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Use of Geoelectric Method for Groundwater Assessment in Awe Brine Area, Awe Nasarawa Nigeria

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Abstract

Forty-five vertical electrical soundings (VES) were conducted in the Awe Brine Field, Nasarawa, Nigeria using the Schlumberger electrode configuration to assess the groundwater condition. Iso-resistivity contour and isopach maps for four distinct geoelectric layers were generated to study the subsurface condition beneath the area. The first layer, comprising a thin top layer of unconsolidated material, exhibited resistivity values ranging from 85 to 2437.8 Ωm, and thicknesses from 0.214 to 2.87 m on VES 4 and VES 30, respectively. The second layer, composed of Shale-sandstone, has a resistivity between 1.2 to 785 Ωm. The third layer showed resistivity ranging from ranging from 1.2 to 785 Ωm. The thickness of this layer varies gradually from 0.502 to 22.47 m. The fourth layer is a thick layer of sandy clay containing fresh water, with resistivity values ranging from resistivity values ranging from 1.2 to 430.5 Ωm, and its thickness varies from 0.411 to 2823 m. The Dar Zarrouk parameters were calculated to evaluate the protective attributes of the aquifers. The result also revealed that the longitudinal conductance varies from 0.06 to 3.86 S, longitudinal resistivity ranges from 71.66 to 3830.4 Ωm and transverse resistance ranges from 2.55 to 1102 Ω. Four aquifer zones (A, B, C, and D) were identified based on the geoelectric layers. The C horizon (third layer) showed lower resistivity, indicating higher salinity, corresponding to the Saliferous Awe Formation. The area around New Awe has high resistivity which is an indication of low salinity. This makes exploring freshwater resources there more promising than in the old area.

Keywords: Schlumberger array, Dar-Zarrouk parameter, aquifer, geoelectric section, Brine field, iso-resistivity

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Introduction

The Awe brine field is situated in the Middle Benue Trough in the North-central Nigeria. The area has salt deposits that exist in the form of underground brine. The origin of this brine is believed to be from the interbedded shale of fractured sandstone that is present in the Awe Formation [1, 2, 3]. However, the occurrence of brine deposits in the area has created a significant hydrogeological problem for the groundwater in the region due to saltwater intrusion into freshwater aquifers. As a result, understanding the point of saline intrusion has become critical for effective groundwater management in the area.

Various researchers employed electrical resistivity techniques to investigate the impact of saltwater intrusion into freshwater aquifers. For example, some workers [4, 5] applied Dar-Zarrouk parameters based on resistivity methods to identify seawater intrusion in the Nile Delta region of Egypt and coastal aquifers in Tamil Nadu, India, respectively. Similarly, Salem and Osman applied the geoelectrical resistivity method to delineate seawater intrusion in the Abu Zenima area in West Sinai, Egypt [6]. Alao *et al.* conducted research using ASSM to evaluate groundwater vulnerability to surface contamination and identify a groundwater promising zone and its protective capacity, thereby enhancing water security and addressing related issues [7]. [8] conducted geophysical studies to locate groundwater aquifers in arid regions, while [9, 10] utilized an integrated geophysical approach to uncover saltwater intrusion in specific areas of Lagos State, Southwestern Nigeria, and the Eastern Mitidja Plain in Algeria, respectively. In a separate study, [11] utilized surface geoelectrical techniques to delineate saline-water intrusion in the Jahanian Area of Pakistan. [12] investigated groundwater resources in Uthal Balochistan, Pakistan, using electrical resistivity sounding and Dar Zarrouk parameters.

On the Awe Brine field, many works were published by different scholars in the area. For instance, [2] focused on the geology and tectonics of the Awe brine field and the broader Benue trough, while [13, 14] employed geological methods to investigate groundwater contamination. Additionally, [15] highlighted groundwater issues within the Awe brine field, while [16] concentrated on salt exploration.

This study aims to utilise geoelectrical resistivity techniques (VES) to locate areas with potential saltwater contamination, determine the interface between saline and freshwater, and identify the properties of subsurface geological formations. This will enable the provision of accessible and clean water for the local population.

Location and description of the study area

The study area is located in Awe Town, within the Awe brine field in the southeastern part of Nasarawa State. It is part of the Benue Brine field in north-central Nigeria, covering an area of approximately 20 km^2. The area's topography is gentle, and the elevation varies between 100 to 145 m, with latitudes ranging from 8° 05′ N to 8° 07′ N and longitudes from 9° 05′ E to 9° 10′ E, as shown in Fig. 1.

