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GEOPHYSICAL ANALYSIS OF GROUNDWATER CAPACITY IN PARTS OF KHANA LGA, RIVERS STATE, NIGERIA, USING TPRF MODEL

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ABSTRACT

Geophysical analysis of groundwater capacity in parts of Khana Local Government Area, Rivers State, Nigeria was carried out using TPRT (an acronym for Thickness, Transmissivity, Porosity, Reflection coefficient, and Fracture contrast) model to identify productive aquifer zones for citing boreholes for community water supply. Electrical resistivity data acquired in twenty-one (21) locations using vertical electrical sounding method of Schlumberger configuration have been used to study the hydrogeological properties and groundwater storage potential of bedrock aquifers in the study area.. The data acquired were processed and interpreted using auxiliary curve matching and computer automation method to delineate the different geo-electric layers, their resistivities, thicknesses, and depths. The hydraulic conductivity, transmissivity, fracture contrast, reflection coefficient were estimated and plotted in the form of 2D maps to describe the spatial variations of these parameters in the area. The results of the study revealed the presence of three to five geo-electric layers. The geo-electric layers from top to the bottom, corresponds to the topsoil layer, lateritic layer, weathered rock layer, fractured rock layer, and the fresh basement rock. Lateritic and/or fractured rock layers were not delineated in some places. The weathered and fractured rock layers correspond to the aquifer units. The thickness of the weathered aquifer ranges from 7.4 to 59.1 m while the resistivity ranges from 8.1 to 2204.0 Ωm. The transmissivity, T_r, and hydraulic conductivity, K, range from 8.8 to 812.5 m^2/day and 0.4 to 54.9 m/day, respectively. The reflection coefficient and fracture contrast map showed the presence of water-bearing fractures and shared some similarities with transmissivty and hydraulic conductivity maps. The consistencies between the overall groundwater potential map and aquifers parameters distributions maps suggest the appropriateness of the model for predicting groundwater potential of weathered rock in a basement complex area. The northern, and southern parts of the study area, having GW_P greater than 0.5 (50%), were recommended for groundwater development through boreholes drilled to a depth ranging from 50 m and above.

Key Words: Geophysical, Groundwater, Khana, Potential, Reflection coefficient, Fracture contrast.

INTRODUCTION

The study area Khana is a Local Government Area in Rivers State, Southern Nigeria within the Tropical Rainforest zone. It is located between latitude 4.67172N and longitude 7.34398E (Figure 1) (Peter and Umweni, 2020). The study location covers 49,631.54 ha of land with a rainfall pattern that is in a bimodal form that usually start effectively from late February to

October with a period of low precipitation in August commonly called August break (Peter and Ayolagha, 2012).
Geophysical investigations of the subsurface to delineate groundwater resource have increased over the years as a result of technological advancement, which have improved the interpretation and modeling of the parameters. The lithoand textural characteristics, pore-water conductivity and fluid saturation of hydrogeological unit affect electrical conductivity of the subsurface geo-materials (Ibanga and George 2016). Groundwater is important in all aspect of life. It is the major source of drinking water and is useful in the agricultural and industrial sectors, and a good knowledge of the aquifer repositories is a concern for its sustainable and effective use (Edet and Worden 2009; Evans et al. 2010; George et al. 2017a; Obiora et al. 2015).

Climate change is anticipated to affect groundwater availability throughout Africa and Nigeria in particular than it was previously forecast. In addition, shortage in rainfall and excessive loss in surface water due to temperature rise and prolonged evaporation, surface and rain water are severely polluted and unfit for human consumption without prior treatment. Currently, there is heavy dependence on groundwater to meet daily global demand for fresh water. Groundwater accounts for more than 95% of worldwide storage for fresh water (Healy *et al.,* 2007). However, groundwater is not evenly distributed in the subsurface. Groundwater distribution is affected by a number of factors including porosity and permeability of the subsurface rocks, amount of rainfall and surface water available for recharge, topography, size of the aquifer, natures of the overburden material among others (Olayinka, 2006).

Groundwater development requires carefully designed pre-drill geophysical survey targeted at determining the hydro-geophysical properties and the approximate thicknesses and depths of the weathered and fractured rock layers in the subsurface. Weathered and fractured rocks are not evenly distributed in the subsurface. Therefore, the knowledge of the spatial distribution of hydraulic properties of rocks is essential for the prediction of groundwater availability, recharge, and yield in bedrock aquifers (Ibim and Obulor, 2022; Ezeh, 2011; Raji, 2014).

Hydraulic properties like yield, recharge, and specific capacity cannot be directly measured through any geophysical method, but can be indirectly inverted from the estimates of closely related parameters such as transmissivity, hydraulic conductivity, fracture coefficient, and fracture contrast (MacDonald et al. 2012; Raji and Abdulkadir 2020). Also, direct measurements of groundwater volume in bedrock aquifer is a difficult endeavour but, quantitative estimates of aquifer thickness, porosity, storativity, fracture contrast, and fracture coefficient, among others, may be used to predict the volume of groundwater storable in an aquifer. Therefore, the evaluation of groundwater potentials and availability in aquifers should be based on sub-regional evaluation of aquifer properties rather than the local, on the spot, assessment as commonly done for borehole survey.

