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Modeling of Geo-Hydraulic Properties from Geophysical and Hydro-Geologic Data in the Imo River Basin, Southeast Nigeria and Similar Geological Formations

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ABSTRACT
This research aims to develop a unique geophysical model that can forecast aquifer geo-hydraulic features reliably from geophysical and hydro-geologic data in the Imo River Basin, Southeast Nigeria, and related geological Formations. To determine the Dar-Zarrouk characteristics, 569 vertical electrical soundings data were collected and analyzed. Dar-Zarrouk was integrated with the diagnostic association between the K values recorded in reference wells and electrical soundings data for the estimation. In the Ameki Formation, a mean transmissivity Tmean = 193.5 m2/day and a mean storativity 5.54 10-5 were calculated. A mean Transmissivity Tmean of 784 m2/day and a mean Storativity of 5.11 x 10-5 were found in the Benin formation. The mean storativity of the aquifers in the Imo Shale Formation is 3.48 10-5, and the mean transmissivity is 205.2 m2/day. The Ogwasi/Asaba Formation's aquifers have a mean transmissivity Tmean = 100.2 m2/day compared to the Nsukka Formation's aquifers' mean transmissivity Tmean = 211.5 m2/day with a mean storativity of 4.8 10-4. Niwas & Singhal, the Heigold model, and the newly generated geophysical model were used to estimate the hydraulic conductivity in the research area, with average values of 13.19 m/day, 1.74 m/day, and 4.62 m/day, respectively. The aquifer depth in the research region is 115.5m, whereas the average thickness of the aquiferous units is 39.8m. The average aquifer resistivity is 1963.2m and the average aquifer conductivity is 0.00186 sm-1. A comparison of the estimates of hydraulic conductivity obtained through the different methods and generated new model shows that the New Model values are very similar to the existing pumping test data.

Keywords:
Aquifer Storativity,
Aquifer Transmissivity,
Da-Zarrock parameters,
Geo – Hydraulic properties,
New Model.

INTRODUCTION

Generally, geophysical methods are cost-effective, non-destructive, and fast to implement as compared to direct in-situ measurements. Researchers conducted a number of experiments to comprehend the interaction between geophysical and hydrogeological parameters while taking into account the physical principles related to subsurface activities (Niwas and Singhal 1981; Niwas and Lima 2003). Ahmed et al. (1988) used a geo-statistical approach to investigate the relationships between transverse resistance and transmissivity. Youssef (2020) used a geostatistical approach to interpret the Dar-Zarrouk parameters calculated for surface electrical measurements, and from these parameters he produced the spatial distribution features of electric anisotropy, aquifer hydraulic properties, and groundwater quality.

Geology and Hydrogeology of the Study Area

The Imo River Basin is a region of around 9100 km^2 that lies between latitudes 4° 38'N and 6° 01'N and longitudes 6° 53'E and 7° 32'E. The boundaries are defined by its drainage splits on the surface.The two main sub-basins are Oramirukwa—Otamiri and Aba River. The Imo River estuary at the Atlantic Ocean establishes the southern border. The Udi-Okigwe-

Arochukwu and the Awka-Umuchu-Umuduru sedimentary cuestas, respectively, lie close to the north-eastern and north-western borders (Uma, 1989). The Imo River Basin is usually covered in two different types of rocks. Around 80% of the basin is made up of the Coastal Plain Sand, which includes non-indurated sediments from the Benin and Ogwashi-Asaba Formations and alluvial deposits close to the estuary at the southern end of the Imo River Basin.The remaining 20 percent is made up of a series of sedimentary rock units that move southwestward parallel to the regional dip of the formations, getting younger and younger as they do so. The oldest exposed formation in the basin is the Maastrichtian-aged Ajali Sandstone, which outcrops along with an NW-SE band at its northeastern edge (2 to 4 km width).It is made up of heavy, weakly cemented, friable sandstones (Uma, 1989). The Nsukka Formation (Maastrichtian-Lower Paleocene), which covers a comparatively wider area of land than the Ajali Sandstone, lies directly beneath it. It is made up of alternating layers of sandy shales, shales, and sandstones. It descends at an average 6° slant to the southwest. Unconformably covering the Nsukka Formation is the Paleocene–Lower Eocene Imo Shale. It is made up of a thick succession of dark-gray and blue shales with sporadic bands of clay-ironstones and sandstones below (Ekwe et al., 2006). The Ameki Formation (Eocene), which is composed of sand and sandstones, is the following form in the depositional sequence. According to Whiteman (1982) and Arua (1986), the lithologic units of the Ameki Formation can be divided into two main groups: the upper unit, which consists of fine to coarse sandstones and intercalations of calcareous shales and thin shelly limestone, and the lower unit, which consists of grey-green sandstone and sandy clay. The Ogwashi/Asaba Formation (Oligocene to Miocene), which is the following in the depositional sequence, is often composed of clays, sands, grits, and seams of lignite that alternate with gritty clay. Within the Imo Basin, this formation is distinguished by its dip and downdip pinch-outs. The Benin Formation, the largest of all the formations and one that spans more than half of the basin's surface, is found on top of the Ogwashi/Asaba Formation. Sands, sandstones, and gravel make up its majority, with interspersed clay and sandy clay. The sands are poorly sorted and have a fine-medium-coarse grain size. Figure 1 depicts a map of the study region.

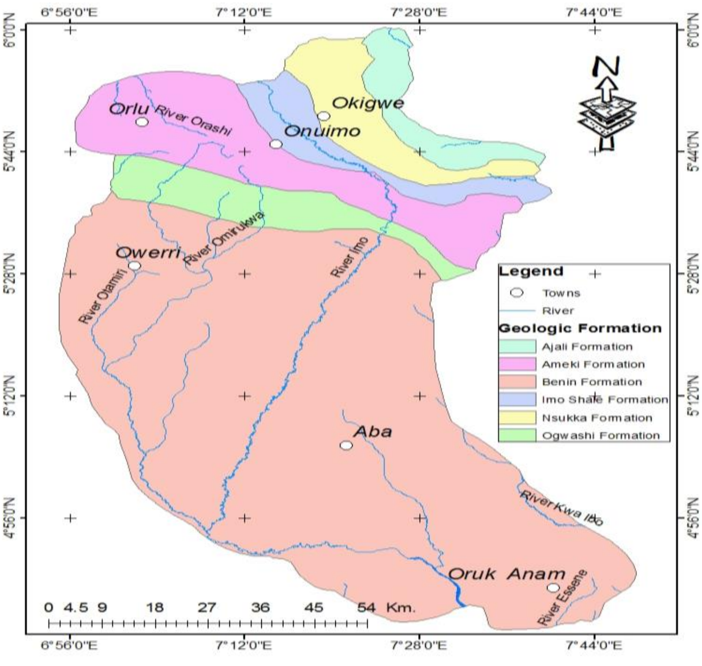


Figure 1: Geological Map of Anambra Imo River Basin (Uma,1989)

MATERIALS AND METHODS

The inquiry for the prediction of aquifer properties within the study region was conducted using three main methodologies. These include statistical modeling, hydrogeological inquiry (pump test), and geophysical investigation. The method's exact implementation is shown in detail in Figure 2. This study used a geophysical investigation technique called vertical electrical sounding. 569 vertical electrical sounding data were gathered using the Schlumberger array technique, with a maximum current electrode separation of 1000m. Figure 2 shows a flow chart that details the many methods this study used.

