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Geoelectrical Subsurface Imaging for the Mapping of Leachate and Contaminant Plume around Septic Tanks Within the Staff Quarters in University of Benin, Benin City, Nigeria

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Authors' contributions

This work was carried out in collaboration between all authors. Author VBO designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors YSO and JOA managed the analyses of the study. Author OMA managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

2-Dimensional imaging was used to investigate the presence of leachate and contaminant plume around septic tank within the Staff Quarters in University of Benin, Benin City, Nigeria. This conventional 2-D electrical resistivity survey method was carried out by engaging the Wenner Alpha array configuration using PASI 16 GL Terrameter. Four traverses with a spread of 160 m each were covered around the septic system using DIPRO and RES2D Inversion software for interpretation so as to delineate the plume and probable trend of migration. To test for the presence of heavy metals, Physiochemical analyses were done on the water collected through the borehole that was very close to the septic system. The interpretation of the inverted 2-D electrical resistivity data revealed five subsurface layer: topsoil, clayey sand and sandy layers, clayey sand and sand zones constitute the major aquifer units in the study area. The 2 D Inversion delineated contamination plumes as low resistivity zones. As revealed by the inversion model, there was a strong evidence of vertical and

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horizontal plume migration westwards in third layer of traverse 1 and 2. Also, traverse 3 displayed a low resistivity anomaly ranging from 60 Ωm to 109 Ωm (15m below the surface) in third layer. It was only traverse 4 that showed a strong evidence of horizontal plume in top soil with a low resistivity <100 Ωm at a depth of 0 to 4 m with a lateral distance of 10 to 160 m. Also, there was strong evidence of topsoil contamination in traverses 2 and 4 (resistivity < 100 Ωm) and this constitutes the contaminated shallow water zone. This low resistivity zone, occasioned by infiltration of leachate from the septic tank. For physiochemical analysis on heavy metals, and with exception of pH, other parameters analyzed compared favourably with WHO, and ASTMD standard for drinking quality water. The pH values of 5.84 obtained from water samples were below 6.5-8.5 as recommended by WHO and this shows that the site was acidic, and a clear evidence of physical pollution exist. However, sodium carbonate should be used as a purifier for acidic groundwater also, future borehole should be constructed beyond far away from the pollution source (septic system).

Keywords: Wenner-alpha configuration; septic system; groundwater investigation; leachate plume; acidic.

1. INTRODUCTION

Life can hardly be sustained without water and good water ensures healthy living. Groundwater is of major importance to civilization since it is the largest reserve of portable water in regions where humans live. Due to urbanization and industrialization the commonest source of water, surface water and rain water have been polluted with waste products from industries and contaminations from individuals and households (from septic tank). The only safe haven is the groundwater and this has been gradually polluted over the years due to many sources of contamination [1]. Pollution can either be in the form of solid or in the liquid or gaseous forms but the most common form is liquid that can easily penetrate down into the aquifer system. Once underground water is contaminated, it is very difficult, time consuming and expensive to clean up. The time and cost of clean-up depends on the extent of contamination even a small amount of contamination can be costly to clean up [2]. The health and well-being of the population depends on abundance and adequate supply of these natural resources [2]. There are various ways or sources of underground water contamination such as use of fertilizer in farming, waste constituents, radioactive waste disposal, salt water intrusion, acid mine drainage, injection wells, leaks from underground storage tanks, leak from septic tanks and this render it unfit for human consumption. [3]. Ground water contamination occurs when ground water comes in contact with naturally occurring contaminants or with contaminants introduced into the environment by human activities. Contaminants associated with human activity most commonly include bacteria, petroleum products, natural and synthetic organic compounds, fertilizer, pesticides, herbicides, and metals [4].

Evidence has shown that geophysical methods are the most reliable and the most accurate means of all surveying method of subsurface structural investigations and rock variation. Electrical resistivity method in geophysical exploration for groundwater in a sedimentary environment has proven reliable [5]. Also, water is an important and essential element for all living creature and it is used for various purposes by man but unfortunately, quality and potable water is not available to many people because most water supply sources are contaminated to the point where odour and taste make it unacceptable for drinking [6]. Research has let us known that water covers about three quarter of the total earth crust and it is the most known and most abundant of all known chemical substances, which occur naturally on the surface of the earth. Therefore, water is a prime solvent and its properties determine many natural phenomena [7]. Lack of adequate supply of portable water is a critical challenge in developing countries such as Nigeria. Portable water which can also called drinking water in reference to its use, is defined as water which is fit for consumption by human and other animals [8]. Groundwater is exploited by digging wells and pumping the water to the surface. However, deep wells and high speed pumps now extract groundwater more rapidly than natural process.

