

GEOELECTRICAL EVALUATION OF GROUNDWATER QUALITY OF GASSOL, TARABA NORTHEAST NIGERIA USING DAR- ZARROUK PARAMETERS

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ABSTRACT: Twenty-five (25) resistivity VES points were sounded in five wards of Gassol, Taraba, Northeastern Nigeria; Gunduma, Shira, Mutum-biyu ward A, Mutum-biyu ward B, and Namne ward to evaluate the groundwater quality of the area using secondary geoelectric resistivity parameters (Dar-Zarrouk parameters; total longitudinal unit conductance S , transverse resistance T and reflection coefficient R_c) acquired from the primary resistivity field data (apparent resistivity and thickness) interpreted by IXD Interpex software. Result from the S proportional to aquifer protective capacity APC of the study area ranging from 0.009069 mho – 10.498660 mho and this shown that 52 % of the VES points APC were poor, 20 % were weak, 4 % were moderate and only 24 % were good and excellent. Transverse resistance T of the area varied from 778.6767 – 352920.9895 $\Omega\text{-m}^2$ and area of very low T yield quality groundwater as seen in Mutum-biyu ward A where VES 13, 14 and 15 were conducted. However, locations with high T values possessed high groundwater potential. The reflection coefficient R_c range from - 0.9996 to + 0.9984, with an average value of -0.3461, indicating that the study area

possessed good prospect for groundwater potential. Groundwater flow direction map revealed areas of recharge and discharge and it is deduced that water recharge areas were located along Southern and North Eastern part while discharge area was visibly situated at the North Western part of the study area. The study area was characterized having poor/weak APC and only 24 % of its VES points APC possessed good and excellent APC rating and the earth material (clay) drives this hydrogeology protection observed in different VES points; VES 9, 11, 12, 13, 14 and 15. Consequently, 76 % of the water bearing formation units due to APC of the study area is prone to contaminant and this hydro-geologically affects the quality of the groundwater exploited from boreholes with high groundwater potential. Measures to protect the anthropogenic pollution of the groundwater resources of the area include; refuse dumping site or any groundwater polluting activity locations should be provided and managed by the government and the development site for this project was recommended at the NW or NE part of the area in order to protect groundwater pollution in areas with low APC as observed in most VES locations.

Keywords: *Groundwater quality, groundwater pollution, Dar-Zarrouk parameters, aquifer protective capacity APC, longitudinal conductance S , transverse resistance T , reflection coefficient R_C , clay, recharge point, discharge point*

INTRODUCTION

Availability of potable water supply is imperative for the survival of humans, animals and even plants and its fundamental prerequisite for the development of thriving communities. While surface water resources may be accessible, its accessibility and reliability are often limited, thus, underscoring the vital role that groundwater plays in meeting the ever-growing water demands of a growing population. Groundwater been the major source of potable water has proven over the years to be reliable for various purposes including; drinking, domestic activities, recreation, irrigation, and livestock farming due to its abundance in the Earth subsurface in a hydrogeologic formation (aquifer). In fact, it is estimated that about 85% of total freshwater demand in Nigeria is met by groundwater sources (Egbueri et al., 2021). Presence of permeable overburden layer contribute to the aquifer protective capacity APC weakness of groundwater reservoir against an anthropogenic contaminants

percolating downward to the aquifer and this have high potential to contaminate and pollute the sub-surface aquifers on the long-run due to the possibility of indiscriminate dumping of waste on the ground surface (Ayuk, 2019). Clay at different depths has strongest blocking effect on Na^+ in groundwater, being systematically greater than its effect on Ca^{2+} and Mg^{2+} . It is believed that the blocking effect of clay has an important influence on the hydro-chemical zoning of groundwater Liting *et al.*, (2018). Protective capacity of an aquifer is driven by thick and low resistivity overburden layer above the subsurface aquifer layer. Thick layers and low resistivity values indicate high total longitudinal unit conductivity which implies a good/excellent aquifer protective capacity area while low protective capacity of a permeable overburden layer are susceptible to the risks of pollution and contamination stemming from leaks and waste sites affecting groundwater quality (Ejepu *et al.*, 2024).

Geoelectrical evaluation of groundwater quality which involves measurement of the electrical resistivity of the subsurface strata and interpreting the data to infer the presence and characteristics of aquifers, the valuable information that may be extracted includes; nature of the subsurface lithology, the depth and thickness of aquifers, potential sites for groundwater development. By understanding the hydrogeologic formation zones and subsurface geologic structures, effective management plans can be establish to ensure long-term availability and accessibility of quality groundwater resources. Geo-electrical resistivity method has emerged as an imperative geophysical method for evaluating groundwater potential and understanding aquifer characteristics (Ibuot *et al.*, 2013; Raji and Abdulkadir 2022).

The implementation of effective groundwater development and aquifer protection strategies in Gassol L.G.A. experiencing a surge in population growth and the demand for quality groundwater has been significantly driven by population. Surface water bodies, such as rivers and lakes contribute to water supply but often suffer from seasonal variations and are vulnerable to pollution. Consequently, the people of Gassol depend on groundwater as the primary source of potable water. The improper waste disposal and other land use practices that may contaminate aquifers which jeopardized the quality of groundwater and rendering it unsuitable for consumption,

this necessitates the geophysical resistivity investigation of the study area in order to determine the first order geoelectrical resistivity parameters (resistivity ρ and thickness h) to delineate the depth to aquifer and its lateral extent and a second order geoelectric parameter (longitudinal unit conductance S) to determine the aquifer protective capacity of the groundwater potential zones. Hence, this systematic assessment would lead to understanding aquifer characteristics, identification of vulnerable areas, and the formulation of protective measures, to ensure the sustainability and resilience of groundwater resources in the study area.

