

Research Article

Integrated Geoelectrical Delineation and Estimation of Aquifer Hydraulic Parameters from Vertical Electrical Sounding Data in Afikpo, Southeastern Nigeria

Nnabuikwe Vincent Edeh*, Alexander Iheanyichukwu Opara and Chidiebere Charles Agoha

Department of Geology, Federal University of Technology, Owerri, Nigeria, Africa

*Corresponding author: Nnabuikwe Vincent Edeh, Department of Geology, Federal University of Technology, Owerri, Nigeria, Africa

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Abstract

Proper understanding of aquifer hydraulic properties is important in the management of groundwater resources. Development of sustainable groundwater in sedimentary terrains requires reliable estimation of aquifer hydraulic parameters, particularly where pumping test data are scarce. This study integrates (24) Vertical Electrical Sounding (VES) acquired with the aid of the Schlumberger array with maximum half-current electrode spacing (AB/2) of 400m and limited pumping test data to delineate aquifer geometry and determine hydraulic parameters in Afikpo and Environs, Southeastern Nigeria. Curve matching and computer-iterative inversion results revealed a 4-7 layers and dominant KH, HK, QK, and QH type geoelectrical curves, indicating multilayered heterogeneous subsurface conditions. Aquifer resistivity ranged from 10.74 Ωm to 13,201 Ωm , aquifer depth ranged from 6.2 m to 92.5 m, with aquifer thickness varying from 2.3 m to 55.87 m. Dar-zarrouk parameters values determination revealed the values of transverse resistance varying from 65.34 Ωm^2 to 7,079.14 Ωm^2 , and longitudinal conductance from 0.00018 Ω^{-1} to 1.65 Ω^{-1} . Aquifer hydraulic conductivity was computed using the Niwas & Singhal (KNS) and Heigold (KHG) empirical relationships ranging from 0.003237m/day to 0.2724m/day and 1.3052m/day to 3.9519m/day, while transmissivity was computed using transverse resistance-based models (TNS) ranging from 0.03819m²/day to 13.432 m²/day. Based on these parameters and the local hydrogeology, the investigated area was sub-divided into four aquifer potential zones (intermediate, low, very low, and imperceptible). The results confirm that integrated geoelectrical techniques provide a cost-effective alternative to extensive pumping tests and can support groundwater resource planning in sedimentary basins.

Keywords: Hydraulic Conductivity, Transmissivity, VES, Dar-Zarrouk Parameters, Afikpo, Groundwater Potential

Introduction

Water is essential for everyday living. Surface water has been in use long time ago, however, its capacity has reached its limit as a result of issues including population expansion, climate change, and pollution from human activity. Groundwater refers to water found within pore spaces or voids that are saturated beneath the ground. This makes groundwater different from other forms of water, e.g surface water which is found on the surface of the earth. Understanding the occurrence, movement, and flow direction of groundwater is essential, especially in regions where it exists beneath the surface. Groundwater supplies nearly 73% of drinking water in rural areas and 45% in urban areas of Nigeria [1-5].

Proper understanding of aquifer hydraulic properties is important in the management of groundwater resources. Development of sustainable groundwater in sedimentary terrains requires reliable estimation of aquifer hydraulic parameters, particularly where pumping test data are scarce. This is because a sustainable and easily accessible groundwater supply is required. These groundwater resources are negatively impacted by the human activities that coincide with the growth of urbanization. The

exploration of groundwater is becoming more significant due to the increased demand for water, especially in regions where surface water is limited as a result of climate variability. Climate, local geology, topography, interaction of rock and water, and anthropogenic activity are among the numerous variables that affect the quality of groundwater [6-8].

Groundwater exploration has shown success with a variety of geophysical techniques. Effective groundwater exploration necessitates a comprehensive understanding of water properties and the subsurface features that house it. Understanding these parameters is essential for effective groundwater management, especially in urban areas experiencing high demand for water resources. The VES method using the Schlumberger array has become the most widely used geophysical method for groundwater exploration among the previously mentioned approaches. Its popularity can be ascribed to its simple field operation, data analysis simplicity, and efficacy in figuring out the resistivity and thickness of different subsurface conducting layers [9-15].

Several researchers have identified, characterized and estimated groundwater potential and hydraulic properties of the aquifer systems using various geological and geophysical techniques [1, 6]. Multiple resistivity empirical equations have been used

to estimate aquiferous units [2]. Crossplots of geoelectrical and aquifer hydraulic properties at known well locations were used to generate functional relations between the two properties. The derived relationships were used to calculate aquifer hydraulic properties (hydraulic conductivity and transmissivity) areas away from well locations in the area. Aquifers—subterranean layers of rock, sand, or gravel—contain and transmit water when accessed through boreholes [1]. Conversely, poorly connected aquifer materials result in reduced groundwater flow and, consequently, lower yields [1]. The ground responses depend on rock type, fluid content in pore spaces, and the hydrogeochemical characteristics of the contained fluids. According to Key parameters such as hydraulic conductivity, transverse resistance, longitudinal conductance, and transmissivity are vital for assessing the groundwater potential of an area [16-19].

This research aims to determine the hydraulic parameters and consequently delineate the aquiferous units with the combination of VES data and pumping tests data in Afikpo and its Environs, Southeastern Nigeria.

Location, Accessibility, Physiography and Geology of the Study Area

Afikpo and its environs, is situated within the Lower Benue Trough of Southeastern Nigeria, bounded by latitudes 5°46'00"N to 5°58'00"N and longitudes 7°52'00"E to 7°59'00"E. The area is well linked by good road networks and easily accessible through the Abakaliki–Afikpo Road, Enugu–Abakaliki–Afikpo Road, Ikom–Ogoja–Abakaliki–Afikpo Road, Owerri–Okigwe–Afikpo Road and through Ohafia–Afikpo Road. Some important towns in the study area include Amasiri, Akpoha, Amuro, Afikpo, Ozizza, Ozara Ukwu and Unwana, this made the collection of data in this area possible (Fig. 1). The study area is drained by the Cross River and its tributaries. In terms of topography, the study area comprises elongated sandstone ridges, gently sloping hills and lowlands, with a mean elevation profile of less than 180 m. Ridges of sandstones, and plains and valleys of shales form prominent and extensive topographic features [20]. The topography is geologically controlled, undulating with the ridges and hills topped by compact argillaceous sandstones, and shale lowlands that can easily weather.

The geology of the study area, Afikpo, which is located in the southern Benue Trough, between the Abakiliki Anticlinorium running northeast and the Cameroon Line in the southeast. The three pronounced stratigraphy of the Afikpo region as described is underlain by the Asu River Group, Ezeaku group and Nkporo group. It is observed that each major phase of sediments deposition in the studied basins terminates with the deposition of prograding deltaic sands during a regressive phase. Sedimentation is believed to have been initiated after the separation of South America from Africa in the Aptian/Albian, and was controlled by three main tectonic events and epeirogenic movements [21-25].

The Asu River group is along the Asu River [21]. The sediments consist of poorly bedded sandy shales, the Abakiliki shales with sandstone and sandy limestone lenses. The Asu River Group also contains brine, and it can be said that all brine beds in Nigeria are in the Asu River Group. The brine deposit occurred during the marine transgression, and salt was deposited in the basin.

