

Spatial and Vertical Distribution of Hydrocarbon Contamination in Coastal Plain Sands of the Niger Delta, Nigeria

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Abstract: The geologic Coastal Plain Sands is host to large numbers of onshore hydrocarbon exploration and processing activities and receives a greater part of the adverse environmental impact, including soil and groundwater contamination. This study explores the spatial and vertical distribution of hydrocarbon contamination in coastal plain sands typified by the Ogoni area (using indicator parameters of TPH and PAH) to assist with identification and delineation of vulnerable horizons as well as target specific contaminated areas as a remediation strategy. The investigations utilized a combination of Electrical Resistivity Tomography (ERT) and geotechnical boring to delineate hydrocarbon contaminated areas and laboratory testing for determination of concentrations/degrees of contamination. The 2-D ERT tomograph for the different survey lines were concatenated to provide a 3-D view which enabled horizontal slices corresponding to depths of interest to be assessed for possible contamination. The lithologs obtained from boring were further used in lithological modelling to precisely define the 3-D distribution of the contaminated zone. The results indicate that the ultimate distribution of hydrocarbons in the subsoil is influenced by topography, the physical and chemical characteristics of the compounds as well as those of the affected soil such as permeability and water table variation. In addition, climatic factors such as rainfall and temperature have a great influence on the reactions and the movement of the hydrocarbons plume in the subsoil. Because of their low densities, light hydrocarbons tend to spread laterally and are therefore commonly found at the interface of unsaturated-saturated zones while denser hydrocarbons tend to move vertically down through the subsoil into the saturated zone and migrate downward until they are restrained by an impermeable layer. This implies that the top soil in aged spill sites within the coastal plain sand become renovated by natural attenuation over time and tend to exhibit low levels of hydrocarbon contaminations.

Keywords: Resistivity, Tomography, Hydrocarbon, Contaminated, Niger Delta,

I. Introduction

The Niger delta is a theatre of intense oil Exploration and Production. With active government collaboration, the entire region was divided into Oil Mining Leases (OML). The area is characterized by an extensive networks of pipelines, flow stations, refineries, oil depots and tank farms, export terminals, etc. As these facilities aged beyond their service life, they became more susceptible to failure. Indeed, many equipment failures have occurred leading to oil spills. Also, vandalization of oil and gas facilities have been widely reported and blamed for many oil spills. According to NOSDRA (2022) 77% of oil spills from 881 cases of oil spillage occurred in only three states resulting in the discharge of about 43,000 barrels of oil into the environment.

Most of these spills occurred within the Quaternary Coastal Plain Sands which constitute about 30% of the superficial geologic formation in the Niger Delta (Fig.1).

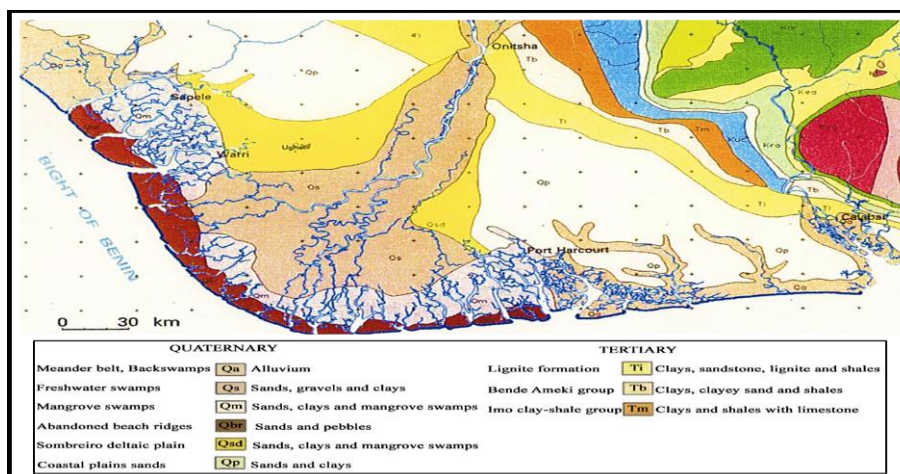


Figure 1: Geologic map of the Niger Delta (after Reijers, 2011).

By the governing laws, oil companies must close off oil spill sites within 24 hours of being notified of an oil spill on their fields. Regrettably, this is hardly the case in the region due to inaccessibility of some oil spill sites and lack of cooperation from the communities. Over time, these spills seep into the ground and contaminant soil and groundwater and become concealed from public view in the medium and long-terms.