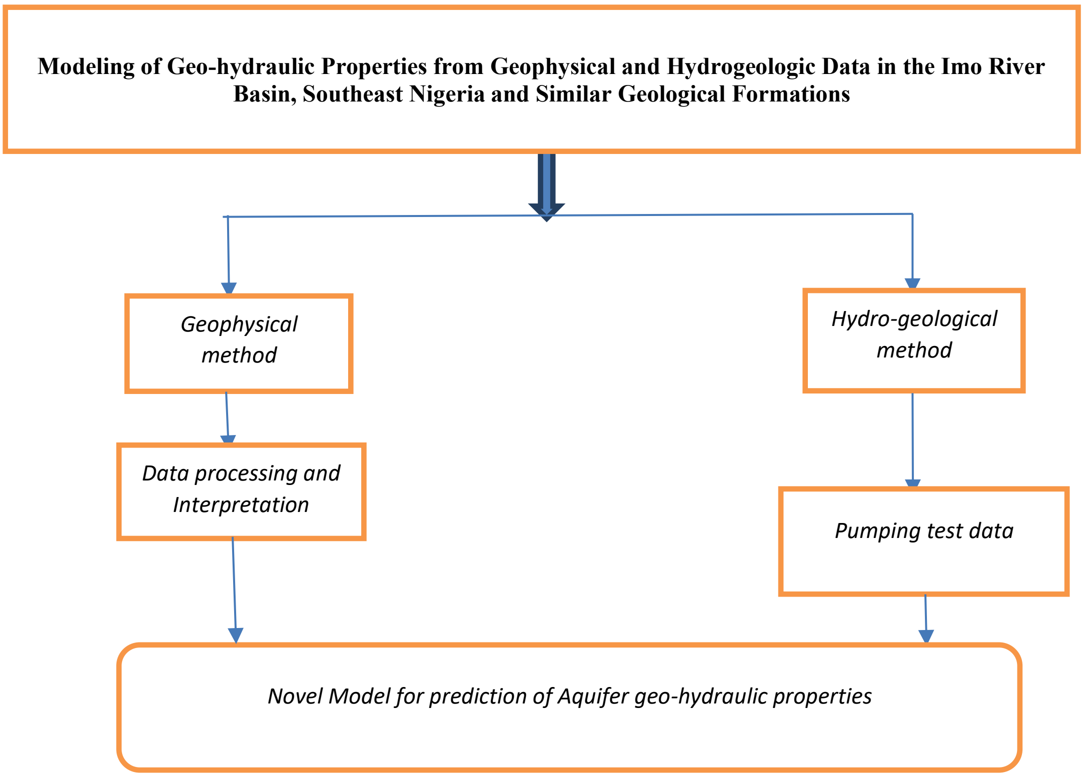


Figure 2: Flowchart Illustrating the Research Methods Used

Utilizing a partial curve matching technique and computer iteration program (WINRESIST), the collected VES data were evaluated in order to accurately estimate the layer parameters (layer resistivities and thicknesses). Groundwater was pumped during the pumping test operation from drilled boreholes while the aquifer's response was observed in terms of water level, discharge rate, and pumping time both before and after the pumping. The collected data were processed using the straight-line approach, and were drawn down was displayed with an arithmetic scale on the y-axis versus the logarithmic time scale on the x-axis.In order to estimate the Dar-Zarrouk parameters, which include transverse resistance, transverse resistivity, longitudinal resistivity (aquifer resistivity), and longitudinal conductance (Maillet 1947), layered parameters obtained from the VES were used.

A geoelectric layer is described by two fundamental parameters: its layer apparent resistivity (ρ_a) and its thickness (h). The geoelectric parameters were derived based on apparent resistivity and thickness, longitudinal conductance (S) as shown in equation 1:

$$S = h/\rho_a \qquad (1)$$

Where S is the longitudinal conductance, h is thickness and ρ_a is the apparent resistivity of the aquiferous layer. Transverse resistance (T) is presented in equation 2:

$$T = h.\rho_a \qquad (2)$$

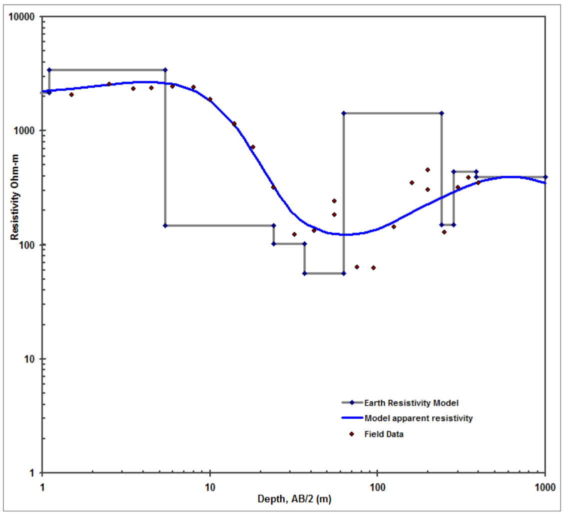
Where T is the transverse resistance, h is thickness and ρ_a is the apparent resistivity of the aquiferous layer. The parameters T and S were named the "Dar –Zarrouk Parameters "by Maillet (1947).

Niwas and Singhal (1981) noted that either of the two hypotheses $K\sigma$ = constant or K/σ = constant holds true for the study area and is also true for other areas with comparable geological settings and water quality. As a result, it is possible to determine the transmissivity values and their variation from place to place even for areas without boreholes by knowing the hydraulic conductivity (K) values of existing boreholes via pumping test and the electrical conductivity (σ) values of the aquifer extracted from the geo-electric data carried out at the borehole location (Niwas and Singhal 1981).

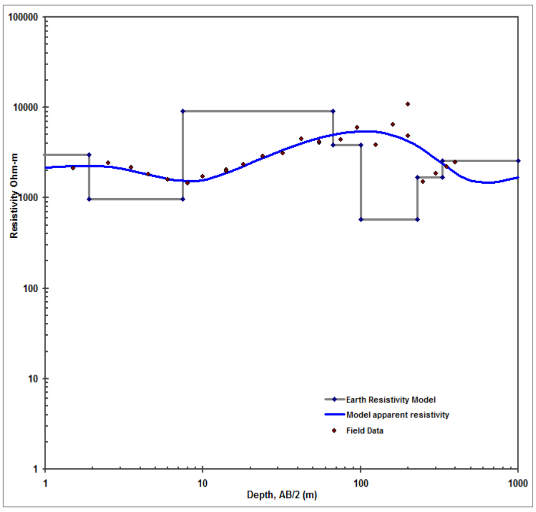
RESULTS AND DISCUSSION

Results Presentation

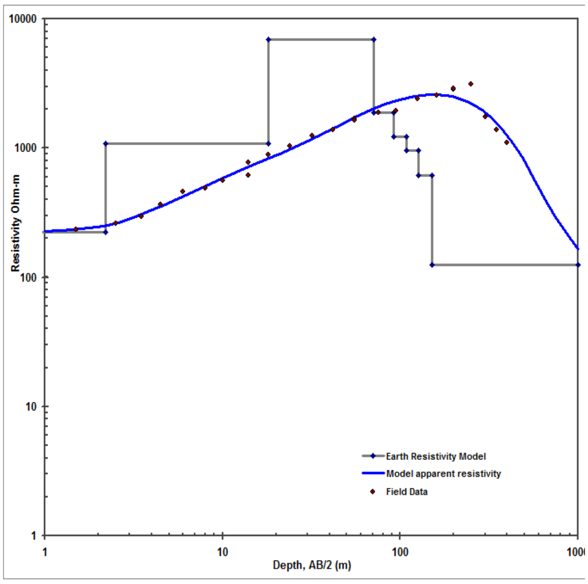
The arrangement of each sounding curve revealed the types of beds or layers between the surface and the maximum depth of penetration. This is true because the configuration of a VES curve depends on the number of layers in the subsurface, their thickness, and their relative resistivity ratios.



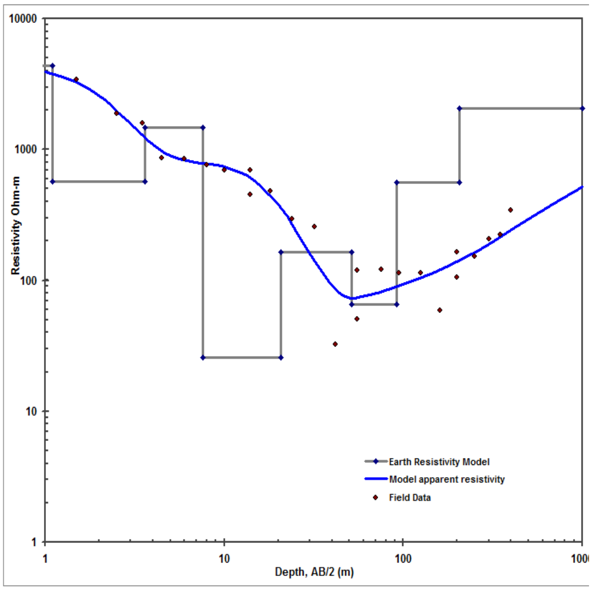
(a) Umololo- Okigwe



(b) Ovim -Isikwuato



(c)Ubaha- Nneato



(d) Anara

Figure 3: (a-d) Depicts Example Curves from the Study Area, While Table 1 Provides Quantitative Curve Descriptions for Boreholes (Niwas and Singhal 1981)

Figure 3 (a–d) shows typical representative geo-electric curves produced from the research area's resistivity data.

According to the quantitative curve description, the kinds identified include A, AH, AK, AKH, AQ, HA, H, HK, HKH, HQ, K, KA, KH, KHK, KK, KQ, Q, QH, QK, QKK, indicating facies or lithological changes in the research region as shown in figure 4 and table 1 below.

