High-Resolution ERT and Geochemical Assessment of Aged Hydrocarbon-Contaminated Soil in Rivers State, Nigeria.

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ABSTRACT

An integrated high-resolution ERT and geochemical Assessment of aged hydrocarbon-contaminated soils was conducted in an oil pipeline environment in Rivers State. The ERT assessment reveals lateral variation of resistivity at a fix depth while geochemical survey reveals total petroleum hydrocarbon (TPH) concentrations. Correlations between ERT and geochemical datasets were identified, highlighting key areas of contamination and demonstrating the effectiveness of this combined approach for subsurface Assessment.

The results from the both methods confirm the wellhead as the primary source of contamination, with consistent findings around **line 10, line 6, line 1** and **BH6, BH5, SS1**and other nearby sampling points. The ERT survey reveals low resistivity values which correspond with high TPH concentrations, reinforcing the conclusion that hydrocarbons have significantly altered the subsurface environment.

Keywords: HighResolution; ERT; Geochemical; Hydrocarbon; Contaminated; TPH

INTRODUCTION

The growth of the oil industry across the world has led to significant environmental contamination, particularly through the exploitation, transportation, refining, and distribution of hydrocarbons (Delgado-Rodríguez*et al.* 2018). This concern has intensified interest in assessing the environmental impacts of oil operations, especially regarding oil spills that adversely affect waterways, aquatic life, and vegetation.

Hydrocarbon pollution notably threatens soil fertility and agricultural productivity, jeopardizing ecosystems and local communities reliant on clean water and agriculture (Eshagberi, 2012; Adeyanju, 2004). In regions like Ogoniland in the Niger Delta, extensive crude oil pollution has necessitated urgent interventions. Although oil production ceased in 1993, the lack of infrastructure maintenance has worsened environmental degradation, leading to social unrest over the oil industry's operations.

An assessment by the United Nations Environment Programme (UNEP, 2011) underscored the ecological consequences of oil operations in Ogoniland; however, there is a significant gap in comprehensive geo-environmental assessments that integrate geophysical and geochemical techniques to address the extent and nature of hydrocarbon contamination.

Traditional methods for detecting hydrocarbon contaminants involve drilling and chemical analyses of soil samples, which can be tedious and inefficient without prior knowledge of contaminant distribution. Contaminants often accumulate above the water table, and unguided deep drilling heightens vulnerability to surface pollutants.

The resistivity contrast between clean and contaminated soils is a critical factor in understanding the environmental impacts of oil spills.

Research has shown that this contrast varies significantly with the age of the spill. Initially, when an oil spill occurs, the contaminated soils often exhibit high-resistivity anomalies (Delgado-Rodríguez*et al.* 2018). This is primarily because recent spill creates a hydrophobic layer that reduces the water saturation in the soil, leading to higher resistivity readings (Loke et al., 2014). However, as time progresses, typically around four to six months post-spill, the situation changes dramatically. Low-resistivity anomalies begin to emerge, indicating increased soil conductivity due to various processes, including microbial degradation of hydrocarbons.

The low-resistivity anomalies observed in contaminated soils during this later phase are influenced by multiple factors, including local lithological characteristics and prevailing weather conditions (Delgado-Rodríguez*et al.* 2018). According to Sauck (2000), the microbial degradation of hydrocarbons in the vadose zone plays a significant role in altering soil resistivity.

This degradation process produces both organic and inorganic acids, which can dissolve minerals within the soil matrix. As these minerals dissolve, ions are released into the pore water, leading to an increase in total dissolved solids (TDS)Abdel-Aal*et al*. (2009. Elevated TDS contributes to the observed low-resistivity anomalies, reflecting a shift in the soil's electrical properties.

Further insights into this biodegradation process have been provided by Abdel-Aal et al. (2009), who explored how microbial activity affects the electrical properties of contaminated soils. Their research indicates that the increase in conductivity in these soils can largely be attributed to the formation of biofilms by bacteria within the pore spaces of the affected rocks.

These biofilms enhance surface conductivity, significantly impacting the overall resistivity of the contaminated soils. As microbial populations proliferate in response to hydrocarbon presence, they create a complex environment that alters the geophysical properties of the soil. Consequently, understanding the temporal changes in resistivity can offer valuable insights into the progression of contamination and inform remediation efforts (Delgado-Rodríguez*et al.* 2018).

Studies by Ojo et al. (2012) investigated hydrocarbon contamination in agricultural soils of the Ogoniland region using electrical resistivity imaging (ERI) and soil sampling techniques. Their study identified elevated concentrations of total petroleum hydrocarbons (TPH) in soil samples collected from areas with anomalous resistivity signatures, highlighting the potential of geophysical methods for rapid screening of contaminated sites in agricultural landscapes.

Sauck et al. (1998), proposed that soil volume impacted by hydrocarbon spills alters the electrically resistive soil to a more conductive (low resistivity) behavior with time due to a variety of biogeochemical processes.

This temporal change in the resistive behavior of hydrocarbon contaminated zones has not been adequately exploited in geophysical interpretations and models at contaminated sites, although it has been suggested that many hydrocarbons and organic chemical contaminant plumes change with time due to a variety of active processes (Olhoeft, 1992; Benson and Stubben, 1995; Benson et al., 1997).

Support. for this hypothesis comes from geochemical studies at hydrocarbon contaminated sites which indicate the presence of highly conductive groundwater below some contaminant plumes Baedecker et al., 1987; Cozzarelli et al., 1990; Baedecker et al., 1993;

Bennett et al., 1993; Eganhouse et al., 1993; Sauck et al. 1998). This study aims to conduct integrated geophysical and geochemical characterization of mature hydrocarbon contaminated sites in Rivers State, Nigeria, using Vertical Electrical Sounding (VES) and geochemical analysis of borehole samples to delineate geoelectric resistivity anomalies and comparing the results with measured Total Petroleum Hydrocarbon (TPH) concentrations at various depths; addressing environmental challenges of crude oil exploration while proposing sustainable development solutions.

