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Application of Electrical Resistivity Techniques for Mapping Bitumen Saturated Zones and Its Geologic Implication over Agbagbu, Southwestern Nigeria

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Abstract: Mapping of bitumen saturated zones in Agbabu, southwestern Nigeria was carried out using electrical resistivity techniques involving 2D resistivity imaging and vertical electrical sounding (VES). The main objective of the research work was to delineate the bitumen saturated zone and their geologic implication(s) especially on the groundwater development over the study area. For the 2D resistivity imaging, a total of four traverses were established in the NE-SW direction with each traverses covering a total distance of between 150m to 160m. Twenty vertical electrical soundings were also carried out with the results showing KQ and HA curve types being predominant. The results of 2D resistivity imaging showed that the underlaying bitumen impregnated layers was overlain by a protective clay layer which has some discontinuities (weak zones) with traverses 1and 4 showing the most vulnerable zones in terms of groundwater pollution while traverses 2 and 3 appears to be less vulnerable. The VES results showed that the bitumen impregnated layers was within the third and fourth layers with resistivities ranged between 86Ωm to 255Ωm and occurring at depths ranged between 1.5m to 6m. The geologic discontinuities across the study area coupled with the shallow depth of occurrence of bitumen might be a drawback to any meaningful groundwater development within the study area.

Keywords: Bitumen, Saturated Zones, Weak Zones, Agbabu, Resistivity Imaging, Clay formation, Wenner Array

1. Introduction

Nigeria is one of those countries in the world that is richly endowed with a variety of different mineral resources. Bitumen is one of the richly deposited minerals in Nigeria just like crude oil, it is found in Ondo, Lagos, Ogun and Edo state [1-3]. Accidental discoveries of bitumen as a black viscous tar oozing out of river valleys and farmlands in areas of Ofosu, Agbabu, Mafowoku and Eregu has been dated back to several decades. Its scientific discovery in Nigeria is dated back to 1907 [4].

In its raw state, bitumen is a sticky and a viscous substance occurring mostly in sands and clays. The physio-chemical data obtained from laboratory analysis [5] showed that the heavy oil extracted from the bitumen deposit has an American petroleum institute gravity (API) ranging between 1.0 and 10.54API. This together with its softening point (44–52°C), ductility (0.1–1.33 mm) and penetration (80–100 mm) enhances its consistency and rheological properties; hence, it is useful in road and highway constructions. Besides, Nigerian bitumen possesses relatively large amounts of naphthalene (10%), aromatics (90%), asphaltenes (18–23%) and trace-metals which makes it unideal for consumption when it interacts with underground water [4].

Furthermore, from previous researches carried out on the occurrence of the bitumen [2-4], it has been postulated that bitumen occurs in three forms namely surface and near surface, bitumen-impregnated sand and bitumen seepages from wells, however bitumen in Agbabu mainly occurs in the near surface mode of occurrence and consequently due to its shallow mode, contamination of the shallow wells becomes a possibility. Bitumen contamination is commonly associated with spills, leaks and seeps of the crude or oil products while its anthropogenic source includes burning of fossil fuels [6]. Also of a great concern to man is the heavy metals and trace metals (Cu, Fe, Mn, Ni, Zn, Cd, Cr and Pb) content of the heavy oil components of the bitumen which are capable being harmful to human health [4], it is however noteworthy to state that in small amounts these trace metals are required in the body for maintaining good health but in large amounts they become toxic or dangerous [7]. The abundant presence of metals can be inimical to the health of humans, plants and marine life. Heavy metals toxicity can lower energy levels and damage the functioning of the brain, lungs, kidney, liver, blood composition and other important organs. Long term exposure can lead to gradually progressing physical, muscular and neurological degenerative processes that imitate diseases such as sclerosis, Parkinson's diseases, Alzheimer's disease, muscular dystrophy [8]. Repeated long term exposure of these metals can at worst cause cancer.

Researches over the years [9−11] has shown that groundwater is the purest form of water, however several factors such as climate, characteristics of soil, human activities on the ground, circulation of ground water through rock types, topography of the area, intrusion of saline water in coastal areas can have adverse effects on the quality of water. It is therefore expedient to understudy the geology and formation of the subsurface to study the vulnerability of the groundwater.

From personal oral interviews in the community (Agbabu), it was discovered that the majority of the community dwellers depend solely on shallow dug wells for water consumption and for domestic usage. It therefore becomes necessary to assess the water quality from various wells to ascertain the levels of pollution especially from the existing underlying bitumen. Groundwater contaminants remain one of the main concerns of earth scientists and researchers worldwide because of its adverse effects on both the environment and human health. Contaminants easily found their ways into the groundwater table where the overburden thickness is thin and where the topsoil happens to be a loose soil (sandy or sedimentary soils) and/or through a fracture or fault zones. Fracture and fault zones are the major ways through which groundwater is been contaminated in the study area. Among the available geophysical methods, electrical resistivity method have been found remarkably suitable for such environmental studies, due to the conductive nature of most contaminants [12]. Electrical resistivity method involving 2D resistivity imaging and vertical electrical sounding (VES) was used for this study. Hydrochemical study was also employed to evaluate groundwater quality that is suitable for human consumption.

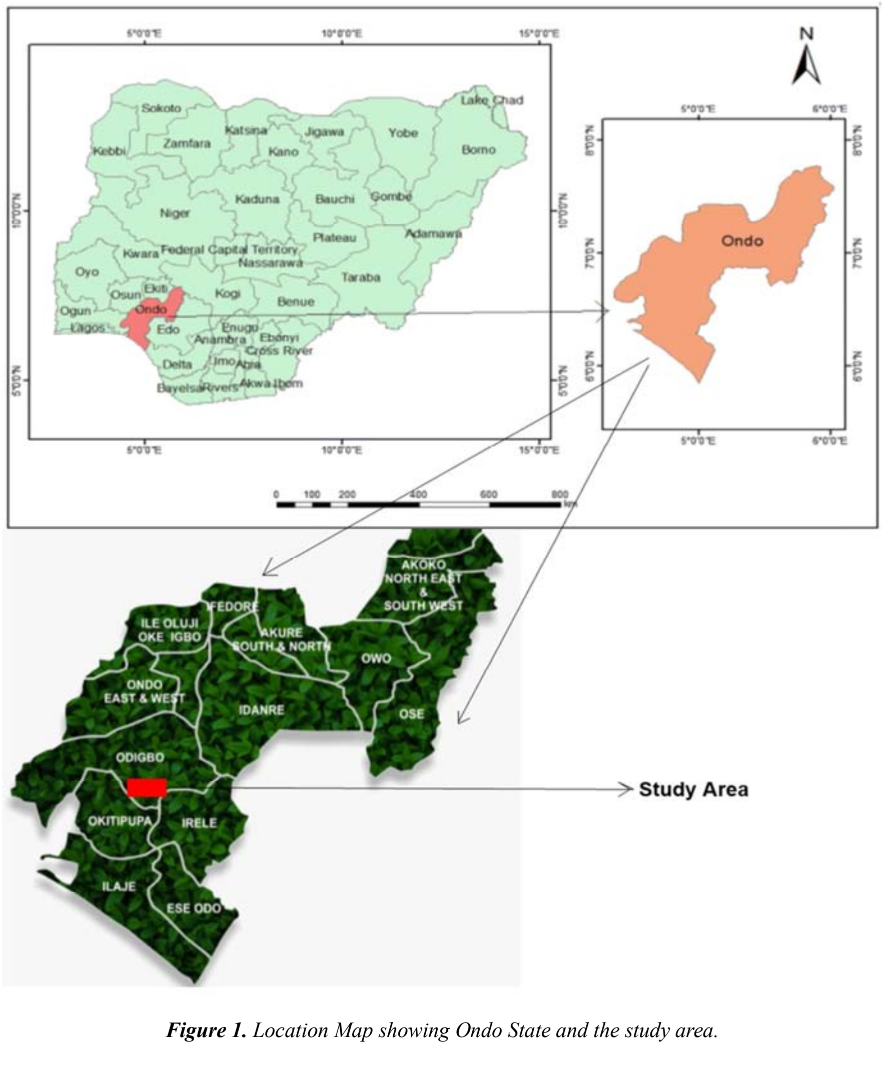

Figure 1. *Location Map showing Ondo State and the study area.*

2. Location, Climate and Geology of the Study Area

The study area (Agbabu) is a settlement to the southern part of Odigbo Local Government area of Ondo State of Nigeria on latitude 6° 35’ 19” to 6° 35’ 05” and longitude 4° 50’ 15” to 4° 15’ 20” (Figure 1). Mangrove and freshwater swamps cover the area, which also contains brackish lagoons. Rainfall in this equatorial zone is high, frequently exceeding 3 m per year [13]. The altitude of the area ranges from 5m-16m above mean sea level and is characterized by November to March (dry) and April to October (wet) seasons.