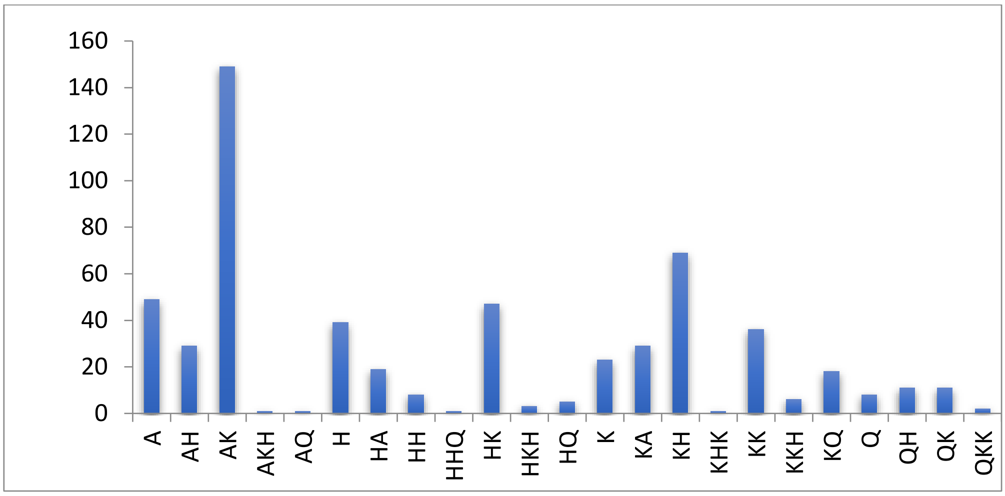


Figure 4: Bar Chart Showing Various Curve Types in the Study Area

Table 1: Statistical Representation of Curve Type in the Study Area

S/N	Curve Type	Frequency	Percentage (%)
1	A	49	8.67257
2	AH	29	5.13274
3	AK	149	26.3717
4	AKH	1	0.17699
5	AQ	1	0.17699
6	H	39	6.90265
7	HA	19	3.36283
8	HH	8	1.41593
9	HHQ	1	0.17699
10	HK	47	8.31858
11	HKH	3	0.53097
12	HQ	5	0.88496
13	K	23	4.0708
14	KA	29	5.13274
15	KH	69	12.2124
16	KHK	1	0.17699
17	KK	36	6.37168
18	KKH	6	1.06195
19	KQ	18	3.18584
20	Q	8	1.41593
21	QH	11	1.9469
22	QK	11	1.9469
23	QKK	2	0.35398

The AK type, which makes up around 26.37% of all curve kinds, is the most prevalent, as seen in the above table 1. The KH-type follows this (12.21 %). The general shape of the curves suggests and conjures up alternating layers of resistant and conductive material.

The study region's representative results of the interpreted layer parameters are presented in table 2, while the representation of the aquifer hydraulic parameters interpreted from the geo-electric section in the study region is shown in table 3 below.

Table 2: Results that are Typical of the Study Area's Interpreted Layer Parameters

VES No.	Location	No. of Layers	Layer Resistivity ρ (Ωm)										Layer Depth d (m)									Layer Thickness h (m)									Curve Type
			ρ_1	ρ_2	ρ_3	ρ_4	ρ_5	ρ_6	ρ_7	ρ_8	ρ_9	ρ_{10}	d1	d2	d3	d4	d5	d6	d7	d8	d9	h1	h2	h3	h4	h5	h6	h7	h8	h9	
AJ 01	Obilozu Ihite-Lokpa,Umunneochi	10	133	422	82	9.2	84	388	2780	2390	2140	3540	1.3	6.4	9.4	20	28.5	41.1	89	136	198	1.3	5.1	3	11	8.1	12.6	48.2	48	62	KH
AJ 02	Eziama Lopkaukwu Umuchieze,Umunneoch	10	64.7	263	34.1	4.6	230	81	28.6	38.6	51.1	48.2	0.9	3	4.4	7	19	35.4	71	115	167	0.9	2.1	1.4	3	11.6	16.4	35.4	44	52	KH
AJ 03	Ubahu Nneato,Umunneochi	10	260	1030	451	8100	4790	667	667	1330	2220	3240	0.7	8.2	19	37	59.1	81.7	106	142	172	0.7	7.5	11	18	22.4	22.6	24.3	36	30	A
AJ 04	Nkwoagu - Amuda,Isuochi,Umunneochi	10	184	284	12.4	70	20600	13100	11900	8700	6740	5810	0.9	2	7.3	17	77.6	118	114	174	235	0.9	1.1	5.3	9.6	60.7	40.4	-	60	61	H
AJ 05	Eluama Lokpoukwu Umuchieze,Umunneochi	10	45.7	463	4	4.1	43.4	208	303	227	174	211	0.6	2.4	6.3	13	21.9	46.5	89	138	186	0.6	1.8	3.9	6.8	8.8	24.6	42.7	49	48	KH
AM 40	Umudimoha -Amike	5	698	450	682	6988	1345	-	-	-	-	-	0.7	3	6.5	##	-	-	-	-	-	0.7	2.7	3.5	139	-	-	-	-	-	A
AM 41	Umuzike,Umuoba 1	9	880	2620	###	1620	2450	4110	6590	3690	1360	-	0.4	8.8	17	39	60.5	88.4	138	184	-	0.4	8.4	8.2	22	21.5	27.9	49.6	46	-	AK
AM 42	Ogberuru	6	3510	8300	1180	840	3560	8000	-	-	-	-	11	20	34	58	83.5	-	-	-	-	11	8.7	14	24	25.5	-	-	-	-	H
AM 43	Onunkwo Umuele	6	598	7360	598	3060	1400	1070	-	-	-	-	8.7	38	103	##	187	-	-	-	-	8.7	29	65	28	56	-	-	-	-	AK
AM 44	Umudim Umuele Amazano	10	3860	2330	406	3020	12100	11800	1700	9200	6430	5000	0.5	2.9	9.9	27	66.3	102	154	204	256	0.5	2.4	7	17	36.4	38.7	52	50	52	A
BN 195	Umuezea -Itu	10	574	2660	1520	7200	11300	2590	2100	1970	820	696	0.6	5.7	15	---	63.1	104	137	171	209	0.6	5.1	9.1	12	36.4	40.9	33	34	38	AK
BN 196	Umuakam Eziudo	6	1030	637	2590	7320	8100	5060	-	-	-	-	9.6	19	35	61	96.4	-	-	-	-	9.6	9.2	16	26	36.3	-	-	-	-	H
BN 197	Amudi Obizi	5	3470	2120	3920	5820	311	-	-	-	-	-	13	51	60	##	-	-	-	-	-	13	39	38	32	-	-	-	-	-	Q
BN 198	Okwelle 1	8	193	4210	1040	1950	2900	1810	645	300	-	-	0.6	3.5	10	23	44.4	60.7	79	-	-	0.6	2.9	6.9	13	21.5	16.3	17.9	-	-	AK
BN 199	Okwele 2	9	193	5260	550	732	9000	3480	1890	1400	222	-	0.6	2.5	5	13	38.4	59.9	80	102	-	0.6	1.9	2.5	8	25.4	21.5	20.4	22	-	AK
IS 501	Copmp. Health Center,Osu	10	604	502	29.8	4.9	71	236	260	1250	1650	2100	0.9	1.9	4.9	10	18.9	32	54	91	125	0.9	1	3	4.9	9.1	13.1	21.5	38	34	H
IS 502	Umuzoho -Ezihe	8	61	186	1570	8300	2130	382	298	87	-	-	0.4	7.2	13	30	44.5	64	91	-	-	0.4	6.8	5.3	18	14.2	19.5	26.9	-	-	AK
IS 503	Umuduruobi Umuohiri Osuachara	10	146	3080	102	171	53.2	49.8	111	249	232	5140	0.4	1.9	14	36	53.9	70.6	91	114	129	0.4	1.5	12	22	17.9	16.7	20.6	23	15	KH
IS 504	Isiebu Umuduru	10	101	2640	23.5	7.4	291	69.2	29.2	23	30.2	9	0.4	1.1	2.6	11	42.7	66.6	96	128	163	0.4	0.7	1.5	8	32.1	23.9	29.1	32	35	KHK
IS 505	Ewuru - Umunachi	10	445	423	5	124	364	511	478	437	520	3190	0.9	7.1	21	35	55.5	80.6	105	128	156	0.9	6.2	14	14	20.8	25.1	24.4	23	28	H
NS 517	Obichie Ovim,Isukwuato	7	582	31400	1860	1380	686	207	13.5	-	-	-	0.7	4.1	8.2	78	93.4	113	-	-	-	0.7	3.4	4.1	69	15.9	19.6	-	-	-	KQ
NS 518	Umuora Agbor Umunneukwu,Isikwuato	10	165	513	1000	1190	49.1	1.8	13.4	40.1	47.8	190	0.6	4.1	6	10	15.3	37	54	77	102	0.6	3.5	1.9	4.2	5.1	21.7	17.1	23	25	KH
NS 519	Umusuh Village,Eluama,Isikwuato	9	223	3460	471	7850	1600	3540	2070	1390	860	53	0.5	2.9	10	23	51,1	71.1	93	118	-	0.5	2.4	7.1	13	28.4	20.6	21.1	25		KK
NS 520	Umuovo - Eluelu,Umuahia South	10	1550	9500	1010	4010	1820	860	1650	2460	2680	7620	0.5	1.9	7	52	79.5	125	164	204	244	0.5	1.4	5.1	45	27.9	45.5	39	40	40	KKH
NS 521	Oguduasa Erosion Site,Isikwuato	10	2320	688	4880	267	714	8600	34600	13700	6520	4930	0.6	1.7	4.2	12	21.9	41.6	117	186	291	0.6	1.1	2.5	8.1	9.6	19.7	75.4	69	##	HH
OG 544	Umuali 1 Mbeke (Lt.Col Okejiegbe's Compound)	10	1650	714	5760	340	71.2	24.1	71.8	147	220	1880	1	2.9	8.7	42	60.1	92	117	143	173	1	1.9	5.8	33	18.2	31.9	25	26	30	HH
OG 545	Anara	10	271	52.1	435	1180	5410	1700	679	421	305	49.3	0.8	4.5	6.8	10	29.3	44.8	61	79	99.6	0.8	3.7	2.3	3.5	19	15.5	16.5	18	21	HK
OG 546	Umuozo Ezumoha	10	295	27100	4840	632	2640	3190	4130	10900	4280	7390	0.4	3.1	8	33	60.1	86.4	121	179	226	0.4	2.7	4.9	25	26.7	26.3	34.6	58	47	KH
OG 547	Umuezeala-Umuduru	7	741	1660	2620	32200	7200	3040	733	-	-	-	0.6	3.2	6.1	20	39.7	74.3	-	-	-	0.6	2.6	2.9	14	19.5	34.6	-	-	-	AK
OG 548	Umulolo-Oboh,Osuama	8	502	4410	1030	40.8	232	1720	170	101	-	-	0.5	2	19	42	62.1	152	243	-	-	0.5	1.5	17	24	19.8	89.9	91	-	-	KH