That is why a combined geophysical and physiochemical/microbial approach is needed to study the residential parts (staff quarters) of University of Benin with the aim to investigate the impact of septic-tank effluent on groundwater quality.

1.1 The Study Area

The study area is a full residential area with a population of more than a five hundred staff and their families. This study was conducted in University of Benin, Benin City and the area is basically a sedimentary area located in south south geopolitical zone of Nigeria. Benin City is the capital of Edo State, bounded by latitudes 06º06ʹ N, 06º30ʹ N and longitudes 005º30ʹ E, 005º45ʹ E and an area of about 500 square Kilometers. Fig. 1 shows the aerial view of the study area showing the location of the septic tanks besides each building and one of the collapsed septic tank is showing in Fig. 2. The sampling site was identified with the Latitudes of 06º24.394ʹ, longitude of 005º36.703ʹ and elevation of 385 ft.

1.2 Why Investigating the Study Area

The study area has been selected for investigation due to infiltration of the contaminants plume that leak from underground septic system to the groundwater. This was observed from samples of water obtained from boreholes within the study area. Thus, this contaminants can be a major threat to the quality of groundwater thereby resulting to various health problems to man. Hence, these problems informed the application of geoelectrical and physiochemical investigations in the study area

2. THEORY

In the resistivity method, artificially-generated electric currents are introduced into the ground by means of two electrodes called current electrodes (A&B) and the resulting potential differences are measured at the surface through pair of electrodes called potential electrodes (C&D) see Fig. 3 [9]. The fundamental physical law used in resistivity surveys is Ohm's Law that governs the flow of current in the ground. The equation for Ohm's Law in vector form for current flow in a continuous medium is given from equations 1 to 7.

Ohm's Law states that the rate of current flow through a conductor is proportional to the potential difference causing that flow, and is inversely proportional to the resistance of the medium [10].

In symbols, it states that

$$\boldsymbol{I} \propto \boldsymbol{V} \quad (1)$$

Where $\boldsymbol{I}$ is current and $\boldsymbol{V}$ is the potential difference

Removing proportionality sign,

$$\frac{\boldsymbol{V}}{\boldsymbol{I}} = \boldsymbol{constant} \quad (2)$$

The value of this constant is a measure of the opposition (resistance) the conductor offers to the flow of current,

$$\frac{\boldsymbol{V}}{\boldsymbol{I}} = \boldsymbol{R} \quad (3)$$

Where the unit of $\boldsymbol{I}$ is in amperes and $\boldsymbol{V}$ is in volts, $\boldsymbol{R}$ is in ohms (Ω).

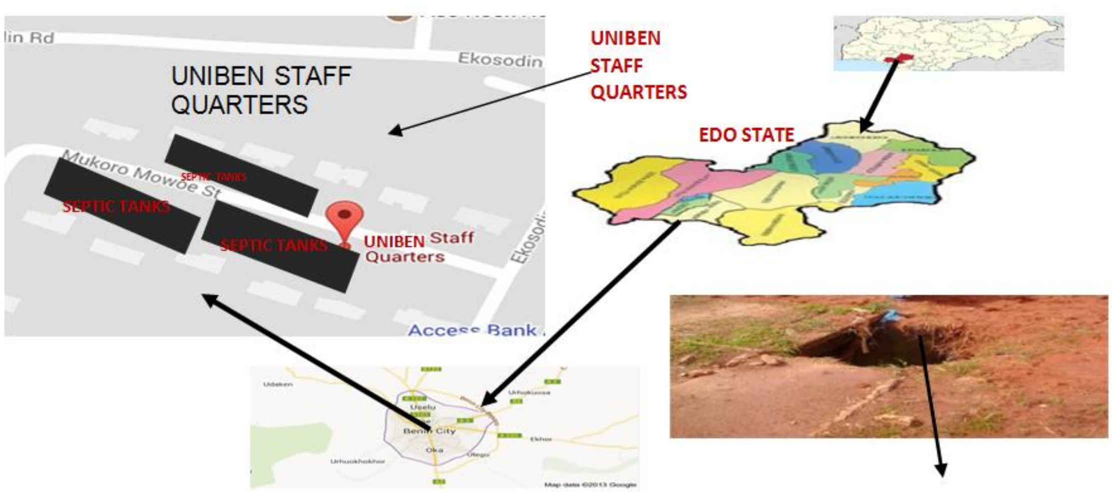
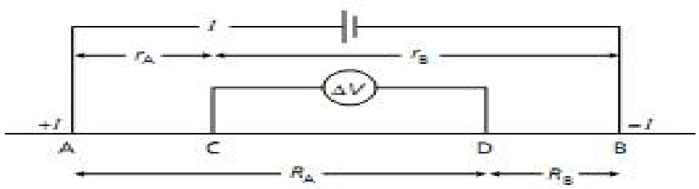