GENERAL GEOLOGY OF THE STUDY AREA

The study area falls within the Middle Benue Trough (see figure 1) and the Middle Benue Trough is separable from the Southern part by the Gboko Line, a NW-SE trending transform fault which is now buried and runs from Gboko to Makurdi and westward to link with the position of the much younger Middle Niger Basin, (Whiteman, 1982). The boundary between the Middle and Upper Benue Trough is defined by the Mutum-Biyu Bashar Line (Najime, 2011).

Taraba State is underlain by Basement Complex and sedimentary rocks, each occupying a distinctive part of the state (Oruonye and Abbas, 2011). The Basement Complex rocks occupied most part of the state (above 80 %), while the sedimentary rocks are found along the valleys of the River Benue and its major tributaries such as Rivers Donga. The Basement Complex rocks are Pre-Cambrian while the Sedimentary rocks date back from Albian to recent (Jeje, 1978). The undifferentiated Basement Complex rocks comprising of gneisses, migmatites, phyllites, schists and pegmatites cover a greater part of the Basement Complex area. The undifferentiated Basement Complex rocks, particularly the migmatites, generally vary from coarsely mixed gneisses to diffused textured rocks of variable grain size and are frequently porphyroclastic (Macleod *et al.*, 1971). This rock unit constitutes principally the undifferentiated igneous and metamorphic rocks of Precambrian age (Grant, 1971).

The sedimentary rocks of the state belong to the Sub Group of the Middle Benue Trough which is one of the rocks of the sedimentary series that covers about 50 % of the surface area of Nigeria. Sedimentary materials filling the basins vary in thickness

and often display complete single or multiple cycles of development characterized by basal continental facies overlain by marine facies and, in turn by continental sediments (Ogezi, 2002). This varied geologic rock types provide rich solid mineral resource potentials for the state.

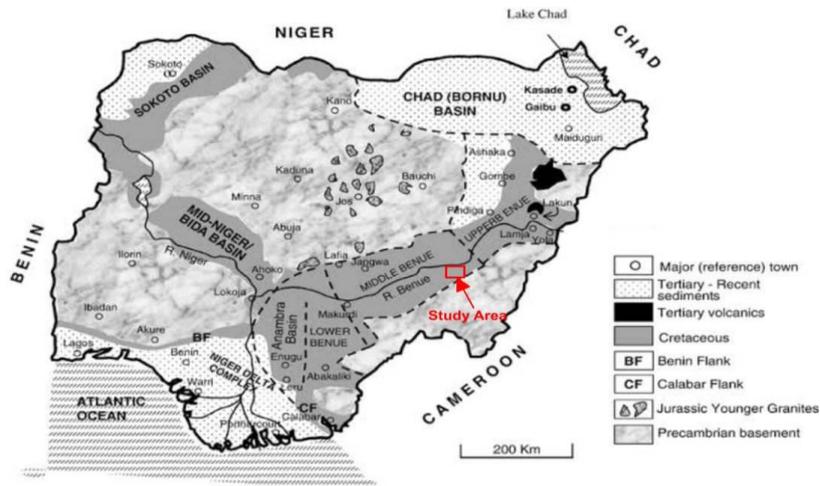


Figure 1: Geology Map of Nigeria Showing Geology of the Study Area

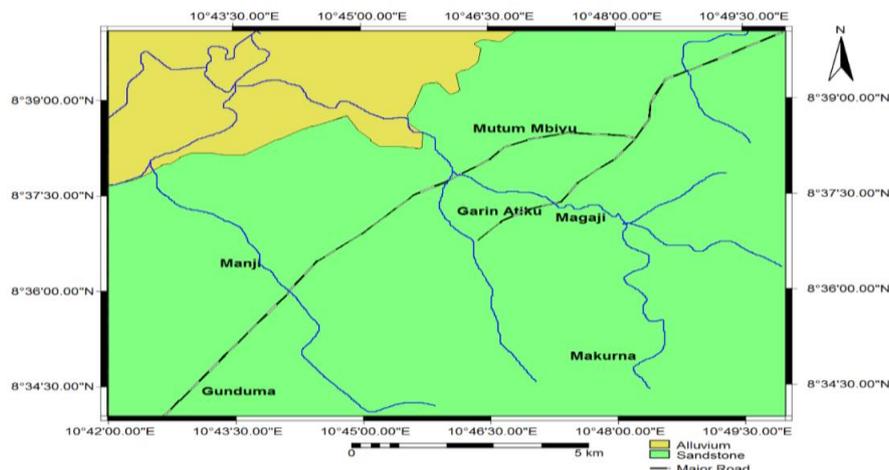


Figure 2: Geology map of the study area

METHODOLOGY

Vertical electrical sounding (VES) was carried out with a four-electrode configuration commonly referred to as the Schlumberger array (Bullard *et al.*, 1966). This geoelectrical technique uses four in-line electrodes; the inner pair (potential electrodes) for recording electrical potential as current is passed through the outer pair (current electrodes). Measurements were made involving successively larger

current electrodes separations. As the distance between current electrodes probes is increased, there is also an increased in the depth at which the current penetrates below the surface of the ground increasing the depth of investigation. The potential electrodes are kept constant whereas the current electrodes are increased. The potential electrode spacing is assumed to be infinitesimal, and the observed value of potential can be adjusted accordingly (Dobrin and Savit, 1988). The apparent resistivity (ρ_a) for Schlumberger configuration (in figure 3) is given by the expression:

$$\rho_a = \frac{\pi}{a} \left[(s^2) - \left(\frac{a}{2} \right)^2 \right] \frac{\nabla V}{I} \quad 1$$

