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Development of A Geophysical and Geochemical Methodology for The Characterization of Oil Spill Sites

OLOZULU LEVI OLABAI
Department of Environmental Geology, Global Wealth University, Togo

Abstract- The presence of hydrocarbon contamination in the subsurface can modify the using an integrated geophysical and geochemical approach. The geophysical response to hydrocarbon contamination varies according to factors related to the contaminant in question and to the contaminated environment. Geophysical methods, including Electrical Resistivity Imaging (ERI) and Ground Penetrating Radar (GPR), were employed to delineate subsurface features and contamination plumes. ERI profiles captured variations in resistivity across depths, identifying hydrocarbon-rich zones, while GPR provided high-resolution images of shallow subsurface anomalies, such as buried hydrocarbon pools and fractured zones. Geochemical analyses focused on soil and water samples collected at varying depths (0–50 cm) and locations, quantifying Total Petroleum Hydrocarbons (TPH), heavy metals (e.g., lead, cadmium, chromium), pH, and salinity. Laboratory analyses adhered to ASTM and EPA guidelines, ensuring data reliability. The findings revealed significant contamination, with low resistivity values (6–8.7 ohm-meters) identifying hydrocarbon-rich layers between 5–15 meters. Geochemical data showed elevated TPH levels (4,800–5,200 mg/kg) and heavy metal concentrations exceeding World Health Organization (WHO) limits. GIS mapping highlighted contamination hotspots near spill points, correlating spatially with hydrocarbon accumulation and geophysical anomalies. This research underscores the value of integrating geophysical and geochemical methods with GIS for accurate environmental assessment and remediation planning. The results provide actionable insights into managing oil spill impacts in the Niger Delta region, emphasizing the need for urgent intervention and sustainable environmental practices.

Keywords: Geophysical Characterisation, Geochemical Characterisation, Oil Spill, Methodology

I. INTRODUCTION

Oil spills are among the most pressing environmental issues facing oil-producing regions, particularly in the Niger Delta area of Nigeria, which includes Bayelsa State. The catastrophic impacts of oil spills on ecosystems, public health, and local economies have garnered significant attention over the years. Despite numerous efforts by governments, international organizations, and oil companies to mitigate these effects, oil spill incidents persist, leaving long-lasting environmental damage (Nwilo & Badejo, 2006). Foropa and Ekeni, two communities in Bayelsa State, epitomize the challenges associated with oil contamination, making them ideal case studies for a comprehensive geophysical and geochemical investigation aimed at assessing and addressing the impacts of oil spills.

The Niger Delta region is one of the most prolific oil-producing areas globally, contributing significantly to Nigeria's economy. However, the activities of multinational oil companies and artisanal refining have resulted in frequent oil spills. According to reports by the National Oil Spill Detection and Response Agency (NOSDRA), more than 2,000 oil spill incidents were recorded in Nigeria between 2015 and 2022 alone, with Bayelsa State being one of the most affected (NOSDRA, 2022). Foropa and Ekeni, two coastal communities in Bayelsa, have suffered from decades of oil exploration activities, leading to extensive environmental degradation (UNEP, 2011). These oil spills typically result from pipeline leaks, operational failures, and sabotage, creating contamination that threatens both terrestrial and aquatic ecosystems (Oviasuyi & Uwadiae, 2010). Oil spills contaminate soil, water, and air, disrupting natural ecosystems and reducing biodiversity. In Foropa and Ekeni, oil spills have led to the destruction of mangrove forests, which serve as critical habitats for aquatic and terrestrial organisms. The contamination of soil by hydrocarbons reduces agricultural productivity, affecting the livelihood of subsistence farmers. In addition, groundwater and surface water sources in these communities are often contaminated with hydrocarbons and heavy metals, rendering them unsafe for consumption and leading to long-term ecological imbalance.

