Hydrogeophysical Evaluation of Parts of River Mamu Sub-Basin, Southeastern Nigeria

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Abstract*—Hydrogeophysical evaluation of parts of River Mamu Sub-Basin, Southeastern Nigeria was carried out using the Vertical Electrical Sounding technique (VES). Schlumberger array was used to acquire thirty (30) VES stations and were interpreted using software 1D-Interpex. The predominate VES curve types within the area are typically K-curves which is about 47%, whereas, the remaining 53% belongs to the other five curve types namely; KH, HK, H, Q, and KHK-curves. The calculated Da-Zarrouk parameters outcomes ranged from low to high within the study area: longitudinal conductance (0.0028-0.0571 mhom); transverse resistance (6630-10290 ohm-m^2); aquifer resistivity (455-4900 ohm-m), aquifer thickness (4.70-38.00 m); depth to the aquifer (33-172 m); conductivity (0.0002-0.0022 mho. Two aquifer parameters were computed within the area namely; hydraulic conductivity (6.137-0.792 m/day) and transmissivity (1.007-20.597 m^2/day). Two major aquifer systems were obtained specifically; a shallow aquifer belonging to Nanka Sands with depth (33-62m) and a far aquifer belonging to Ebenebe Sandstone with depth (69-172m). The groundwater flow paths within the study area trend predominantly in the NW-SE direction. The findings revealed that the study area possesses high groundwater potentials in some areas, hence, it is more economical to drill a borehole at the southwestern part of the study area than the southeastern part.

***Index Terms*—Schlumberger array, VES curve, aquifer parameters, aquifer system, Nanka Sands**

I. Introduction

Mamu is one of the major watersheds in southeastern Nigeria. Mamu River is evidently being fed by various major tributaries and reverets at various locations along its course. It maintains a progressively increasing volume of water and geometrically variable channel configuration from its headwaters around Ihite Amagu in Awgu Area of Enugu State to its terminus in River Niger [1]. The River more or less maintains the natural border between Anambra and Enugu States. The Mamu River Basin has been persistently erratic in evolutionary time-scale, varying in size and ecosystem structure, and has recently displayed a massive ecosystem change in a relatively short (three decade) period. The changes have been induced by natural factors coupled with human activities mainly associated with increasing population, economic growth and governance. However, despite the various services/function the Mamu River basin provides the basin and other ecosystems that benefits from it are experiencing threats that are negatively impacting on the socioeconomic development and the natural resource base.

In addition, the study area lies within latitudes 6⁰ 14¹ and 6⁰ 26¹N and longitudes 6⁰ 57¹30¹¹ and 7⁰ 19¹ E and it is situated within the lower Mamu River sub basin and comprises communities such as Amansea, Achalla, Ugbenu, Ugbene, Urum, Awba Ofemili, Isuanocha, Ebenebe (Fig. 1).

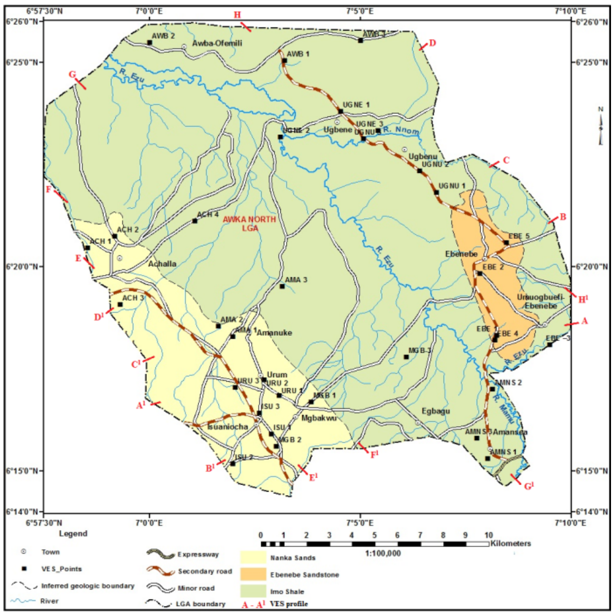

Figure 1. The location and geologic map of the study area showing sounding points.