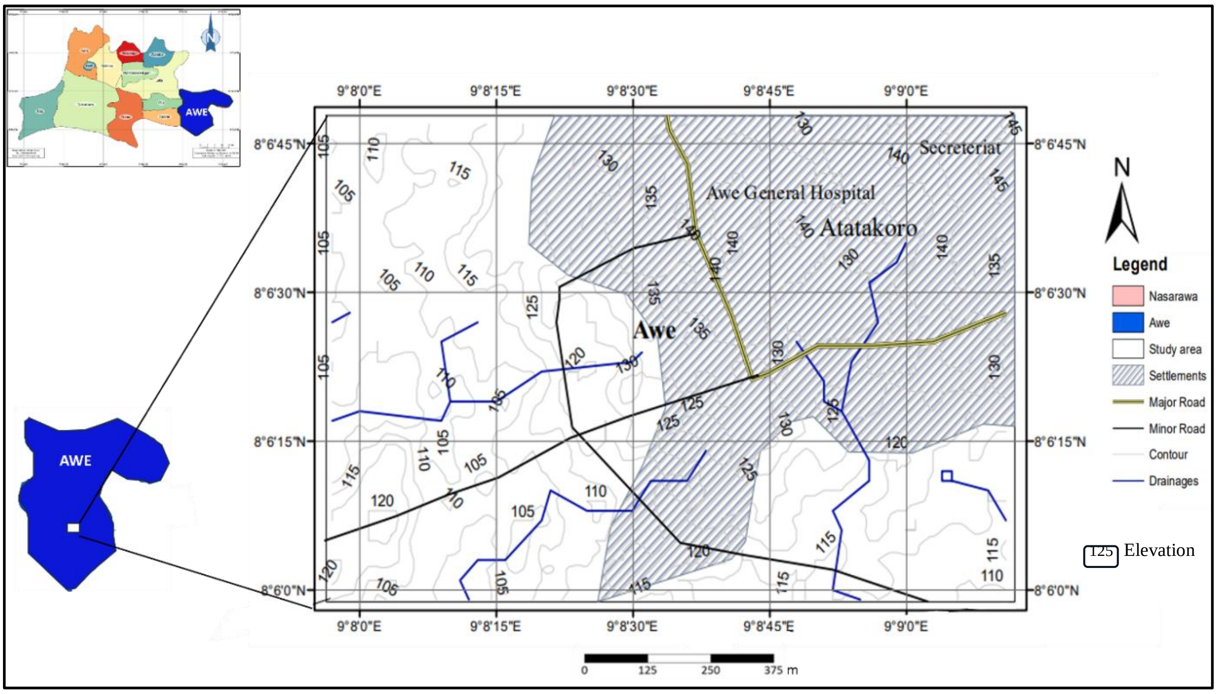

Figure 1: Location map of the study area

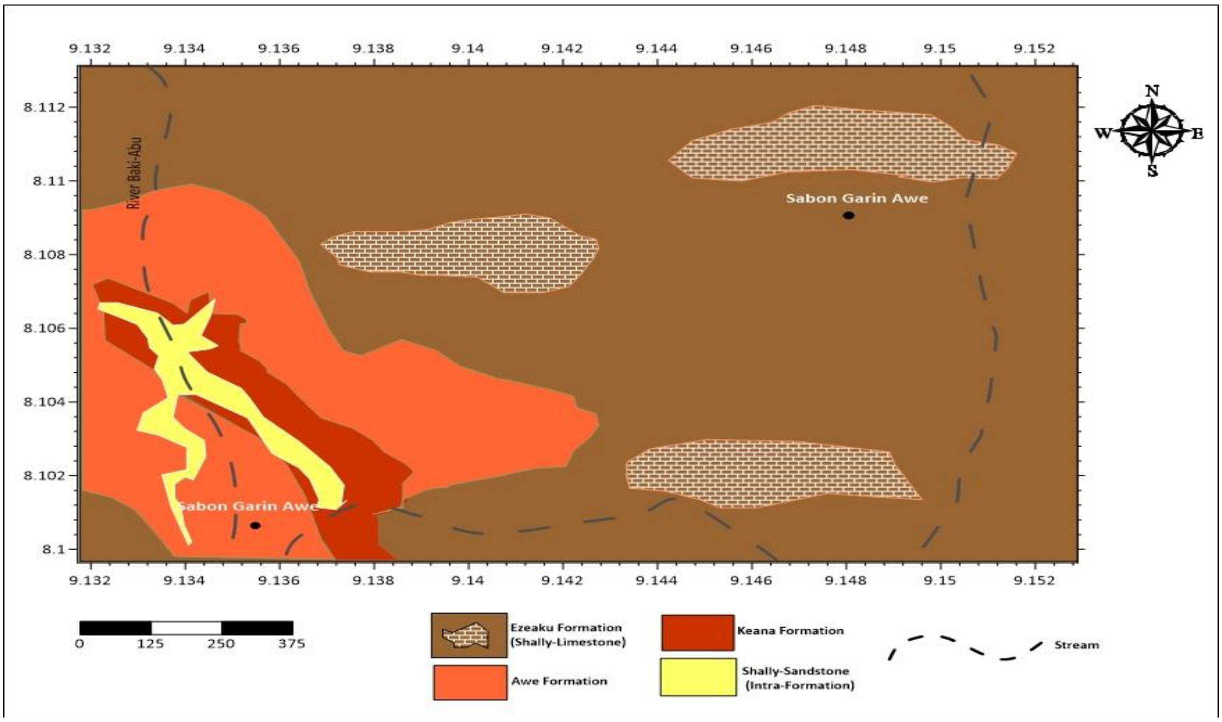

Figure 2: Geological map of the study area modified from [15]

Age	Formation		Lithology	Palaeoenvironment
Turonian		Ezeaku Formation	Calcareous shale, micaceous and fine to medium grained sandstone	Shallow Marine
Cenomanian	Upper	Keana Formation	Crystalline fine, coarse and pebbly sandstone	Fluviodeltaic
	Lower	Awe Formation	Flaggy, whitish, medium to coarse, sometimes calcareous sandstone or limestone and interbedded shale or clay from which brine issue	
Albian		Asu River Group	Marine shale, clay siltstone and mudstone	Marine
Pre-Albian		Basement Complex	Granite, Gneisses, Schist, Migmatite	Igneous/Metamorphic

Figure 3: Stratigraphy of Awe Brine field modified from [15]

Geology and hydrogeology of the study area

The Awe brine field is situated on the eastern flank of the Keana anticlinorium within the Benue Trough [2]. A comprehensive understanding of the geology is crucial for accurately evaluating the subsurface rocks and formation fluid in a particular region. Based on the available data, the stratigraphic sequence in the Awe brine field descends from Quaternary deposits, Pliocene, Lower Eocene, and Upper Cretaceous. The geological succession comprises four formations: Ezeaku, Keana, Awe, and the oldest Asu River Group. Asu river group which is Middle to Late Albian in age is the oldest geological formation in Awe brine field. The formation is deposited on top of the basement complex of the Pre-Cambrian age. The Awe Formation overlays the Asu River group and belongs to the Lower Cenomanian, while the Upper Cenomanian Keana Formation rests atop the Awe Formation. The youngest geological formation overlying the Awe brine field is the Ezeaku Formation, Turanian in age. Figs. 2 and 3 depict the geology and stratigraphy of the study area.

The study area has a unique hydrogeological situation where there is an alternating pattern of brine and freshwater horizons [15], grouped into the Keana, Asu river group and brine-bearing Awe formations based on the data from a borehole drilled.

Materials and Methods

Forty-five (45) vertical electrical were conducted within Awe Brine field Town using distances between current electrodes (AB/2) and potential elecrodes that (MN/2) ranges respectively to located to delineate the freshwater aquifer. The Schlumberger electrode configuration applying the vertical electrical sounding method (VES) was used to acquire the resistivity data using an ABEM SAS 4000C Terrameter. The VES method is a simple method that employs four electrodes, two for injecting current (C1 & C2) and two for measuring voltage (P1 & P2). The electrical field extends deeper into the ground as the electrodes are moved apart, allowing for deeper measurements. IPI2win 1D inversion software was used to generate a model of resistivity versus depth beneath the electrode spread from raw data. The distance between current electrodes is AB, while that of potential electrodes is MN. The current penetration depth is approximately 20–30% of half of the spacing between the current electrodes, but [18] proposed half of the electrode spacing AB/2 as the penetration depth.