The Ezeaku Formation is believed to represent typical shallow water deposit, consisting mainly of hard grey to black shales and siltstone [20]. Kogbe 1976 regarded the shales of the Eze-Aku Formation as transgressive deposits in shallow shelf settings. The shales laterally grade into the sandstone of the Amasiri Sandstone, with type locality at Amasiri near Afikpo, and Ezillo Formation. Sandstone outcrops extend from Afikpo through Ugep, and then to Apiampu. The Eze-Aku Formation was deposited in the Turonian transgressive phase but in a shallow marine environment. The lithologies include shale, sandstones, and calcereous sandstones. The fossils in this Formation include vascocerastids, pelecypods, gastropods, echinoids, fish teeth, decapod, and plant fragments [21].

The Nkporo Group is made up of three members – Afikpo/Owelli Sandstone, Nkporo and Enugu Shales. The arenaceous facies of the Afikpo and Owelli Sandstones are lateral equivalents to the Nkporo Formation in the Afikpo and Anambra Basins respectively. The Nkporo Group is essentially marine sediments of deposited by the third transgressive cycle within the Anambra Basin. Its deposition ended in the Early Maastrichtian in both Abakaliki-Anambra and Afikpo Synclines [25]. The deposits of the transgressive Nkporo cycle were overlain by the Lower Maastrichtian sandstones, shales, siltstones and mudstones, and the interbedded coal seams of the deltaic Mamu Formation in most parts of the Anambra Basin. The Mamu Formation was deposited as the broad shallow sea that existed at the time of deposition of the Nkporo/Enugu Formations, gradually became shallower. Predominance of regression resulted to the deposition of the continental sequence of Ajalli Formation on top of the Mamu Formation, followed by a return to partially paralic conditions that were responsible to the deposition of Nsukka Formation. The Mamu Formation is restricted to the Anambra Basin and Afikpo Syncline in southeastern Nigeria. The Mamu Formation is dated Ler to Mid Maastrichtian [26-29]. Figure 2 illustrate the three geology of the study area.

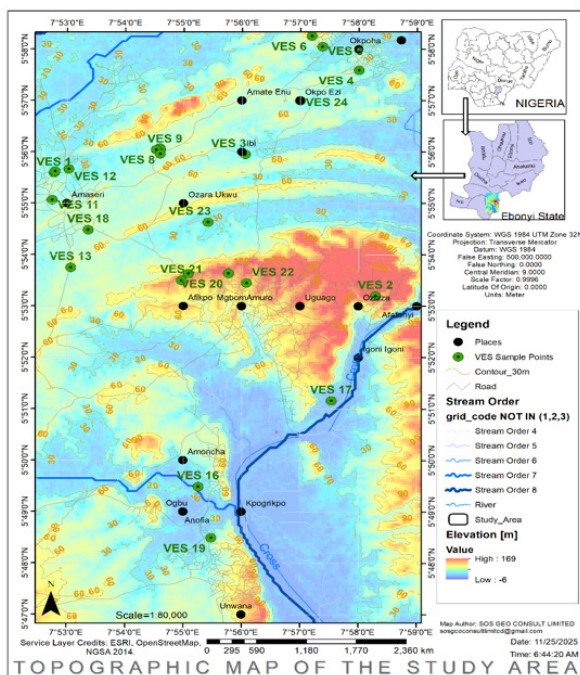


Figure 1: Accessibility and topographical map of the study area

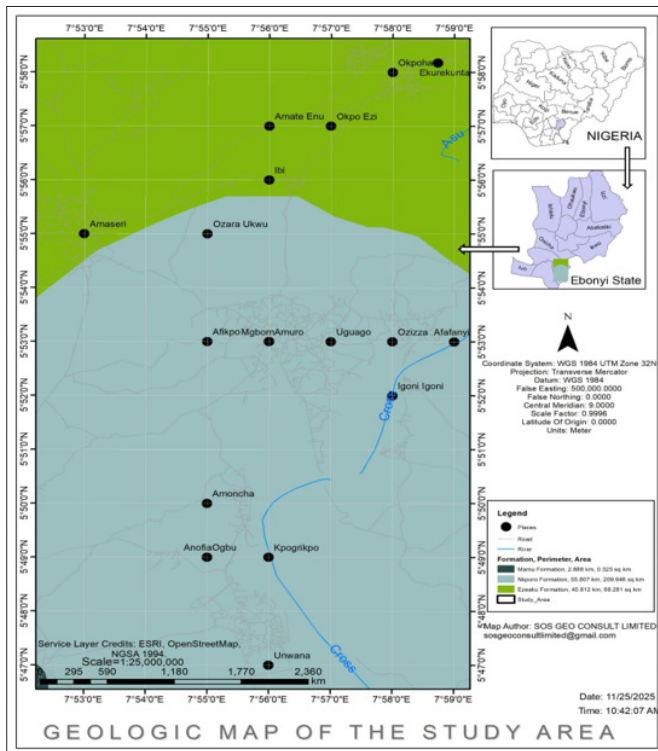


Figure 2: Geology map of the study area

Materials and Methods

Data Acquisition

The geophysical survey comprised twenty-four (24) Vertical Electrical Sounding (VES) stations established across the study area. The Schlumberger electrode configuration was employed with a maximum current electrode half-spacing ($AB/2$) of 400 m, ensuring sufficient depth penetration to intercept deep saturated zones. The ABEM Terrameter SAS 1000 was utilized for data collection due to its signal stacking capabilities, which improve the signal-to-noise ratio in conductive shale environments.

The Vertical Electrical Sounding (VES) is a technique used to examine the Earth's subsurface using geoelectric methods. It operates on the principle that injecting current into the Earth through two electrodes along a profile line produces an electric field in the subsurface. The variation in electric potential is measurable by placing two additional electrodes properly in line with the current electrodes. The apparent resistivity of the Subsurface can be determined based on the electrode spacing using different configurations, which include Schlumberger, Wenner, or a Dipole-Dipole array [30-31]. The choice of configuration depends on the objective of the investigation. The four measurement electrodes determine the potential difference (MN) when a current (AB) is injected between A and B. For this study, the Schlumberger array was used owing to its good balance between depth and penetration, which makes it appropriate for groundwater exploration study, also it is more sensitive to horizontal layers which aid in the detection of water bearing units.

Direct current (D.C.) was passed into the ground through two electrodes (current electrodes) in order to employ the electrical resistivity method. The potential difference (ΔV) that results from the current flow was then measured through two electrodes (potential electrodes). Figure 3 shows a schematic representation of the relationship between subsurface current and field data gathering. The depth of investigation, which is a function of electrode spacing, determines how well the current is sensed. The deeper the electric current flows in the earth, the wider the

distance between the outer current electrodes; therefore, the deeper the research [32-33]. The apparent electrical resistivity obtained results from multiplying the measured electrical resistance by a coefficient influenced by the position of the four electrodes.

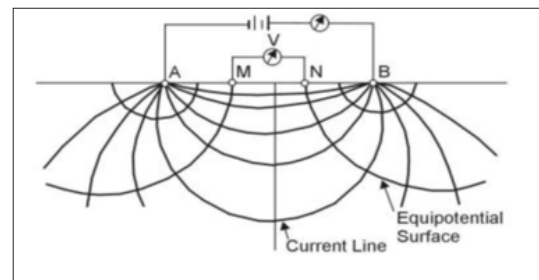


Figure 3: Schematic representation of the relationship between subsurface current and field data gathering

Data Processing

Field resistance measurements were converted to apparent resistivity values and processed using computer-assisted iterative modelling software (IP2WIN and Win Resist). This process generated quantitative geoelectric layers defined by their resistivity (ρ) and thickness (h).