Agbabu bitumen belt is made up of the main Agbabu, inhabited by a few hundred people and other smaller farm settlements such as Mulekangbo, Ilu-binrin and Mile 2 Agbabu village. Agbabu bituminous belt sand deposits in south western Nigeria are naturally occurring in a sticky tar-like form [14]. Its geology suggests a large deposit of bitumen and Cretaceous tar sand formations typical of the Dahomey basin. The Dahomey basin is an Atlantic margin basin containing Mesozoic-Cenozoic sedimentary succession reaching a thickness of over 3,000m. It extends from south-eastern Ghana to the western flank of the Niger Delta. Its stratigraphy is classified by various authors into Abeokuta Group, Imo Group, Oshosun Formation, Ilaro Formation and Coastal Plain sands and Alluvium [15, 16]. The Agbabu area is underlain by the sediments of the Imo Group.

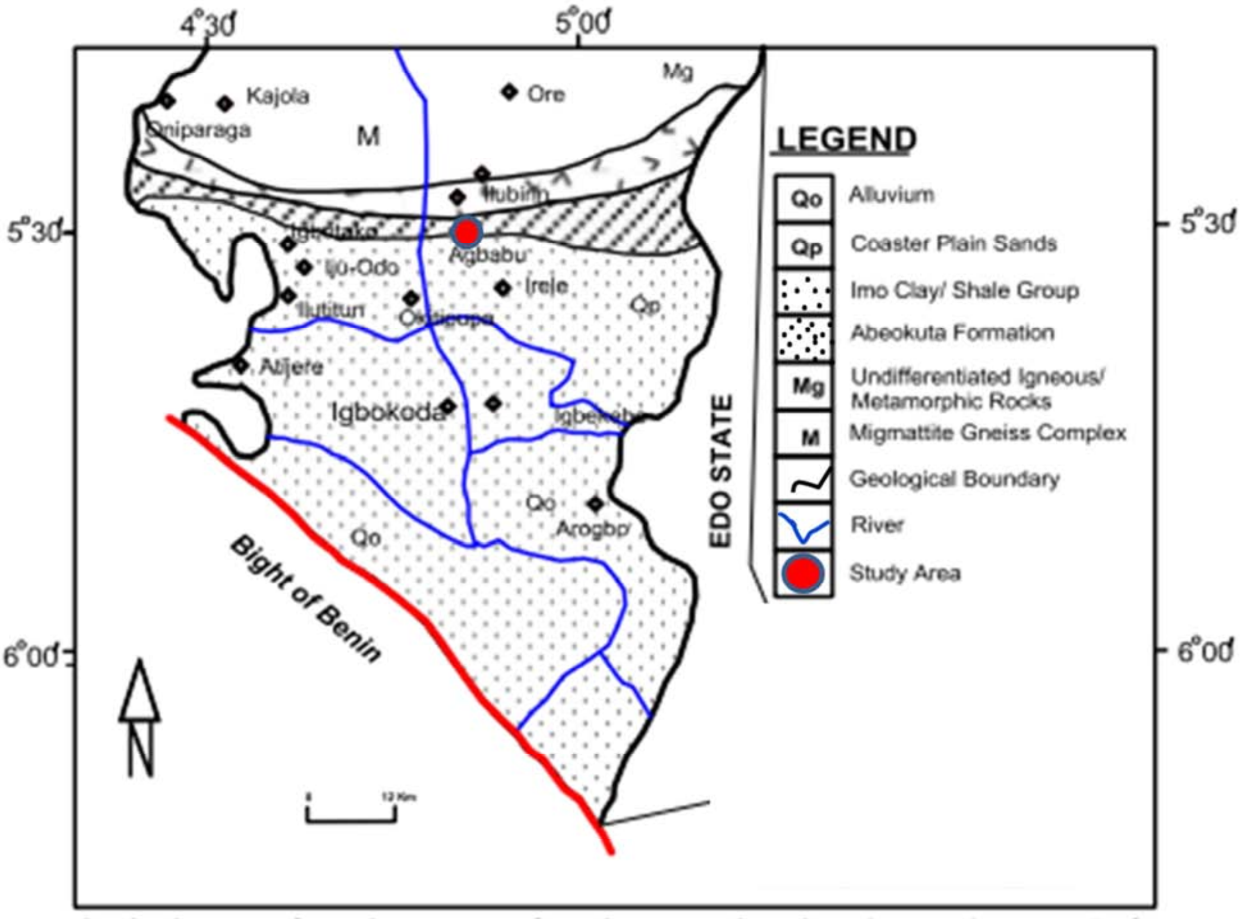

Figure 2. *Geologic map of the Study area.*

3. Materials and Method

3.1. Electrical Resistivity Method

For the electrical resistivity method, two field techniques were utilized, the vertical electrical sounding (VES) using the Schumberger array and the combined horizontal profiling and vertical electrical sounding (2D electrical imaging) using Wenner array. The equipment used was the resistivity meter.

3.2. 2D Electrical Resistivity Imaging

Four geophysical traverses were established across the study area in the NE – SW direction; these traverses were targeted near existing wells to understand the subsurface lithology within and around these wells as well as tie the results of the geophysical studies with the hydro chemical analysis; with each traverse covering a total distance between 150m to 165m (Figure 3). The traverses were set up to cover

Agbagbu community and neighboring Mile 12 where mining activities had occurred in the past. Traverses 1, 2 and 3 where setup within Agbagbu community while Traverse 4 was set up within Mile 12 community.

The inter electrode spacing of 5m, 10m and 20m were all occupied along the set-up traverses adopted while inter dipole separation factor (n) was varied from 10 to 20. Transmitting dipole which is powered by low frequency dc source was stationed at station 0 and 30. The receiving dipole was initially stationed at station 10 and 20 (n-1) and subsequently moved to stations 30 and 40 (n-2), station 40 and 50 (n-2), 50 and 60 (n-2), 60 and 70 (n-2), stations 70 and 80 (n-2) ditto every other traverse. The transmitting dipole was moved to stations 10 and 40 and the expansion procedure repeated. The apparent resistivity values were calculated using $\pi an+1n+2n$ as the geometric factor. The apparent resistivity values obtained were plotted. 2D inversion modeling of the wenner data was carried out using a computer software package DIPRO, which provides a rapid, fully automated inversion just with the keyboard input of the measured data. It provides high resolution color or contoured images of both the field data Pseudosection and the 2D resistivity structure that resulted from the inversion.

