2140	175	59.7	489	1320	19700			1.3	6.6	15.8	21.1	28.4			1.3	3.5	9.2	5.3	7.3		

Table 3. Iso - resistivity (depth slice) values of the study area

VES no	AB/2=10	AB/2=20	AB/2= 25	AB/2= 30	AB/2= 40	AB/2= 60	AB/2= 75	AB/2=100	AB/2=150	AB/2=200	AB/2=300
1	110	105.2	89	125.3	150	172.6	215	299.2	362.4	500	526
2	27.2	36.8	40	43.8	49.1	49.3	50.8	54.2	65.6	86.1	94.4
3	150.1	243.4	334.5	376.2	548	744	952.7	2390	2560	3210	3263
4	142.3	114	120.4	141.1	158	357	364	421.2	600	771	787
5	125.1	244	252	321	358	420.2	400	450	532	740	768
6	98	94	106.2	114	151	164.3	235	268.4	300	402	583
7	110.2	110	128.3	150	198.2	250	342.3	422.1	590	800	821
8a	127	155	160	162	190	235	350	460	468.3	587	622
8b	118	132	141.3	150	155	240	255.8	282	360	490	528
9	54.3	94.2	100	107.3	130.6	156.5	182.1	239.6	306.2	264.1	250
10	45.4	62.4	72.5	82.6	103.5	130.1	145.1	193	222.2	215.5	232
11	35	65.2	86.85	100	122.2	178.5	120.7	259	232.6	210	231
12	216.1	194.8	185	185	210	320.8	390	464.4	555.4	528.7	532
13	27.2	32	40.1	43.8	48	49.2	50	54.2	65.6	86.1	90.2
14	192.5	120	122.3	124.9	144.5	145.1	104.3	70.2	38.5	14.4	12.7
15	7.8	11.5	13.7	15.2	20.4	27.3	29.5	32.6	41	40.3	45.3
16	7.8	11.2	12	13.8	16.4	16.4	16.92	18.7	21.9	21.6	32.1
17	524.8	420	384.2	410.2	508.3	729.8	750.8	908	835.6	514.8	502
18	36.4	49.8	51.8	55.2	57.9	56.1	43.2	34.5	48.2	61.5	63.5
19a	320	253.3	240	167.7	137.1	114.3	110	100.5	73.3	60	57.9
19b	248.9	75.3	60	64.2	59.7	80.2	90.1	94.8	108.1	123.4	140
20	55.3	70.2	72.8	75.1	62.4	59.5	55.2	50.9	45.2	36.4	32.1
21	57.5	62.8	62.8	71.3	67.3	59.2	58.1	61.7	47.4	43.1	38.3
24	92	121	125	127.3	134	138	141	146.1	149.2	163	173.2
25	100	90.1	80	72	80	110	110	150	180.2	253	273.2
26	394	400.1	412.3	423.1	431	450	455.1	550	550	550	556
27	150	180	220.1	221.5	242	253.7	255	280	331	340	348
28	155	262	270	300	350.2	388	392	410	447	452	465
29	18	27.3	28.5	34.3	37.2	43.2	45	60	70	92	100

VES no	AB/2=10	AB/2=20	AB/2= 25	AB/2= 30	AB/2= 40	AB/2= 60	AB/2= 75	AB/2=100	AB/2=150	AB/2=200	AB/2=300
30	54.2	50	52	55.2	58	65	67.3	80	100	120	132
31`	37	42	43.7	45	47.3	50	65	80	100	118.7	132
32	142	175.2	180	200	200	164	132	100	64.7	47.2	38.2
33	90	100	99.1	90	80	63.1	57.3	48	46.3	54	58
34	1040	720	690	650	642	540	470	377	247	230.1	221.1
35	920	810	685.2	645	637.2	520	493	333	250.7	243	257
36	59.3	80	90.1	94	123.4	137	143	147.3	137	132	126.4
37	22.2	28	30	34.7	43	54	60.1	72.1	92	100	113
38	36	50	58.2	67	78.2	87	98.2	100	98.2	78.2	85.2
39	18	24.2	28	30	32.4	35.2	37	38.5	48.2	57.2	62.3
40	33.4	42.8	52	56.1	60.4	58.2	42.5	36.2	47.3	60.3	72.4