Electrical resistivity survey (ERS) is the most commonly use geophysical method for groundwater study in different geological terrains. ERS is a non-invasive depth probing techniques that is most suited for shallow subsurface study in built-up and undeveloped environments. ERS is environmentally friendly, operationally simple, cost effective, time inexpensive, and easy to deploy regardless of the geological terrain. 2D/3D electrical resistivity survey has evolved with technology, and is currently being used for groundwater survey in geologically complex areas. The VES method using Schlumberger electrodes array will be applied to interrogate subsurface geology for groundwater potential in this study. Data acquired for the study and the results obtained from the study, when published, will improve experts' understanding of the hydrogeology of the hard rock terrain. The study is therefore aimed at interrogating the subsurface geology for groundwater availability and to identify the productive aquifer zones for groundwater development in the study area.

Geology and Geomorphology of the Study Area

The study area is in the Niger Delta basin. The geology and geomorphology of the Niger Delta have been described in details by various authors (Short and Stauble 1967; Etu-Efeotor and Akpokoje, 1990). The formation of the present day Niger Delta started during Early Paleocene and it resulted mainly from the build-up of fine grained sediments eroded and transported by the River Niger and its tributaries.

Stratigraphically, three formations are locally designated in the Niger Delta Basin (from the bottom) as Akata Formation, Agbada Formation and Benin Formation respectively which are in turn overlain by quaternary sediments (Fatoke, 2010; Short and Stauble, 1967)

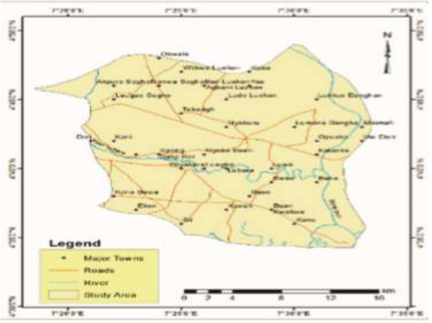

Figure 1: Map of Khana Local Government Area.
Sources: Government of Rivers State, Office of Surveyor General (2014)

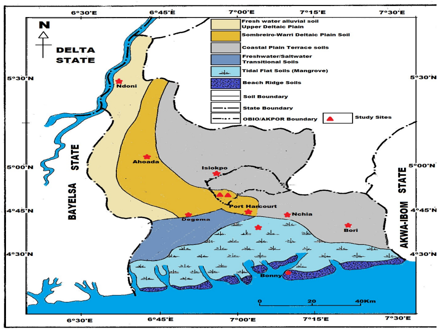

Figure 2: Geologic Map of the Study Area
(Adapted from Ehirim and Nwankwo, 2010)

The topmost unit is the Benin formation; it is comprised of over 90% sandstone with shale intercalations. It is coarse grained, gravely, locally fine grained, poorly sorted, sub angular to well-rounded and bears lignite streaks and wood fragments. The thickness of the Formation ranged from 0 to 2,100 m (Tuttle *et al.*, 2015). The unit is thickest in the central area of the Delta. The contact with the underlying Agbada formation is defined by the base of sandstones which also corresponds to the base of the fresh water bearing strata. The Benin Formation has been described as "Coastal Plain Sands" which outcrop in Benin, Onitsha and Owerri provinces and elsewhere in the delta area. The sediments present upper deltaic deposits. The sand may represent braided stream point bars and channel fills and or crevasse splay deposits. The shales are few and thin and they may represent back swamp deposits.

Among the minor components, limonite coating, lignite streaks, hemalite and feldspar are common. However, the formation lacks faunal content and this makes it uneasy to date although an Oligocene Recent age is generally accepted. The Niger Delta Petroleum System as it is obtained in Tuttle *et al*. (2015) has it that up till now, very little oil has been found in the Benin Formation (mainly minor oil shows), and, the formation is generally water bearing. This formation is the most prolific aquifer in the region. It is the main source of potable groundwater in the Niger Delta area.

The Agbada Formation underlies the Benin Formation and forms the second of the three strongly diachronous Niger Delta complex formations. Agbada Formation consists mainly of sands, sandstones and siltstones. It is the overlying paralic sequence which consists of interbedded sands and shale with a thickness of 300 m to about 4,500 m, thinning both seawards and towards the Delta margin. It consists of numerous off lap rhythms, the sandy parts of which constitute the main hydrocarbon reservoirs in Delta oil-fields. The shales constitute seals to reservoirs and as such are so very important. In the Agbada Formation, the sequence is divided into:

- an upper unit consisting of sandstone-shale alternations with the former predominating over the later, and
- a lower unit in which the shales predominate and are thicker than the intercalated sandstones or sands.

The sandstones percentage ranges from 75% near the upper limit of the formation to 50% and below in the lower part of the unit. The thickest known section of the Agbada is around 10,000 ft to 15,000 ft (3,000m to 4,500m) (Tuttle *et al*., 2015).