Equation 1 below shows therelationship between apparent resistivity ρ_a, $\frac{AB}{2}$, and $\frac{MN}{2}$. For each electrode spacing, the resistivity values for each electrode spacing are obtained by multiplying the resistance measured from the resistivity meter with its corresponding geometric factor (K). These values are then plotted on a bi-logarithmic graph as sounding curves against $AB/2$.

$$\rho_a = \pi \left| \frac{(AB/2) - (MN/2)}{MN} \right| . Ra \qquad 1$$

Where, ρ_a is the apparent resistivity, AB is the distance between the two current electrodes, MN and Ra are the distance between the potential electrodes,

In addition, Dar Zarous (DZ) parameter, which includes longitudinal conductance S_C, transverse resistance (T_R), longitudinal resistivity$\rho_L$were applied to characterise and delineate the fresh-saline water interface [18]. DZ are derived from the various combinations of thickness (h) and resistivity (ρ) of geoelectric layers acquired from the 1-D inversion of the resistivity data [4, 18, 19]. The longitudinal conductance involves measuring the impermeability of the confining clay layer and is proportional to the protective capacity of the overburden layers [19, 20] S_L, T_R, and ρ_L, were estimated from h the thickness and ρ_a the apparent resistivity obtained from the modelled VES curves using the following formulas below:

$$S_L = \frac{h_i}{\rho_i} \qquad 2$$

The number of layers from the surface to the top of the aquifer varies in the range i = 1, ..., n, where, h_i is the layer thickness and, ρ_i is the layer resistivity. The areas were classified into four categories based on their aquifer protective capacity: good, moderate, weak, and poor, using the results of the longitudinal unit conductance (Table 1). This was done using the classification given by some researchers [20, 21].

$$T_R = h_i \rho_i \qquad 3$$

where T is the transverse resistances, ρi is the layer resistivity and h_i layers with thicknesses

$$\rho_L = {}^{h}/_{S_C} \qquad 4$$

Transverse resistance is measured in Ωm^2, longitudinal conductance in mho and longitudinal resistivity Ωm

Table 1: Protective capacityrating [22, 7]

Rating	Protective capacity
< 0.1	Poor
0.1–0.19	Weak
0.2–0.69	Moderate
0.7–4.9	Good
5–10	Very good
> 10	Excellent

Results and Discussion

A resistivity survey (VES) was conducted in Awe Town located within the Middle Benue Brine field to delineate freshwater aquifers in the area. All interpreted depth-sounding curves of VES data exhibit a steep descent from dry to wet or salty formation. The decrease in resistivity observed can be linked to a combination of factors, including enhanced porosity, hydraulic conductivity, fluid content, and potential changes in conductivity brought about by the influx of saline water from a nearby brine-bearing formation [23]. The typical resistivity-sounding curves of VES 1, 8, 21, and 43 obtained from the Awe Brine field are respectively, shown in Fig. 5. The resistivity curves obtained are comparable to the ones obtained by many workers [7, 10, 12 and 22] in the coastal area of the Niger Delta. The shape of the curves indicates the alternation of saline and freshwater horizons. The interpreted resistivity depth-sounding data in the Awe Brine field 9 is presented as a geoelectric section, Isoresistivityand isopach contour maps produced using the computer software Oasis Montaj and Surfer, respectively. Also, Dar Zarrouk parameters were computed to determine the protective aquifer capacity. The location of VES stations is shown in Fig. 4.