Table 4. Summary of aquifer characteristics of the study area

VES no	Locations	Lat. (N)	Long (E)	Aquifer depth(m)	Aquifer Thickness(m)	Aquifer resistivity	Aquifer conductivity	Transverse resistance (T)	Longitudinal conductance (S)
1	Ugep 1	$5^0$48'01.5''	$8^0$04'16.8''	73.2	49.2	3970	0.00025	19532	0.0124
2	Obioko Afaben	$5^0$48.436'	$8^0$09.723'	77.9	51.0	720	0.00139	36720	0.0708
3	Ugep 3	$5^0$39'39''	$8^0$31'30''	12.4	5.9	990	0.00101	5841	0.0060
4	Obubra rd 1	$5^0$51'15''	$8^0$05'15''	25.3	11.6	1030	0.00097	11948	0.0113
5	Obubra rd 2	$5^0$52'32''	$8^0$05' 18''	17.1	9.5	1200	0.00083	11400	0.0079
6	Obubra rd 3	$5^0$54'15''	$8^0$05'22''	101	66.4	1280	0.00078	84992	0.0519
7	Itigidi rd 2	$5^0$48'01.5''	$8^0$04'16.8''	27.6	13.6	850	0.00118	11560	0.0160
8a	Itigidi rd 3	$5^0$48'01.5''	$8^0$04'16.8''	64.5	44.6	1380	0.00073	61548	0.0323
8b	Itigidi rd 4	N$5^0$48'01.5''	E$8^0$04'16.8	114	123	1710	0.00059	21033	0.0719
9	Lebolokakom	$5^0$49.599'	8^0 09.538'	103	66.4	790	0.00127	52456	0.0841
10	Ajendu	$5^0$49.538'	8^0 09.647'	85.2	69	380	0.01163	26220	0.1816
11	Afaben	$5^0$49.409'	8^0 09.485'	12.8	18.9	169	0.00592	3194.1	0.1118
12	Kokomkpol	$5^0$49.606'	8^0 09.688'	78.8	46.1	1730	0.00058	79753	0.0267
13	Okpirike	$5^0$49.259'	8^0 09.462'	77	63.2	529	0.00189	33432.8	0.08715
14	Ekori -Ekpenti	$5^0$53.006'	8^0 07.022'	30.7	17.6	336	0.00298	5913.6	0.0524
15	Assiga 1	$5^0$56.23.3'	$8^0$10'14.1''	54.2	43.7	66.8	0,01497	2919.2	0.6515
16	Assiga 2	$5^0$56'3.8''	$8^0$10'03.4''	147	58.3	48	0.02083	2798.4	1.2146
17	Nko 2	5^0 58'3.8''	8^0 21.0''	54	28	1070	0.00094	29960	0.02617
18	Nko 1	$5^0$56'20.9''	$8^0$10'31.9''	21.6	13.2	118	0.00848	1557.6	0.11186
19a	Ekori inika	$5^0$52.50.0'	$8^0$07'03.4''	63	39	681	0.00147	26559	0.05727
19b	GSS Ugep	$5^0$48'01.5''	$8^0$04'16.8''	58	38.9	327	0.00306	12720.3	0.1190
20	Lokpoi	$5^0$52' 11.5'	$8^0$18'01.0''	10	5.7	151	0.00662	860.7	0.03775
21	Inyima	$5^0$53'23.7''	$8^0$21'03.5''	36.8	31.4	72.7	0.01376	2282.78	0.43191
24	Ketabebe 1	$5^0$48^{1}39.	$8^0$05^{1}04	92	62.9	190.8	0.00524	12001.3	0.3297

VES no	Locations	Lat. (N)	Long (E)	Aquifer depth(m)	Aquifer Thickness(m)	Aquifer resistivity	Aquifer conductivity	Transverse resistance (T)	Longitudinal conductance (S)
25	Ketabebe 2	$5^{0}48^{1}37.9$	$8^{0}05^{1}04.6$	100	68.6	505.6	0.00198	34684.2	0.1357
26	PCN Ijiman	$5^{0}48^{1}38.1$	$8^{0}05^{1}01.2$	110	32.0	548.2	0.00182	17542.4	0.0584
27	Obioko Ijiman 1	$5^{0}48^{1}40.8$	$8^{0}04^{10}55.$	112	87.2	416.4	0.00240	36310.08	0.2094
28	Obioko Ijiman 2	$5^{0}49^{1}33.4$	$8^{0}05^{1}04.$	121	99.4	61.5	0.01626	6113.1	1.6163
29	Akugom Ijom	$5^{0}48^{1}31.8$	$8^{0}04^{1}49.1$	87	63	180.8	0.00553	11390.4	0.3485
30	Ijom 1	$5^{0}414\ 24$	$8^{0}09^{1}\ 34$	72	65.2	127.2	0.00786	8293.44	0.5126
31`	Ijom 2	$5^{0}45^{11}22.$	$8^{0}05^{1}09.9$	62	89.4	141.9	0.00705	12685.9	0.6300
32	Idomi; 1	$5^{0}45^{11}27.$	$8^{0}25^{1}21.0$	46.42	31.7	34.9	0.02867	1106.33	0.9083
33	Idomi; 2	$5^{0}45^{11}24.$	$8^{0}05^{1}27.0$	41.39	28.27	136.9	0.00731	3870.2	0.2065
34	Adim rd,Idomi	$5^{0}45^{1}20.$	$8^{0}05^{1}24.1$	68.9	52.4	142.9	0.0070	7487.96	0.3667
35	Kowo st ,Idomi	$5^{0}49^{'}35^{''}$	$8^{0}05^{1}02.4$	135	94.52	79.08	0.0126	7474.64	1.1953
36	Ntankpo 1	$5^{0}49^{'}33^{''}$	$8^{0}25^{'}10.5^{'}$	67.7	63.1	125.4	0.00797	7912.74	0.5032
37	Ntankpo 2	$5^{0}49^{'}49^{''}$	$8^{0}\ 09^{'}\ 48.$	59.6	18.26	183.3	0.00546	3347.06	0.0996
38	Afaben rd, Mkpani	$5^{0}41^{'}42^{''}$	$8^{0}\ 09^{'}\ 34^{''}$	79	53.5	1309	0.00076	70031.5	0.04087
39	GPS Mkpani	$5^{0}49^{'}32^{'}$	$8^{0}\ 09^{'}47.4$	91	62.2	82.8	0.01208	5150.6	0.7512
40	Nko	$5^{0}56^{'}21^{''}$	$8^{0}23^{'}31.9^{''}$	28.4	7.3	1320	0.00076	9636	0.0055

