Delineating Saline Water Zones in an Inland Brine Area Using Electrical Resistivity Indicators

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ABSTRACT: *This paper presents results of saline groundwater zone delineation using electrical resistivity sounding. The geologic setting of the study area, Awe Town is that of the Biddle Benue Trough, a structure filled with Cretaceous sediments that include Awe Formation. The town is a predominantly rural area plagued with saline groundwater resulting from brines associated with Awe Formation. As a result of this challenge, water supply scheme for the area was situated about 6km away from the main settlement making access to potable water difficult. The present study was prompted by the need to delineate the extent of groundwater contamination by the brines and in so doing identify aquifers close to the settlement for exploitation. Electrical resistivity method has been applied extensively in delineation of saline groundwater zones. Electrical resistivity surveys were done around the town with the sole aim of delineating the saline groundwater and fresh groundwater regions around the settlement. A total of 20 vertical electrical soundings were carried out using the Schlumberger configuration. Geophysical indicators (longitudinal conductance and transverse resistance (S and T respectively) as well as transverse resistivity (ρt) and longitudinal resistivity (ρl)) were used to assess saline water distribution in the aquifers of the study area. Of the four indicators, Longitudinal Unit Conductance and Transverse Unit Resistance clearly demarcated saline groundwater zones. Contour maps showing the distribution of these indicators aided in the identification of fresh groundwater, 1.2km from the main town. Analysis of borehole logs in the fresh groundwater region revealed fresh groundwater aquifers within Younger rocks i.e. Ezeaku and Keana Formations, which overlie the Awe Formation. Geologic setting of the study area is such that Awe Formation is exposed in the Old Town due to uplift and weathering, while younger rocks of Ezeaku and Keana Formations overlie Awe Formation in the New Town area. Aquifers in these formations have resistivity in the range of 150 to 300Ωm, with thicknesses ranging between 20m and 35m; these zones were interpreted to have high yield potential in terms of quality.*

KEY WORDS: saline, groundwater, inland brine, electrical resistivity

INTRODUCTION

Inland brine areas are those associated with saline water within continents as opposed to coastal areas where salinity is introduced into the water cycle due to sea (salt) water intrusion. Salinity in inland aquifers originates either from natural saline groundwater or as a result of contact with salt deposits or anthropogenic activities. In either case, salinity deteriorates groundwater quality.

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The present study was done in Awe town, a predominantly rural settlement in Nasarawa State, Central Nigeria. It is geologically situated in the Middle Benue Trough of Nigeria and is popular for the occurrence of Brines (TDS up to 64,000mg/l) which are produced from the shale unit of the Awe Formation (Offodile, 2014; Tijani *et al.*, 2004). These Brines are locally mined for salt production; this constitutes one of the major economic activities in the area. The Brines in the aquifer however, led to contamination of groundwater resources, impacting on the availability of 'clean' water. Government intervention in the past, led to the construction of a water supply scheme more than 6km away from the main settlement. This probably motivated the expansion of the community towards the water works in the search for non saline water an area now known as New Awe Town.

