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Research Article
Geoelectrical Characterization of Matured Petroleum Hydrocarbon Impacted Soil in Port Harcourt, Nigeria

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Abstract
Electrical Resistivity Tomography (ERT) and vertical electrical resistivity sounding (VES) surveys were jointly carried out to characterize a petroleum hydrocarbon impacted site. Both surveys were carried out after 14 months of spill and repeated after 28 months of the first survey (42 months of spill) using same traverse and electrode positions. The objective is to characterize the electrical structure and determine the lateral and depth extensions of the hydrocarbon contaminated horizons in soil and groundwater. Results revealed that the soil and groundwater in the investigated site have been contaminated by petroleum hydrocarbon, with a characteristic low resistivity anomaly associated with microbial degradation over time. The minimal depth of impact is approximately 13 m below the groundwater table, with a lateral spread in excess of 100 m on either side of the spill point parallel to the pipeline right of way. The contaminant strength is higher for season one than two, since it is a recent spill. Results also show that soil degradation arising from petroleum hydrocarbon contamination may result to changes in bulk density of the impacted soils. This may likely affect the compressibility and surface hydrogeology of the soils and therefore, alter the infiltration rate and direction of groundwater flow. This way, groundwater recharge from surface precipitation in the investigated site could be adversely affected.

Key words: ERT, VES, groundwater, petroleum hydrocarbon, TDS

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Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

The discovery of mineral oil in the Niger delta and the production, processing and transport through buried petroleum pipelines has led to a total degradation of the environment and key renewable and non-renewable natural resource[1].

Port Harcourt is a major oil producing area in Niger delta region (Fig. 1). Most of the produced oils are transported through a network of buried pipelines that criss-crossed the major parts of the city, from the wells to the refining and storage centers. Most of these pipelines have remained buried for over 30 years of hydrocarbon production and are therefore, susceptible to mechanical failures due to environmental and anthropogenic factors[2,3].

Most frequently, contaminations by petroleum hydrocarbons occur through leaks and spills due to corrosion and sabotage of oil and gas facilities. These have remained the dominant point-sources of soil and groundwater contaminations in the area. Once spilled, the soil and groundwater systems are contaminated and the options available for their use becomes both limited and costly. The major impacts of these are environmental degradation, human health hazards, economic hardship and social dislocation[4].

The vulnerability of these systems to petroleum hydrocarbon contamination is high, largely due to permeable soil media, poor sealing capacity of the groundwater aquifer and proximity of ground water table to the surface and climatic factors[5].

Geoelectrical methods have been used extensively for the characterization of recent and mature hydrocarbon impacted soil and groundwater in different parts of the globe. According to the results of study[6-9], recent hydrocarbon contaminations is characterized by high resistivity anomalies, while processed and mature hydrocarbon contaminations correlates with low resistivity anomalies.

However, recent investigations by various researches[10-14] reported highly conductive (low resistive) anomalies correlating with regions of petroleum hydrocarbon contaminations in matured hydrocarbon spills.

In the present study, a petroleum hydrocarbon spill occurred in March, 2012 due to sabotage from a buried pipeline. Consequently, the spill site was investigated in May, 2013 and September, 2015, after 14 and 42 months of spill, respectively (Fig. 2). The objective is to characterize the electrical resistivity structure of the site due to petroleum hydrocarbon contamination within these intervals of time (time lapse) and to determine the lateral and depth extensions of the hydrocarbon contaminated horizons in soil and groundwater using the Electrical Resistivity Tomography (ERT) and vertical electrical resistivity sounding (VES) surveys.

The theoretical basis for the use of geoelectrical methods for the detection of petroleum hydrocarbon contaminants is dependent on the contrasting electrical properties of the hydrocarbon versus the soil and groundwater. The magnitude of the contrast depends on the contaminant age and environmental processes.