Curve Types

Generally, the apparent resistivity (ρ) curve for layers basically has one or four different shapes, determined by the vertical sequences of the resistivity of the layers. Theoretically, the major curves are: K-type, H-type, A-type and Q-type curves.

Type-K Curve

This type of curve, resistivity decreases then increases with depth ($\rho_1 > \rho_2 < \rho_3 \dots$), indicating that the middle layer has resistivity higher than the top and bottom layers, relatively a conductive layer (e.g., clay or clayey sand) sandwiched between more resistive layers, which often points to clay-rich horizons that are less favorable for groundwater flow.

Type-H Curve

Resistivity increases then decreases with depth ($\rho_1 < \rho_2 > \rho_3 \dots$) middle strata has good conducting power greater than the upper and lower strata Lowrie. A high-resistivity layer overlain or underlain by lower resistivity, often indicating alternating sand and clay layers.

Type-A Curve

This type of curve show that apparent resistivity normally rises continuously with increasing electrode separation ($\rho_1 < \rho_2 < \rho_3 \dots$), indicating that the true resistivity increases with depth from layer to layer. This could be interpreted as sand or gravel formations with good porosity and permeability.

Type-Q Curve

This type of curve, apparent resistivity decreases continuously along with a progressive decrease of resistivity with depth ($\rho_1 > \rho_2 > \rho_3 \dots$). Often interpreted as dominantly conductive layers, containing majorly clayey sand having low permeability and less aquifer potential.

Hybrid or secondary curve types, interpretation will be based on which curve type is combining with which, reflecting layer alternations.

Dar Zarrouk Parameters

The longitudinal conductance of a unit or layer is given by Niwas and Singhal (1981) as:

$$S = h/\rho = h\sigma$$

Where, S = longitudinal conductance, h = layer thickness, ρ = layer resistivity and σ = layer conductivity.

High longitudinal conductance suggests a protective overlying layer, reducing vulnerability, while low conductance indicates higher susceptibility to contamination [10].

Transverse Resistance

Transverse resistance (RT) is among the parameters used to define target areas of good groundwater potential. Sand and gravel are more resistive and are good aquifer materials because of high apparent resistivity, which also represents areas with high Transverse Resistance [1]. Similarly, clay, clayey-sand and shale that have less resistivity indicate low transverse resistance. For computation of Transverse resistance, aquifer resistivity will be multiplied with the thickness.

Hydraulic Conductivity

Hydraulic conductivity is the ability of an aquifer to transmit groundwater. It is defined as the volume of water transmitted in a unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow. Hydraulic

conductivity is symbolically represented as K, which is a property of rock that describes the ease with which water can move through pore spaces or fracture [34-35]. From the pumping test and resistivity of the aquifer. The determination of multiple aquifer hydraulic conductivities aimed at comparing the different hydraulic conductivities to ascertain a more reliable model for an area [3]. Poorly connected aquifer materials result in reduced groundwater flow and, consequently, lower yields [1].

The empirical formulas of hydraulic conductivity by Niwas and Singhal 1981 and Heighold 1979 were used in this study.

Transmissivity

Aquifer transmissivity is defined as the ability of the entire aquifer material to transmit groundwater. According to [34], it's the rate of transmission of water through a unit width of the aquifer under a unit hydraulic gradient. Niwas and Singhal 1981 equation was used to estimate the aquifer transmissivity in the area. [36] proposed a six-class system based on the transmissivity coefficient (T), using physical values (in m²/day) to determination of groundwater supply potential in an area (Table 1).

The unit of transmissivity is m²/ day

Table 1: Six-class system based on the transmissivity coefficient (T), for determination of groundwater supply potential in an area [36].

Class	Transmissivity Magnitude	Transmissivity (m ² /day)	Groundwater Supply Potential
I	Very High	>1000	Withdrawals of great regional importance.
II	High	100–1000	Withdrawals of lesser regional importance (e.g., small towns, irrigation).
III	Intermediate	10–100	Withdrawals for local water supply (small communities, plants).
IV	Low	1–10	Smaller withdrawals for local water supply (private consumption).
V	Very Low	0.1–1	Sources for local water supply (private consumption) are possible but difficult.
VI	Imperceptible	<0.1	Sources for local water supply are difficult or impossible.

Results Presentation

Goelectric Characterization and Aquifer Architecture.

The interpretation of the VES data revealed a complex, heterogeneous subsurface characteristic of the Afikpo Sub-basin. The goelectric sections delineated a multi-layered system ranging from 4 to 7 layers (Table 2), reflecting the rapid lithological variations between the sandstone ridges and shale lowlands.

