Hybrid Wenner-Schlumberger Electrical Resistivity Investigation for Groundwater at Nasarawa State University Keffi, Keffi Sheet 208 NE, North-Central Nigeria.

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Abstract

Geological traversing at Nasarawa State University Keffi, part of Keffi Sheet 208NE, North-central Nigeria, revealed that the area is underlain by the Basement Complex rocks consisting of biotite gneiss, granitic gneiss and schist. The structural trends are mostly in NNW-SSE and NE-SW directions and foliation in the NE-SW direction. Surface geophysical investigation was conducted using the new hybrid Wenner-Schlumberger array, where fifty (50) stations were investigated along seven established profiles to determine the groundwater potential of the area. Six curve types were observed; HA, KA, QH, HAK and KHA; QHA-types has the highest frequency of occurrence while KA and HAK-types has the least. Results revealed that the top soil being the 1st layer with resistivity (62-5800 Ωm) and thickness (1-2 m). Laterite is the 2nd layer with resistivity (20-5550 Ωm), and thickness (2-7 m). The weathered basement is the 3rd layer with resistivity (43-2080 Ωm) and thickness (5-20 m). The fractured basement is the 4thlayer in the five (5) geoelectric layer case with resistivity (115-1700 Ωm) and thickness (25-50 m); while the partially weathered/fractured basement forms the 4thlayer in the six (6) geoelectric layer case with resistivity (66-2059 Ωm) and thickness (10-30 m). The fresh basement forms the 5thlayer in the five (5) geoelectric layer case with resistivity (312-2170 Ωm), while the fractured basement forms the 5thlayer in the six (6) geoelectric layer case with resistivity (139-2800 Ωm), and thickness (10-50 m). The fresh basement forms the 6thlayer in the six (6) geoelectric layer case with resistivity (310-3800 Ωm). The depth to fresh basement or overburden thickness range from 29-79.5 m, which implies that the area is generally good for groundwater development, especially places with distinctive weathered and/or fractured layers thicknesses. Groundwater potentials were zoned into low, medium and high potentials for groundwater development. Wenner data extracted and interpreted have a good degree of correlation with the Schlumberger results, the structural trends observed on the geological structures and with existing geology.

Keyword: Geological, geophysical, groundwater, geoelectrical section and Borehole

Introduction

The study area is located at the Nasarawa State University Keffi, part of Keffi Sheet 208NE, North-central Nigeria. It lies within latitudes N08˚50'56" to N08˚49'34" and longitudes E7˚53'40" to E7˚55'00", covering about 4.74 km^2; and can be accessed through the Keffi-Akwanga road(Figure1).The demand for potable water for human consumption and other usage has increased immensely as a result of population growth and hence, the need to evaluate her groundwater potentials for proper harnessing and sustainable supply, due to the fact that the aquifer in the Basement Complex are known to be discontinuous in nature. Sources of water supply in the area come from Mada water works, hand dug wells, hand pumps, streams and boreholes drilled in high weathered and/or fractured basement rocks. Most groundwater explorations have failed due to inadequate pre-drilling information (Gomes, 2006). Electrical resistivity hybrid Wenner-Schlumberger survey was adopted in the groundwater exploration and useful in reviling the geology of the subsurface layer of the study area for a well plan water development and management schemes.

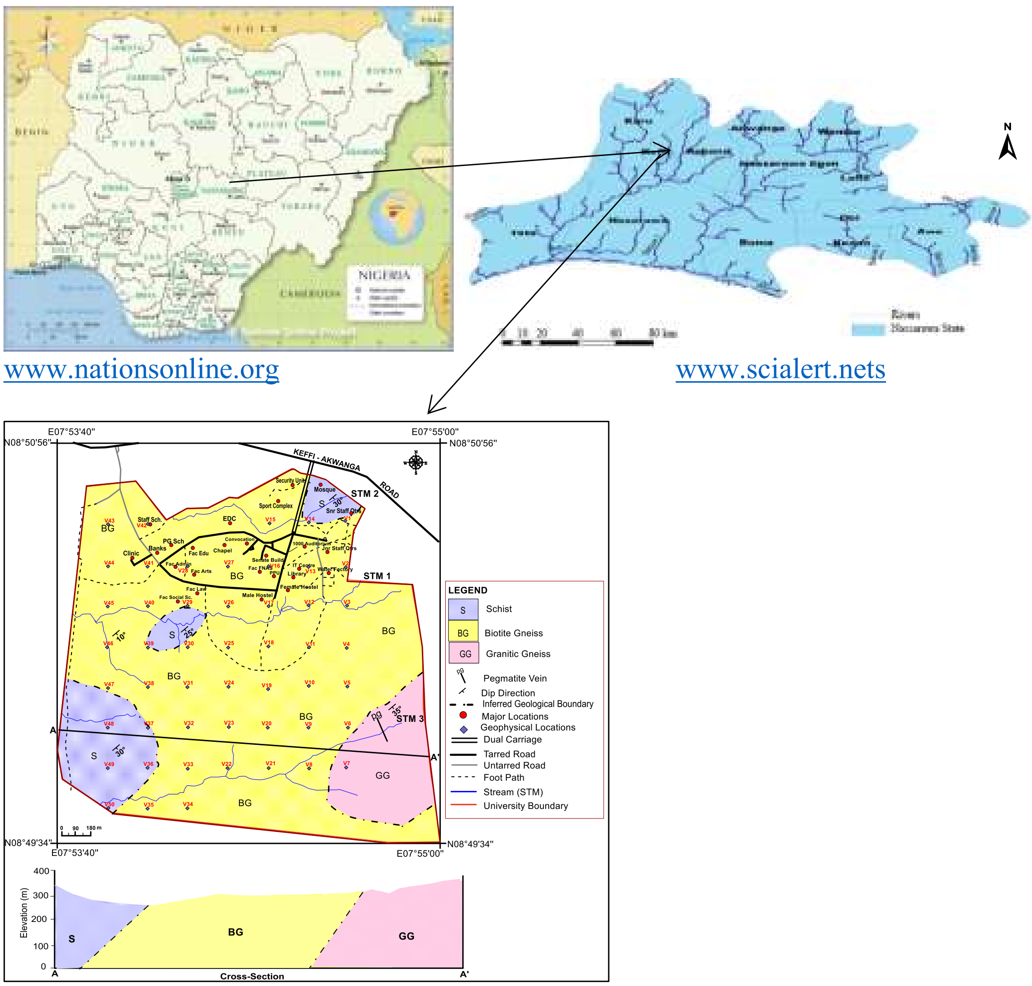
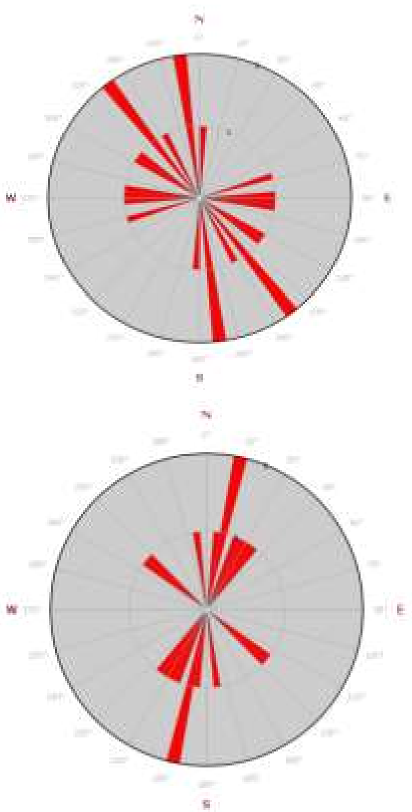


