



Environmental impacts of hydrocarbon contaminants and associated potential public health risks

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ABSTRACT

Hydrocarbons no doubt remain a major wheel of global energy and economic development. However, the insidious environmental impact of hydrocarbon contaminants (HCCs) presents a pressing concern due to the potential health risks associated with elevated levels of Polycyclic Aromatic Hydrocarbons (PAHs), Total Petroleum Hydrocarbons (TPH), and heavy metals (HMs). This study investigates the impact of HCCs at the Kaduna Refinery Petrochemical Corporation (KRPC) in Nigeria, a site selected due to its history of spills and high potential for contamination. The primary goal was to evaluate both the levels and distribution of HCCs in the area, utilizing hydro-chemical analysis and electrical resistivity imaging (ERI) to measure contaminant concentration and spatial spread. Analytical results indicated PAH levels ranging between 0.65 and 1.47 µg/l, TPH concentrations of (0.3421 - 0.5716) µg/l, and HM values from 0.038 to 1.711 mg/l, many falling within and few slightly exceed safety thresholds, established by the World Health Organization (WHO) and Nigeria's National Directorate of Petroleum Resources (NDPR). ERI data also showed significant anomalies in topsoil resistivity, with values between 5000 and 50000 Ωm, far exceeding the typical regional range of 300–3000 Ωm, indicating notable contamination concentrated near the surface. Although contamination levels relatively align with regulatory standards, continued monitoring is strongly recommended to prevent potential long-term impacts. This study demonstrates the significance of integrating hydrochemical and geophysical methods for detailed environmental assessments, enhancing contamination detection, guiding sustainable environmental management and regulatory enforcement.

1. Introduction

Hydrocarbons remain an indispensable resource in our modern world, fuelling industries, powering economies, and driving the engines of innovation on a global scale. From transportation to manufacturing, hydrocarbons have proven to be the cornerstone of economic vitality, a force to be reckoned with in the relentless pursuit of advancement and prosperity. However, hydrocarbon contamination (HCC) remains a significant environmental challenge that threatens ecosystems and public health. Hydrocarbons are organic compounds that consist of hydrogen and carbon atoms, popularly found in petroleum products like gasoline,

crude oil, and diesel fuel (Adeniran, et al., 2024). The discharge of HCCs into the environment is notably exemplified by the Exxon Valdez oil spill in 1989, when an oil tanker collided with a rock in Prince William Sound, Alaska, resulting in the release of approximately 42 million litres of crude oil into the ocean (Schab, 2022). The predominant release of HCCs into the environment typically transpires through diverse human activities, including inappropriate waste disposal, industrial discharges, and oil spills, which can last in the environment for extended durations, resulting in detrimental impacts on air, water, and soil quality (Khan and Islam, 2020; Kuppusamy, et al., 2020). In addition to these environmental impacts, HCCs can also pose serious health risks to individuals

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living in affected zones through the consumption of affected groundwater, plants, and hydrocarbon-polluted air. (Sam, et al., 2017; UNEP, 2019; Ambade, et al., 2023; Sankar, et al., 2023). HCCs can accumulate in the soil, affecting soil structure and fertility, which may become unsuitable for agriculture and other land uses, leading to reduced crop yields and biodiversity loss (Truskewycz, et al., 2019). Research indicates a significant connection between groundwater and the host soil (Saqr, et al., 2021; Omeiza, et al., 2023). This indicates that HCCs in soil leach into surface water bodies and groundwater, contaminating drinking water sources and aquatic ecosystems, resulting in significant consequences for aquatic organisms and human health. Additionally, volatile hydrocarbons can evaporate into the atmosphere, exacerbating air pollution and contributing to smog, which adversely affects respiratory health and climate change. Summing these implications (Sharma, et al., 2023; Alden, et al., 2024; Venkatraman, et al., 2024).