The communities within the study area have peculiar water problems: They have surface water in excess and do not have the need for groundwater. Most of the communities depend exclusively on the major rivers and their tributaries as source of water supply for various socio-economic activities (including drinking) For example, people from Awba-Ofemili, Ugbene, Ugbenu and Achalla drink directly from the Mamu River with little or no concern about the water quality. The risk of

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water quality deterioration is expected to be high in these communities considering the heterogeneity of the benefiting population, the sporadic variation in pedology and rock types along the river course, the numerous tributaries and riverets that feed the Mamu River, and perhaps more importantly, non-existence of regulatory policies or guides among the users. Thus, the quality (pollution status) of this river is not fully known.

Furthermore, this area is underlain by various topographic and geological formations that have hydrogeological implications. The depths of aquifers in these geological formations vary widely. Despite the fact that Anambra State government has spent heavily in providing potable and sustainable water supply for her populace by drilling many water boreholes around the state, there are no functional boreholes within communities like Ugbene, Ugbenu and Awba-Ofemili.

As a result of the aforementioned, and especially the satisfaction of the demands of the growing population of the study area, the search for potable source of water (both quantity and quality) becomes apparent. Groundwater constitutes the only reliable water supply for drinking and irrigation purposes. It is exceptionally important as a source of relatively low-cost and high-quality municipal and domestic water supply in urban centers of the developing world [2], [3]. In this study therefore, a comprehensive hydrogeophysical investigation will be carried out within the study area using a vertical electrical sounding technique. The findings of the study will be beneficial to the immediate communities who depend on the waters for their livelihood, all stakeholders in the water sector and the government. The study will also provide accurate depths of water boreholes and become a pilot study for all water related projects within the lower Mamu River Sub Basin.

A. Geology of the Area

The study area is underlain by the Imo Formation (Palaeocene) and its sand member the Ebenebe Sandstone which is overlain by the Nanka Formation (Eocene) (Fig. 1). The Imo Formation is the basal unit of the Niger Delta Basin [4]. The formation is essentially a mudrock unit consisting of dark grey to bluish grey shale, with occasional admixtures of clay, ironstone, thin sandstone bands and limestone intercalations. The Ebenebe Sandstone is a sandstone member of the Imo Formation. As documented in [5], the Nanka Formation is a facies of Ameki Formation and it overlies the Imo Formation in the southwestern part of the study area.

II. Methodology

Thirty (30) Vertical Electrical Sounding (VES) were acquired from ten communities in the study area using Schlumberger electrode array with maximum electrode separation of 300m. Petro-zenith (PZ-03) resistivity meter was used for the data acquisition process. The acquired VES data which comprises apparent resistivity values and current electrode spacing were plotted on a bi-logarithmic graph and were interpreted both manually and by use of computer iteration process in order to determine the geoelectrical attributes such as apparent resistivity, thickness, and depth of various layers penetrated. This technique has been functional in groundwater exploration according to some previous studies as in [2], [6]-[17]. Eight different profiles namely; A-A^{l}, B-B^{l}, C-C^{l}, D-D^{l}, E-E^{l}, F-F^{l}, G-G^{l}, and H-h^{l} were taken in order to carry out VES correlation (Fig. 1). Also, available borehole log was correlated with VES to aid interpretation. The VES results formed the input data for estimating and modeling aquifer parameters. Various distribution maps of the aquifer attributes were generated in order to portray the groundwater potentials in the study area. Also, the watertable across the study area were deduced by subtracting the elevation values from their respective VES interpreted aquifer values in order to correct the VES results to mean sea level.

III. Results and Discussion

A. VES Curves

The VES curves generated from the thirty sounding points from the study area are K, KH, HK, H, Q, and KHK-curves (Fig. 2), which is characteristically of a sedimentary environment [2], [8], [17]. The predominant VES curve types within the area is typically K-curves which is about 47%, whereas, the remaining 53% belongs to other five curve types namely; KH, HK, H, Q, and KHK-curves within the study area (Fig. 2 and Table I).

