

Geophysical Evaluation for Groundwater Potential, Aquifer Protective Capacity, and Corrosivity in Gurgu and Environs North Central Nigeria

¹Emmanuel, V., ²Sani, J. M., and ³Dominic, P.

¹Department of Geology, University of Jos, Plateau State Nigeria.

²National Metallurgical Development Centre, Jos, Plateau State Nigeria.

³School of General and Applied Sciences Shehu Idris College of Health Sciences and Technology, Makarfi, Kaduna State Nigeria.

Corresponding Author: emmvins@gmail.com

ABSTRACT

Geophysical evaluation for groundwater is a scientific method of examine the subsurface geologic formation in order to study the target zones for groundwater. The aim of the research is to investigate the aquifer properties of the study area, while the objectives are to; determine the depth to bedrock, aquifer thickness, delineate the various lithology within the overburden, estimate the depth suitable for siting wells/boreholes, determine the corrosivity, aquifer protective capacity and groundwater flow direction. Thirty (30) vertical electrical sounding (VES) were carried out with current spacing (AB/2) of 1 to 125 m using Schlumberger array and ABEM SAS 300C Terrameter. The geo-electric sections from data interpretations have indicates three (3) layers which are topsoil, weathered and fresh basement. Four (4) zones of soil corrosivity were recognized in the area namely, very strongly corrosive (VSC) zone (<10 Ω m), moderately corrosivity (MC) zone (10-60 Ω m), slightly corrosivity (SC) zone (60-180 Ω m), and practically non-corrosive (PNC) zone (>180 Ω m). The aquifer protective capacity (APC) rating shows that VES 5, 12, 21, 24, and 26 are good aquifer protective capacity, VES 6, 7, 8, 9, 10, 12, 14, 15, 16, 17, 19, 20, 22, 23, 25, 27, 28 and 29 are considered to be moderate, VES 4, 13 and 30 are considered to be weak while VES 1, 2, 3 and 18 are poor. Information on the geo-electric properties of the subsurface materials is very important for delineating aquifer potential of the study area. It is recommended that borehole should be drilled based on the interpreted geophysical data.

Keywords: Aquifer, Corrosivity, Groundwater, Gurgu, Protection.

INTRODUCTION

The most important and abundant natural resources found across the entire world is the groundwater, and it is a mixture of connate, meteoric, and juvenile. Groundwater is often withdrawn for agricultural, industrial, household, recreational and environmental activities through construction and operation of boreholes or wells. Groundwater is mostly used as a source of drinking and irrigation

(UNESCO, 2004). The use of resistivity method as a geophysical evaluation for groundwater proves to be effective as a scientific means for ground water exploration (Emenike, 2001), (Ogungbemi *et al.*, 2013), and (Okolie *et al.*, 2005). This method was employed for investigating ground water potential, soil corrosivity, and aquifer protective capacity in Gurgu and Environs area of Jos East LGA of Plateau State, North central part of Nigeria.

According to Omosuyi *et al.*, (2007), resistivity method for ground water exploration gives an information about highly weathered basement materials which are the target zones for groundwater. In the crystalline basement rocks such as those found in the study area, electrical current is conducted mainly along geologic structures such as joints, faults, fractures, weathered zones and fissures. The occurrence and distribution of groundwater in the crystalline basement complex, is due to the development of secondary porosity and permeability by weathering /fracturing of the parent rocks; Acworth (1987), Okwueze and Ezeanyim (1991), and Edet and Okereke (1997). Therefore, low resistivity values indicate possible water saturated formation known as the aquifer. Previous work carried out by different researchers on the use of geophysical evaluation for groundwater precisely resistivity method, includes the work of; Iserhien-Emekeme *et al.*, (2004), Okwueze (1996), Olowofela *et al.*, (2005), Oseji *et al.*, (2005), (2006), (2020), Batayneh (2009), Chinyem (2017), Ezeh and Ugwu (2010), Nwankwo (2011), Onu and Ibeh (1998), Olorunfemi and Fasuyi (1993), and Shemang *et al.*, (1994). The use of surface sources of water like streams, rivers, seas, lakes, and ponds has health implications due to contamination and pollution. According to Abdullahi *et al.*, (2005), groundwater is more hygienic than surface water as a reliable source of water supply. Generally, the mode of occurrence for groundwater are controlled by geologic factors such as lithology, texture of the rock and the climatic factors such as rainfall. Groundwater is extracted from the aquifer which is a unit of rock or an unconsolidated deposit that can yield a significant quantity of water to the well Onugba and Eduvie (2003) and Tammaneni *et al.*, (2006). The

aim of this research is to investigate the aquifer properties of the study area, while the objectives are to determine the; depth to bedrock, aquifer thickness, various lithology within the overburden, estimated depth suitable for siting wells/boreholes, corrosivity, aquifer protective capacity and groundwater flow direction.

Location, Accessibility and Lateral Extent

Gurgu the study area is located in Jos East Local Government Area of Plateau State, North Central Nigeria. It lies on a coordinate (longitudes 9° 05' 00" to 9° 08' 00" E and latitudes 9° 58' 00" to 10° 00' 00"N) with a land area of about 907.2 km² and estimated population of 82, 260 peoples based on the 2006 census. The area is part of the Maijuju rock formation with an elevation between 577m to 1752m (Ibrahim *et al.*, 2020). The area is accessible due to the presence of minor road and footpath. The climatic condition of the area is controlled by two seasons namely: the wet and dry season. The former prevails between the months of April and October, while the later starts in the month of November and ends in the month of March. The mean annual temperature in Jos and its environs ranges from 21-25°C, with the peak Just before the rains in April recording about 26°C. The coolest period is in January, at the peak of the harmattan with temperatures as low as 20°C (Nanfa *et al.*, 2022). Previous work written by different authors in the study area on Groundwater supply, Hydrogeophysical investigation, and Access to save water includes the work of; Hassan *et al.*, (2014), Mbiimbe *et al.*, (2012) and Listorti (1996). Human activities associated with the study area are mostly farming activities, while others

engage in irrigation farming during dry season due to the presence of river/stream

and these serves as a source of employment to the citizens.