Table 2: Summary of goelectric layer parameters

VES NO.	GEOGRAPHIC COORDINATES		RESISTIVITY OF LAYERS (Ωm)							CONDUCTIVITY OF LAYERS (Ωm) ⁻¹							LAYER DEPTH (m)						LAYER THICKNESS (m)						NO. OF LAYERS	CURVE TYPES	ERROR (%)
	Lat. (N)	Long. (E)	ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	σ_1	σ_2	σ_3	σ_4	σ_5	σ_6	σ_7	d1	d2	d3	d4	d5	d6	h1	h2	h3	h4	h5	h6			
VES 1	5°55'35.360" N	7°52'46.850" E	141	45.3	19.5	617	113			0.0071	0.0221	0.0513	0.0016		0.0088		1.36	3.01	15	61.7			1.36	1.65	12	46.7			5	KH	0.0553
VES 2	5°53'12.000" N	7°56'17.720" E	156	61.9	27.7	776				0.0064	0.0162	0.0361	0.0013				1.33	1.73	23	69			1.33	0.408	21.3	46			4	KH	0.0771
VES 3	5°55'57.180" N	7°56'3.620" E	156	26.8	16792	53.3				0.0063	0.0373	0.0001	0.0181				1.72	16.1	57.6				1.72	14.4	41.6			4	KH	0.0639	
VES 4	5°57'35.530" N	7°58'0.530" E	118	172	20	926				0.0085	0.0056	0.0500	0.0011				0.576	1.53	16.9	58.9			0.58	0.951	15.4	42			4	KH	0.0666
VES 5	5°58'3.180" N	7°57'22.860" E	101	3.6	11445	145				0.0099	0.2632	0.0001	0.0069				2.23	5.32	54.6				2.23	3.09	49.3			4	KA	0.454	
VES 6	5°58'15.490" N	7°57'12.020" E	152	24.2	92.8	1000				0.0096	0.0413	0.0108	0.0010				1.74	17.6	43.3	74.3			1.74	15.9	25.7	31			4	KH	0.0574
VES 7	5°56'4.500" N	7°54'35.700" E	93650	568	85.7	805				0.0000	0.0018	0.0117	0.0012				0.149	2.12	99.2	125			0.15	1.97	97.1	25.5			4	QH	0.303
VES 8	5°56'3.000" N	7°54'36.300" E	1246	219	78.5	212	46.91			0.0008	0.0046	0.0127	0.0047	0.0023			0.784	3.06	10.5	23.7			0.78	2.27	7.47	13.2			5	OK	0.0842
VES 9	5°56'2.500" N	7°54'32.000" E	39.4	8.7	6787	13.2	175			0.0515	0.1149	0.0001	0.0758	0.0057			0.746	19.7	45.3	100			0.75	18.9	25.7	54.7			5	HA	0.0532
VES 10	5°55'37.500" N	7°52'48.000" E	564.4	111	18.3	136	41			0.0018	0.0090	0.0546	0.0074	0.0244			0.786	6.3	11	22.8			0.79	5.51	4.71	11.8			5	OK	0.101
VES 11	5°55'4.000" N	7°52'45.000" E	49060	918	0.97	115				0.0000	0.0011	1.0308	0.0087				0.312	34.9	64.6				0.31	34.6	29.7			4	OK	1.04	
VES 12	5°55'40.000" N	7°53'2.000" E	657	46.2	4.48	21.1	363			0.0015	0.0216	0.2232	0.0474	0.0061			0.46	2.73	4.39	23.5	51.5		0.46	2.27	1.47	19.3	28		5	QH	0.43
VES 13	5°53'45.000" N	7°53'4.000" E	41	4.53	97	22.8				0.0244	0.2208	0.0108	0.0439				1.77	12.4	63.3				1.77	10.6	50.9			4	KH	0.0656	
VES 14	5°53'38.000" N	7°55'5.000" E	794	9202	339	2144				0.0013	0.0001	0.0029	0.0005				4.03	6.43	64.3	95.3			4.03	2.4	57.8	31			4	KH	0.048
VES 15	5°55'57.800" N	7°54'36.000" E	221	32.6	970	94.1				0.0045	0.0307	0.0010	0.0106				1.41	48.1	79.6				1.41	46.7	31.5			4	KH	0.111	
VES 16	5°49'29.200" N	7°55'15.500" E	279	95	32.8	1171	23.6	42.2		0.0036	0.0105	0.0305	0.0009	0.0434	0.0237		1.6	10.6	29.2	66.6	126		1.6	9	18.6	39.4	57.3		6	KH	0.0825
VES 17	5°51'9.676" N	7°57'32.485" E	3423	549	314	199	549	197		0.0003	0.0018	0.0032	0.0050	0.0018	0.0051		1.2	2.7	11.4	28.5	97.7		1.2	1.5	8.7	17.1	69.2		6	KH	0.0918
VES 18	5°54'29.000" N	7°53'22.000" E	132	11.6	9111	2638	69			0.0076	0.0662	0.0001	0.0040	0.0145			1.16	2.51	11.4	30			1.16	1.35	8.89	16.6			5	KH	0.394
VES 19	5°48'29.400" N	7°55'29.000" E	1224	3764	392	508	13203	1345	497	0.0008	0.0003	0.0030	0.0000	0.0001	0.0007	0.0020	1.6	3.32	3.8	8.53	29.7	68	1.6	1.72	0.48	4.73	21.2	37.8	7	KHK	0.0781
VES 20	5°53'38.200" N	7°55'46.400" E	1029	5886	2112	17850	556	9108		0.0010	0.0002	0.0005	0.0001	0.0018	0.0001		1	1.9	4.58	24.3	57.4		1	0.9	2.68	19.7	33.1		6	AK	0.0466
VES 21	5°53'30.000" N	7°54'58.000" E	3761	1720	14586	57.9	3962			0.0003	0.0006	0.0001	0.0173	0.0003			1	3.53	17.2	33.5			1	2.53	13.7	16.3			5	KH	0.069
VES 22	5°53'27.000" N	7°56'5.000" E	55.4	2025	150	1155	99.3			0.0181	0.0005	0.0067	0.0009	0.0101			0.18	2.41	23.6	56.1			0.18	2.23	21.2	34.5			5	KH	0.0693
VES 23	5°54'38.000" N	7°55'25.400" E	196	270	358	74.1	1632			0.0051	0.0037	0.0028	0.0135	0.0006			1.45	2.83	32	106	118		1.45	1.38	29.2	74.3	12		5	AH	0.0799
VES 24	5°57'0.000" N	7°57'0.000" E	941	492	913	308	859			0.00106	0.002	0.0011	0.0032	0.00116			1.2	11.1	34.7	89.9			1.2	9.9	23.6	55.2			5	KH	0.0423

Layer Resistivity Curves

A or H-dominant curves generally signal more resistive layers (sands, weathered/fractured rocks) that tend to be more porous and permeable, therefore often correlated with better groundwater potential. K and Q-dominant curves are typically associated with more conductive materials (clays, clayey sands or laterite), indicating lower permeability and consequently poorer aquifer quality, unless overlain/underlain by resistive layers.

Hybrid curves reflect layer alternations (conductive and resistive units) which can represent complex aquifer systems (multiple water-bearing zones or semiconfined aquifers). Multiple VES curve types were identified in the study area, which include dominantly KH, HK, QK, and QH curves indicating resistive top layers over conductive saturated zones or vice-versa, often linked to weathered/fractured rocks and enhanced groundwater potential, because curve shapes help infer lithology and potential aquifer quality. These interpretations were integrated with Dar-Zarrouk parameters to delineate aquifer units and assess groundwater prospectivity. Figure 4 shows the different curve types obtained in the area.