Studies have indicated that HCCs have severe impacts on groundwater quality, leading to significant public health risks (Mao, et al., 2016; Srivastava, et al., 2019; Capozzoli, et al., 2022). For instance, HCCs such as polycyclic aromatic hydrocarbons (PAHs), total petroleum hydrocarbon (TPH), benzene, toluene, ethylbenzene, xylene (BTEX), and other persistent organic pollutants can dissolve in groundwater, leading to long-term contamination, which can have long-term effects, making remediation a difficult task (Falih, et al., 2024). Prolonged exposure to HCCs is typically linked to an elevated risk of leukaemia, vertigo, cephalalgia, cognitive deficits, and further malignancies (Srivastava, et al., 2019). Besides, more vulnerable to the exposure of HCCs are pregnant women and children, especially in their developmental stages (Babuji, et al., 2022; Agbasi, 2023). HCCs typically eradicate microbial species or associated soil organisms, which might alter the microbial community functionality, and subsequently the ecosystem (Babuji, et al., 2022; Guo, et al., 2024). Moreover, plants subjected to hydrocarbons experience direct toxicity, limited light availability, and impaired nutrient and water acquisition due to the oil's impediment to their mobility within the soil matrix, all of which substantially reduces plant productivity (Srivastava, et al., 2019; Ajeh, et al., 2021; Guo, et al., 2024). The contaminated habitat's capacity to support higher-order life forms is limited without main producers and functional microbial biogeochemical networks (Babuji, et al., 2022).

However, chemical pollutants, microbiological illnesses, medications, pesticides, heavy metals (HMs), and novel contaminants remain the major water contaminants (Abdullahi, et al., 2010; Abdelkader, et al., 2014; Abdel-Shafy and Mansour, 2018; Abanyie, et al., 2023; Abdo, et al., 2023), that pose a risk to the health of humans (Adeyemo, et al., 2008; Abdel-Shafy, et al., 2023; Abdelkader, et al., 2023). Studies indicate that leachate plumes originating from unlined landfills and open dumpsites significantly contribute to contemporary worldwide environmental issues, impacting human health (Gogoi, et al., 2024; Alao, 2025). HCCs can increase the HMs in soil and groundwater because crude oil contains HMs. With ever-increasing human activities, the concentration of HMs in the soil is increasing with significant effects in some places (Alao, et al., 2024a). Unveiling the narrative of a silent struggle against the relentless invasion of toxic hydrocarbons, this study exposes the harrowing consequences on ecosystems and human health. In recent years, electrical resistivity imaging (ERI) and hydro-chemical methods have become essential for analyzing the environmental effects of hydrocarbon contamination and identifying related health hazards (Vold, et al., 2012; Abdullahi, et al., 2013; Hunkeler, 2016). Nonetheless, oil spills at the KRPC in Nigeria have persistently posed harmful consequences to the environment and public health in the region (Dogara, et al., 2017). Through integrating geophysical and hydro-chemical methodologies, researchers and environmental specialists can acquire critical insights regarding the distribution, behaviour, and potential hazards of ecological HCCs. This study employed 3D ERI and hydro-chemical methodologies to evaluate the environmental effects of HCCs and their related health hazards.