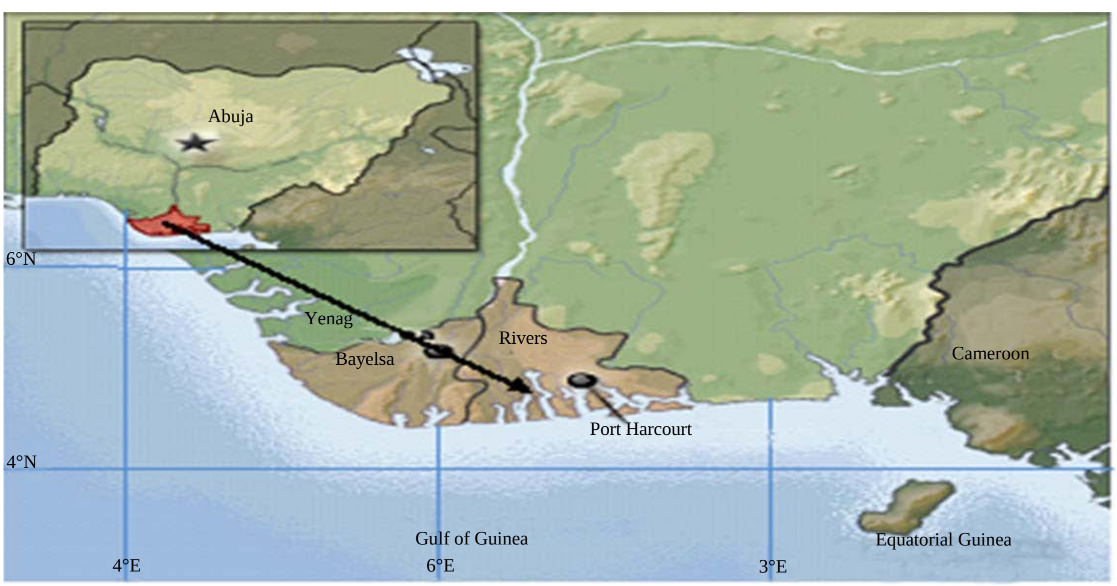

Fig. 1: Location map of the study area (modified from en.Wikipedia.org)

Fig. 2: Petroleum hydrocarbon spill site in the study area

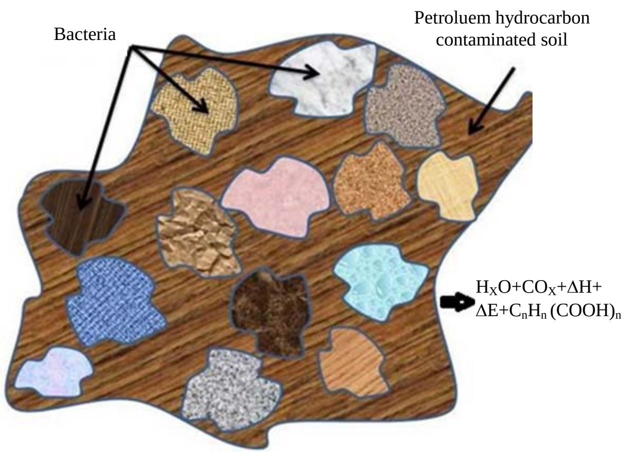

Fig. 3: Action of micro-organisms on mature petroleum hydrocarbon impacted soil

The resistivity of any fluid saturated soil depends principally according to Eq. 1 as:

$$\rho_s = \rho\,(\Phi, S_w, \rho_w, T \text{ and } P) \tag{1}$$

Where:
ρ_s = Resistivity of the saturated soil
Φ = Porosity of the sediment
S_w = Fluid Saturation
ρ_w = Resistivity of permeating fluid
T = Temperature
P = Pressure

Electrical resistivity typically correlate with variations in porosity, fluid saturation and resistivity, temperature and pressure of the soil.

Equation 1 is related to the Archie's law[15] given in Eq. 2:

$$\rho_s = a\Phi^{-m} S_w^{-n}\rho_w \tag{2}$$

where, m, n and a are the cementation factor, saturation exponent and empirical factor, respectively.

The action of micro-organisms on mature petroleum hydrocarbon impacted soil (Fig. 3) results in biodegradation products of CO_x, H_xO, heat (ΔH), energy (ΔE) and organic acids $(C_nH_nCOOH)_n$.

The organic acids interacts with the soil reducing the pH. This results in mineral weathering and enrichment of groundwater with cations of Fe^{2+}, Mn^{2+}, Ca^{2+} and Mg^{2+}. This results in elevated levels of Total Dissolved Solids (TDS) in soil and groundwater, which has a direct relation to groundwater electrical resistivity. This relationship can be expressed in Eq. 3 as:

$$\rho_w = ATDS^{-K} \tag{3}$$

Where:
ρ_w = Resistivity of groundwater
TDS = Total dissolved solids
A and K = Empirical constants

Further analysis of Eq. 3 yields Eq. 4:

$$\ln\rho_w = \ln A+(-K)\ln TDS \tag{4}$$

This is a straight line graph with slope (-K) and intercept lnA. The K is the ion concentration factor, while A is a matrix property. These empirical constants have values of the order of ≤ 1 and >1, respectively.

