GEOELECTRIC DELINEATION OF AQUIFER PROTECTIVE CAPACITY USING GIS TECHNOLOGY: A CASE STUDY IN OPOLO YENAGOA, BAYELSA STATE NIGERIA

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Abstract

Electrical drilling carried out with nine profiles across the area help to determine the Aquifer Protective Capacity (APC) using GIS Techniques in Opolo Yenagoa Bayelsa State, Nigeria using ABEM Terrameter, SAS 1000, Deep meter, IPI2win, and ArcGIS software. The results revealed the subsurface layers ranging from the topsoil, clay, silty sand, and fine-medium sand of the aquifer types, thickness, depth, and longitudinal conductance Two distinct APC potential zones were delineated, namely good (VES 1, 2, 4 to 9) with longitudinal conductance ranging from 1.16 to 2.99 mΩ, good prospects for groundwater development in the study area with an estimated land area of 0.20 km^2, the productive groundwater potential zones are identified in almost all the area which is about 94.24 % indicating blue while moderate (VES 3) with longitudinal conductance of 0.61 mΩ, the estimated land area is 0.01 km^2 which represents 4.76 % of areas in the northeast part indicated low apparent resistivity and aquifer thickness values. It is worthy to note that despite the slight differences observed in the low potential zones (Moderate), groundwater can still be exploited within the zone, but the difference will be the thickness of the aquifers. Integrating all the geo-electric parameters determined, the best sites for sitting wells or boreholes are all the VES stations, except VES 8 due to these VES stations have less aquifer thickness and is too close to the static water level. Therefore, VES and GIS have proven to be useful for Aquifer delineation of groundwater potential zone.

Keywords: Aquifers Protective Capacity; GIS; VES; Kriging; Electrical Resistivity

INTRODUCTION

Opolo is a satellite village located in Bayelsa State, Yenagoa Local Government Area in Nigeria. The area is experiencing a rise in population placing pressure on the local water supply system. The aquifer is the subsurface layer with a storage facility provided by nature capable of holding water. Environmental pollution is a common challenge facing the area because water plays the most important role in both the lives of animals and plants and its importance cannot be over-emphasized. In recent times, population growth has not been balanced by successive governments in upgrading water supply, inadequate maintenance for oil and gas infrastructure of storage facilities that have contributed to the recurrence of hydrocarbon spills, indiscriminate distortion of an oil pipeline, and in most communities, poor management practices. Most of the above-mentioned activities have not only caused environmental destruction but also depleted and contamination. The need for adequate exploration for groundwater is important to determine the aquifer protective capacity in the area using the electrical resistivity method (Abiola et al., 2009). This research was carried out with the aid of GIS techniques to delineate shallow, aquifer potential zones, aquifer thickness in the region, and aquifer protective capacity in the study area using Vertical Electrical Sound to generate various maps that clearly showed the spatial distribution of aquifer thickness, Aquifer depth, longitudinal conductance, and Aquifer protective capacity of groundwater in the study area. The aim of this study is to delineation the Aquifer protective capacity using vertical electrical sounding with geospatial technology, to determine the thickness of the aquifer and the Aquifer protective capacity rating of the study area, and identify groundwater potential zone.

MATERIALS AND METHODS

Location and Geology of the study area

The study area is Opolo community in Yenagoa Local Government, Bayelsa State, which is situated in the Southern Nigeria sedimentary basin. The study area covers an area of about 170 km^2. It is bounded by Latitude 4^{0}56'15"N - 4^{0}56'25"N and Longitude 6^{o}20'45"E - 6^{0}21'0"E of the equator. Geographically, the study area is within the coastal area of the recent Niger Delta (Figure. 1) where the ground surface is relatively flat, sloping very slightly seawards and is devoid of any outcrop. Its elevation is only few meters above mean sea level (msl). Numerous lakes and rivers such as Epie Creek, Ikoli and River Nun etc in the surrounding area form a complex river network which exhausts into the Atlantic Ocean through the Nun River Estuary. The Niger Delta is basically an alluvial plain and formation of the present day Niger Delta started during the early Paleocene. The sediments are as a result of the deposition of sediment loaded discharges transported to the area by the River Niger and its tributaries. The geologic arrangement of the Niger Delta comprises of three main tertiary lithostratigraphic subsurfaces namely, Akata, Agbada and Benin Formations, overlain by various types of Quaternary deposits (Short, 1967 ; Etu–Efeotor, 1997) reported that these sediments are an admixture of fluvial/tidal channel, tidal flats and mangrove swamp deposits. The sands of the Benin Formation constitute the main regional aquifer in the study area. Groundwater in the Benin Formation occurs mainly under unconfined (phreatic) conditions. The lithology of the Benin Formation consists mainly of loose fine-medium-coarse sands, while gravel and pebbles are minor components (Oki, and Eteh., 2019).