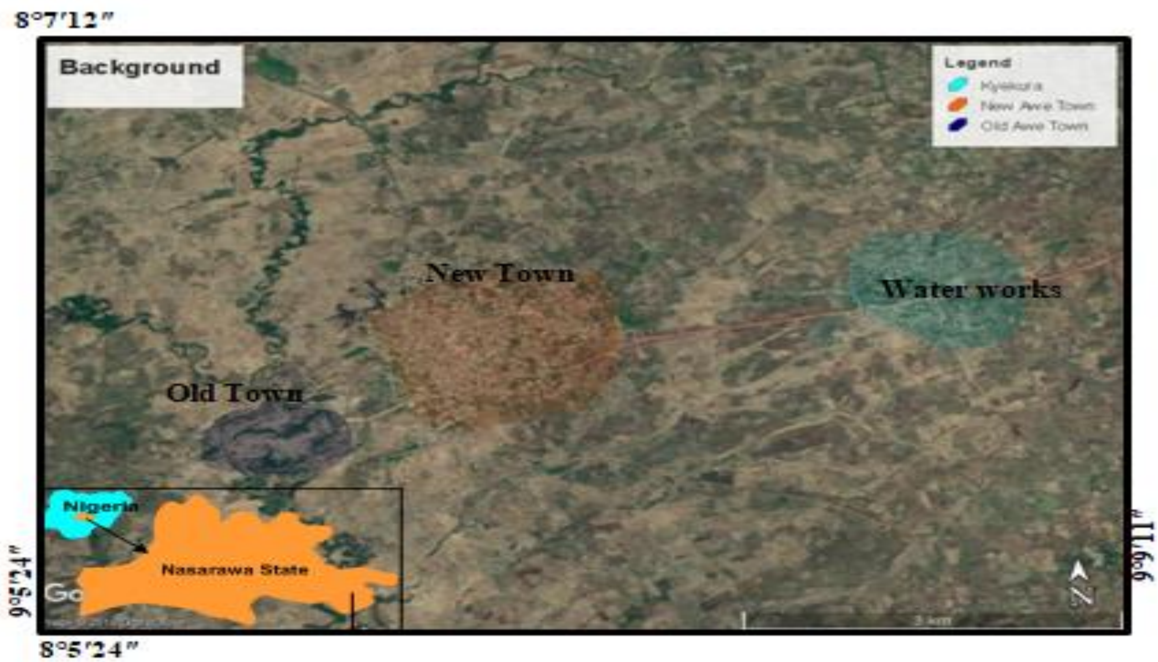

Figure 1. Map of the Study Area showing: the Old and New Towns and also the region where the water works is situated.

Electrical resistivity surveys aim at using electrical resistivity variations in the subsurface to delineate different geologic units and their hydrologic characteristics (Zohdy *et al.,* 1984). Geologic units exhibit varying electrical conductivity depending on the type of fluids they contain (Hwang *et al.*, 2004) thus making the electrical resistivity method ideal for delineating saline groundwater regions. The objective of the present study therefore, is to delineate the extent of groundwater contamination by the Brines using electrical resistivity indicators obtained from Vertical Electrical Sounding data. In so doing aquifers closer to the main settlement will be identified for exploitation. The indicators estimated using layer resistivity and thicknesses are: Longitudinal Unit Conductance, S (Ω^{-1}); Transverse Unit Resistance, T (Ωm^2); Average Longitudinal resistivity, Rs (Ωm); Average Transverse resistivity, Rt (Ωm) and electrical

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anisotropy. These indicators are used in studies related to: saline-fresh water interface, fresh groundwater potential, groundwater recharge, contamination studies, salt water intrusion into aquifers (MacDonald *et al.*, 1999; Singh *et al*., 2004*;* Mohammed, 2006*;* Frohlich *et al.*, 2008; Mondal *et al.*, 2013; Mohamed, 2006).

GEOLOGIC SETTING

The study area forms part of the Middle Benue Trough, MBT of Nigeria. The Benue Trough is a 1,000-km northeast-southwest trending intra-cratonic rift structure that extends from the northern limit of the Niger delta to the southern margin of the Chad Basin and is partitioned into Lower, Middle, and Upper Benue Troughs. The trough lies conformably on the Precambrian Basement of Nigeria. The consensus by various researchers on the origin of the Benue Trough is that it was formed in response to the continental separation of Africa and South America (Wright, 1968; Burke and Dewey, 1974; Olade, 1978; Benkhelil, 1989 amongst others). Geologically, it consists of the following sedimentary formations from the oldest: Asu River Group, Awe Formation, Keana Formation, Ezeaku Formation, Awgu Formation and the youngest which is the Lafia Formation.
Awe town is geologically popular for the occurrence of brines and for this reason a lot of studies have been done ranging from geology to hydrogeology and geochemical analysis on soil, rock and water (brine) samples (Offodile, 1984; Nwajide, 1990; Abiola *et al.,* 2014; Jatau and Nandom, 2013; Sallau *et al.,* 2017).