Exposure to petroleum hydrocarbons and heavy metals has severe health implications. Communities in Foropa and Ekeni often report cases of respiratory issues, skin irritation, and waterborne diseases due to direct contact with contaminated water and soil. Prolonged exposure to toxic substances such as benzene, cadmium, and lead increases the risk of cancer, kidney damage, and neurological disorders.

The socio-economic consequences of oil spills are significant, particularly for coastal communities like Foropa and Ekeni that depend heavily on fishing and farming. Contaminated waterways lead to declining fish stocks, forcing fishermen to abandon their primary source of livelihood. Similarly, the destruction of arable land reduces agricultural yields, exacerbating poverty and food insecurity in these regions. Additionally, the constant threat of spills and associated cleanup operations destabilizes the social fabric of affected communities, leading to conflicts over resource allocation and compensation.

Traditional approaches to addressing oil spills often focus on cleanup and remediation without thoroughly assessing the extent of contamination. However, a deeper understanding of the subsurface and surface contamination patterns is essential for developing effective remediation strategies. Geophysical and geochemical methods offer a robust framework for characterizing oil spill sites by providing critical insights into subsurface conditions, contamination pathways, and the spatial distribution of hydrocarbons and heavy metals.

Geophysical techniques, such as Electrical Resistivity Imaging (ERI) and Ground Penetrating Radar (GPR), are widely used for environmental assessments. ERI is particularly effective for mapping subsurface resistivity variations, which can indicate the presence of hydrocarbons. Hydrocarbons often reduce soil resistivity, making ERI a valuable tool for identifying contaminated zones (Ibeneme et al., 2021). Similarly, GPR provides high-resolution images of shallow subsurface anomalies, such as hydrocarbon pools and fractures. The application of these techniques in Foropa and Ekeni can reveal critical information about the extent of contamination and help guide remediation efforts (Obasi et al., 2022).

Geochemical investigations complement geophysical methods by quantifying contamination levels in soil and water. Parameters such as Total Petroleum Hydrocarbons (TPH), heavy metals, pH, and salinity provide valuable information about the severity of contamination. High TPH concentrations, for example, indicate significant hydrocarbon pollution, while elevated levels of heavy metals like cadmium and chromium pose serious health risks. By combining geochemical data with geophysical findings, researchers can create a comprehensive model of contamination, enabling targeted remediation.

The choice of Foropa and Ekeni as study areas is strategic. These communities have been subjected to repeated oil spills over the years, making them emblematic of the broader challenges faced by oil-producing regions in Nigeria. Preliminary reports suggest that both locations exhibit significant contamination of soil and water resources. However, no comprehensive geophysical and geochemical study has been conducted to assess the full extent of this contamination. By focusing on these communities, this research aims to fill a critical knowledge gap and contribute to the development of science-based solutions for environmental remediation.

Globally, oil spills have spurred considerable research and policy interventions. For instance, the Deepwater Horizon oil spill in 2010 highlighted the need for advanced technologies and robust regulations to prevent and manage spills (Atlas & Hazen, 2011). Countries like Norway and Canada have implemented stringent environmental regulations and adopted advanced geophysical techniques to monitor oil spill sites. In contrast, Nigeria's regulatory framework, though robust on paper, suffers from weak enforcement and inadequate funding (Amnesty International, 2018). The Petroleum Industry Act (PIA) of 2021 aims to address some of these gaps by mandating more stringent environmental standards and increased

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community involvement. However, the effectiveness of these measures remains to be seen (PIA, 2021).

Despite the widespread occurrence of oil spills in Nigeria, there is a paucity of studies that integrate geophysical and geochemical methods to assess contamination. Most existing studies focus on isolated aspects, such as water quality or soil remediation, without considering the interconnectedness of these elements. This research seeks to bridge this gap by employing a multidisciplinary approach that combines geophysical imaging, geochemical analysis, and Geographic Information Systems (GIS) to provide a holistic understanding of contamination patterns. The findings will not only advance scientific knowledge but also inform policy and practice, offering practical solutions for environmental remediation. Therefore, this study examines geophysical and geochemical characterization of oil spill sites using Foropa and Ekeni in Bayelsa State, Nigeria as a case study.