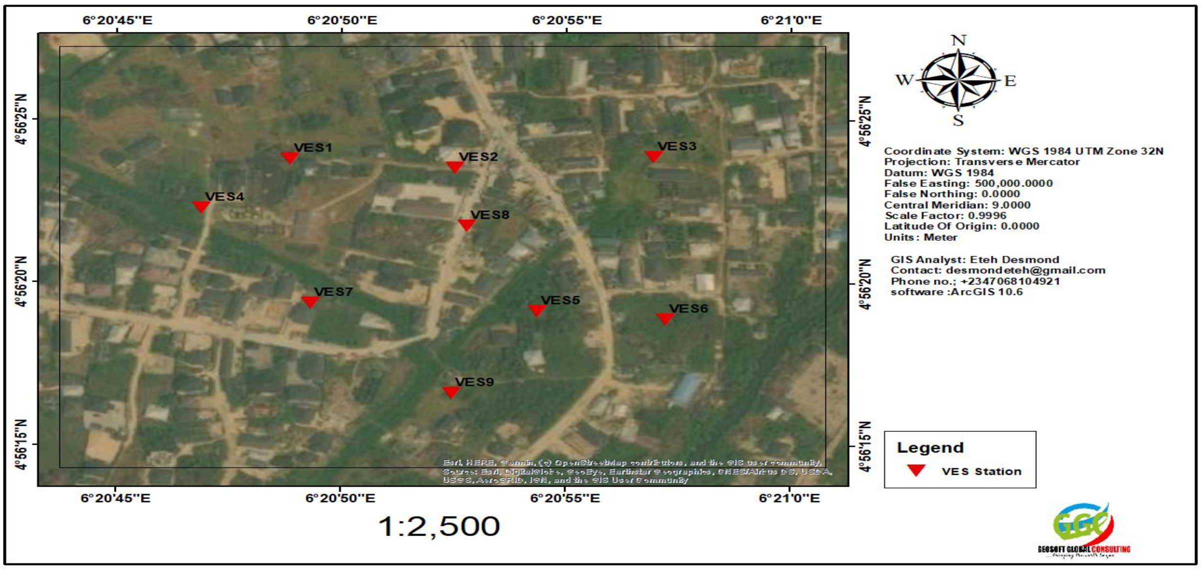

Figure. 1: Map of Study Area

Electrical Method

In this study, the Schlumberger array was performed using the vertical electrical sounding field procedure to assess the electrical resistivity of the subsurface and the thickness of the aquifer. The apparent resistivity (ρ_a) was calculated using:

$$\rho_a = \pi \left(\frac{(AB/2)^2 - (MN/2)^2}{MN} \right) R_a \quad (1)$$

where AB is the distance between the two current electrodes, MN is the distance between the potential electrodes, and Ra is the apparent electrical resistance measured from the equipment (Anomohanran 2015).

The equation can be simplified to $\rho_a = K \, x \, R_a$ (2)

where the geometric factor K is given as $\pi \left(\frac{(AB/2)^2 - (MN/2)^2}{MN} \right)$

The obtain apparent resistivity, ρa, values were plotted against the electrode spacing $(AB/2)$ on a log-log scale to obtain the VES sounding curves using a computer software IPI2win+IP. The field curves were at first interpreted through partial curve matching techniques, using theoretically calculated master curves, in conjunction with the auxiliary curves of A, Q, K, and H types. This information (layer parameters) was then used to interpret the sounding data through a 1-D inversion technique (IPI2win).

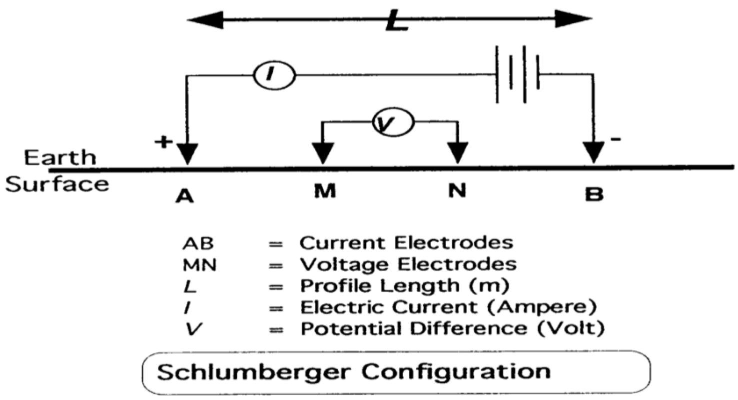

Figure 2: The Schlumberger Configuration

Geographical information systems

The use of GIS technology has significantly increased the assessment of environmental concerns, natural resources, soil, and groundwater (Clake 1986). In groundwater research, GIS is mostly used for managing site inventory data, suitability analyses, estimation of groundwater vulnerability in terms of contamination, leaching and modeling solute transport, groundwater flow mapping, and modeling and linking of groundwater quality index assessment models (Oki and Eteh, 2018).

Data collection

Schlumberger array is an array where four electrodes are placed in a line around a common midpoint. The two outer electrodes, A and B, are current electrodes, and the two inner electrodes, M and N, are potential electrodes placed close together. Vertical Electrical Sounding using Schlumberger array was carried out at different points along with Nine profiles within the study area, with the current electrode spacing of AB/2 =80m that is, the largest current electrode spacing AB used was 160m. The tool used in this study is the Abem Terrameter SAS 1000, a sophisticated tool that automatically displays the resistance value of each VES point on a digital display screen and these values were written down on a book provided during the fieldwork and high-resolution image of about 3m from https://google.com/earth , water level meter was used to get the static water level of the area and Sample location of wells were collected using Global Position System before processing using ArcGIS Software.

Data processing

Vertical Electric Sounding Processing

Step 1. Software

PI2win+IP and Microsoft Excel 2013 software for sample parameter spreadsheet preparation.

Step 2. Method of analysis VES

The obtain apparent resistivity, ρa, values were plotted against the electrode spacing ((AB)/2) on a log-log scale to obtain the VES sounding curves using a computer software IPI2win+IP.