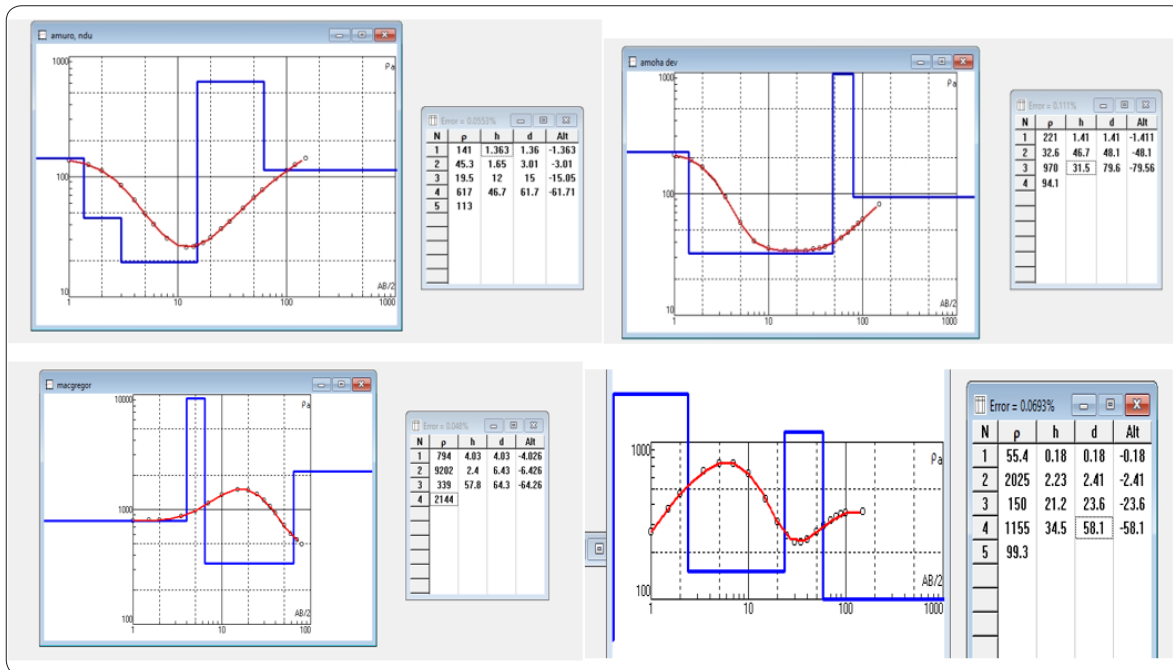


Figure 4: Modelled curve types of some locations in the study area

Table 3: Aquifer Dar-Zarrouk and hydraulic parameters

VES NO.	LOCATION	Lat (N)	Long. (E)	Aquifer Resistivity (Ωm)	Aquifer Conductivity (Ωm^{-1})	Aquifer depth (m)	Aquifer thickness (m)	Transverse Resistance (TR)	Longitudinal Conductance (SL)	Pumping test, Hydraulic conductivity (K^* m/day)	Pumping test, Transmissivity (T^* m^2/day)	Diagnostic constant ($\text{K}^* e$)	Average Diagnostic constant	$\text{K}^* \text{ (m}^2/\text{day)}$	$\text{T}^* \text{ (m}^2/\text{day)}$	$\text{K.H.G. (386.4p-0.93283)}$
VES 1	MODERN PRY. SCH., AMURO, NDUKWE AMASIRI	5°55'35.36"	7°52'46.85"	617	0.0016207	61.7	46.7	28813.9	0.075689	0.01509	0.120757	2.45E-05	0.0000238	0.014685	0.685771	0.964218
VES 4	ST. JOHN CATHOLIC CHURCH, AKPOHA	5°57'35.53"	7°58'0.52"	926	0.0010799	58.9	42	38892	0.045356	0.02443	0.195415	2.64E-05	0.0000238	0.022039	0.92563	0.660227
VES 5	COMPREHENSIVE SEC. SCH., AMATA-AKPOHA	5°58'3.18"	7°57'22.86"	11445	8.737E-05	54.6	49.31	564353	0.004308			0.0000238	0.272391	13.4316	0.063247	
VES 6	OKPOTOKUM PRY SCH, AMATA-AKPOHA	5°58'15.49"	7°57'12.02"	1000	0.001	74.3	31	31000	0.031	0.02056	0.16449	2.06E-05	0.0000238	0.0238	0.7378	0.614536
VES 7	APOJO AMASIRI	5°56'04.5"	7°54'35.7"	805	0.0012422	124.7	25.5	20527.5	0.031677			0.0000238	0.019159	0.488555	0.752356	
VES 8	APOJO AMASIRI 2	5°56'03"	7°54'36.3"	212	0.004717	23.7	13.2	2798.4	0.062264			0.0000238	0.005046	0.066602	2.611928	
VES 9	APOJO AMASIRI 3	5°56'2.5"	7°54'32"	6787	0.0001473	45.3	25.7	174425.9	0.003787			0.0000238	0.161531	4.151336	0.102975	
VES 10	OKOBO-IHIE, AMASIRI 1	5°55'37.5"	7°52'48"	136	0.0073529	22.8	11.8	1604.8	0.086765			0.0000238	0.003237	0.038194	3.951919	
VES 11	OKOBO-IHIE, AMASIRI 2	5°55'4"	7°52'45"	918	0.0010893	34.9	34.6	31762.8	0.037691			0.0000238	0.021848	0.755955	0.665593	
VES 12	OKOBO-IHIE, AMASIRI 3	5°55'40"	7°53'2"	163	0.006135	51.5	28	4564	0.171779			0.0000238	0.003879	0.108623	3.33766	
VES 15	AMOHA DEV. CENTRE, APOJO, AMASIRI	5°55'57.8"	7°54'36"	970	0.0010309	79.6	31.5	30555	0.032474			0.0000238	0.023086	0.727209	0.632247	
VES 2	IMAMA OZIZA	5°53'12"	7°58'17.72"	776	0.0012887	69	46	35696	0.059278	0.016778	0.134224	2.16E-05	0.0000114	0.008846	0.406934	0.778552
VES 3	IBIL PRIMARY SCHOOL	5°55'57.18"	7°56'3.62"	16732	5.977E-05	57.6	41.6	696051.2	0.002486	0.01978	0.158223	1.18E-06	0.0000114	0.190745	7.934984	0.04438
VES 13	PRECIOUS SCH, AMANGWU EDDA (NGUZU)	5°53'45"	7°53'04"	2144	0.0004664	95.3	31	66644	0.014459			0.0000114	0.024442	0.757669	0.301697	
VES 14	MACGREGOR HILL	5°53'38"	7°55'05"	339	0.0029499	64.3	57.8	19594.2	0.170501			0.0000114	0.003865	0.223374	1.685741	
VES 16	EZIKWU AFIKPO NORTH	5°49'29"	7°55'15.5"	1171	0.000854	68.6	39.4	46137.4	0.033646			0.0000114	0.013349	0.525966	0.53039	
VES 17	AKPOHA AFIKPO NORTH	5°51'9.68"	7°57'32.49"	549	0.0018215	97.7	69.2	37990.8	0.126047			0.0000114	0.006259	0.433095	1.075182	
VES 18	NNPC FILLING STATION AMASIRI	5°54'29"	7°53'22"	2638	0.0003791	30	18.6	49066.8	0.007051			0.0000114	0.030073	0.559962	0.248639	
VES 19	AKANU IBIAM FEDERAL POLY. UWANA	5°48'29"	7°55'29"	13203	7.574E-05	29.7	21.2	279903.6	0.001606			0.0000114	0.150514	3.190901	0.055354	
VES 20	GOVERNMENT COLLEGE AFIKPO	5°53'38"	7°55'46.4"	17850	5.602E-05	24.3	19.7	351645	0.001104			0.0000114	0.20349	4.008753	0.041781	
VES 21	NYS ORIENTATION CAMP AFIKPO	5°53'30"	7°54'58"	14556	6.87E-05	17.2	13.7	199417.2	0.000941			0.0000114	0.165938	2.273356	0.050539	
VES 22	UKPA BY OKO OGENYI ROAD AFIKPO	5°53'27"	7°56'5"	1155	0.0008658	58.1	34.5	39847.5	0.02987			0.0000114	0.013167	0.454262	0.537241	
VES 23	EZI-EGWU UBANA UGWU-EGU	5°54'38"	7°55'25.4"	1632	0.0006127	118	12	19584	0.007353			0.0000114	0.018605	0.223258	0.389149	
VES 24	EZI NWACHINDIBE, AFIKPO NORTH	5°57'00"	7°57'00"	913	0.0010953	34.7	23.6	21546.8	0.025849			0.0000114	0.010408	0.245634	0.668992	

Results Discussion

Aquifer Resistivity

From the sounding data, high aquifer resistivity was recorded at VES 20 in Government College, Afikpo, with a resistivity value of 17850 Ωm , while the least aquifer resistivity was observed at Okobo-Ihie, Amasiri, in VES 10 with a resistivity value of 136 Ωm , which indicates a sand body with clay admixtures (Fig. 5). The average aquifer resistivity of the entire study area is approximately 4068.21 Ωm . Aquifer with higher resistivity value will make a better choice, this is according to that high resistivity values generally indicate the presence of sandstones, which are conducive to groundwater flow [18].