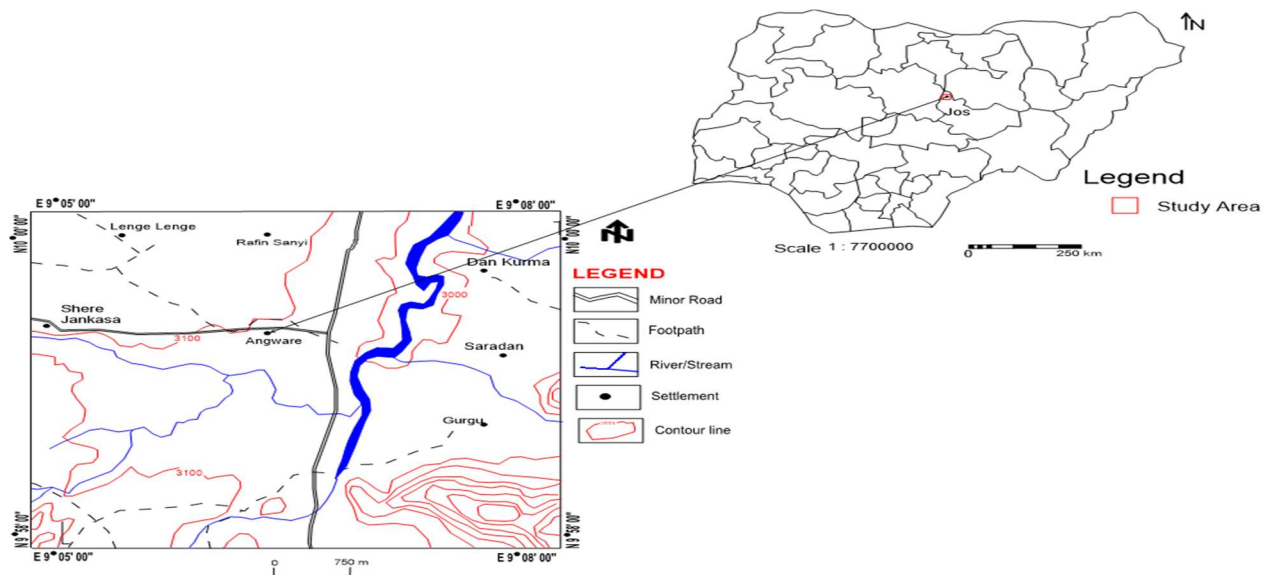


Figure 1: Location map of the study area (Federal Survey of Nigeria, 1962)

Geologic Setting of The Study Area

The geology of the study area falls within the Jurassic Younger Granites and Basement Complexes of Jos Plateau, North Central Nigeria. The area is made up of three lithologic units; Rhyolite, Hornblende-biotite granite porphyry, and Migmatite (Figure 2). The Younger granite of Jos Plateau is made up of Rhyolite and Hornblende-biotite granite and they occur mainly as sub-volcanic intrusive complexes of ring dykes and related annular intrusions. The granites have been mapped by a number of geologists these includes Abba (1991), Aina and Olarewaju (1992), Mucke (2003), and Ogunleye *et al.*, (2005). The Basement rocks are the Migmatite which is the predominant rocks in the area, and these have been subjected to multiple episodes of

deformation such as the; Liberian (2700 Ma), Eburnean (2200 Ma), Kibaran (1300-1400 Ma), and Pan-African (450-1100 Ma). Each of these Orogenies left its structural imprints on the basement rocks due to the poly-phase deformation (Ekwueme, 1994). Based on the previous work carried out around the area on petrographic analysis of the rocks by Dung and Ifeanyi (2022), the rocks are composed of minerals such as orthoclase, hornblende, biotite, quartz, and alkali-rich feldspar. Geologic structures of the area that are imprints of deformation on the rocks are joints, dykes, fractures, foliations, faults, veins, and folds. These structures trend N-S to NE-SW and this conforms to Pan-African structural pattern Annor *et al.*, (1990) and Amigun *et al.*, (2015).

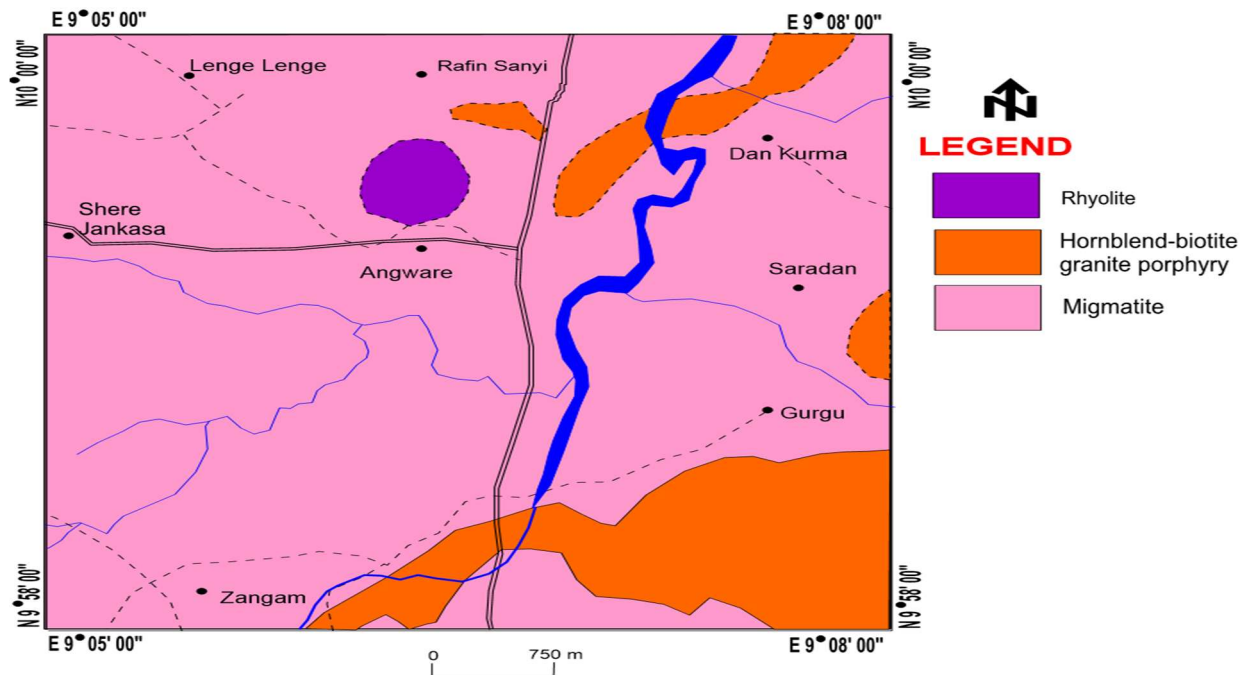


Figure 2: Geological map of the Study Area (Geological Survey of Nigeria, 1963).