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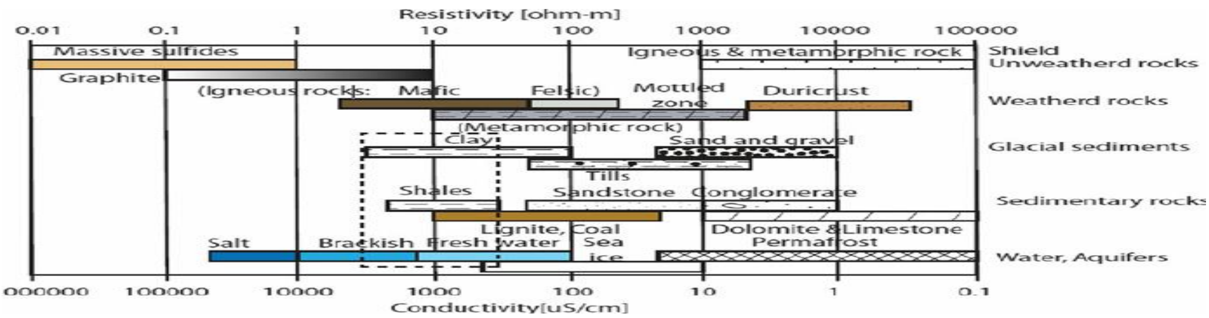


Figure 3a: The estimated range of resistivity values of common rock types (Keller and Frisschknecht 1966)

Earth Material	Resistivity, Average or Range (Ohm-m)	Earth Material	Resistivity, Average or Range (Ohm-m)
Granite	10^2-10^6	Sandstone	1-10^8
Diorite	10^4-10^5	Limestone	50-10^7
Gabbro	10^3-10^6	Dolomite	10^2-10^4
Andesite	10^2-10^4	Sand	1-10^3
Basalt	10-10^7	Clay	1-10^2
Peridotite	10^2-10^3	Brackish water	0.3-1
Air	~ 0	Seawater	0.2

Figure 3b Resistivities of some common rocks, minerals, and chemicals (Robinson and Cahit., 1988).

Geospatial Techniques

ArcGIS software spatial analyst extension was used to generate study area map by collecting data from GPS location from the study area in degree, minute, second and imported into Microsoft Excel where the data was converted to degree decimal and transferred to Geographical Information System environment in Data BaseFormat to produce sample location map before using ArcGIS software in spatial analyst tool on the interpolation method using Kriging method. The Step toward reclassification is found below.

Step 1 Click the Spatial Analyst dropdown arrow and click Reclassify.

Step 2 Click the Input raster dropdown arrow and click the raster with the values you want to change.

Step 3 Click the Reclass field dropdown arrow and click the field you want to use.

Step 4 Click the New values you want to change and type a new value.

Raster reclassification tools to reclassify the Aquifer protective capacity and estimate the land area cover base Aquifer potential Zone.

Aquifer Protective Capacity

The Aquifer protective capacity map provides visual information for more vulnerable zones which helps to protect groundwater resources and is also employed to evaluate the potential for water quality improvement. The aquifer protective capacity rating was derived from the measured longitudinal conductance (S) using the protective capacity rating as shown in Table 3 (Kumar et al., 2016), where S is the sum of all the n-1 layer thickness/resistivity ratios that overlap a semi-infinite resistivity substratum n, such that $S = h1/\rho1 + h2/\rho2 + h3/\rho3 + ... + hn\text{-}1/\rho n\text{-}1$ (mho), where h1, h2, etc. are the depths and ρ1, ρ2, etc. the resistivities, of successive layers. A knowledge of h_i/ρ_i for the ith layer when it is sandwiched between two layers of much higher resistivity is of importance in resolving the problem of equivalence (Henriet 1976; Obiora et al., 2015). Protective capacity rating is used to predict how safe a layer is as to if it can allow containments or collapses of the layer.

Table 1: Rating of the protective capacity of aquifers (Henriet 1976)

Longitudinal conductance (mho)	**Aquifer Protective capacity rating**
>10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak

RESULTS AND DISCUSSION

RESULTS

This chapter discusses the results and interpretation of the results. The Following result for the Study area such as the Resistivity, the thickness of the bed, depth, longitudinal conductance, and protectivity capacity area found below.

Table 2: Simulated result of resistivity data from the study area.