II. STATEMENT OF THE PROBLEM

Oil spills in the Niger Delta region of Nigeria have become an enduring environmental crisis, causing extensive damage to ecosystems, livelihoods, and public health. Despite decades of oil exploration and extraction, the affected communities continue to grapple with the severe consequences of hydrocarbon contamination. Among these communities, Foropa and Ekeni in Bayelsa State are particularly vulnerable, as they have experienced recurrent oil spill incidents due to pipeline ruptures, operational failures, and artisanal refining activities.

The environmental consequences of these spills are far-reaching. Contaminated soils have become infertile, leading to a decline in agricultural productivity. Polluted water sources expose residents to toxic substances such as benzene, cadmium, and chromium, posing significant health risks, including cancer and organ damage. Furthermore, the destruction of mangrove ecosystems has disrupted fishery activities, depriving the communities of their primary source of livelihood. This confluence of environmental degradation and socio-economic hardship has created a complex challenge that demands urgent and targeted solutions.

Efforts to address oil spills in the Niger Delta have been largely fragmented and insufficient. Traditional remediation approaches often fail to consider the full extent of contamination, particularly the subsurface migration of hydrocarbons and their spatial distribution. Additionally, most studies focus on isolated environmental parameters, such as water quality or soil contamination, without integrating geophysical and geochemical data. This lack of comprehensive characterization impedes the development of effective remediation strategies, leaving critical gaps in understanding the contamination dynamics in oil spill-impacted areas like Foropa and Ekeni.

Moreover, there is a glaring absence of site-specific studies that incorporate advanced geophysical techniques, such as Electrical Resistivity Imaging (ERI) and Ground Penetrating Radar (GPR), alongside detailed geochemical analyses. These methods are crucial for accurately delineating contamination zones, identifying hydrocarbon migration pathways, and quantifying the severity of pollution. Without such integrated approaches, remediation efforts risk being ineffective, costly, or environmentally unsustainable.

This research seeks to address these gaps by employing a multidisciplinary approach that integrates geophysical and geochemical methods. By focusing on Foropa and Ekeni, the study aims to provide a comprehensive characterization of the contamination, enabling the development of targeted remediation strategies. This approach not only advances scientific understanding but also offers practical solutions for mitigating the environmental and socio-economic impacts of oil spills in these vulnerable communities. It is against this background that this study examines geophysical and geochemical characterization of oil spill sites using Foropa and Ekeni in Bayelsa State, Nigeria as a case study.

Objectives of the Study

The primary aim of this research is to characterize the oil spill sites in Foropa and Ekeni using geophysical and geochemical methods. The specific objectives include:

1. To delineate subsurface features and contamination plumes using Electrical Resistivity Imaging (ERI) and Ground Penetrating Radar (GPR).
2. To analyze soil and water samples for Total Petroleum Hydrocarbons (TPH), heavy metal concentrations, pH, and salinity levels.
3. To integrate geophysical and geochemical findings into Geographic Information Systems (GIS) for mapping contamination patterns and identifying critical hotspots for remediation.

III. LITERATURE REVIEW: OVERVIEW OF GEOPHYSICAL AND GEOCHEMICAL CHARACTERIZATION OF OIL SPILL SITES

Oil spills are one of the most severe environmental challenges, especially in regions like Bayelsa State, Nigeria, where oil exploration and extraction activities are prevalent. The impact of oil spills on the ecosystem, including soil, water, and air quality, as well as human health, has prompted research into methods for assessing and managing these disasters. Geophysical and geochemical techniques have proven effective in characterizing and assessing the extent of contamination in oil spill sites.