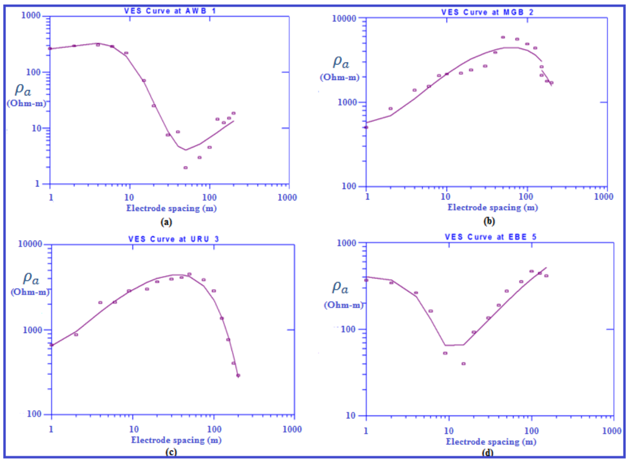


Figure 2. VES curves across the study area.

TABLE I. Curve Types within the Study Area

Curve type	Frequency	% of Frequency
K	14	47
KH	3	10
HK	6	20
H	2	7
Q	4	13
KHK	1	3
Total	30	100

B. VES Interpretation and Borehole Correlation

The outcomes of the VES analyses together with the core or borehole data in the study area (Fig. 3 and Fig. 4) depict that the study area is essentially of three (3) to five (5) geo-electric layers namely; top soil, silt/clayey-sand, sand, water saturated sand and shale (Fig. 3). Eight different profiles (namely; A-A^{I}, B-B^{I}, C-C^{I}, D-D^{I}, E-E^{I}, F-F^{I}, G-G^{I} and H-H^{I}) were taken along the study area in order to correlate the VES results and reveal different geo-electric layers at a glance. The first layer which is interpreted to be top soil across the study area possesses apparent resistivity values which range from 58.20-3600.00 Ohm-m. This was underlain by the second layer, which is interpreted to be silty-sand or clayey sand with apparent resistivity values that range from 29.60-5600.00 Ohm-m. Next is the third layer, interpreted to be sand or sandstone unit with apparent resistivity values in the range of 238.00-4134.00 Ohm-m. Underlying this layer is the fourth layer, which is interpreted to be water saturated sand or sandstone with apparent resistivity values which range from 450.00-2100.00 Ohm-m. Following this is the last layer (fifth layer), which is interpreted as shale unit with very low apparent resistivity values which range from 3.76-76.00 Ohm-m.

However, the correlation of borehole and VES sections from Achalla and Amansea parts of the study, reveal that the thickness of the top soil in the borehole section is 7.8m while in geo-electric section it is 4.6m in the Achalla area (Fig. 4). Also, in the Amansea area, the thickness of the top soil in the borehole section is 8.2m while in geo-electric section it is 4.9m (Fig. 4). In the underlying layers, the geo-electric units demonstrate amalgamation of some lithologic layers from the borehole. These occur due the fact that geo-electric units are not the same as borehole lithologic units.

Furthermore, at Achalla axis, the depth to water saturated sandstone varies such that the geo-electric unit has depth value of 42 meters while the borehole section has 44.2 meters (Fig. 4a). In Amansea area, the depth to water saturated sandstone varies such that the geo-electric unit has depth value of 172 meters while the borehole section has 176 meters (Fig. 4b).

From the geological map of the study area, the southwestern part comprising parts of Achalla, Amanuke, Urum, Isuanocha and Mgbakwu towns are underlain by Nanka Sand. The VES correlation along profile E-E^{I} indicates a good correlation of the aquiferous unit in ACH 1, ACH 3, ISU 1 and MGB 2 (Fig. 3). But EBE 3 and EBE 4 could not be correlated with MGB 3, URU 2 and URU 3 along profile A-A^{I} (Fig. 3) because Ebenebe areas are underlain by Imo Shale. This shows that the two aquifers are not the same. Stratigraphically, the shale unit that overlies the aquifer in EBE 4 is correlated with the shale units underlying the aquifers of MGB 3, URU 2 and URU 3.

In general, these delineated layers across the study area aligned with some characteristics of the three observed geologic formations in the area namely; Nanka Sands, Ebenebe Sandstone and Imo Shale. The VES results really depict different stratal units with distinct composition based on their resistivity attributes. In support of this [4], [18] and the outcome of the geologic mapping from the present study recognized that the study area is underlain by Imo Shale of Palaeocene age, followed by the Ebenebe Sandstone of Palaeocene age and overlain by the Nanka Formation of Eocene age. These formations fall within the Anambra Basin. They observed that Imo Shale consists of mudrock unit consisting of dark grey to bluish grey shale, with alternating sequences of clay, sandstone, limestone and ironstone intercalations.