This is the basal major time transgressive lithologic unit in the Niger Delta complex. This is a marine pro-delta megafacies, comprising mainly of shales with occasional turbidite sandstones and siltstones. The approximate range of thickness is from 550-6000 m and the formation crops out subsea in the outer delta area but is not seen on shore (Tuttle *et al.,* 2015). Very little hydrocarbon has been associated with the formation. The formation consists mainly of dark grey uniform marine shales. In some areas, it is sandy and silty in the upper part of the formation where it grades into the Agbada Formation. The quaternary deposits is about 40 – 150 m thick and generally consist of rapidly alternating sequences of sand and silt/clay with the latter becoming increasingly more prominent seawards.

The Akata Formation is the basal major time transgressive lithologic unit in the Niger Delta Complex. This is a marine pro-delta megafacies, comprising mainly of shales with occasional turbidite sand stones and siltstone. The approximate range of thickness is from 0 – 6000 m and the formation crops out subsea in the outer delta area but is not seen on shore. The formation consists of dark grey uniform shales, especially in the upper part. In some areas, it is sandy or silty in the upper part of the formation where it grades into the Agbada Formation. As defined by paleontological evidence mainly planktonic formation, the marine shales of the Akata Formation range from Paleocene to Holocene in age and are over pressured.

The surface distribution of the various geomorphic units is shown in Table 1.

Table 1: Stratigraphic Column of the Niger Delta (after Allen, 1965)

Geologic Unit	Lithology	Age
Alluvium (general)	Gravel, sand, clay, silt	
Freshwater Blackswamp, Meander Belt	Sand, clay, some silt, gravel	
Mangrove, Saltwater/ Blackswamps	Medium-fine sand, clay and some silt	Quaternary
Active /Abandoned Beach Ridges	Sand, clay and some silt	
Sombreiro- Warri Deltaic Plain	Sand, clay and some silt	
Benin Formation (Coastal Plain Sand)	Coarse to medium sand with sourdinate silt and clay lenses	Miocene
Agbada Formation	Mixture of sand, clay and silt	Eocene
Akata Formation	Clay	Paleocene

MATERIALS AND METHODS

Different physical parameters are distributed in the earth subsurface and the use of non-destructive and non-invasive geophysical methods can help provide information about these parameters. It is an indirect method that predicts a model of the subsurface as a result of interpreting the physical parameters. The electrical resistivity method though may be plagued with ambiguities and uncertainties in interpretation, provides an economical and reliable means to identify and delineate the subsurface characteristics/properties through the measurement of apparent resistivity (Batayneh 2009; Ibim and Womuru, 2018; Ebong *et al.,* 2014; Okiongbo and Mebine, 2015). flow and recharge of the aquifer repositories unit is affected by the aquifer characteristics and the knowledge of these parameters such as hydraulic conductivity, transmissivity, porosity, formation factor and tortuosity is necessary to describe the hydrogeological units quantitatively. There is need for adequate information about the pore properties and the interrelationship with other aquifer parameters (George *et al*., 2015). Electrical and hydraulic conductivity are functions of the pore size and have different sensitivity to the characteristic pore size (George *et al.,* 2014). The subsurface is characterized by pores linking the formation particles and a good understanding of the pore properties gives idea about fluid movement in the subsurface (George *et al.,* 2015). Porosity which measures the amount of pores in a formation is given by the relation:

$$Porosity\ (\emptyset) = \frac{Volume\ of\ Pores}{Total\ Rock\ Volume} \qquad (1)$$

Porosity is a formation property whose spatial variability depends on several factors like density, clay contents, tortuosity, hydraulic conductivity (Jackson *et al.,* 2018). Induration or lithification of sedimentary formation leads to significant deviations in pore geometry system (George *et al.,* 2016a). Archie's law summarized the occurrence of groundwater in rocks and soil, and gave the relationship between porosity, bulk resistivity and water resistivity in Eq. 2;

$$\rho = \alpha \rho_w \emptyset^{-m} \qquad (2)$$

where ρ is the bulk resistivity, ρ_w is water resistivity, a and m are the pore geometric factor and cementation factor, respectively (Keller and Frischnecht 2006). Cementation factor is fixed but varies with formation lithostratigraphy, permeability dependent factors and geologic age of geomaterials (Archie 1942) according to different tabulated values. The maximum amount of information about pore structure is embedded in transport processes. Aquifer hydraulic conductivity (K) is the ease with which water can move through an aquifer. It varies in a geological unit over relatively short distances, particularly in fractured rock aquifer. The K-values are important as they help in differentiation of aquifer bodies and their yield. According to Heigold et al. (2009), the values of K for a similar formation can be estimated using the relation below;

$$K = 386.40(R_{rw})^{-0.93283} \qquad (3)$$

where R_{rw} is the resistivity of the aquifer. Transmissivity (T_r) is the ability of the aquifer to transmit groundwater throughout its entire saturated thickness. It is a measure of the rate at which groundwater can flow through an aquifer section of unit width under a hydraulic gradient. Niwas and Singhal (1981) established an analytical relationship between transmissivity and transverse resistance, and also between transmissivity and longitudinal conductance. The discharge (Q) of fluid according to Darcy's law is given as:

$$Q = KIA \qquad (4)$$

But from Ohm's law:

$$J = \sigma E \qquad (5)$$

where σ is electrical conductivity, K is the hydraulic conductivity, A is cross sectional area perpendicular to the direction of flow, J is current density, E is electric field intensity, I is the hydraulic gradient. From equations 2 & 3, Niwas and Singhal (1981) obtained relationships given as:

$$T_r = K\sigma T = \frac{KS}{\sigma} = Kh \qquad (6)$$

where Tr is aquifer transmissivity, T is transverse resistance and S is longitudinal conductance. The longitudinal conductance and transverse resistance (S and T) referred to as Dar-Zarrouk parameters and are given as

$$S = \frac{h}{\rho} \qquad (7)$$

and

$$T = \rho h \qquad (8)$$

where h and ρ are the values of aquifer thickness and resistivity, respectively. The flow/percolation of fluid in subsurface may be influenced by these parameters which depends on the geometry, nature of grain size, non-uniformity of pore grain orientations and type of pore grains and pore channels and hydraulic pressure (*George et al.,* 2017).

The reflection coefficient and fracture contrast of the weathered aquifers were computed following equations 9 and 10, respectively.

$$R_C = \frac{\rho_n - \rho_{n-1}}{\rho_n - \rho_{n+1}} \tag{9}$$

$$F_C = \frac{\rho_n}{\rho_{n-1}} \tag{10}$$

where ρ_n is the apparent resistivity of a geo-electric layer and ρ_{n-1} is the apparent resistivity of the geo-electric layer overlying nth layer. Finally, the groundwater potential of the area was estimated using a combination of different aquifer parameters which include combined aquifer thickness, fracture density, hydraulic conductivity and transmissivity, porosity, and overburden thickness. An empirical equation linking the overall groundwater potential (GW_P) of the weathered rock aquifer to the different aquifer parameters is defined in equation 11.

$$GW_p = \frac{h_w T_r^{\theta}}{(R_C F_C^{-1})^{\theta}} \tag{11}$$

where h_w is the thickness of the weathered aquifer; T_r is transmissivity; θ is the porosity; R_c is the reflection coefficient; and F_c is the fracture contrast.

Twenty-one (21) points were surveyed in the different parts of the study area using Vertical Electrical Sounding Technique of Electrical Resistivity with Schlumberger electrodes array. The ABEM 3000 Earth Resistivity Meter (IGIS Resistivity meter), two current and two potential electrodes, four reels of electrical cables, hammers, measuring tapes, battery, and portable geographic positioning system, GPS were used for the acquisition of data. The spacing between one survey point and the other ranged between 100 and 350 m depending on the available space for spreading electrodes and cables for the survey. The obstruction caused by the presence of building, roads, and other engineering infrastructure prevented regular spacing of VES stations. Current electrode spacing, AB, ranges from 1 to 400 m. The GPS coordinates and elevation of every survey point were measured and recorded against the survey number for ease of geo-referencing.

Resistances measured and resistivities computed were recorded against the respective current and potential electrode separation, and resistivity curve were plotted on the field for quality assurance purposes. In situation where a curve exhibits anomaly peaks in difference to the previous stations, the experiment is repeated to clear any doubt and reduce uncertainties. VES data were subjected to manual and automated processing to invert different geo-electric parameters. The raw data were processed in advance, where necessary to remove spikes and instrumental errors (e.g., contribution from low voltage, poor electrode contact, etc.) using a curve smoothing algorithm (Raji and Adeoye 2017) and the pre-processed/raw data were re-plotted on double logarithm papers. The curves on double logarithm papers were transferred to tracing papers and carefully interpreted using auxillary curve matching techniques (Telford et al. 1990) to deduce the approximate number of layers, the resistivity, and thickness of each geo-electric layer.

The field data and the number of layers obtained from the manually interpretation were input to WinResist—a computer iterative curve-matching software for final interpretation. The number of geo-electric layers obtained from auxiliary curve matching is used as the starting model in WinResist, rather than guessing the starting model. For an example, if three geo-electric layers were obtained from the manual interpretation, a minimum of two and maximum of four geo-electric layers are set as the model in WinResist. After a pre-set number of iterations, the software matches the curve from field data to a computer defined curve and output the estimated number of layers, resistivities, thickness and depth of each geo-electric layers, and the inversion uncertainties (RMS error). Some results from the curve-matching procedure are shown in the appendix. The inversion error defines the misfit or mismatch between the field data curve and the computer defined curves. Where the misfit is higher than 10%, the preset values, for examples, the number of layers, or number of iterations is reset, and the interpretation process is repeated until the RMS error falls within a reasonable limit (less than 10%).

To describe the hydraulic properties of the aquifers and the groundwater potential of the area, some parameters including hydraulic conductivity, transmissivity, fracture coefficient, and the groundwater potential using equations 3, 6, 9, 10, and 11 were estimated at each of the 21 VES points.

An effective porosity of 7.5% was used for this study. The value was adopted from range of values of 1–10% available in the literature on series of local, national, and regional studies on different types of crystalline aquifers across Africa and other parts of the world (Petford 2003; Samaila and Singh 2010; MacDonald et al. 2012). The equation is applied at every VES survey point to compute the spatial distribution of groundwater potential for the study area. GW_P at every point was normalized to a scale of 0–1 by dividing the value estimated at each VES point by the maximum values in the survey area. Areas with values greater than 0.6, were considered to have high groundwater potential ($GW_P > 0.6$).