Geologic setting of Awe Town in particular starts with the Asu River Group deposited directly on the Basement Complex by the initial transgression from the Gulf of Guinea in the Middle Albian. Albian Awe Formation was deposited during regression that followed. The transgression was facilitated by subsidence in the southern and the middle segment of the Benue Trough. Awe Formation is overlain by the Keana Formation. The youngest rock unit in the area is the Ezeaku Formation. Structural elements include the anticline structure in the Old Awe town and also joints cutting across all rock units in the study area (Kana and Wubon, 2019).

Awe Formation outcrops around Old Awe Town where River Baki Abu has eroded the overlying Keana formation. It consists of thin alternating beds of sandstones, shales, and mudstones, brines issue from the transitional beds of the Awe Formation exposed by differential erosion on a local anticlinal structure (Offodile, 1984)

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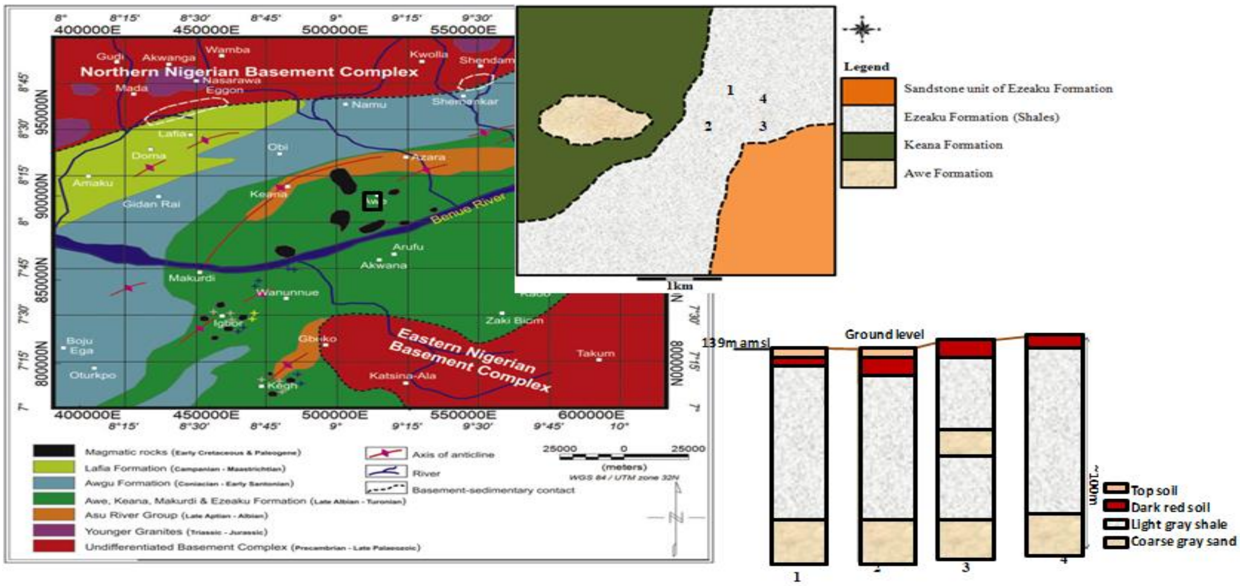

Figure 2. Geological map of the Middle Benue Trough (Anudu *et al., 2020*); inset is the geological map of Awe town (Kana and Wubon, 2019); also shown are lithological logs prepared from samples collected during drilling of four boreholes within the study area.

Keana Formation outcrops around Old Awe Town but seems to hem the outcrop of Awe Formation. It consists of thick beds of coarse grained sometimes pebbly sandstone, gray in colour. It is highly fractured with orthogonal joint sets; brines are seen to issue from these fractures that probably connect the Keana Formation to the Awe Formation.

Away from the Old Town towards the New Town i.e. east of the Old Town, thinly bedded light gray shales believed to be part of the Ezeaku Formation outcrop in a culvert adjacent the Local Government Lodge. Lithological logs of boreholes within the New Town area revealed the presence of the shale unit of the Ezeaku Formation. In the south-eastern part of the study area, light brown sandstone outcrops believed to be part of the Ezeaku Formation. The sandstones are relatively medium grained and light brown in colour.