Geophysical methods, such as electrical resistivity tomography (ERT), ground-penetrating radar (GPR), and seismic refraction, have been widely used to assess the subsurface conditions of contaminated sites. These techniques help to map the spatial distribution of contaminants and understand the flow of hydrocarbons in soil and groundwater. For example, in the Niger Delta region, studies by Nwachukwu et al. (2019) demonstrated the application of ERT to identify zones of oil contamination in soil, revealing that oil spills often lead to significant changes in the electrical properties of the affected soils. ERT was particularly useful in mapping the spread of oil spills at different depths, which is critical for determining the scope of contamination in inaccessible or remote locations.

Geochemical characterization, on the other hand, involves the analysis of soil, water, and sediment samples to determine the presence and concentration of hydrocarbons and related contaminants. Studies conducted by Okwuosa et al. (2018) in the Niger Delta have employed geochemical methods to assess the concentration of petroleum hydrocarbons in soils around oil spill sites, including the use of gas chromatography-mass spectrometry (GC-MS) to detect and quantify specific compounds. These studies highlighted the persistence of petroleum hydrocarbons in the soil and the slow natural remediation processes, emphasizing the need for effective cleanup strategies.

In Bayelsa State, the communities of Foropa and Ekeni have experienced numerous oil spills due to oil exploration activities. Research by Akinmoladun et al. (2020) has focused on these regions, employing both geophysical and geochemical methods to assess contamination levels. Their findings indicate that oil spills in these areas have led to severe environmental degradation, affecting agricultural productivity, water resources, and biodiversity. The combined use of geophysical and geochemical techniques in these areas provides a comprehensive approach to mapping the extent of contamination and formulating appropriate remediation plans.

In conclusion, the use of geophysical and geochemical methods in the characterization of oil spill sites offers a reliable means of assessing environmental damage and guiding remediation efforts. Future studies should aim to enhance these methods for more accurate and cost-effective environmental monitoring in oil-affected areas, such as Bayelsa State.

IV. METHODOLOGY

The methodological framework for this research integrates geophysical and geochemical investigations to characterize the extent of contamination, subsurface features, and hydrocarbon

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distribution patterns in the oil spill sites of Foropa and Ekeni in Bayelsa State.

The geophysical investigations involved the application of Electrical Resistivity Imaging (ERI) and Ground Penetrating Radar (GPR) to map subsurface features and delineate contamination zones. To begin, survey grid lines were established across the contaminated areas in both study locations. The ERI technique was employed using a multi-electrode resistivity system, with electrode spacing of 2–5 meters, to capture variations in soil and groundwater resistivity. These resistivity profiles helped to identify potential contamination plumes and hydrocarbon migration pathways. GPR complemented this method by providing high-resolution images of shallow subsurface anomalies, such as hydrocarbon accumulation and buried debris, using antennas with frequencies between 100–500 MHz. The data obtained from these techniques were processed and interpreted using specialized software, such as RES2DINV for resistivity data and radargram analysis for GPR data.

The geochemical investigations focused on soil and water sampling to quantify contamination levels and analyze the chemical properties of the affected environment. Soil samples were collected from grid points at varying depths (0–15 cm, 15–30 cm, and 30–50 cm) to capture vertical variations in contamination. Similarly, water samples were obtained from wells, boreholes, and surface water sources in the study areas. The laboratory analysis of these samples included measuring Total Petroleum Hydrocarbons (TPH) using Gas Chromatography-Mass Spectrometry (GC-MS), analyzing heavy metals (e.g., lead, cadmium, chromium) through Atomic Absorption Spectroscopy (AAS), and determining pH and salinity levels using pH and conductivity meters. All analyses will adhere to standard procedures as outlined by ASTM or EPA guidelines, with quality control ensured through the use of field blanks and duplicate samples.

The geophysical and geochemical data were integrated to produce a comprehensive model of contamination patterns. Geographic Information Systems (GIS) was employed to map the spatial distribution of hydrocarbons and subsurface anomalies, enabling a holistic understanding of the affected areas. This integration of datasets allowed for a more detailed characterization of contamination and provide valuable insights into hydrocarbon distribution and subsurface features.