RESULTS AND DISCUSSION

Application of the aquifer thickness as well as resistivity values extracted from the sounding interpretation for the aquifer at the different locations has made it possible to estimate the aquifer parameters as shown in the table 2 below. The map of the aquifer thickness shown in figure 3 below, displays the distribution of variance in the thickness of aquifer within the study area. The fluid potential at any point in a porous material (aquifer) can simply be found from the product of hydraulic head and acceleration due to gravity. Since gravity is, for all practical purposes, almost constant near the Earth's surface. In this study, the groundwater potential was estimated using equation 11. Table 2 displays the results of the aquifer parameters from the measured resistivity and thickness of the aquifer layer.

Table 2: Results of Aquifer Parameters from measured Resistivity and Thickness of the Aquifer layers

VES Station	**Long. (°E)**	**Lat. (°N)**	ρ_a *(Ωm)*	h_a *(m)*	h_w *(m)*	*K* *(m/day)*	T_r *(m^2/day)*	R_C	F_C	GW_P
1	7.3336	4.5419	23.4	23.5	6.5	20.4	479.6	-0.1	1.2	0.0
2	7.3341	4.5421	31.6	27.7	6.6	15.4	427.1	0.2	0.5	11.1
3	7.3348	4.5416	407.8	47.9	10.4	1.4	68.0	0.4	0.5	14.5
4	7.3361	4.5435	377.8	17.4	7.9	1.5	26.6	0.2	0.6	10.7
5	7.3343	4.5426	107.3	56.3	4.4	4.9	277.5	2.8	6.3	7.1
6	7.3355	4.5418	219.0	37.0	8.8	2.5	93.8	0.1	0.8	14.2
7	7.3363	4.5438	1125.8	30.6	11.2	0.6	16.8	-0.6	5.2	0.0
8	7.3359	4.5433	190.1	40.9	12.5	2.9	118.3	1.7	5.0	19.4
9	7.3356	4.5441	8.1	14.8	1.1	54.9	812.5	0.1	0.6	2.2
10	7.3353	4.5436	64.7	42.5	12.6	7.9	335.9	-0.3	2.2	0.0
11	7.3217	4.5677	804.0	27.9	4.7	0.8	21.0	-2.5	0.4	0.0
12	7.3035	4.5566	1682.0	55.3	5.3	0.4	20.9	1.0	3.2	7.3
13	7.3331	4.5058	1006.0	33.7	18.8	0.6	20.6	1.2	0.2	20.5
14	7.3293	4.5858	2204.0	30.0	15.3	0.3	8.8	-3.6	0.4	0.0
15	7.3339	4.5420	31.6	25.6	6.6	15.4	394.8	0.1	0.7	12.0
16	7.3355	4.5426	392.5	32.6	9.2	1.5	47.9	0.3	0.5	12.8
17	7.3349	4.5422	163.2	46.7	6.6	3.3	155.7	-0.2	1.2	0.0
18	7.3361	4.5436	658.0	35.7	11.9	0.9	32.4	-0.7	5.2	0.0
19	7.3355	4.5439	83.0	40.9	14.2	6.3	256.2	-0.7	4.4	0.0
20	7.3126	4.5622	655.5	27.9	32.8	0.9	25.4	-5.5	0.4	0.0
21	7.3312	4.5958	1103.0	59.1	32.1	0.6	33.1	1.1	0.3	37.8

