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Geophysical Investigation of Aquifer Vulnerability in Gauta Buzu Area of Keffi Local Government, Nigeria

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Abstract

Taking into account the significance of quality groundwater for good health and quality of life, this research explored the vulnerability of the aquifer in the Gauta Buzu region of Keffi, located within the Keffi local government of Nasarawa State. The electrical resistivity method utilizing the Schlumberger electrode configuration was employed for the research to characterize the subsurface lithology and aquifer vulnerability. The research identified four (4) geological layers which comprise topsoil, weathered basement, fractured basement, and fresh basement. The weathered and fractured basements of the study area form the aquiferous zones. The depth to the weathered layer in certain locations within the study area is shallow, making the aquifer vulnerable to contamination from leachate or other chemical substances transported by erosion or runoff. The findings of the study indicated that 47% of the aquifer in the region are weakly protected, whereas 53% of the aquifer are moderately protected. The findings also revealed that shallow boreholes and wells in the study area are likely to be contaminated owing to their closeness to the surface. This observation supported the claims of groundwater contamination in the study area as documented in the literature. Given the results of this study, shallow boreholes and wells should be decommissioned in the study area, while new boreholes with substantial depths should be established in regions that possess moderate aquifer protective capacity.

Keywords: Aquifer, contamination, vulnerability, groundwater, electrical resistivity.

INTRODUCTION

Water is one of the most vital commodities for survival. It exists in both surface and subsurface forms on Earth. Surface water comprises rivers, lakes, streams, springs, and oceans, while subsurface water is referred to as groundwater. Surface water is predominantly susceptible to contamination due to the rise in industrial and agricultural activities. Industrial and agricultural waste is a primary source of pollutants to both surface water and groundwater. Health risks such as cholera, diarrhea, dysentery, and typhoid have been linked to the ingestion of contaminated water (Agada and Yakubu, 2022). Water-related health issues are escalating due to inadequate sanitation and waste management in many rural and urban regions across Nigeria (Ahmed et al., 2017).

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Leachate from municipal solid waste contains hazardous components such as volatile organic compounds and heavy metals that are significantly harmful to human health when ingested (ATSDR, 2000). These chemical substances, when present in elevated concentrations in groundwater, can lead to kidney disease, lung damage, liver and bladder complications, cancer, and stomach pain (WHO, 2000). A majority of the waste produced daily from domestic, agricultural, and industrial operations is disposed of openly at dumping sites with minimal concern for environmental safety. Solid waste at these dumping sites, under the influence of moisture and precipitation, undergoes anaerobic decomposition, generating leachates, landfill gas, heavy metals, and various hazardous pollutants that infiltrate the subsurface and contaminate groundwater (Abdullahi *et al*., 2011; Agada *et al*., 2020).

Solid waste disposal has been recognized as one of the foremost environmental issues related to leachate production. Given the numerous health risks linked to consuming contaminated water, various researchers have employed electrical resistivity techniques to assess the aquifer protective capacity of groundwater in several regions (Olayinka and Olayinwola, 2001; Amidu and Olayinka 2006; Oladunjoye *et al.* , 2011; Mosuro et al. , 2016; Olagunju *et al.* , 2017; Onyenwife *et al.* , 2020). Daniel *et al.* (2015) assessed the aquifer protective capacity in Makurdi, Benue State, Nigeria. They noted that the longitudinal conductance of the area under study was comprised of 36. 6% weak, 10% poor, 40% moderate, and 13. 3% good (Daniel *et al*., 2015). They proposed that the locations with moderate and good protective capacities are suitable for borehole siting (Daniel *et al*., 2015). Onyenweife *et al.* (2020) explored the aquifer protective capacity in Akwa, where the area's aquifer protective capacity exhibited weak to poor proactive capacity lenses.

Ibrahim and Gomo (2016) studied groundwater potential in the rural area of North-central Nigeria utilizing the Vertical Electrical Sounding (VES) method. Their findings indicated three to five geoelectric layers including topsoil, lateritic layer, weathered basement, fractured basement, and fresh basement (Ibrahim and Gomo, 2016). Obaje *et al.* (2020) stated that water from hand-dug wells and certain boreholes in the study area is unsuitable for consumption. Groundwater quality is predominantly influenced by the materials that seep into the subsurface. Pharmaceutical wastes from hospitals and clinics, such as disinfectants, expired medications, radionuclides, effluents, and sewage from dumpsites, contribute to groundwater pollution, especially when management practices are inadequate.
Kyari *et al*. (2023) indicated that the groundwater in the studied region near dumpsites is unfit for consumption due to contamination. Tabugbo *et al.* (2024) found that groundwater in the Keffi area is tainted by excess Radon metal.