Table 3: Representation of the Geoelectric Section Interpreted Aquifer Hydraulic Parameters in the Study Area

VES No.	Aquifer				Transverse Resistance $R = h\rho$ (Ωm^2)	Longitudinal Conductance $C = h\rho^{-1}$ (Ω^{-1})	Hydraulic Conductivity from Pumping Test K (m/day)	Diagonastic Constant Kσ	Average Diagonastic Constant Kσ(ave)	Trasmissivity T=Kh (m^2/day)	Storativity $S=1.3h/10^6$	Diffusivity $D = TS^{-1}$ (m^2/day)	Hydraulic Conductivity from N& S Model (K_{NSM}) $KNS = K\sigma\rho$	Hydraulic Conductivity from New Model (K_{NM})	Hydraulic Conductivity from Heigold Model(K_{HM}) KH $=386.40\sigma^{-0.93283}$
	Depth (m)	Thickness h (m)	Resistivity ρ (Ωm)	Conductivity $\sigma = \rho^{-1}$ (Sm^{-1})											
AJ 01	89.3	46.7	2780	0.000359712	129826	0.016798561				238.17	0.00006071	3923076.923	9.0379468	4.798479039	0.236771165
AJ 02	115	52	38.6	0.025906736	2007.2	1.347150259				265.2	0.0000676	3923076.923	0.125490916	6.641564144	12.79442823
AJ 03	142	30	1330	0.00075188	39900	0.022556391				153	0.000039	3923076.923	4.3239098	5.07502612	0.470993151
AJ 04	174	61	8700	0.000114943	530700	0.007011494				311.1	0.0000793	3923076.923	28.284222	4.399947995	0.081683695
AJ 05	89.2	48.8	303	0.00330033	14786.4	0.161056106				248.88	0.00006344	3923076.923	0.98507118	5.678862675	1.871858391
AM 40	184	46	3690	0.000271003	169740	0.012466125				310.04	0.0000598	5184615.385	49.61158506	1.454637715	0.181805875
AM 41	83.5	25.5	3560	0.000280899	90780	0.007162921				171.87	0.00003315	5184615.385	47.86375144	1.516814477	0.187991415
AM 42	187	56	1330	0.00075188	74480	0.042105263				377.44	0.0000728	5184615.385	17.88168242	4.785636938	0.470993151
AM 43	153	46	1400	0.000714286	262200	0.008070175				310.04	0.0000598	5184615.385	18.8228236	4.507577425	0.121183747
AM 44	175	50	1700	0.000588235	235000	0.010638298				337	0.000065	5184615.385	22.8562858	3.593690914	0.145075499
BN 195	137	33	2100	0.00047619	69300	0.015714286				156.75	0.0000429	3653846.154	6.0739707	4.014299971	0.307589349
BN 196	35.2	16.4	2590	0.0003861	42476	0.006332046				77.9	0.00002132	3653846.154	7.49123053	3.488075749	0.252934866
BN 197	51.2	39.2	2120	0.000471698	83104	0.018490566				186.2	0.00005096	3653846.154	6.13181804	3.988886903	0.304881615
BN 198	60.7	16.3	1810	0.000552486	29503	0.009005525	4.75	0.002624309	0.002892367	77.425	0.00002119	3653846.154	5.23518427	4.434576023	0.353326989
BN 199	80.3	20.4	1890	0.000529101	38556	0.010793651				96.9	0.00002652	3653846.154	5.46657363	4.307917136	0.339355782
BN 200	80.4	33.9	1140	0.000877193	38646	0.029736842				161.025	0.00004407	3653846.154	3.29729838	6.044640815	0.543831758
IS 501	91	37.5	1250	0.0008	46875	0.03				252.75	0.00004875	5184615.385	73.848185	7.91151708	0.499052862
IS 502	44.5	14.2	2130	0.000469484	30246	0.006666667				95.708	0.00001846	5184615.385	125.8373072	7.953796329	0.30354618
IS 503	91.2	20.6	111	0.009009009	2286.6	0.185585586				138.844	0.00002678	5184615.385	6.557718828	7.722250752	4.776375736
IS 504	42.7	14.1	291	0.003436426	4103.1	0.048453608				95.034	0.00001833	5184615.385	17.19185747	7.797037083	1.943765282
IS 505	80.6	25.1	511	0.001956947	12826.1	0.049119374				169.174	0.00003263	5184615.385	30.18913803	7.841061837	1.149584368
OG 544	143	26	147	0.006802721	3822	0.176870748				107.38	0.0000338	3176923.077	0.299096784	4.990104755	3.675348185
OG 545	44.8	15.5	1700	0.000588235	26350	0.009117647	2.39	0.001405882	0.002034672	37.045	0.00002015	1838461.538	3.4589424	2.394253807	0.374608347
OG 546	60.1	26.7	2640	0.000378788	70488	0.010113636				63.813	0.00003471	1838461.538	5.37153408	2.098087928	0.248463344
OG 547	74.3	34.6	3040	0.000328947	105184	0.011381579				82.694	0.00004498	1838461.538	6.18540288	2.011142242	0.217825216
OG 548	152	89.9	1720	0.000581395	154628	0.052267442				214.861	0.00011687	1838461.538	3.49963584	2.385867542	0.370543429

The hydraulic conductivity, transmissivity, storativity, and diffusivity of an aquifer are all highly helpful indicators of the location of prolific aquifers. According to Fetter (1994), hydraulic conductivity is a material's capacity to move fluids down a single hydraulic gradient. The unit of measurement is m/day and is denoted by K. In this investigation, K was calculated by multiplying the diagnostic constant K with the apparent resistivity of the aquifer.