Three main aquifer units exist in the study area, viz: sandstone units of the Awe, Keana and Ezeaku Formations. Ground water is found in pore spaces of these rocks. Static water level in the study area ranges from 109.6 to 126.9 meters above mean sea level (Kana and Wubon, 2019). TDS values range from 80mg/l to 64,000mg/l; higher values are associated with the brines in the area of the old Awe town. Away from the Old Town, towards Sabon Gari and Kyekwura, electrical conductivity improves. The implication of this is that water from the boreholes in the Sabon Gari area is good for domestic water supply.

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VES DATA AQUISITION AND INTERPRETATION

Vertical Electrical sounding data acquisition

A total of 20 vertical Electrical Sounding surveys were conducted in the study area (figure 3). Current electrode spacing (AB) ranged from 2m to 250m. VES points covered both Old and New Awe Towns. In addition to VES data, groundwater was sampled across the study area. Samples were collected from hand dug wells, springs and boreholes for geochemical analysis.

VES curves were interpreted in three stages: (1) smoothening of the field derived curve; (2) preparation of initial models in each case of geo-electric layers using the information on geology from previous literature (e.g. Offodile, 2014), borehole logs and fieldwork; (3) finally, introduction of the initial models into RES1D software for iteration to obtain a best fit between the field curve and the calculated one. RMS error for the best fit models ranged from 4% to 10%.

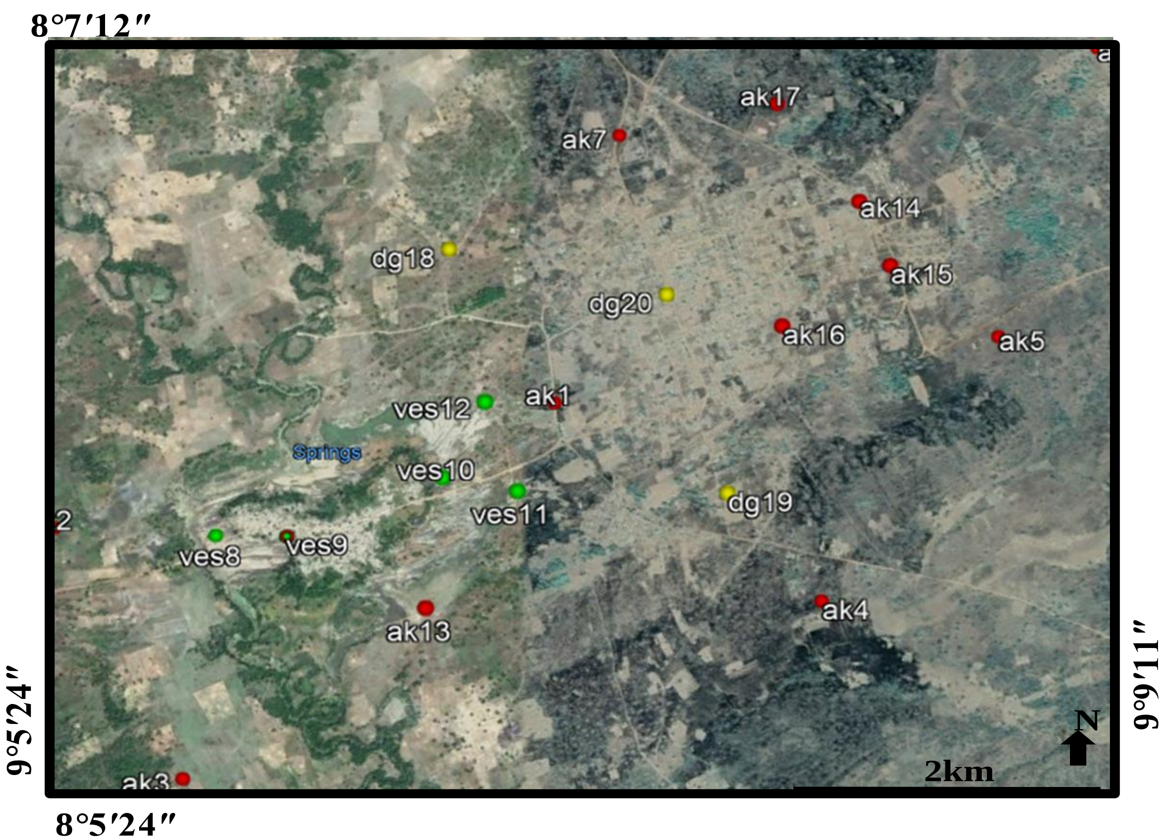

Figure 3. VES data acquisition points.