In summary, this methodological framework employs a field-based, experimental approach combining geophysical techniques with geochemical analysis. It ensures a robust and accurate assessment of oil spill impacts in Foropa and Ekeni, facilitating effective environmental remediation and sustainable management strategies.

V. RESULTS AND FINDINGS

Demographics of Collected Data

To ensure transparency and reproducibility, Table 1 presents the basic characteristics of the collected data, including the number of sampling points, types of samples collected, and depths surveyed.

Table 1: Summary of Basic Characteristics of the Collected Data

Parameter	Foropa	Ekeni	Total
Soil Samples (0–15 cm depth)	14	17	31
Soil Samples (15–30 cm depth)	14	17	31
Soil Samples (30–50 cm depth)	14	17	31
Water Samples (Surface)	9	8	17
Water Samples (Boreholes)	5	5	10
Geophysical Profiles (ERI)	3	3	6
GPR Transects	4	4	8

The data presented in Table 1 provides a detailed summary of the basic characteristics of the samples collected from the Foropa and Ekeni oil spill sites, offering insight into the scope and depth of the research. This data includes the number of sampling points, types of samples collected, and depths surveyed, ensuring transparency and reproducibility in the study.

In terms of soil samples, a total of 81 samples were collected, distributed across three different depth levels: 0–15 cm, 15–30 cm, and 30–50 cm. For

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Foropa, 12 soil samples were taken at each of the three depth levels, amounting to 36 soil samples in total. In Ekeni, 17 samples were collected at each depth level, resulting in 45 soil samples. The total number of soil samples from both locations was therefore 81, with 31 samples at each depth level.

Water samples were collected from both surface and borehole sources. For surface water, 8 samples were taken from Foropa and 7 from Ekeni, leading to a total of 17 surface water samples. In terms of borehole water samples, 5 samples were collected from each location, resulting in a total of 10 borehole water samples.

Geophysical surveys using Electrical Resistivity Imaging (ERI) were conducted with 3 profiles taken at Foropa and 3 at Ekeni, totaling 6 ERI profiles for both locations. Ground Penetrating Radar (GPR) transects were also conducted at both sites, with 4 transects performed at each location, adding up to 8 GPR transects overall.

This sampling strategy illustrates a comprehensive approach to understanding the extent of contamination at the oil spill sites, with a balanced distribution of samples from Foropa and Ekeni. While the number of samples collected from Ekeni slightly surpasses those from Foropa in most categories, the overall data collection is evenly spread across the two locations. The total number of soil samples stands out as the most substantial data category, followed by water samples and geophysical survey results. This diverse set of data provides a robust foundation for analyzing the severity and spread of contamination in the study areas.

Research Objective 1: Subsurface Features and Contamination Plumes

Table 2: Resistivity Values Indicating Contamination

Depth Range (m)	Foropa Mean Resistivity (ohm-m)	Ekeni Mean Resistivity (ohm-m)	Interpretation
0–5	12.5	11.8	Mixed soil, minimal contamination
5–10	8.7	7.9	Contaminated zone (hydrocarbons)
10–15	6.2	6.0	Highly contaminated, hydrocarbon-rich layers
15–20	9.5	8.8	Transition zone, moderate contamination

Descriptive statistics (means and ranges) were used to summarize resistivity data. Correlation analysis between resistivity and depth was performed, showing a negative correlation ($r = -0.81$, $p < 0.05$), indicating increasing contamination with depth.

The Electrical Resistivity Imaging (ERI) profiles revealed zones of low resistivity (less than 10 ohm-meters) at depths ranging from 5 to 20 meters, consistent with hydrocarbon-contaminated layers. Ground Penetrating Radar (GPR) radargrams confirmed the presence of shallow subsurface anomalies, such as buried hydrocarbon pools and fractured zones, particularly around known spill points.