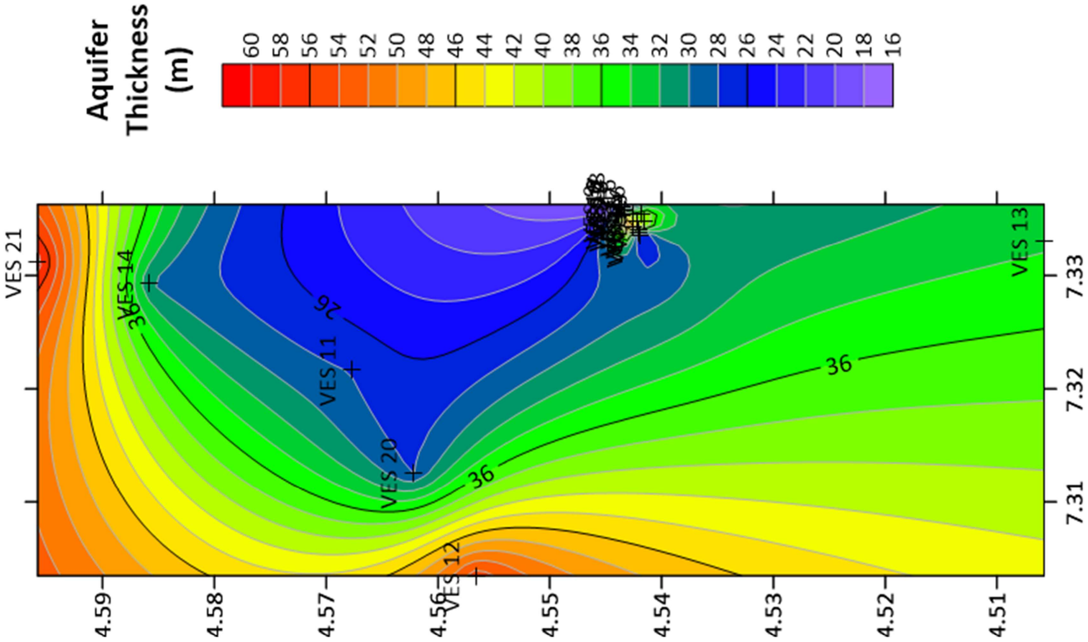

Figure 3 shows the thickness of the weathered aquifer. The thickness of weathered aquifer ranges from 7.4 to 59.1 m. The thickest weathered aquifer zones are located in the extreme northern part and western part of the study area around VES stations 3, 5, 8, 10, 12, 17, 19, 21; in the southern part around VES stations 6, 7, 13, 14, 16 and 18. Variation in the thickness of weathered zone suggests differences in the resistance of the rocks to weathering. The table 4.2 shows that the thickness of overburden layer h_w (unsaturated zone) in the study area ranges from 1.1 to 32.8 m. Overburden thickness is estimated as the sum of the thicknesses of the topsoil and the lateritic layer in the respective VES stations. The thicker the unsaturated zone, the greater is the capability to retain water from runoff during rainfall and transmit water to the aquifer zone. Areas having thick aquifer are potential places for groundwater storage.

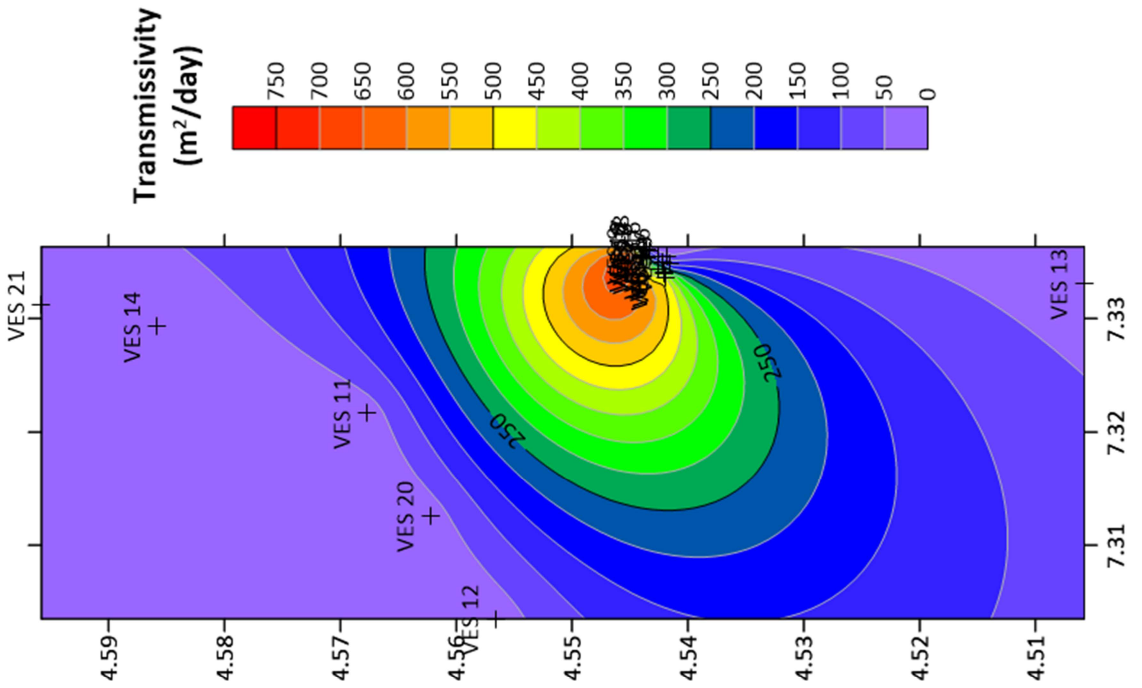

Figure 4: Spatial Distribution of the Transmissvity of the Aquifer in the Study Area.

The aquifer transmissivity (T_r) plot presented in Figure 4 shows that the estimated transmissivity ranges from 8.8 to 812.5 m^2 /day. Highest values were recorded in the eastern parts of the study area. Aquifer transmissivity is an indirect indicator of yield (MacDonald *et al.,* 2012), and it describes the lateral movement of groundwater in the aquifer. This is why some authors including Acheampong and Hess (1998) and Graham *et al.* (2009) have found borehole yields to be directly related to transmissivity. A joint evaluation of the two parameters (hydraulic conductivity and transmissivity) suggests that the aquifers in the eastern parts of the study area have the highest potentials for groundwater in terms of borehole yield and aquifer recharge potential