A thorough comprehension of aquifer parameters is vital for the successful management of groundwater resources, particularly in regions susceptible to environmental contamination (Agada and Yakubu, 2022). The rising demand for groundwater in recent periods, attributable to population growth and expansions in agriculture and industry, necessitates a clear and quantitative delineation of aquifer parameters to ensure accessible and fair distribution of groundwater resources (Agada and Yakubu, 2022). The ongoing trend of climate change has had a direct impact on both the availability and quality of groundwater resources (Agada and Yakubu, 2022). Climate change has led to fluctuations in water tables, groundwater contamination, and reduced groundwater rechargeability. These challenges have been intensified by the frequent occurrence of extreme weather conditions, including heatwaves, droughts, and floods (Agada and Sonloye, 2022). The recent rise in both hydrological and hydrogeological issues can be effectively managed with a solid understanding of aquifer parameters such as longitudinal conductance, transverse resistance, hydraulic conductivity, aquifer thickness, and aquifer transmissivity (Agada and Yakubu, 2022).

Waste management and sanitation were severely inadequate in Gautu Buzu and its surroundings due to careless waste disposal and open defecation. The rising amount of waste produced in the study region due to population growth and agricultural development could threaten the quality of groundwater in the area if not properly monitored. Assessing the aquifer protective capacity in Gautu Buzu and its surroundings will greatly aid effective groundwater management in the study region. Given the importance of quality drinking water for human health and overall development, this study evaluates the aquifer protective capacity in Gautu Buzu and its surroundings, employing the electrical resistivity method.

Theory

The aquifer protective capacity was determined using equation (1),

$$S = \sum_{i=0}^{n} \frac{h_i}{\rho_i} = \frac{h_1}{\rho_1} + \frac{h_2}{\rho_2} + \frac{h_3}{\rho_3} + \ldots + \frac{h_n}{\rho_n} \qquad (1)$$

Where S is the longitudinal conductance, ρ_i is the ith layer resistivity, and h_i is the ith layer thickness.

The transmissivity of an aquifer quantifies its capability to transmit water throughout its entire saturated thickness (Egbai and Iserhien, 2015). An increase in the transmissivity of a geological layer corresponds to a greater transport of contaminants through its saturated zones. Most dissolved contaminants and leachate percolate into the subsurface and are released into the aquifer, where they are moved through the processes of diffusion, advection, and adsorption. Niwas and Singhal (1981) formulated an equation for estimating transmissivity values within a saturated aquifer.

$$T = Kh \qquad (2)$$

Where K= hydraulic conductivity and h = formation thickness.

Marotz (1968) in his experiment using sandstone established a relationship between hydraulic conductivity and effective porosity as:

$$\emptyset = 25.5 + 4.5LNK \qquad (3)$$

Archie (1942) provided an equaton which relates the resistivity of rock (ℓ_r) , porosity ($\emptyset$), degree of water saturation (S_w) and formation factor as shown below.

$$\ell_r = \frac{a.\ell_w}{\emptyset^{-m} S_w^{-n}} \qquad (4)$$

For a fully saturated rock s_w= 1. Then ,

$$\ell_r = \frac{a.\ell_w}{\emptyset^{m}} \qquad (5)$$

By re-arranging equation (5)

$$\frac{\ell_r}{\ell_w} = \frac{a}{\emptyset^{m}} = F \qquad (6)$$

Where $\emptyset$ = porosity, s_w= degree of fluid saturation, m = cementation factor, n = coeffient of saturation, ℓ_r = resistivity of rock, ℓ_w= resistivity of water in the porespaces and a = tortuosity factor.

Aquifer Protective Capacity (APC)

Aquifer protective capacity refers to the capability of the layers of rock situated above the aquifer unit (overburden) to obstruct, filter, and retain percolating fluids or leachate from reaching the aquifer (Agada and Yakubu, 2022). It was assessed based on the extent of the total longitudinal conductance measured in the study area. Impervious substances like clay and shale exhibit elevated longitudinal conductance values, whereas permeable materials such as sand and gravels show lower longitudinal conductance values (Oladapo *et al*., 2004).