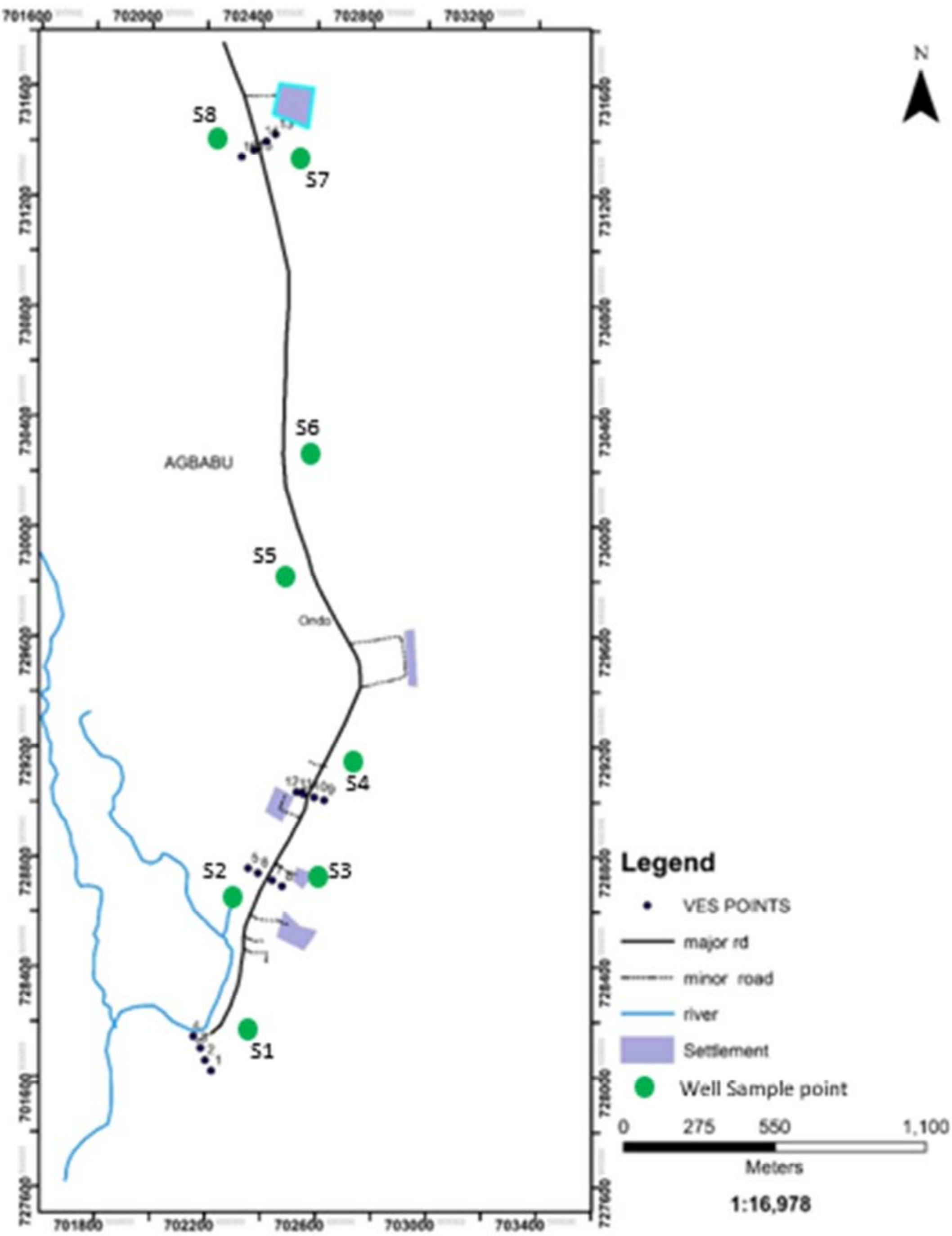

Figure 3. *Base map of the study area.*

3.3. Vertical Electrical Sounding (VES)

The vertical electrical sounding (VES) technique was adopted because information on the variation of geophysical characteristics of the subsurface layers with depth was desired. The Sounding station was marked and pegged along the traverses. In the vertical electrical sounding (VES) technique, vertical variations in the ground apparent resistivity are measured with respect to a fixed center of array. Along Traverse 1, sounding stations were occupied at stations 20, 60, 105 and 130m from the zero station (E-W) while Along Traverse 2, stations 40m, 90m, 125m and 165m were all occupied along the E-W direction from the starting station. Furthermore, Stations 30m, 85m, 105m and 135m were all occupied along traverse 3 while stations 15m, 55m, 100m and 165m were sounded along traverse 4.

The location of all sounding stations in both geographic and universal traverse Mercator (UTM) co-ordinates was recorded with the aid of the GARMIN 12 channel personal navigator Geographic positioning system (GPS) unit. The current electrode spacing (AB/2) was varied from 1m to 130m and 1m to 165m in traverse 1 and traverse 2 respectively while it (AB/2) varied from 1m to 135m and 1m to 165m for traverse 3 and traverse 4 respectively. The metal electrodes were driven into the ground with hammers to ensure good contact with the ground. The measurements were taken at the stations with in-line arrangement of the electrodes with respect to traverse lines and the apparent resistivity values were calculated. The apparent resistivity measurements at each station were plotted against spacing on bi-logarithmic graph sheets. The resulting curves were then inspected visually to determine the nature of the subsurface layering. In this way, each curve was characterized depending upon the number and nature of the subsurface layers. Partial curve matching was carried out for quantitative interpretation of the curves. The results of the curve matching (layer resistivities and thickness) were fed into the computer as a starting model parameter in an iterative forward modeling technique using RESIST version 1.0 (Vander velper., 1988) to generate VES curves used for the interpretation.

The curves were inspected to determine the number and nature of the layering. The result of the forward model was fed to the computer and various geoelectrical parameters were estimated. The geoelectric parameters estimated are aquifer resistivity, aquifer thickness, unsaturated zone thickness, total longitudinal conductance of the unsaturated zone, total transverse resistance of the unsaturated zone, hydraulic Resistance and hydraulic conductivity.

3.4. Data Presentation

Generally, data were presented in form of maps, curves and tables. Geophysical survey data are presented as sounding curves (i.e. plots of apparent resistivity against electrode spacing).

3.5. Data Interpretation

Generally, interpretation was done qualitatively and quantitatively. Qualitative interpretation involves visual inspection of curves and maps. Quantitative interpretation involves diagnosis of parameters value and statistical analysis of values obtained from the maps. Geophysical data interpretation and water chemistry data interpretation were done qualitatively and quantitatively.

4. Results and Discussions

The results were presented as field curves, tables, charts, geoelectric sections, 2D resistivity inversion images and maps.

4.1. 2D Electrical Imaging

The results of the processed imaging data by dipro are displayed as inverted models representing sections versus depth of the subsurface along the 2D resistivity inverse model section of the profile. The horizontal scale on the section is the lateral distance while the vertical scale on the section is the depth (in meters).

Traverse 1 (Figure 4) covers a total spread of 165m with an electrode spacing of 5m and runs in the East-West direction. The resistivity values range from 15.1 ohm-m to 1093 ohm-m along the traverse. Four major subsurface geologic layers are observed in the 2D resistivity structure along this traverse. The first layer (red color) with resistivity value ranging from 181 ohm-m to 525 ohm-m is interpreted to be a sandy layer. It has a uniform distribution between stations 0 to 40, covering a depth of about 5m. There is an observed downward extension of this layer between stations 40 to 60, 85 to 110 and 125 to 160 where it forms a downward facing cone shaped layering. Meanwhile two major discontinuities are observed along the traverse, the first occurs between stations 65 to 80 and the second discontinuity between stations 110 to 125. These discontinuity zones are possible weak zones for the upward migration of bitumen and therefore potential zones. The second layer (yellow color) which is suspected to be a clay-cap over the underlying bitumen has resistivity values ranged between 106 ohm-m to 200 ohm-m occurs non-uniformly distributed along the traverse.

The third layer (green colour) with a thickness of about 12m occurs as an isolated geologic body in 3 major zones as along the traverse trending in the upward direction to the depth of about 5m from the surface especially towards the discontinuity zones on the first layer. This layer is characterized with resistivity values ranging from 33.9 ohm-m to 65.2 ohm-m. This third layer is suspected to be the bituminous zones and observed trending in the upward direction especially towards the discontinuity zones in the first layer. This suggests that the weak zones are easy pathways for bitumen migration once the surface is disturbed.

The fourth layer (blue colour) suspected to be saline water with resistivity value ranged from 15 ohm-m to 24 ohm-m occurring at the flanks of the traverse at stations 10-35 and 115-125 at a depth from 15m to the probed depth. Stations between 65 to 80 and 110 to 125 are potential active zones for pollution and should be avoided for groundwater investigation.

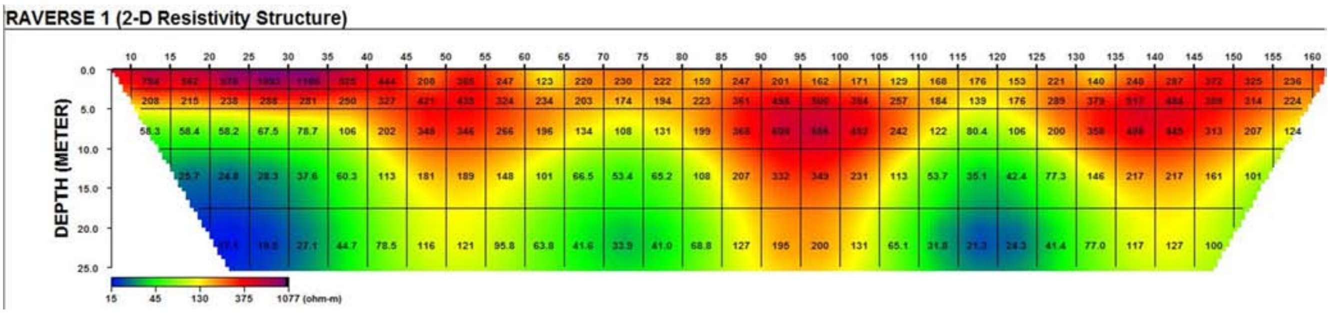

Figure 4. *Werner (2D) resistivity structure for traverse 1.*

Traverse 2 (Figure 5) covers a total spread of 175m with an electrode spacing of 5m and runs in the East-West direction. The resistivity value ranges from 0.96 Ωm to 889 Ωm along the traverse. Four major geologic layers are observed in this 2D resistivity structure. The first layer (red color) with a resistivity value ranging from 59.9 Ωm to 261 Ωm is observed to be uniformly spread across the traverse with a thickness of about 6m except between stations 135 to 155 where it is exhibits an appreciable thickness as much as 30m is suspected to be sandy layer. The second layer (yellow) revealed a structure interpreted to be clay cap protecting the underlying bitumen layer which has resistivity values ranging from 18.1 Ωm to 51.6 Ωm has a depth of 10m between station 0 to 100 however from station 100 to 130, this layer has a depth of about 15m. The third layer (green) is indicative of the bituminous layer which is not uniformly spread along the traverse has a resistivity values ranging from 6.69 to 14.6 Ωm. It can be inferred from the figure 5 that this layer only occurs from station 0 to 110, however stations 110 to 170 shows no indication of the presence of the bituminous layer therefore this region is the least active zone within the traverse as such is best suited for groundwater studies. The fourth layer (blue) is suspected to be saline water with resistivity value ranged from 0.96 Ωm to 2.13 Ωm occurs at the eastern flank of the traverse between stations 0 to 55.