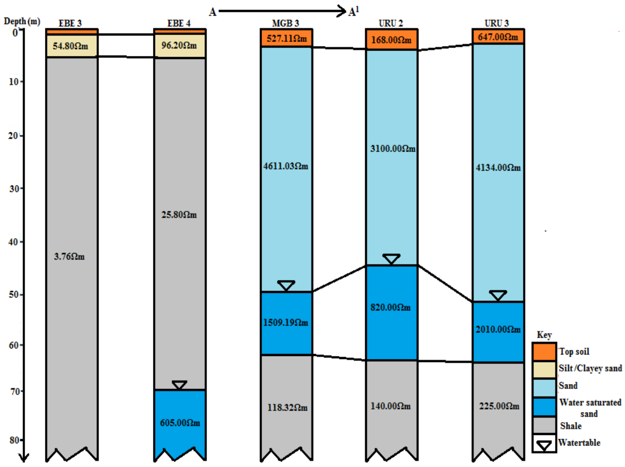


Figure 3a. VES cross-section and correlation along profile A-A^{I}.

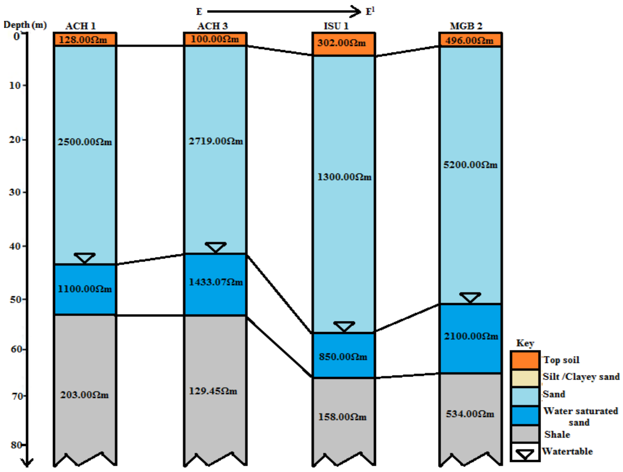
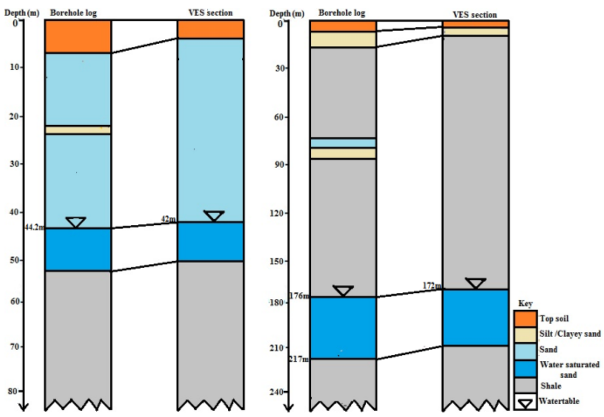


Figure 3b. VES cross-section and correlation along profile E-E^{I}.



(a) Achalla area (b) Amansea

Figure 4. VES cross-section and correlation.

TABLE IIA. CALCULATION OF DAR-ZARROCK AND AQUIFER PARAMETERS AT NANKA SANDS OF THE STUDY AREA

VES Name	VES Point	ρ_a (Ω-m)	b_a (m)	Z_a (m)	S (mhom)	TR (Ωm^2)	σ_a (mho)	K_a (m/day)	T_a (m^2/day)
ACH1	1	1100	9.4	44.0	0.0085	10340	0.0009	0.328	3.080
ACH2	2	1500	7.8	56.4	0.0052	11700	0.0006	0.240	1.874
ACH3	3	1433	11.0	42.0	0.0077	15764	0.0007	0.252	2.767
AMA1	5	1100	7.4	58.6	0.0067	8140	0.0009	0.328	2.425
AMA2	6	1830	10	33.0	0.0055	18300	0.0005	0.197	1.970
URU1	8	2100	11.1	49.3	0.0053	23310	0.0004	0.172	1.905
URU2	9	820	17.6	45.0	0.0215	14432	0.0012	0.440	7.736
URU3	10	2010	11.8	51.0	0.0059	23718	0.0005	0.179	2.116
MGB2	12	1708	12.7	51.3	0.0074	21691	0.0005	0.211	2.680
MGB3	13	2100	12.4	49.7	0.0059	26040	0.0004	0.172	2.128
ISU1	14	850	7.8	58.0	0.0092	6630	0.0011	0.424	3.308
ISU2	15	1682	4.7	62.3	0.0028	7905	0.0005	0.214	1.007
ISU3	16	1250	8.1	55.9	0.0065	10125	0.0008	0.288	2.336
Mean		1499	10.1	50.5	0.0075	15238	0.0007	0.265	2.719