The hydraulic conductivity values determined in 1979 using the Heigold model, employing the formula KH =386.40-0.93283, range from 0.0745 m/day to 37.467 m/day, with a mean value of 1.736 m/day, as shown in table 3 and figure 5. The estimated hydraulic conductivity values from Niwas & Singhals, 1982 vary from 0.55 m/day to 125.84 m/day with a mean value of 13.19 m/day, as shown in table 3 and figure 5.

In this study, the hydraulic conductivity values have been calculated using a new model that is formation sensitive via the following model equations: equ.1 (Ajali Formation), equ.2 (Ameki Formation), equ.3 (Benin Formation), equ.4 (Imo Shale Formation), equ.5 (Nsukka Formation), and equ.6 (Ogwasi/Asaba), respectively. On the other hand, figures 5 and 6 depict the estimated aquifer hydraulic conductivity obtained using the Heigold model, Niwas, and Singhals.

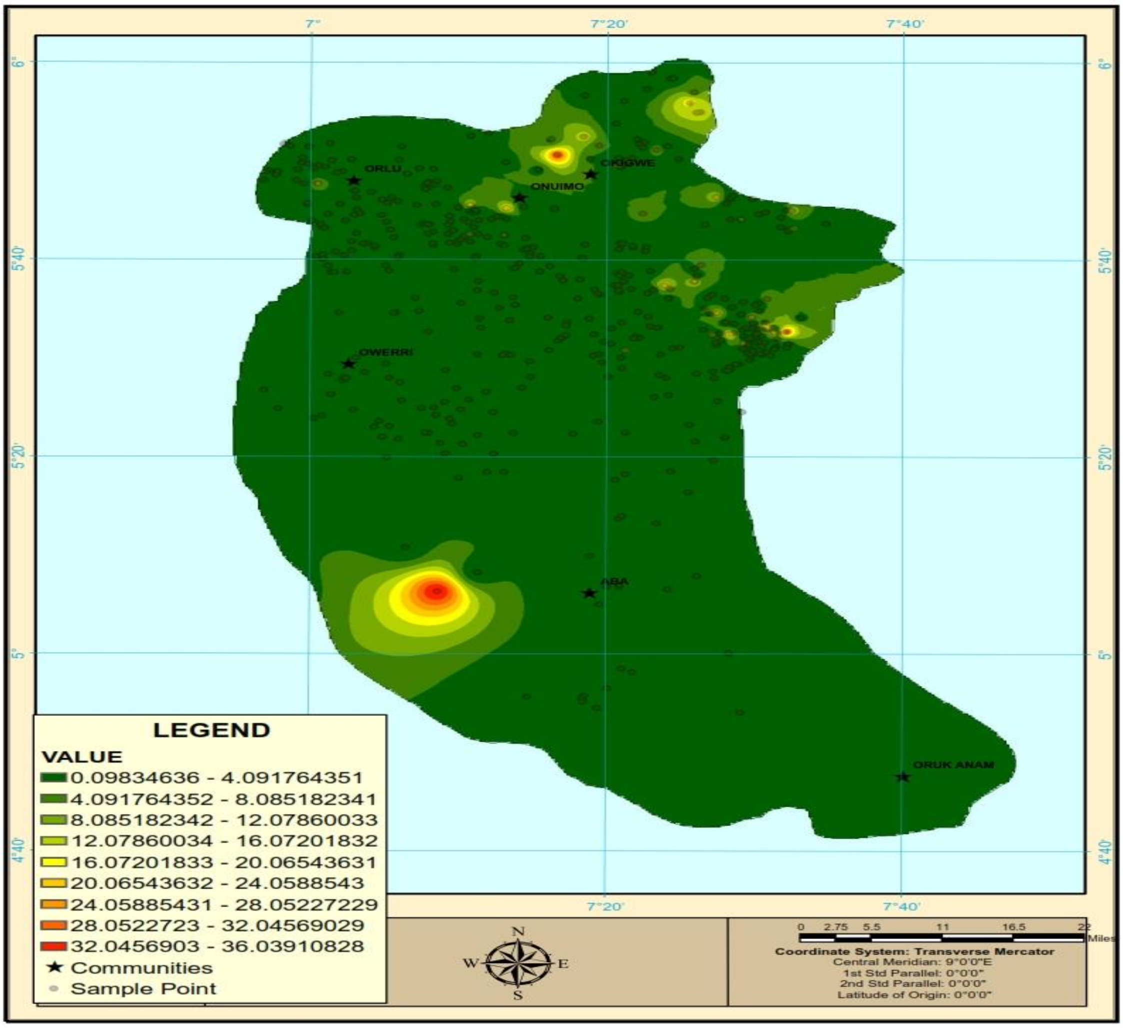


Figure 5: Map Showing Estimated Hydraulic Conductivity Using the Heigold Model (1979)

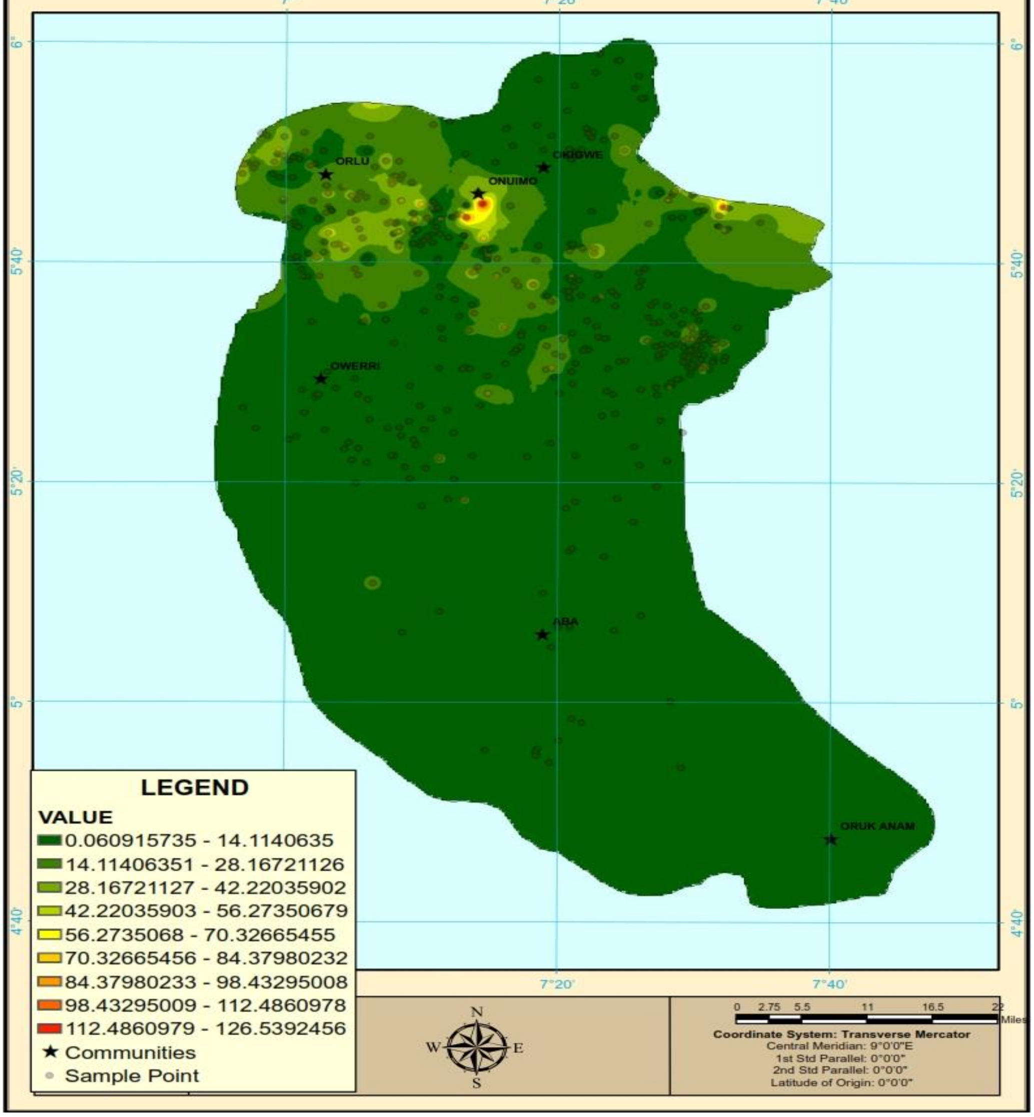


Figure 6: Map Showing Estimated Aquifer Hydraulic Conductivity from Niwas & Singhals (1981)

Table 4 below shows statistics regarding the Ajali Formation's aquifer conductivity and pumping test results. As illustrated in figure 7, where a model equation (equ.3) was generated, the available hydraulic conductivity (pump test) values are plotted against the aquifer conductivity. The correlation coefficient of 1 shows that the parameters have a good connection. The hydraulic conductivity of the Ajali Formation can be easily determined if the aquifer conductivity is known, as shown in equation 3 below.