VES No	LAYERS	APPARENT RESISTIVITY(Ωm)	THICKNESS h (m)	DEPTH d (m)	RMS ERROR (%)	CURVE TYPE	LITHOLOGY	LONGITUDE (E)	LATITUDE (N)	LONGITUDINAL CONDUCTANCE (mΩ) $(\frac{h}{\rho})$	LONGITUDINAL CONDUCTANCE (mΩ) $\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	PROTECTIVE CAPACITY RATING
	1	28.99	1.53	1.53	0.17		Top Soil			0.05277682	1.158316086	Good
VES 1	2	5.19	2.19	3.72		HA	Clay			0.421965318		
	3	33.87	1.19	4.91			Silty Sand			0.035134337		
	4	113.8	5.94	10.86			Fine-Medium Sand			0.052196837		
	5	34.6	20.63	31.49			Silty Sand			0.596242775		
	6	2202					Fine-Medium Sand	6.346999	4.939944			
VES 2	1	38	0.6	0.6	0.28	HK	Top Soil			0.015789474	0.769622811	Good
	2	9.92	0.79	1.39			Silty sand			0.079637097		
	3	5.38	1.83	3.22			Clay			0.340148699		
	4	118.5	4.24	7.46			Fine-Medium Sand			0.035780591		
	5	32.89	9.81	17.27			Silty Sand			0.29826695		
	6	0.08					Clay	6.348019	4.939871			
VES 3	1	31.18	1.19	1.19	0.31	HA	Top Soil			0.038165491	0.612001537	Moderate
	2	12.28	1.61	2.7			Clay			0.131107492		
	3	34.06	12.53	15.33			Silty Sand			0.367880211		
	4	214.3	16.04	31.36			Fine-Medium Sand			0.074848343		
	5	2.02					Clay	6.349250	4.939965			
VES 4	1	29.81	1.31	1.31	0.14	HA	Top Soil			0.043944985	0.945838177	Good
	2	8.01	1.56	2.87			Clay			0.194756554		
	3	9.79	3.41	6.28			Silty Sand			0.348314607		
	4	315.7	7.44	13.72			Fine-Medium Sand			0.023566677		
	5	48.56	16.28	30			Silty Sand			0.335255354		
	6	6.12					Clay	6.346454	4.939524			
VES 5	1	48.88	0.6	0.6	0.10	HA	Top Soil			0.012274959	1.477957154	Good
	2	25.12	0.79	1.39			Silty sand			0.031449045		
	3	4.09	1.83	1.22			Clay			0.447432763		
	4	121.4	4.24	7.46			Fine -Medium Sand			0.034925865		
	5	274.7	9.81	17.27			Fine- Medium Sand			0.035711685		
	6	24.81	22.73	40			Silty Sand			0.916162838		
	7	47.96					Silty Sand	6.348536	4.938645			
VES 6	1	43.24	1.01	1.01	0.9	HA	Top Soil			0.023358002	0.782047452	Good
	2	28.28	0.09	1.11			Silty Sand			0.003182461		
	3	3.77	1.81	2.92			Clay			0.480106101		
	4	684.2	3.17	6.089			Fine- Medium Sand			0.004633148		
	5	41.29	11.18	17.27			Silty Sand			0.27076774		
	6	55.03					Silty Sand	6.349328	4.938575			
VES 7	1	41.33	0.6	0.6	0.03	HA	Top Soil			0.0145173	0.835294209	
	2	24.22	0.79	1.39			Silty Sand			0.032617671		
	3	9.79	6.07	7.46			Clay			0.620020429		
	4	62.71	9.81	17.27			Silty Sand			0.15643438		Good
	5	1942	22.73	40			Fine- Medium Sand			0.011704428		
	6	178.2					Fine-Medium Sand	6.347128	4.938711			
VES 8	1	494.8	0.24	0.24	0.27	HA	Top Soil			0.000485044	2.989623017	
	2	1.1	0.54	0.78			Clay			0.490909091		Good
	3	466.8	1.047	1.83			Fine- Medium Sand			0.002242931		
	4	62.56	3.03	4.85			Silty Sand			0.048433504		
	5	2.86	7	11.86			Clay			2.447552448		
	6	0.63					Clay	6.348096	4.939371			
VES 9	1	52.36	0.45	0.45	0.27	HA	Top Soil			0.008594347	1.794491689	Good
	2	6.91	1.39	1.84			Silty Sand			0.201157742		
	3	1.07	0.14	1.98			Clay			0.130841121		
	4	2.05	2.94	4.92			Clay			1.434146341		
	5	351	6.933	11.86			Fine-Medium Sand			0.019752137		
	6	1353					Fine-Medium Sand	6.348002	4.937945			

Table 3: Summary of result for Aquifer depth, thickness, Aquifer apparent resistivity, and aquifer protectivity capacity from the study area.

S/N	Long	lat	Aquifer Depth(m)	Aquifer App. Resistivity (mΩ)	Aquifer Thickness	LC	APC
VES1	6.346999	4.939944	10.86	113.8	5.94	1.16	Good
VES2	6.348019	4.939871	7.46	118.5	4.24	0.77	Good
VES3	6.349250	4.939965	31.36	214.3	16.04	0.61	Moderate
VES4	6.346454	4.939524	13.72	315.7	7.44	0.95	Good
VES5	6.348536	4.938645	17.27	274.7	9.81	1.48	Good
VES6	6.349328	4.938575	6.089	684.2	3.17	0.78	Good
VES7	6.347128	4.938711	40	1942	22.73	0.83	Good
VES8	6.348096	4.939371	1.83	466.8	1.047	2.99	Good
VES9	6.348002	4.937945	11.86	351	6.933	1.79	Good