2. Materials and methodology

2.1. Site description

As illustrated in Fig. 1, The KRPC facility is located in the City of Kaduna on the geographical coordinates of longitude and latitude of 07.4902 E to 7.4965 E and 10.4326 N to 10.429 N, respectively with an average height of 615 m above the sea level. Both surface water and groundwater drain the site (Alao, et al., 2022). The site's climate is similar to Kaduna's overall tropical climate, which has distinct rainy and dry seasons. The two separate seasons reflect the effects of equatorial maritime and tropical continental air masses across the nation. The regional rainfall occurs from early April to late October, with an annual total of 1000 to 1500 mm (Omeiza and Dary, 2018). However, according to Yusuf et al. (2023), maximum temperatures range from 38°C in March and April to 24°C in the remaining months. Research has indicated that the hydrogeology of a particular region is generally determined by its climate and drainage features (Dogara, et al., 2017; Omeiza and Dary, 2018). The characteristics of the aquifer and the structure of the underlying geological formations determine its replenishment. Infiltration, evaporation, runoff, and other surface water flow components are the main factors influencing groundwater recharge/discharge and accumulation in the region. These factors are directly impacted by the underlying geology (Alao and Abubakar, 2025). The study area belongs to two primary lithological units (the Cretaceous-Tertiary sedimentary rocks and the Precambrian Crystalline Basement) that make up Nigeria's geology (Oyawoye, 1970), which is influenced by the general geology of Kaduna. This basement complex is largely made up of granitic gneisses, biotites, and migmatites within the Migmatite-Gneiss Complex. Reactivated meta-sediment is represented by the magnetite gneiss complex, which exhibits a range of textures and structures (Oyawoye, 1970). These minerals typically can create aquitards and porous zones inside the bedrock of the surrounding country rocks. Joints, veins, fissures, fractures, and other structural deformities of the basement complex are associated with crystalline rocks and influence groundwater flow, as well as the discharge and recharge rates of the principal aquiferous units. Groundwater is localized in the weathered mantle or by the fracturing, fissuring, and jointing of the bedrock (Aboh, 2009; Dogara, et al., 2017).

2.2. Data acquisition and processing

2.2.1. Hydro-chemical data

Six hand-dug wells (HDWs) were utilized to evaluate the groundwater chemical composition and the HCCs' presence. This included the collection of water samples using appropriate sampling equipment and techniques to minimize contamination and ensure sample integrity. Samples were collected using 0.75-litre clean plastic bottles. A laboratory analysis was performed to measure parameters such as the potential of hydrogen, electrical conductivity (EC), (pH), HMs, TPH, and PAHs. Analytical methodologies, including gas chromatography-mass spectrometry (GC-MS), were adopted to quantify and identify HCCs, whereas atomic absorption spectrometry (AAS) was utilized for the quantification and detection of HM pollutants. Furthermore, the elevation from global positioning systems (GPS) was recorded at each water sampling location, specified by latitude and longitude, to estimate the hydraulic head of the area (Table 1), which was subsequently utilized to evaluate the direction of groundwater flow. This was performed to assist in determining the groundwater flow metrics of the research area, physical measurements were taken for wells drilled at the sampling locations.

2.2.2. Electrical resistivity imaging data

This work created a three-dimensional (3D) image of the surface by integrating the findings of parallel two-dimensional (2D) ERI survey lines. The 2D survey lines were executed utilizing a Wenner-alpha arrangement. This array was chosen for its increased sensitivity to