Table 5. The aquifer classification in the study area

Ves no	Hydraulic conductivity K(GPD/FT)	Aquifer type	LITHO-FACIE	Aquifer system	Aquifer rating	Formation	Hydrogeologic remarks
1	1687.5	L FSA	Sandstone-Siltstone	Semi confined	Good	Asu river	Very high
2	89.30	LFSA	Fractured Shale/Siltstone	Semi confined	Moderate	Eze Aku	Moderate
3	510.0	UF SA	Sandstone-Siltstone	Shallow –Unconfined	Fairly Good	Asu river	High
4	1735	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	High
5	1687.5	LFSA	Sandstone-Siltstone	Semi confined	Fairly Good	Eze Aku	High
6	544.0	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	High
7	1742.5	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	High
8a	896.7522	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	High
8b	921.0	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	High
9	398.75	LFSA	Doleritic Fractured -Shale/Siltstone	Confined	Moderate	Eze Aku	High
10	266.5	LFSA	Doleritic Fractured -Shale/Siltstone	Confined	Moderate	Eze Aku	High
11	7815.0	UFSA	Doleritic Fractured -Shale/Siltstone	Shallow – Unconfined	Moderate	Eze Aku	High
12	1207	LFSA	Doleritic Fractured -Shale/Siltstone	Semi confined	Moderate	Eze Aku	High
13	222.5	LFSA	Doleritic Fractured -Shale/Siltstone	Semi confined	Moderate	Eze Aku	High
14	1046.25	UFSA	Sandstone Shale	Shallow - Unconfined	Fair	Eze Aku	High
15	49.0	LFSA	Fractured -Shale/Siltstone	Confined	Fair	Eze Aku	High
16	37.75	LFSA	Doleritic -Shale/Siltstone	Confined	Fair	Eze Aku	High
17	1462	UFSA	Sandy Clay –Shale	Shallow - Unconfined	Fair	Eze Aku	Moderate
18	50.25	UFSA	Sandy Clay –Shale	Shallow - Unconfined	Fair	Eze Aku	Moderate