Key: ρ_a = Aquifer resistivity; b_a= Aquifer thickness; Z_a= Depth to aquifer, **S**=Longitudinal conductance; **TR** = Transverse resistance; σ_a =Aquifer conductivity; K_a = Hydraulic conductivity of aquifer; T_a= Transmissivity of aquifer

TABLE IIB. CALCULATION OF DAR-ZARROCK AND AQUIFER PARAMETERS AT IMO SHALE AND EBENEBE SANDSTONE OF THE STUDY AREA

VES Name	VES Point	ρ_a (Ω-m)	b_a (m)	Z_a (m)	S (mhom)	TR (Ohm^2)	σ_a (mho)	K_a (m/day)	T_a (m^2/day)
EBE1	21	1200.0	23.7	82.3	0.0198	28440.0	0.00083	0.300	7.119
EBE2	22	4900.0	21.0	84.0	0.0043	102900.0	0.00020	0.074	1.545
EBE4	24	605.0	21.0	69.0	0.0347	12705.0	0.00165	0.596	12.511
EBE5	25	455.0	26.0	87.0	0.0571	11830.0	0.00220	0.792	20.597
AMNS1	26	589.3	15.0	112.0	0.0255	8839.5	0.00170	0.612	9.175
AMNS2	27	2400.0	35.0	108.0	0.0146	84000.0	0.00042	0.150	5.256
AMNS3	28	2630.0	38.0	172.0	0.0144	99940.0	0.00038	0.137	5.208
Mean		1825.6	25.7	102.0	0.0243	49807.8	0.00105	0.380	8.773

C. Computation of Aquifer Parameters

1) Da-Zarrouk parameters

The calculated Da-Zarrouk parameters outcome from the VES interpretations (Table II) prove that, the values of various parameters range from low to high within the study area: longitudinal conductance from 0.0028 mhom at VES of Isuaniocha-2 to 0.0571 mhom at VES of Ebenebe-5; transverse resistance from 6630 ohm-m^2 at VES of Isuaniocha-1 to 10290 ohm-m^2 at VES of Ebenebe-2; conductivity from 0.0002 mho at VES of Ebenebe-2 to 0.0022 mho at VES of Ebenebe-5 (Table II). Actually, some of these obtained values aligned with those obtained by [2], [8], [9], [13], [15] from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials.

2) Aquifer resistivity

The distribution map of the aquifer resistivity reveals high resistivity values in the northeastern part compare with other parts of the study area (Fig. 5 and Table II). The generated resistivity map within the area at contour interval of 100 Ohm-m indicates that there are three distinct zones based on the resistivity parameter namely; high resistivity, moderate resistivity and low resistivity. The reddish colour which occurs at the northeastern parts of the map reveals the existence of relatively high resistivity of the aquiferous unit (2800 to 4900 ohm-m); while the light red colour at eastern part corresponds to relatively moderate resistivity of 1200 to 2800 ohm-m). The light green colour at the western part corresponds to relatively low resistivity of 455 to 1000 ohm-m). Actually, some of these obtained values aligned with those obtained by previous researchers [2], [8], [9], [15] from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials.

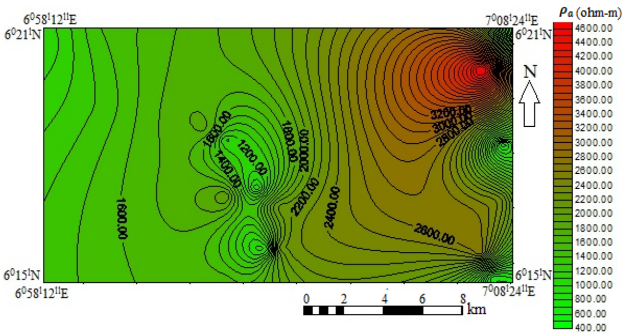


Figure 5. The distribution map showing aquifer resistivity in the study area (Contour Interval~100 Ohm-m).