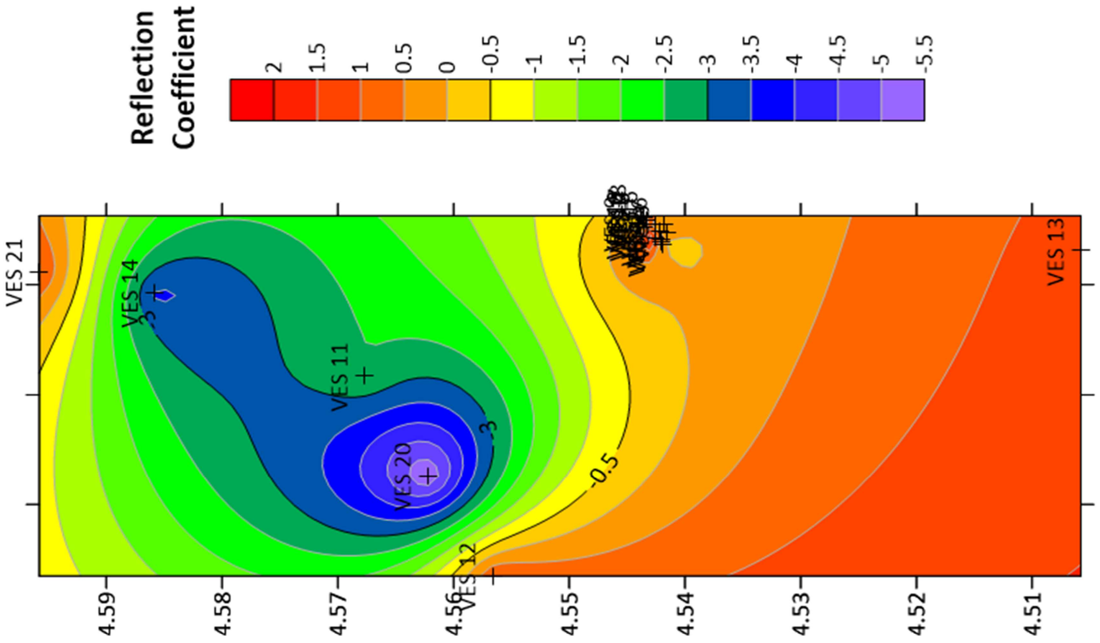

Figure 5: Reflection Coefficient Map of the Study Area.

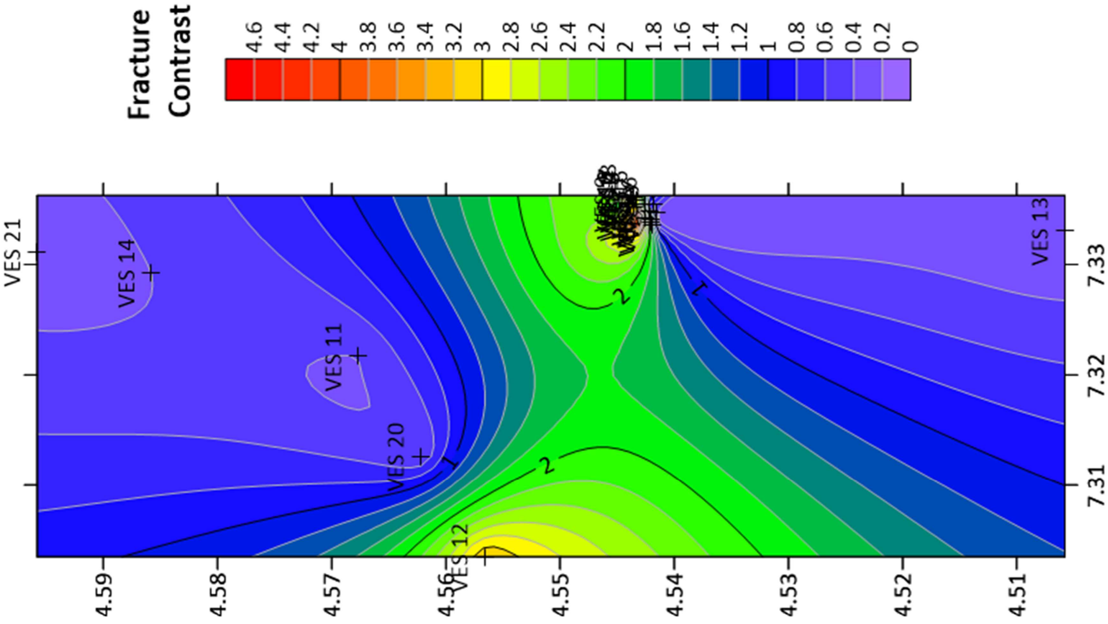

Figure 6: Fracture Contrast Map of the Study Area.

The values of the estimated hydraulic conductivity of the aquifers (K) in the area are generally moderate, ranging from 0.4 to 54.9 m/day with the highest values concentrated in the eastern parts of the study area. Hydraulic conductivity is an indicative parameter for aquifer recharge potential. It describes the vertical movement of water in the aquifer and can be used to express aquifers potential recharge where borehole pump data are unavailable (George *et al.,* 2015).