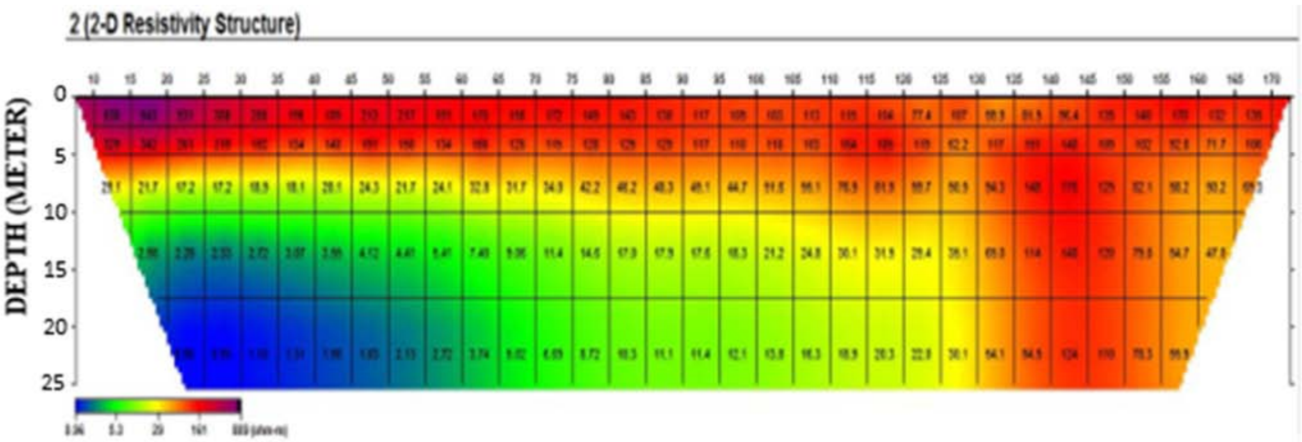

Figure 5. *Werner (2D) resistivity structure for traverse 2.*

The 2D electrical resistivity section along Traverse 3 (Figure 6) is a reflective of subsurface resistivity along the traverse 3. It covers a total spread of 140m with an electrode spacing of 5m and runs in the East-West direction. The resistivity values range from 2.10 Ωm to 606 Ωm along the traverse. Firstly, a pocket of high resistivity (purple) obtained between station 50 to 80 is suspected to be due to the tarred major road between the traverse. Four major layers are observed in this 2D resistivity structure. The first layer (red color) is observed uniformly across the traverse with a thickness of about 10m postulated with resistivity values ranging 76.7 Ωm ohm-m to 229 Ωm which suspected to be sandy layer. The second layer (yellow color) has resistivity value ranging from 27.4 Ωm to 92.0 Ωm which reveals a clay cap directing covering the underlying bituminous layer has a depth between 9m – 15m at the eastern flank between stations 0-45, 9m to 10m at the center of the traverse between stations 50 to 110 and at the western end of the traverse between stations 110 to 140, an increase in the depth was observed trending westward between 10m to 20m. The third layer (green color) is interpreted to be the bituminous layer appearing across the traverse but most pronounced at the flanks of the traverse with varying resistivity values between 6.79 Ωm to 28.5 Ωm. It occurs at a depth of about 15m to depth investigated between station 0 to 50 while from station 55 to 105, it occurs at a depth between 11m while between station 105 to 135, this layer occurs at a depth of about 17m. The fourth layer suspected to be saline water impregnated layer with resistivity value ranged from 2.1 Ωm to 3.35 Ωm predominantly occurs at the center of the traverse between stations 50 to 105 forming a cone-like shape that does not extend to the flanks of traverse occurs at a depth of about 17m. It was observed that, stations 50m-110m constitute the most active zone along the traverse.

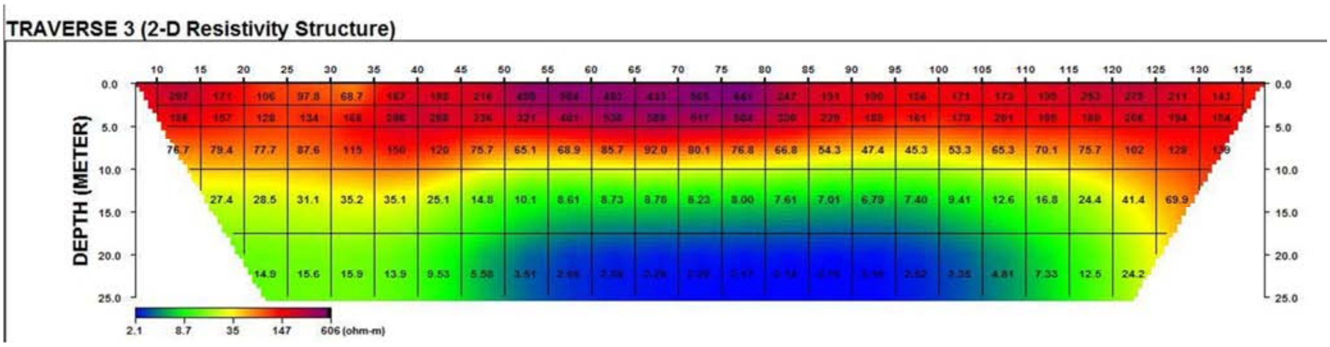

Figure 6. *Werner (2D) resistivity structure for traverse 3.*

Figure 7 represents the 2-D resistivity inversion depth section of Traverse 4; this is a part within the study area where mining activities had occurred in the past which led to the disturbance of the subsurface. This region appears to have the highest evidence of bitumen in the study area occurring at a very shallow depth from the subsurface. It shows a thin top sand layer at the extreme ends of the traverse with resistivity varying between 2109 Ωm to 346 Ωm with a thickness of just few meters and is only well pronounced along stations 140m to 170m while yellow color indicative of the clay layer occurs sporadically within the bitumen impregnated layer (green color) showing that these subsurface strata had been mixed together due to the overtime disturbance of the subsurface. This totally agrees with the presence of natural bitumen which can be easily by visual inspection within this area. Another point of note from the 2D resistivity image is the upward movement of the bitumen layer at stations 135m-140m which is due to the activities of an injection pump used to pump the flowing bitumen over the years from the subsurface.

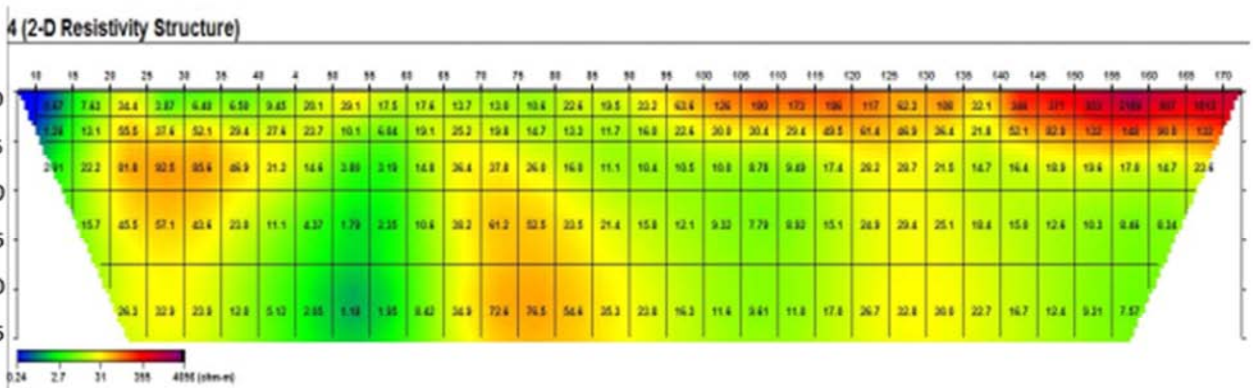

Figure 7. *Werner (2D) resistivity structure for traverse 4.*

In terms of pollution, Figures 4 and 7 are the most active and vulnerable due to the fact that these traverses showed several discontinuities which could serve as weak zones for the possible migration of the underlying bitumen deposit. Traverse 4 shows that the bitumen has already spread across the traverse potentially contaminating any water source within the region. Two water wells were seen within this area of the study area, one was completely abandoned while the other is still used for domestic consumption by the inhabitants of the area. Traverse 2 and Traverse 3 are shown to be less vulnerable to pollution because they showed less discontinuities and weak zones, and the clay cap is almost stable across these two traverses.