Fig. 1. Aerial view of the study area showing the location of the septic tanks besides the quarters (Google satellite)

Fig. 2. One of the collapsed septic system in the study area



Where:
- ***A*** and ***B*** – current electrodes
- ***C*** and ***D*** – potential electrodes
- ***I*** – current
- ***ΔV*** – potential differences

Fig. 3. The generalized form of the electrode configuration used in resistivity acquisition [9]

The Fig. 3 shows the four electrode spread consisting of two current electrodes and two potential electrodes.

The Resistance (R) is proportional to length (L) divided by area (A) i.e

$$R \; \alpha \; \frac{L}{A} \tag{4}$$

Removing proportionality sign,

$$R = \frac{\rho L}{A} \tag{5}$$

Where: **ρ** is the resistivity and the unit is in ohm-meter (Ωm)
L is the length of wire in meter
A is the cross sectional area of the wire
R is the resistance in ohm

The conductivity, **σ,** is defined as

$$\sigma = \frac{1}{\rho} \tag{6}$$

Unit of conductivity is siemens / meter $= \frac{s}{m}$

Using the above relationship,

$$R = \frac{\Delta V}{I} = \frac{\rho \, L}{A} = \delta A \, \frac{dV}{dl} \tag{7}$$

$$\rho = \frac{A \, \Delta V}{L} \tag{8}$$

The equation 8 above is the equation for finding the resistivity of a homogenous isotropic medium, provided the geometry is simple such as cube, cylinder, and parallel pipe among others. Equations 9 and 10 are the electric field potential that we measured in field.

$$j = \frac{I}{A} = \delta \frac{dv}{dt} \tag{9}$$

Where j is current density that is in vector equivalent, ohms law defined as:

$$j = \frac{E}{\rho} = \delta\epsilon \tag{10}$$

Where ϵ is the electric field [9]

In order to derive a ground apparent resistivity (ρ_a) in terms of geometric factor (G_r), from Fig. (2), the current electrode A and B act as source and sink respectively. At the detection electrode C the potential due to the source A is $\frac{+\rho \, L}{2\pi r_{AC}}$ while the potential due to the sink at C is $\frac{-\rho \, L}{2\pi r_{CB}}$ is giving the combined potential as stated in equations 11 to 13.

$$V_C = \frac{\rho \, L}{2\pi}\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) \tag{11}$$

In the same way the potential at D is:

$$V_D = \frac{\rho \, L}{2\pi}\left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right) \tag{12}$$

Thus the potential difference measured between C and D is

$$V_{CD} = \frac{\rho \, L}{2\pi} \left[\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) -- \left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right)\right] \tag{13}$$

The ground apparent resistivity (ρ_a) can be expanded as shown in equations 14 and 15 below

$$\rho_a = \frac{\Delta V}{1}\left[\frac{1}{\left(\frac{1}{r_{AC}} - \frac{1}{r_{CB}}\right) -- \left(\frac{1}{r_{AD}} - \frac{1}{r_{DB}}\right)}\right] \tag{14}$$

$$\rho_a = \frac{\Delta V}{1} \, G_{(r)} \tag{15}$$

Where $\Delta V = V_{CD}$ and $G_{(r)}$ is a geometric factor and is dependent upon the spatial arrangement of electrodes for specific arrays.

3. METHODOLOGY

2-D Resistivity methods were used in this research using the PASI resistivity meter in the geophysical measurement. The interpretations of the data acquired were done by using the DIPRO and RES2D Inversion Software, these software were used in order to ascertain the areas of anomalies (concentrations). The 2-D data points were separated by 5 m intervals and they were conducted up to 160 m in the traverse beside the septic systems.

Water samples were collected using plastic bottles and the bottles were already rinsed with water to be sampled before sample collection. The sample locations was geo-referenced with the Latitudes of 06º24.394', longitude of 005º36.703' and elevation of 385 ft. The collected samples was stored in a cool environment before taking them to the laboratory and they were collected from borehole that is close to each septic tanks.