Figure 1: Location, accessibility, geophysical investigating points and geologic map of the study area (Mamza, 2018).

Geology of the Study Area

Geological mapping showed that the Basement Complex rocks present in the study area comprises of the following rock units; Biotite Gneiss (BG), Granitic Gneiss (GG) and Schist (S), where Biotite Gneiss

(BG) predominantly underlies the study area covering more than 80 % (Figure 1). The structural features found within the study area are veins (quartz and quartzo-feldspathic) trending NNW-SSE, joints trending NE-SW and foliations in the NE-SW direction, which corresponds with the major structural trends in Basement rocks (Jatau *et al.,* 2014; Ancho, 2015).



2a

2b

Figures 2a & b: Rosette diagram (2a) Vein (NNW-SSE) and (2b) Joint (NE-SW)

Methodology

A geological mapping of the area was carried and the Electrical Resistivity method of geophysical survey was conducted, using hybrid Wenner-Schlumberger array (Pazdirek and Blaha,1996). It is defined by K=(N+1) a where K is the geometric factor and “n’ is the ratio of the distances between the C1-P1 (orP2-C2) electrodes to the spacing between the P1-P2 potential pair. The sensitivity pattern for the Schlumberger array is slightly different from the Wenner array with a slight vertical curvature below the centre of the array and slightly lower sensitivity values regions between the C1 and P1 (and also C2 and P2) electrodes. There is a slightly greater concentration of high sensitivity values below the P1-P2 electrodes. This means that this array is sentive to both horinzontal and vertical structures. In areas where both types of geological structures are expected, this array might be a good compromise between the Wenner and the dipole –dipole array (Pazdirek and Blaha, 1996). This involved a combination of both Vertical Electrical Sounding (VES) using Schlumberger array and Constant Separation Traversing (CST) using Wenner array in the study area. For every point or station that a VES reading was taken while spreading-out the cables, a CST reading was taken likewise while rolling back the cables. Fifty (50) VES and CST readings were taken coherently, with 200m station interval (Figure1). The field results were interpreted using IX1D and Surfer-12 computer software. Qualitative data were contoured using Surfer 12 software to produce piezometric, true aquifer resistivity, Wenner iso-resistivity, isopach or depth to fresh basement maps from the quantitative data and geo-electric sections were deduced and correlated with existing geology.

Results and Discussion

The quantitative data for Schlumberger array and qualitative data for Wenner were deducted as shown in Tables1 and 2

Table 1. Quantitative Interpretation of Data for Vertical Electrical Sounding (VES) Results

S/N	Sample ID	VES No	Coordinate	Thickness of Layers (m)							Total Depth (m)	Resistivity of Layers (Ωm)							No of Layers	Curve Type
				h1	h2	h3	h4	h5	h6	h7		ρ1	ρ2	ρ3	ρ4	ρ5	ρ6	ρ7		
1	V1	VES 1	N 8°50'37.0" E 7°54'40.0"	1	3.5	5	20	15	-	-	44.5	850	280	130	258	370	900	-	6	QHA
2	V2	VES 2	N 8°50'29.0" E 7°54'40.0"	1	3.5	5	10	25	-	-	44.5	406	135	78	68	151	340	-	6	QHA
3	V3	VES 3	N 8°50'21.0" E 7°54'40.0"	1	3.5	5	20	15	-	-	44.5	81	31	43	121	174	520	-	6	HA
4	V4	VES 4	N 8°50'13.0" E 7°54'40.0"	1	3.5	5	20	15	-	-	44.5	688	138	114	323	465	840	-	6	QHA
5	V5	VES 5	N 8°50'05.0" E 7°54'40.0"	2	2	5	10	25	-	-	44	270	170	150	180	291	717	-	6	QHA
6	V6	VES 6	N 8°49'57.0" E 7°54'40.0"	2	7	20	15	15	-	-	59	778	300	239	281	313	409	-	6	QHA
7	V7	VES 7	N 8°49'49.0" E 7°54'40.0"	1	3.5	5	20	30	-	-	59.5	234	20	50	575	139	702	-	6	HAK
8	V8	VES 8	N 8°49'49.0" E 7°54'32.0"	2	7	5	30	-	-	-	44	3237	150	92	213	404	-	-	5	QHA
9	V9	VES 9	N 8°49'57.0" E 7°54'32.0"	1	1.5	7	10	25	-	-	44.5	771	329	111	110	267	747	-	6	QHA
10	V10	VES 10	N 8°50'05.0" E 7°54'32.0"	1	3.5	5	20	15	-	-	44.5	688	227	133	153	230	473	-	6	QHA
11	V11	VES 11	N 8°50'13.0" E 7°54'32.0"	1	3.5	5	20	30	-	-	59.5	835	83	49	132	201	567	-	6	QHA
12	V12	VES 12	N 8°50'21.0" E 7°54'32.0"	1	3.5	5	20	15	-	-	44.5	656	147	124	177	217	389	-	6	QHA
13	V13	VES 13	N 8°50'29.0" E 7°54'32.0"	1	3.5	5	20	15	-	-	44.5	414	360	306	125	155	360	-	6	KHA
14	V14	VES 14	N 8°50'37.0" E 7°54'32.0"	1	3.5	5	20	15	-	-	44.5	287	99	200	583	888	2070	-	6	HA
15	V15	VES 15	N 8°50'37.0" E 7°54'23.5"	2	7	10	40	-	-	-	59	558	95	92	199	350	-	-	5	QHA
16	V16	VES 16	N 8°50'29.0" E 7°54'23.5"	1	3.5	5	10	30	-	-	49.5	1779	695	128	66	150	352	-	6	QHA