4.2. Vertical Electrical Sounding (Field Curve)

Vertical Electrical Soundings were conducted within the study area at Twenty (20) different locations and four curve types namely KQ, HA, H and QH were identified**.** The KQ and HA curve types are the most preponderant with both constituting about 90% of the curve types while H, k and QH accounts for about 10% [Figures 14-23], appearing in the APendix). The VES curves represent a subsurface condition within the study area and it was generally noticed that the resistivity values were decreasing as we probed deeper. This is suspected to be as a result of the underlying saline water present within the study area. Three to four sub-surface layers were generally delineated where a resistive top sandy layer underlies a conductive clay cap which serves as a protective layer for a preceding bitumen impregnated layer in turn overlies the saline water intruded layer.

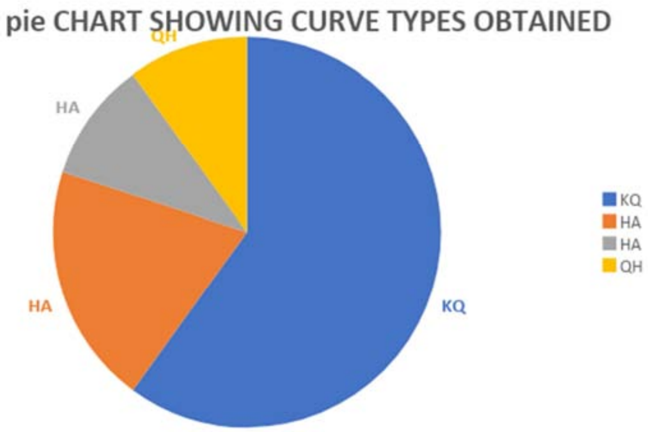

Figure 8. *Chart Showing the curves obtained from the field.*

Table 1 gives a summary of the results of the VES curves at the study area while figure 10 shows a Chart Showing the depth variation of the bitumen within the study area.

Table 1. *Summary of the VES Interpretation Results.*

VES NO	CURVE TYPE	RESISTIVITY ($\rho_1/\rho_2....\rho_n$)	THICKNESS ($h_1/h_2....h_n$)	DEPTH (m)
1	KQ	140/539/27	1.9/3.1/1.4	1.9/5/6.3
2	KQ	17/474/54/27	0.5/2.1/3.7	0.5/2.6/6.2
3	KQ	51/407/100/4.2	1.5/6.9/1.4	1.5/8.3/9.7
4	KQ	49/159/441/17	1.2/1.1/5.6	1.2/2.3/7.9
5	HA	89/46/86/1361	0.9/1.4/5	0.9/2.3/7.3
6	KQ	58/206/162/58	1.3/0.5/5.6	1.3/1.8/7.4
7	KQ	101/316/112/28	2.3/3.3/1.4	2.3/5.6/7
8	KQ	58/167/255/11	0.9/0.8/4.4	0.9/1.7/6.1
9	KQ	94/127/79/36	1.1/5/16.6	1.1/6.1/23
10	KQ	151/528/141/5.5	2.2/2.8/2.5	2.2/5/7.5
11	KQ	63/261/90/9.3	1.7/3.2/1.4	1.7/4.9/6.2
12	K	78/331/7.9	1.6/3.5	1.6/5.1
13	QH	83/12/38	0.8/27.5	0.8/28.3
14	QH	214/12/20	0.6/15	0.6/16
15	HA	125/31/11/24	1.8/1.9/16.4	1.8/3.7/20.1
16	KQ	617/198/7.5/117	2.5/1.3/13.1	2.5/3.8/16.9
17	H	48/14/21	1/20	0.8/21.2
18	H	90/13/16	1.5/20	0.7/2.0
19	HA	97/33/14/20	2/4/20	2.2/20.1
20	HA	540/206/19/34	2/4/32.5	1.0/1.8/19.7

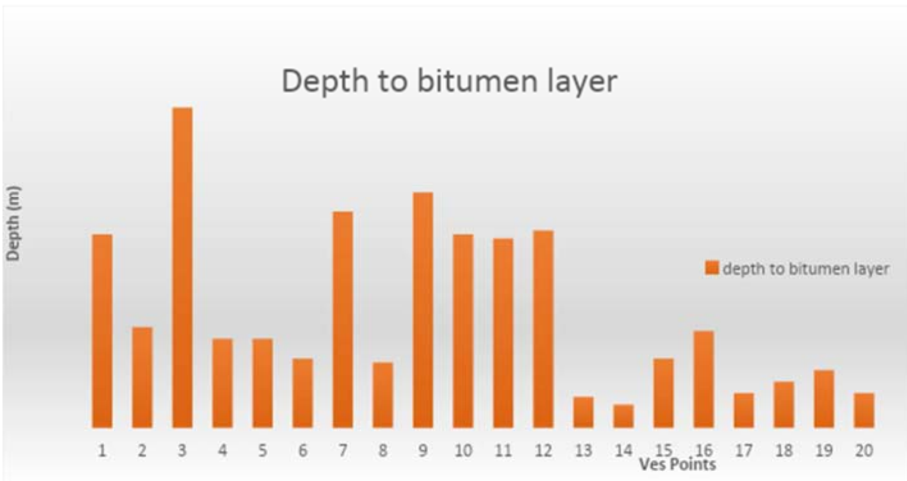

Figure 9. *Chart Showing the depth to bitumen variation in the study area.*

From the chart, it can be deduced that the bitumen within the study area has its deepest occurrence at VES locations 1, 3, 7, 9, 10, 11 and 12 where it occurs at an average depth of 6m while it occurs at a moderate depth at stations 2, 4, 5, 6, 8, 15 and 16 at an average depth of 3.4m while at VES locations 13, 14, 17, 19 and 20, it occurs at a really shallow depth of about 1.5m. It can be suggested from the above deductions that the bitumen occurrence within the study area can be generally considered to be of shallow depth of occurrence [17], coupled with some weak zones that can aid the migration of bitumen into the wells. Geologically, the subsurface conditions within the study area does not favour development of viable groundwater.

4.3. Geo-electric Sequence

In order to produce a subsurface geological model across the set traverses, the VES interpretation results (Table 1) were used to prepare 2D geo-electric section. These sections give respective layer resistivity values and thickness. Figures 10-13 shows the geo-electric section, the section identifies three/four geologic subsurface layers comprising the top sandy layer, clay-cap, the bitumen impregnated zone and the saline water intruded layer**.** The geoelectric characteristics along the setup traverses are illustrated in the following:

4.4. Geoelectric Characteristics Along Traverse 1

Traverse 1 was set up just few meters away from river Agbabu, and showed four geoelectric layers (Figure 10). The first layer which is the top soil (interpreted to be sandy) has resistivity ranging between from 59Ωm to 160 Ωm occurs uniformly across the traverse at a depth between 1.1m to 1.5m. The second layer (green color) has resistivity varying from 123 Ωm to 255Ωm with layer thickness between 0.8m to 6.9m occurs at a depth range between 5m to 7.3m. This layer is interpreted to be clay. It has a thickness of about 5m between VES1 and VES 2 but as it approaches VES 3, it becomes relatively thin to about 1.8m. This is followed by a third layer interpreted to be the bituminous zone with resistivity ranged between 174 Ωm to 247 Ωm along the traverse with a thickness of 2m to 10m. At VES 1 and VES 3, it has a thickness of about 3m however at VES 2 and VES 4 its thickness was increased to about 8m. VES 3and VES4 can be seen to have thin clay protective cap, this can be considered to the most vulnerable zones along the traverse. This is further underlain by saline water intruded layer with resistivity ranging from 38 Ωm to 174 Ωm.

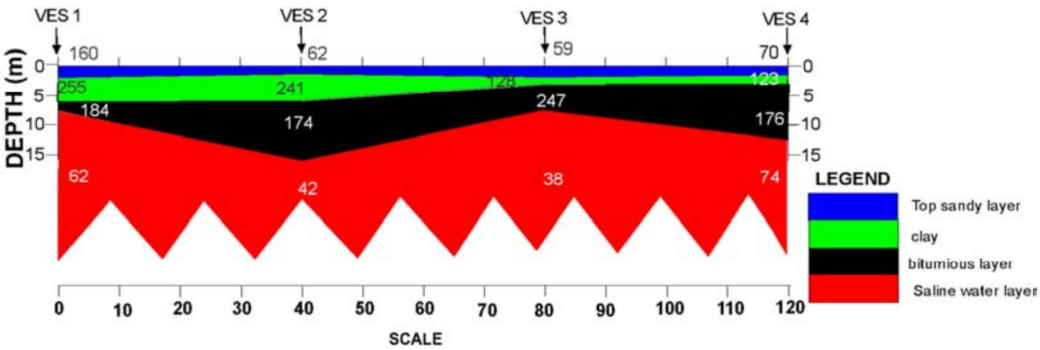

Figure 10. *Geo-Electric Section along the traverse 1.*

4.5. Geoelectric Characteristics Along Traverse 2

Along this traverse (Figure 11) the result shows the topsoil interpreted to be sand is uniformly spread across the traverse with resistivities varying from 72Ωm to 190Ωm, the topsoil thickness varies from 0.7m to 1.1m underlain by a clay layer with resistivity varying from 51Ωm to 380Ωm having a thickness 2.3m to 7.9m which serves as a protective cap for the third layer interpreted as bitumen (93 Ωm to 120 Ωm) layer is relatively thin along the traverse with a thickness of 2.3m to 10.7m underlain by the saline water with resistivity ranging from 27 Ωm to 467Ωm. The geo electric section along traverse shows VES 6 and VES 8 are the active zones across the traverse, i.e. prone to contamination.