The VES points were selected based on the accessibility and applicability of this method in the study area. Schlumberger electrodes configuration was employed during the field measurement for the purpose of determining the vertical variation of resistivity and greater depth of investigation. The current and potential electrodes was maintained at the same relative spacing and the whole spread was progressively expanded about a fixed central point (Kearey and Brooks, 1984). The electrodes are usually placed along a straight line with half current electrode spacing $\frac{AB}{2}$ and $\frac{MN}{2}$ potential electrodes spacing ranging from 1.00 m to 200.00 m and 0.20 m to 26.00 m respectively.

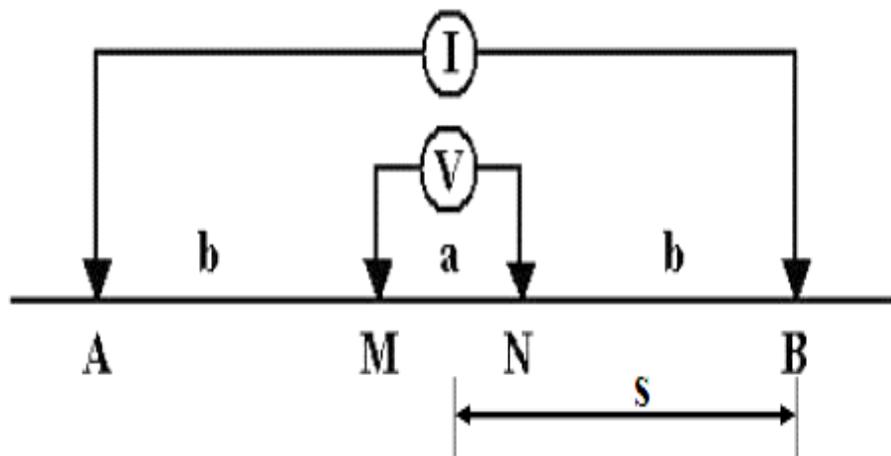


Figure 3: Schlumberger Electrodes Configuration

Application of Dar Zarrouk Parameters

Dar-Zarrouk Parameters Longitudinal unit Conductance (S) and Transverse Resistance (T) are imperative in aquifer protection studies and evaluation of hydrologic properties of aquifer. Abiola *et al.*, (2009) established that the protective capacity of a clayey overburden layer is proportional to its total longitudinal unit conductance S. The secondary electrical resistivity parameters; longitudinal conductance (S), transverse resistance (T), and reflection coefficient (R_C) reflecting the characteristics of the earth layers were determined. Current flows parallel to the geoelectric boundaries, is influence by total longitudinal unit conductance (S) and when the current flows normal to the bed boundaries, the transverse resistance (T) is significant (Telford *et al.* 1978). The ‘S’ and ‘T’ values also known as Dar-Zarrouk parameters for a layer of thickness ‘h’ and resistivity ‘ρ’ are defined as:

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad 2$$

$$T = \sum_{i=1}^n h_i \rho_i \quad 3$$

When a number of layers with thicknesses $h_1, h_2, h_3 \dots$ transverse resistances of T_1, T_2, T_3, \dots and longitudinal unit conductance of S_1, S_2, S_3, \dots , respectively, are involved in a geoelectric section, their total longitudinal unit conductance (S) or total transverse resistance (T) is given by:

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \dots + \frac{h_n}{\rho_n} \quad 4$$

$$T = \sum_{i=1}^n h_i \rho_i = h_1 \rho_1 + h_2 \rho_2 + h_3 \rho_3 + \dots + h_n \rho_n \quad 5$$

Transverse Resistance (T)

The VES points with high transverse resistance values possess high groundwater potential. Thus, transverse resistance is one of the parameters used to define target areas of good groundwater potential. It has a direct relation with transmissivity and the highest transverse resistance values reflect most likely the highest transmissivity groundwater zone (Opara *et al.*, 2012).

Reflection Coefficient R_c

Reflection Coefficient (R_c) of hydro-geologic formation was evaluated from the expression:

$$R_c = \frac{\rho_n - \rho_{n-1}}{\rho_n + \rho_{n-1}} \quad 6$$

ρ_n is the layer resistivity of the nth layer and ρ_{n-1} is the layer resistivity overlying the nth layer.

RESULTS AND DISCUSSIONS

AQUIFER PROTECTIVE CAPACITY (APC)

The Aquifer Protective Capacity APC of the study area VES points has been evaluated and characterized using Dar-Zarrouk parameter (total longitudinal unit conductance S) to be 52 % poor, 20 % weak, 4 % moderate and 24 % good and excellent. Hydrogeological observation in different VES locations showed that 76 % of the water formation units of the area are vulnerable to contaminants and this result affects the groundwater potential quality.