Estimation of Geophysical Indicators

The geophysical indicators used to delineate saline groundwater zones in the study area are: Longitudinal Unit Conductance, S (Ω^{-1}); Transverse Unit Resistance, T (Ωm^2); Average

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Longitudinal resistivity, Rs (Ωm); Average Transverse resistivity, Rt (Ωm) and electrical anisotropy λ. These indicators are also known as the Dar Zarrouk parameters (Maillet 1947). The indicators are determined from geo-electric layer thickness and resistivity obtained from VES data interpretation. A geoelectric layer can be defined by its resistivity (ρ) and its thickness (h); so that for multiple layers, h_i/ρ_i will be for *i*=1, 2, 3….*nth*, layer where *n* = total number of layers.
Therefore, for a column of subsurface with a unit cross sectional area consisting of geoelectric layers, the parameters were derived using the following equations.

$$S\ (\Omega^{-1}) = h_1/\rho_1 + h_2/\rho_2 + h_3/\rho_3 + \cdots + \cdots + h_n/\rho_n \quad (1)$$

$$T\ (\Omega m^2) = h_1.\rho_1 + h_2.\rho_2 + h_3.\rho_3 + \cdots + \cdots + h_n.\rho_n \quad (2)$$

$$Rs\ (\Omega m) = H/S \quad (3)$$

$$Rt\ (\Omega m) = T/H \quad (4)$$

$$H\ (m) = h_1 + h_2 + h_3 + \cdots + \cdots + h_n \quad (5)$$

$$\lambda = (T.S/H)^{1/2} \quad (6)$$

Table 1. Geoelectric layers, thicknesses, and geophysical indicators used to delineate saline groundwater zones in the Study Area.

	Layer Resistivity (Ωm)			Layer thickness (m)		Longitudinal Conductance, S (Ω^{-1})	Transverse Resistance, T (Ωm^2)	Total thickness (m)	Longitudinal Resistivity, Rs (Ωm)	Transverse Resistivity, Rt (Ωm)
VES	**ρ1**	**ρ2**	**ρ3**	**h1**	**h2**					
ak1	220.00	430.00	1629.00	15.00	7.91	0.09	19335.39	22.91	264.62	843.97
ak2	26.00	225.00	868.40	7.23	15.68	0.35	15243.26	22.91	65.88	665.35
ak3	44.00	112.00	672.00	5.00	12.40	0.22	8892.80	17.40	77.56	511.08
ak4	91.00	202.20	1305.70	5.00	19.00	0.15	25819.30	24.00	161.17	1075.80
ak5	101.00	200.00	1309.00	9.75	26.57	0.23	36730.13	36.32	158.34	1011.29
ak6	125.00	376.00	1025.00	10.62	55.38	0.23	60757.62	66.00	284.18	920.57
ak7	211.20	523.00	1862.00	24.95	11.37	0.14	34219.79	36.32	259.66	942.17
ves8	3.90	6.10	18.50	33.19	40.59	15.16	953.37	73.78	4.87	12.92
ves9	40.90	13.80	40.60	18.23	55.55	4.47	2506.90	73.78	16.50	33.98
ves10	15.50	7.10	40.00	18.23	91.77	14.10	3800.23	110.00	7.80	34.55
ves11	5.70	3.70	5.70	33.19	76.81	26.58	560.62	110.00	4.14	5.10
ves12	8.10	4.00	17.40	10.01	23.18	7.03	443.37	33.19	4.72	13.36
ak13	277.00	72.00	305.00	12.75	53.25	0.79	17159.25	66.00	84.01	259.99
ak14	45.00	140.00	320.00	15.30	50.70	0.70	18366.00	66.00	94.00	278.27
ak15	88.00	163.60	300.00	10.62	55.38	0.46	18351.43	66.00	143.73	278.05
ak16	146.30	404.80	933.20	17.90	9.62	0.15	16223.30	27.52	188.34	589.51
ak17	33.00	17.00	36.00	12.75	9.30	0.93	551.55	22.05	23.62	25.01
dg18	775.00	24.00	4033.00	2.50	4.00	0.17	16192.00	6.50	38.26	2491.08
dg19	21.00	270.00	6.56	9.00	11.00	0.47	2502.16	20.00	42.62	125.11
dg20	61.20	108.00	329.00	10.00	22.00	0.37	8318.00	32.00	87.17	259.94

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Applicability of the indicators in delineating saline groundwater zones
The results of the preceding analysis are presented inform of contour plots (figure 4).