Ves no	Hydraulic conductivity K(GPD/FT)	Aquifer type	LITHO-FACIE	Aquifer system	Aquifer rating	Formation	Hydrogeologic remarks
19a	50.25	UFSA	Doleritic -Shale/Siltstone	Shallow - Unconfined	Fair	Eze Aku	Low
19b	564	UFSA	Sandstone-Siltstone	Shallow - Unconfined	Fairly Good	Asu river	High
20	96.5	UFSA	Fractured -Shale/Siltstone	Confined	Fair	Asu river	High
21	31	UFSA	Doleritic -Shale/Siltstone	Shallow - Unconfined	Fair	Asu river	High
24	506.25		Sandstone-Siltstone	Confined	Fairly Good	Asu river	Very High
25	640	LFSA	Sandstone-Siltstone	Confined	Fairly Good	Asu river	Very High
26	623.23	LFSA	Sandstone-Siltstone	Semi confined	Fairly Good	Eze Aku	High high
27	501.5	LFSA	Sandstone-Siltstone	Semi confined	Fairly Good	Asu river	High
28	54.0	UFSA	Sandy Clay	Shallow - Unconfined	Fairly Good	Eze Aku	High
29	60.25	LFSA	Sandy Clay	Shallow	Fairly Good	Eze Aku	High
30	618.5	LFSA	Sandstone-Siltstone	Semi confined	Fairly Good	Eze Aku	High
31`	77.25	LFSA	Sandstone/Siltstone & Shale	Semi confined	Moderate	Asu river	Very High
32	58.25	LFSA	Sandstone/Siltstone & Shale	Confined	Moderate	Asu river	Very High
33	43.25	LFSA	Sandstone/Siltstone & Shale	Confined	Moderate	Asu river	Very High
34	187	UFSA	Sandstone/Siltstone & Shale	Shallow - Unconfined	Moderate	Asu river	High
35	53.25	UFSA	Sandstone-Siltstone	Shallow - Unconfined	Fairly Good	Asu river	Very High
36	78	UFSA	Sandstone-Siltstone	Shallow - Unconfined	Fairly Good	Asu river	Very High
37	22.5	LFSA	Sandstone -Shale	Semi confined	Moderate	Eze Aku	High
38	539.75	UFSA	Sandstone-Siltstone	Shallow - Unconfined	Fairly Good	Asu river	Very high
39	35.25	LFSA	Sandstone-Shale	Semi confined	Moderate	Eze Aku	Moderate
40	58.75	UFSA	Sandy Clay –Shale	Shallow - Unconfined	Fair	Eze Aku	Moderate

Note: LFSA = Lower fine Sand Aquifer, UFSA = Upper fine Sand Aquifer

3.5.4 Profile D-D^1

The D-D^1 profile covers a distance of about 16km along the northwest-southeast (NW - SE) axis and cuts across VES stations 17, 2, 9, and 10 (Fig. 10d). Seven geoelectric layers with interpreted lithological sequences which include top soil, fine grained sands, siltstone, thick layer of shale which decreases towards the southeastern part of the profile, whitish medium to coarse grained sands and finally shale which occupies the base.

3.6 Hydrostratigraphic Interpretation of the Study Area

The result of the study as represented by the geo-electric sections were correlated with lithostratigraphic informations extracted from strata-logs or boreholes drilled in the study area. Some of this litho-logs were correlated with one another to infer possible spatial variation in geology across the study area (Fig. 11). Similarly, the geoelectric sections were correlated with litho-logs from boreholes to establish the regional lithostratigraphy of the study area. This approach aided the full interpretation of the regional hydrostratigraphy of the study area. The analysis of the correlations revealed the subsurface lithologic units: Top soil ranging from lateritic sand to clay (14.8 – 66800 Ωm), clay/clayey sand (3.6 – 800 Ωm), shale / siltstone (6.0 – 1833 Ωm), silty clay/silty sand (9.6 – 1380 Ωm), shaly sand (5.1 – 4100 Ωm), fine to medium grained sands occassionally shaly (9.9 – 19,700 Ωm), and coarse grained sandstone (77– 3910 Ωm). It was revealed that the resistivity of the various formations has a wide range of variation due to variations of the particle size of materials, state of water saturation, degree of consolidation, nature of the cement (siliceous or carbonate), and chemistry of the water. Based on these correlations aquifer rating and hydrostratigraphic correlations were carried out. Using the methods adopted by [1,2,18,19], the aquifers of the study area as classified as fairly good, low, moderate and fair as shown in Table 5.

3.7 Aquifer Vulnerability Assessment Based on DRASTIC Index

The interpreted result of the vulnerability assessment of the aquifer to contamination was characterized by three vulnerability zones: low, moderate, and high zones (Table 6 and Fig. 13). About 2.5% of the study area has a low class of groundwater vulnerability to contamination, whereas a total of 55% of the study area are of moderate vulnerability. This pattern is mainly dictated by the variation in depth to water from east to west. About 42.5% of the study area falls within the high class vulnerability zone, which is an indication of overburden rock materials with no significant impermeable clay/shale overlying strata, which can impede contaminant infiltration. This is interpreted as overburden layers with smaller capacity of protection to contaminants and probable risk to soil and groundwater contamination.