The pH, salinity, temperature, Total Dissolved Solids (TDS) and conductivity were determined on the spots where samples were taken with the pH meter and conductivity meter.

4. RESULTS, INTERPRETATION AND DISCUSSION

Figs. 4 to 7 shows the results of the 2-D electrical resistivity inverse models and they are displayed as cross sections of the true resistivity distribution of the subsurface with depth along each of the seven profiles. The figures also show the similarities of the maps of the contoured pseudo sections obtained by the two different software (RES2D INVERSION software and DIPROfWIN software) along traverse 1 to 7. These two software were used so as to ascertain the area of anomalies in the study areas.

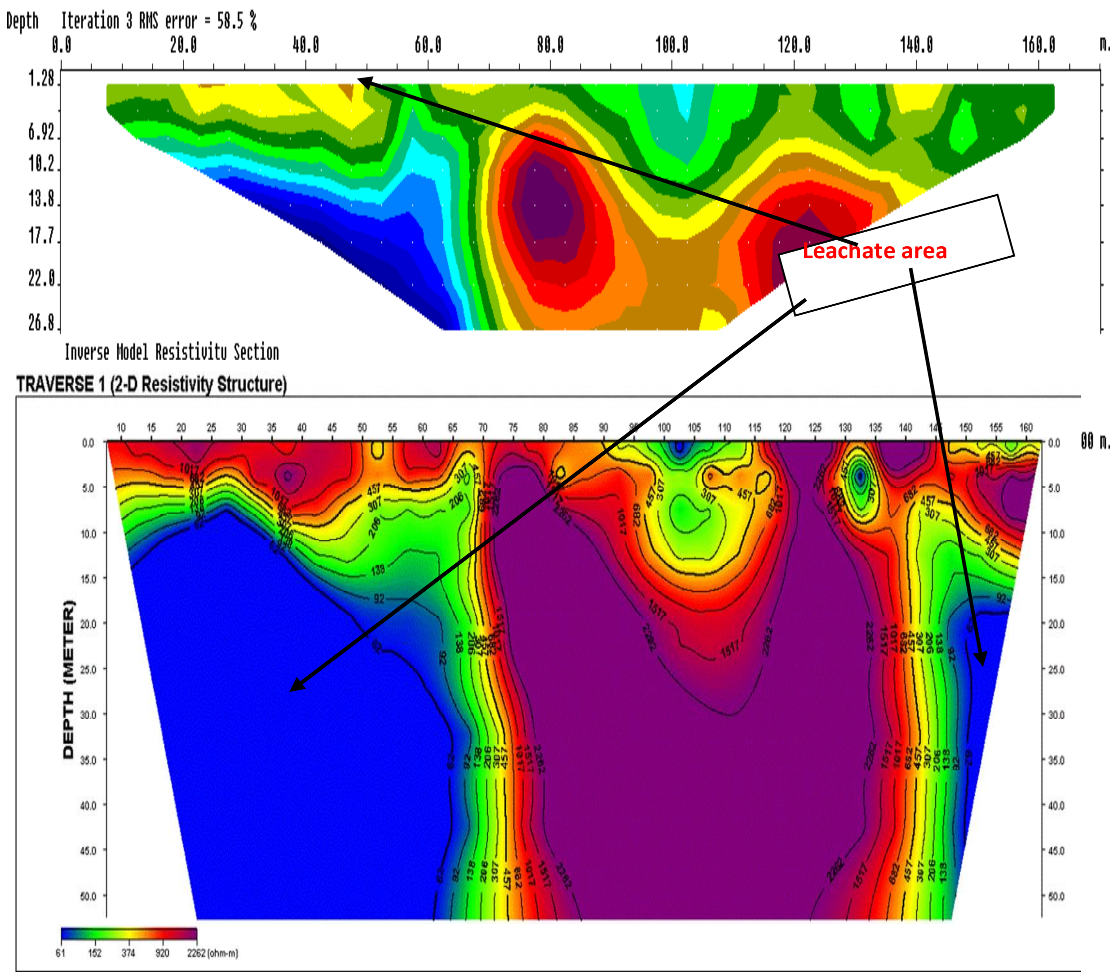


Fig. 4. Similarities of RES2-D maps and DIPRO maps of electrical resistivity imaging along Tr. 1