MATERIALS AND METHOD

A total of thirty (30) Vertical Electrical Sounding (VES) profiles were carried out via the use of ABEM SAS 300 Terrameter and were interpreted quantitatively and qualitatively. The field data obtained was processed using the Software IX1D (version 3.20) and surfer 9 (version 9.0) and were interpreted quantitatively and qualitatively in order to understand the geo-electric layers of the area. The Schlumberger array method of vertical electrical sounding (VES) was used to give the detailed information on the vertical succession of different layers and their thickness as well as their apparent resistivity. This method was used by Okiongbo and Akpofure (2012), in the determination of Aquifer properties and Groundwater Vulnerability mapping in Yenagoa City and its Environs in Bayelsa

State, South Southern Nigeria. In the vertical electrical sounding, the potential electrode (MN) remains fixed in the same position until voltage becomes too small to measure. At these point the potential electrodes are moved outward, while the current electrode (AB) is varied over time which tends to send current deeper as it penetrates into the ground (figure 3). The basis of making electrical sounding irrespective of electrode array used is that the further the current source, the measurement of the potential difference is made and the deeper the investigation. The vertical electrical sounding (VES) is based on Ohm's law which states that; current passing through a metallic conductor is directly proportional to the potential difference between the two ends of the conductor provided that temperature and other physical condition remain constant.

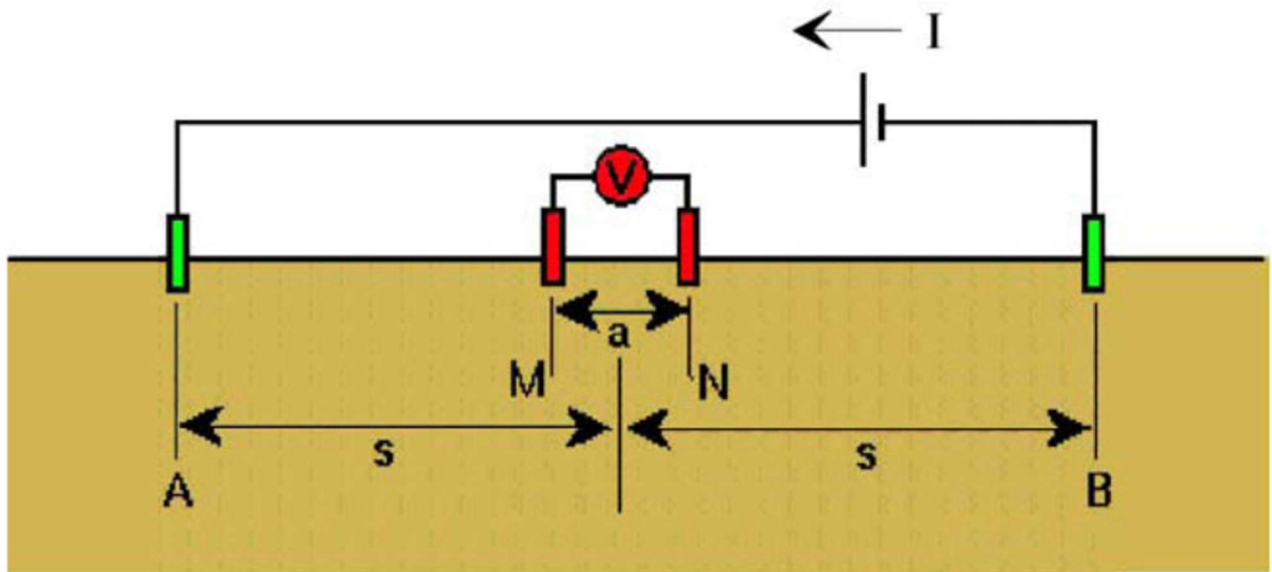


Figure 3: Schlumberger array and apparent resistivity after Keller and Frischknecht (1966)

RESULTS AND DISCUSSIONS

The thirty (30) vertical electrical soundings (VES) data acquired were interpreted qualitatively and quantitatively. The result show details of the measured parameters such as resistivity of layers, thickness of layers, depth, inferred lithology, and curve type which were presented in Table 1, while the corrosivity and aquifer protection capacity for all the sounded points were presented in Table 2. The qualitative and quantitative interpretation has helped in delineating aquiferous zones in the study area. Base on the qualitative analysis of the acquired data the subsurface lithology constitutes a non-uniform distribution within the various locations. According to Offodile (2002), the non-uniform distribution of subsurface lithology in various locations is due to discontinuous weathering which is a common characteristic of crystalline rock typical of H-type curve. From the thirty (30) VES point, there are eight (8) different curve types that were obtained, these are Q, A, H, QH, HK, KH, HA and KHK. Nine (9) of the curves are H and QH, four (4) of the curves are Q, three (3) of the curves are KH while

the remaining curve are only one (1) that is for HK, KHK and HA. The characteristics of geo-electric curves varied greatly as typical of the basement complex which is an indication of the degree of weathering and fracturing (Adeniji *et al.*, 2014), (Akintorinwa and Abiola, 2011), and Oladapo *et al.*, (2004). The study area is characterized by three (3) layers of geo-electric sections and these layers have been identified to portray different resistivities resulting from the variations in the lithologic units. The inferred lithology of the three (3) geo-electric section can be classified into; top soil for the first layer, weathered basement for the second and third layer, and fresh basement for the fourth and fifth layer. The first layer is the zone of aeration, thus serve as medium for recharge and this is extended from top soil surface to the upper boundary of zone of saturation. The second and the third layer are expected aquiferous zones, and these can serve as shallow aquifers for hand dug wells and boreholes. The fifth layer is an impervious zone, if weathered or fractured and well connected can also serve as aquifer. Nur and Goji (2005) is of the opinion that

the weathered or fractured aquifer in the basement areas has low to moderate hydraulic conductivity and transmissivity values which gives rise to low and moderate yields and specific capacities in boreholes tapping these aquifer systems. The formation of the weathered or fractured zones which is the target for aquifer are

form as a result of weathering and development of joints caused by contraction, expansion, and deformation of consolidated sedimentary, igneous, metamorphic, and volcanic rocks due to geologic process that occurred beneath the earth such as temperature change and pressure (Ferris, 1962).

Table 1: The resistivity, thickness, depth, inferred lithology and curve type of the 30 VES points.