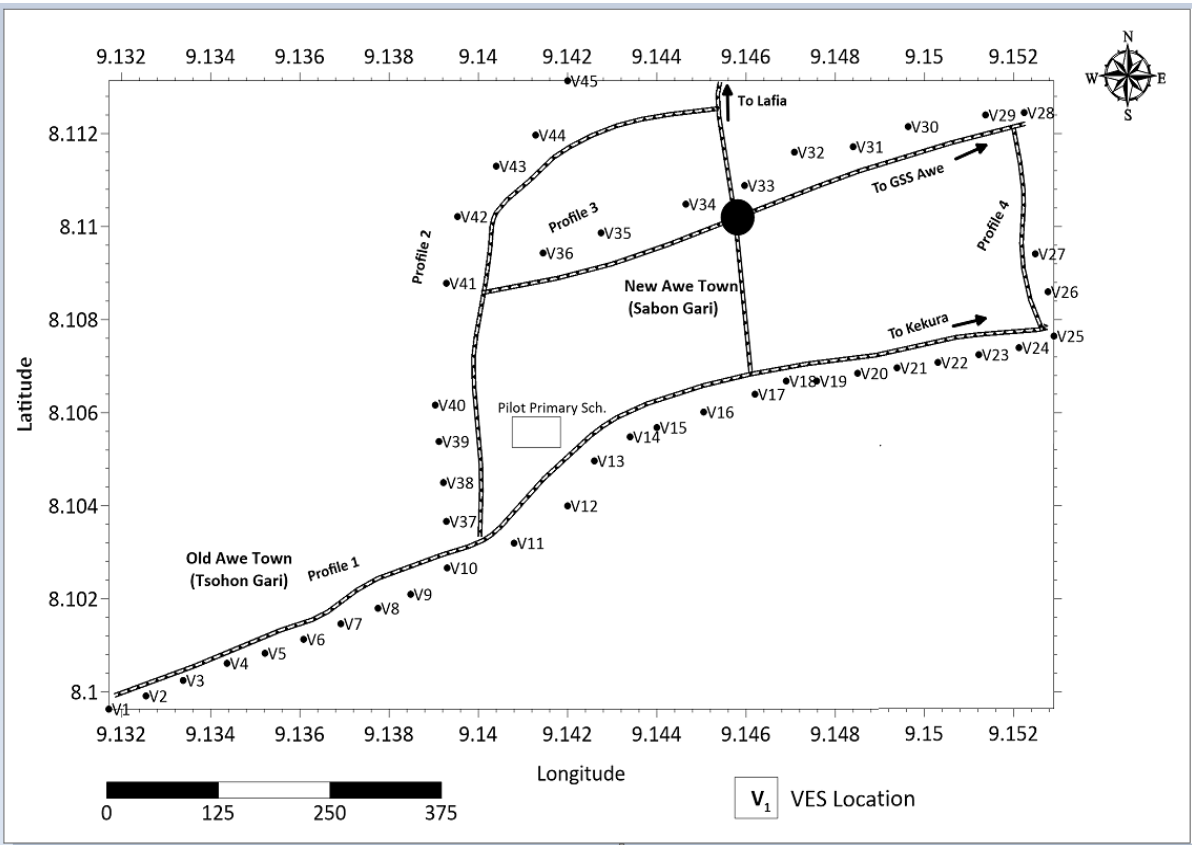

Figure 4: Location of survey profiles and VES Locations

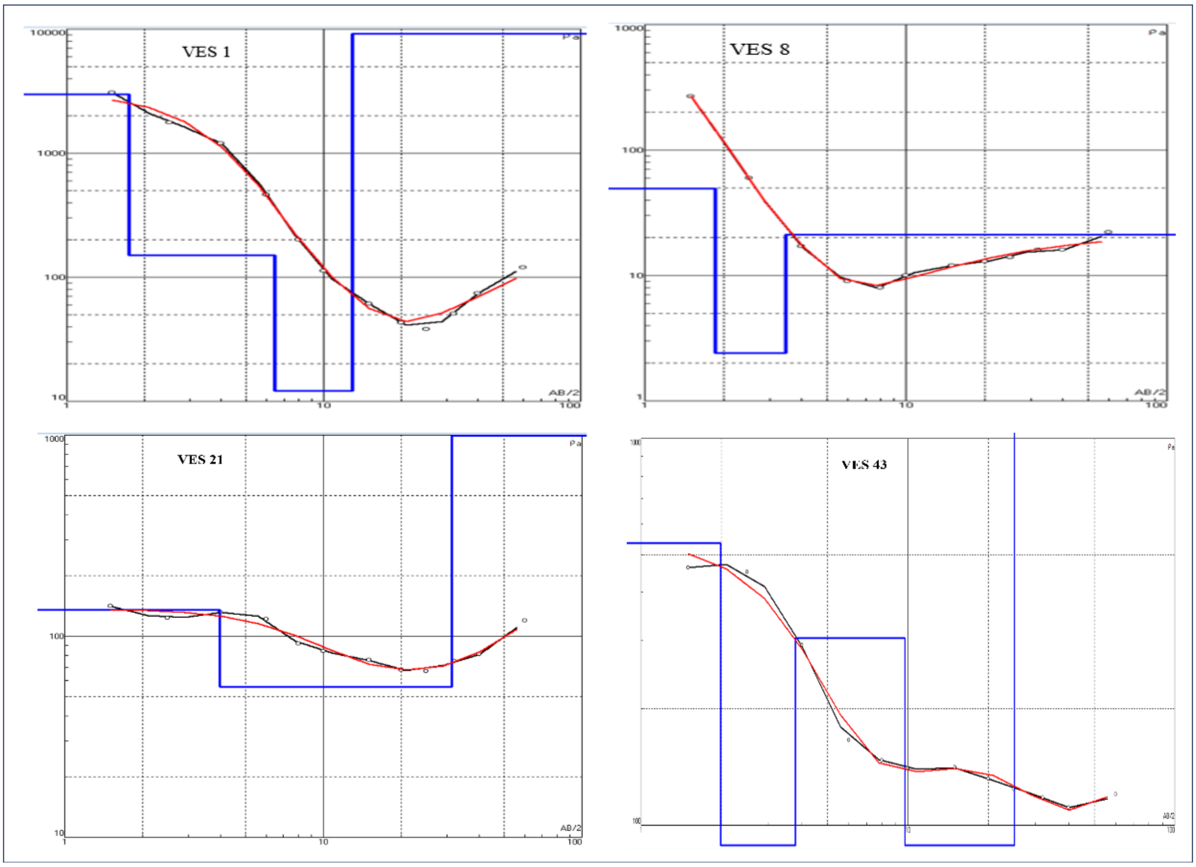

Figure 5: Sample of VES curves

Isoresistivityand isopach contours maps

The maps offer detailed and informative characteristics that facilitate reliable subsurface geologic inferences when combined with previous geologic and topographic information.

The first geoelectric layer (Fig. 6a), which represents the topsoil, has resistivity values ranging from 85 to 2437.8 Ωm. However, the isopach map (Fig. 6b), indicates that this layer is relatively thin, with a thickness ranging from 0.214 to 2.87 m on VES 4 and VES 30, respectively. Due to the superficial deposits being dried and highly compacted by overburden weight, along with less brine deposit. The resistivity contour map shows that the southeastern to the southern part of this layer has high resistivity values, while the eastern and western portion has materials of average resistivity.

Figures 7b and 7b show that the second geoelectric layer in the area has resistivity values ranging from 1.2 to 785 Ωm. The thickness of this layer varies gradually from 0.502 to 22.47 m across the area. High resistivity materials are present in the southeastern part, through the centre to the south and some parts of the central east, while the southeastern and northeastern parts have an average resistivity value. This layer is believed to be the Keana Formation, as confirmed by the isopach map in Fig. 6a and the resistivity contour map.

The third layer has resistivity values ranging from 1.2 to 430.5 Ωm (Fig. 8a), and its thickness varies widely across the area, ranging from 0.411 to 2823 m, as shown in Fig. 8b. Although most of this layer is covered by a geological formation with low resistivity, some areas in the north and southeast have high resistivity values. The low resistivity values in the layer may be due to the presence of strong brine. This layer is similar to the Awe formation, which is known to contain brine deposits based on the geological records of the region.

The fourth layer is the last layer delineated. The resistivity of the layer varies from 27 to 1825.9 Ωm. The iso-resistivity contour map of the layer (Fig. 9a) Shows that the rock materials that occupy the north and south through the central part of the area have significantly low resistivity values. At the same time, the east and western portions revealed high resistivity values. Also, the isopach map (Fig. 9b) indicates that the thickness of this layer varies from 44.78 to 5.34 m on VES 9 and 20, respectively. The low reveal at some points may result from brine infiltration into that layer.