Soil pollution is becoming increasingly prominent and polycyclic aromatic hydrocarbons (PAHs) are key pollutants because of their toxicity. Previous studies (Li et al 2006; Liu et al 2019; Yanguo et al 2013) have reported that harmful pollutants in the urban environment may severely harm human health, and therefore need to receive particular attention. Other researchers (Liu et al (2019); Song et al (2017); Fazali et al (2019) have called for urgent solution to the environmental problems caused by soil contamination. Although previous studies have been very important for understanding PAH contamination, some information is still lacking, especially an in-depth analysis of the factors that affect the spatial distribution of PAHs and their vertical accumulation.

According to Weber and Miller (1989), once the organic contaminants reach the soil, they can move in one or more than seven directions: they can be vaporized into the atmosphere without chemical changes (evaporation); they can be absorbed into the soil (absorption); they can move downward through the soil in liquid form or be lost by leaching (filtration); they can undergo chemical reactions with or in the soil surface (adsorption, oxidation-reduction); organic compounds can be broken by the microorganisms action which are in the soil (biodegradation); they can reach rivers and streams by surface runoff; they can be absorbed by plants or animals and get into the food chain.

The ultimate behavior of hydrocarbons in the subsoil is influenced by the physical and chemical characteristics of these compounds as well as those of the affected soil such as permeability, particle size, moisture content, structure, organic matter content, water table. In addition, climatic factors such as rainfall and temperature have a great influence on the reactions and the movement of the hydrocarbons plume in the subsoil. Because of their low densities, BTEX and other Light Non-Aqueous Phase Liquids tend to spread laterally (Lesage and Jackson, 1992) and are therefore commonly found at the interface of unsaturated-saturated zones also called the smear zone. Denser hydrocarbons such as diesel tend to move vertically through the sand and gravel layers below (USEPA, 2010). When crude oil is released to the subsoil through spillage or leakage, the denser components move down through the subsoil into the saturated zone and migrate downward until they are retained by an impermeable layer (US EPA, 2010).

The suitability of a non-intrusive ERT technique for detecting crude oil have been evaluated by several authors (Olhoeft 1992, Sauck and McNeil, 1994, Godio and Naldi 2003, Shevlin *et al* 2002, 2006, Manuel Arrubarrena-Moreno and Claudia Arango 2013, Abam *et al* 2025). The resistivity contrast between an oil-polluted area and the surrounding rock depends on the spill age. According to Nash et al 1997, Delgado-Rodríguez et al., 2006, the resistivity is a very versatile and conclusive parameter in many studies. Because of the applicability and reliable results obtained in the detection of contamination plumes, ERT is currently used as a technique to monitor and diagnose the state of water resources and soil pollution by hydrocarbons (Rosales et al., 2012). De la Vega (2003) suggests that one way to characterize a contaminated site is through the electrical resistivity of the soil. Sauck, (1998) has proposed that the volume affected by oil spills in the environment changes from electrically resistive to a conductive behaviour over time due to the variety of biogeochemical process like: weathering, volatilization, microbial redox processes, adsorption, among others. Support for this hypothesis comes from geochemical studies in hydrocarbons contaminated areas, indicating the presence of highly conductive groundwater below some hydrocarbon's plumes (Baedecker et al., 1987; Baedecker et al. 1993, Bennett et al. 1993; Eganhouse et al. 1993; Atekwana et al. 2001; Delaney et al., 2001). It has been argued that the existence of a conductive layer with a minimum resistivity may be in part due to the biodegradation of the pollutant mass (Atekwana et al., 2000

The low resistivity anomaly in polluted areas appears three to four months after the spill ("mature spill"), but in the case of a fresh spill the presence of a high resistive anomaly is expected. Therefore, the age of spill influences the selection and optimization of the applied technology. Low resistivity findings in oil-polluted zones appeared rather recently (Sauck and McNeil, 1994; Modin et al., 1997; Sauck, 1998, 2000; Atekwana et al., 2001; Abdel-Aal et al., 2001). According to Sauck et al (1998), the source of low resistivity is the acid-rich leachate from created by intense bacterial action on residual hydrocarbons (Boopathy 2004, Baedecker et al 1993, Farhadian et al 2008) near the base of the vadose zone. This low resistivity zone is produced by high total dissolved solids in the zone where microbial activity is maximal (Sauck, 1998; 2000; Atekwana et al., 2001). The leachate is a result of chemical reactions between organic acids, CO₂ and mineral grains and grain coatings.