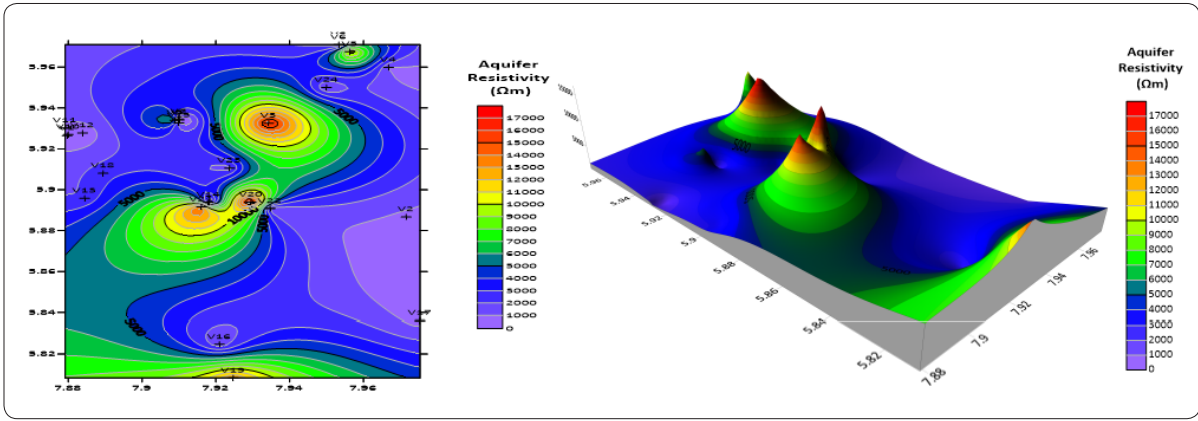


Figure 5: 2D & 3D aquifer resistivity model

Aquifer Conductivity

From the sounding data, low aquifer conductivity was recorded at VES 20 in Government College, Afikpo, with a conductivity value of $0.000056(\Omega\text{m})^{-1}$, while the high aquifer conductivity was observed at Okobo-Ihie, Amasiri, in VES 10 with a conductivity value of $0.00735(\Omega\text{m})^{-1}$ (Fig. 6). The average aquifer resistivity of the entire study area is approximately $0.001504(\Omega\text{m})^{-1}$.

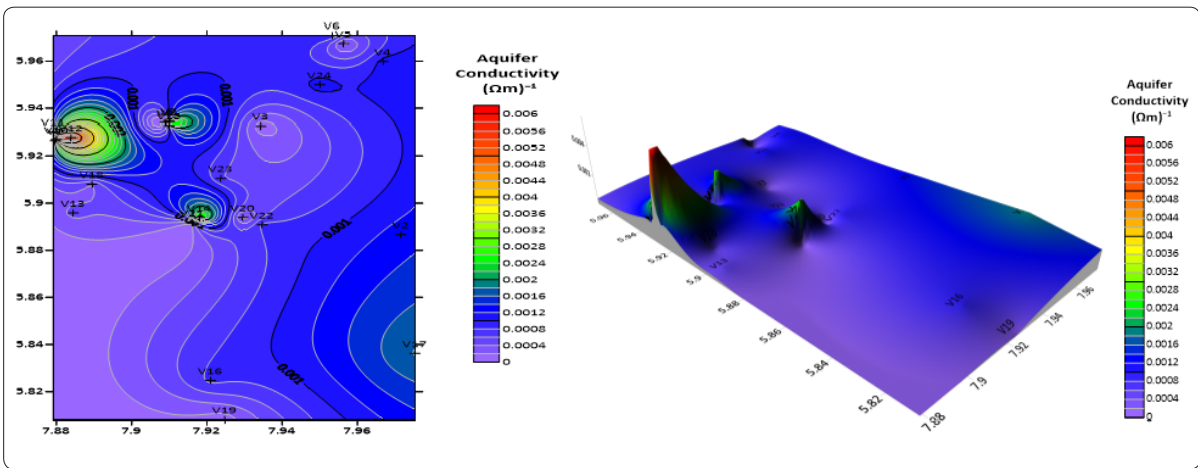


Figure 6: 2D & 3D aquifer conductivity model

Aquifer Depth

Electrical resistivity sounding acquired within the study area, a shallow aquifer depth of 23.7m was recorded at VES 8 in Apojo Amasiri 2, while a deeper aquifer depth of 124.7m and 118m was recorded on VES 7 and VES 23 at Apojo Amasiri 1 and Ezi-Egwu Ubana Ugwu-Egu, respectively (Fig. 7). Average aquifer depth of 58.19m was observed within the entire study area, which corresponds with the regional aquifer depth of the study area and previous studies [17].

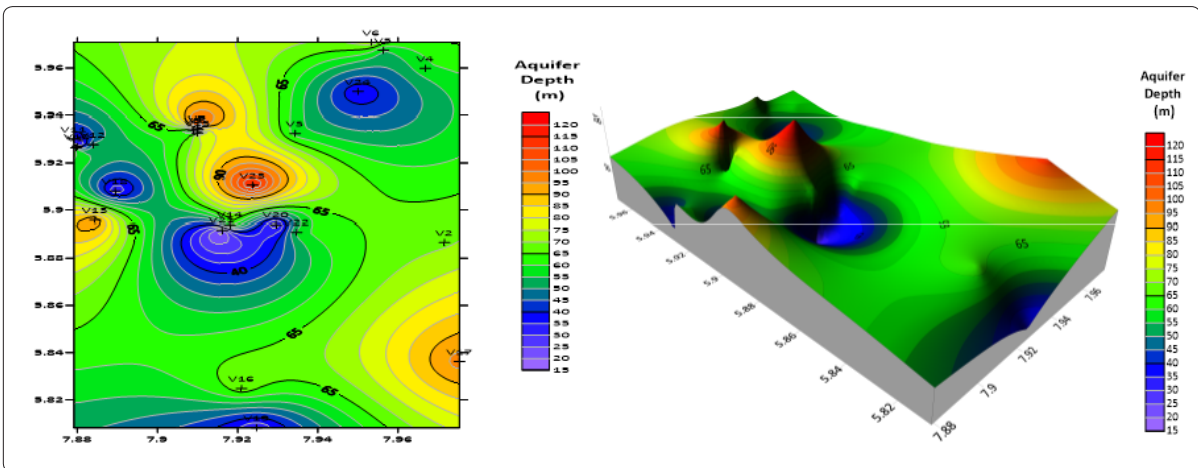


Figure 7: 2D & 3D geospatial model of aquifer depth

Aquifer Thickness

The aquifer with the highest thickness of 69.2m observed was on VES 17 obtained at Akpo, Afikpo North, which would be a prolific aquifer unit and can accommodate a borehole for commercial water supply in the study area. The least aquifer thickness of 11.8m was recorded on VES 7 at Okobo-Ihie, Amasiri 1. An average aquifer thickness of 31.98m was observed within the entire study area (Fig. 8).

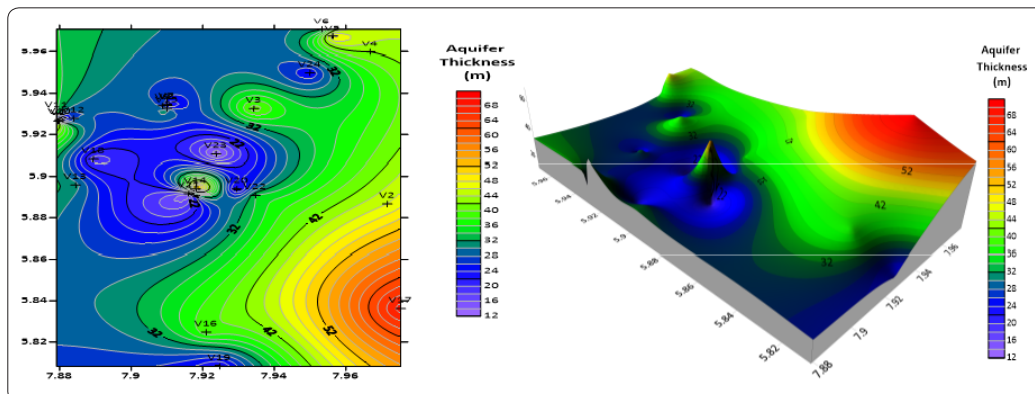


Figure 8: 2D & 3D geospatial model of aquifer thickness

Longitudinal Conductance (S)

A minimum Longitudinal Conductance (S) of 0.00094 Ω^{-1} was observed at NYSC Orientation Camp, Afikpo, on VES 21, and a maximum of 0.172 Ω^{-1} was recorded on VES 12 at Okobo-Ihie 3, Amasiri. An average value of 0.0443 Ω^{-1} was observed within the study area (Fig. 9). Study from revealed that high longitudinal conductance suggests a protective overlying layer, reducing vulnerability, while low conductance indicates higher susceptibility to contamination [10].