17	V17	VES 17	N 8°50'21.0" E 7°54'23.5"	1	3.5	5	20	15	-	-	44.5	840	381	99	111	140	371	-	6	QHA
18	V18	VES 18	N 8°50'13.0" E 7°54'23.5"	1	3.5	5	20	30	-	-	59.5	62	34	44	126	260	565	-	6	HA
19	V19	VES 19	N 8°50'05.0" E 7°54'23.5"	1	3.5	5	20	15	-	-	44.5	1480	234	77	122	165	407	-	6	QH
20	V20	VES 20	N 8°49'57.0" E 7°54'23.5"	1	3.5	5	20	50	-	-	79.5	656	289	163	139	277	367	-	6	QH
21	V21	VES 21	N 8°49'49.0" E 7°54'23.5"	1	3.5	5	20	30	-	-	59.5	4701	668	191	378	689	1200	-	6	QH
22	V22	VES 22	N 8°49'49.0" E 7°54'15.0"	1	3.5	10	15	15	-	-	44.5	1288	487	273	293	345	617	-	6	QH
23	V23	VES 23	N 8°49'57.0" E 7°54'15.0"	1	3.5	10	15	30	-	-	59.5	322	181	168	190	245	345	-	6	QH
24	V24	VES 24	N 8°50'05.0" E 7°54'15.0"	1	3.5	5	20	15	-	-	44.5	1142	227	197	418	667	1450	-	6	QHA
25	V25	VES 25	N 8°50'13.0" E 7°54'15.0"	1	3.5	5	20	15	-	-	44.5	321	188	110	130	160	310	-	6	QHA
26	V26	VES 26	N 8°50'21.0" E 7°54'15.0"	1	3.5	10	15	50	-	-	79.5	112	69	60	73	212	310	-	6	QHA
27	V27	VES 27	N 8°50'29.0" E 7°54'15.0"	1	3.5	5	20	15	-	-	44.5	346	140	177	370	450	810	-	6	HA
28	V28	VES 28	N 8°50'29.0" E 7°54'07.0"	1	3.5	5	20	30	-	-	59.5	216	232	183	243	370	673	-	6	KA
29	V29	VES 29	N 8°50'21.0" E 7°54'07.0"	1	3.5	10	15	15	-	-	44.5	1652	578	183	329	495	1145	-	6	QHA
30	V30	VES 30	N 8°50'13.0" E 7°54'07.0"	1	3.5	5	20	15	-	-	44.5	201	135	74	188	261	733	-	6	QHA
31	V31	VES 31	N 8°50'05.0" E 7°54'07.0"	1	3.5	5	20	30	-	-	59.5	760	295	211	253	331	442	-	6	QHA
32	V32	VES 32	N 8°49'57.0" E 7°54'07.0"	1	3.5	5	20	30	-	-	59.5	780	193	153	196	291	514	-	6	QHA
33	V33	VES 33	N 8°49'49.0" E 7°54'07.0"	1	3.5	10	15	30	-	-	59.5	3246	3330	1800	2059	2800	3800	-	6	KHA
34	V34	VES 34	N 8°49'41.0" E 7°54'07.0"	1	3.5	5	20	15	-	-	44.5	293	152	145	261	418	1200	-	6	QHA
35	V35	VES 35	N 8°49'41.0" E 7°53'59.0"	1	3.5	5	20	15	-	-	44.5	1340	340	115	235	363	867	-	6	QHA
36	V36	VES 36	N 8°49'49.0" E 7°53'59.0"	1	3.5	5	20	30	-	-	59.5	1595	539	290	227	297	430	-	6	QHA
37	V37	VES 37	N 8°49'57.0" E 7°53'59.0"	1	3.5	10	15	30	-	-	59.5	400	195	143	171	240	350	-	6	QHA

38	V38	VES 38	N 8°50'05.0" E 7°53'59.0"	1	3.5	5	20	15	-	-	44.5	1127	237	119	208	256	500	-	6	QHA
39	V39	VES 39	N 8°50'13.0" E 7°53'59.0"	1	3.5	5	20	15	-	-	44.5	2979	352	168	376	535	1612	-	6	QHA
40	V40	VES 40	N 8°50'21.0" E 7°53'59.0"	1	3.5	10	30	-	-	-	44.5	1100	354	70	115	312	-	-	5	KHA
41	V41	VES 41	N 8°50'29.0" E 7°53'59.0"	1	3.5	5	20	15	-	-	44.5	758	277	197	275	372	576	-	6	QHA
42	V42	VES 42	N 8°50'37.0" E 7°53'59.0"	1	3.5	15	40	-	-	-	59.5	1563	571	110	175	342	-	-	5	QHA
43	V43	VES 43	N 8°50'37.0" E 7°53'50.5"	2	2	5	10	10	-	-	29	5800	5550	2080	342	320	1100	-	6	QH
44	V44	VES 44	N 8°50'29.0" E 7°53'50.5"	2	7	20	50	-	-	-	79	1043	224	650	1700	2170	-	-	5	HA
45	V45	VES 45	N 8°50'21.0" E 7°53'50.5"	1	3.5	5	20	30	-	-	59.5	720	250	158	300	600	1010	-	6	QHA
46	V46	VES 46	N 8°50'13.0" E 7°53'50.5"	1	3.5	5	20	15	-	-	44.5	330	190	153	275	366	650	-	6	QHA
47	V47	VES 47	N 8°50'05.0" E 7°53'50.5"	1	3.5	10	30	35	-	-	79.5	2296	350	160	253	474	623	-	6	QHA
48	V48	VES 48	N 8°49'57.0" E 7°53'50.5"	2	4.5	7.5	30	-	-	-	44	731	264	184	220	368	-	-	5	KHA
49	V49	VES 49	N 8°49'49.0" E 7°53'50.5"	1	6	12.5	25	-	-	-	44.5	332	162	210	323	526	-	-	5	HA
50	V50	VES 50	N 8°49'41.0" E 7°53'50.5"	1	3.5	5	35	-	-	-	44.5	1173	350	200	277	760	-	-	5	QHA

NOTE: For 5 Layers; the 1st Layer is Topsoil, 2nd Layer is Laterite, 3rd Layer is Weathered basement, 4th Layer is Fractured basement and the 5th Layer is Fresh basement.