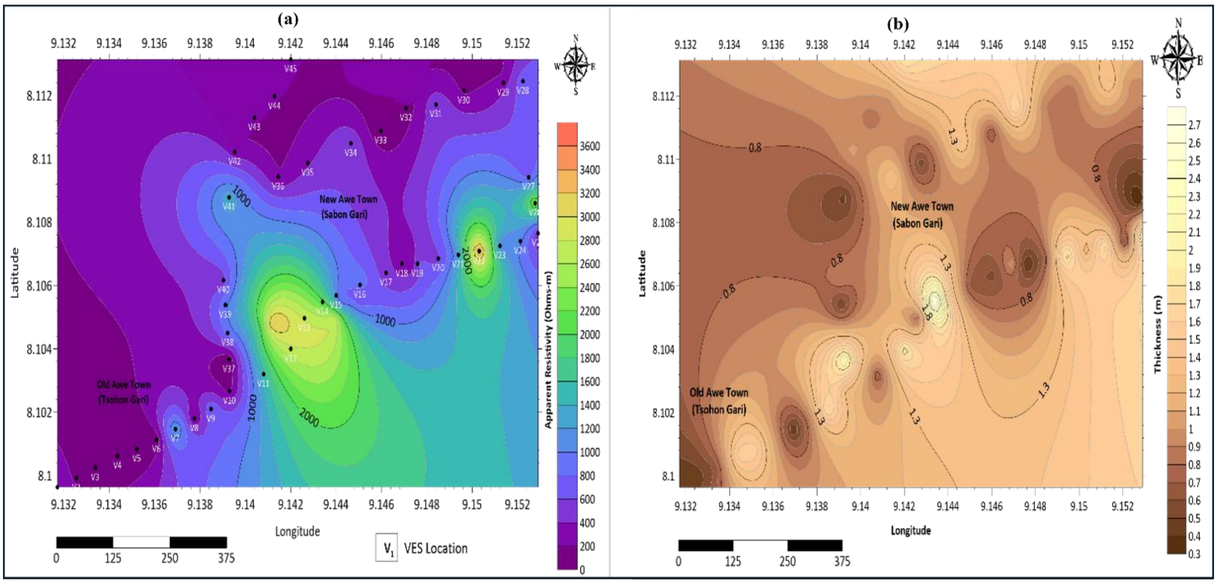

Figure 6: (a) Isoresistivity and (b) isopach of the third geoelectric layer

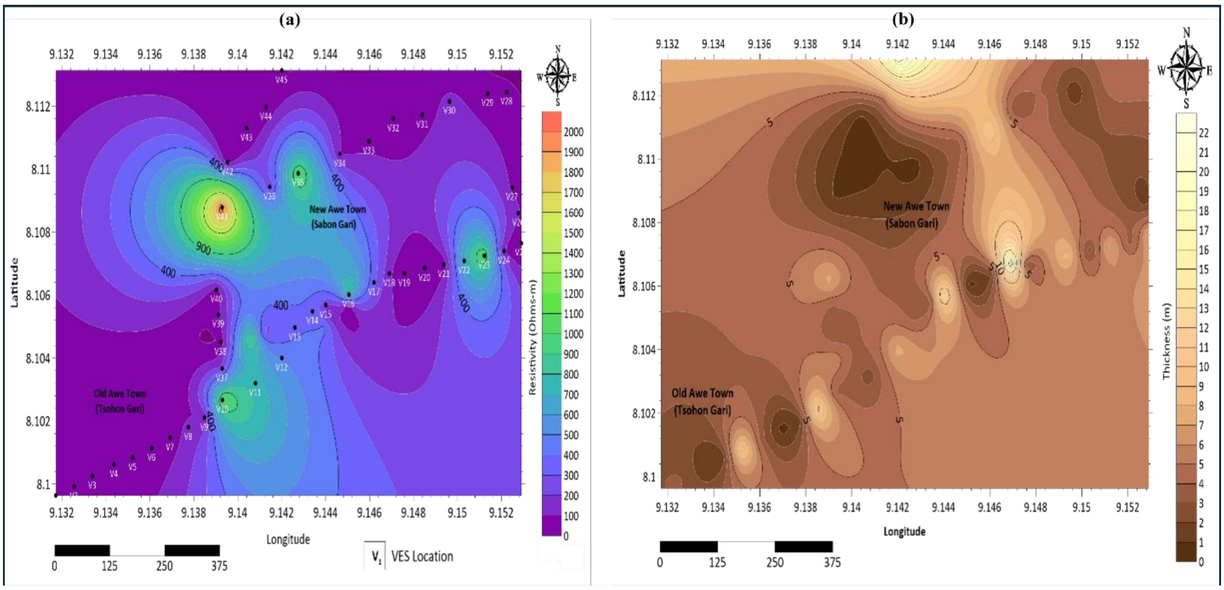

Figure 7: (a) Isoresistivity and (b) isopach of the first geoelectric layer

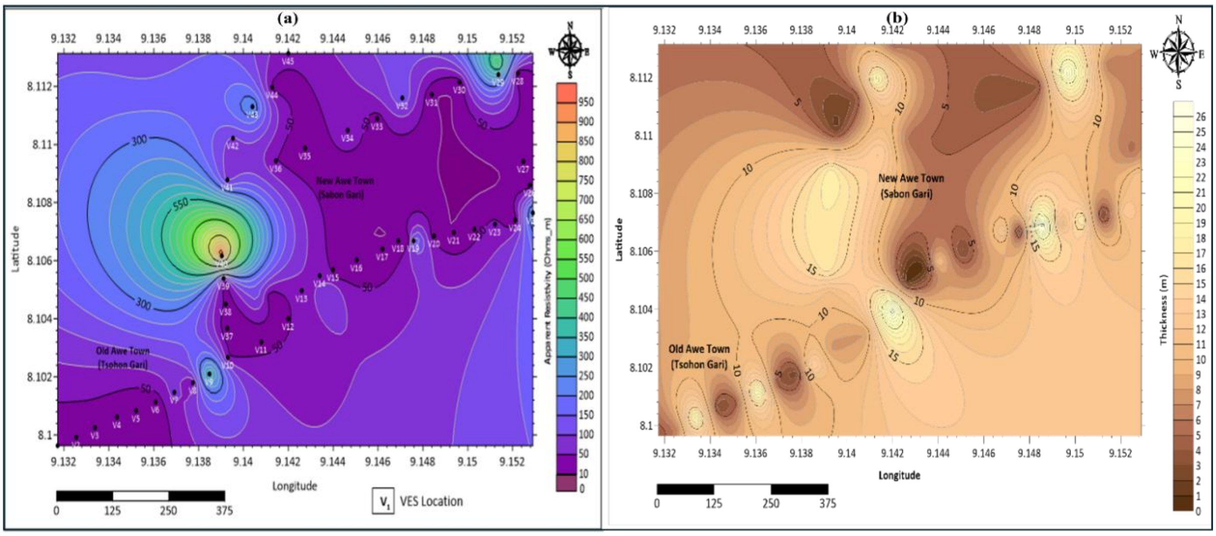

Figure 8: (a) Isoresistivity and (b) isopach of the third geoelectric layer

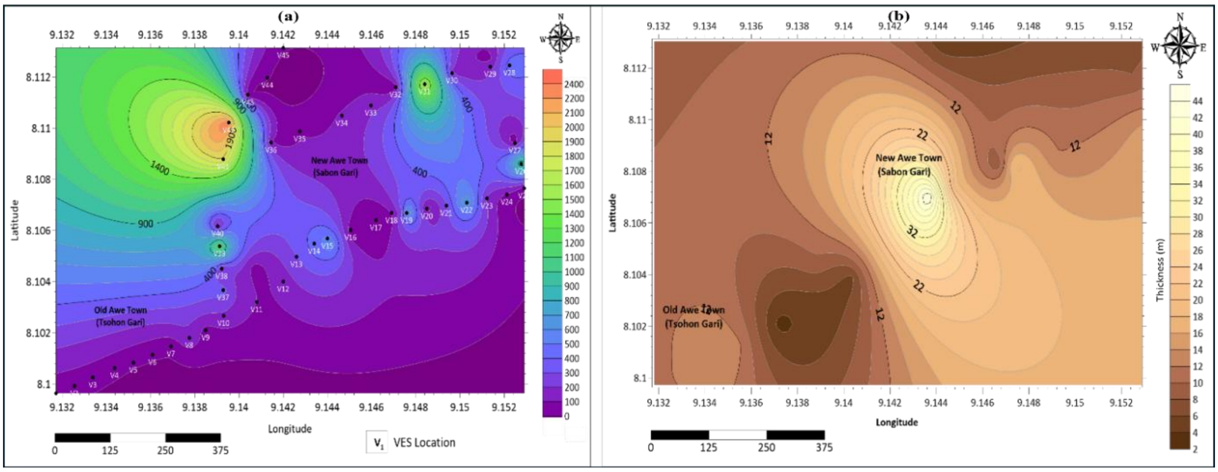

Figure 9: (a) isoresistivity and (b) isopach of the third geoelectric layer

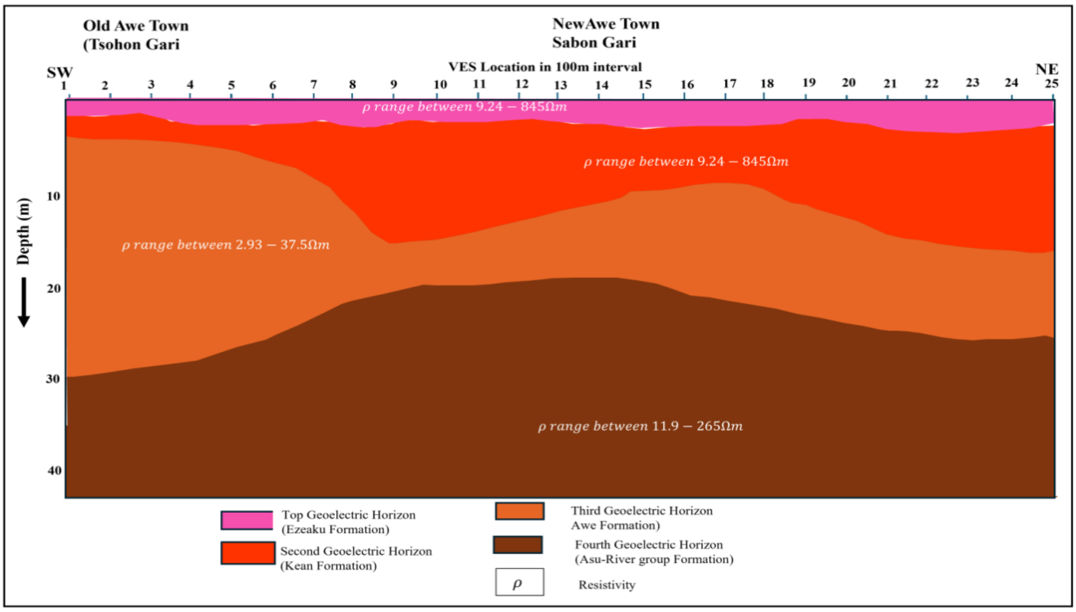

Figure 10: Geoelectric section across Profile 1

Geoelectric section

A geoelectric section is a diagrammatic section of stratified layers deduced from electrical resistivity depth probing, where layers are identified by their apparent resistivities and thickness. Such sections help detect water-table levels and reveal the location with saline or fresh at the water-table. In this study, we developed a geoelectric section from profile 1 (Fig. 10) to study vertical and lateral variation in resistivity across the study area. The profile extends about 2.8 km and runs across the study area from the southwestern part to the northeastern part (from VES1 to VES 25). This profile is the longest of all the profiles and is situated at a more prominent location from areas of low resistivity (suspected brine location) to points of high resistivity.

Four geoelectric horizons, A, B, C and D horizons, were delineated from the section based on their thickness and resistivity values deduced from VES data interpretation of the 25 data. The first horizon is considered to be the topsoil. The layer reveals a relatively high resistivity ranging from 14-1886 Ωm. The high resistivity values of the layer may be due to the dried nature of the superficial deposits, high compaction due to overburden weight and less brine deposit. The layer is presumed to be the equivalent of the top Ezeaku Formation. The resistivity values of the layer increase relatively towards the northeast and central parts (New Awe) of this section as compared with the values recorded around the Southwestern part (Old Awe) in the rest of the section for the same layer. The thickness of the layer varies between 0.4 and 10.0 m. This layer forms the first geoelectric horizon delineated under this profile. Though the layer is brine-free, as indicated by the high resistivity recorded across it, its thickness is insufficient for a highly productive aquifer.