Table 4: Resistivity, Conductivity, and Pumping Test Values for Ajali Formation

Resistivity(Ωm)	Conductivity(sm^{-1})	Pumping test(m/day)
1230	0.000813008	5.1
2080	0.000480769	4.9

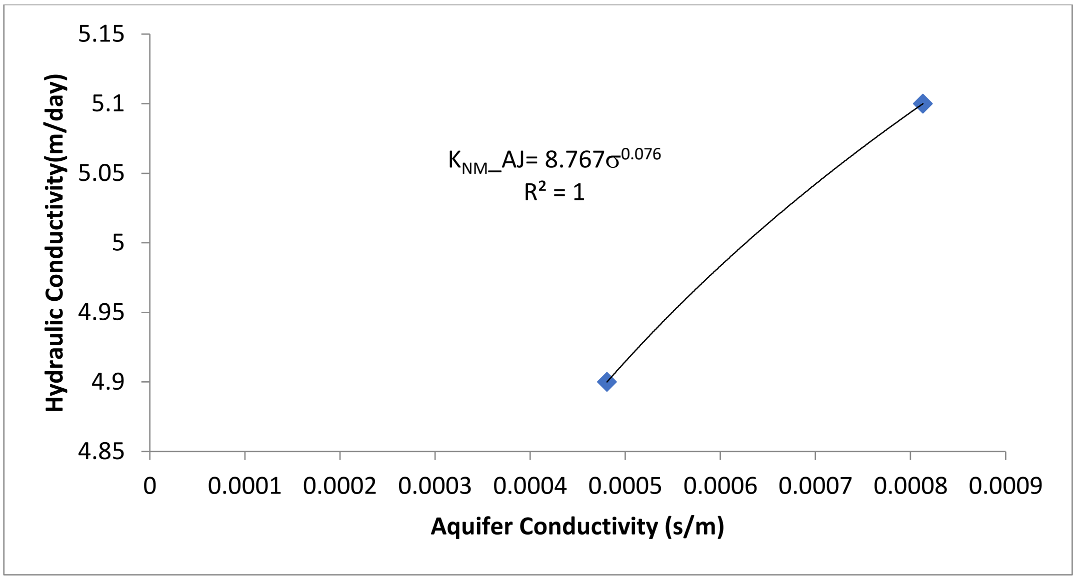


Figure 7: Shows a Plot of the Ajali Formation's Aquifer Hydraulic Conductivity vs its Aquifer Conductivity

Model equation (3) for Ajali Formation is generated from the plot of hydraulic conductivity 9 pumping test) against aquifer conductivity as shown in figure 7 (Heigold, 1979):

$K_{NM-AJ} = 8.767\sigma^{0.076}$ (3)

Table 5 shows the Ajali Formation's aquifer conductivity and pumping test results. Figure 8 shows a plot of the available hydraulic conductivity (pump test) measurements vs the aquifer conductivity along with a model equation (equation 4). The parameters are strongly correlated, as shown by the correlation coefficient of 0.872.

If the aquifer conductivity is known, it is simple to calculate the hydraulic conductivity of the Ameki Formation, as indicated in equation 4:

Table 5: Ameki Formation: Resistivity, Conductivity and Pumping Test values

Resistivity(Ωm)	**Conductivity (S/m)**	**Pumping Test (m/day)**
1260	0.000793651	4.53
1880	0.000531915	3.2
1080	0.000819672	5.83

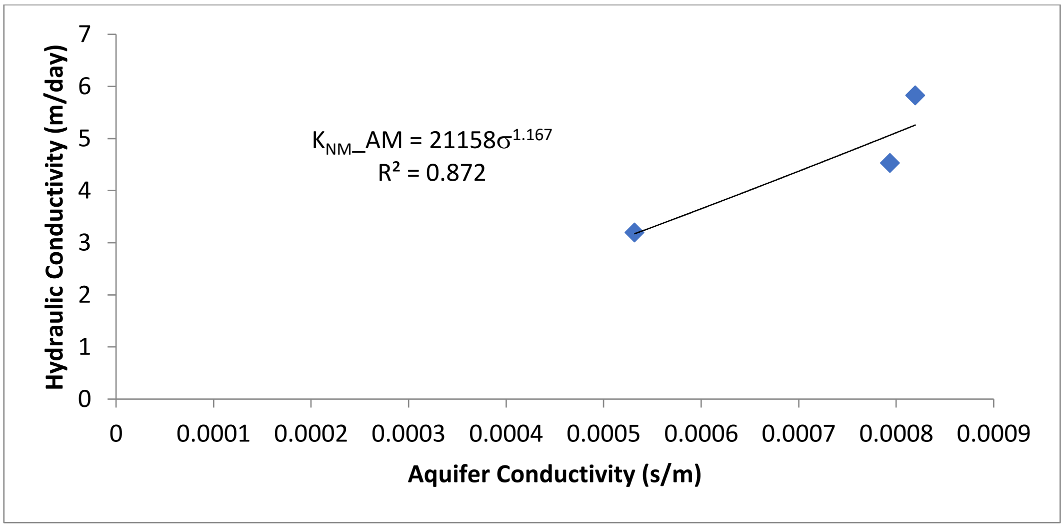


Figure 8: Shows a Plot of Hydraulic Conductivity of the Ameki Formation Aquifer vs Aquifer Conductivity

Model equation (4) for Ameki Formation is generated from the plot of hydraulic conductivity (pumping test) against aquifer conductivity as shown in figure 8 (Heigold, 1979):

$K_{NM-AM} = 21155\sigma^{1.167}$ (4)

Aquifer conductivity and the results of the Ajali Formation pumping test are displayed in table 6 below.Figure 9 displays a graph of the available hydraulic conductivity (pump test) measurements against the aquifer conductivity together with a model equation (equ. 5) that was created. The metrics' significant link, as shown by the derived correlation coefficient of 0.914, is clear.

Equation 5 demonstrates how knowing the aquifer conductivity makes it simple to calculate the hydraulic conductivity of the Benin Formation.

Table 6: Benin Formation: Resistivity, Conductivity and Pumping Test Values

Resistivity (Ωm)	Conductivity (S/m)	Pumping Test (m/day)
1810	0.000552486	4.75
5650	0.000867257	4.9
1700	0.000588824	4.8
1180	0.000847458	6.57
1970	0.000507614	4.06
1120	0.000892857	7
6820	0.000146628	1.99
3410	0.000293255	2.39
1160	0.000862069	5.62

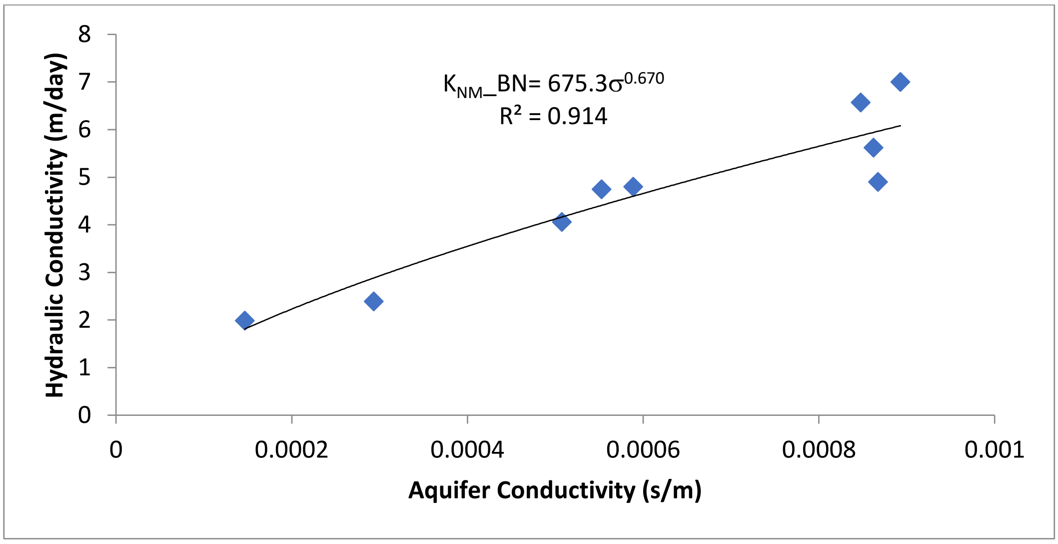


Figure 9: A Plot of the Benin Formation's Aquifer Hydraulic Conductivity Against Aquifer Conductivity

Model equation (5) for Benin Formation is generated from the plot of hydraulic conductivity (pumping test) against aquifer conductivity as shown in figure 9. (Heigold (1979)

$$K_{NM\text{-}BN} = 675.3\sigma^{0.670} \quad (5)$$

Table 7 provides data on aquifer conductivity and pumping tests for the Imo Shale Formation. Plotting the available hydraulic conductivity (pump test) measurements against the aquifer conductivity yields a model equation (equ.6), as shown in figure 10. The achievement of a correlation coefficient of 1 illustrates the significance of the relationship between the parameters. If the aquifer conductivity is known, it is simple to calculate the hydraulic conductivity of the Imo Shale Formation, as indicated in equation 6 below.