Table 1: Aquifer Protective Capacity Rating of the Study Area

VES corresponding Longitudinal Conductance (mhos)	VES Protective Capacity Rating	VES Number	Percentage (%)
> 10	Excellent	13	4
5-10	Very good	14	4
0.7-4.9	Good	9, 11, 12 and 15	16
0.2-0.69	Moderate	7	4
0.1-0.019	Weak	2, 4, 10, 16 and 19	20
< 0.10	poor	1, 3, 5, 6, 8, 17, 18, 20, 21, 22, 23, 24 and 25	52

Protective capacity rating of the groundwater reservoir corresponding to the total longitudinal unit conductance of the five wards showed that Mutum-biyu ward A, possessed quality groundwater due to it corresponding VES points APC rating while Namne ward lacks quality groundwater potential.

Table 2: Result of Dar-Zarrouk Parameters of Gunduma ward of Gassol L.G.A

VES NO.	Location	No. of Layers	Resistivity Value ($\Omega\text{-m}$)	Thickness(m)	Longitudinal Conductance	Transverse Resistance	Reflection Coefficient
1	Gunduma	1	324.7	0.305	9.39329×10^{-4}	99.0335	-0.75996
		2	3440.3	0.711	2.06668×10^{-4}	2446.0533	
		3	254.9	1.5	5.88466×10^{-3}	382.35	
		4	883.5	51.77	5.85965×10^{-2}	45738.795	
		5	120.5	—	—	—	
					Total	0.06563	48666.2318
2	Gunduma	1	184.2	0.304	1.65038×10^{-3}	55.9968	-0.95326
		2	261.6	2.78	1.06269×10^{-2}	727.248	
		3	2873	2.38	8.28402×10^{-4}	6837.74	
		4	531.1	74.17	1.39654×10^{-1}	39391.687	
		5	12.71	—	—	—	
					Total	0.15276	47012.6718
3	Gunduma	1	619.3	8.42	1.35960×10^{-2}	5214.506	0.6816
		2	716.7	28.41	3.96400×10^{-2}	20361.447	
		3	3785.2	—	—	—	
					Total	0.05324	25575.953
4	Gunduma	1	345.6	0.383	1.10822×10^{-3}	132.3648	-0.84957
		2	177.9	4.48	2.51827×10^{-2}	796.992	
		3	808.2	8.07	9.98515×10^{-3}	6522.174	
		4	688.9	80.76	1.17230×10^{-1}	55635.564	

		5	56.03		—	—	
				Total	0.15351	63087.0948	
5	Gunduma	1	668.2	2.97	4.44478×10^{-3}	1984.554	-0.48744
		2	1083.6	46.8	4.25249×10^{-2}	49932.288	
		3	373.4		—	—	
				Total	0.04697	51916.842	

Table 3: Result of Dar-Zarrouk Parameters of Shira ward of Gassol L.G.A

VES NO.	Location	No. of Layers	Resistivity Value (Ω -m)	Thickness(m)	Longitudinal Conductance	Transverse Resistance	Reflection Coefficient
6	Shira	1	1065.8	2.64	2.47701×10^{-3}	2813.712	0.71816
		2	7659.5	2.8	3.65559×10^{-4}	21446.6	
		3	123.6	8.09	6.54531×10^{-2}	999.924	
		4	753.5		—	—	
				Total	0.068296	25260.236	
7	Shira	1	294.2	7.29	2.47791×10^{-2}	2144.718	0.38032
		2	800.5	8.86	1.10681×10^{-2}	7092.43	
		3	150.8	43.71	2.89854×10^{-1}	6591.468	
		4	335.9		—	—	
				Total	0.3257	15828.616	
8	Shira	1	1526.6	0.427	2.79707×10^{-4}	651.8582	-0.76659
		2	1515.3	30.52	2.01412×10^{-2}	46246.956	
		3	200.2		—	—	

				Total	0.02042	46898.8142	
9	Shira	1	1567.2	0.498	3.17764×10^{-4}	780.4656	-0.64874
		2	205.6	15.38	7.48054×10^{-2}	3162.128	
		3	405.5	69.95	1.72503×10^{-1}	28364.725	
		4	86.39		—	—	
				Total	2.47626	32307.3186	
10	Shira	1	1607.8	0.208	1.29369×10^{-4}	334.4224	-0.86536
		2	532.6	6.33	1.18851×10^{-2}	3371.358	
		3	99.54	7.33	7.36287×10^{-2}	729.6282	
		4	625.8	25.77	4.11793×10^{-2}	16126.866	
		5	45.17	—	—	—	
				Total	0.12683	20562.2746	

Table 4: Result of Dar-Zarrouk Parameters of Mutum-biyu ward A of Gassol L.G.A

VES NO.	Location	No. of Layers	Resistivity Value (Ω -m)	Thickness(m)	Longitudinal Conductance	Transverse Resistance	Reflection Coefficient
11	Mutum-Biyu Ward A	1	16.25	3.34	2.05538×10^{-1}	54.275	-0.93973
		2	12.47	1.55	1.24298×10^{-1}	19.3285	
		3	3842.5	2.19	5.69941×10^{-4}	8415.075	
		4	26.52	13.16	4.96229×10^{-1}	349.0032	
		5	0.824	—	—	—	
				Total	0.82663	8837.6817	
12	Mutum-Biyu	1	25.08	3.02	1.20415×10^{-1}	75.7416	-0.9898