Table (1) shows the aquifer protective capacity rating in aquifer vulnerability studies (Henriet (1976); Oladapo *et al*., 2004).

Table 1. Aquifer protective capacity rating (Henriet (1976) and Oladapo *et al*., 2004)

Longitudinal conductance (mho)	Protective capacity rating
<0.10	Poor
0.10 - 0.19	Week
0.20-0.69	Moderate
0.70- 0.49	Good
5.0-10.00	Very Good
>10.00	Excellent

MATERIALS AND METHODS

Materials

To achieve the goals of this study, the following tools were utilized to conduct the research: Allied Ohmega resistivity meter, Global Positioning System (GPS), 12V Car Battery, personal computer, Electrodes, Reels of Cables and Jumpers, Hammers, Measuring tape, UPS, pegs, ABEM SAS external Battery Adapter (EBA), Surfer 11 Software and WINRESIST version 1. 0 Software.

The Study Area

The study area is Gauta Buzu in Keffi (Figure 1), which is situated within the tropical Guinea Savannah, characterized by a long dry season lasting from November to April and a short rainy season from May to October (Achohwora, 1986). The study area is situated atop Basement Complex rocks (Rahaman, 1976). Annual rainfall fluctuated between 1290 to 1596 mm. The annual average temperature ranged from 21. 5°C to 22. 2°C, with the annual maximum mean temperature reaching approximately 23. 5°C (Achohwora, 1986). This area comprises rocks such as schists, gneisses, migmatites, and granites, with pegmatite, quartz, and aplite veins visible on the surface (Ahmed *et al*., 2017). The schists are intensely weathered metamorphic rocks with their minerals oriented in one direction due to deformation stress. The outcrops are hard, dark-colored, fine to medium coarse-grained, with biotite mica as the predominant mineral.

The large pond located in the central part of Keffi town drains the study area along with its tributaries and forms a dendritic drainage pattern (Figure 1) with River Antau, which flows westward (Kyari *et al*. , 2023). The pond's water is unsuitable for drinking because local residents dispose of their waste into it, and individuals in the vicinity often defecate in the pond during the dry season.