3) Aquifer thickness

The distribution map of the aquifer thickness reveals high thickness values in the eastern part compare with other parts of the study area (Fig. 6 and Table II). The generated thickness map within the area at contour interval of 2 meters indicates that two distinct zones can be identified within the area. The sky blue colour which occurs at the eastern part of the map reveals the existence of relatively high thickness of the aquiferous unit (22.0 to 38.0m), while the brownish colour at other parts corresponds to relatively low thickness (4.7 to 20.0 m). The area is generally characterized by a thick and prolific aquiferous unit. Nevertheless, some of these obtained values aligned with those obtained by previous researchers [2], [8], [9], [15] from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials.

4) Depth to the aquifer

The distribution map of the depth to the aquifer reveals high thickness values in the south-eastern part compare with other parts of the study area (Fig. 7 and Table II). The generated thickness map within the area at contour interval of 10 meters indicates there are two distinct zones identified within the area. The light green colour which occurs at the south-eastern part of the map reveals the existence of relatively deeper depth to the aquifer (90 to 172m), while the pinkish colour at other parts corresponds to relatively shallow depth (33 to 80m). However, some of these obtained values aligned with those obtained by [2], [8], [9], [13], [15] from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials.

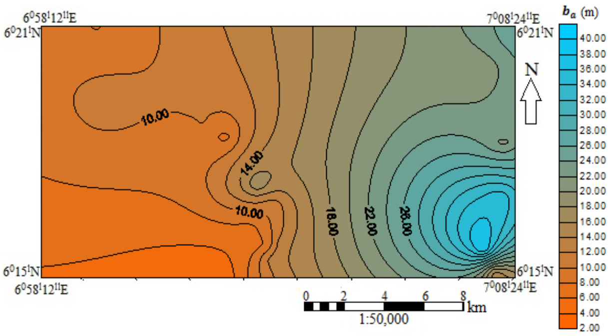


Figure 6. The distribution map showing aquifer thickness in the study area (Contour Interval~2m).

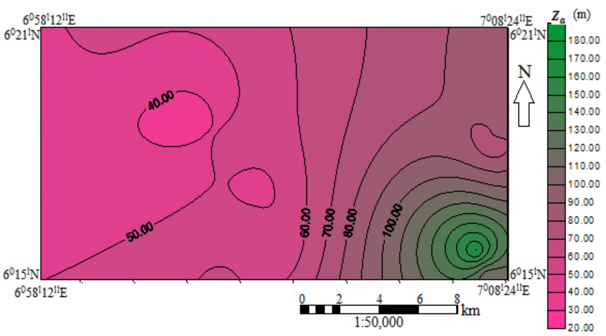


Figure 7. The distribution map showing depth to the aquifer in the study area (Contour Interval~10m).

5) Hydraulic conductivity

At the study area, the estimated hydraulic conductivity of aquifers range from 0.137 m/day at VES of Amansea-3 to 0.792 m/day at VES of Ebenebe-5 (Table II). The distribution map of hydraulic conductivity created depicts that at the extreme eastern and central parts with bluish colour of the map (Fig. 8), there are relatively higher hydraulic conductivity of the aquifer range from 0.32 to 0.80 m/day, while the yellowish colour at the other parts of the area matches with relatively lower hydraulic conductivity of the aquifer which range from 0.137-0.28 m/day. In addition, some of these obtained values aligned with those obtained by [8] from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials; where they established that the hydraulic conductivity within the area ranged from 0.000667 to 0.006944 m/day. Some of these values also conform to those obtained by previous researchers [1], [11], [14].

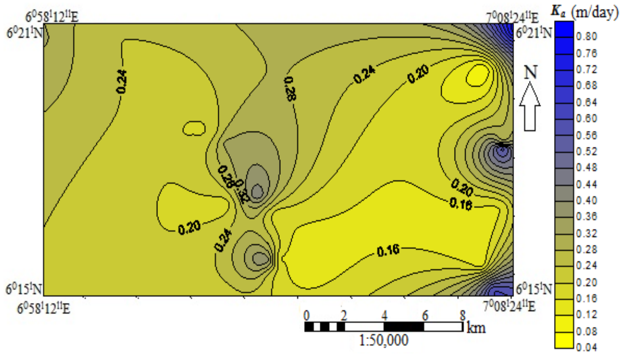


Figure 8. Hydraulic Conductivity map of the Leachate across the study area (Contour Interval~0.04 m/day).