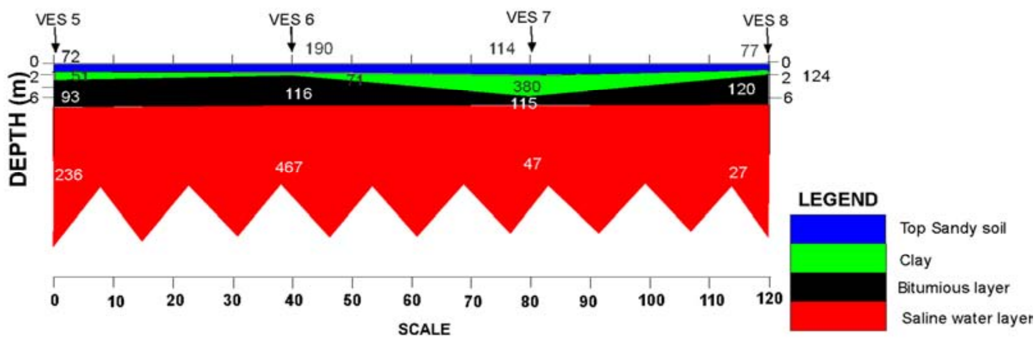

Figure 11. *Geo-Electric Section along the traverse 2.*

4.6. Geoelectric Characteristics Along Traverse 3

This traverse (Figure 12) was set up just in front of the community health center within Agbagbu community. The geo-electric section in this Traverse shows the topsoil interpreted to be sandy is uniformly spread across the traverse with resistivity ranging from 75Ωm to 167 Ωm, the topsoil has thickness varies from 0.8 m to 1.8 m underlain by a thick clay layer with resistivity varying from 120 Ωm to 136Ωm having a thickness 1.1m to 3.7m. This is followed by the bitumen impregnated layer which is relatively thick along the traverse with a resistivity of 95 Ωm to 174 Ωm with thickness ranging from 5.0m to 14.1m underlain by sandy clay with resistivity ranging from 16 Ωm to 95 Ωm. This result shows hand dug wells should not be dug within this area.

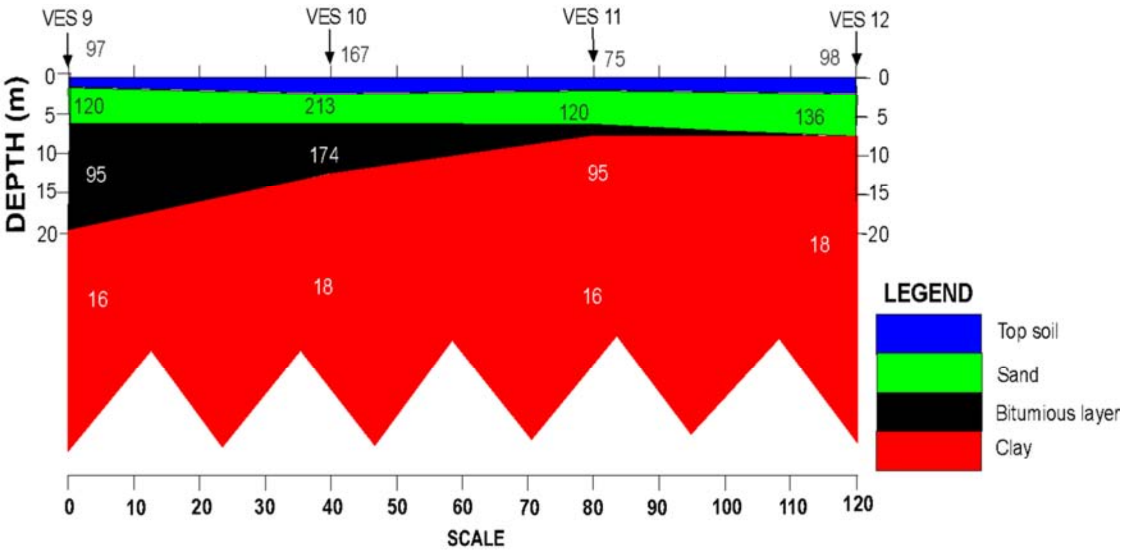

Figure 12. *Geo-Electric Section along the traverse 3.*

4.7. Geoelectric Characteristics Along Traverse 4

This traverse (Figure 13) was setup along mile 12 where mining had occurred in the past, this makes the region the most interesting part of the study area. The topsoil varies in resistivity from 48 Ωm to 540Ωm, the topsoil thickness varies from 0.7m to 2.2m underlain by a sand layer with resistivity of 33Ωm having a thickness 0.8m. This is followed by the bitumen impregnated layer which is relatively ranging from 13 Ωm to 19 Ωm along the traverse which is of relatively high thickness. This region within the study has the highest quantity of suspected bitumen for commercial purpose and it occurs at a very shallow depth meaning every hand dug wells within this area is most prone to pollution. This completely agrees with the evidence of an existing abandon well within this area just few meters to traverse 4.

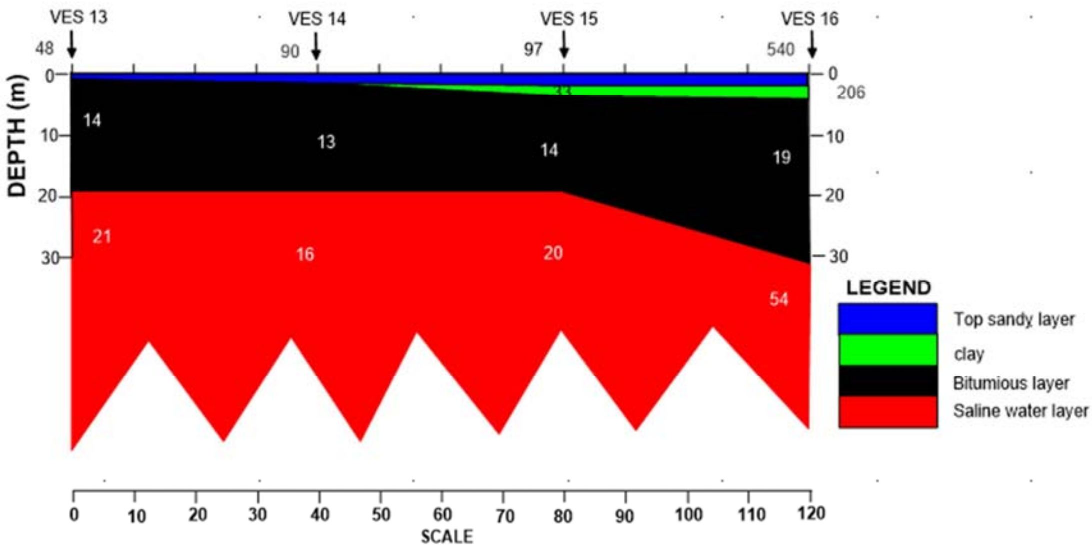

Figure 13. *Geo-Electric Section along the traverse 4.*

5. Conclusion

An integrated electrical resistivity survey involving VES and 2D resistivity imaging has been carried out over Agbabu to map the bitumen saturated zones and its geologic implication over the study area. The results of both VES and 2D imaging revealed that the subsurface geological structures hosting bitumen across the study area occurs at shallow depth. The techniques also revealed geologic discontinuities (weak zones) across the study area which could easily serve as pathways for migration of bitumen to available groundwater source, and hence reducing the groundwater quality in the area, and making it unfit for domestic and other uses. Geologically, the subsurface within the study area does not favour development of viable groundwater.