II. Method of study

The crude oil spills of interest are those that are manifested on the surface such as from surface or shallow pipelines and Well head blowouts which spread on the surface due to relief and gravity. For this source of spill, understanding the topography provides insight and indication as to the possible directions of surface movement and dispersion. On the basis of the conceptual model, and considering the necessity for good spatial coverage, an initial layout of the survey lines was determined (Fig.2).

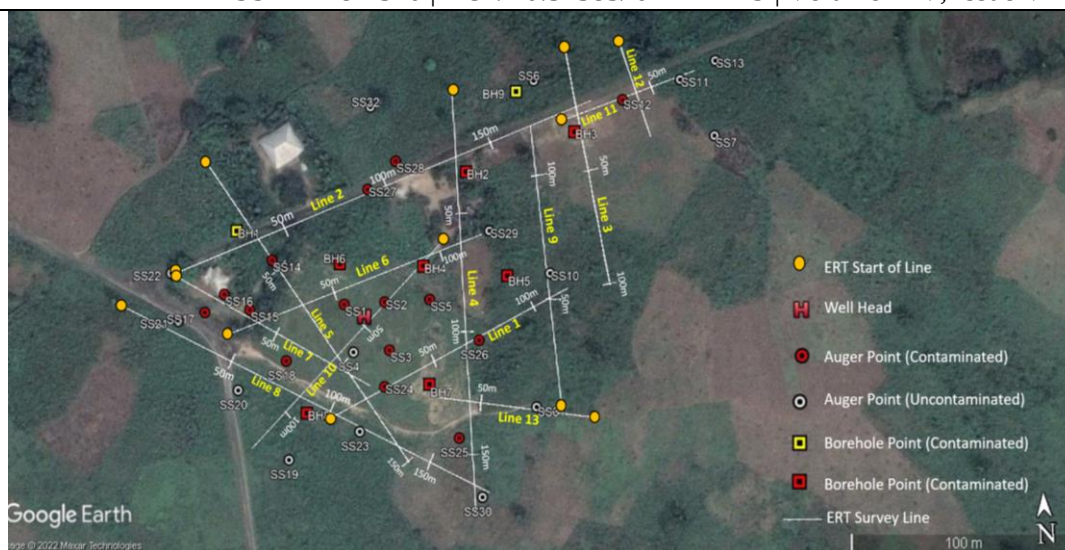


Fig. (2) Electrical Resistivity Survey lines

These surveys are made to intercept each other as much as possible and to enable concatenation of the lines. The acquisition of resistivity data involves the injection of current into the ground via a pair of electrodes as described in Loke (2010) and then the resulting potential field is measured by a corresponding pair of potential electrodes. The resistivity survey consisted of thirteen profiles, some of 200 m length, using a Wenner array. The depth of investigation depends on the electrode separation and geometry, with greater electrode separations yielding bulk resistivity measurements from greater depths.

The recorded data were processed using RES2DINV (ver 5.1) software ERT profiles consist of a modeled cross-sectional (2-D) plot of resistivity (Ωm) versus depth. Modeling and inversion were carried observing all necessary precautions as described by Looke 2010, Ritz et al 1999, Rucker et al 2006, LaBrecque and Yang 2001. Several geotechnical borings were carried out and enabled lithologic descriptions of soils at different depths. ERT interpretations, supported by borehole data or alternate geophysical data was utilized to accurately represent the geometry and lithology of subsurface geologic formations. Laboratory chemical testing for PH, PAH and Barium as indicator parameters as well as Benzene, Toluene, Ethylbenzene and o-xylene were performed to show both spatial and vertical distributions of contamination.

III. Results and Discussions

A sample result of pseudo section and tomograph based on the electrical resistivity is selectively presented in Fig. (3) for illustrative purposes. All imaging has been performed after removing the geological noise. The vertical cross-section of apparent resistivity is a traditional presentation for soundings along a profile.