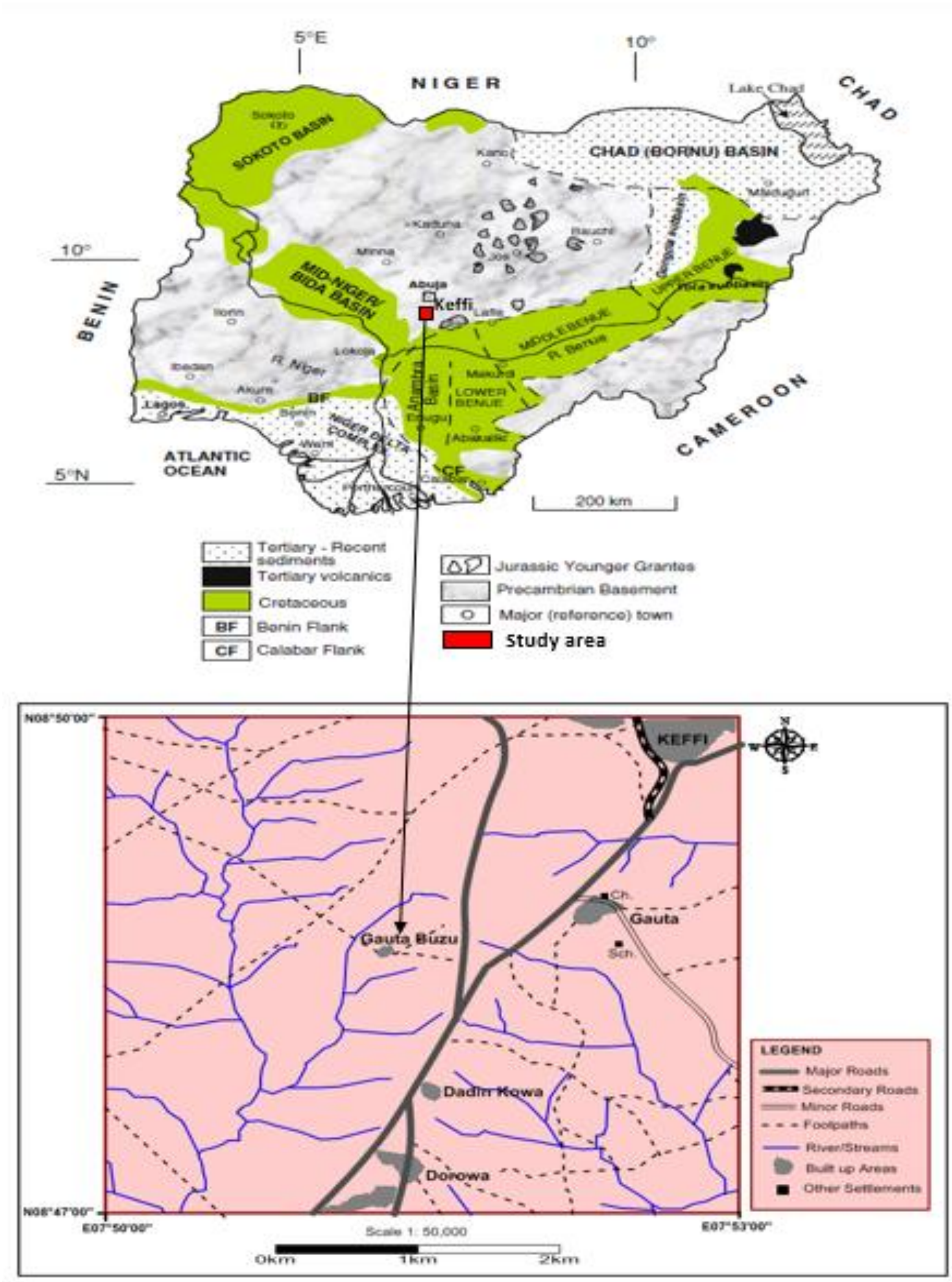

Figure 1. Geological map of Nigeria showing the study area.

Methodology

In this study, Vertical Electrical Sounding (VES) utilizing a Schlumberger array was employed to gather the geophysical field data. One-dimensional electrical resistivity field data were collected by transmitting electric current through the current electrodes and measuring the corresponding voltage via the voltage electrodes. The spacing of both the current and voltage electrodes was significantly varied concerning the intended depth of investigation. Prior to acquiring the field data, the field data acquisition setup was verified for correct connections and efficient electrical contacts. Fifteen (15) Vertical Electrical Sounding (VES) data points were gathered in the study area. The collected data were initially interpreted manually, and the results obtained were utilized as input data to derive the true resistivity of the subsurface layers and their respective depths. An Allied Ohmega resistivity measuring instrument was employed to collect the subsurface resistivity data. Palacky (1987) true resistivity chart was referenced to identify the different geologic layers present in the study area (Figure 2).

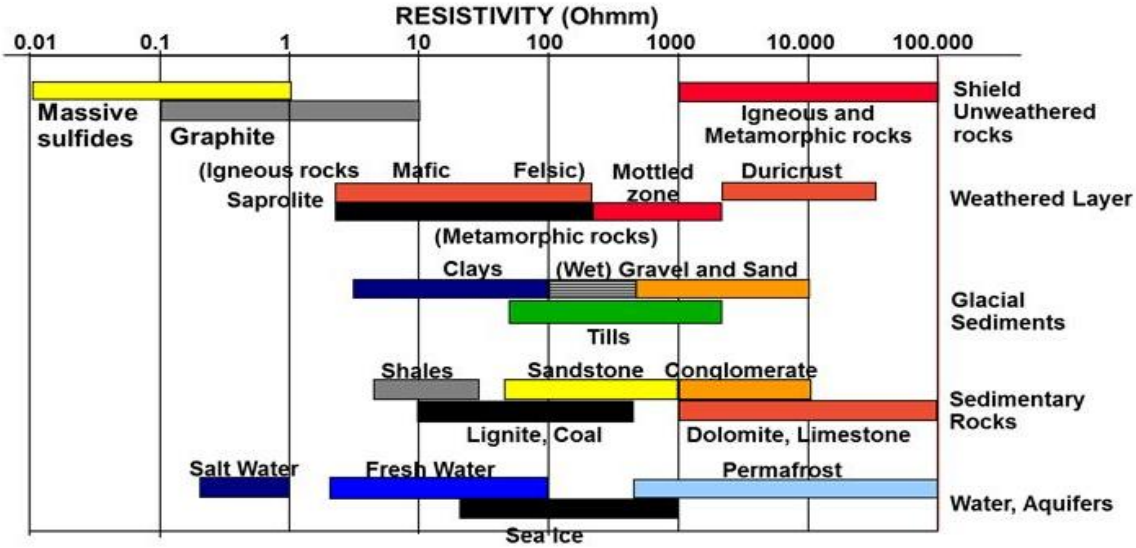

Figure 2: Rock true resistivity values (After Palacky, 1987).