For 6 Layers; the 1st Layer is Topsoil, 2nd Layer is Laterite, 3rd Layer is Weathered basement, 4th Layer is Partially Weathered/Fractured basement 5th Layer is Fractured basement and the 6th Layer is Fresh basement.

. Table 2. Qualitative Interpretation of Data for Wenner Reslts

S/N	Sample ID	LONGDD	LATDD	Elevation (m)	Spacing / depth a=15	a=20	a=30	a=40
1	V1	7.9111	8.8436	306	115	380	1856	2209
2	V2	7.9111	8.8414	307	197	200	262	331
3	V3	7.9111	8.8392	300	122	172	287	397
4	V4	7.9111	8.8369	306	254	459	594	683
5	V5	7.9111	8.8347	310	271	357	517	622
6	V6	7.9111	8.8325	309	269	247	329	354
7	V7	7.9111	8.8303	300	112	170	258	367
8	V8	7.9089	8.8303	310	173	394	285	510
9	V9	7.9089	8.8325	309	199	219	281	339
10	V10	7.9089	8.8347	306	216	241	336	448
11	V11	7.9089	8.8369	312	538	1531	2306	2871
12	V12	7.9089	8.8392	302	210	240	308	410
13	V13	7.9089	8.8414	312	206	220	235	359
14	V14	7.9089	8.8436	300	200	660	950	1768
15	V15	7.9065	8.8436	302	143	154	264	290
16	V16	7.9065	8.8414	306	200	104	1943	2400
17	V17	7.9065	8.8392	309	181	172	170	389
18	V18	7.9065	8.8369	310	215	348	281	436
19	V19	7.9065	8.8347	310	120	175	298	370
20	V20	7.9065	8.8325	310	195	206	264	438
21	V21	7.9065	8.8303	303	526	152	594	2834
22	V22	7.9042	8.8303	299	399	388	497	606
23	V23	7.9042	8.8325	300	170	245	341	434
24	V24	7.9042	8.8347	303	202	449	700	1667
25	V25	7.9042	8.8369	298	150	226	288	524
26	V26	7.9042	8.8392	300	130	171	302	342
27	V27	7.9042	8.8414	304	409	492	552	900
28	V28	7.9019	8.8414	306	299	473	1185	640
29	V29	7.9019	8.8392	299	200	340	523	1250
30	V30	7.9019	8.8369	306	188	183	373	451
31	V31	7.9019	8.8347	306	191	351	388	448
32	V32	7.9019	8.8325	309	222	319	342	469
33	V33	7.9019	8.8303	310	256	273	850	2430
34	V34	7.9019	8.8281	300	150	254	396	2726
35	V35	7.8997	8.8281	297	154	287	1098	635
36	V36	7.8997	8.8303	300	293	908	300	325
37	V37	7.8997	8.8325	309	621	379	532	655
38	V38	7.8997	8.8347	306	326	443	1952	497
39	V39	7.8997	8.8369	308	436	501	692	1549
40	V40	7.8997	8.8392	290	209	275	350	987
41	V41	7.8997	8.8414	297	310	336	482	2314
42	V42	7.8997	8.8436	294	165	259	342	362
43	V43	7.8974	8.8436	295	302	279	712	558
44	V44	7.8974	8.8414	294	264	338	413	528
45	V45	7.8974	8.8392	292	258	353	480	765
46	V46	7.8974	8.8369	296	352	452	604	660
47	V47	7.8974	8.8347	300	232	459	443	617
48	V48	7.8974	8.8325	302	289	386	485	607
49	V49	7.8974	8.8303	300	337	454	499	637
50	V50	7.8974	8.8281	290	539	263	386	523

Field curves

The six curve types identified in the study are HA, KA, QH, HAK and KHA; QHA-types which correlates (Keller & Frischknecht, 1966). The curve type with the highest frequency of occurrence is the QHA-type, while the HA and HAK-types has the lowest frequency of occurrence in the study area.

Geoelectric Section

Geoelectric section along profile NE-SW (based on geological structures in the study area), revealed 5-6 geoelectric layers which correlates with the works of (Olatokunbo-Ojo & Akintorinwa, 2016). The first layer consists of the top soil from 1-2 m with resistivity value range of 112-1779 Ωm. The second layer consists of laterite with thickness of 3.5-4.5 m and is characterized by resistivity value range of 69-695 Ωm. The third layer is weathered basement with thickness of 5-10 m and is characterized by resistivity value range of 60-200 Ωm. The fourth layer is partially weathered/fractured basement with thickness of 10-20 m and is characterized by resistivity value range of 66-583 Ωm. The fifth layer is the fractured basement with thickness of 15-50 m and is characterized by resistivity value range of 150-888 Ωm, while the sixth layer is the fresh basement with thickness ranging to infinity and resistivity range of 310-2070 Ωm. Generally, the thickness of the overburden or depth to basement is highest towards north central of this profile line (Figure 4).Furthermore, V16 (Biotite Granite) and V48 (Schist) shows that the aquiferous layer (weathered and/or partially weathered/fractured basement layer is not very thick to warrant good accumulation of groundwater; while V26 (Biotite Granite) has the thickest aquiferous layer, though could be susceptible to surface water infiltration and high contamination risk due to its proximity to the stream when correlated with the geology of the area (Figure 1). The lithology log of an existing borehole at BH 3 (Fac. FNAS) showed good correlation with geophysical data (Figures 3and 4).