Equation 4 shows that ρ_w is nearly linearly related to TDS. Although not a direct evidence of biodegradation, TDS is a geochemical parameter that relates groundwater electrical properties to petroleum hydrocarbon degradation. The low resistivity associated with mature petroleum hydrocarbon impacted soils is strongly linked to higher Total Dissolved Solids (TDS) in groundwater permeating the pore spaces of the soil.

Port Harcourt is underlain by the tertiary Niger delta Benin formation. The Formation consists of unconsolidated, massive, highly porous and permeable fresh water bearing sand stones with minor clay intercalations[16]. It is water bearing and the main source of potable groundwater for domestic and industrial applications in the area. The water table and potable groundwater aquifers have a seasonal variation of 3-15 and 27-45 m, respectively, depending on the season of the year. These are high during the rainy season and approach its maximum subsurface depth at the peak of dry season. The groundwater aquifers are recharged mainly by surface precipitation. The topography of the sites is generally flat enhancing maximum infiltrations with negligible runoff, while the vegetation is predominantly rainforest.

MATERIALS AND METHODS

The ERT and VES surveys were conducted in two traverses A and B parallel to and 20 m off the pipeline right of way, respectively, with a digital readout ABEM Terrametre SAS 1000°C at the onset of the rainy season. The ERT surveys were carried out with electrode spacing's (a-spacing's) ranging from 5 to a maximum of 30 along a 200 m traverse with Wenner array, while a maximum AB/2 and MN/2 of 200 and 15 m, respectively were occupied for the VES surveys with the Schlumberger electrode array. The VES's were situated at the centre of the ERT traverses, which coincides with the actual spill point. This is for convenience in correlation and analysis of data. Both surveys were carried out after 14 months of spill and repeated after 28 months of the first survey (42 months of spill) using same traverse and electrode positions.

The measured resistance R (Ω) data in each survey were converted to apparent resistivity ρ_a (Ωm) using the appropriate geometric factor and propriately softwares (RES2DINV and IPWIN) were used for data processing using the same processing workflows for the two data sets.

From the analysis of these measurements, the true resistivities of the subsurface formations penetrated and the depth of impact could be estimated and petroleum hydrocarbon contaminations inferred.

RESULTS AND DISCUSSION

ERT survey: The results of the ERT surveys are presented as two dimensional (2-D) inverse model sections of true resistivity distributions along the traverses (Fig. 4a, b). These sections were visually examined for indications of petroleum hydrocarbon contaminations.

The results of the investigation show low resistivities (blue) coincident with locations of petroleum hydrocarbon contamination. The resistivities vary from 1.38-21.00 Ωm at maximum depth of impact of 13.4 m. The first season tomogram (Fig. 4a) has high resistivity distribution than season two (Fig. 4b). Generally, the contaminant strength (grade) in the investigated sites is higher in the first season tomogram than season two. This could be attributed to the fact that the first season tomogram is a recent event and may not have undergone any appreciable physical alteration in composition, compared to season two tomogram, which has actually been biodegraded by microbial activity.

The depth of impact is smaller in the first season survey than season 2, probably due to the seepage of contaminants into underlying formations over this time lapse. Results also show that lateral extent of contamination has gone beyond 100 m from either side of the spill point (VES point).

Below this contaminated zones, the resistivity increases uniformly with depth reflecting background uncontaminated saturated zones in the investigated site.

VES survey: The VES results show five interpretable geoelectric layers (Table 1 and Fig. 5a, b). The curve type is AA for the two VES points, which reflects a continuous resistivity increase with depth in the investigated soils.

The resistivities vary from 2.92-506.50 Ωm, with a maximum depth of 46.82 m in the two sites. The results show a 1st layer of clayish, 2nd layer of lateritic and 3rd layer petroleum hydrocarbon contaminated sandy soils, while the 4th and 5th layers are uncontaminated saturated sandy soils in the entire geoelectric section. The VES survey show that the maximum depth of petroleum hydrocarbon impact is 13 m. The first season VES has a higher resistivity distribution with depth than the second season survey.

The resistivities and depths of impact from the VES's are in close agreement with the results of the ERT surveys in the two seasons. This is a justifiable reason to believe that the soil and groundwater in the investigated site has actually been contaminated by petroleum hydrocarbon. The estimated groundwater table from geoelectrical surveys is 3.40 m and groundwater features (aquifers) were delineated at average depths of 12.76 to >46.80 m. A typical geoelectric section which fits the VES model curves in each site is shown in Fig. 6.