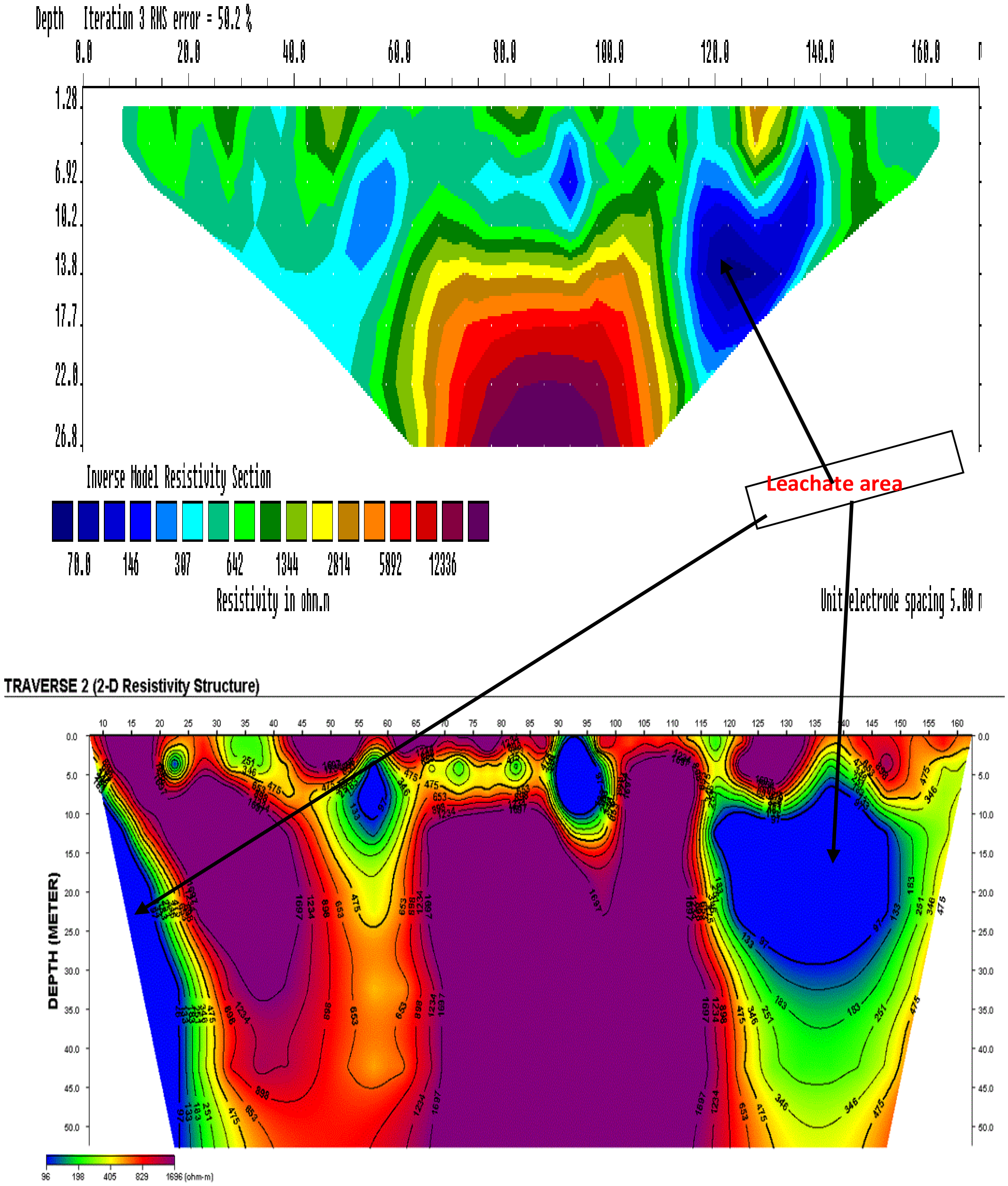


Fig. 5. Similarities of RES2-D maps and DIPRO maps of electrical resistivity imaging along Tr. 2

Figs. 4 to 7 below represent the 2-D resistivity section along traverses one to four conducted at University of Benin Staff Quarters with a maximum spread of 160m using the Wenner Alpha array configuration and a maximum depth of 50m was investigated. There was a strong evidence of vertical and horizontal plume migration westwards in third layer of traverse one with the low resistivity values ranging between 61 to 105 Ωm at depth of 10 m beneath the subsurface. Also, traverse 3 displayed a low resistivity anomaly in third layer. This anomaly occurred at a depth of 15m below the surface at resistivity from 60 to 109 Ωm In traverse 2, the low resistivity value ranging between 96 and 110 Ωm were indicated at lateral distance between 55 to 60 m, 117 to147 m and 23 m westwards at a depth ranging between 5 to 13 m, 0 to 10 m and 5 to 30 m respectively. All these low resistivity values occurred as a result of leachate from the septic tank. It was only traverse 4 that showed a strong evidence of horizontal plume in top soil with a low resistivity ranging between 94 and 110 Ωm at a depth of 0 to 4 m with a lateral distance of 10 to 160 m.