VES NUMBER	LAYER NUMBER	RESTIVITY (Ωm)	THICKNESS (m)	DEPTH (m)	INFERRED LITHOLOGY	CURVE TYPE
1	1	641.32	1.339	1.339	Top soil	Q TYPE
	2	324.71	14.722	16.056	Weathered basement	
	3	167.49	-	-	Weathered basement	
2	1	567.71	1.2571	1.2571	Top soil	Q TYPE
	2	328.79	15.365	16.623	Weathered basement	
	3	159.15	-	-	Weathered basement	
3	1	597.34	1.1391	1.1391	Topsoil	Q TYPE
	2	332.90	15.365	16.765	Weathered basement	
	3	148.01	-	-	Weathered basement	
4	1	673.33	2.7060	2.7060	Topsoil	Q TYPE
	2	476.48	46.393	49.099	Weathered basement	
	3	109.56	-	-	Weathered basement	
5	1	61.944	2.6068	2.6068	Top soil	H TYPE
	2	34.686	53.708	56.315	Weathered basement	
	3	76.663	-	-	Weathered basement	
6	1	2728.8	1.7560	1.7560	Top soil	H TYPE
	2	128.10	94.372	96.128	Weathered basement	
	3	1594.3	-	-	Fresh basement	
7	1	912.38	1.8311	1.8311	Top soil	QH TYPE
	2	178.76	8.5526	10.384	Weathered basement	
	3	52.963	22.988	33.372	Weathered basement	
	4	7006.3	-	-	Fresh basement	
8	1	2861.9	0.65256	0.65256	Top soil	QH TYPE
	2	1288.2	7.4084	8.0610	Weathered basement	
	3	119.64	61.080	69.141	Weathered basement	
	4	10326	-	-	Fresh basement	
9	1	327.44	1.3533	1.3533	Top soil	H TYPE
	2	144.73	44.718	46.071	Weathered basement	
	3	2000.2	-	-	Fresh basement	
10	1	72.855	2.0217	2.0217	Topsoil	HK TYPE
	2	39.682	19.545	21.567	Weathered basement	
	3	459.25	20.419	41.986	Weathered basement	
	4	5.1572	-	-	Fresh basement	
11	1	449.82	2.2179	2.2179	Top soil	QH TYPE
	2	199.89	20.029	22.247	Weathered basement	
	3	52.336	-	-	Weathered basement	

12	1	700.50	0.93347	0.93347	Top soil	QH TYPE
	2	187.37	7.2292	8.1627	Weathered basement	
	3	23.494	29.066	37.228	Weathered basement	
	4	2670.3	-	-	Fresh basement	
13	1	1033.8	1.9840	1.9840	Top soil	H TYPE
	2	259.93	31.983	33.967	Weathered basement	
	3	306.88	-	-	Weathered basement	
14	1	2053.6	0.30364	0.30364	Top soil	QH TYPE
	2	154.98	6.0914	6.3951	Weathered basement	
	3	30.094	5.0708	11.466	Weathered basement	
	4	1303.8	-	-	Fresh basement	
15	1	8.7561	0.56815	0.56815	Top soil	KH TYPE
	2	256.07	2.6209	3.1891	Weathered basement	
	3	29.136	12.332	15.521	Weathered basement	
	4	12796	-	-	Fresh basement	
16	1	82.444	3.9392	3.9392	Top soil	A TYPE
	2	90.846	41.484	45.423	Weathered basement	
	3	141.77	-	-	Weathered basement	
17	1	757.67	1.8452	1.8452	Top soil	H TYPE
	2	94.022	60.764	62.609	Weathered basement	
	3	9308.2	-	-	Fresh basement	
18	1	244.97	0.42855	0.42855	Top soil	H TYPE
	2	165.49	13.112	13.540	Weathered basement	
	3	706.80	-	-	Fresh basement	
19	1	243.65	0.37313	0.37313	Top soil	H TYPE
	2	131.92	12.947	13.320	Weathered basement	
	3	836.66	-	-	Fresh basement	
20	1	59.709	2.5861	2.5861	Top soil	HA TYPE
	2	16.430	3.3561	5.9422	Weathered basement	
	3	162.47	43.035	48.977	Weathered basement	
	4	24995	-	-	Fresh basement	
21	1	41.092	1.6711	1.6711	Top soil	KH TYPE
	2	303.55	2.3264	3.9975	Weathered basement	
	3	7.7365	6.6815	10.679	Weathered basement	
	4	2230.1	-	-	Fresh basement	
22	1	97.471	3.1941	3.1941	Topsoil	KHK TYPE
	2	283.63	3.3174	6.5115	Weathered basement	
	3	21.506	14.336	20.848	Weathered basement	
	4	2726.0	5.7227	26.571	Fresh basement	
	5	394.52	-	-	Fresh basement	
23	1	174.47	2.2010	2.2010	Top soil	H TYPE
	2	102.73	53.624	55.825	Weathered basement	
	3	1290.6	-	-	Fresh basement	
24	1	8.7957	4.9923	4.9923	Top soil	A TYPE
	2	29.689	22.989	27.981	Weathered basement	
	3	5351.9	-	-	Fresh basement	
25	1	582.32	1.5604	1.5604	Top soil	QH TYPE
	2	222.57	11.111	12.671	Weathered basement	
	3	112.62	55.378	68.049	Weathered basement	
	4	1218.4	-	-	Fresh basement	
26	1	1615.2	0.41931	0.41931	Top soil	QH TYPE
	2	703.93	5.1542	5.5735	Weathered basement	

	3	8.2621	7.1698	12.743	Weathered basement	
	4	1709.0	-	-	Fresh basement	
27	1	629.22	1.4285	1.4285	Top soil	QH TYPE
	2	227.44	10.752	12.181	Weathered basement	
	3	114.38	54.872	67.053	Weathered basement	
	4	1017.5	-	-	Fresh basement	
28	1	14.983	1.5686	1.5686	Top soil	KH TYPE
	2	135.27	2.7691	4.3376	Weathered basement	
	3	13.151	7.4091	11.747	Weathered basement	
	4	5464.3	-	-	Fresh basement	
29	1	188.94	1.3308	1.3308	Top soil	H TYPE
	2	36.742	3.3871	4.7179	Weathered basement	
	3	2562.5	-	-	Fresh basement	
30	1	793.82	0.57528	0.57528	Top soil	QH TYPE
	2	380.00	4.4124	4.9877	Weathered basement	
	3	121.96	23.426	28.413	Weathered basement	
	4	1587.8	-	-	Fresh basement	

Table 2: Corrosivity and aquifer protection capacity computed output from thirty (30) VES.