Geoelectric section (Figure 5) along profile NW-SE (based on geological structures in the study area), revealed 5-6 geoelectric layers. The first layer consists of the top soil from 1-2 m with resistivity value range of 234-5800 Ωm. The second layer consists of laterite with thickness of 2-7 m and is characterized by resistivity value range of 20-5550 Ωm. The third layer is weathered basement with thickness of 5-10 m and is characterized by resistivity value range of 50-2080 Ωm. The fourth layer is partially weathered/fractured basement with thickness of 10-20 m and is characterized by resistivity value range of 122-575 Ωm. The fifth layer is the fractured basement with thickness of 10-30 m and is characterized by resistivity value range of 139-495 Ωm, while the sixth layer is the fresh basement with thickness ranging to infinity and resistivity range of 310-1145 Ωm. Generally, the thickness of the overburden or depth to basement is highest towards southeast of this profile line. Furthermore, V8 (Biotite Granite) shows that the aquiferous layer (weathered and/or partially weathered/fractured basement layer is not very thick to warrant good accumulation of groundwater; while V29 (Biotite Granite) has the thickest aquiferous layer, though could be susceptible to surface water infiltration and high contamination risk due to its proximity to the stream when correlated with the geology of the area (Figure 1). The lithology log of an existing borehole at BH 3 (Fac. FNAS) showed good correlation with geophysical data (geoelectric section), (Figure 4).

Isoresistivity and Isopach Map of the Aquifer

This reveals the observed resistivity values of the aquifer (weathered or fractured basement), and the observed thickness of the aquifer (weathered basement and/or fractured basement) this plays an important role in identifying or zoning groundwater potential in the Basement Complex terrain (Olatokunbo-Ojo & Akintorinwa, 2016). The resistivity of the aquiferous layer ranges from 110-1800 Ωm at V9 and V33 respectively, but generally less than 300 Ωm. This reveals the heterogeneous variation in the composition of the weathered or fractured basement layer from sandy clay, laterite, lateritic clay, weathered and fractured gneiss when compared with the lithology log at BH 3 (Figure 4). The study area has a moderate resistivity, green-lemon green in colour; with areas of few high resistivity in brown-light yellow-blue in colour at the south (Figure 5a).

The Isopach Map reveals the variation in thickness of the weathered or partially weathered/fractured basement layer. It ranges from 7-55 m, but generally less than 36 m. The areas with deep purple colour (less than 10 m) indicate thin aquifer thickness of low groundwater potential, in part of northcentral, east and northeast, northwest and south. Light purple indicates moderate aquifer thickness (10-32 m) and of medium groundwater potential, towards the northwest, south, east and part of north, northcentral, northeast, southeast and southwest; while yellowish-brown colour indicates thick aquifer (34-56 m) of high groundwater potential, occur in part of the north, northwest, northcentral, northeast, southeast and southwest. It implies that the major aquifer units in the study area is moderately thick and of high groundwater yield. Therefore, the groundwater potential of this research can be zoned into low, medium and high potentials (Omosuyi *et al.,* 2003; Jatau *et al.,* 2014; Anudu *et al.,* 2014; Olatokunbo-Ojo & Akintorinwa, 2016) as observed in Figure 5b.

Isopach Map of Depth to Fresh basement

The depth to fresh basement is also known as the overburden thickness; reveal the thicknesses of each of the layers encountered to the top of the fresh basement beneath the sounding stations (Jatau *et al.,* 2014; Olatokunbo-Ojo & Akintorinwa, 2016). This include the top soil, laterite, weathered basement, fractured basement; and partially weathered/fractured basement (for 6-layer case). The depth to fresh basement ranges from 29-79.5 m. The areas whose overburden thickness is thin, implies that the fresh basement is very close to the surface. Generally, the study area has moderately thick overburden at portion with blue-army green-light green in colour, towards the north, northeast, part of northwest, northcentral and south, east, southeast and southwest. Thick overburden can also be observed at portion of yellow-red colour towards the west and part of northwest, north central and south (Figure 7); hence the study area is of moderate-high groundwater potential.

Resistivity Map of the Basement

This reveals that the resistivity of the basement ranges from 310-3800 Ωm at V25/V26 and V33 respectively, but generally with less than 800 Ωm (Figure 5). The green and light green colour are dominant within the study area with 400-800 Ωm implying fractured basement (Olayinka & Olorunfemi, 1992). Yellow-brown colour (1000-2200 Ωm) occur towards the south and trend northwest-southeast, northeast-southwest; and light-deep blue (2400-3800 Ωm) occur in part of the south (Figure 7). From 1000-3800Ωm signify fresh basement geoelectric units (Olayinka & Olorunfemi, 1992).

Piezometric Map

The Piezometric map was obtained when the total depth is subtracted from the elevation values for each VES station (Jatau *et al.,* 2014). It ranges from 215-267.5 m. Portions with blue colour have the least values, areas with yellow are moderate; and red colour for high piezomettric values. This indicates that areas with low-moderate piezometric values (blue and yellow colour), trending west-east (top of the map), and northwest-southeast are towards stream 2 and; 1 and 3 respectively, which serves as convergence zones for surface and groundwater flow; while high piezometric value areas towards the northeast, east, northcentral and part of the south, form ridges and divergence zones for surface and groundwater flow (Figure 8). This geophysical interpretation correlates with the geology of the study area.

Bedrock Relief Map

The 3-D bedrock relief map of the study area ranges in elevation from 291-311 m (Figure 9). It reveals the uneven nature of the bedrock comprising of ridges (areas of high relief) and depressions (areas of low relief). Low relief areas are represented by purple-blue colour, medium relief represented by lemon green-yellow colour; and high relief are represented by red colour. Areas of low-medium reliefs trending west-east at the top, northwest-southeast and part of the northeast-southwest, acts as convergence zones for good groundwater flow/accumulation; while areas of high reliefs in part of the northeast, west and eastern portion of the study area acts as divergence zones for groundwater flow/accumulation due to the presence of the ridges and also serves as structural control to the streams, which correlates with the works of (Jatau *et al.,* 2014; Omosuyi*et al.,* 2003). The bedrock relief map also correlates to structural trends, observed on the geological structures as also observed in (Jatau *et al.,* 2013).