	Ward A						
		2	9.74	3.14	3.22382×10^{-1}	30.5836	
		3	118.2	30.79	2.60491×10^{-1}	3639.378	
		4	0.606	—	—	—	
				Total	0.70329	3745.7032	
13	Mutum-Biyu Ward A	1	16.36	1.74	1.06357×10^{-1}	28.4664	0.99841
		2	1.45	0.337	2.32414×10^{-1}	0.48865	
		3	176.4	4.15	2.35261×10^{-2}	732.06	
		4	1.32	13.38	1.013636×10^{-1}	17.6616	
		5	1655.2	—	—	—	
				Total	10.49866	778.6767	
14	Mutum-Biyu Ward A	1	16.76	1.89	1.12768×10^{-1}	31.6764	-0.97867
		2	1.26	2.58	2.04762	3.2508	
		3	17.25	53.2	3.08406	917.7	
		4	0.186	—	—	—	
				Total	5.24445	952.6272	
15	Mutum-Biyu Ward A	1	404	0.887	2.19554×10^{-3}	358.348	0.78883
		2	1.55	1.43	9.22581×10^{-1}	2.2165	
		3	30.22	72.53	2.40007	2191.8566	
		4	256	—	—	—	
				Total	3.32485	2552.4211	

Table 5: Result of Dar-Zarrouk Parameters of Mutu-biyu ward B, of Gassol L.G.A

VES NO.	Location	No. of Layers	Resistivity Value (Ω -m)	Thickness(m)	Longitudinal Conductance	Transverse Resistance	Reflection Coefficient
16	Mutum-Biyu Ward B	1	1951.100	1.330	6.81667×10^{-4}	2594.9630	-0.79111
		2	734.400	6.020	8.19717×10^{-3}	4421.0880	
		3	9536.500	11.840	1.24155×10^{-3}	112912.1600	
		4	55.820	9.650	1.72877×10^{-1}	538.6630	
		5	6.510	—	—	—	
					Total	0.183000	120466.8740
17	Mutum-Biyu Ward B	1	1408.200	0.656	4.65843×10^{-4}	923.7792	-0.70528
		2	648.400	3.260	5.02776×10^{-3}	2113.7840	
		3	1915.800	47.530	2.48095×10^{-2}	91057.9740	
		4	331.100	—	—	—	
					Total	0.030300	94095.5372
18	Mutum-Biyu Ward B	1	3419.500	0.517	1.51192×10^{-4}	1767.8815	-0.44290
		2	656.000	3.280	5.00000×10^{-3}	2151.6800	

		3	17858.900	5.540	3.10209×10^{-4}	98938.3060	
		4	4762.200	52.510	1.10264×10^{-2}	250063.1220	
		5	1838.700	—	—	—	
				Total	0.016490	352920.9895	
19	Mutum-Biyu Ward B	1	53.330	2.000	3.75023×10^{-2}	106.6600	+0.99614
		2	3963.900	4.020	1.01415×10^{-3}	15934.8780	
		3	153.100	14.030	9.16395×10^{-2}	2147.9930	
		4	79095.200	—	—	—	
				Total	0.130160	18189.5310	
20	Mutum-Biyu Ward B	1	1933.900	0.286	1.47888×10^{-4}	553.0954	-0.60993
		2	530.900	5.070	9.54982×10^{-3}	2691.6630	
		3	1543.600	18.970	1.22895×10^{-2}	29282.0920	
		4	374.000	—	—	—	
				Total	0.021990	32526.8504	

Table 6: Result of Dar-Zarrouk Parameters of Namne ward of Gassol L.G.A

VES NO.	Location	No. of Layers	Resistivity Value ($\Omega\text{-m}$)	Thickness(m)	Longitudinal Conductance	Transverse Resistance	Reflection Coefficient
21	Namne	1	1148.400	0.249	2.16823×10^{-4}	285.9516	-0.30833
		2	229.100	2.720	1.18725×10^{-2}	623.1520	
		3	617.400	21.380	3.46291×10^{-2}	13200.0120	
		4	326.400	—	—	—	
					Total	0.046720	14109.1156
22	Namne	1	976.100	0.911	9.33306×10^{-4}	889.2271	-0.99392
		2	21.240	1.220	5.74388×10^{-2}	25.9128	
		3	6463.500	11.080	1.71424×10^{-3}	71615.5800	
		4	19.710	—	—	—	
					Total	0.060090	72530.7199
23	Namne	1	440.300	0.451	1.02430×10^{-3}	198.5753	+0.49137

		2	213.600	2.850	1.33427×10^{-2}	608.7600	
		3	626.300	—	—	—	
				Total	0.014370	807.3353	
24	Namne	1	634.300	2.020	3.18461×10^{-3}	1281.2860	-0.61680
		2	2878.800	16.940	5.88440×10^{-3}	48766.8720	
		3	682.300	—	—	—	
				Total	0.009069	50048.1580	
25	Namne	1	1764.300	0.220	1.24695×10^{-4}	388.1460	-0.99960
		2	410.000	8.280	2.01951×10^{-2}	3394.8000	
		3	4037.300	12.190	3.01934×10^{-3}	49214.687	
		4	0.807	—	—	—	
				Total	0.023340	52997.6330	

The values of the total longitudinal unit conductance S proportional to the APC rating of VES 1, 2, 3, 4, and 5 conducted in Gunduma ward varied from 0.046970 - 0.153510 mho. APC rating of the ward was weak as observed in VES 2 and 4 while in VES 1, 3 and 5 was poor and this confirmed the porous and permeable nature of the geologic earth materials overlying the aquifer zone. The total transverse resistances T also varied from 25575.9530 - 63087.0948 $\Omega\text{-m}^2$ which implies that the groundwater potential is good.