Longitudinal conductance (LC), * Aquifer protectivity capacity

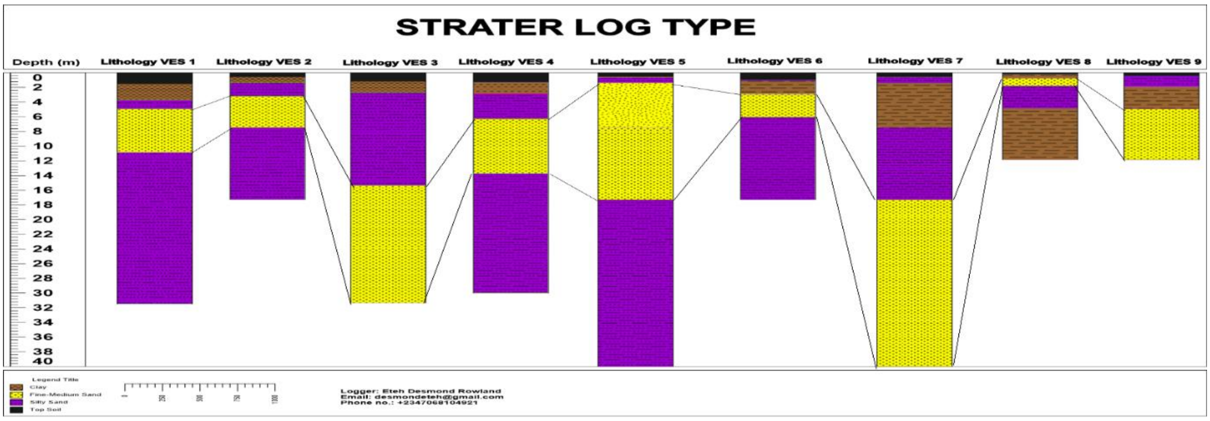


Figure 4a: Borehole Resisivity Strater log of the study area

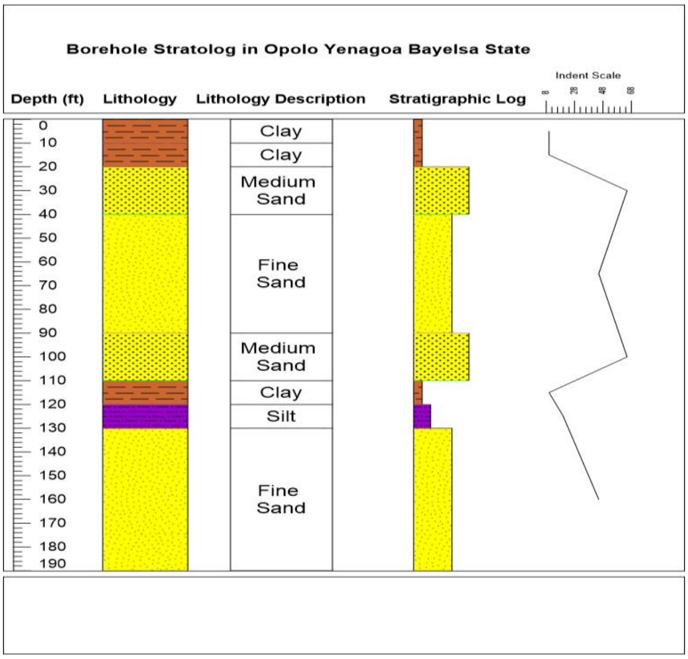


Figure 4b Lithological profile of a borehole from Opolo Community

From Figure 4b the Strata log of a 63.3m borehole was drilled in Opolo Community which shows that the aquifer is mainly sand. From the surface to a depth of 6.66m is clay, we have medium grain sand occurring from 6.66m to 13.3m. From 13.33m to 30m depth is sand, and from 30m to 36.66m depth we have medium grained sand. We have clay between 36.66m to 40m depth and silt occurring from 40m to 43.33m depth. Fine grained sand occurring from 45m to 63.33m