MATERIALS AND METHOD

Study Area

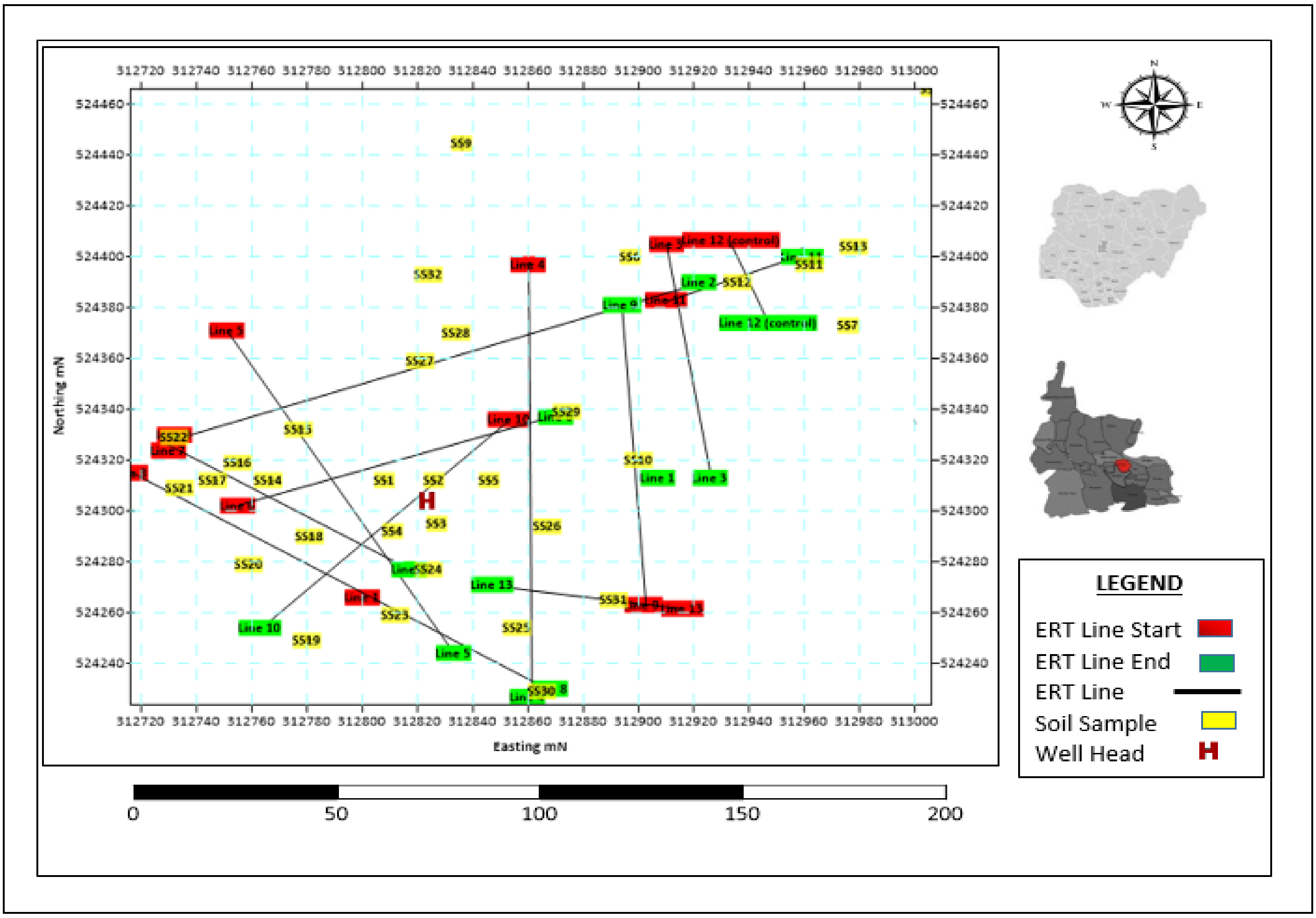

Fig.1: Base map of Study area showing traverse lines, well Head and soil sample points

The study area Korokoro community in Tai Local Government Area (L.G.A.) in Rivers State, Nigeria, is characterized by sedimentary rock formations within the Niger Delta basin, notably the Akata, Agbada and Benin Formations, which hold significant hydrocarbon reserves. The region's geology includes clastic sediments, complex tectonics, and environmental considerations such as erosion and subsidence. The Shell pipeline traverses Korokoro Tai L.G.A., facilitating the transportation of crude oil and natural gas, while also posing environmental risks that necessitate regulatory oversight. Located approximately at coordinates 4.5969° N, 7.1622° E, Tai L.G.A. plays a crucial role in the oil and gas sector, underscoring the importance of understanding its geological context for sustainable resource management.

METHOD

The geophysical part focuses on identifying subsurface contamination through electrical resistivity measurements. In contemporary applications, the resistivity method employs various electrode configurations and advanced inversion models to capture detailed images of subsurface structures. The foundational principle of measuring electrical resistivity is Ohm's law, expressed as:

$V = IR$- - - - (1)

In the geophysical aspect of this study, a grid layout consisting of thirteen traverses was conducted, as depicted in Fig 1. The Wenner array method was utilized for collecting 2-Dimensional resistivity data, which was processed using the Res2Dinv software to invert the resistivity data to generate 2D resistivity images (ERT), visualizing the contaminant distribution along each profile line. This was subsequently collated and processed using Res3Dinv software was used to generate 3D block models and depth slices to illustrate the spatial distribution contaminants across the study area. The application of 2D and 3D imaging allows researchers to interpret the extent of contamination effectively.

Complementing ERT, geochemical assessment is crucial for evaluating hydrocarbon contamination in soil, beginning with a well-designed sampling strategy that accounts for historical contamination, land use, and geology. Soil samples were collected using standardized techniques to minimize cross-contamination. Sampling was conducted at specific depth ranges: 0 to 0.3m; 0.5m; 0.7m; 1m; 2m; 3; 4; up to 7m before being transported to the laboratory for Total Petroleum Hydrocarbon (TPH) analysis using gas chromatography-mass spectrometry (GC-MS) were used to quantify hydrocarbon concentrations, providing insights into the nature and extent of contamination and this procedure was replicated at subsequent sampling locations. The samples were collected and referenced utilizing a Global Positioning System (GPS) for precise location tracking. The overall methodology was aims to provide a comprehensive understanding of contamination in the area, which is essential for developing effective remediation strategies.

Data Interpretation: TPH concentration values for individual sample points were used to generate geospatial contaminant maps using Rockworks software and correlated with the 3D depth slices.