The partial field curve matching technique was employed to manually determine the resistivities and thicknesses of the subsurface geologic layers. The outcomes of the manually interpreted field data were enhanced by using WINRESIST version 1. 0 software to obtain the true resistivity values of the subsurface geologic layers within the study area.

RESULTS AND DISCUSSION

The resistivity of the initial layer, which is the topsoil, varied from 10. 7 to 831. 3 Ωm with a mean value of 277. 1 Ωm (Table 2). Examples of the geoelectric curves obtained from the study area are shown below (Figure 3).

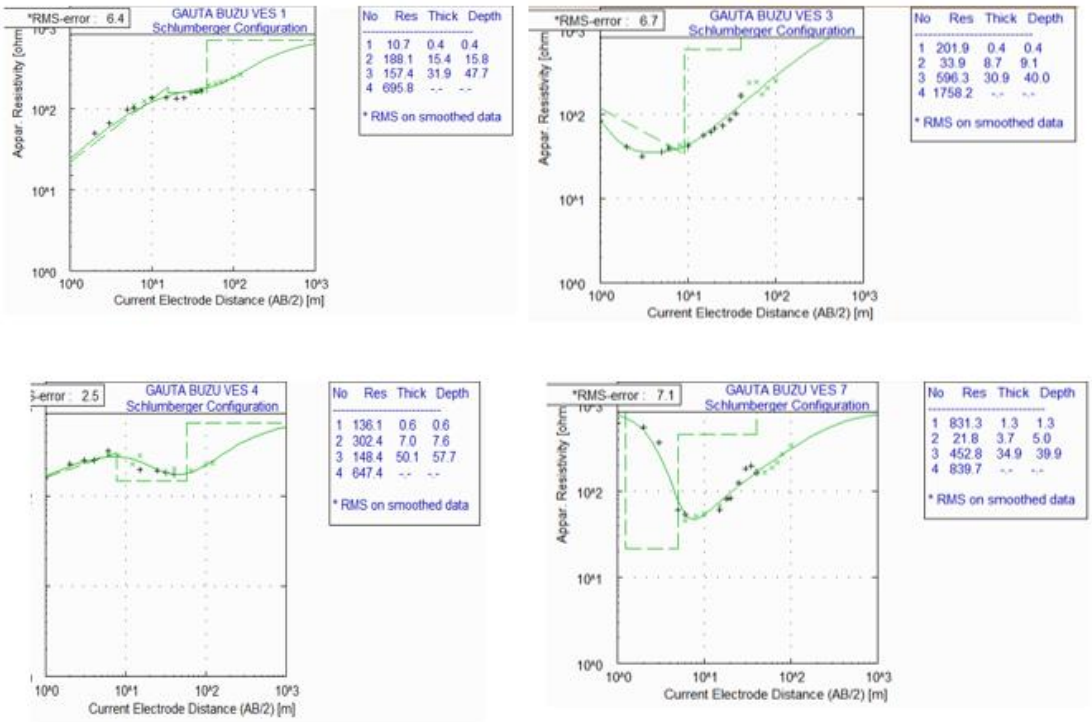

Figure 3. Typical geoelectric curves obtained from the study area.

The resistivity feature of the topsoil demonstrates that it is a combination of clay and sand. The thickness of the topsoil varied from 0. 4 to 1. 3 m, with an average thickness of 0. 8 m (Table 2).

The second layer exhibited resistivity values ranging from 33. 9 to 1524. 1 Ωm, with an average value of 410. 5 Ωm. The resistivity of the second layer implies that it is a weathered basement. The thickness of the second layer varied from 3. 7 to 25. 1 m, with an average thickness of 11. 8 m. A majority of the hand-dug wells and shallow boreholes are located within this layer. The resistivity of the third layer ranged from 97. 3 to 596. 3 Ωm, and its average resistivity value is 266. 8 Ωm. The resistivity characteristics indicate that the third layer in the study area is a fractured basement. The thickness of the fractured basement varied from 16. 5 to 25. 1 m (Table 2).