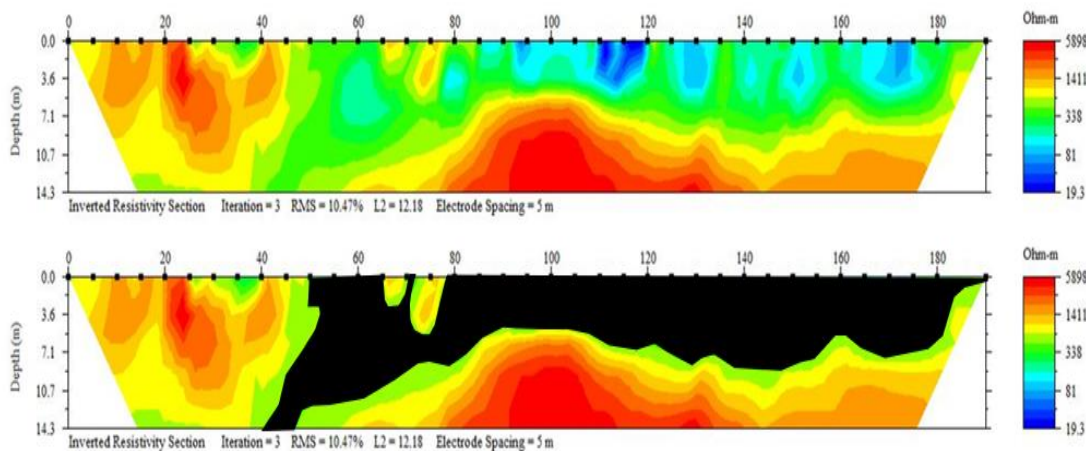


Fig. (3) Processed electrical resistivity tomogram for Line 2 using Earth-Imager software (dark area highlighted on second tomogram shows oil contaminated zones with resistivity values $\leq 600 \Omega\text{m}$)

These tomographs which are in 2-D are then concatenated to produce a solid 3-D image which can then be sliced at the depth of interest to reveal the spatial distribution and persistence of the contamination. Based on the tomographs, the lateral and vertical extents of contamination were delineated. For convenience, only a selection of these is presented in Figs (4 and 5).



Soil cuttings from borings at the project area were analyzed for TPH, PAH and Ba as indicator parameters as well as for Benzene, Toulene, Ethylbenzene and o-xylene. 72 soil samples were tested for the heavier and more toxic fractions of Benzene, Toulene, Ethylbenzene and o-xylene and all reported concentrations were less than 0.001 mg/kg, far lower than the target values of 0.5mg/kg and intervention values varying from 1mg/kg to 130mg/kg (USEPA: method 8260b). Results of spatial variation of TPH concentrations in the soil is presented in Fig. (7). The spatial distribution of PAH follows a similar pattern as TPH with both reflecting the surface gradient in the area. Evidently, the results show a decreased concentration away from the source of contamination along the path of surface runoff. It also indicates that the contamination was highest within the spatial envelop enclosing BH2 to BH5.



With the confirmation of free phase hydrocarbon in groundwater, it was considered important to understand groundwater flow pattern in the area by first measuring the spot height at the boring locations and reducing the measured groundwater level to datum. This resulted in the groundwater level contours indicating the equipotential lines from which indicative groundwater flow directions was determined.

The monitoring wells installed were designed based on the understanding of the nature of the contaminant of concern and the environmental variables. Since hydrocarbon is known to exist in three phases as contaminant free phase which largely floats on the surface of groundwater, dissolved phase which is in solution with groundwater and that which is co-mingled with soils, the monitoring well was designed to promptly register the presence of contaminant irrespective of the phase and took into account the seasonal variability of the groundwater level.

Results of the spatial variation in concentration of TPH and PAH in groundwater within study area were similarly investigated and found to follow the same pattern as in the soil. The variation in concentration of TPH and PAH with depth within the soils of the study area is presented in Fig. (8). These show a consistent pattern of peak concentrations in the zone of seasonal groundwater variation, also called the smear zone in BH2 to BH5. It further confirms that the spilled crude comprises mostly of light fractions which are largely buoyant and are always around the region of the groundwater table.