Appendix

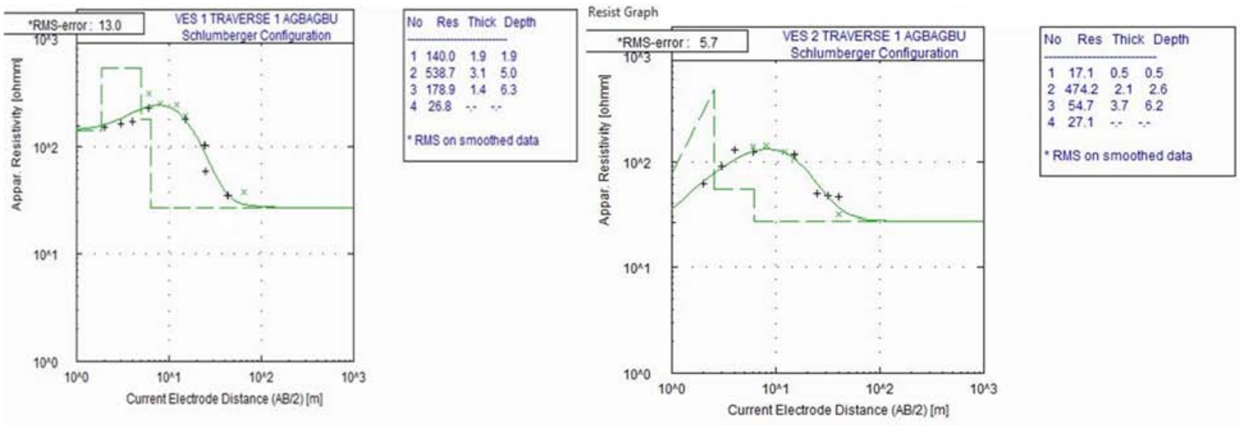

Figure 14. *Curve type obtained at VES 1 and VES 2 along traverse 1.*

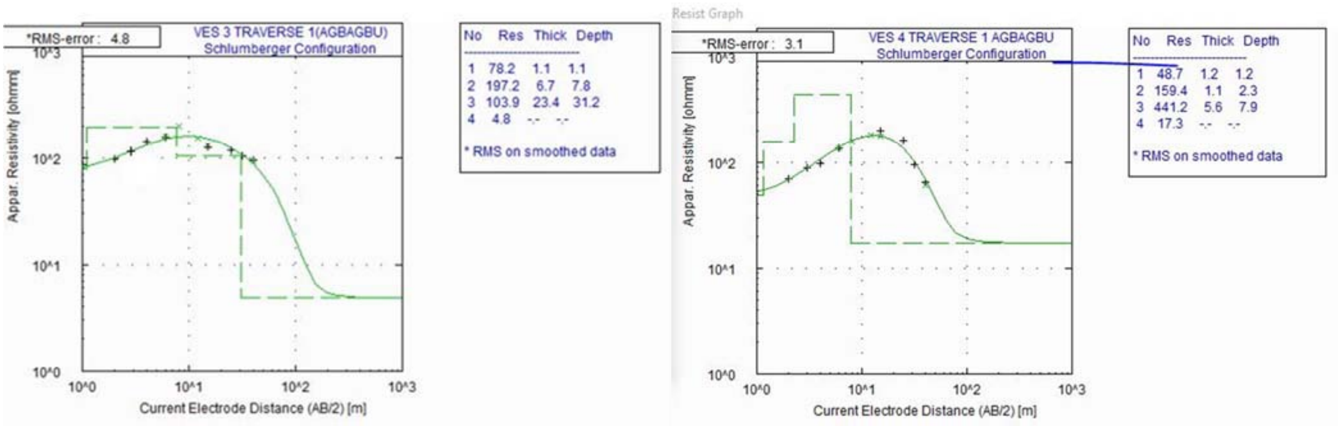

Figure 15. *Curve type obtained at VES 3 and VES 4 along traverse 1.*

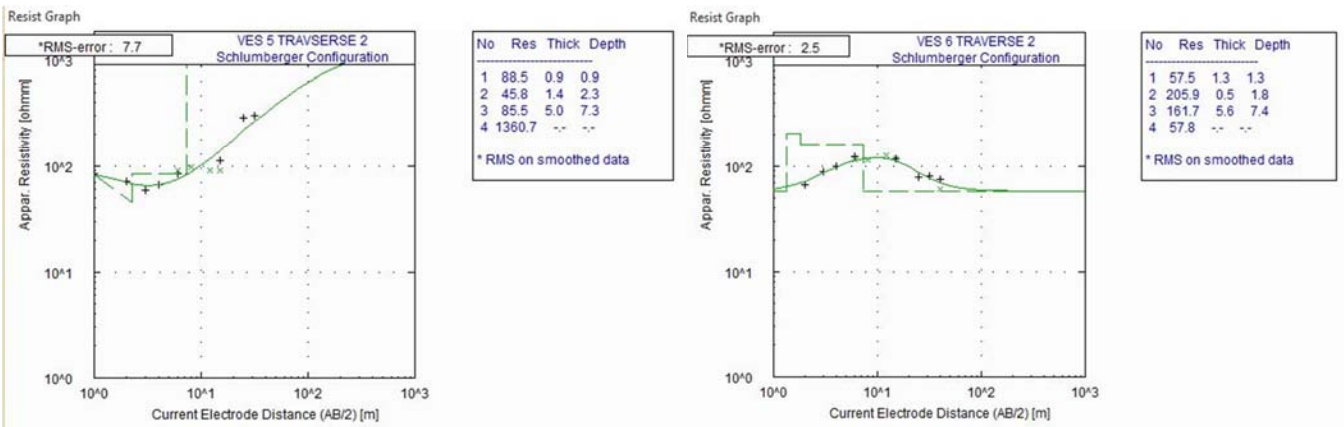

Figure 16. *Curve type obtained at VES 5 and VES 6 along traverse 2.*

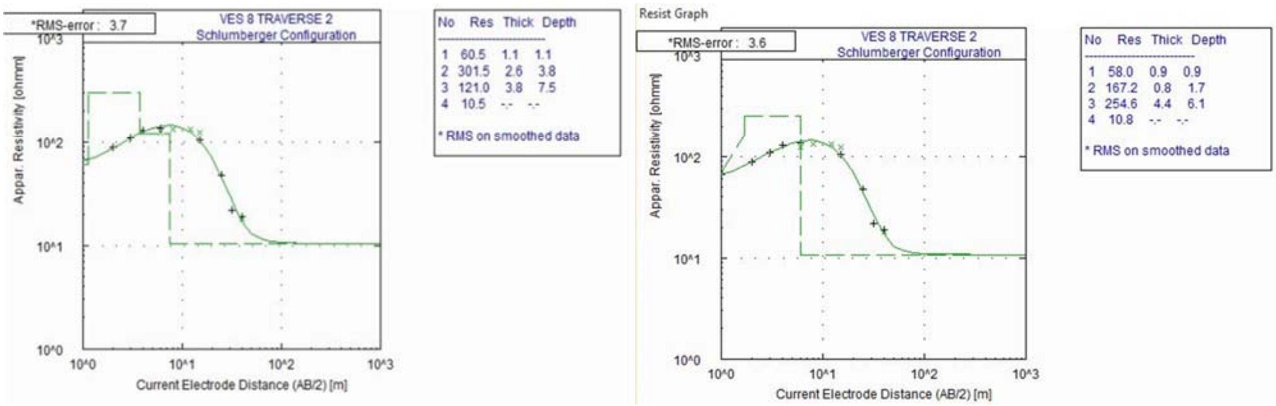

Figure 17. *Curve type obtained at VES 7 and VES 8 along traverse 2.*

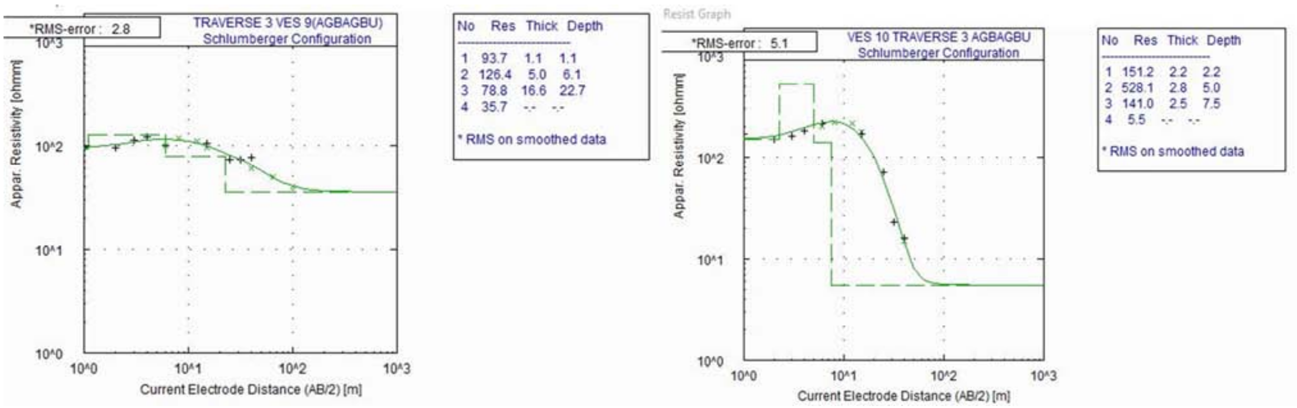

Figure 18. *Curve type obtained at VES 9 and VES 10 along traverse 3.*