The APC rating for the water bearing formation in Shira ward where VES 6, 7, 8, 9 and 10 were carried out, VES 7 and 9 showed a moderate and a good APC due to appreciable S value and VES 10 possessed a weak APC while VES 6 and 8 exhibited poor APC. This implies that only 20 % of the ward aquifer protective capacity is good while 80 % is poor and this made the area vulnerable to contaminants from the water percolating in to the reservoir under the influence of gravity which affects the groundwater quality. The S ranges from 0.020420 - 2.476260 mho and the T varied from 15828.6160 - 46898.8142 $\Omega\text{-m}^2$, this signified a good groundwater potential.

The APC rating of Mutum-Biyu ward A was high which gave the area protection against contaminants that tends to flow into the aquifer. VES 11, 12, 13, 14 and 15 were conducted in the ward and VES 13 and 14 were identified with an excellent and very good APC corresponding to high S values while VES 11, 12 and 15 were characterized with a good APC. The S value ranged from 0.703290 - 10.498660 mho and T values ranges from 778.6767 - 8837.6817 $\Omega\text{-m}^2$ signifying quality groundwater presence with low yield.

VES points conducted in Mutum-Biyu ward B, which include VES 16, 17, 18, 19 and 20 possessed a very low Protective Capacity for the water bearing layers, were VES 16 and 19 possessed a weak APC and VES 17, 18 and 20 were characterized with a poor APC due to their very low total longitudinal unit conductance S value and this made the area prone to pollutants from the surface. The S varied from 0.016490 - 0.183000 mho and the total transverse resistance T values ranged from 18189.5310 - 352920.9895 $\Omega\text{-m}^2$ respectively.

Name Ward APC rating based on the corresponding total longitudinal unit conductance values obtained from the first order resistivity parameters is poor which included VES 21, 22, 23, 24 and 25 carried out in the ward. The total longitudinal unit conductance values of

the VES points proportional to APC varied from 0.009069 - 0.060090 mho and the total transverse resistance values ranged from 807.3353 - 72530.7199 $\Omega\text{-m}^2$ which signified good groundwater potential area.

Aquifer protective capacity map (as seen in figure 4) showed the distribution of the total longitudinal unit conductance S across the study area, where the North Eastern part was characterized with good and excellent protective capacity while other parts were characterized with moderate, weak and poor aquifer protective capacity respectively. These results correlated with the locals experienced; where Mutum-biyu ward A had more quality groundwater potential than experienced in other wards of the study area.

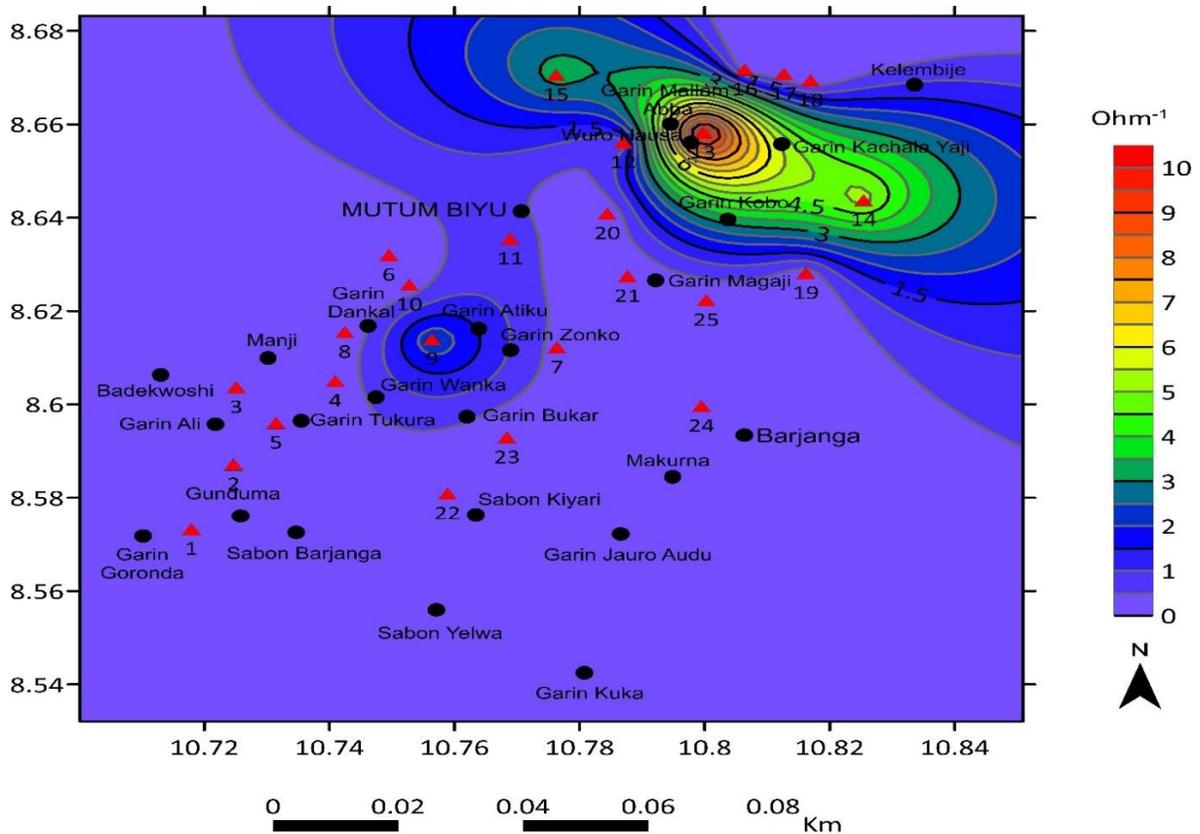


Figure 4: Aquifer protective capacity map of study area

The moderate, weak and poor APC VES points coincide with zones of thin and permeable overburden layers with relatively high resistivity which made these parts of the study area vulnerable to easy and quick migration of surface contaminants into the aquifer formation which resulted to groundwater pollution. Silts and clays are suitable overburden protective