Refection coefficient (R_C) and fracture contrast (F_C) in weathered aquifers in contrast to fractured aquifers are plotted in Figures 5 and 6 respectively. Refection coefficient and fracture contrast are indicators of water-filled fractures (Olayinka *et al.,* 2000; Obiora *et al.,* 2016). Comparing the fractured layer (n) and the weathered layer (n−1), in this study, low values indicate low contrast between two aquifers, thereby suggesting good fractured network in the aquifers. Good fracture network implies high groundwater accumulation and fluid flow in the aquifers. As shown in Figures 5 and 6, R_C ranges from −0.7 to 2.8, while F_C ranges from 0.2 to 6.3. The low values of refection coefficient and fracture contrast are found in the northern parts of the study area. This suggests that the aquifers in the northern parts of the study area have higher density of water-filled fractures than the aquifer in the eastern parts

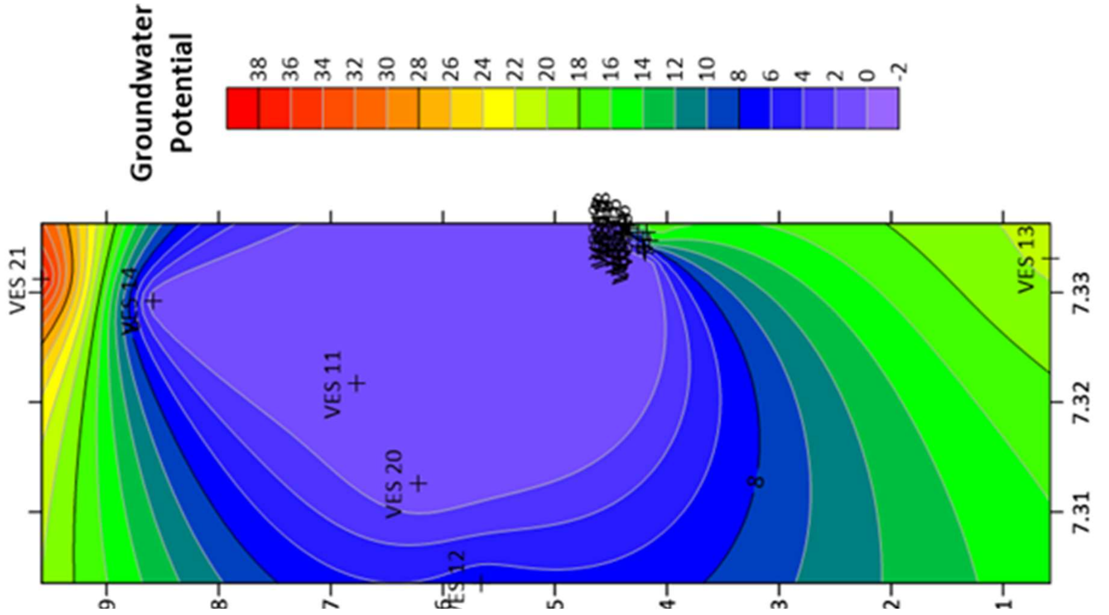

Figure 7: Indicative Groundwater Potential Map in the Study Area.

Finally, the joint parameters map here known as the indicative groundwater potential map is shown in Figure 7. The map is a model of the overall groundwater potential comprising the direct and indirect groundwater parameters (aquifer thickness, transmissivity, hydraulic conductivity, and fracture contrast, refection coefficient, and porosity) as defined in equation 11. The values of the indicative groundwater potential ranged from 0 to 38. The areas with groundwater potential of 0.5 (i.e., 50%) and above, on a scale of zero to one (0–1) are recommended for borehole drilling. Figure 7 also shows that the highest values of groundwater potential correspond to the extreme northern and southern parts of the study area. In consideration of the groundwater potential of aquifers in a hard rock terrain (basement rock terrain), the size of the weathered aquifer and the availability of water-bearing fractures might be the key indicators of high potential for groundwater. The larger the size of the aquifer adjudged from the thickness of the weather rock and the higher the fracture density, the higher the storage potential.

CONCLUSION

Groundwater aquifer parameters and hydraulic properties of rocks estimated from geo-resistivity data acquired in 21 VES stations in an area within geological sheet in Khana, Rivers State, Nigeria have been used to evaluate the groundwater potential of the bedrock aquifers in the area. Five geo-electric layers were delineated. The estimated thickness of the weathered aquifer ranges from 7.4 to 59.1 m while the resistivity ranges from 8.1 to 2204.0 Ωm. The estimated hydraulic conductivity, transmissivity, and fracture density maps revealed wide variation in aquifer properties across the study area. The highest values of groundwater potential correspond to the extreme northern and southern parts of the study area. The northern, southern and eastern parts of the study area were recommended for citing boreholes for community water supply. Although the groundwater potential model is subject to improvement for a more robust estimate, the consistencies between the overall groundwater potential map and the hydraulic properties of the aquifer confirmed the appropriateness of the model, developed in this study, for estimating groundwater potential of bedrock aquifers.

From this study, the distribution of these two parameters (Figures 5, and 6) are spatially consistent with the overall groundwater potential map (Figure 7). Therefore, it is reasonable to conclude that the extreme northern and the southern parts have the highest groundwater potential in the study area. It is recommended that boreholes should be drilled in these areas to depth ranging from 50 m and above.

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