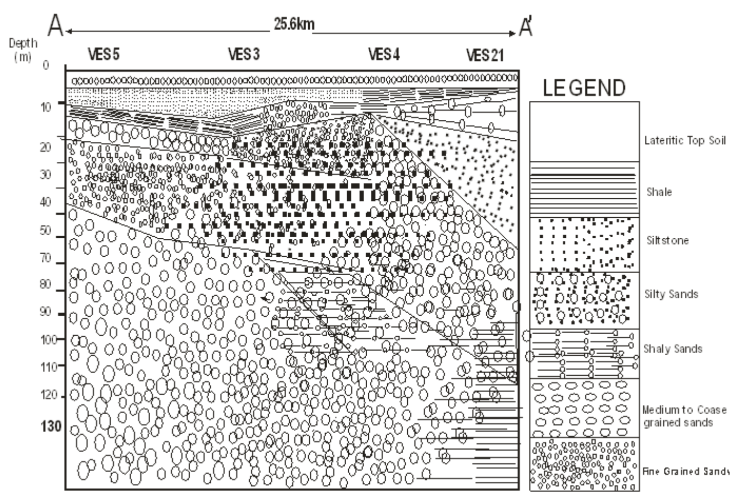


Fig. 10a. Interpretative cross section along profile A-A1

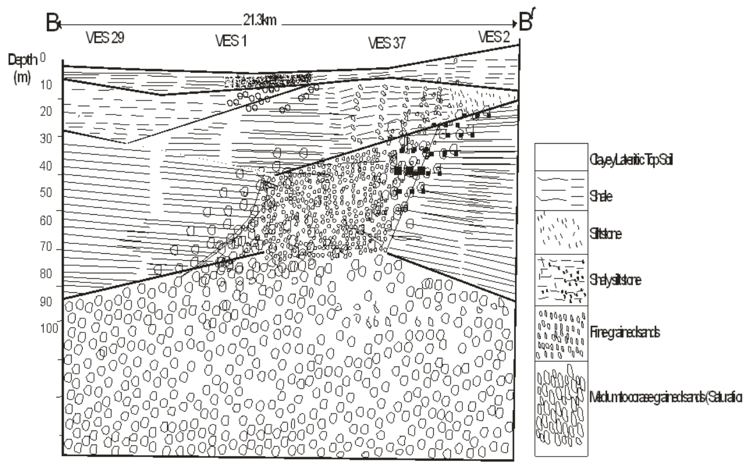


Fig. 10b. Interpretative hydrogeologic crosssection along profile B-B[1]

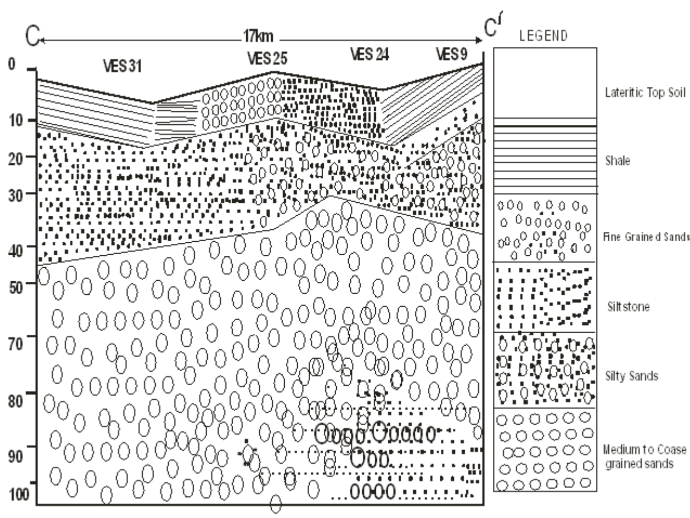


Fig. 10c. Interpretative cross section along profile C-C[l]

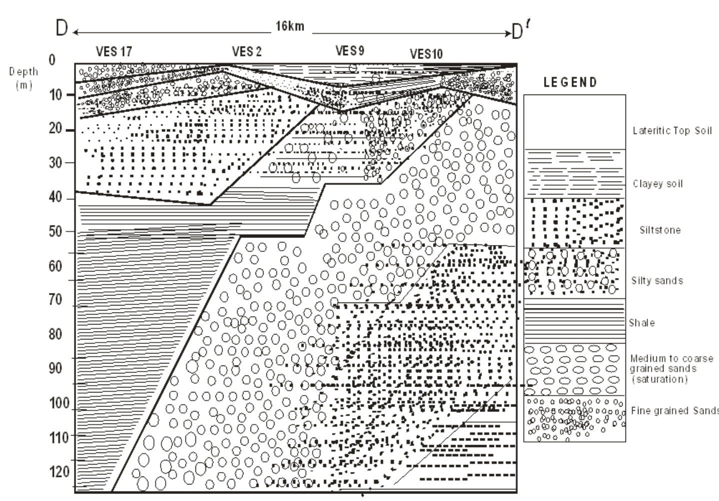


Fig. 10d. Interpretative geo-electric cross section along profile D-D[1]