S/N	Resistivity (Ω m)					Thickness (m)				Depth (m)				APC	Corrosivity
-	P1	P2	P3	P4	P5	H1	H2	H3	H4	D1	D2	D3	D4	0.047298	641.32
1	641.32	324.71	167.49	-	-	1.3	14.7	-	-	1.3	16.0	-	-	0.049128	567.71
2	567.71	328.79	159.15	-	-	1.3	15.4	-	-	1.3	16.6	-	-	0.048702	597.34
3	597.34	332.90	148.01	-	-	1.1	15.6	-	-	1.1	16.8	-	-	0.100472	873.33
4	873.33	476.48	109.56	-	-	2.7	46.4	-	-	2.7	49.1	-	-	1.590866	61.94
5	61.94	34.67	76.66	-	-	2.6	53.7	-	-	2.6	56.3	-	-	0.737584	2728.80
6	2728.80	128.10	1594.30	-	-	1.8	94.4	-	-	1.7	96.1	-	-	0.484372	912.38
7	912.38	178.76	52.96	7006.3	-	1.8	8.6	23	-	1.8	10.4	33.4	-	0.515852	2861.90
8	2861.90	1288.20	119.64	10326	-	0.7	7.4	61	-	0.7	8.1	69.1	-	0.313127	327.44
9	327.44	144.73	20002	-	-	1.4	44.7	-	-	1.4	46.1	-	-	0.555741	72.86
10	72.86	39.68	459.25	5.16	-	2.0	19.2	20.4	-	2.0	21.6	42	-	0.104946	449.82
11	449.82	199.89	52.34	-	-	2.2	20.0	-	-	2.2	22.2	-	-	1.278498	700.50
12	700.50	187.37	23.41	2670.3	-	0.9	7.2	29	-	0.9	8.2	37.2	-	0.124563	1033.80
13	1033.80	259.93	306.88	-	-	1.9	31.9	-	-	1.9	34	-	-	0.208998	2053.60
14	2053.60	154.98	30.09	1303.8	-	0.3	6.1	5.1	-	0.3	6.4	11.5	-	0.500747	8.76
15	8.76	256.07	29.14	12796	-	0.6	2.6	12.3	-	0.5	3.2	15.5	-	0.504166	82.42
16	82.42	90.84	141.77	-	-	3.9	41.5	-	-	3.9	45.4	-	-	0.663102	757.67
17	757.67	94.02	9308.2	-	-	1.8	60.8	-	-	1.8	62.6	-	-	0.080792	244.97
18	244.97	165.49	706.80	-	-	0.4	13.1	-	-	0.4	13.5	-	-	0.099428	243.65
19	243.65	131.92	83666	-	-	0.4	12.9	-	-	0.4	13.3	-	-	0.515147	59.71
20	59.71	16.43	162.47	24995	-	2.6	3.4	43	-	2.6	5.9	49	-	0.919079	41.09
21	41.09	303.55	7.70	2230.1	-	1.7	2.3	6.7	-	1.7	4.0	10.7	-	0.710338	97.47
22	97.47	283.63	21.51	2726	394.52	3.1	3.3	14.3	5.7	3.1	6.5	20.8	26.6	0.534366	174.47
23	174.47	102.73	1290.6	-	-	2.2	53.6	-	-	2.2	55.8	-	-	1.342853	8.80
24	8.80	29.69	5351.9	-	-	5.0	23.0	-	-	5.0	28.0	-	-	0.544368	582.32
25	582.32	222.57	112.62	1218.4	-	1.5	11.1	55.4	-	1.5	12.7	68.0	-	0.875105	1615.2
26	1615.2	703.93	8.3	1709.0	-	0.4	5.2	7.2	-	0.4	5.6	12.7	-	0.529689	629.22
27	629.22	227.44	114.38	1017.5	-	1.4	10.8	54.9	-	1.4	12.2	67.1	-	0.690246	14.98
28	14.98	135.27	13.15	5464.3	-	1.6	2.8	7.4	-	1.6	4.3	11.7	-	0.099423	188.94
29	188.94	36.74	2562.5	-	-	1.3	3.4	-	-	1.3	4.7	-	-	-	793.83
30	793.83	380.0	121.96	1587.8	-	0.6	4.4	23.4	-	0.6	5.0	28.4	-	-	178.5

The aquifer protective capacity (APC) rating shows that VES 5, 12, 21, 24, and 26 are good aquifer protective capacity, VES 6, 7, 8, 9, 10, 12, 14, 15, 16, 17, 19, 20, 22, 23, 25, 27, 28 and 29 are considered to be moderate, VES 4, 13 and 30 are considered to be weak while VES 1, 2, 3 and 18 are

poor (Figure 4). According to Olorunfemi (2004), the earth material acts as natural filter to percolating fluids. Therefore, its ability to retard and filter percolating ground surface polluting fluid is a measure of its protective capacity.