RESULTS

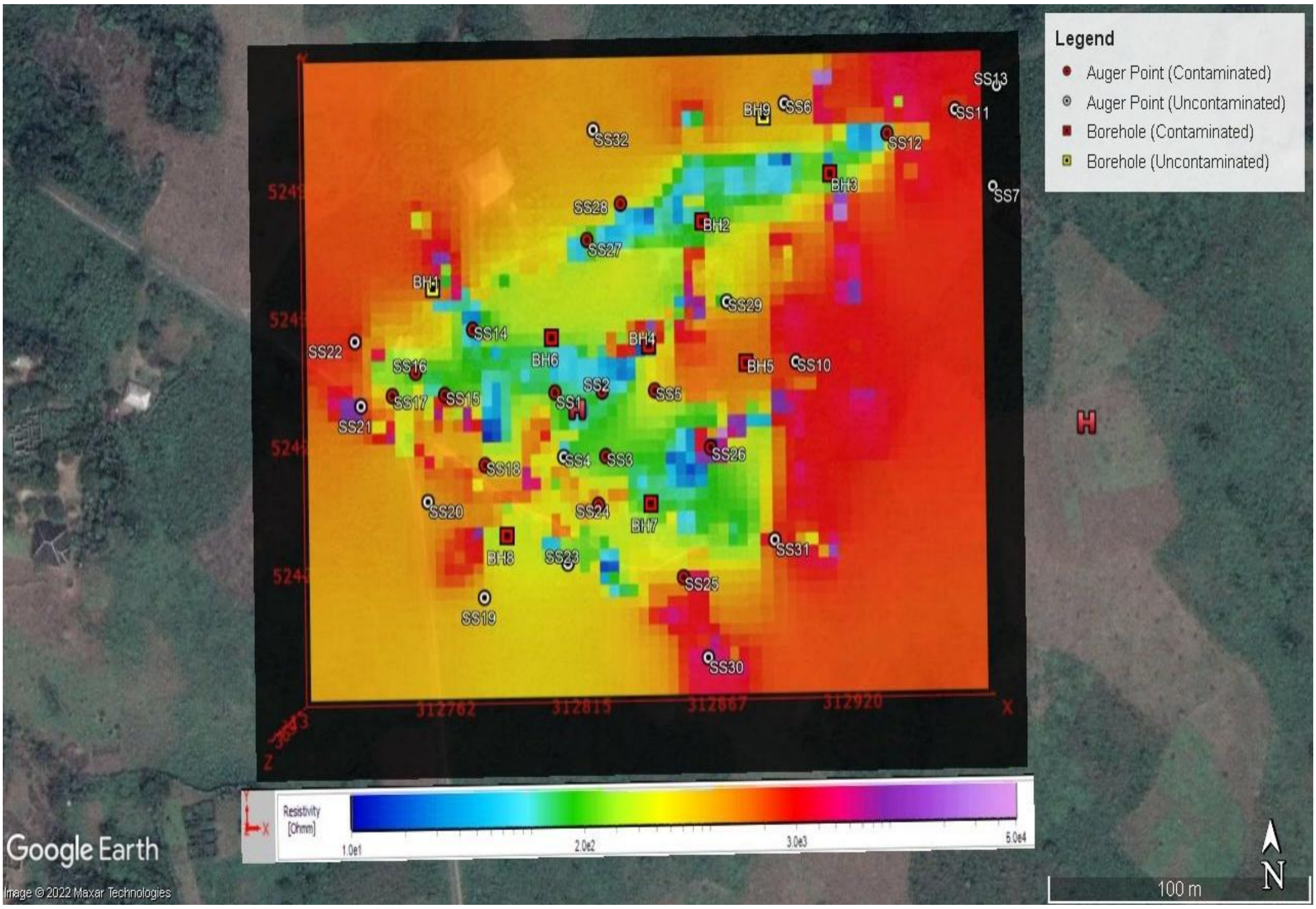

Fig. 2: Resistivity grid for 1.0m depth overlaid on google map along with auger points and borehole points

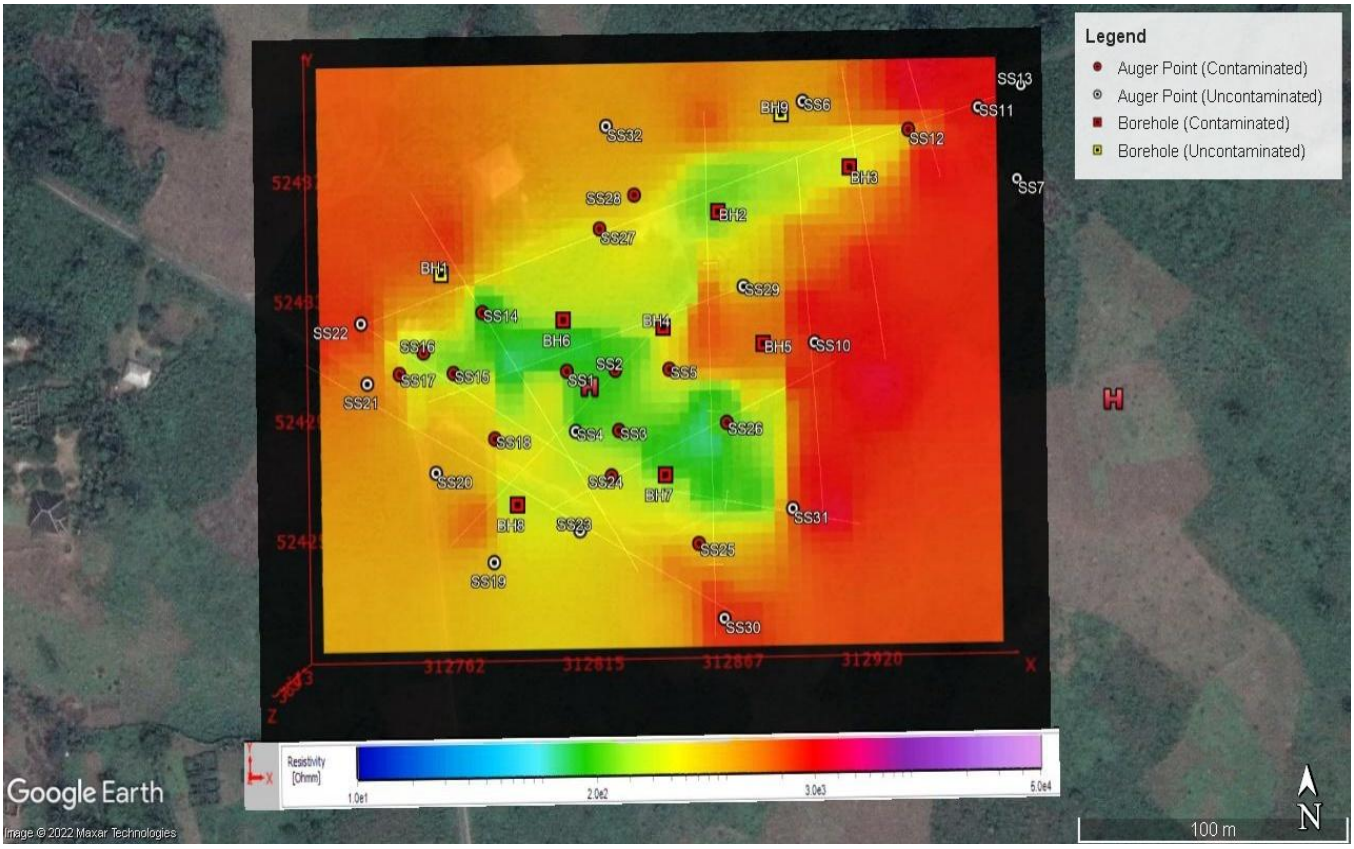

Fig. 3: Resistivity grid for 5.0m depth overlaid on google map along with auger points and borehole points