Results of interpretation show that low resistivity anomalies are coincident with regions of petroleum hydrocarbon contamination in the investigated site. Until recently, it has been reported that hydrocarbon impacted sites can be effectively imaged only by their high resistivities compared to the background[13,17-21]. This observation is correct

Table 1: Layer parameters of the geoelectric section (VES A and B)

Parameters	No. of layers	Resistivity (Ωm)	Depth (m)	Layer thickness (m)
VES A	1	3.13	1.87	1.87
	2	11.85	4.93	3.06
	3	46.22	12.55	7.62
	4	200.10	46.80	34.25
	5	506.50		
VES B	1	2.92	1.90	1.90
	2	10.80	4.87	2.97
	3	42.70	13.00	8.13
	4	120.00	46.82	33.82
	5	312.00		

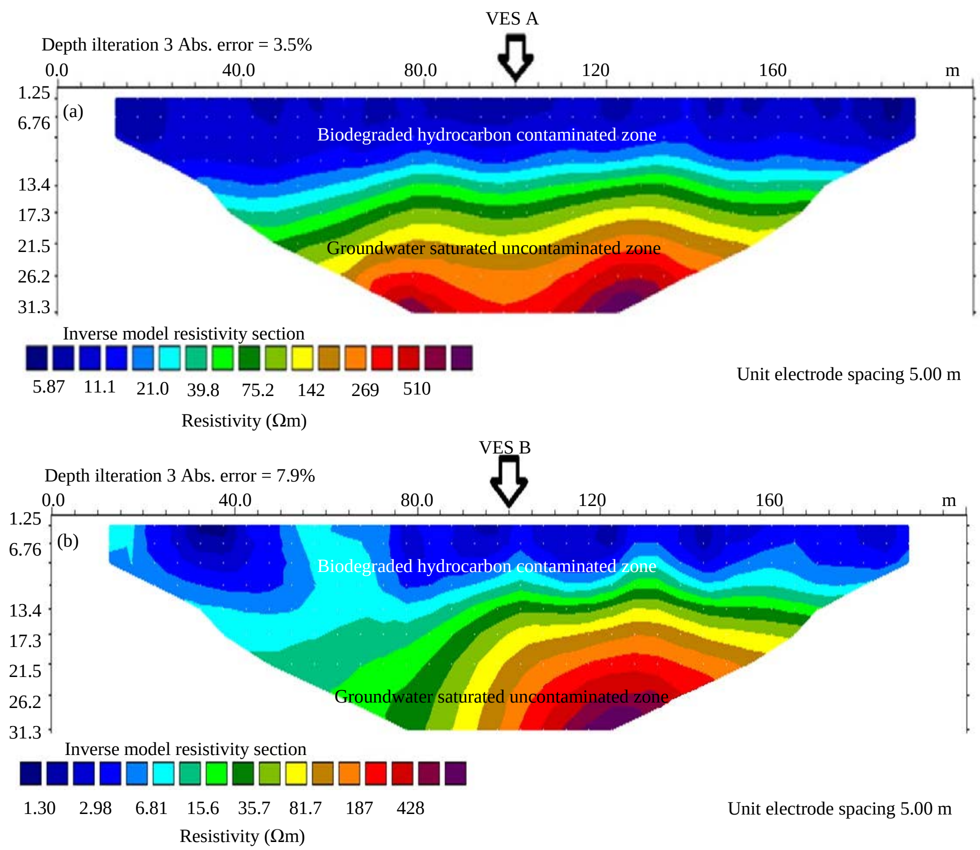

Fig. 4(a-b): ERT image site, (a) 1 along traverse A (27 months of spill) and (b) 2 along traverse B (42 months of spill), ERT: Electrical resistivity tomography and VES: Vertical electrical resistivity sounding

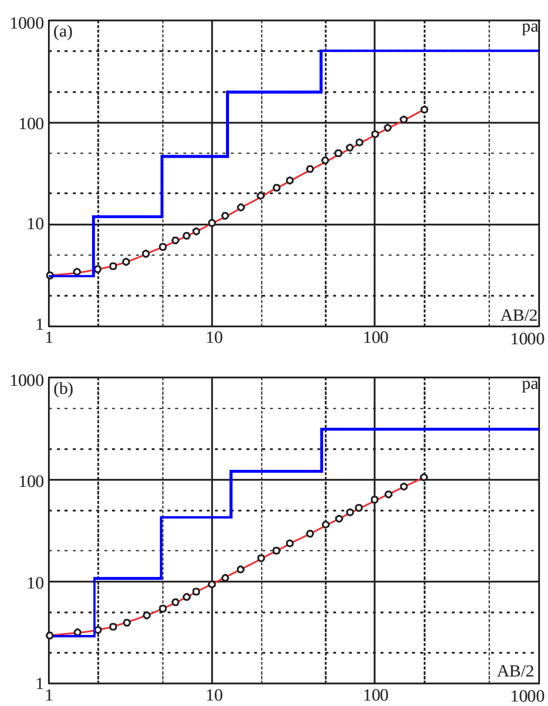

Fig. 5(a-b): AA curve types of interpreted (a) VES A and (b) VES B, VES: Vertical electrical resistivity sounding