Table 7: Resistivity, Conductivity, and Pumping Test Values for Imo Shale Formation

Resistivity (Ωm)	Conductivity (S/m)	Pumping Test (m/day)
142	0.000704225	8.16
130	0.007692308	7.89

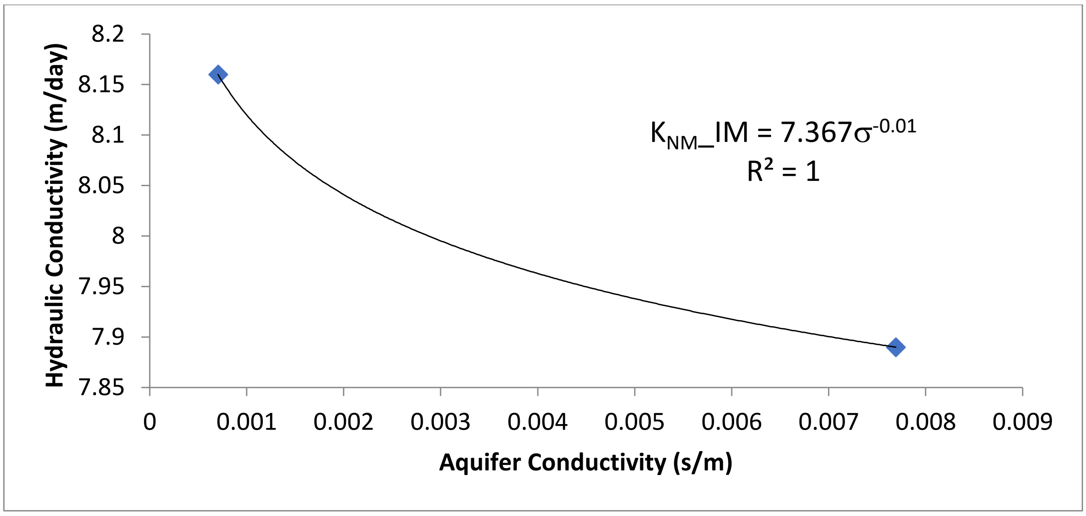


Figure 10: A plot of Imo Shale Formation Aquifer Hydraulic Conductivity Against Aquifer Conductivity

Model equation (6) for Imo Shale Formation is generated from the plot of hydraulic conductivity (pumping test) against aquifer conductivity as shown in figure 10.
(Heigold (1979)

$K_{NM\text{-}IM} = 7.367\sigma^{0.01}$ (6)

The Nsukka Formation's aquifer conductivity and pumping test data are displayed in table 8 below. Plotting the available hydraulic conductivity (pump test) measurements against the aquifer conductivity values results in the generation of model equation (equ.7) as seen in figure 11. The significant association between the parameters is shown by the achievement of a correlation coefficient of 1. The hydraulic conductivity of the Nsukka Formation can be easily calculated using equation 7 if the aquifer conductivity is known.

Table 8: Nsukka Formation Resistivity, Conductivity, and Pumping Test Values

Resistivity (Ωm)	**Conductivity (S/m)**	**Pumping Test (m/day)**
343	0.002915494	5.01
173	0.005780347	4.13

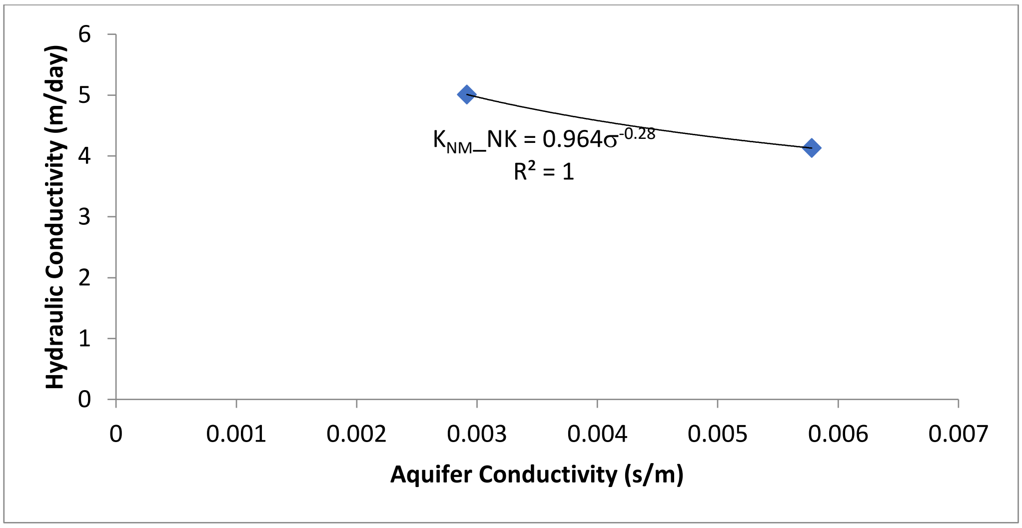


Figure 11: A Plot of the Nsukka Formation's Aquifer Conductivity and Hydraulic Conductivity

Model equation (7) for Nsukka Formation is generated from the plot of hydraulic conductivity (pumping test) against aquifer conductivity as shown in figure 11. (Heigold (1979)

$K_{NM\text{-}NS} = 0.964\sigma^{0.28}$ (7)

Table 9 below provides statistics for the Ogwasi/Asaba Formation's aquifer conductivity and pumping test results. Figure 12 shows a plot of the available hydraulic conductivity (pump test) measurements vs the aquifer conductivity using a model equation (equ.8) that was created. The significant association between the parameters is shown by the achievement of a correlation coefficient of 1. The hydraulic conductivity of the Ogwasi/Asaba Formation can be easily determined if the aquifer conductivity is known, as shown in equation 8 below.

Table 9: Ogwasi/Asaba Formation: Resistivity, Conductivity, and Pumping Test Values

Resistivity (Ωm)	Conductivity (S/m)	Pumping Test (m/day)
1700	0.000588235	2.39
1040	0.000961538	2.77

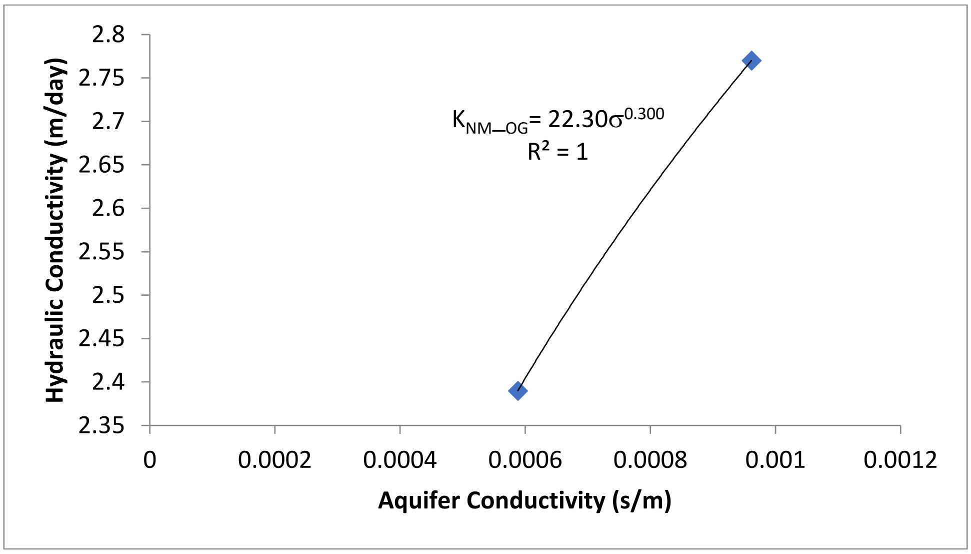


Figure 12: A Plot of the Ogwasi/Asaba Formation's Aquifer Conductivity and Hydraulic Conductivity