The second layer delineated under this section is presumed to be a clayey sand formation Keana Formation. The layer is composed of a material whose resistivity ranges from 7.7-3280 Ωm and thickness between 1.5 and 12 m.

This layer's high resistivity value indicates the low salinity of water within the aquifer. The section revealed that the thickness of the layer is lower around the extreme southwest but increases toward the northeast from a little distance after VES1. As a result, the new town area (Sabon gari) provides a more favourable environment for freshwater exploration in the Awe area than the old town (Tsohon gari).

The third aquifer delineated under this profile revealed resistivity values of range 2.93-37.3 Ωm, and its thickness varies from 3 – 26 m. The low values shown by most VES locations can be attributed to the brine deposit within the layer. Thus, the layer is assumed to be the equivalent of saliferous Awe formation. The fourth aquifer showed a resistivity value that varies between 106 and 1005 Ωm with a thickness that ranges from 6 – 22 m.

The fourth aquifer underlying this profile is presumed to be the shally sand Asu-River group formation. The resistivity values range between 11.9 and 603 Ωm with thickness from 12 to 24 m. The presence of the brine layer on top of this layer makes it difficult to explore the aquifer because water from the overlying brine layer can easily flow and contaminate water within it. Therefore to explore this aquifer, blind casing can be used around the overlying brine layer during borehole construction to seal off the brine from contaminating the water from this deeper aquifer. The geoelectric section further revealed that the saliferous layer occupies the southwestern part of the study area (Old Awe area). Its presence makes the water around that area very salty.