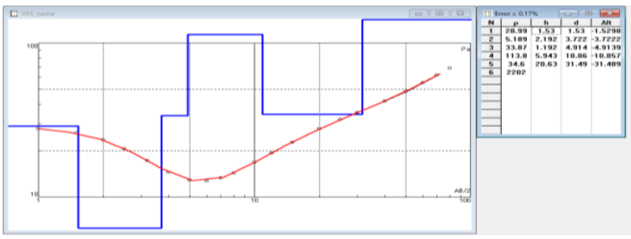


Figure 5: VES 1 quantitative interpretation from IPI2win

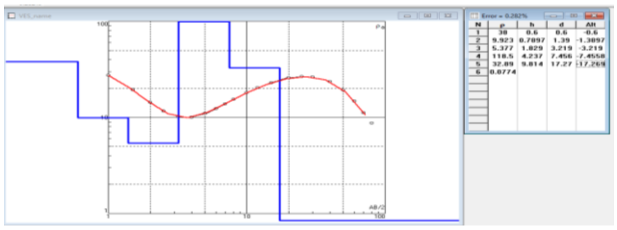


Figure 6: VES 2 quantitative interpretation from IPI2win

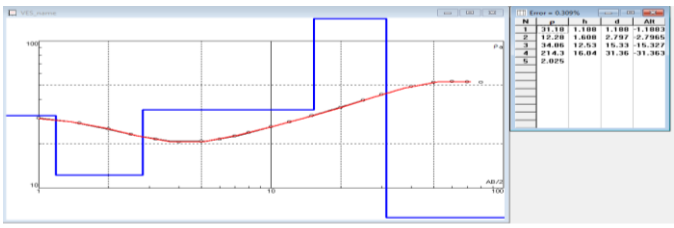


Figure 7: VES 3 quantitative interpretation from IPI2win

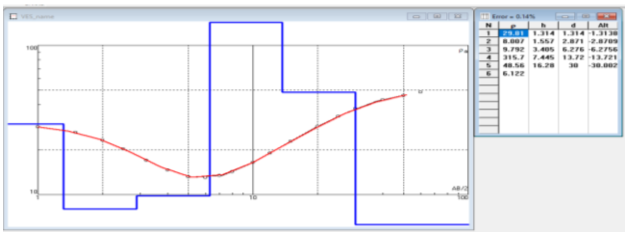


Figure 8: VES 4 quantitative interpretation from IPI2win

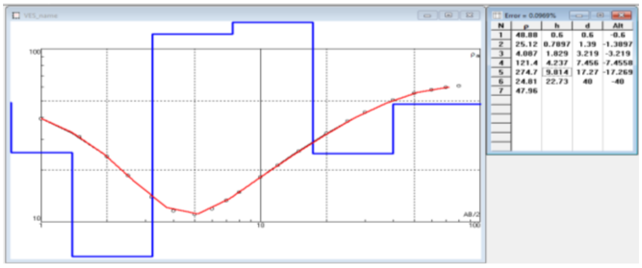


Figure 9: VES 5 quantitative interpretation from IPI2win

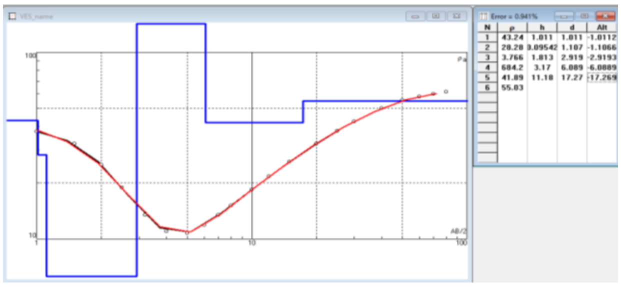


Figure 10: VES 6 quantitative interpretation from IPI2win

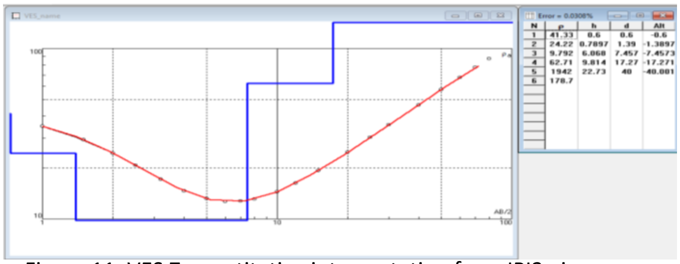


Figure 11: VES 7 quantitative interpretation from IPI2win

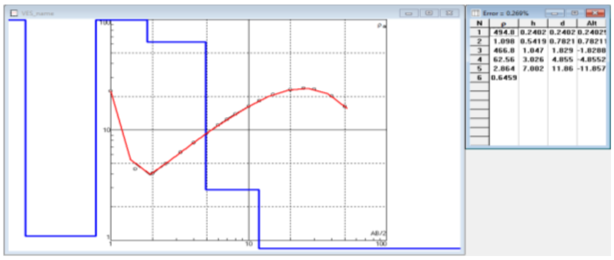


Figure 12: VES 8 quantitative interpretation from IPI2win

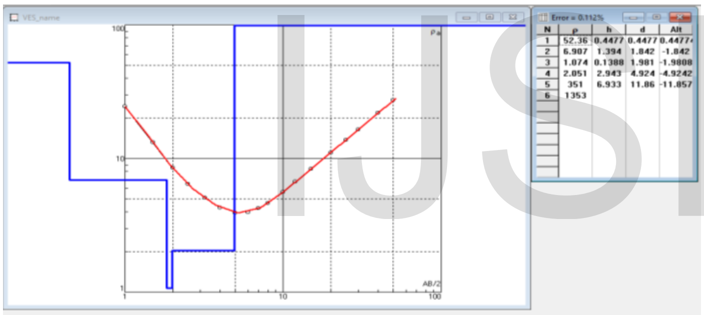


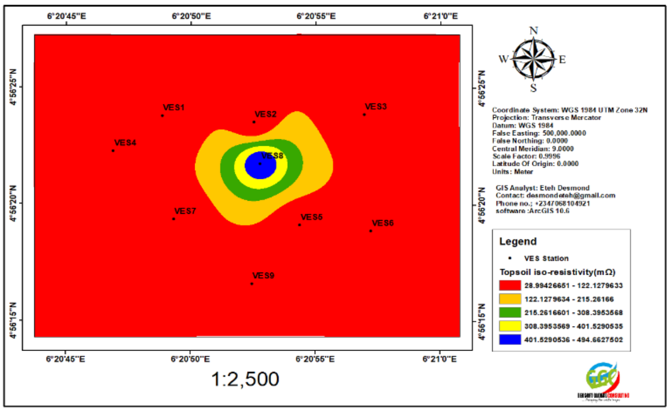
Figure 13: VES 9 quantitative interpretation from IPI2win

Geographical Information Systems Analysis using Kriging Method

The ordinary kriging method was used to analysis for Topsoil resistivity, Aquifer thickness, Aquifer depth, Aquifer resistivity, and Longitudinal conductance. Kriging assumes that the distance or direction between the sampling points reflects a spatial correlation that can be used to explain the variation of the ground surface. The kriging tool adapts a mathematical function to a specified number of points, and specified radius, to decide the output value for each location.

Iso-resistivity Map of the Topsoil, Thickness, Depth , Aquifer and 3D visualization

The iso-resistivity of the topsoil map (Figure 14) shows the apparent resistivity values ranging from 28.99 to 122.13 mΩ reflecting red,112.14 – 215.26 mΩ reflect orange colour,215.26-308.39 mΩ contain green, 308.40 -401.53 mΩ represent yellow and 401.54- 494.66 mΩ reflect blue while the most frequently occurring resistivity values are between 28.99 - 494.8 mΩ. This revealed the highly heterogeneous variation in the composition of the topsoil from clay, sandy clay, clayed sand, and silty sand. The middle parts of the area contain an apparent resistivity value greater than 401.53 Ωm, while the remaining parts have resistivity values less than 401.53 Ωm (Figure 14). The Iso-Resistivity Maps, Aquifer Thickness, and depth of the Study Area Were Generated Using ArcGIS Software with ordinary kriging Method from Tables 2 and 3. The thickness of the aquifer thickness ranges from 01.05 – 22.73 m in Figure 17 and the aquifer depth ranges from 6.09 to 40 m in Table 2, Figure 16, the aquifer resistivity map vary from 133.83 mΩ to 1941.94 mΩ in Figure 17. One major application of aquifer thickness map is where the ranking of geology is concerned because a good volume of water from a Vertical Electrical Station is dependent on the thickness of the aquifer (Alile et .al, 2008). The 3-D Visualization of Geoelectric well map in Figure 18 indicate the various well and there position on the earth surface , blue colour indicate the water table of the area of 0.6 m and the red colour reflect the highest aquifer depth and thickness among the wells which is VES 7 in Table 3. The thickness of the aquifer map is reliable for groundwater accumulation especially within the areas where the thickness is generally above meters 15 m in Figure 4a.



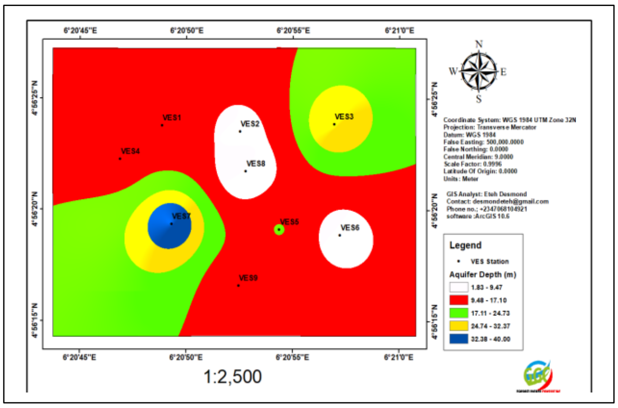
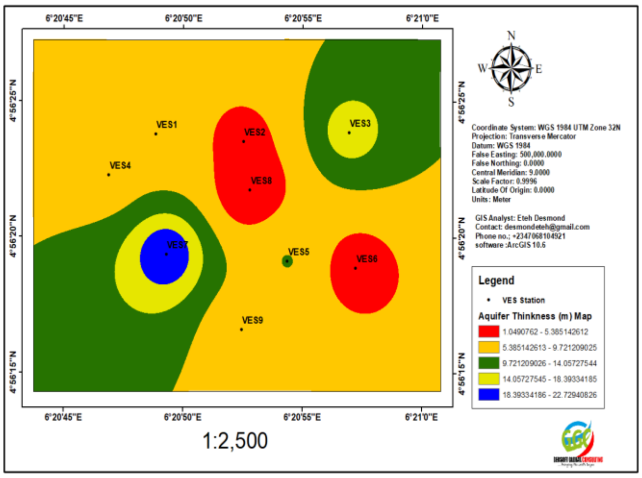