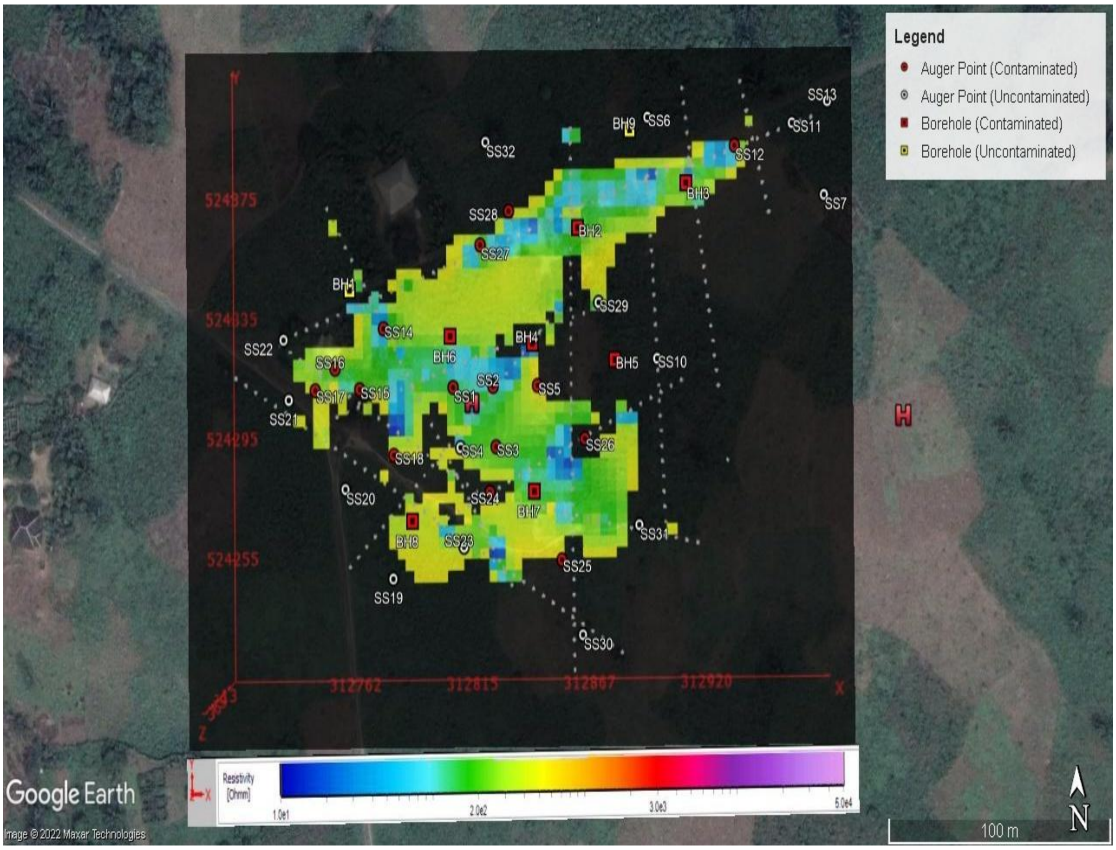

Fig. 4: Resistivity grid display for 1.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

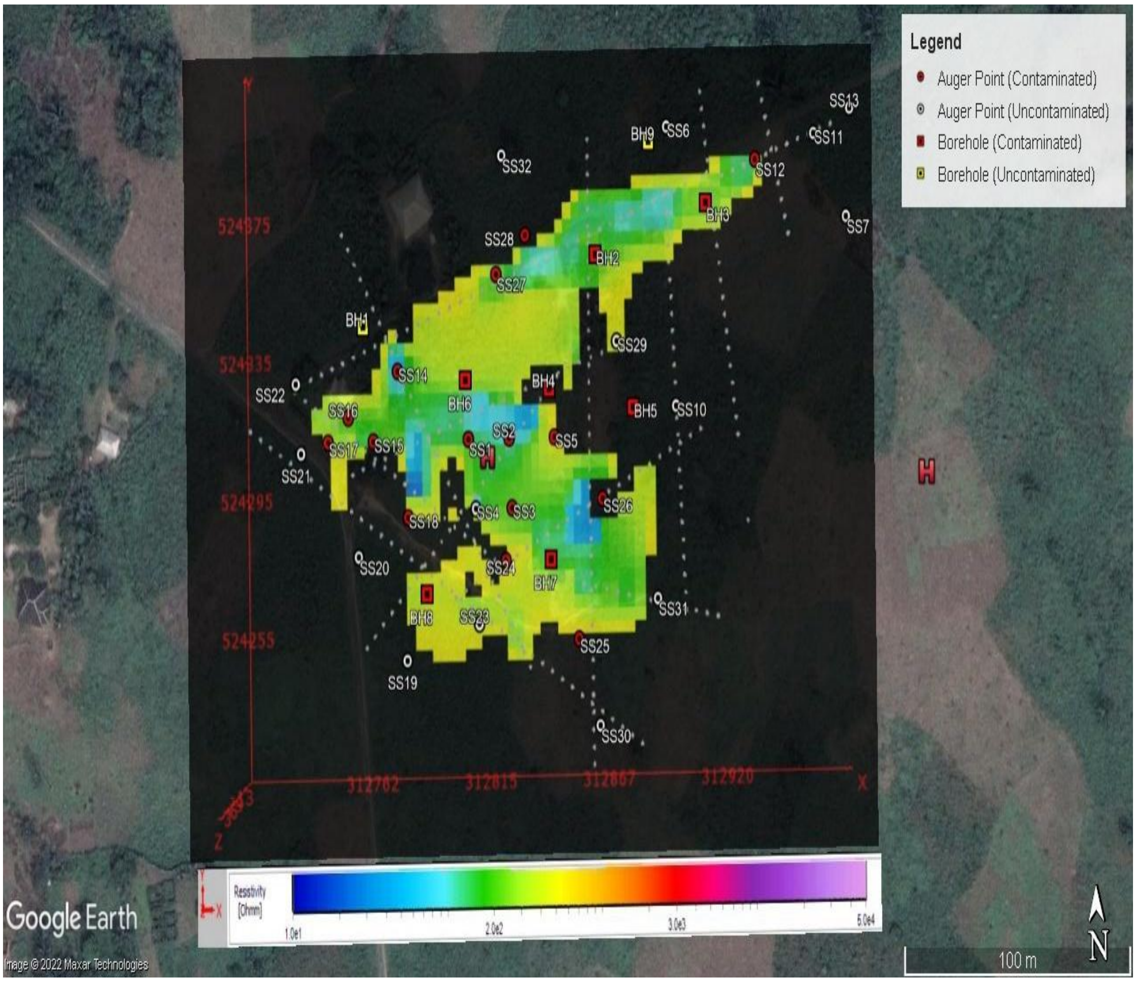

Fig. 5: Resistivity grid display for 3.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