Longitudinal Unit Conductance – the contour map for longitudinal unit conductance (figure 4a) shows that the highest values are cantered around the Old Awe Town; the values decrease in a radial manner away from the town. This indicator has clearly demarcated the saline GW zone; the saline zone coincides with that of the contour map of EC (figure 4e) measured in water wells in the study area. This region is centred on the Old Awe Town where the Brines are currently being mined for salt production.

Transverse Unit Resistance – while the contour map of the transverse unit resistance demarcates a region of very low resistivity around the Old Awe town (figure 4b), the belt extends north eastwards towards the New Town. EC measured in the New Town region (figure 4e) is however low compared with that in the Old Town. The low resistivity in the New Town region is explained by the geology as determined from litho logs of boreholes drilled in the area; the area is underlain by shale of the Ezeaku Formation

Average Longitudinal Resistivity – in this case (figure 4c), a low resistivity region coincides with the Old Town region, agreeing with contour maps of the Longitudinal Unit Conductance and EC.

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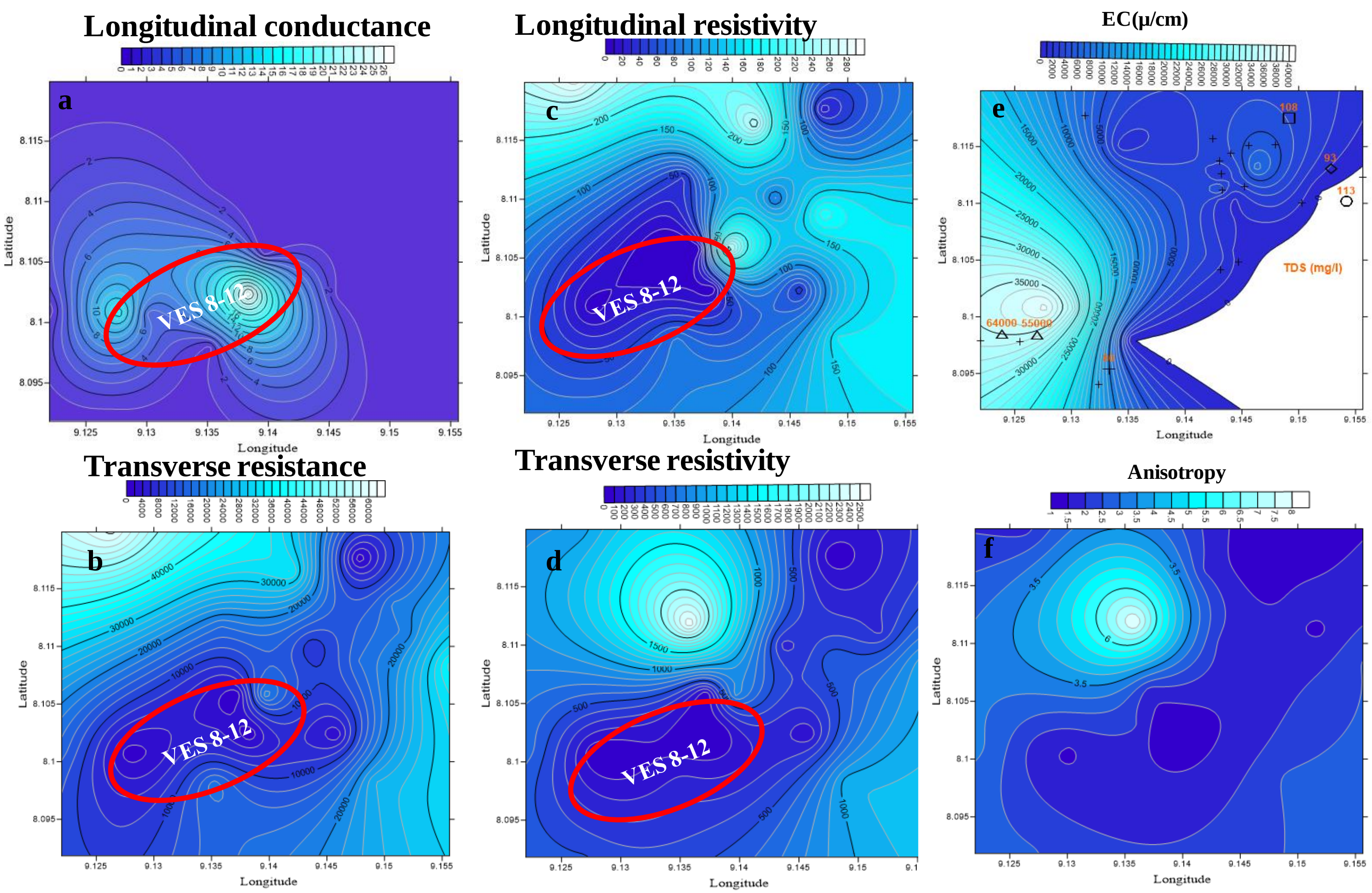