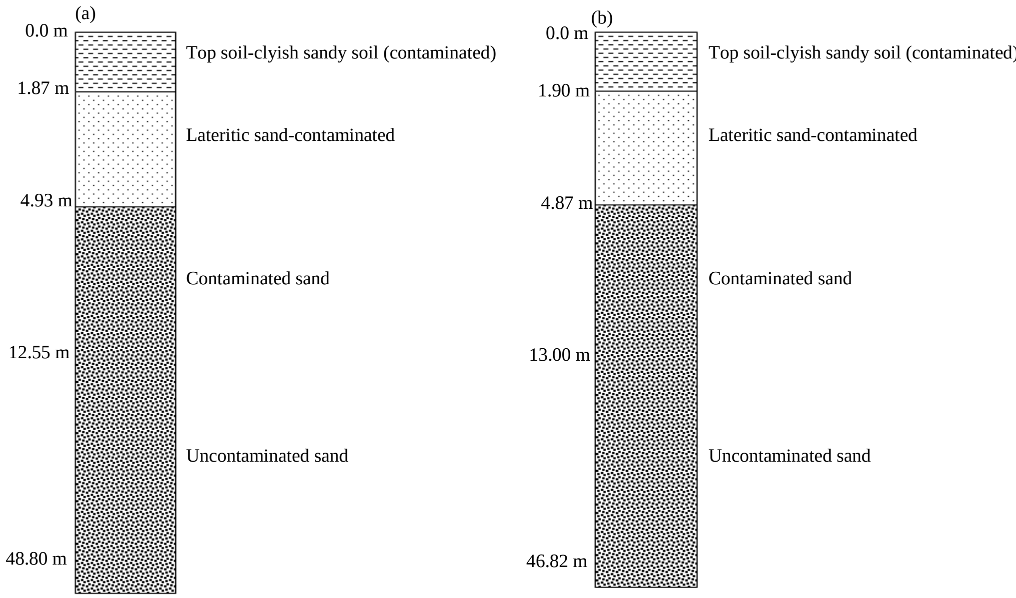

Fig. 6(a-b): Interpreted geoelectric sections for (a) VES A and (b) VES B

as long as the petroleum hydrocarbon is fresh or has not been altered by any physical process. The scale of the alteration varies with contaminant age, depth of ground water, level and cause of contamination.

However, recent findings at sites impacted with hydrocarbons over time show a conductive response characterized by low resistivities[7,8,10,13,14,22,23]. This the authors attributed to high pore water conductivity due to elevated levels of Total Dissolved Solids (TDS) in groundwater resulting from enhanced mineral weathering accompany the production of carbonic and organic acids during biodegradation by bacteria action on petroleum hydrocarbon contaminants in the vadose zone and below the groundwater table.

Apart from human and ecological impacts, soil degradation arising from petroleum hydrocarbon contamination may result to changes in bulk density of the impacted soils. This may likely affect the compressibility and hydrogeological properties of the soils and therefore, alter the infiltration rate and direction of groundwater flow. This way, groundwater recharge from surface precipitations in the investigated site could be adversely affected.

CONCLUSION

The ERT and VES surveys revealed that the soil and groundwater in the investigated site have been contaminated by petroleum hydrocarbon with a characteristic low resistivity anomaly associated with microbial biodegradation over time. The minimal depth of impact is 13 m below the groundwater table, with a lateral spread in excess of 100 m on either side of the spill point. The contaminant strength is higher for the first than the second season surveys, while the depth of impact is higher for the second season survey.

The estimated groundwater table from geoelectrical surveys averages 3.40 m. Groundwater features (aquifers) were delineated at average depths of 12.76 to >46.80 m. This reflects the proximity of the groundwater table to the surface and the shallow nature of the groundwater aquifer in the investigated site. Apart from human and ecological impacts, soil degradation may result to changes in the hydrogeological properties of the soil which may alter groundwater flow direction and recharge from surface precipitation.

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