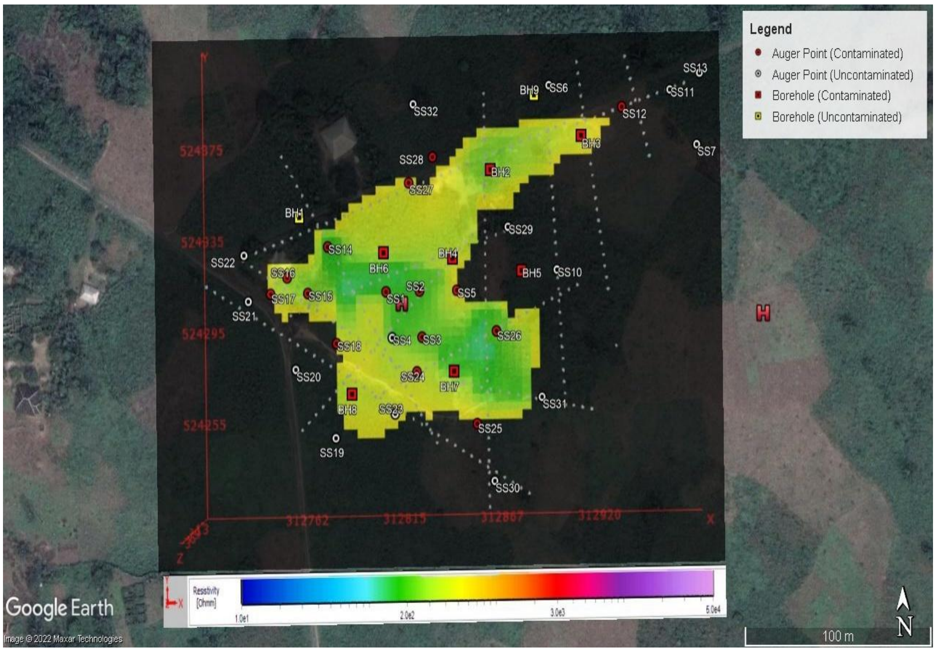

Fig 6: Resistivity grid display for 5.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

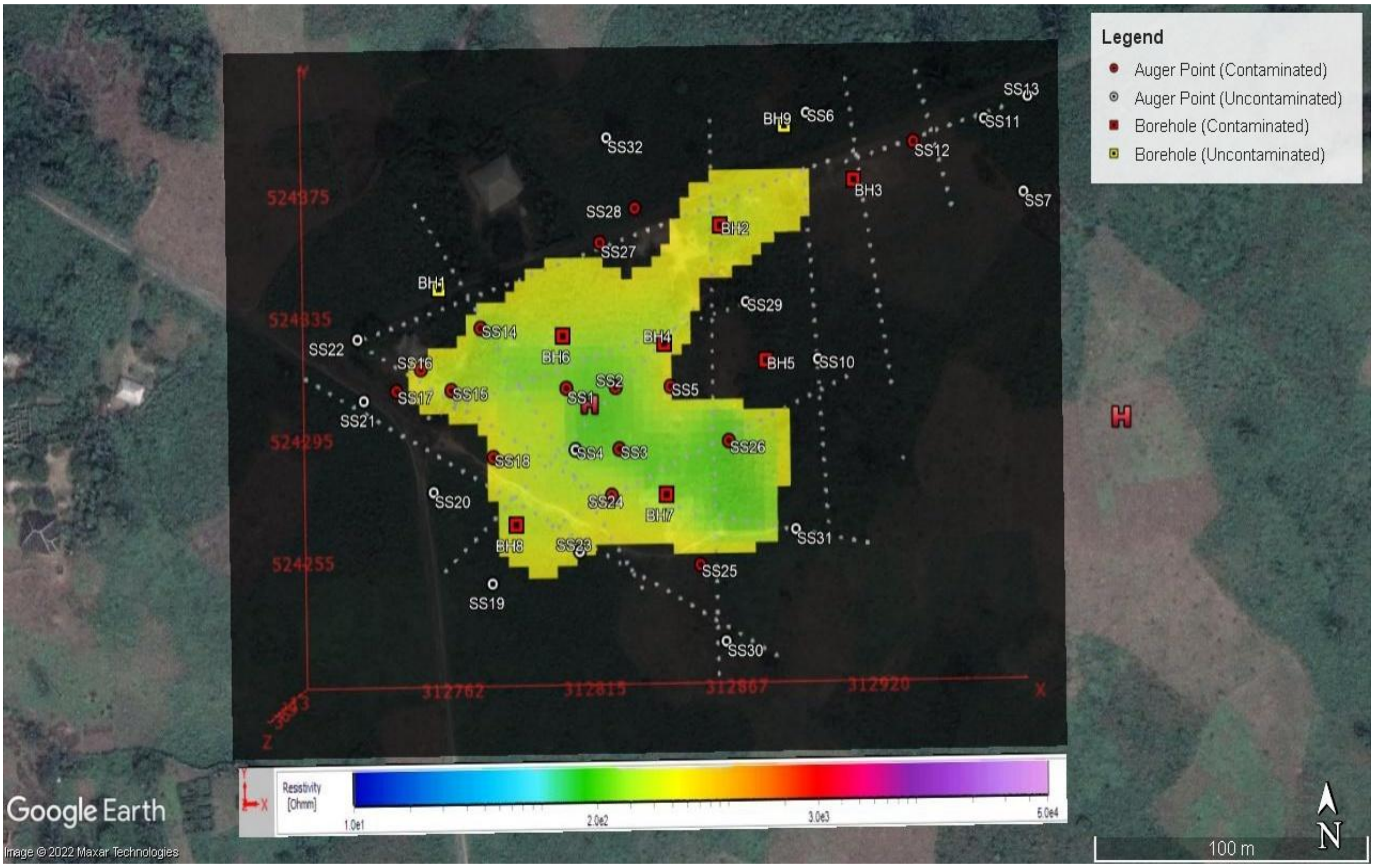

Fig. 7: Resistivity grid display for 8.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