6) Transmissivity

At the study area, the estimated transmissivity of aquifers range from 1.007 m^2/day at VES of Isuaniocha-2 to 20.597 m^2/day at VES of Ebenebe-5 (Table II). The distribution map of transmissivity created depicts that at the extreme eastern and central parts with bluish colour of the map (Fig. 9), there are relatively higher transmissivity of the aquifer range from 10.00 to 20.60 m^2/day, while the violet colour at the other parts of the area matches with relatively lower transmissivity of the aquifer which range from 1.01-9.00 m^2/day. In addition, some of these obtained values aligned with those obtained by some previous researchers from analyzed VES readings around some parts of Anambra Basin, Nigeria for groundwater potentials [8]; where they established that the transmissivity from their analyzed results within the area ranged from 0.048 to 0.590 m^2/day. Some of these values also conform to those obtained by previous researchers [8], [9], [15].

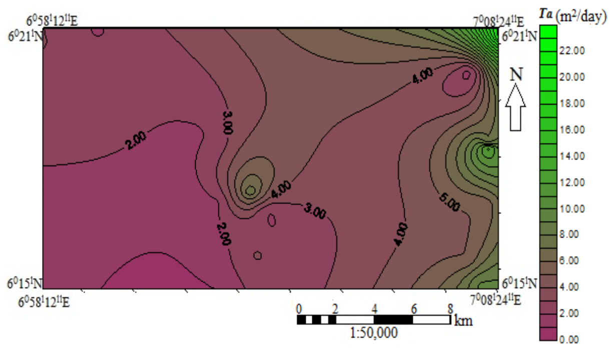


Figure 9. Transmissivity map of the Leachate across the study area (Contour Interval~1.00 m^2/day).

D. Groundwater Potential Implication

The VES interpretations agree with the geology and reveal that the entire study area is underlain by two major aquifer systems namely; shallow aquifer system (aquifer 1) the one at the southwestern part belonging to Nanka Sand with thickness and depth to aquifer ranging from 4.7-17.6 and 33-62m respectively (Fig. 10 and Table IIa). The one at the southeastern part, far aquifer system (aquifer 2) belonging to Ebenebe Sandstone has thickness and depth to aquifer in the range of 15.0-38.0m and 69-172m respectively ((Fig. 10 and Table IIb). None of the VES acquired north of Latitude 6^{o} 22^{I}N contain any aquiferous unit (Fig. 10) and it is classified as zones were aquifer depth was not reached. The area includes Awba-Ofemili, Ugbene and part of Ugbenu (Fig. 10). Also, VES acquired on the eastern part of Ebenebe Sandstone did not show any aquifer (Fig. 10). Actually, VES interpretation along with borehole log at Umuogbuefi, Ebenebe (EBE 3) confirmed the presence of shale for more than 172m depth (Fig. 3a and Fig. 10). The pronounced thickness of Imo Shale in the central part of the study area constitute a sealing unit, that put Ebenebe Sandstone under pressure thus, explaining its artesian to sub artesian nature.

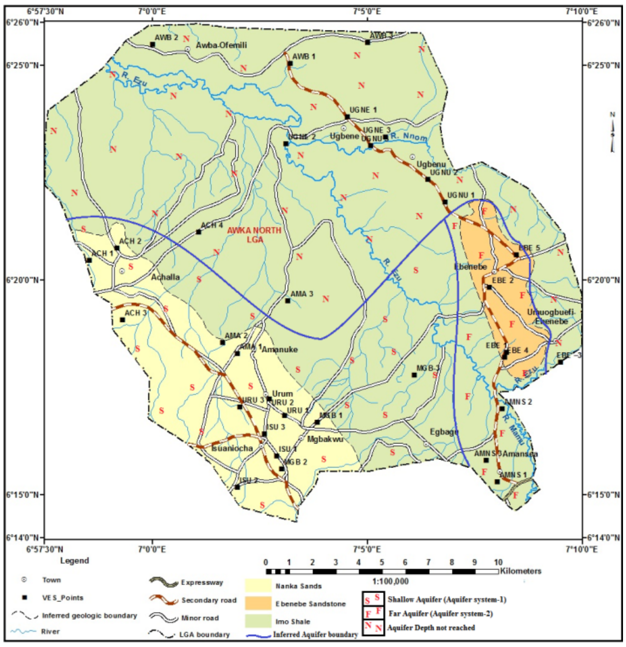


Figure 10. Groundwater potential map of the study area.