Research Objective 2: Geochemical Analysis

Table 3: Mean Contaminant Concentrations

Parameter	Foropa (Mean ± SD)	Ekeni (Mean ± SD)	WHO Limit
TPH (mg/kg, soil)	4,800 ± 450	5,200 ± 500	50
Lead (mg/L, water)	0.12 ± 0.03	0.15 ± 0.04	0.01
Cadmium (mg/L, water)	0.09 ± 0.02	0.11 ± 0.03	0.003
Chromium	0.18 ± 0.05	0.21 ± 0.06	0.05

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Parameter	Foropa (Mean ± SD)	Ekeni (Mean ± SD)	WHO Limit
(mg/L, water)			
pH (water)	6.2 ± 0.5	6.0 ± 0.4	6.5–8.5
Salinity (ppt)	4.5 ± 0.8	5.2 ± 0.9	< 1.0

A t-test was used to compare TPH and heavy metal concentrations between Foropa and Ekeni. Significant differences were observed for TPH ($p = 0.03$), cadmium ($p = 0.04$), and salinity ($p = 0.02$), indicating varying contamination levels between the sites.

Soil and water samples revealed significant contamination by Total Petroleum Hydrocarbons (TPH) and heavy metals (e.g., lead, cadmium, and chromium), exceeding acceptable environmental thresholds. The pH values of water samples were slightly acidic, while salinity levels were elevated.
Research Objective 3: GIS-Based Contamination Mapping

Table 4: Contamination Spread and Hotspots

Parameter	Foropa Hotspot Area (sq. km)	Ekeni Hotspot Area (sq. km)
Hydrocarbon Contamination	1.8	2.4
Heavy Metal Contamination	2.0	2.6

GIS spatial analysis was supported by Kriging interpolation, which generated contamination distribution maps. Correlation between contamination levels and proximity to spill points was statistically significant ($r = -0.85$, $p < 0.01$).

The integration of geophysical and geochemical data into GIS provided spatial maps of contamination hotspots. Foropa showed a concentrated contamination zone near the primary spill site, extending radially to a 2 km radius. Ekeni exhibited a more dispersed contamination pattern, likely influenced by water flow and sediment transport.

VI. DISCUSSION OF FINDINGS

The findings from the subsurface analysis demonstrate significant hydrocarbon contamination at depths between 5–15 meters in Foropa and Ekeni. The Electrical Resistivity Imaging (ERI) data revealed low resistivity values (below 10 ohm-meters), which are indicative of hydrocarbon-rich layers. These contaminated zones corresponded with Ground Penetrating Radar (GPR) radargrams that confirmed anomalies such as buried hydrocarbon pools and fractured subsurface structures near spill points. The strong negative correlation ($r = -0.81$, $p < 0.05$) between resistivity and depth highlights increasing contamination with depth, transitioning to moderate contamination at greater depths (15–20 meters).

This aligns with the work of Nwachukwu et al. (2019), who found that ERI is effective for delineating hydrocarbon-contaminated zones in oil spill sites in the Niger Delta, reporting similar resistivity trends in contaminated soils. Similarly, Ibeneme et al. (2021) confirmed the reliability of GPR in detecting hydrocarbon pools and subsurface fractures near oil spill points, consistent with this study's findings.

In contrast, Obaje et al. (2018) observed minimal subsurface contamination in clay-dominated soils, where hydrocarbon migration was restricted due to low permeability. The sandy soils in Foropa and Ekeni, characterized by higher permeability, explain the discrepancy and the more extensive contamination observed in this study.

The geochemical analysis reveals significant contamination in Foropa and Ekeni, exceeding the World Health Organization (WHO) limits for Total Petroleum Hydrocarbons (TPH), heavy metals, and salinity. TPH levels in soil were exceptionally high, with means of 4,800 mg/kg in Foropa and 5,200 mg/kg in Ekeni, far surpassing the 50 mg/kg WHO limit. Similarly, lead, cadmium, and chromium concentrations in water samples were significantly elevated. Cadmium, for instance, was 0.09 mg/L in Foropa and 0.11 mg/L in Ekeni, compared to the permissible limit of 0.003 mg/L. Additionally, water

pH levels were slightly acidic, and salinity levels were elevated at 4.5 ppt in Foropa and 5.2 ppt in Ekeni, against the acceptable threshold of 1.0 ppt.
These findings align with the work of Nwachukwu et al. (2020), who reported elevated TPH and heavy metal concentrations in oil-impacted sites in the Niger Delta, attributing these to persistent hydrocarbon contamination. Similarly, Akintoye et al. (2019) found significantly acidic water pH and high salinity in areas affected by oil spills, consistent with this study's observations.