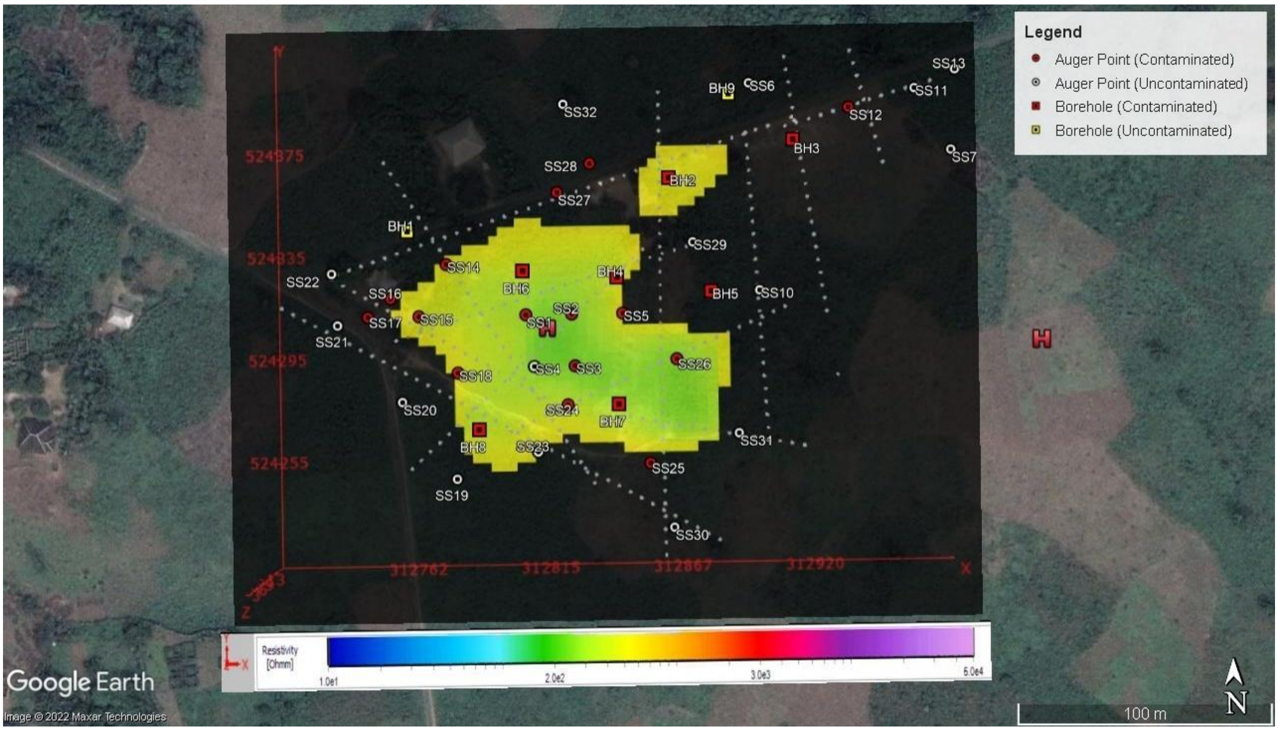

Fig. 8: Resistivity grid display for 12.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

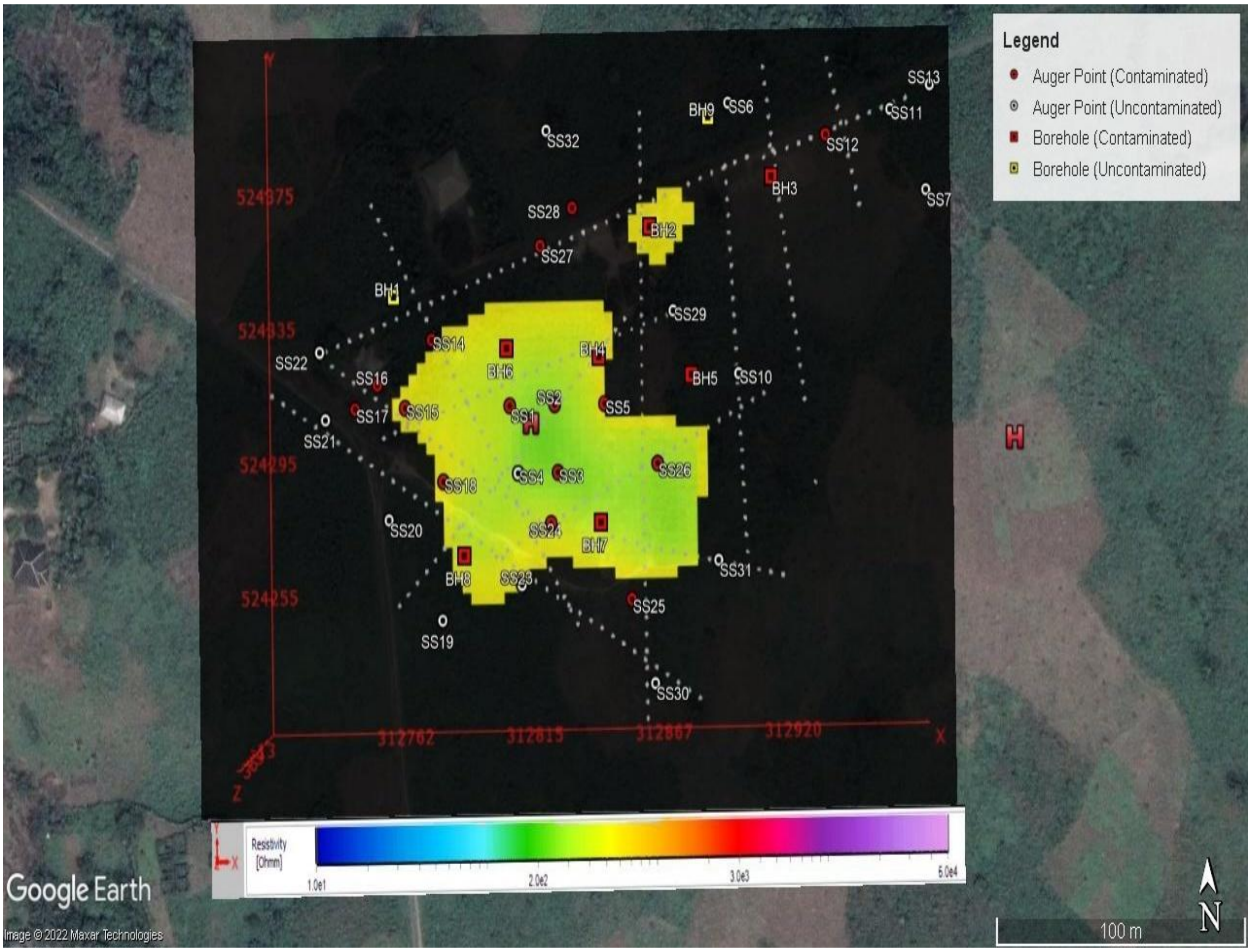

Fig. 9: Resistivity grid display for 16.0m depth overlaid on google map along with auger points and borehole points after applying a resistivity cut-off for oil contamination at ≤600 Ohm.m using both borehole and auger point constraints)