Table 1: Longitudinal conductance, longitudinal resistivity, transverse resistance and aquifer protective capacity of the study area

VES	Coordinates		Longitudinal Conductance(S_C) (Siemens)	Longitudinal Resistivity	Transverse Resistance(T_R) (ohms-meter)	Overburden's aquifer protective capacity rating
	Northing (N)	Easting (E)				
1	8.110883	9.145967	0.402	9.8	39.09	Moderate
2	8.099917	9.13255	0.541	18.76	81.65	Moderate
3	8.10025	9.133383	0.799	15.26	500.2	Moderate
4	8.100617	9.134367	0.89	2.78	179.2	Moderate
5	8.100833	9.135217	0.669	20.98	37.75	Moderate
6	8.101133	9.136083	4.65	2.66	281.5	Very High
7	8.101467	9.136917	0.0331	125.38	522.3	Poor
8	8.1018	9.13775	0.32	10.34	721.9	Moderate
9	8.1021	9.138483	0.0275	536.36	7903	Poor
10	8.102667	9.1393	0.0396	144.7	2605.6	Poor
11	8.104633	9.140633	0.0755	70.73	1966.7	Poor
12	8.104817	9.141183	1.21	22.17	593.2	Moderate
13	8.104967	9.143967	6.232	0.1	85030	Very High
14	8.105483	9.144167	0.375	1.1	408.9	Moderate
15	8.105683	9.14505	0.765	58.54	149.3	Moderate
16	8.106017	9.14505	0.045	424.89	243	Poor
17	8.1064	9.146733	0.72	12.1	105.4	Moderate
18	8.106683	9.1474	0.0782	105.75	420	Poor
19	8.106683	9.147583	0.00373	5029.49	7667.6	Poor
20	8.10685	9.1485	1.58	17.87	501.9	Moderate
21	8.106967	9.149383	3.2	3.9	27.68	Moderate
22	8.107083	9.1503	0.547	32.89	591	Moderate
23	8.10725	9.151217	1.68	0.92	1190.4	Moderate
24	8.1074	9.152117	1.45	8.95	251.2	Moderate
25	8.10765	9.1529	0.0269	553.9	4757.8	Poor
26	8.1086	9.152767	0.774	15.6	88.38	Moderate
27	8.109417	9.152483	0.613	13.13	574.1	Moderate
28	8.11245	9.152233	0.0103	674.76	4688.6	Poor
29	8.112767	9.151367	1.43	4.42	102.6	Moderate
30	8.11215	9.149633	1.32	18.74	460	Moderate
31	8.111717	9.1484	0.568	6.39	24	Moderate
32	8.1116	9.147083	0.0184	195.65	702	poor
33	8.110883	9.145967	0.599	6.49	370.4	Moderate
34	8.110483	9.14465	0.0393	104.83	311.8	Poor
35	8.109867	9.14275	0.0567	91.35	1142.3	Poor
36	8.109433	9.14145	0.287	50.1	719	Moderate
37	8.103667	9.139283	5.804	1.61	119.8	Very High
38	8.1045	9.139217	0.24	42.46	432.5	Moderate
39	8.105383	9.139117	0.53	34.17	533.8	Moderate
40	8.106167	9.139033	0.225		225	Moderate
41	8.108783	9.139283	0.136	136.92	2336.6	Moderate
42	8.110217	9.139533	0.287	5.78	59.37	Moderate
43	8.1113	9.1404	0.00905	374.44	1259.9	Poor
44	8.111967	9.141283	0.578	34.24	677.8	Moderate
45	8.113133	9.135567	1.42	3.34	62.43	Moderate