layers and when they are found as thick layers above aquifer, they constitute a protective cover (Olusegun *et al.* 2016) and these conditions were found only in 24 % of the VES locations of the study areas. This result correlated with the inferred lithology across the study area overburden layers and the inferred lithology layers were mostly Sandy-Clay and Laterite and this lithologic units are weak and poor in terms of protective capacity and could offered little or no protection to the underlying aquifer as contaminating fluids can migrate relatively easily through the lithologic unit and pollute the aquifer.

TRANSVERSE RESISTANCE (T)

The transverse resistance T of the study area was very low at VES points with low permeable overburden layers due to their low interconnection (permeability) of the pore spaces which resulted to low groundwater potential at these VES locations and this implies that locations with good APC rating and above tends to have lower T as observed in VES 13, 14 and 15. Transverse resistance values ranged from 778.6767–352920.9895 $\Omega\text{-m}^2$ and area of lower T values tends to yield quality groundwater

Table 7: Transverse Resistance T and Reflection Coefficient of the Study Area R_C

VES Number	Transverse Resistance T (Ωm^2)	Reflection Coefficient R_C $-1.0000 < R_C < +1.0000$	Groundwater Potential (permeability and porosity)	Overburding Protective Capacity Rating
1	48666.2318	-0.75996	Very high	Poor
2	47012.6718	-0.95326	Very high	weak
3	25575.9530	+0.68160	High	Poor
4	63087.0948	-0.84957	Very high	weak
5	51916.8420	-0.48744	Very high	Poor
6	25260.2360	+0.71816	High	Poor
7	15828.6160	+0.38032	High	Moderate
8	46898.8142	-0.76659	Very high	Poor
9	32307.3186	-0.64874	High	Good
10	20562.2746	-0.86536	High	Weak
11	8837.6817	-0.93973	Low	Good
12	3745.7032	-0.98980	Low	Good
13	778.6767	+0.99841	Very low	Excellent

DIRECTION OF GROUNDWATER FLOW

From the water static level measurement across the study area, the groundwater flow direction map was made using golden surfer 18, the map revealed areas of recharge and discharge as seen in figure 6. Groundwater flow direction shown as vector with arrow head showing the flow direction from higher elevation to lower elevation areas and its deduced that water recharges areas were located along Southern and North Eastern part, while discharges area was visibly situated at the North Western part of the study area.

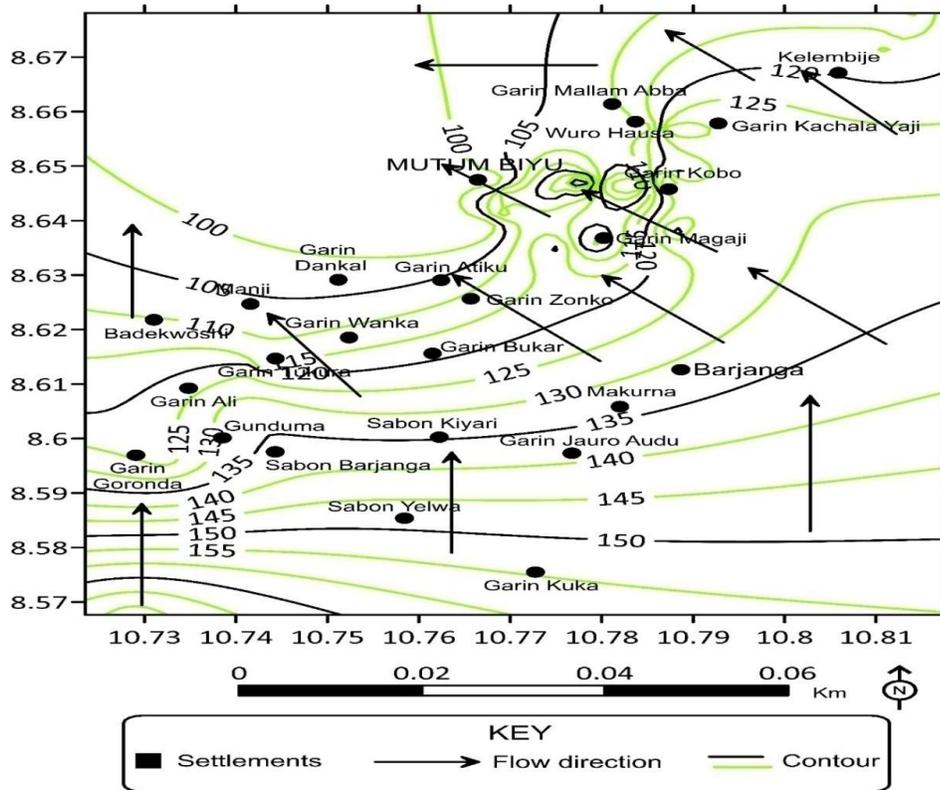


Figure 6: Direction of Groundwater Flow Map of the Area

CONCLUSION

For extensive hydrogeological information within Gassol L.G.A. there should be corresponding geoelectrical resistivity survey of longer electrode spacing above 200 m which reveal more first and second order resistivity parameters for detail evaluation of the aquifer properties. The aquifer protective capacity map (APC-map) reveals that north-eastern parts of the study area has good and excellent protective capacity ratings while other parts are characterized with poor/weak protective capacity rating. This indicates that