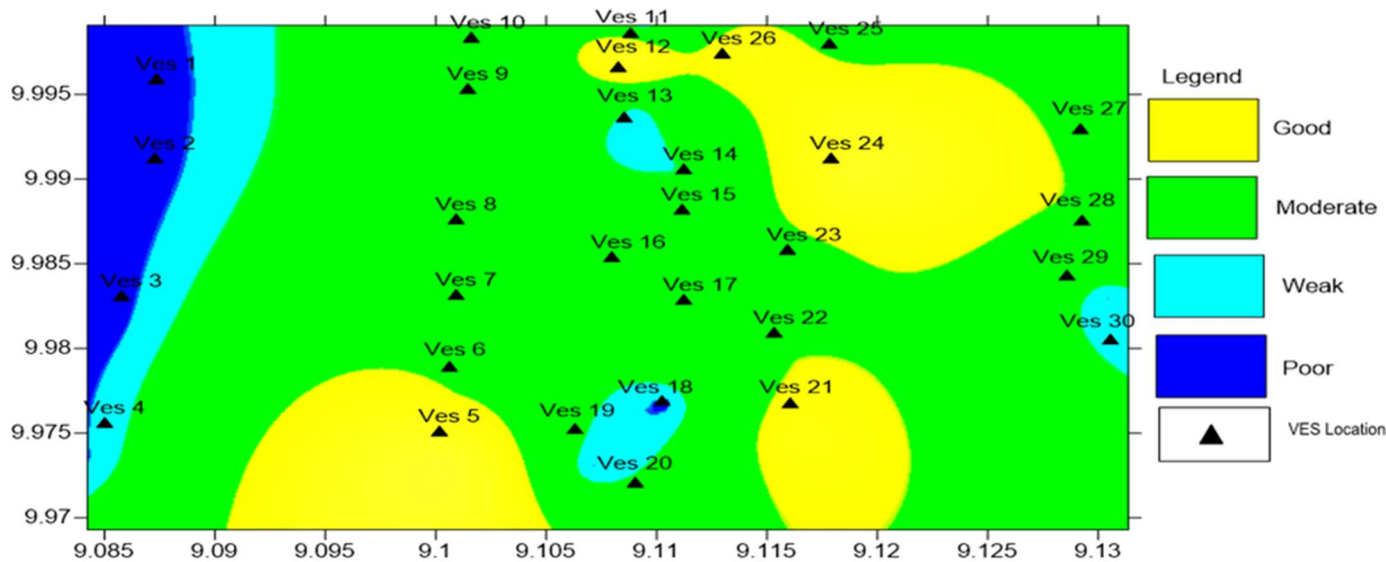


Figure 4: Aquifer Protective Capacity Map of the Study Area

They are four zones of soil corrosivity that were recognized in the area namely: very strongly corrosive (VSC) zone ($<10 \Omega\text{m}$), moderately corrosive (MC) zone ($10\text{--}60 \Omega\text{m}$), slightly corrosive (SC) zone ($60\text{--}180 \Omega\text{m}$) and practically non-corrosive (PNC) zone ($>180 \Omega\text{m}$) (Figure 5). The corrosivity of groundwater may be influenced by the geologic characteristics of the aquifer material within the groundwater flow path,

elevated microbial load, high amount of dissolved oxygen, and elevated concentration of anions (Shams *et al.*, 2012) and (Egbueri, 2018). The very strongly and moderately corrosive zones could be vulnerable to surface contamination while the slightly and practically non-corrosive zones have higher protection against surface contaminated fluids and are apparently safe.

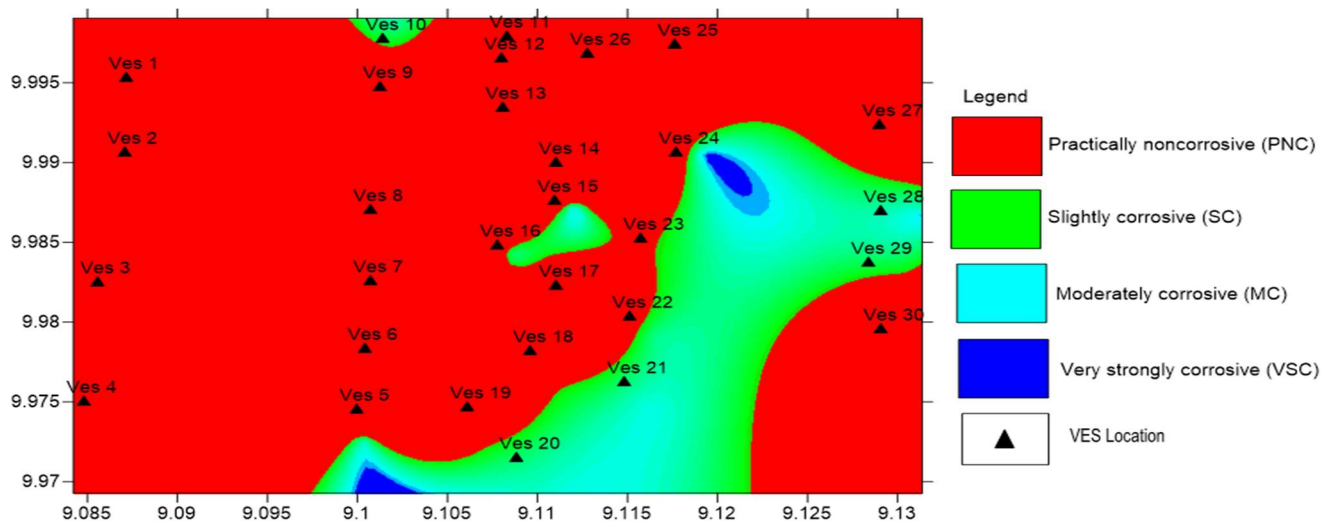


Figure 5: Corrosivity Map of the study Area

The highest point observed from the groundwater flow map is located in the Eastern part at the VES 29. The groundwater flows towards the North-eastern, South-eastern, and Western part of

VES 29 (Figure 6). The fundamental of the ground water flow direction has indicates features of the bedrock, and these is characterised by low, moderate, and high groundwater potential.