Isoresistivity Map for Wenner at 15 m depth

The isoresistivity map at 15 m depth (Figure 10) ranges from 112-621 Ωm (Table 2). Portions with dark purple colour (100-200 Ωm) have the low resistivity values, areas with light purple (220-380 Ωm) are moderate; and yellow-brown colour (400-620 Ωm) have high resistivity values. Areas with low-moderate resistivity values (dark-light purple colour), trending northwest-southeast and northeast-southwest, indicates high conductivity for groundwater accumulation vertically, at 15 m depth in the study area; which also correlates with structural trends, observed on the geological structures and isopach map of the true aquifer (Schlumberger data); while areas with high resistivity values (yellow-brown colour), part of the east, west, southwest and south indicates low conductivity and shows how extensive and near the fractured/fresh basement is at 15 m depth; which correlates with the works of (Jatau &Bajeh, 2007).

Isoresistivity Map for Wenner at 20 m depth

The isoresistivity map at 20 m depth (Figure 11) ranges from 104-1531 Ωm (Table 2). Portions with dark purple colour (100-350 Ωm) have the low resistivity values, areas with light purple (400-850 Ωm) are moderate; and yellow-brown colour (900-1600 Ωm) have high resistivity values. Areas with low resistivity values (dark purple colour), trending northwest-southeast and northeast towards northcentral, indicates high conductivity for groundwater accumulation vertically, at 20 m depth in the study area; which also correlates with structural trend, observed on the geological structures and isopach map of the true aquifer (Schlumberger data); while areas with moderate resistivity values (light purple colour), occur in part of northeast, north, northwest, west, southwest and east, indicate moderate conductivity for groundwater accumulation; while high resistivity values (yellow-brown colour), part of the east, indicates low conductivity and shows how near the fractured/fresh basement is at 20 m depth; which correlates with previous work of (Jatau &Bajeh, 2007).

Isoresistivity Map for Wenner at 30 m depth

The isoresistivity map at 30 m depth (Figure 12) ranges from 170-2306 Ωm (Table 2). Portions with dark purple colour (100-500 Ωm) have the low resistivity values, areas with light purple (600-1200 Ωm) are moderate; and areas with yellow-brown colour (1300-2300Ωm) have high resistivity values. Areas with low resistivity values (dark purple colour), trending northwest-southeast and northeast-southwest, indicates high-moderate conductivity for groundwater accumulation vertically, at 30 m depth in the study area; which also correlates with structural trends, observed on the geological structures and isopach map of the true aquifer (Schlumberger data); while areas with moderate-high resistivity values (light purple - yellow-brown colour), occur in part of north, northeast, west, southwest and east which indicate low-extremely low conductivity for groundwater accumulation and shows how near the fresh basement is at 30 m depth.

Isoresistivity Map for Wenner at 40 m depth

The isoresistivity map at 40 m depth (Figure 13) ranges from 290-2871 Ωm (Table 2). Portions with dark purple colour (200-600 Ωm) have the low resistivity values, areas with light purple (700-1600 Ωm) are moderate; and areas with yellow-brown colour (1700-2900 Ωm) have high resistivity values. Areas with low resistivity values (dark purple colour), trending northeast-southwest, southeast towards northcentral and part of the north, indicates moderate-low conductivity for groundwater accumulation vertically, at 40 m depth in the study area; which also correlates with structural trend, observed on the geological structures and isopach map of the true aquifer (Schlumberger data); while areas with moderate-high resistivity values (light purple - yellow-brown colour), occur in part of north, northeast, northwest, northcentral, east and south which indicate extremely low-negligible conductivity for groundwater accumulation and shows how near the fresh basement is at 40 m depth this correlates well with the work of (Jatau & Bajeh, 2007)