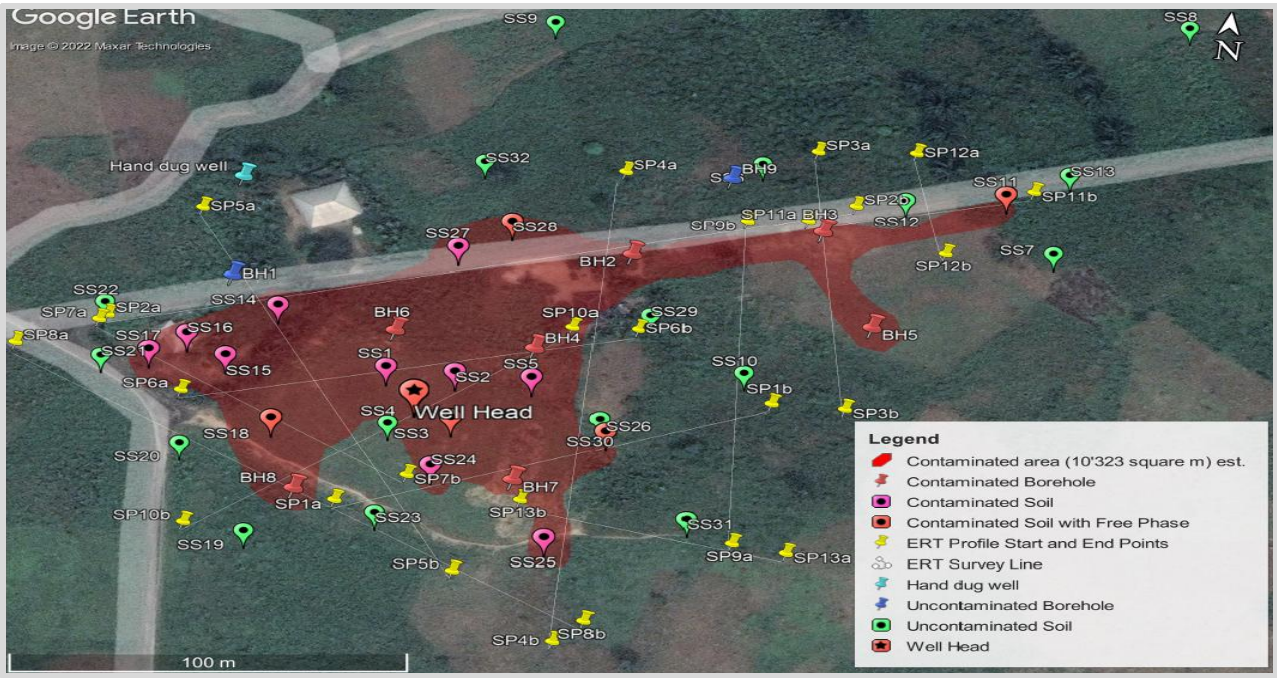

Fig. 10: Hydrocarbon contaminated delineated area based on soil sample data and borehole data. The surface area delineated is 10323sq

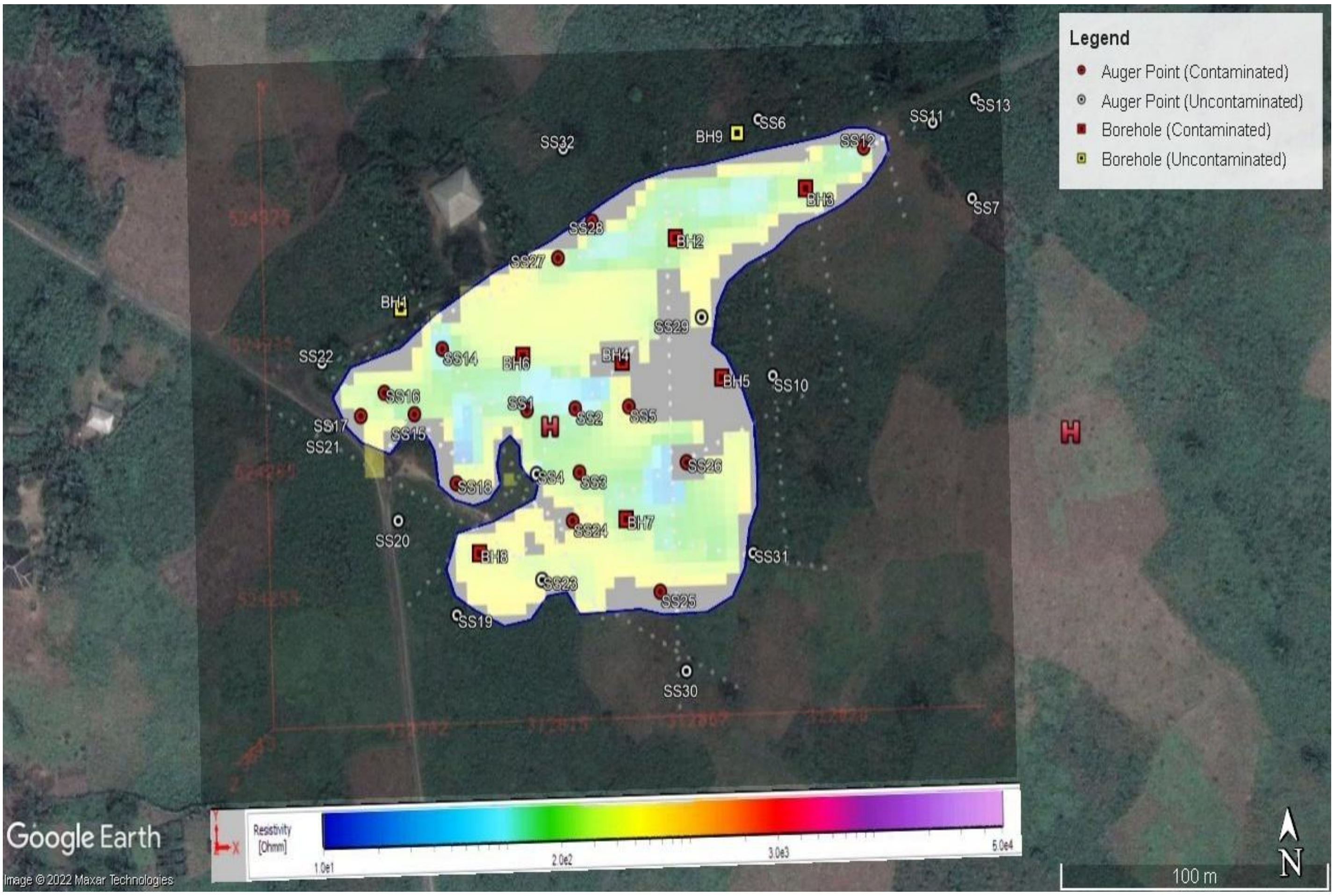

Fig. 11: Hydrocarbon contaminated area delineated based on resistivity and borehole data. The surface area delineated is 711m