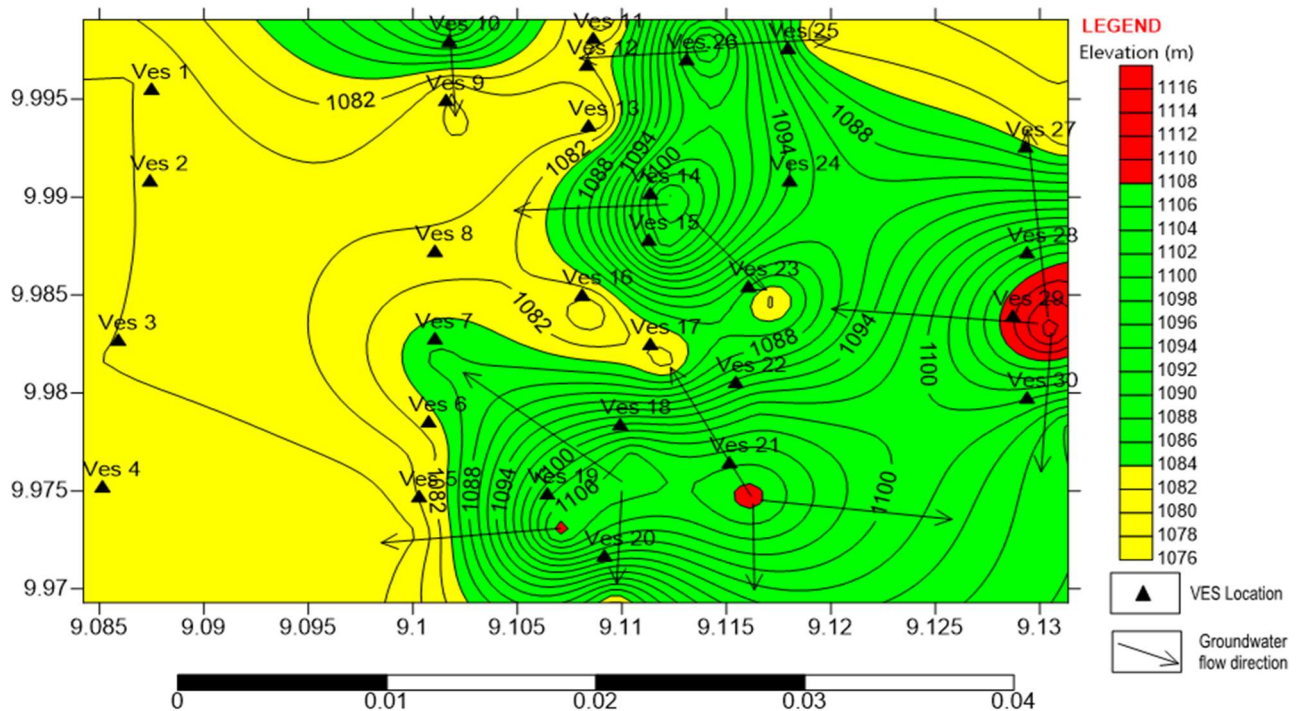


Figure 6. Ground Water Flow Direction of the Study Area

CONCLUSION

The findings have revealed that the geophysical method used in this study have greatly assisted in geophysical evaluation for groundwater potential, aquifer protective capacity, and corrosivity in Gurgu and Environs area of Jos East Local Government Area, Plateau State North Central Nigeria. The results obtained from the area has showed three different layers, which has been interpreted as; top soil, weathered and fresh basement. The data acquired therefore gives reasonably accurate results among other methods that can be used to explore and to understand the subsurface layers and basement configuration in groundwater prospecting. The viable point for sitting wells/boreholes with appreciable thickness of highly weathered basement were identified. It is concluded that the data presented here are representative and can serve as significant value as guide to the development of groundwater resources in the study area.

REFERENCES

- Abaa, S. I., (1991). Hydrothermal fluids responsible for the formation of precious minerals in the Nigerian Younger Granite Province. *Mineralium Deposita*, 26, 34-39.
- Aina, A., & Olarewaju, V.O., (1992). Geological interpretation of Aeromagnetic data in some parts of North Central Nigeria. *Journal of African Earth Sciences*, 14(1), 103-109.
- Abdullahi, A. S., Musa, S. M., & Iliya, A. G., (2005). Aquifer Depletion and Groundwater situation in Damaturu, Northeastern Nigeria. *Water Resources.*, 16, 59-64.
- Acworth, R. I., (1987). The Development of Crystalline Basement Aquifers in a Tropical Environment. *Quarterly Journal of Engineering Geology*, 20, 265-272.
- Adeniji, A. E., Omonona, V. O., Obiora, D. N., & Chukudebelu, J. U., (2014). Evaluation of Soil Corrosivity and Aquifer Protective Capacity using Geo-electrical Investigation in Bwari Basement Area, Abuja. *Journal of Earth System Science*, 123(3), 491-502.
- Akintorinwa, O. J., & Abiola, O., (2011). Sub-soil Evaluation for Pre-foundation Study Using Geophysical and Geotechnical Approach. *Journal of Emerging Trends in Engineering and Applied Sciences*, 2(5), 858-863.
- Amigun, J. O., Faruwa, R. A., & Komolafe, A. A., (2015). Integrated Landsat Imagery and Geophysical Exploration for Groundwater Potential Evaluation of Okene and Its Environs, Southwestern Nigeria. *International Journal of Geoscience*, 6(3), 209-229.
- Annor, A. E., Olasehinde, P. I., & Pal, P. C., (1990). Basement fracture patterns in the control of water channels – An Example from Central Nigeria. *Journal of Mining and Geology*, 26 (1), 5-12.
- Batayneh, A. T., (2009). A Hydrogeophysical Model of the Relationship Between Geoelectric and Hydraulic Parameters, Central Jordan. *Journal of Water Resources and Protection*, 1(6), 400-407.

- Chinyem, F. I., (2017). Evaluation of Groundwater potentials for Borehole drilling by Integrated Geophysical Mapping of Auchi-South Western Nigeria Using Very Low Frequency Electromagnetic Profiling (VLF-EM) and Vertical Electrical Sounding (VES). *Journal of Applied Science and Environmental Management*, 4, 693-700.
- Dung, J. J., & Ifeanyi, A., (2022). Study of the Origin, Geology and Geochemical Classification of the Granitoids of Imori Area, North Central Nigeria. *International Journal of Engineering Research and Advanced Technology*, 8(3), 16-26.
- Edet, A. E., & Okereke, C. S., (1997). Assessment of Hydrogeological conditions in Basement aquifers of the Precambrian Oban Massif, Southeastern Nigeria. *Journal of Applied Geophysics*, 36, 195-204.
- Egbueri, J. C., (2018). Assessment of the quality of Groundwater proximal to dumpsites in Akwa and Nnewi Metropolis: A comparative approach. *International Journal Energy and Water Resources*, 2(1-4), 33-48.
- Ekwueme, B. N., (1994). Structural features of Southern Obudu Plateau, Bamenda Massif, S.E. Nigeria: Preliminary Interpretations. *Journal of Mining and Geology*, 30(1), 45-59.
- Emenike, E. A., (2001). Geophysical exploration for Groundwater in a Sedimentary Environment; A case study from Nanka over Nanka formation in Anambra Basin South East, Nigeria. *Global Journal of Pure and Applied Science*, 2, 97-101.
- Ezeh, C. C., & Ugwu, G. Z., (2010). Geoelectrical Sounding for Estimating Groundwater Potential in Nsukka L. G. A. Enugu State, Nigeria. *International Journal of the Physical Sciences*, 5(5), 415-420.
- FSN (1962). *Topographic Map of Naraguta Area of Jos Plateau Sheet 168*.
- Ferris, J. G., (1962). *Theory of Aquifer Test, U.S Geological Survey Water Supply paper 1536E*.
- GSN (1963). *Geological map of the Plateau State, North Central part of Nigeria*.
- Hassan, B. A., Choji, V. D., & Wuyep, S. Z., (2014). Groundwater Supply in Jos-East Local Government Area of Plateau State, Nigeria. *Journal of Environmental Science and Water Resources*, 3(1), 1-6.
- Ibrahim, E. S., Gajere, E. N., Dang, B. A. Jerome, I., Dashan, T., Mwada, H., & Ojih, S., (2020). Geospatial Tools for Suitable Assessment of Small Holder Irrigation Water, towards Increased Food Production and Poverty Eradication in Nigeria: A case of Jos East LGA, Plateau State. *Journal of Remote Sensing and GIS*, 9(3), 2469-4134.
- Iserhien-Emekeme, R. E., Atakpo, E. A., Emekeme, O. L., & Anomohanran, O., (2004). Geoelectric Survey for Groundwater in Agbede, Etsako West L.G. A., Edo State. *Advances*