Table 2. Hydrogeological Parameters of the Study Area

VES	Layer	Resistivity (Ωm)	Thickness (m)	Lithology	Longitudinal Conductance ($m\Omega^{-1}$)	Protective Capacity ($m\Omega^{-1}$)	Protective Capacity Rating	Depth to Bedrock (m)	Porosity(∅)
	1	10.7	0.4	Topsoil	0.0373832				0.1100661
VES 1	2	188.1	15.4	Weathered basement	0.0818713	0.3219229	Moderate		
	3	157.4	31.9	Fractured basement	0.2026684			47.7	
	4	695.8		Fresh Bedrock	------------				
	1	65.8	0.6	Topsoil	0.0091185				
VES 2	2	335.8	25.1	Weathered basement	0.0747469	0.2606906	Moderate		0.0704859
	3	149.3	26.4	Fractured basement	0.1768252			52.1	
	4	107.2		Fresh Bedrock	________				
	1	201.9	0.4	Topsoil	0.0019812				
VES 3	2	33.9	8.7	Weathered basement	0.2566372	0.3104379	Moderate		0.4110881
	3	596.3	30.9	Fractured basement	0.0518196			40	
	4	1758.2		Fresh Bedrock	________				
	1	136.1	0.6	Topsoil	0.0044085				
VES 4	2	302.4	7	Weathered basement	0.0231481	0.3651577	Moderate		0.0760139
	3	148.4	50.1	Fractured basement	0.3376011			57.7	
	4	647.4		Fresh Bedrock	________				
	1	1221.4	0.7	Topsoil	0.0005731				
VES 5	2	42.9	6.5	Weathered basement	0.1515152	0.2198685	Moderate		0.3412719
	3	413.1	28	Fractured basement	0.0677802			35.2	
	4	1269.3		Fresh Bedrock	________				
	1	549.6	0.9	Topsoil	0.0016376				
VES 6	2	74.5	12.8	Weathered basement	0.1718121	0.2560028	Moderate		0.22324
	3	235	19.4	Fractured basement	0.0825532			33.1	
	4	765		Fresh Bedrock	_________				
	1	831.3	1.3	Topsoil	0.0015638				
VES 7	2	21.8	3.7	Weathered basement	0.1697248	0.2483646	Moderate		0.5743639

	3	452.8	34.9	Fractured basement	0.077076			39.9	
	4	839.7		Fresh Bedrock	________				
	1	556.7	1	Topsoil	0.0017963				
VES 8	2	1524.1	12.3	Weathered basement	0.0080703	0.1266275	Weak		0.0219141
	3	212.4	24.8	Fractured basement	0.1167608			38.1	
	4	4521		Fresh Bedrock	________				
	1	492.6	0.5	Topsoil	0.001015				
VES 9	2	796	8.9	Weathered basement	0.0111809	0.1664816	Weak		0.0361125
	3	192.5	29.7	Fractured basement	0.1542857			39.1	
	4	5200.7		Fresh Bedrock	________				
	1	169.5	0.7	Topsoil	0.0041298				
VES 10	2	273.8	13.5	Weathered basement	0.0493061	0.1077122	Weak		0.0820491
	3	304	16.5	Fractured basement	0.0542763			30.7	
	4	4521		Fresh Bedrock	________				
	1	344.5	1.2	Topsoil	0.0034833				
VES 11	2	1164.5	20.7	Weathered basement	0.0177759	0.2000875	Moderate		0.0269525
	3	97.3	17.4	Fractured basement	0.1788284			39.3	
	4	214.6		Fresh Bedrock	________				
	1	185	0.9	Topsoil	0.0048649				
VES 12	2	674	8.4	Weathered basement	0.0124629	0.1227041	Weak		0.0410413
	3	232.5	24.5	Fractured basement	0.1053763			33.8	
	4	3125		Fresh Bedrock	________				
	1	305.6	1	Topsoil	0.0032723				
VES 13	2	501.8	12.6	Weathered basement	0.0251096	0.1540725	Weak		0.0514935
	3	217.2	27.3	Fractured basement	0.1256906			40.9	
	4	4127		Fresh Bedrock	________				
	1	284	1.1	Topsoil	0.0038732				
VES 14	2	97.4	10.7	Weathered basement	0.1098563	0.1847987	Weak		0.1816596
	3	318	22.6	Fractured basement	0.0710692			34.4	
	4	5122		Fresh Bedrock	________				
	1	189.6	0.6	Topsoil	0.0031646				
VES 15	2	126.3	11.4	Weathered basement	0.0902613	0.1603336	Weak		0.1487582
	3	276.5	18.5	Fractured basement	0.0669078			30.5	
	4	1157.3		Fresh Bedrock					