Model equation (8) for Ogwasi/Asaba Formation is generated from the plot of hydraulic conductivity (pumping test) against aquifer conductivity as shown in figure 12. (Heigold (1979)

$$K_{NM\text{-}OG} = 22.30\sigma^{0.300} \quad (8)$$

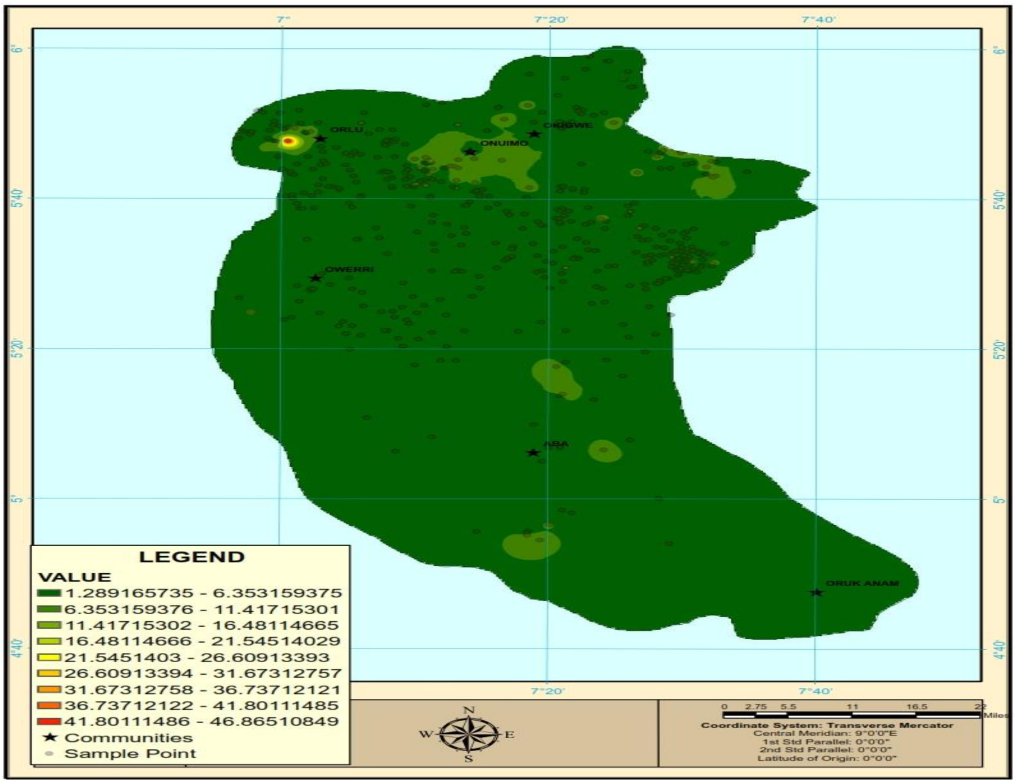


Figure 13: Map of Aquifer Hydraulic Conductivity Estimated from New Model in the study area

Discussion

The parameters of the aquifer layer, such as resistivity, depth to the water table, and aquifer thickness of the research area, were determined by analyzing the geo-electric curves. According to Ekwe et al. (2012), Eke et al (2015), Ejiogu et al 2019; Emberga et al 2019; the interpretation of geo-sounding data and geological information from available boreholes had a high degree of agreement.

Groundwater exploration is frequently conducted using the vertical electrical resistivity sounding technique, which has been implemented successfully in numerous locations (Onuoha, K.M., and Mbazi, F.C.C., 1988). Despite the vast range of applications, this technique has two common drawbacks, namely the equivalency and suppression issues (Zohdy A.A.R., 1976).

The thickness and resistivities of the various subsurface layers can, however, be calculated from the surface resistivity measurements using computer-oriented direct interpretation techniques, which were commonly employed in this work. Furthermore, unlike conventional curve matching techniques, computer iterative modeling techniques frequently lack human bias.

The aquifer's electrical and geometrical properties were analyzed, and the results showed that the resistivity of the aquifer ranged from 16.38 m to 4772 m, with a mean of 1963 m. The aquifer thickness ranges from 5.7 m to 123 m with a mean value of 47.3 m, while the depth to the water table ranges from 10 m to 310 m with a mean value of 89.3 m. The results of the current study are in close accord with those of past studies conducted in the area, and they have helped to map out areas for the drilling of productive boreholes in the study area (Uma., 1989; Opara et al.,2012; Ekwe and Opara., 2012; Ugada et al.,2013; Ejiogu et al.,2019Emberga et al,2019).The hydraulic conductivity of the aquifer in the research area was calculated using Niwas & Singhal (1981), Heigold (1979), and the new model proposed and used in the present work. Average values of 13.19 m/day, 1.74 m/day, and 4.62 m/day were obtained using these methods, respectively. The Imo Formation had the lowest aquifer hydraulic conductivity, while the Benin Formation had the highest value. According to Opara et al. (2012), the Benin Formation has high aquifer potentials and an estimated high aquifer hydraulic conductivity value that ranges between 5.49 and 6.63 m/day. The outcomes of previous tests carried out close by are comparable to the expected hydraulic conductivity levels in the study area (Fatoba et al. 2014; Ebong et al. 2014).

According to estimates of hydraulic characteristics derived from resistivity measurements, the aquiferous units in the Ajali Formation have a mean transmissivity Tmean of 140.8 m^2/day and a mean storativity of 5.3 10^{-5}. In the Ameki Formation, mean storativity 5.5410^{-5} and mean transmissivity Tmean = 193.5 m^2/day were calculated. The mean Transmissivity Tmean and mean Storativity of the Benin formation were both 784 m^2/day and 5.11 x 10^{-5}, respectively. The aquifers in the Imo Formation have a mean transmissivity Tmean of 205.2 m^2/day and a mean storativity of 3.48 10-5. The aquifers in the Nsukka Formation have a mean transmissivity Tmean = 211.5 m^2/day with a mean storativity of 4.810^{-4} while the aquifers in the Ogwasi/Asaba Formation have a mean transmissivity Tmean = 100.2 m^2/day with a mean storativity of 4.8610^{-5}. The Benin Formation reported the highest transmissivity value, whereas the Imo Shale Formation was projected to have the lowest value. The study's findings are similar to those of other international studies (Fatoba et al. 2014; Ebong et al. 2014; Kazakis et al. 2016; Joel et al. 2016; Hasan et al. 2018; Oyeyemi et al. 2018; Rabeh et al. 2019). According to Akhter and Hassan (2016), clay and shale aquifer materials often have low hydraulic conductivity and transmissivity values while sand and gravel aquifer materials frequently have high values. The Imo Shale Formation has little groundwater potential, according to Ijeh and Onu (2012), which is consistent with the study's findings of low aquifer hydraulic conductivity and transmissivity values. A restricted aquifer's normal storativity, which most usually varies depending on the storage and aquifer thickness, ranges from 5 x 10^{-5} to 5 x 10^{-3}. (Todd 1980). Emberga et al.'s 2019 investigation in the upper Imo River Basin corroborated the findings of the current study.

CONCLUSION

Aquifer thickness and depth to the water table were calculated to range from 16.7 meters to 263 meters and 7.1 meters to 119 meters, respectively, with an average value of 39.8 meters for aquifer thickness and 115.5 meters for depth to the water table. The aquifer zones in the research area had resistivities ranging from 13.5 to 8700 m with an average of 1963 m. A mean hydraulic conductivity value of 7.73 m/day was produced for the region using an average transmissivity value of 504.4 m^2/day derived from the pumping test, and the New Model developed from the geophysical technique in this work were used to calculate hydraulic conductivity (K) values. Utilizing Niwas and Singhal, hydraulic conductivity values ranged from 0.55 to 125.8 m/day. The hydraulic conductivity measurements made use of Heigold's method from 1979 ranged from 0.0745 to 37.5 meters per day, whereas those made use of the New Model ranged from 1.4 to 47.2 meters per day, which are in agreement with the results of pumping tests conducted in the study region.

When the estimates of hydraulic conductivity from the various methods—Niwas and Singhal (1981), Heigold et al (1979), and the newly generated model are compared, as is done in table 3, it becomes clear that the New Model values are extremely similar to the already-existing pumping test results. The research area's hydraulic conductivity shows average rates of 13.19 m/day, 1.74 m/day, and 4.62 m/day, respectively.

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AVAILABILITY OF DATA AND MATERIALS
The data used in this will be provided on request by the corresponding author.

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