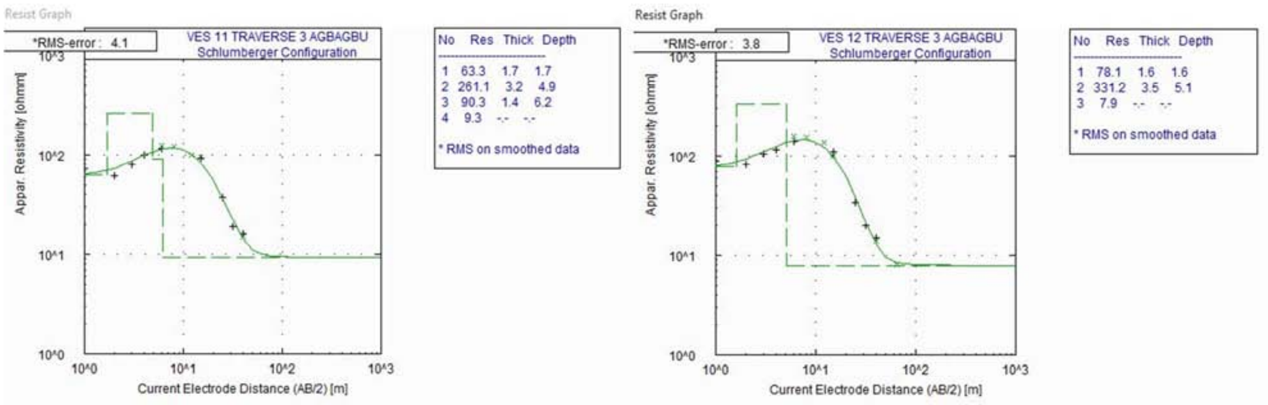

Figure 19. *Curve type obtained at VES 11 and VES 12 along traverse 3.*

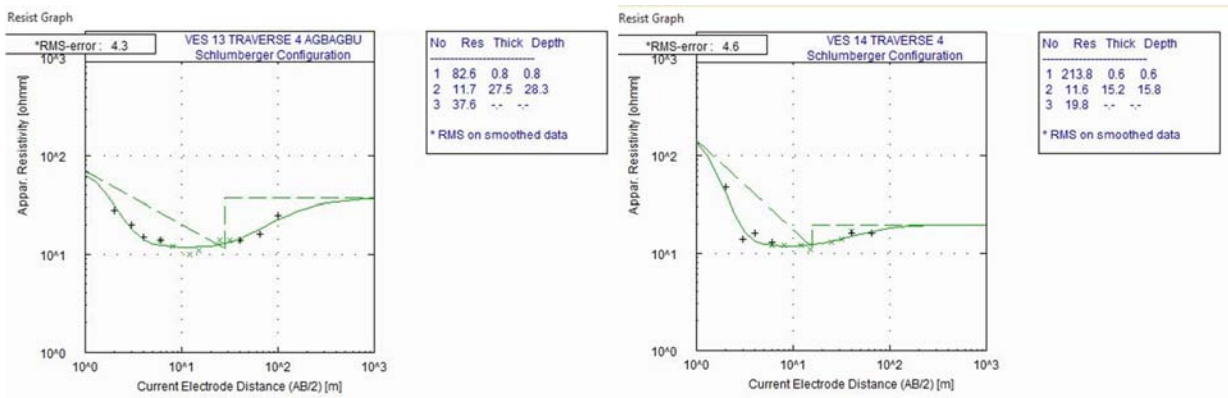

Figure 20. *Curve type obtained at VES 13 and VES 14 along traverse 4.*

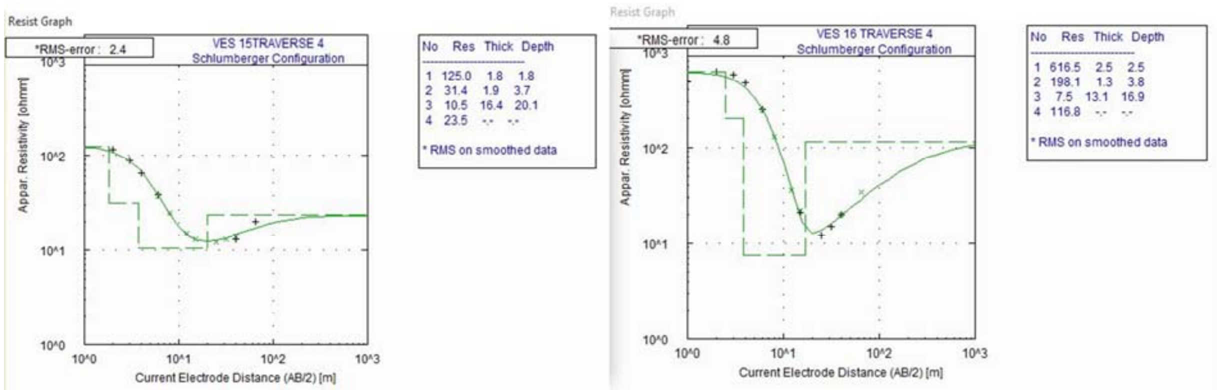

Figure 21. *Curve type obtained at VES 15 and VES 16 along traverse 4.*

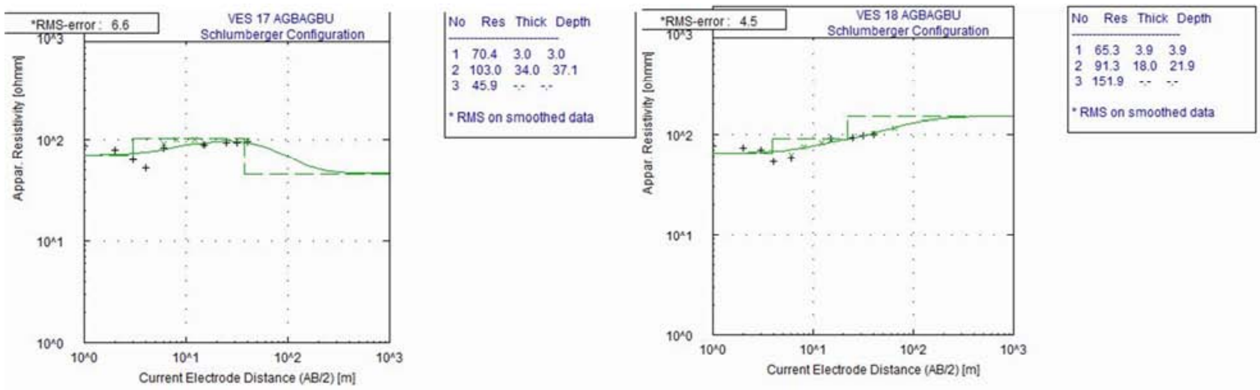

Figure 22. *Curve type obtained at VES 17 and VES 18.*

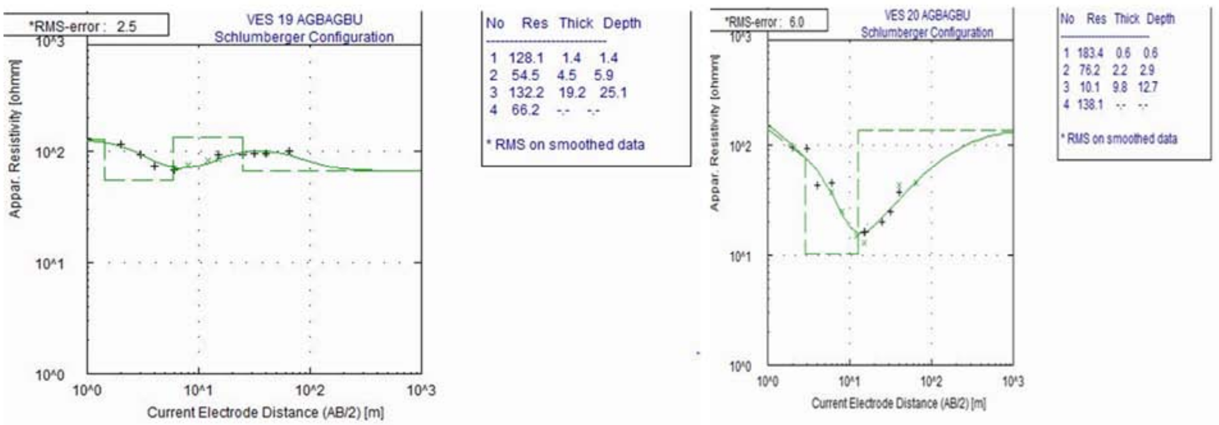

Figure 23. *Curve type obtained at VES 19 and VES 20.*

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