Figure 14:Topsoil iso-resistivity of the study area , Figure 15: Aquifer depth map of the Study area



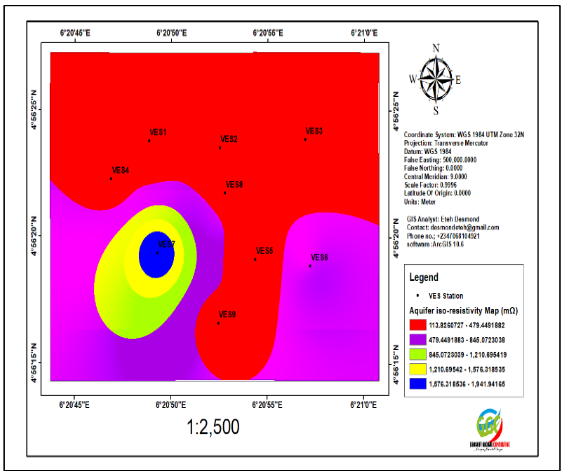


Figure 16: Aquifer thickness of study area , Figure 17: Iso-resistivity Map of Aquifer resistivity of Study area

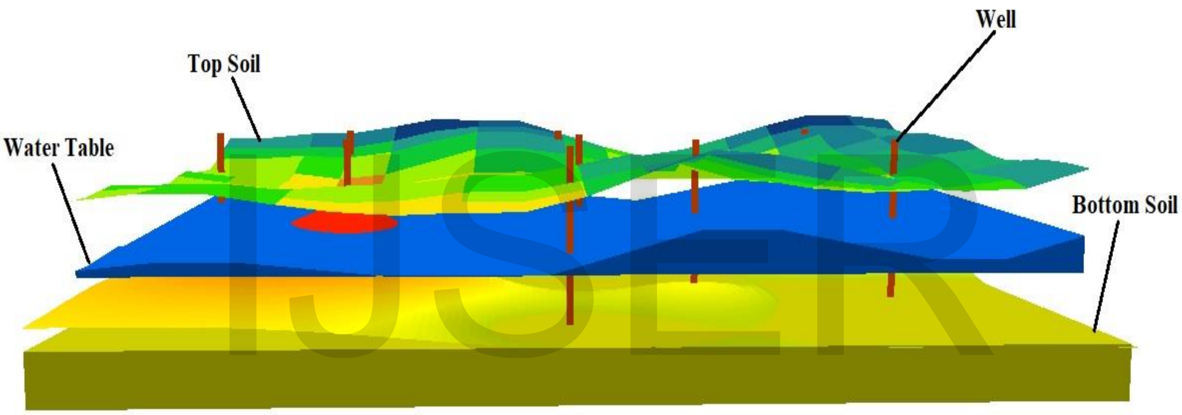


Figure 18: 3-D Visualization of Geoelectric Well in the Study area.

GIS Analysis using reclassification method

For the final prediction of the protective capacity aquifer map, the criteria under evaluation are required to be expanded. The GIS application using the Ordinary kriging method provided a set of map classes occurring on each input by using the reclassification tools to reclassify base on the rating of the protective capacity of aquifers (Henriet 1976) and result from the analysis. This method could help in tackle real-world problems using this technique.

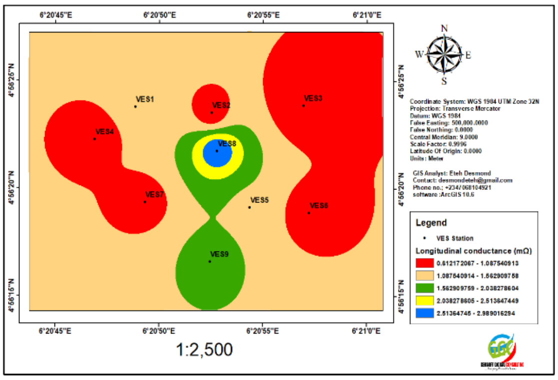


Figure 19: Longitudinal conductance variations over the study area

The Longitudinal conductance variations Map presented in Figure 19 with red colour having a range value 0.61 – 1.09 mΩ, 1.09 – 1.56 mΩ represent light brown, green colour contain a range of value of 1.56 – 2.04 mΩ, 2.04 – 2.51 mΩ reflect yellow and blue have range value of 2.52 mΩ. From the protective capacity rating variation map in Figure 20, almost all the study area shows Good when compared with Table 3, and represent by colour notation with estimate area of 20.94 km^2 in Table 4 and contain the following VES No. VES 1,2,4,5,6,7,8,9 and represent Blue expect VES 3 which is moderate when compared with Table 3 with an estimated area of 0.21 km^2 in Table 4.