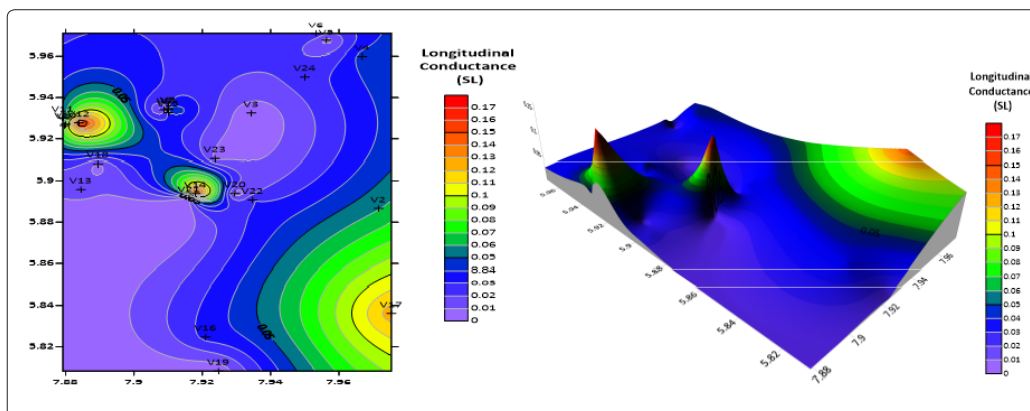


Figure 9: 2D & 3D geospatial model of longitudinal conductance

Transverse Resistance (RT)

Results from the VES data highlighted a high value of aquifer transverse resistance of 696051.2 Ωm^2 recorded at Ibil Primary School on VES 3 while the least value was recorded at Okobo-Ihie, Amasiri on VES 10 with a RT value of 1604.8 Ωm^2 . The average transverse resistance value in the study area is 116343.406 Ωm^2 (Fig. 10). Transverse resistance (RT) is among the parameters used to define target areas of good groundwater potential. Sand and gravel are more resistive and are good aquifer materials because of high apparent resistivity, which also represents areas with high Transverse Resistance [1]. Similarly, clay, clayey-sand and shale that have less resistivity indicate low transverse resistance.

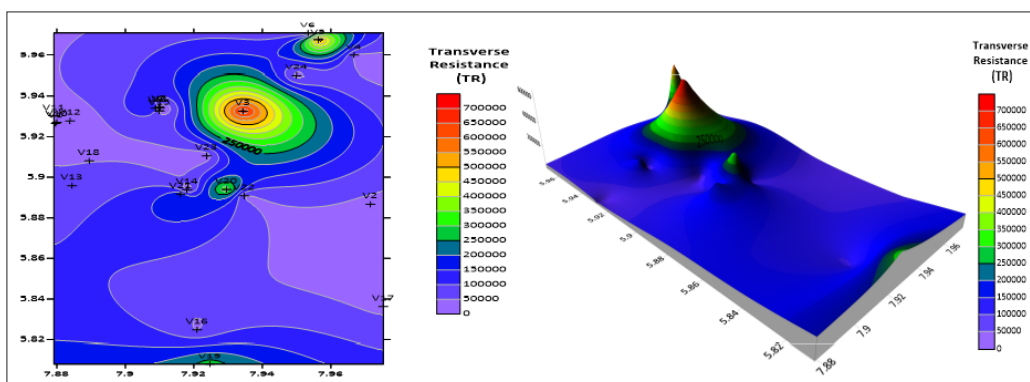


Figure 10: 2D & 3D geospatial model of transverse resistance

Diagnostic Constant ($k'\sigma$)

The aquifer diagnostic parameter is obtained by multiplying hydraulic conductivity obtained through pumping test and the electrical conductivity of the aquifer, i.e. $K\delta$. This parameter can be used to determine areas with almost the same geologic characteristics and water quality [37]. Such areas will consist of almost similar diagnostic parameters [3]. Average value of the diagnostic constant was used in the calculation of Niwas and Singhal hydraulic conductivity and transmissivity of area where there is pumping test data and where pumping was not available. Five pumping test was conducted in an existing well within the study area and five hydraulic conductivity K' was obtained and was used to calculate the average diagnostic constant ($k'\sigma$). 0.0000238 and 0.0000114 were obtained as the average diagnostic constant for the Amasiri sandstones and Afikpo sandstones respectively which was used to calculate the Niwas & Singhal hydraulic conductivity and transmissivity. From the pumping test and resistivity of the aquifer. The determination of multiple aquifer hydraulic conductivities aimed at comparing the different hydraulic conductivities to ascertain a more reliable model for an area [3].

Hydraulic Conductivity

K Niwas & Singhal, KNS

KNS which is the product of average diagnostic constant and the aquifer resistivity, it can be shown that KNS value ranges from 0.0032368m/day at Okobo-Ihie, Amasiri 1 on VES 10 to 0.272391m/day from VES 5 at Comprehensive secondary School, Amata-Akpoha. Average KNS within the study area is 0.051881836m/day for the Amasiri sandstones formation, while for the Afikpo sandstones, ranges from 0.0038646m/day at VES 14 from Macgregor Hill to 0.20349m/day from VES 20 at Government College, Afikpo with an average value of 0.0645924m/day (Fig. 11).

Heigold, KHG

The empirical relationship to estimate hydraulic conductivity formula was used. From the empirical relationship above, maximum KHG value was observed at Okobo-Ihie, Amasiri 1 with value of 3.951918848m/day on VES 10, while least KHG was observed at Comprehensive secondary School, Amata-Akpoha with KHG value of 0.063246798m/day on VES 5 with an average value of 1.305173363m/day for the Amasiri sandstone, while the maximum value of 1.685741324m/day on VES 14 from Macgregor Hill to 0.041781251m/day from VES 20 at Government College, Afikpo with an average value of 0.492895064m/day (Fig. 12). The values were generally low, and could mean low aquifer yield [1]. Reported that poorly connected aquifer materials result in reduced groundwater flow and, consequently, lower yields [38].