the aquifers are poorly protected and thus the earth materials overlying the aquifers are permeable to pollutants. Moreover, Only 24 % of VES points possess good and excellent APC. Consequently, refuse dumping site or any groundwater polluting activity site should be rightly provided and managed by the government and the development site for this project are recommended at the NW or NE part of the area.

REFERENCES

1. Abiola, O., Enikanselu, P., & Oladapo, M. (2009). Groundwater potential and aquifer protective capacity of overburden units in Ado-Ekiti, Southwestern Nigeria. *International Journal of Physical Sciences*, 4(3), 120–132.
2. Adeniji, A. E., Obiora, D. N., Omonona, O. V., & Ayuba, R. (2013). Geoelectrical evaluation of groundwater potentials of Bwari Basement area, Central Nigeria. *International Journal of Physical Sciences*, 8(25), 1350–1361.
3. Ayuk, M. A. (2019). Groundwater aquifer vulnerability assessment using a Dar-Zarrouk parameter in a proposed Aboru Residential Estate, Lagos State, Nigeria. *Journal of Applied Sciences and Environmental Management*, 23(12), 2081–2090.
4. Dobrin, M. B., & Savit, C. H. (1988). *Introduction to geophysical prospecting*. McGraw-Hill International Edition.
5. Egbueri, J. C., Mgbenu, C. N., Digwo, D. C., & Nnyigide, C. S. (2021). A multi-criteria water quality evaluation for human consumption, irrigation and industrial purposes in Umunya area, Southeastern Nigeria. *International Journal of Environmental Analytical Chemistry*, 103, 1–25.
6. Ejepu, S., & Olasehinde, P. (2014). Groundwater potential evaluation of a part of Gidan Kwano Campus of the Federal University of Technology, Minna, Central Nigeria using geoelectric methods. *Nigerian Journal of Technological Research*, 9(1), 43.
7. Grant, N. K. (1971). A compilation of radiometric age from Nigeria. *Journal of Mining and Geology*, 6, 37–54.

8. Ibuot, J. C., Akpabio, G. T., & George, N. J. (2013). A survey of the repository of groundwater potential and distribution using geo-electrical resistivity method in Itu Local Government Area (L.G.A), Akwa Ibom State, Southern Nigeria. *Central European Journal of Geosciences*, 5(4), 538–547.
9. Jeje, L. K. (1978). Aspects of geomorphology of Nigeria. In J. A. S. Oguntoyinbo (Ed.), *The geography of Nigeria*. [Publisher location/Name missing in original—usually Heinemann].
10. Kearey, P., & Brooks, M. (1984). *Introduction to geophysical exploration*. Blackwell.
11. Liting, X., Linxian, H., Yi, Y., Junxiang, X., Wenjing, Z., Guangyao, C., & Xinyu, H. (2018). The blocking effect of clay in groundwater systems: A case study in an inland plain area. *International Journal of Environmental Research and Public Health*, 15(9), 1816.
12. Macleod, W. N., Turner, D. C., & Wright, E. P. (1971). *The geology of the Jos Plateau* (Geological Survey of Nigeria Bulletin No. 32). Geological Survey of Nigeria.
13. Najime, T. (2011). Depositional framework and Cretaceous stratigraphy of the Gboko area, Lower Benue Trough, Nigeria. *Journal of Mining and Geology*, 47(2), 147–163.
14. Ogezi, E. A. (2002). Geology. In *Africa Atlases: Nigeria* (pp. 60–61). Les Éditions J.A.
15. Olusegun, O. A., Adeolu, O. O., & Dolapo, F. A. (2016). Geophysical investigation for groundwater potential and aquifer protective capacity around Osun State University (UNIOSUN) College of Health Sciences. *American Journal of Water Resources*, 4(6), 137–143.
16. Opara, A., Onu, N., & Okerefor, D. (2012). Geophysical sounding for the determination of aquifer hydraulic characteristics from Dar Zarrouk parameters: Case study of Ngor, Okpala, Imo River basin, Southeastern Nigeria. *Journal of Water Resource and Protection*, 4, 993–1000.
17. Oruonye, E. D., & Abbas, B. (2011). *The geography of Taraba State, Nigeria*. LAP Lambert Academic Publishing.

18. Raji, W. O., & Abdulkadir, K. A. (2022). Quantitative estimates of groundwater resource parameters in non-sedimentary aquifers of North-Central Nigeria. *Journal of African Earth Sciences*, 196, Article 104695.
19. Telford, W. M., Geldart, L. P., Sheriff, R. E., & Keys, D. A. (1978). *Applied geophysics*. Cambridge University Press.
20. Whiteman, A. J. (1982). *Nigeria: Its petroleum geology, resources and potentials*. Graham & Trotman.