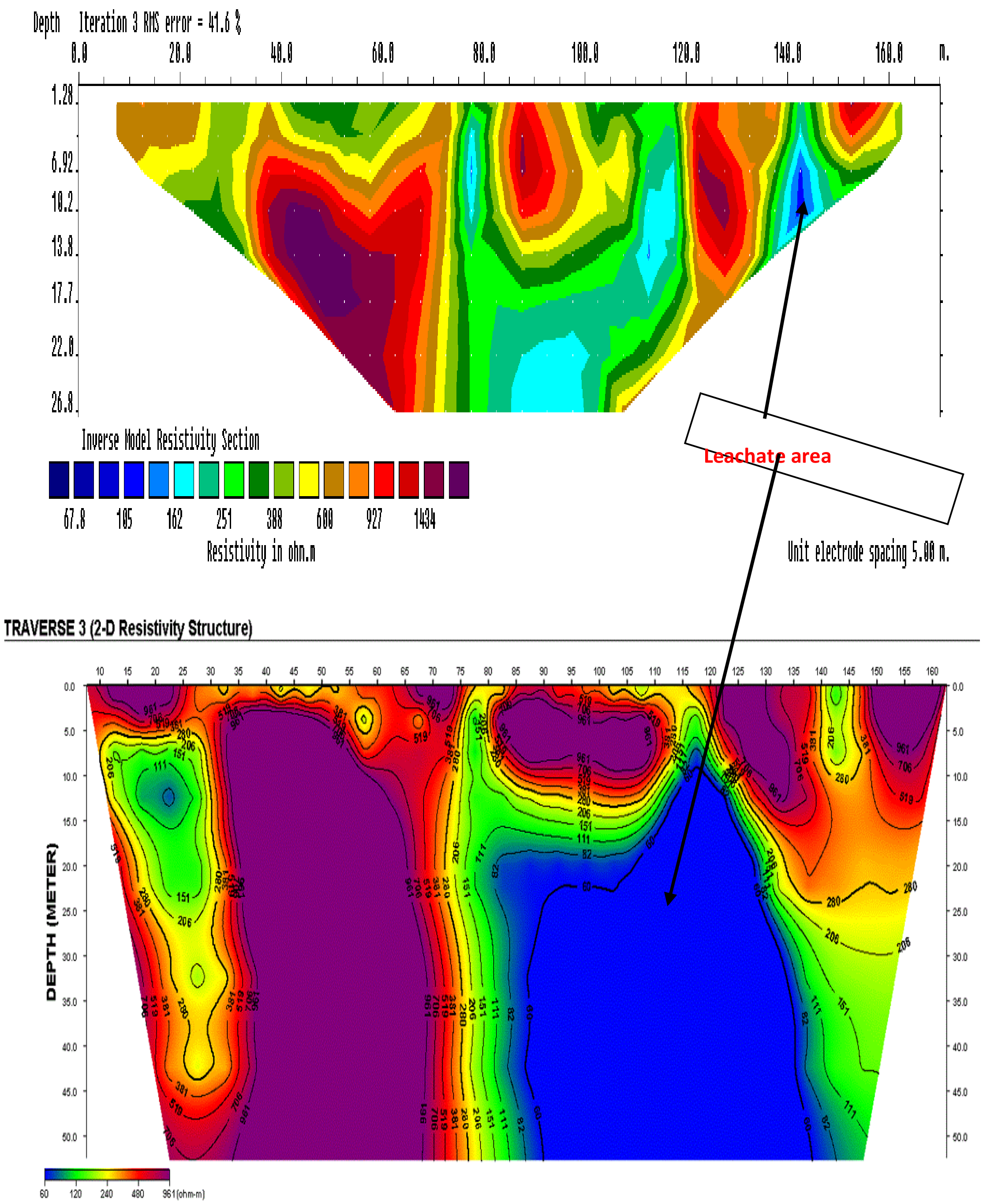


Fig. 6. Similarities of RES2-D maps and DIPRO maps of electrical resistivity imaging along Tr. 3