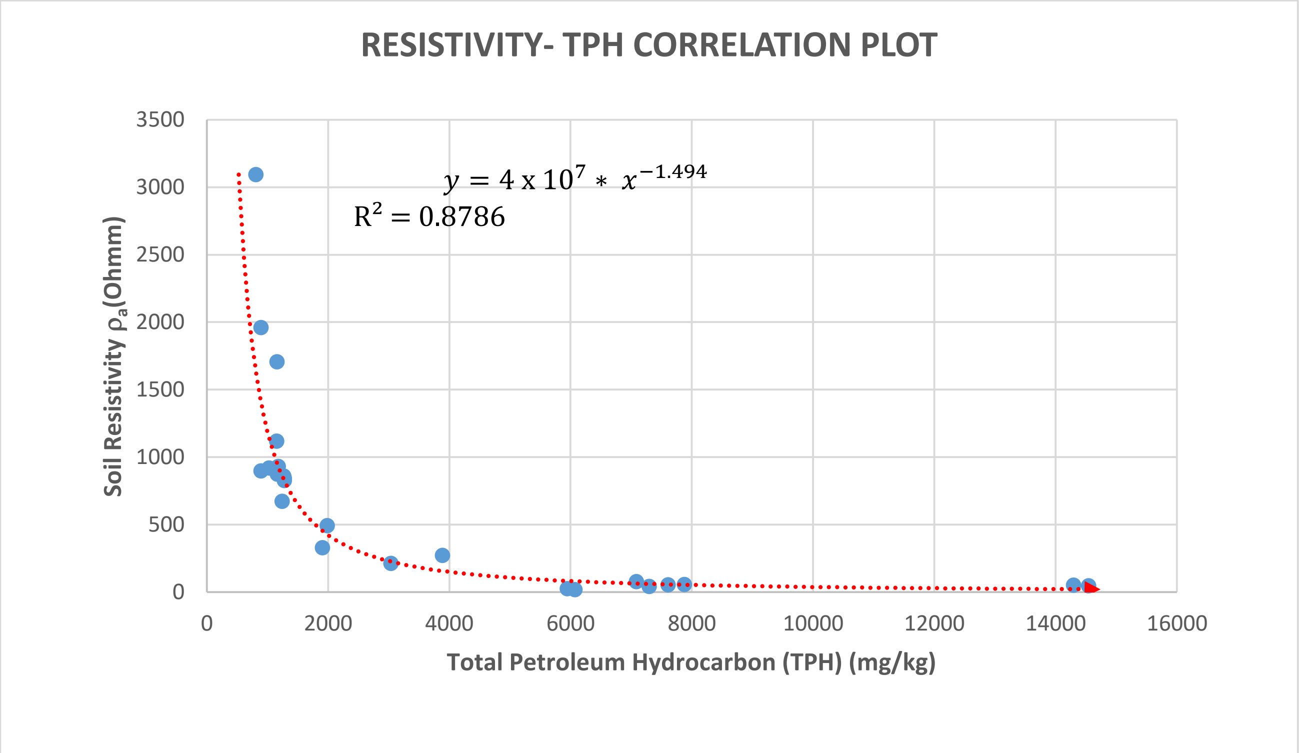

Fig. 12: Cross Plot showing correlation between ERT Resistivity and TPH concentration across the study area

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DISCUSSION

Geophysical Resistivity Results

The geophysical resistivity map reveals significant variations in subsurface resistivity, which can be correlated with hydrocarbon contamination. In fig. 3 to fig 9 we observe that the contaminant spread reduces with depth; this is evident when a resistivity cut-off for oil contamination at ≤600 Ohm's is applied to the depth slices of the 3D model. It shows that the top layers have greater contaminated area compared to deeper layers, suggesting that hydrocarbon migration was probably at the near surface.

Mature hydrocarbons are known to lower resistivity by displacing groundwater and altering the pore fluid chemistry, making resistivity surveys a useful tool for identifying contamination zones. Low-resistivity zones, depicted by blue, green, and yellow colors on the resistivity map, suggest areas of higher contamination. Notably the central portion of the map, around ERT **line 1, line 6, line 10**and parts of **line 5** and around sampling points **BH6, SS1, SS5, SS14**, and extending towards **line 3** and sample points **BH3, SS12**, shows a marked reduction in resistivity. This is indicative of a hydrocarbon plume that appears to have spread from the wellhead outward, possibly following subsurface permeability features such as fractures or porous zones.

The geophysical results show that the resistivity anomalies extending beyond the main contaminated zone near the wellhead suggesting potential migration of hydrocarbons along subsurface pathways offering early warnings of contamination spread even in areas where geochemical evidence might still be minimal.

Geochemical TPH Results

The geochemical TPH map, based on direct measurements of hydrocarbon concentrations in soil samples, confirms the presence of contamination and offers precise insights into its distribution and intensity. The map shows that the highest TPH concentrations are localized around the wellhead, particularly near boreholes **BH6, BH5**, and **SS1**, which are highlighted as high-contamination areas.

Unlike the resistivity map, which shows a broader spread of contamination, the TPH map indicates a more confined plume centered on the wellhead. The red-shaded area on the geochemical map represents the core contamination zone, where hydrocarbons are most concentrated. Further from this zone, TPH concentrations decrease, suggesting limited lateral migration of hydrocarbons in significant quantities.

Correlation between Geophysical and Geochemical Data

The cross plot of resistivity and TPH values indicate a high correlation justifying the effective integration of ERT and geochemical approach which provide a comprehensive understanding for the analysis. Both methods confirm the wellhead as the primary source of contamination, with consistent findings around **line 10, line 6, line 1** and **BH6, BH5, SS1**, and other nearby sampling points. In these areas, the geophysical map's low resistivity values correspond with high TPH concentrations, reinforcing the conclusion that hydrocarbons have significantly altered the subsurface environment.

However, there are notable differences between the two datasets in terms of spatial distribution. The resistivity map shows a broader anomaly, indicating potential contamination spread towards the northeast, especially around **SS12** and **SS29**. In contrast, the TPH map does not show high concentrations in these areas, suggesting that hydrocarbons may be migrating in smaller quantities, which have not yet reached detectable levels through chemical analysis. This highlights the sensitivity of resistivity methods in detecting early-stage or lower-concentration hydrocarbon contamination, where geochemical methods might not yet capture significant pollution.

Implications for Environmental Assessment and Remediation

The combined use of geophysical and geochemical methods offers a more robust approach to understanding subsurface hydrocarbon contamination. The resistivity survey provides early detection of potential contamination spread, which is essential for proactive monitoring, while the TPH data offers precise localization of high-concentration contamination zones that require immediate remediation.

From a remediation perspective, the wellhead area, as confirmed by both datasets, should be prioritized for cleanup due to the high concentrations of hydrocarbons detected there. However, the geophysical anomalies extending towards the northeast suggest that monitoring should continue in these peripheral zones to prevent the further spread of contamination. The resistivity map's broader coverage may also help in planning future sampling locations and guiding the expansion of remediation efforts if necessary.

CONCLUSION

The (ERT) and geochemical investigation successfully delineated aged hydrocarbon contamination in the study area at Korokoro, Tai L.G.A., Rivers State. The ERT results revealed prominent low-resistivity anomalies around Lines 1, 6, and 10 and sampling locations BH6, BH5 and SS1, while the geochemical results recorded elevated Total Petroleum Hydrocarbon (TPH) concentrations in the same areas.

The strong spatial agreement between low resistivity and high TPH concentrations confirms the wellhead as the major source of contamination. The shallow distribution of the anomalies also indicates that the hydrocarbon plume is predominantly concentrated near the surface, with possible lateral migration through permeable subsurface pathways.

The high- coefficient correlation in the plot of ERT and (TPH) provides an effective, non-invasive approach for delineating hydrocarbon-contaminated zones and guiding environmental monitoring and remediation activities in Niger Delta.

RECOMENDATION

1. Geophysical and Geochemical data techniques should be improved on, utilized and applied to both pre-remediation and post- remediation activities in hydrocarbon characterization studies.

2. Further geophysical and geochemical investigations should be carried out at intervals during and after the remediation exercise has commenced within the study area to adequately monitor the progress of remediation efforts.

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