Contrarily, Okoro et al. (2018) found that contamination was less severe in soils with high clay content, where hydrocarbon absorption and reduced mobility mitigated pollution. The sandy, permeable soils in Foropa and Ekeni may explain the contrasting findings.

The GIS-based contamination mapping effectively identified hydrocarbon and heavy metal contamination hotspots in Foropa and Ekeni. In Foropa, the hydrocarbon contamination hotspot covered 1.8 square kilometers, while heavy metal contamination extended to 2.0 square kilometers. Ekeni demonstrated larger contamination hotspots, with 2.3 square kilometers for hydrocarbons and 2.5 square kilometers for heavy metals. These variations may be attributed to factors such as proximity to spill points, water flow, and sediment transport. The Kriging interpolation method used in GIS analysis revealed a significant negative correlation ($r = -0.85$, $p < 0.01$) between contamination levels and distance from spill points, confirming the spatial dependence of contamination on the spill locations.

These findings align with the work of Adedeji et al. (2019), who used GIS to map contamination in the Niger Delta and found a similar pattern of concentrated hotspots around spill points, with contamination decreasing with distance. Similarly, Okafor et al. (2021) demonstrated the influence of water flow and sediment transport in dispersing contaminants, explaining the larger hotspot areas in Ekeni. However, Bello et al. (2018) reported minimal spatial spread of contamination in clay-dominated regions due to limited hydrocarbon mobility, contrasting with the more extensive contamination observed in the sandy soils of Foropa and Ekeni.

VII. CONCLUSION

This study highlights the significant environmental impacts of oil spills in Foropa and Ekeni, Bayelsa State, Nigeria, through an integrated approach combining geophysical, geochemical, and GIS-based analyses. The findings revealed extensive subsurface contamination, with low resistivity values indicating hydrocarbon-rich layers at depths of 5–15 meters. Geochemical analysis showed elevated levels of Total Petroleum Hydrocarbons (TPH), heavy metals such as lead, cadmium, and chromium, and increased salinity, all exceeding World Health Organization (WHO) limits. GIS spatial mapping further identified contamination hotspots, with significant correlations between contamination intensity and proximity to spill points.

These results underscore the need for urgent remediation efforts and stricter regulatory measures to mitigate environmental degradation. The study also emphasizes the importance of integrating advanced analytical techniques like GIS for effective environmental monitoring and planning. Future research should explore the long-term ecological and socio-economic effects of such contamination to inform sustainable management strategies.

VIII. RECOMMENDATIONS

Based on the findings of the study, the following recommendations were made.

1. Immediate remediation efforts, such as bioremediation, soil washing, or in-situ chemical oxidation, should be prioritized in Foropa and Ekeni to address the severe contamination of soil and water by hydrocarbons and heavy metals.
2. Stricter enforcement of environmental laws and penalties for oil spill incidents are necessary to ensure accountability by oil companies and reduce future contamination risks.

3. Deploy advanced technologies, such as Electrical Resistivity Imaging (ERI), Ground Penetrating Radar (GPR), and GIS, for continuous environmental monitoring to detect and address contamination early.
4. Organize community education programs to raise awareness about the health risks of contaminated soil and water and involve local stakeholders in monitoring and remediation efforts.
5. Encourage oil companies to adopt sustainable practices, such as improved pipeline maintenance, spill prevention measures, and eco-friendly drilling methods, to minimize environmental damage in the Niger Delta.

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