- in Natural and Applied Science Research*, 2(1), 65-72.
- Keller, G. V., & Frischknecht, F. C., (1966). *Electrical Methods in Geophysical Prospecting*. Pergamon Press, Oxford, 91-135.
- Listorti, J. A., (1996). *In Water Resources, Environment and Sustainable Development in Nigeria by Orubu, C. O. Department of Economics, Delta State University, Abraka, Nigeria, 14th September 1996.*
- Mbiimbe, E.Y., Olasehinde, A., & Bute, I. S., (2012). Hydrogeophysical Investigation of the Area Around Angware in Jos East Plateau State, North Central Nigeria. *Global Journal of Geological Science*, 1(18), 141-148.
- Mucke, A., (2003). Fayalite, Pyroxene, Amphibole, Annite and their decay products in Mafic clots within Younger Granites of Nigeria: Petrography, Mineral Chemistry and Genetic Implications. *Journal of African Earth Sciences*, 36(1-2), 55-71.
- Nanfa, C. A., Aminu, M. B., Christopher, S. D., Akudo, E. O., Musa, K. O., Aigbadon, G. O. & Millicent, O. I., (2022). Electric Resistivity for Evaluating Groundwater Potential along the Drainage Zones in the part of Jos North, Plateau State, Nigeria. *European Journal of Environment and Earth Sciences*, 3(6), 59-68.
- Nur, A., & Goji, M., (2005). Hydro-geoelectrical Study in Takum and Environs of Taraba State, NE Nigeria. *Global Journal of Geological Sciences*, 3(2), 109-115.
- Nwankwo, L. I., (2011). 2D Resistivity Survey for Groundwater exploration in a Hard rock terrain: A case study of MAGDAS observatory, UNILORIN, Nigeria. *Asian Journal of Earth Sciences*, 4, 46-53.
- Offodile, M. E., (2002). *Groundwater Study and Development in Nigeria*, Ehindero Nigeria Limited Jos, 453.
- Ogunbemi, S., Badmus, O., Ayemi, O., & Ologe, B., (2013). Geoelectric investigation of Aquifer Vulnerability within Afe Babalola University, Ado-Ekiti South Western Nigeria. *Journal of Applied Geology and Geophysics*, 1(5), 28-34.
- Ogunleye, P. O., Ike, E. C., & Garba, I., (2005). Geochemical characteristics of the Niobium-rich Arfvedsonite Granite, Younger Granites Province of Nigeria, *Chemie de Erde*, 65(3), 279-296.
- Okiongbo, K. S., & Akpofure, E., (2012). Determination of Aquifer Properties and Groundwater Vulnerability Mapping using Geoelectric Method in Yenagoa City and its Environs in Bayelsa State, South-South Nigeria. *Journal of Water Resources and Protection*, 4(6), 354-362.
- Okolie, E. E., Osemeikhian, J. E. A., & Asokhia, M. B., (2005). Estimate of Groundwater in Parts of Niger Delta Area of Nigeria using Geoelectric Method. *Journal of Applied*

- Sciences and Environmental Management*, 9(1), 31-37.
- Okwueze, E. E., & Ezeanyim, V. I., (1991). Geophysical Exploration for Fresh water Groundwater source in a Saline Shale area. *African Journal of Science and Technology, Series B, Science*, 2, 52-60.
- Okwueze, E. E., (1996). Preliminary findings of Groundwater Resources Potentials from a regional Geoelectric Survey of the Obudu Basement Area, Nigeria. *Global Journal of Pure and Applied Science*, 2, 201-211.
- Oladapo, M. I., Mohammed, M. Z., Adeoye, O. O., & Adetola, B. A., (2004). Geoelectrical Investigation of the Ondo State Housing Corporation Estate, Ijapo Akure, South-Western Nigeria. *Journal of Mining and Geology*, 40(1), 41-48.
- Olorunfemi, M. O., & Fasuyi, S. A., (1993). Aquifer types and Geoelectrical/Hydrogeologic Characteristics of the Central Basement Terrain of Nigeria. *Journal of African Earth Sciences*, 16, 309-317.
- Olorunfemi, M. O., (2004). Application of Electrical Resistivity Method in Foundation failure Investigation. *Global Journal of Geology of Geological Sciences*, 2(1), 139-151.
- Olowofela, J. A., Jolaosho, V. O., & Badmus, B. S., (2005). Measuring the Electrical Resistivity of the Earth using a Fabricated Resistivity Meter. *European Journal of Physics*, 26, 501-515.
- Omosuyi, G. O., Adeyemo, A., & Adegoke, A. O., (2007). Investigation of Groundwater Prospect Using Electromagnetic and Geoelectric Sounding at Afunbiowo, near Akure, Southwestern Nigeria. *Pacific Journal of Science and Technology*, 8(2), 172-182.
- Onugba, A., & Eduvie, O. M., (2003). Hydrogeology of Nigeria. *Paper on Groundwater Work Shop, Organized by United Nations Children's Fund*, Jos, 20.
- Onu, N. N., & Ibeh., K. M., (1998). Geophysical Investigation for Groundwater in Idah, Lower Benue Trough, Nigeria. *Journal of Mining and Geology*, 34(1), 43-53.
- Oseji, J. O., Atakpo, E. A., & Okolie, E. C., (2005). Geoelectric Investigation of the Aquifer characteristics and Groundwater Potential in Kwale, Delta State, Nigeria. *Journal of Applied Science and Environmental Management*, 9, 157-160.
- Oseji, J. O., Asokhia, M. B., & Okolie, E. C., (2006). Determination of Groundwater Potential in Obiaruku and Environs using Surface Geoelectric Sounding. *Environmentalist*, 26, 301-308.
- Oseji, J. O., Egbai, J. C., & Emuobonuvie, I. A., (2020). Aquifer vulnerability using Geophysical and Physiochemical methods in Parts of Ethiope West Local Government Area of Delta State, Nigeria. *AIP Advances*, 10, 10-20.

- Shams. M., Mohamadi, A., & Sajadi, S. A., (2012). Evaluation of Corrosion and Scaling Potential of water in rural water supply distribution networks on Tabas, Iran. *World Applied Science Journal*, 17(11), 1484-1489.
- Shemang, E. M., Umaru, J. R., & Umaru, A.F.M., (1994). Geophysical investigations for Groundwater in the Area around Bauchi town. *Journal of Mining and Geology*, 30, 81-86.
- Tammaneni, K. R., Hanuman, D. S., & Malisethy, J. G., (2006). *Site investigations for the identification of a Groundwater Source for Sullurupeta, Andhra Pradesh, India. IAEG Publication*, 36.
- UNESCO (2004). Groundwater Resources of the World and their use. In: Zekster IS, Everett LG (eds), IHP-VI, *Series on Groundwater*, 6.