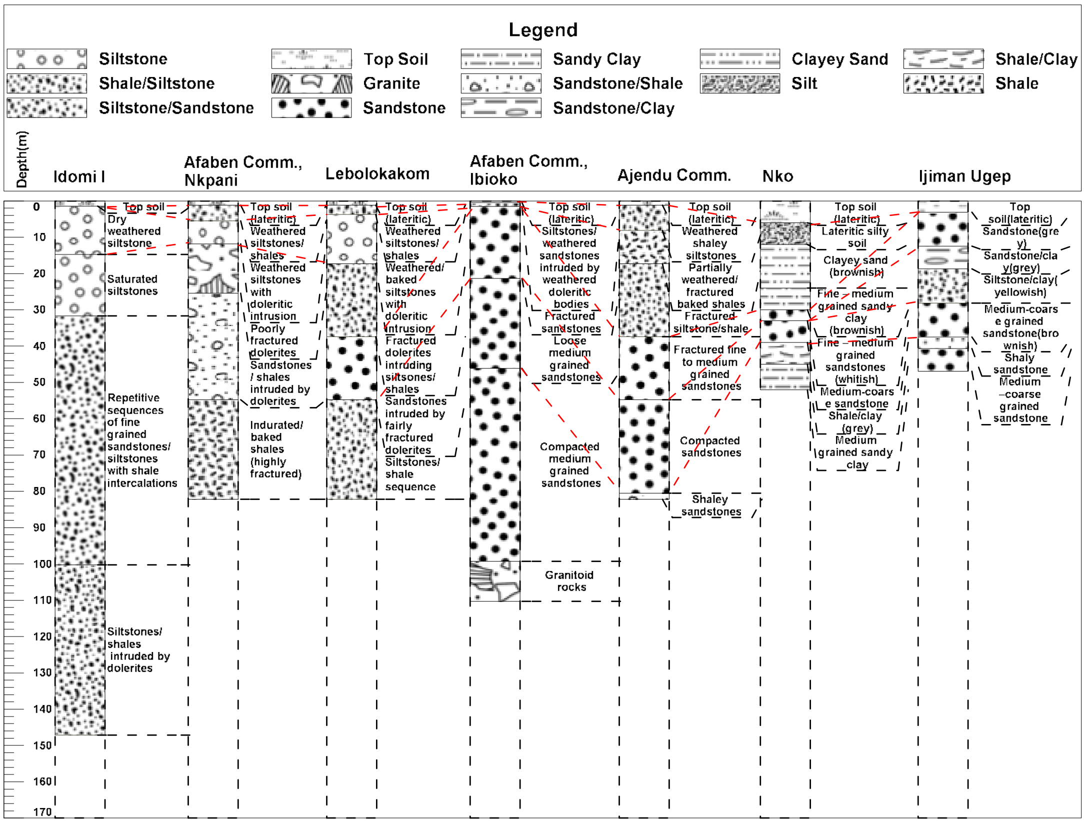
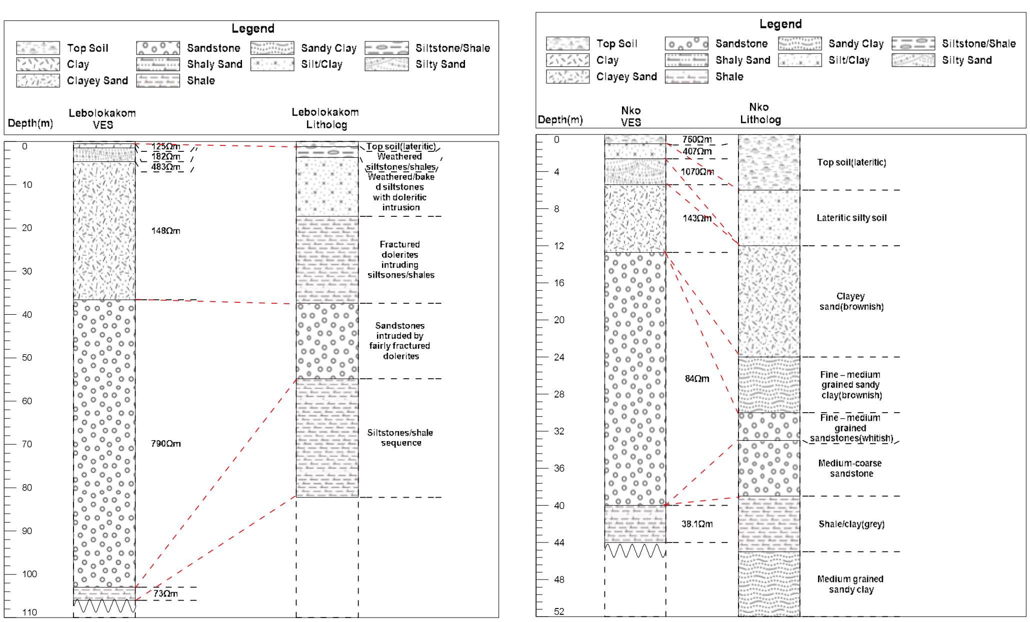