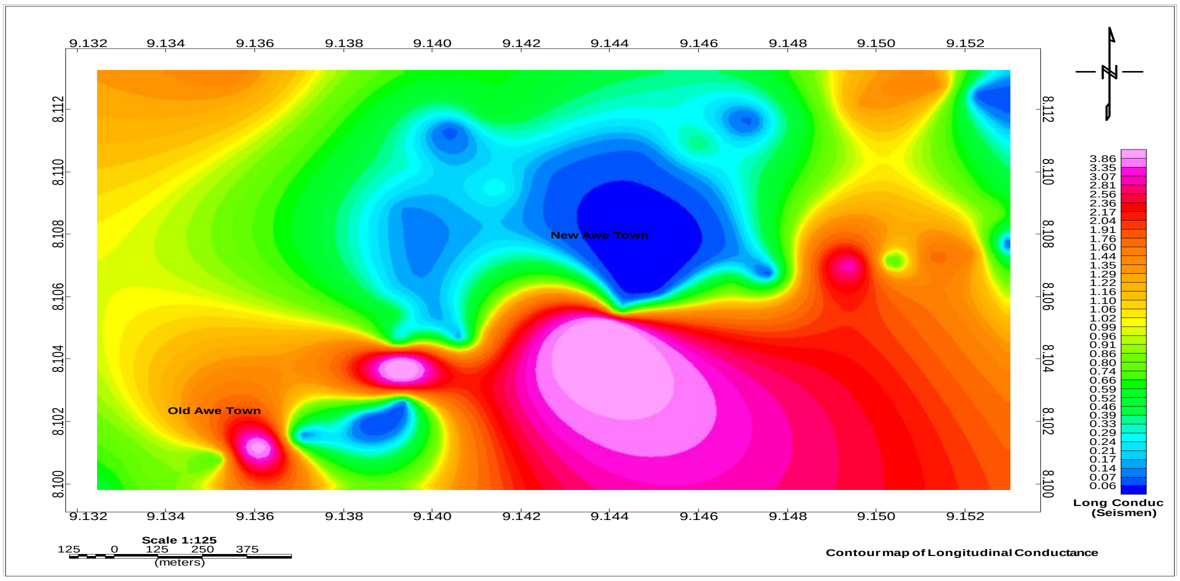

Figure 11a: A contour map of longitudinal resistivity

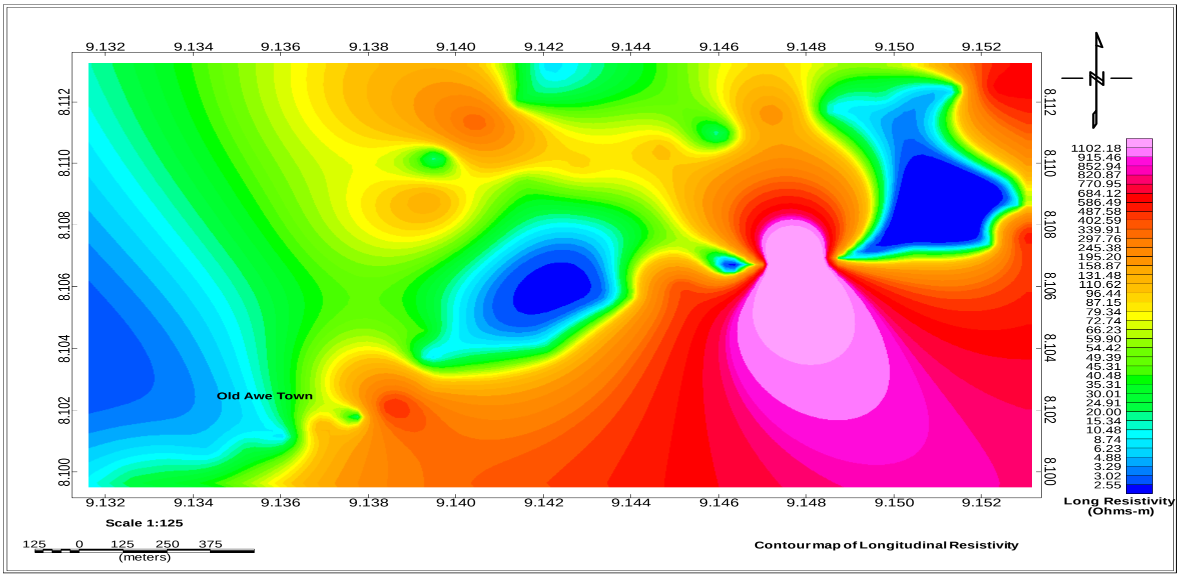

Figure 11b: A contour map of longitudinal resistivity

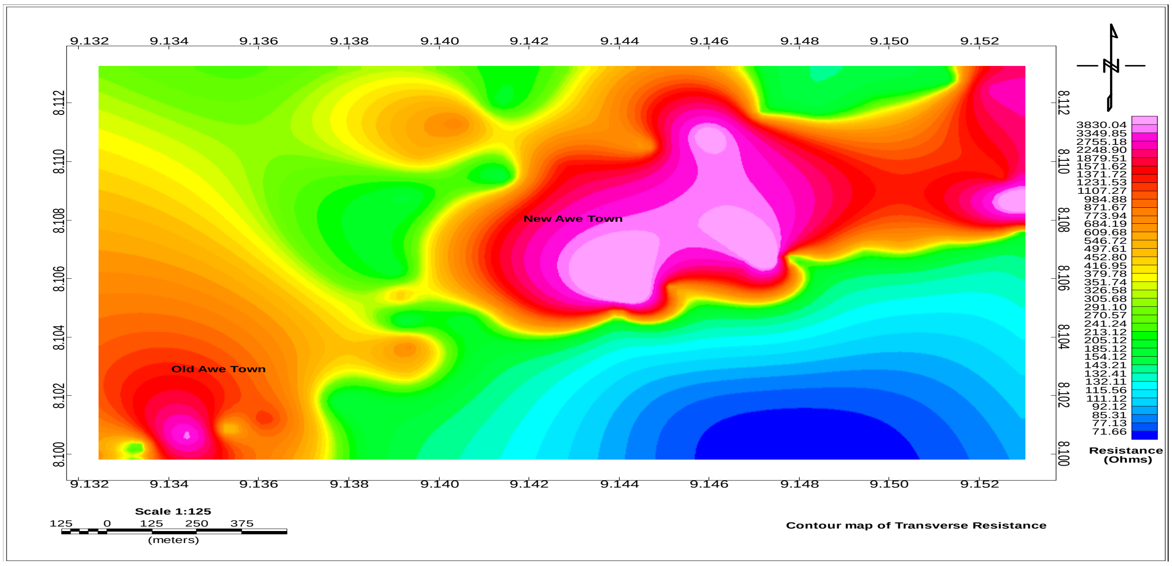

Figure 11c: A contour map of longitudinal resistivity

Assessment of aquifer protective capacity

The protective capacity of the aquifer underlying the area was calculated using Dar Zarouk parameters, longitudinal conductance S_C longitudinal resistivity (ρ_L) and transverse resistance (T_R), as well as the aquifer protective capacity rating in Table 2. Assessment of the Aquifer Protective Capacity of the area revealed poor weak, and moderate capacity ratings changes in longitudinal conductance from one VES point to the next indicated the change in the total thickness of low-resistivity materials. Dar Zarrouk parameters were applied on prospective aquifers to delineate fresh and saltwater and demarcate a safe zone for groundwater exploration. This was done using a method of aquifer classification adopted by some scholars [19, 24], that distinguished aquifer zones based on the range of value of the parameters. They, thus, classified aquifers as freshwater aquifers if the transverse Resistance (T_R)> 1700 Ωm2, longitudinal Resistivity (ρ_L)> 25 Ωm, and Longitudinal conductance S_C< 2.6 mhos. However, it is referred to as saline water aquifer if the T_R< 700 Ωm2, ρ_L< 15 Ωm, and C_L> 3.3 mhos. However, the aquifer is termed a brackish water aquifer if T_R ranges from 700 to 1700 Ωm2, ρ_L from 15 – 25 Ωm, and S_C ranges between 2.6 and 3.3 mhos. As shown in Fig. 11a, the longitudinal conductance increases from the west and Southeast to NNE and extreme northeast and the southwest. In contrast, the longitudinal resistivity (Fig. 11c) decreases from northeast to north and extreme northeast. As shown in Fig. 11c, T_R is one of the geoelectric characteristics used to define the most significant area of groundwater potential [25, 26 & 27]. It has a direct relationship with transmissivity, with the most significant values most likely reflecting the highest transmissivity values of the aquifers or aquifer zones and vice versa). In this case, the transverse resistance reveals a higher value around the northeast, north and southwest to the south, indicating an increase in salinity. While on the southwest portion, the transverse resistance is low and at a point around the northwest while low at a portion around NNE. The same trend can be seen in Figs 11b & c, longitudinal resistivity and transverse resistance. The salinity increases from the new Awe area at SW towards the old Awe at SW. Therefore, exploring freshwater areas around New Awe can be more favourable.

Conclusion

A total of 45 Vertical Electrical Sounding (VES) surveys were carried out in the Awe brine field located in Awe LGA, Nasarawa State. These surveys were conducted to gather essential information about the hydrogeological system of the aquifers in the area. The goal was to identify the subsurface configuration of the saline and freshwater zones. The result of the resistivity survey demonstrates a consistent trend of decreasing resistivity with increasing depth. This trend suggests that salinity increases with depth. The variations in resistivity observed can be attributed to lithologic types, water saturation, and salt content fluctuations. The study area contains four distinct zones of resistivity values. The top layer is unconsolidated dry sand (A horizon), with resistivity values ranging from 14-1886 Ωm. The underlying layer (B horizon), which corresponds to fresh water-saturated soil, has resistivity values of 7.7-3280 Ohms. A brine zone (C horizon) exists with resistivity values ranging from 2.93-37.3 Ωm, reflecting an aquifer containing saltwater whose depth varies across the profile. There are distinct saline water contamination zones within the region. The overlying freshwater zone (B horizon) is primarily free of saline water contamination, but there are some indications of saltwater intrusion at some points. Layer four (D horizon) is characterised by resistivity values that vary between 11.9 and 603 Ωm. The investigation has identified areas where groundwater development can be done with minimum risk of brine contamination and critical areas where groundwater withdrawal needs to be limited or preventive measure such use of blind casing to seal off the brine layer overlyin the freshwater aquifer. Also, the research revealed area where the salt exploration can be done at a profit. The study demonstrates the effectiveness of the Schlumberger method as a tool for investigating the saltwater-freshwater interface in a coastal environment.

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