Its mean thickness is 26. 3 m. The weathered and fractured sections form the aquiferous zone of the research area. The closeness of the weathered layer to the surface heightens its vulnerability to pollution. The fourth layer is the fresh basement in the research area, with a resistivity ranging from 107. 2 to 5200. 7 Ωm and an infinite thickness (Table 2).

Groundwater yield in the research area fluctuates based on the thickness of both the weathered and fractured layers. The thicknesses of the weathered and fractured basement range from 3. 7 to 25. 1m and 16. 5 to 50. 1m respectively.
The aquifer protective capacity varied from 0. 1077 to 0. 3651 Ωm^{-1}, with an average of 0. 2137 Ωm^{-1}. Employing the aquifer protective capacity rating method of Henriet (1976) and Oladapo *et al*. (2004), the aquifer protective capacity rating of the research area is 46. 7% weak and 53. 3% moderate (Figure 4).

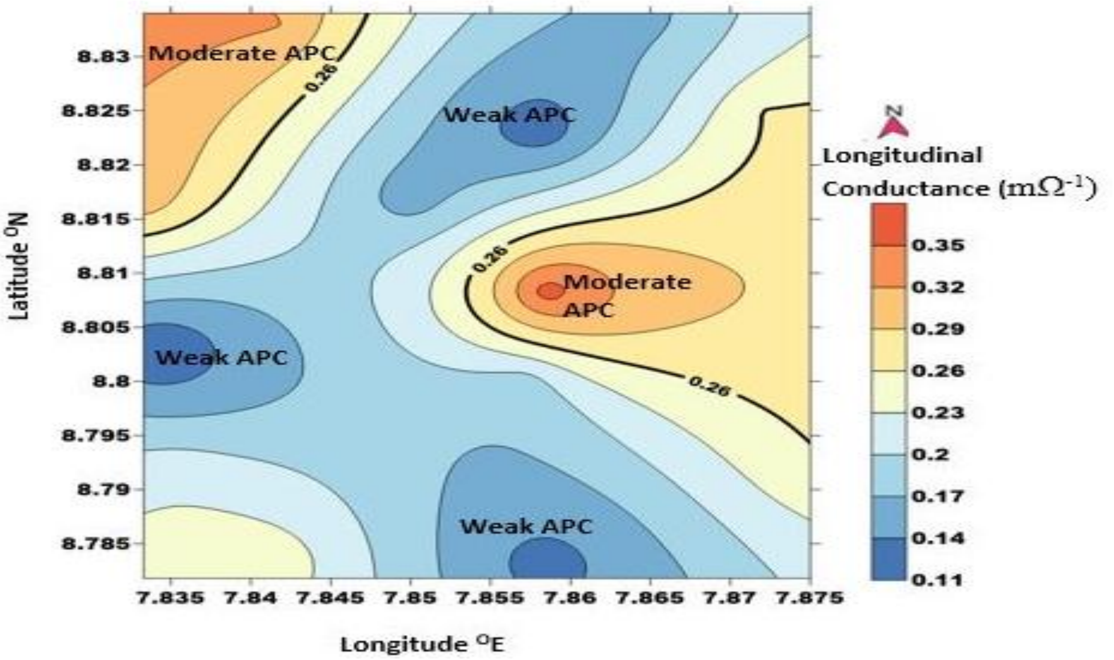

Figure 4. Spatial distribution of aquifer protective capacity in the study area.

The northeastern section of the research area exhibits weak aquifer protective capacity, extending into both the western and southeastern sections of the research area (Figure 4). The eastern and northwestern sections of the research area exhibit moderate aquifer protective capacity. The regions with weak aquifer protective capacity are unsuitable for borehole placement. Shallow aquifers in the research area are susceptible to contamination from leachate and other chemical substances emitted from waste dumpsites.