Fig. 11. Lithostratigraphical correlation using strata-logs of available wells in the study area



(a) (b)

Fig. 12. Correlation of borehole strata-logs with geoelectric sections: (a) Lebolokakom (VES 9) (b) Nko (VES 17)

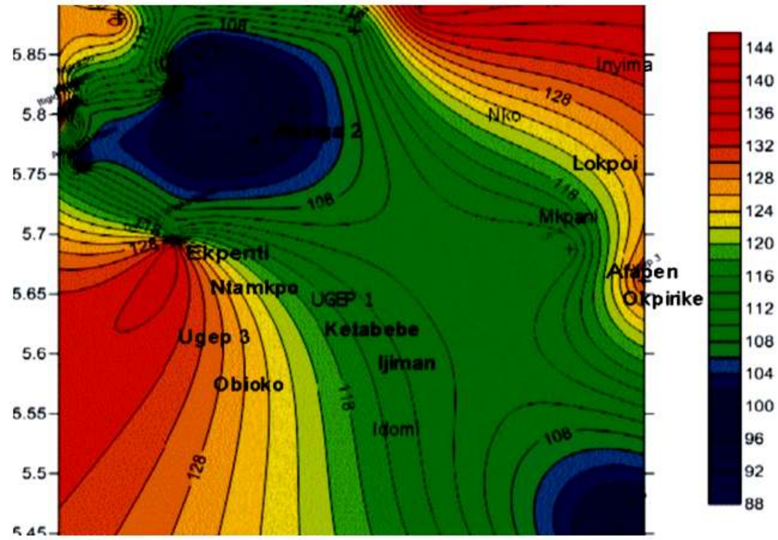


Fig. 13. Aquifer vulnerability assessment Map of the area

Table 6. Summary of aquifer DRASTIC vulnerability ratings

VES	D		R		A		S		T		I		C		Drastic index (D)	Classification
no	w	r	w	r	w	r	w	r	w	r	w	r	w	r		
1	5	3	4	8	3	6	2	9	1	3	5	7	3	8	133	Moderate
2	5	2	4	8	3	6	2	5	1	1	5	7	3	1	141	High
3	5	5	4	8	3	6	2	9	1	1	5	7	3	4	141	High
4	5	1	4	8	3	6	2	9	1	1	5	7	3	8	133	Moderate
5	5	2	4	8	3	6	2	9	1	1	5	7	3	8	138	Moderate
6	5	1	4	8	3	6	2	9	1	1	5	6	3	4	116	Moderate
7	5	1	4	8	3	6	2	9	1	1	5	6	3	8	128	Moderate
8a	5	1	4	8	3	9	2	5	1	1	5	8	3	6	133	Moderate
8b	5	1	4	8	3	9	2	5	1	3	5	8	3	6	133	Moderate
9	5	1	4	8	3	9	2	5	1	3	5	8	3	4	141	High
10	5	1	4	8	3	9	2	5	1	3	5	8	3	2	143	High
11	5	5	4	8	3	9	2	5	1	3	5	8	3	8	161	High
12	5	3	4	8	3	9	2	5	1	3	5	7	3	8	146	High
13	5	3	4	8	3	9	2	5	1	3	5	6	3	2	143	High
14	5	5	4	8	3	6	2	4	1	1	5	7	3	8	145	High
15	5	1	4	8	3	6	2	4	1	1	5	7	3	1	146	High
16	5	1	4	8	3	6	2	4	1	1	5	6	3	1	97	Low
17	5	5	4	8	3	6	2	2	1	2	5	6	3	8	142	High
18	5	7	4	8	3	9	2	2	1	2	5	7	3	1	144	High
19a	5	5	4	8	3	6	2	9	1	2	5	8	3	1	143	High
19b	5	3	4	8	3	6	2	9	1	1	5	9	3	4	142	High
20	5	1	4	8	3	9	2	5	1	2	5	8	3	1	118	Moderate
21	5	5	4	8	3	9	2	5	1	1	5	8	3	1	139	Moderate
24	5	4	4	8	3	6	2	9	1	1	5	6	3	4	131	Moderate
25	5	2	4	8	3	6	2	9	1	1	5	6	3	4	121	Moderate
26	5	2	4	8	3	6	2	9	1	1	5	6	3	4	121	Moderate
27	5	2	4	8	3	6	2	9	1	1	5	9	3	4	136	Moderate
28	5	3	4	8	3	6	2	9	1	1	5	9	3	1	127	Moderate
29	5	3	4	8	3	6	2	9	1	4	5	9	3	1	127	Moderate
30	5	2	4	8	3	6	2	9	1	4	5	6	3	4	124	Moderate
31	5	3	4	8	3	7	2	4	1	4	5	7	3	1	118	Moderate
32	5	1	4	8	3	7	2	4	1	4	5	7	3	1	108	Moderate
33	5	2	4	8	3	7	2	4	1	4	5	6	3	1	108	Moderate
34	5	3	4	8	3	7	2	4	1	4	5	7	3	2	121	Moderate
35	5	5	4	8	3	6	2	4	1	3	5	7	3	1	125	Moderate