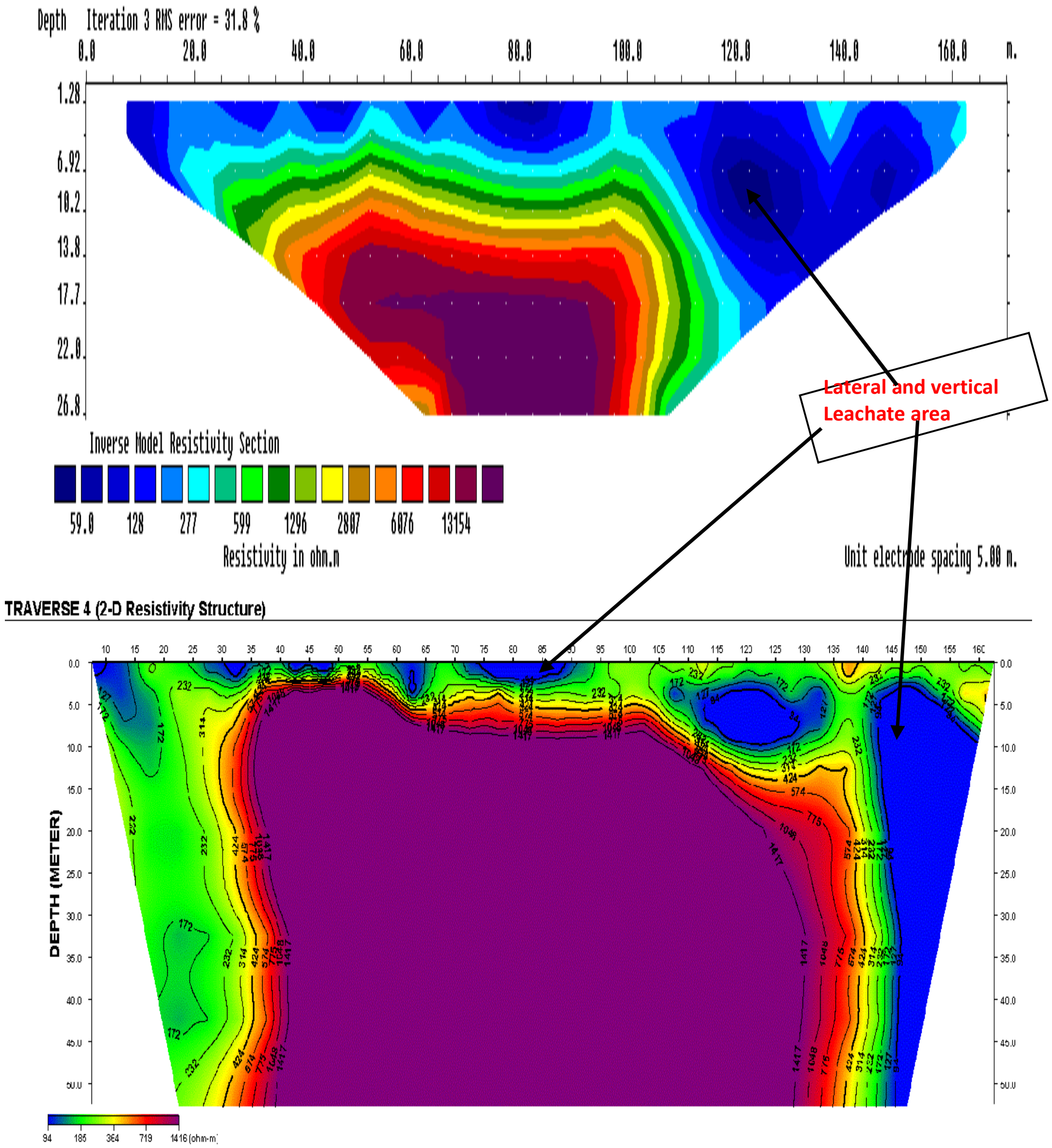


Fig. 7. Similarities of RES2-D maps and DIPRO maps of electrical resistivity imaging along Tr. 4

As revealed by the inversion model, there was evidence of topsoil contamination in all traverses apart from traverse 3, since the average value of all low resistivity is above 100 Ωm, however, there is evidence of ground water contamination in the study area. The 2-D pseudo section and resistivity structure obtained from the data acquired in all the traverses also show the low resistive layers indicated by the bluish coloration of resistivity value that is less than 100 Ωm which indicates contaminated or leachate zone (see the arrow). Just beneath the topsoil layer is a highly resistive layer indicated by the greenish color, which may possibly be a combination of alluvium and sand deposited over the years, since there is a nearby river just behind the campus compound.