Rock porosity serves as a significant factor in groundwater contamination, as it regulates the transport of contaminants through advection, dispersion, diffusion, and capillary flow within the rocks. Within a saturated medium, the dissolved contaminants in the groundwater move at the same velocity as the groundwater. The aquifer porosity of the research area ranged from 0. 027 to 0. 574 (Table 2), with an average porosity of 0. 16. The northeastern and southern sectors of the research area display low porosity, whereas the northwestern and southwestern sections show high porosity (Figure 5). The central area of the research area is marked by moderate porosity in relation to the porosity values observed in the research area (Figure 5).

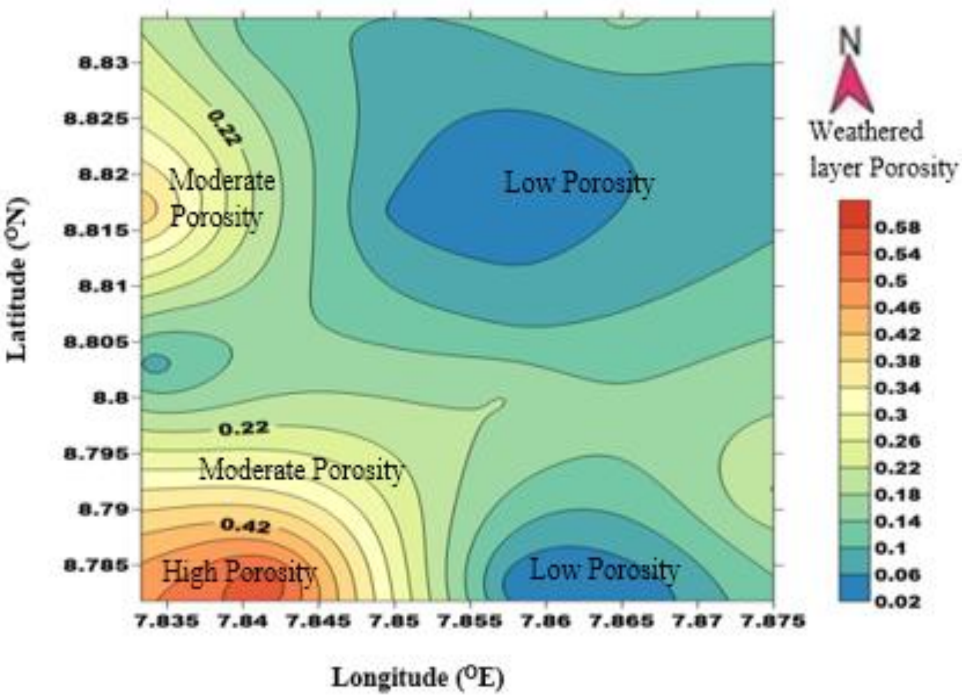

Figure 5. Spatial distribution of aquifer porosity in the study area.

The findings of this study support the observations made by Kyari *et al*. (2023) and Tabugbo et al. (2024) that the groundwater in Keffi Local Government Area is polluted, particularly the hand-dug wells and some shallow boreholes situated close to solid waste dumpsites. The nearness of the weathered layer, which is the initial aquifer to the earth's surface in the research area, has contributed to the pollution of the groundwater in the research area.

CONCLUSION

This research examined the vulnerability of aquifers in the Gauta Buzu region of Keffi local government, Nasarawa State. The Vertical Electrical Sounding (VES) Survey identified four (4) geological layers, which are as follows; the topsoil, comprising a blend of clay and sand, weathered basement, fractured basement, and the fresh basement. The aquifer units of the study area comprise the weathered and fractured basement. The closeness of the weathered layer to the earth's surface renders the groundwater vulnerable to contamination from leachates and various chemical substances. The findings indicate that a considerable number of hand-dug wells and shallow boreholes in the area may be at risk of contamination due to the weak aquifer protective capacity of 47% of the study area, while 53% of the aquifer in the other regions is moderately protected. Wells and shallow boreholes that are contaminated in the area ought to be sealed for the safety and health of the population, while boreholes in the study area should be located within zones where the aquifer protective capacity is moderate. A suitable drainage system should be implemented to facilitate the effective flow of runoff and wastewater in the study area to prevent their seepage into the subsurface.

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