Figure 4. Contour plots of the geophysical indicators: (a) Longitudinal Unit Conductance, S (Ω^{-1}); (b) Transverse Unit Resistance, T (Ωm^2); (c) Average Longitudinal resistivity, Rs (Ωm); (d) Average Transverse resistivity, Rt (Ωm); Electrical Conductivity (μS/cm) and (f) electrical anisotropy λ. Boxes, triangles and diamonds on figure 4e are water sample collection points.

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Average Transverse Resistivity – contour map of this indicator (figure 4d) also as in the case of the Transverse Unit Resistance shows a belt of low resistivity extending from the Old Town area, north eastwards towards the New Town Area. Again the low resistivity is attributed to the underlying shale of Ezeaku Formation.
Anisotropy – low values (1.00) of electrical anisotropy were recorded along the saline region (figure 4f). This indicates high groundwater potential and agrees with the productive nature of boreholes sited in the regions with low anisotropy.

GROUNDWATER SAMPLING AND GEOCHEMICAL ANALYSIS

Four boreholes were drilled in the New Town area; in the course of drilling, samples were collected for lithological logging. In addition to these, electrical conductivity profile for the four wells was taken; while samples of water from these wells and also from wells in the Old Town area were taken for geochemical analysis.

For the water samples, parameters measured *in – situ* are: Electrical conductivity (and TDS); while elemental composition (Ca^{2+}, K^{+}, Mg^{2+}, Na^{+}, HCO_3^{-}, SO_4^{2-}, NO_3^{-} and Cl^{-}) was determined in the lab using Ion Chromatography and Atomic Absorption Spectrometry. In addition to assessing salinity, the objective of groundwater analysis includes ascertaining groundwater type and also information from the analysis will aid in interpretation of geophysical data.

Table 2. Cation and Anion concentrations (mg/l) in groundwater samples from saline and non saline regions of the study area.

LOCATION	Ca	Mg	K	Na	Fe	Mn	Cl	HCO_3	SO_4	NO_3	TDS
New Town	48.50	0.59	2.50	34.20	0.41	0.80	0.50	9.40	0.71	0.02	93
New Town	50.7	0.58	2.50	30.00	0.26	0.23	1.20	9.60	0.12	0.02	108
New Town	46.80	0.62	3.80	43.90	0.99	0.02	0.80	3.20	0.94	0.01	80
New Town	42.00	0.51	3.30	53.10	0.73	0.02	1.00	13.60	7.29	0.02	113
Old Town	**1180.00**	0.72	**65.70**	**3580.00**	0.76	0.03	**960.00**	11.60	0.71	0.01	**64000**
Old Town	**935.00**	0.70	**63.40**	**2775.00**	0.67	0.07	**825.00**	6.20	1.41	0.05	**55000**

Table 2 shows the TDS and major ion concentration in groundwater samples from the study area. It is seen that the water samples from the Old Town Area have higher TDS values and elemental compositions dominated by Ca, Na and Cl reflecting a Na- Ca - Cl type saline water. Water samples from the New Town Area have relatively lower TDS values and are dominated by Ca,

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Na, and HCO_3, reflecting a non saline Ca-Na-HCO_3 water type. Conductivity logs for two of the four boreholes drilled in the new area using the information from the resistivity indicators is shown in figure 5. The EC profiles from these wells show low EC values for groundwater in these boreholes.