The progress of underground water contamination can be monitored through physicochemical parameters such as pH, electrical conductivity, alkalinity and total dissolved solids (TDS) and the results are shown in Table 1 which also has a column of units of parameters and standard method for drinking quality water.

The pH value for Staff quarters is 5.84 and it's a little bit lower than the standard range of pH value for drinking water (6.5-8.5) see Table 1. This indicates that the majority of the water covered in this study were acidic for human consumption and it could also result in the metallic taste that is frequently associated with some groundwater. The heavy metals analyzed in this study were lead, chromium, copper, zinc, iron, manganese, cadmium and nickel. From Table 1, it can be seen that the concentration of cadmium likewise chromium was undetectable in the groundwater samples obtained from the site. The concentration values of zinc, iron and copper are very minimal and much more less than the standard value, also the values of lead and Manganese were very infinitesimal i.e less than 0.005 mg/l. Therefore, they have no effect on the groundwater of the location. Hardness in water is a product of dissolved calcium and magnesium ions and it can be observed that the concentrations of calcium among the sites were greater than that magnesium ion. This indicated that the water samples from both sites were soft since these values were within the standard range of 0-96 mg/l.

A pure water is a bad conductor of electricity. As shown in table 1, the electrical conductivity values at Staff quarters was 40µs/cm which is far below the stipulated value of 250µs/cm by WHO (2008) [11]. According to Hem, 1985, the electrical conductivity of underground water is directly related to total dissolved solids (TDS) and this is based on the assumption that the TDS in the water consists mainly of ionic constituents that conduct electricity. However, in this study, the average values of total dissolved solids at Staff quarters was 20mg/l which could be attributed to the contamination of the water samples from septic tank, which have the potential of increasing the ionic content of the groundwater. The concentration of alkalinity at the site was 18.3 mg/l. However, from Table 1, the alkalinity values and other parameters analyzed compared favorably with WHO, APHA and ASTMD standard for drinking quality water [12,13,11].

Table 1. Result of geochemcal analysis

S /N	Test	Staff quarters	Unit	Water quality standards
				Standard resistivity values
1	Ph	5.84		WHO 6.5-8.5
2	EC	40	µs/cm	WHO 250
3	TDS	20	mg/l	ASTMD 500
4	CALCIUM	4.48	mg/l	ASTMD 96B
5	MAGNESIUM	1.92	mg/l	ASTMD1126-96
6	SULPHATE	0.33	mg/l	APHA 427C
7	NITRATE	1.45	mg/l	ASTMD 3.0
8	PHOSPHATE	0.48	mg/l	ASTMD 50
9	ALKALINITY	18.30	mg/l	ASTMD 92
10	CHLORIDE	11.60	mg/l	API-RP-45
11	SODIUM	8.00	mg/l	ASTMD 2791-93
12	POTASSIUM	10.40	mg/l	ASTMD 2791-93
13	LEAD	<0.005	mg/l	ASTMD 3559-96
14	CHROMIUM	0.01	mg/l	ASTMD 1687
15	COPPER	0.02	mg/l	ASTMD 1688
16	ZINC	0.04	mg/l	ASTMD 1691-95
17	IRON	0.07	mg/l	ASTMD 1068
18	MANGANESE	<0.005	mg/l	ASTMD 858
19	CADMIUM	ND	mg/l	ASTMD 3557-95
20	NICKEL	ND	mg/l	ASTMD 1886
21	DO	8.40	mg/l	ASTMD 888-92
22	BOD	1.8	mg/l	ASTMD 507
23	COD	2.12	mg/l	ASTMD 152-95
24	TSS	<0.001	mg/l	ASTMD 507-10

5. CONCLUSION

In conclusion, as revealed by the inversion model, there was strong evidence of topsoil contamination in traverses 1, 2 and 4 and this constitutes the contaminated shallow water zone. This low resistivity zone, occasioned by infiltration of leachate from the septic tank.

In this study, low pH values of 5.62-5.84 were obtained from water samples which were below 6.5-8.5 as recommended by WHO and this shows a clear evidence of physical pollution. However, sodium carbonate should be used as a purifier for acidic groundwater and again, future borehole should be constructed beyond far away from the pollution source (septic system).

It is recommended that for further studies other geophysical techniques such as 3-D imaging should be employed in investigating groundwater contamination. This would enable a better resolution or delineation of the extent of the spread of the leachate plume in 3D view.

It is suggested that boreholes should be cited far away from septic tank so as to reduce the influence of contamination leakage from septic system to underground water sources.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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