In addition, the generated distribution map of watertable in the area (Fig. 11) also reveals that the groundwater potentials across the study area are considerably high at the southwestern part compared to the southeastern part. This conforms to the hydrogeological implications of the study area where the southwestern part is composed of mainly Nanka Sands, which has shallower depth to groundwater resource than the southeastern part which is dominated by the Imo Shale with its sand member called Ebenebe Sandstone that have deeper depth. Invariably, it is economical to drill borehole at the southwestern part of the study area than the southeastern part. Also, the aquifer parameters obtained in this study aligned with this assertion. However, this map reveals that the groundwater flows within the study area is predominantly in the Northwestern to Southeastern (NW-SE) direction (Fig. 11).

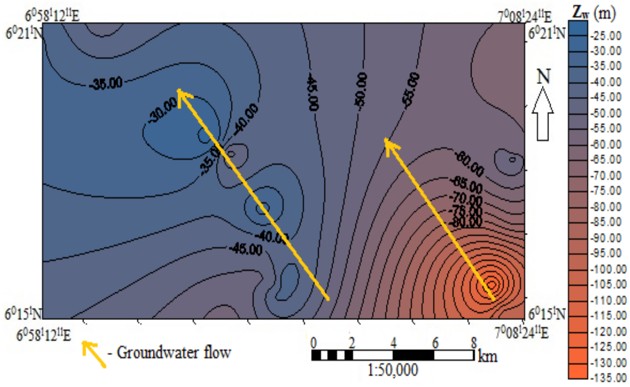


Figure 11. Watertable map of the study area (Contour Interval~5.00 m).

IV. CONCLUSIONS

Thirty Vertical Electrical Soundings (VES) conducted in ten communities within the River Mamu Sub-Basin, Southeastern Nigeria have been used to evaluate the groundwater potential of the area. The study integrated both drilled hole logs and vertical electrical soundings to establish the two major aquifer systems in the area namely; the shallow aquifer belonging to Nanka Sands at the southwestern part with depth to aquifer range of 33-62m and the deep aquifer belonging to Ebenebe Sandstone at the southeastern part with depth range of 69-172m. The calculated Da-Zarrouk parameters outcomes ranged from low to high within the study area: longitudinal conductance (0.0028-0.0571 mhom); transverse resistance (6630-10290 ohm-m^2); aquifer resistivity (455-4900 ohm-m), aquifer thickness (4.70-38.00 m); depth to the aquifer (33-172 m); conductivity (0.0002-0.0022 mho). Two aquifer parameters were computed within the area namely; hydraulic conductivity (6.137 to 0.792 m/day) and transmissivity (1.007 to 20.597 m^2/day). The study reveals high groundwater potentials within the southern part of the study area. Nevertheless, actual drilling and geophysical study confirm that these two aquifer system are not found in the northernmost and eastern boundary of the study area.

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CONFLICT OF INTEREST

There is no conflict of interest.

AUTHOR CONTRIBUTIONS

The authors collectively produced this manuscript, which is time bound and suitable for this Journal because hydrogeophysical study is an essential field in geosciencific applications. Here, the quality of the surface water sources in the study area has been under serious threat as such, there is need to search for better water sources like the groundwater. Hence, the study will provide accurate depths of water boreholes and it becomes a pilot study for all water related projects within the lower Mamu River Sub Basin.

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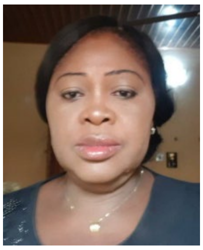

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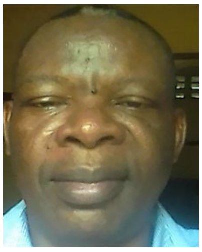

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