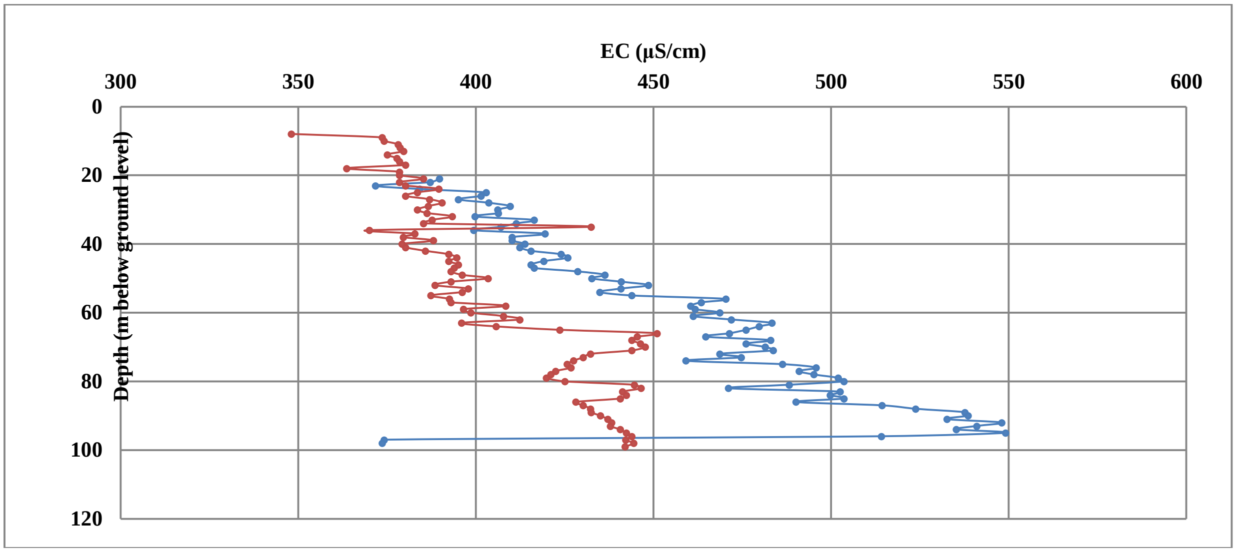

Fig. 5 EC (µS/cm) log of boreholes drilled in the New Town Area

CONCLUSIONS

The preceding analysis led to the delineation of saline groundwater regions around Awe Town using geophysical parameters determined from Vertical Electrical Sounding resistivity data. The indicators used are: Longitudinal Unit Conductance; Transverse Unit Resistance; Average Longitudinal and Transverse Resistivity. Of the four indicators, the Longitudinal Unit Conductance and Average Longitudinal Resistivity gave clearer demarcation of the saline groundwater regions; while the shale present in the non saline region affected the distribution of the Transverse Unit Resistivity and Average Transverse Resistivity.

The saline Groundwater region is around the Old Awe Town where Mining of Brines had been the major economic activity. These Brines issuing from the Awe Formation at the Old Town Area contaminated groundwater in other aquiferous units in the region. Non saline regions close to the New Town coincide with groundwater from the Younger Keana Formation which hasn't been affected by the brines.

The aquifers in Younger Keana Formation were confirmed from litho logs of four water wells drilled by the State Government in the New Town Area. The choice of drill points was informed by the recommendations of the present study. The logs characterized the region as having a lateritic soil from the ground surface to 2m; this is followed by the shale unit of thickness between 30m and 52m below which the sandstone unit that constitutes the aquifer extends for about 40m (end of well).

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