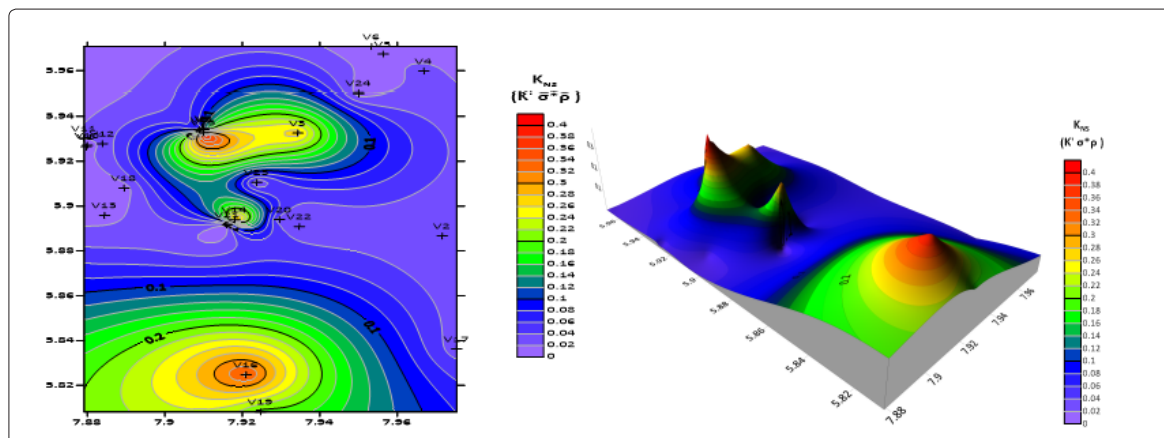


Figure 11: 2D & 3D geospatial model of KNS

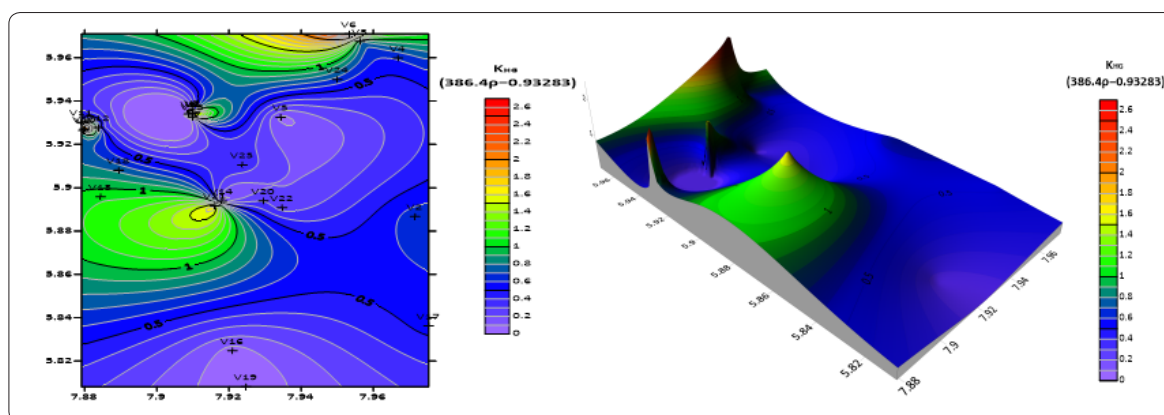


Figure 12: 2D & 3D geospatial model of KHG

Transmissivity

TNiwas & Singhal, TNS

Aquifer Transmissivity (T) using TNiwas & Singhal (TNS) model within the study area was calculated as a product of the diagnostic constant ($k'\sigma$) and transverse resistance (RT) ($k'\sigma RT$). Average diagnostic constant ($k'\sigma$) of 0.0000238 and 0.0000114 was used for Amasiri and Afikpo respectively for the study area, T_{NS} value was highest at Comprehensive Secondary School, Amata-Akpoha on VES 5, with T_{NS} value of 13.43160021m²/day. Least T_{NS} value of 0.03819424m²/day, was observed at Okobo-Ihie, Amasiri 1 on VES 10. Average T_{NS} value in the study area recorded was 2.010661323m²/day and 1.633659023m²/day for Amasiri and Afikpo respectively (Fig. 13). The ground water potential within the area of study is intermediate, low, very low to imperceptible according to Krasny (1993) which classify values from 100-10 m²/day, 10-1m²/day, 1-0.1 m²/day and <0.1 m²/day as corresponding magnitude values.

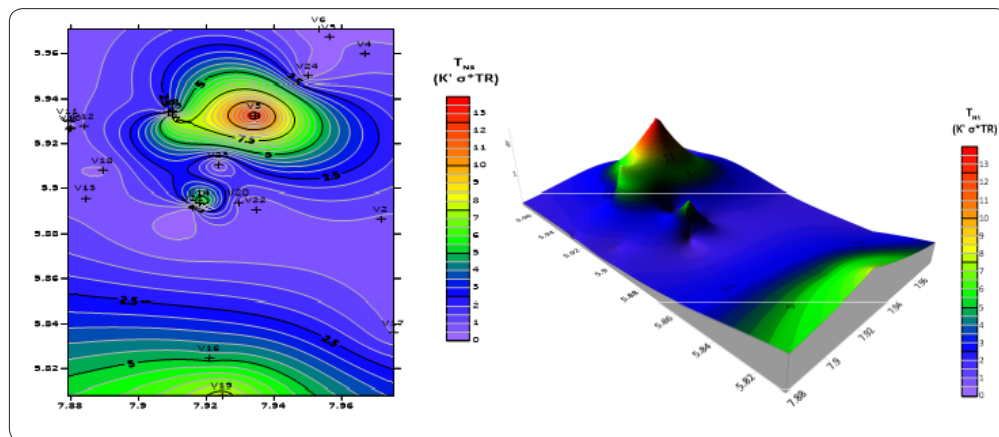


Figure 13: 2D & 3D geospatial model of TNiwas and Singhal

Conclusion

This study employed Vertical Electrical Sounding (VES) and geoelectrical interpretation techniques to delineate subsurface lithology and evaluate aquifer parameters in the study area. The integration of resistivity values, layer thicknesses, transverse resistance, longitudinal conductance, hydraulic conductivity, and transmissivity from pumping tests and using empirical relationships from Niwas and Singhal and Heigold enabled a comprehensive assessment of the aquifer potential. The interpreted VES curve types revealed predominantly multiple KH, HK, QK, and QH, which correspond to varying subsurface lithologic successions. High resistivity sand and sandstone units identified from A and H type curves constitute the principal aquiferous formations in the area. Aquifer depths vary significantly across the study area, with an average depth of 58.19m reflecting heterogeneous nature of the in subsurface and appreciable average thickness of the area at 11.8m. Hydraulic conductivity and transmissivity values derived from empirical relationships show moderate groundwater productivity potential, typically highlighting Government College, Akanu Ibiam Federal polytechnic, Unwana, Amata Akpoha, Ibii and some other zones as potentially viable locations for groundwater exploitation. Overall, the integration of pumping tests and geoelectrical sounding data adopted in this study has proven effective in delineating aquifer geometry, estimating hydraulic parameters, and identifying zones suitable for sustainable groundwater exploitation [39-41].

Recommendations

Based on the study of this area, it is recommended that:

1. For sustainable water supply, boreholes should be drilled within the locations characterized by high-by-high transverse resistance and transmissivity values, most importantly locations underlain by thick sandy formations identified from A and H type VES curves. Deeper, well saturated sand units should be a target for drilling.
2. Aquifer vulnerability studies should be done in the area

especially for shallow aquifers to ascertain the aquifer protection capacity before drilling.

Author Contribution and Acknowledgment

This work was carried out in collaboration among all authors.

Nnabuikie Vincent Edeh: Conceptualization, Data acquisition, Methodology, Formal analysis, Writing – original draft.
Alexander Iheanyichukwu Opara: Supervision, Project administration, Review & Editing, Validation, geospatial plots.
Chidiebere Charles Agoha: Co-supervision, Data curation, Technical Validation, Review & Editing. All authors read and approved the final manuscript.

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