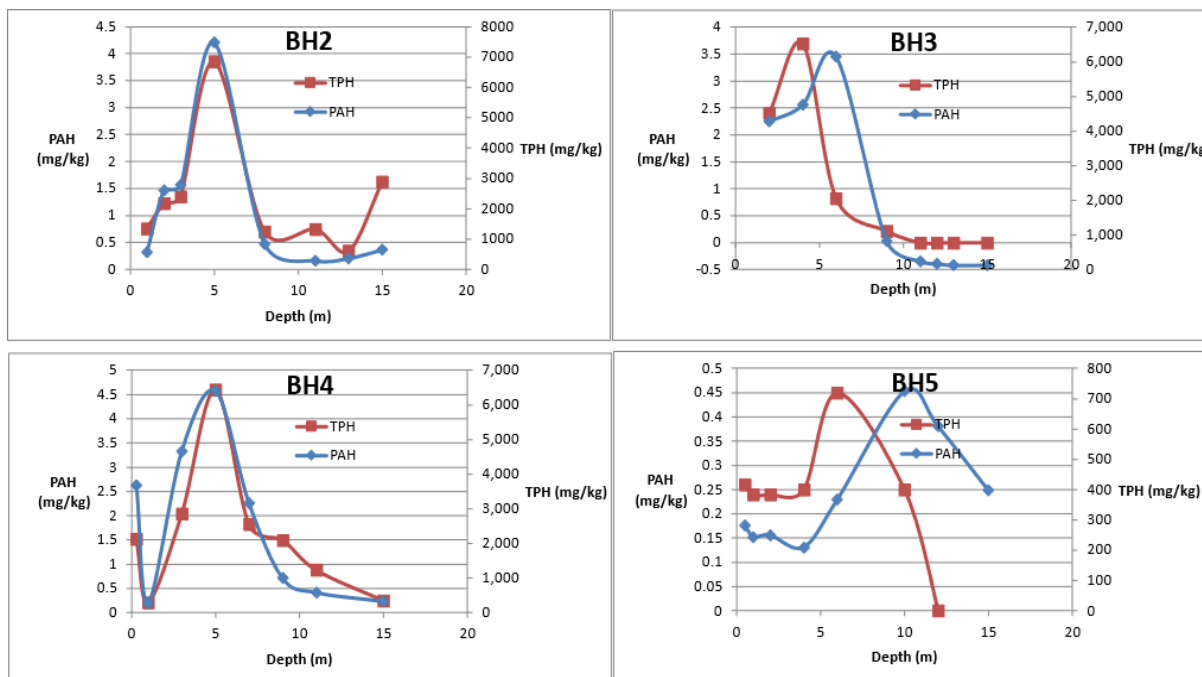


Fig. (8): Vertical distribution of TPH and PAH in most soil sampling locations around study area

However, a departure from this regular pattern of vertical distribution was observed in a few cases, where peak pollution was not in the smear zone. For example, in BH2 which was close to a hand dug well where hydrocarbon contamination extended from the ground surface deep into the sandy aquifer at about 15m. It would thus appear that the built-up concentration within the smear zone as observed in BH2 to BH5 occurs only where the spilled crude oil has infiltrated from the surface and have percolated over the years into the groundwater. In the same vein, the distribution of nutrients in the soil of the study followed a similar pattern. The only nutrient present at a significant concentration was sulphate. The highest concentrations of nutrients were also found to be around the smear zone irrespective of the degree of hydrocarbon contamination level.

IV. Conclusion

Assessment of the spatial and vertical distribution of hydrocarbon contamination has been carried out from a multi-dimensional approach, each providing a scenario of contaminant distribution in which the geometry of contaminated soils by hydrocarbon is revealed. This work clearly demonstrates that site characterization is indeed the first step towards designing a pragmatic and cost-effective remediation programme. ERT deserves an increased attention since it is a low-cost and high-resolution technique that can rapidly image states and processes. ERT has also proved effective in the identification of contaminated zones with medium fraction hydrocarbons. Repetition of the characterization process with time intervals on the order of one year may help to monitor the effectiveness of an eventual remediation process. Comparison between chemical and geophysical data allow us to assess the sensitivity of the physical property to the presence of the contaminant, and it was possible to visualize that electrical resistivity varies depending on volume and residence time of the hydrocarbon in the ground. It is further concluded that seasonal variation in groundwater level concentrates buoyant contaminants such as the Bonny light crude within the smear zone. Consequently, remediation efforts need not extend much beyond the lowest groundwater level which is the groundwater level in the dry season.

Lastly, the top soils can be stripped, stockpiled and backfilled after remediation due to their relatively low-level concentration, thus saving cost and conserving soil fertility.

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