VES	D		R		A		S		T		I		C		Drastic index (D)	Classification
no	w	r	w	r	w	r	w	r	w	r	w	r	w	r		
36	5	3	4	8	3	6	2	9	1	3	5	9	3	1	134	Moderate
37	5	2	4	8	3	9	2	5	1	3	5	6	3	1	145	High
38	5	5	4	8	3	6	2	9	1	1	5	9	3	4	153	High
39	5	2	4	8	3	9	2	5	1	1	5	6	3	1	143	High
40	5	3	4	8	3	9	2	6	1	1	5	5	3	1	141	High

4. DISCUSSION

The analysis of the aquifer geometrical parameters revealed that the aquifer resistivity ranges from 34.9 Ωm to 3920 Ωm with a mean aquifer resistivity of 629.63 Ωm. The depth to the water table ranges between 12.4 m to 147 m with a mean value of 67.96 m, while aquifer thickness ranges from 5.7 m to 123 m with a mean value of 47.3 m. The result of the aquifer vulnerability assessment using DRASTIC model clearly revealed that the area is generally moderately vulnerable to groundwater contamination with the depth to water table and vadose zone having the highest impact on the intrinsic vulnerability of the aquifer systems in the area. The present study has helped to map out zones for the drilling of productive boreholes in the study area. The analysis of the geoelectric curves have helped in determining aquifer layer parameters which includes resistivity, depth to water table and aquifer thickness of the study area. The close agreement of the interpretation of geo-sounding data with geological information from available boreholes gave an indication of the usefulness of the present study in characterizing aquifer geo-materials [18,19]. The vertical electrical resistivity sounding method is widely used for groundwater exploration. Two important limitations are however inherent in this method. These are the problems of equivalence and suppression [38]. However, computer oriented direct interpretation methods used in this study are capable of resolving the thickness and resistivities of various subsurface layers from the surface resistivity measurements. Similarly, the interpretation from computer modeling is free from human bias which is always present in the conventional curve matching techniques.

In this work, we have also attempted to assess the aquifer vulnerability of the Ugep area by employing the DRASTIC Index model of the U.S. Environmental Protection Agency (EPA). Seven environmental parameters were used to represent the natural hydrogeological setting of the Ugep aquifer; Depth to water, net Recharge, Aquifer media, Soil media, Topography, Impact of vadose zone, and hydraulic Conductivity. Results of this analysis revealed that 2.5% of the study has a low class of groundwater vulnerability to contamination which is believed to be due to a combination of deep water table, less porous vadose and aquifer media, steep topography, presence of fine grained size material such as clay or silt and low hydraulic conductivity of the aquifer. Whereas a total of 55% of the study area are of moderate vulnerability which ranges from 108 to 133, 42.5% of the study area fall within the high class vulnerability zone ranging from 141-161. This means that almost half of the study area has groundwater with high vulnerability risk. These areas are mainly in the southwestern and northeastern parts of the study area where the physical factors like gentle slope, high hydraulic conductivity, coarse soil media and high water table favours the chances of getting shallow aquifer water polluted.

5. CONCLUSION AND RECOMMENDATION

This study has helped to provide data on the characteristics of aquifer geomaterials in the study area. It has also helped to map out zones for the drilling of productive boreholes in the study area. This study produced very valuable data for those who are in groundwater management because it gave very comprehensive information on aquifer the vulnerability to groundwater contamination across the study area. The high vulnerability of groundwater contamination in parts of the study area makes it absolutely necessary for appropriate measures and policies to mitigate groundwater contamination from anthropogenic sources. Similarly, efforts should be made to constantly monitor the groundwater system for sustainability of the groundwater quality. Apart from groundwater vulnerability assessment, the DRASTIC model can be used in the prioritization of areas for monitoring purposes. It can also help town planners and environmental policy makers in selecting areas for waste disposal and industrial sites. High vulnerability zones are usually difficult to monitor, as it requires the drilling of many monitoring wells, which in most cases are very expensive.

Based on the results obtained from this study we hereby make the following recommendations:

a) A thorough hydrogeochemical investigation is recommended to ascertain the water quality status of the study area.
b) The relevant authorities and agencies should monitor the manner in which industrial and domestic wastes are disposed within the study area.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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