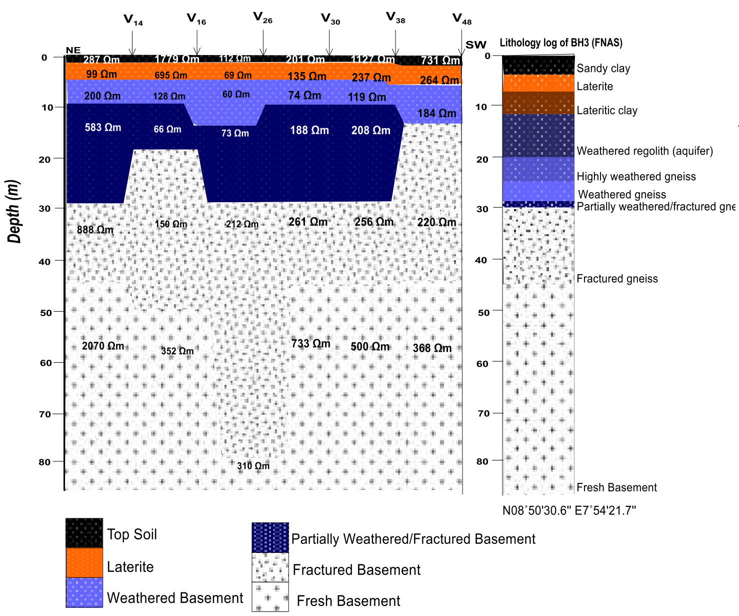


Figure 3: Geoelectric section along Profile NE-SW

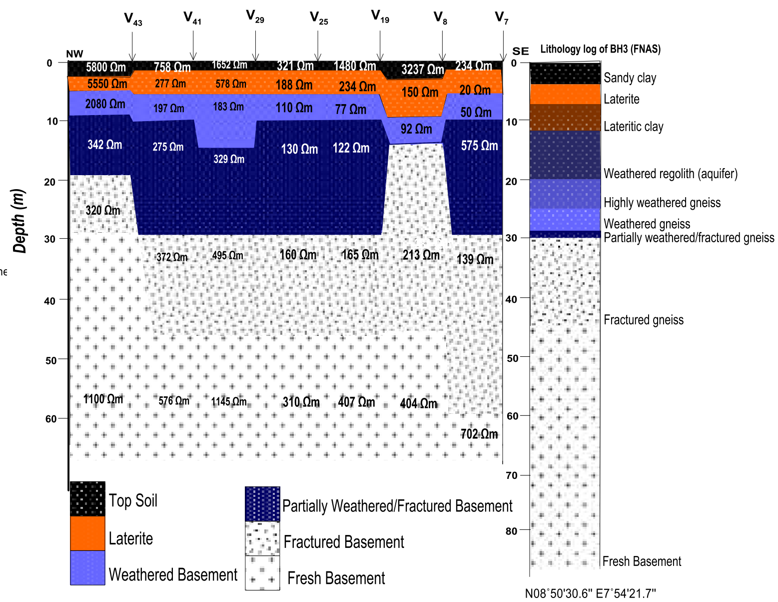


Figure 4: Geoelectric section along Profile NW-SE

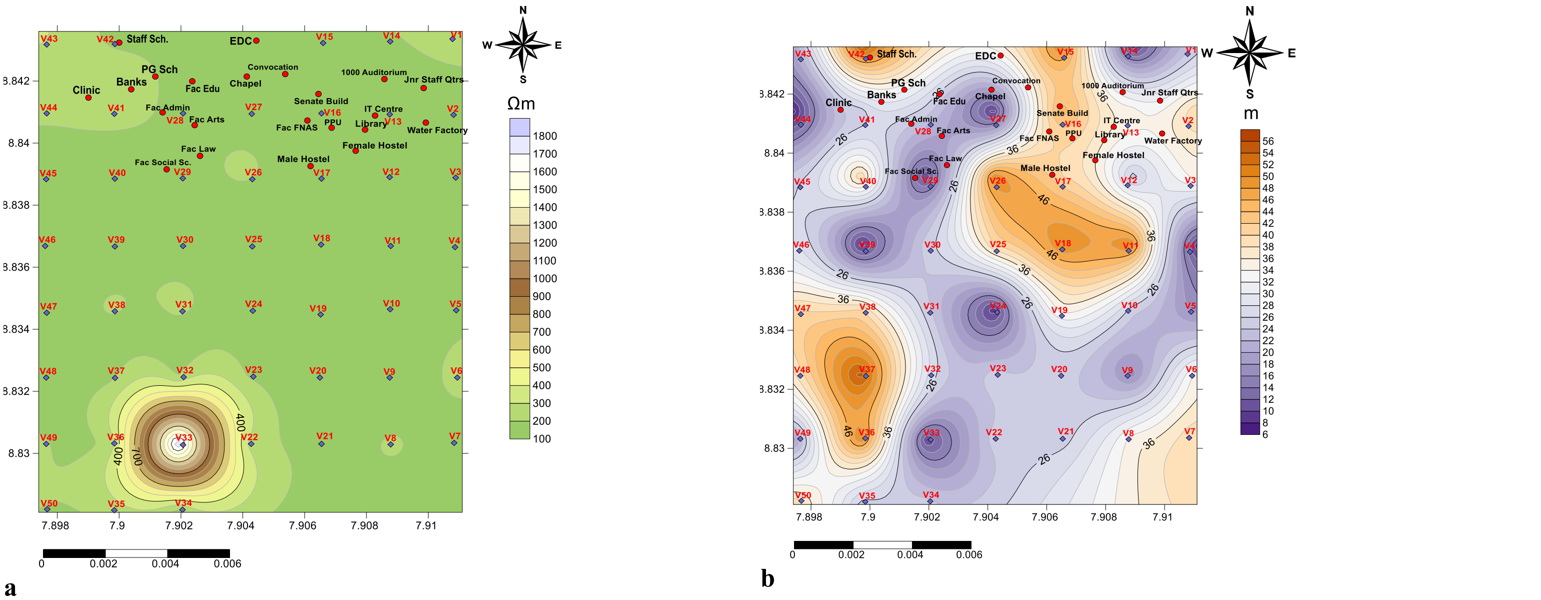


Figure 5: (a) Isoresistivity and (b) Isopach map of the Aquifer

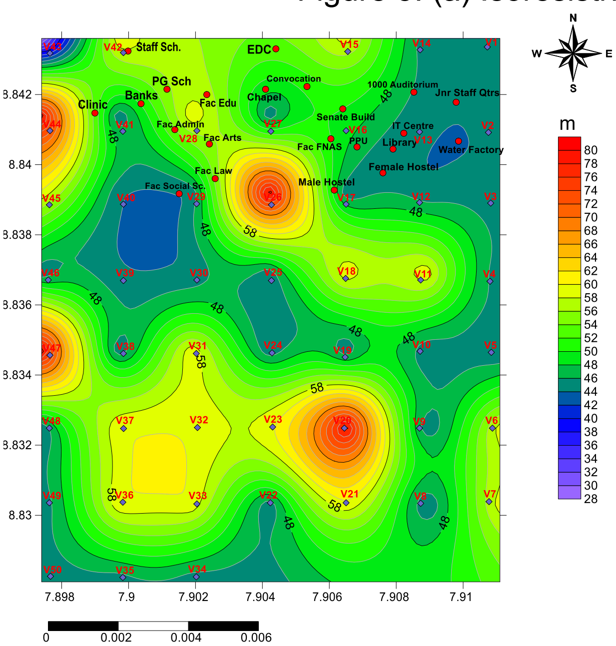


Figure 6: Isopach map of Depth to Basement

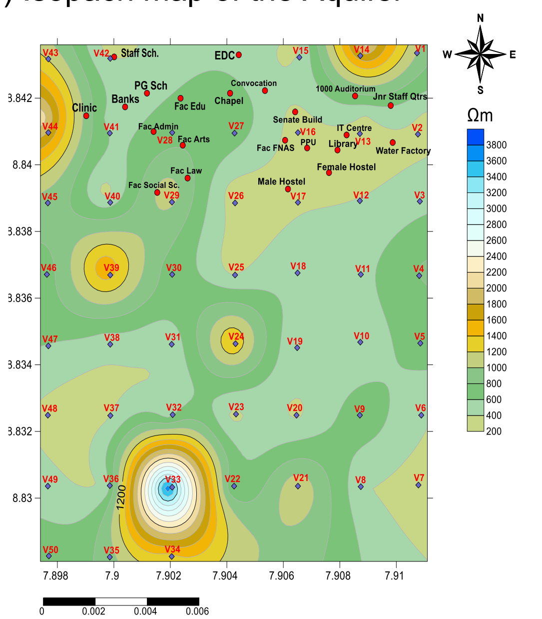


Figure 7: Resistivity map of the Basement

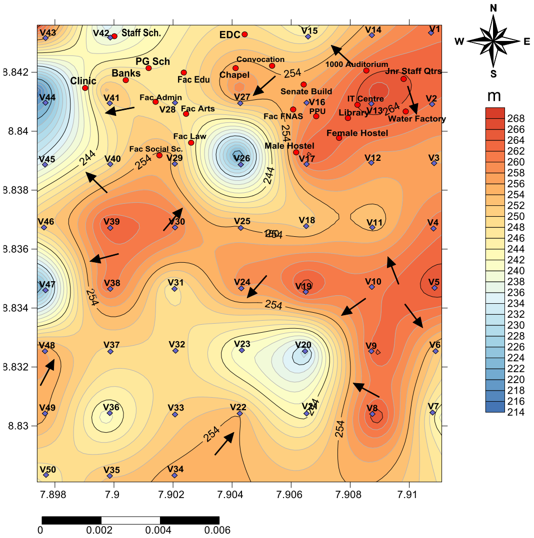


Figure 8: Piezometric Map

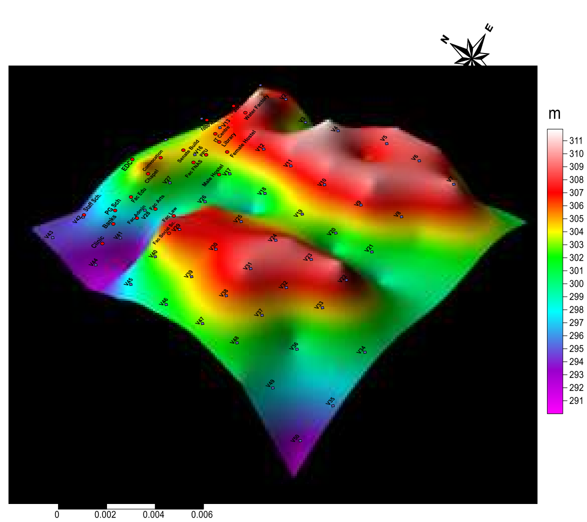


Figure 9: 3-D Bedrock Relief Map

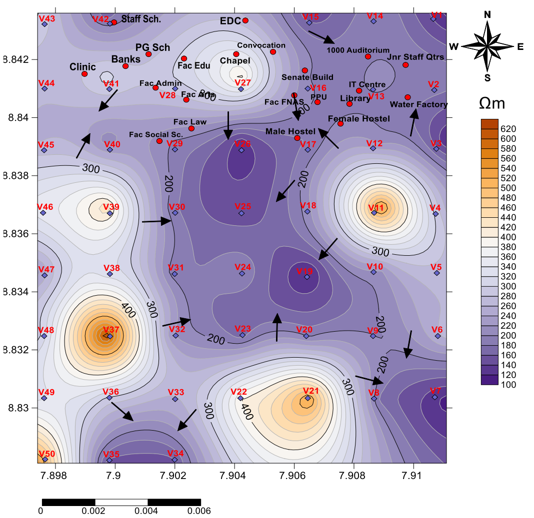


Figure10: I soresistivity map for Wenner at 15m depth

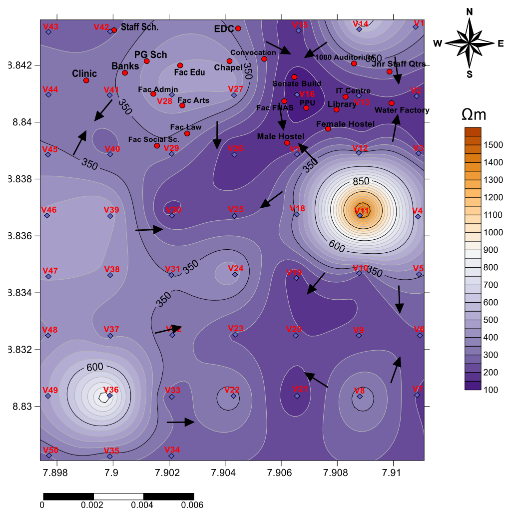


Figure11: Isoresistivity map for Wenner at 20 m depth

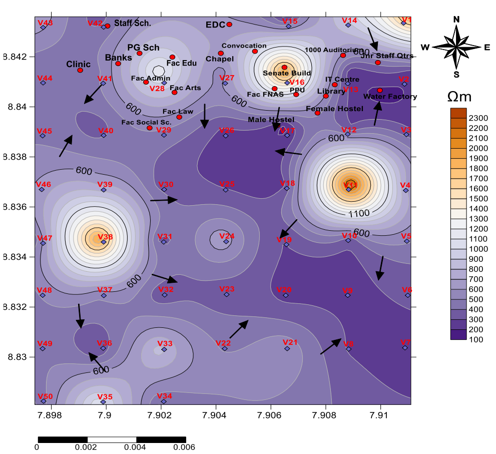


Figure 12: Isoresistivity map for Wenner at 30 m depth

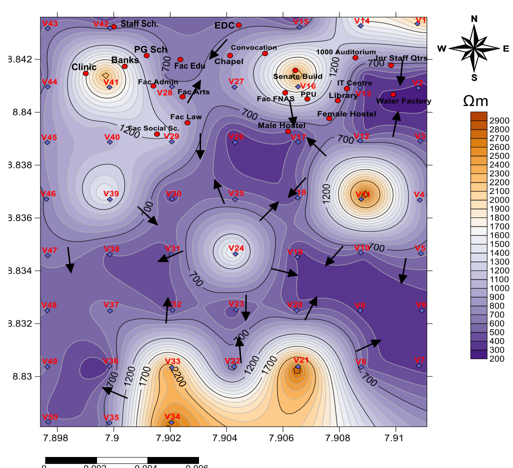


Figure 13: Isoresistivity map for Wenner at 40 m depth

Conclusion

Geophysical survey revealed 5-6 geoelectic layers comprising of top soil, laterite, weathered basement, partially weathered/fractured basement, fractured basement and fresh basement; which gave rise to the weathered and fractured aquifer that are peculiar to the Basement Complex terrain. The depth to fresh basement or overburden thickness ranged from 29-79.5 m, which implies that the area is generally good for groundwater development, especially places with distinctive weathered and/or fractured layers thicknesses. Boreholes drilled through these stations, may provide sufficient water for sustainable supply. The groundwater potential of this research can be zoned into low, medium and high potentials. Wenner quantitative and qualitative data correlated well with Schlumbergers' results, while the structural trends observed on the geological structures have a good degree of correlation with the subsurface geophysical structures and with existing geology.

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