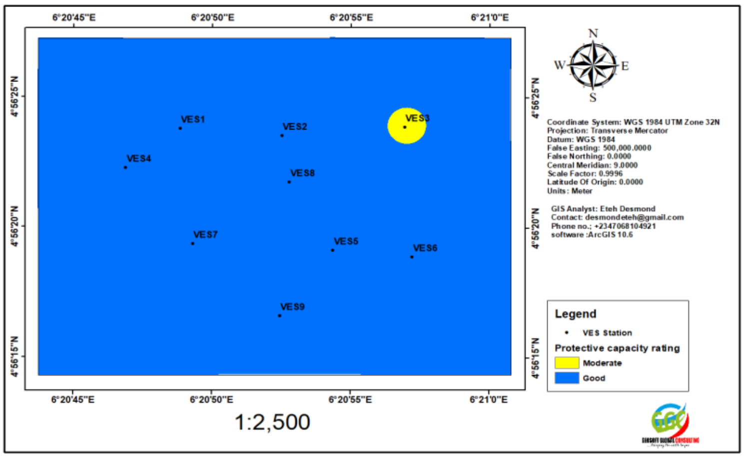


Figure 20: Aquifer Protective Capacity rating variations map over the study area

Table 4: Rating of the protective capacity of aquifers (Henriet 1976) and area estimation

Longitudinal conductance (mΩ)	**Aquifer Protective capacity rating**	**Area (km²)**	**Percentage (%)**
>10	Excellent	0.00	0
5 – 10	Very good	0.00	0
0.7 – 4.9	Good	0.20	94.24
0.2 – 0.69	Moderate	0.01	4.76
0.2 – 0.19	Weak	0.00	0
Total Area (km²)		21.17	

CONCLUSION

Vertical Electrical Sounding has helped to delineate the study area in Opolo Yenagoa Bayelsa State into two aquifer protective capacity potential zones using Geographical information Systems techniques for aquifer and apparent resistivity modelling. The importance of electrical resistivity survey in delineating different layers of subsurface layers ranging from the topsoil units, thickness, depth, and longitudinal conductance. Two distinct aquifer protective capacity potential zones were delineated, namely good (VES 1, 2, 4, 5, 6,7,8,9), with good prospects for groundwater development in the study area with an estimated land area of 0.20 km^2, the productive groundwater potential zones are identified in almost all the area which is about 94.24 % indicating blue notation in Figure 20 and Table 4 while moderate (VES 3) in Table 4 and Figure 20, estimated land area is 0.01 km^2 which represent 4.76 % of areas in the northeast part indicated low apparent resistivity and aquifer thickness values. It is worthy to note that despite the slight differences observed in the low potential zones (Moderate), groundwater can still be exploited within the zone, but the difference will be the thickness of the aquifers. The rating was based on longitudinal conductance values. Vertical electrical sounding stations, computed longitudinal conductance values, were obtained (Table 3). Good and moderate aquifer protective capacity zones are less vulnerable to contamination. Integrating all the geo-electric parameters determined, the best sites for sitting wells or boreholes are all the VES stations, except VES 8 due to VES stations have less aquifer thickness and is too close to the static water level in Figure 4a.

RECOMMENDATION

Estimation of main aquifer parameters using geoelectric measurements should be used to select the suitable wells.

REFERENCES

Abiola, O; Enikanselu, PA; Oladapo, MI (2009). Groundwater Potential and Aquifer Protective Capacity of Overburden Units in AdoEkiti, Southwestern Nigeria. Intl. J. of Physical Sci., 4(3): 120–132

Alile, M. O; Jegede, S. I; Ehigiator, O. M (2008). Underground water exploration using electrical resistivity method in Edo State, Nigeria. Asian Journal of Earth Sciences. 3(1):57-61.

Anomohanran O. (2015), Hydrogeophysical investigation of aquifer properties and lithological strata in Abraka, Nigeria, (Journal of African Earth Sciences102, pp. 247-253

Clarke, K. C., 1986. Advances in geographic information systems, computers, environment and urban systems, Vol. 10, pp. 175–184.

Etu–Efeotor, J. O. (1997). Fundamentals of petroleum geology. Paragraphic publications, Port Harcourt, Nigeria, Press page 135.

Henriet JP.(1976). Direct application of the Dar Zarrouk parameters in groundwater surveys; Geophys. Prospect. 24:344–353.

Keller, G. V., and Frischknecht, F. C., (1966) Electrical methods in geophysical prospecting: New York, Pergamon Press, 519 p.

Kumar, T.J.R., Balasubramanian, A., Kumar, R.S. et al (2016) Assessment of groundwater potential based on aquifer properties of hard rock terrain in the Chittar–Uppodai watershed, Tamil Nadu, India. Appl Water Sci. 6, 179–186. https://doi.org/10.1007/s13201-014-0216-4.

Obiora, D.N., Ajala, A.E. and Ibuot, J.C. (2015) Evaluation of aquifer protective capacity of overburden unit and soil corrosivity in Makurdi, Benue State, Nigeria, using electrical resistivity method. J Earth Syst Sci. 124, 125–135. https://doi.org/10.1007/s12040-014-0522-0.

Oki Austin Oyinkuro and Eteh Desmond Rowland (2018): Spatial Groundwater Quality Assessment by WQI and GIS in Ogbia LGA of Bayelsa State, Nigeria. Asian Journal of Physical and Chemical Sciences 4(4):1-12: DOI: 10.9734/AJOPACS/2017/39055

Oki, O. A, and Eteh D. R., (2019): Application of VES for aquifer Characterization in Ishiayi Community, Ahoada West Local Government Area of Rivers State, Southern Nigeria. American Journal of Engineering Research (AJER) Vol.-8 Issue-5, pp-115-120

Robinson Edwin S. and Cahit Coruh, (1988) Basic Exploration Geophysics,"Virginia Polymeric Institute and State University, pp 445-478.

Short, K.C; Stauble ,A.J (1967) Outline of the geology of the Niger Delta. Bull. AAPG. 51: 761- 779.