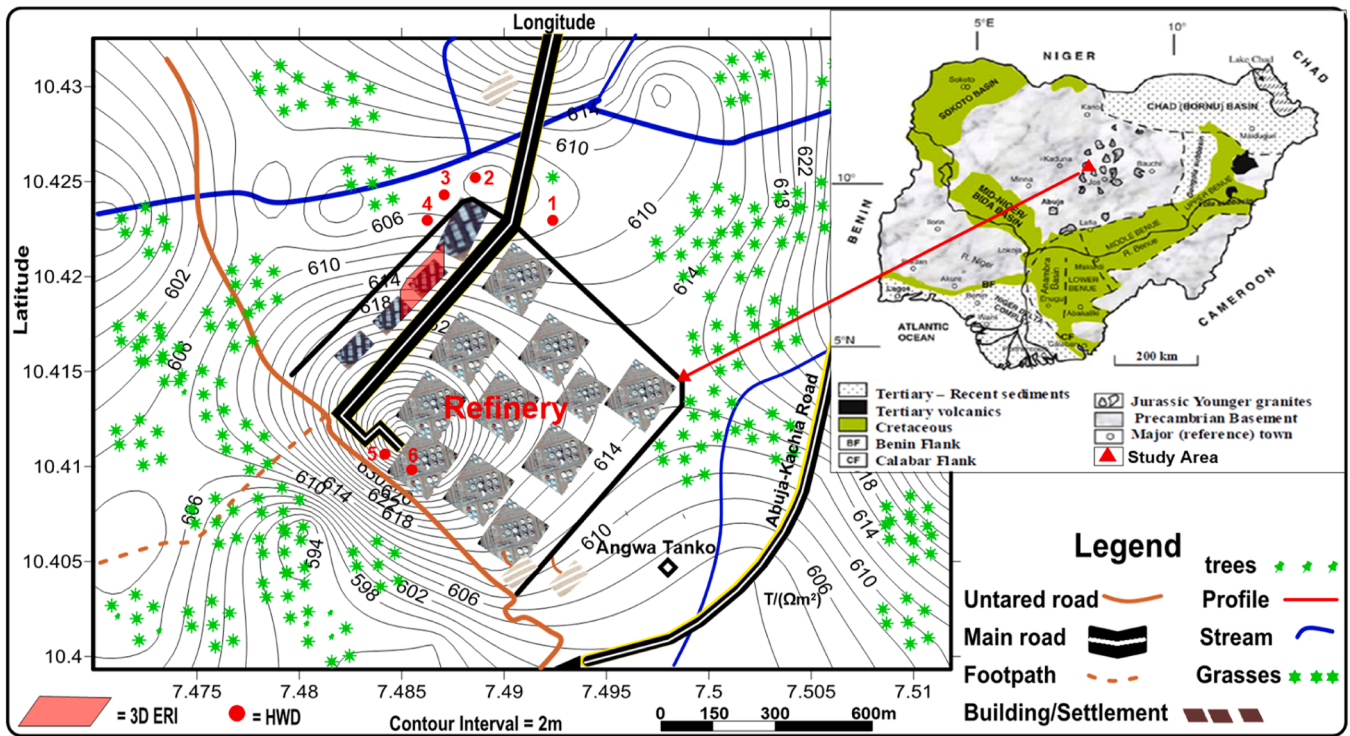


Fig. 1. Description map of the region under investigation.

Table 1

Coordinates, elevations, water levels, and hydraulic heads of five boreholes.

HDWs	GPS coordinates Longitude (E) Latitude (N)	GPS elevation (m)	SWL in HDW (m)	Hydraulic head (m)
HDW ₁	10° 25' 17.58" N 07° 29' 32.28" E	612	4.9	607.1
HDW ₂	10° 25' 23.19" N 07° 29' 21.99" E	614	5.1	608.9
HDW ₃	10° 25' 17.08" N 07° 29' 18.46" E	614	3.9	610.1
HDW ₄	10° 25' 13.31" N 07° 29' 17.34" E	618	6.7	611.3
HDW ₅	10° 24' 32.32" N 07° 29' 02.36" E	644	6.4	637.6
HDW ₆	10° 24' 27.46" N 07° 29' 02.85" E	640	5.7	634.3

Note: SWL = Static water level within the wells, HDW = Hand-dug well.

resistivity variations beneath the electrodes in each dipole pair and its reactivity to horizontal changes with depth, making it the optimal array for distinguishing vertical features like dykes. Furthermore, among the frequently utilized arrays, it exhibited the highest sensitivity to 3D structures (Loke, et al., 2003). The continuous direction of the lithology was selected for the profile to ascertain the lateral extent of each lithological layer. ERI data acquisition was designed to cover a total area of 100 by 50 m using a Terrameter SAS 4000 and electrode selectors. Data was gathered along ten parallel profiles, each five meters apart, via the dipole-dipole electrode arrangement with an electrode spacing of 2.5 m. The apparent resistivity data set was examined for poor datum points before data inversion, following the recommendation of a previous study (Alao, et al., 2024b). The RES2DINV program (Geotomo software) was utilized to invert the 2D ERI of each profile initially to evaluate the data acquisition quality. The robust constraint algorithm inversion technique (L1 norm) produced models with more defined bounds; hence, A script file was created to consolidate the 2D dataset into a 3D format and later invert it utilizing the RES3DINV application (Geotomo

software) (Loke, et al., 2003), with an absolute root mean square (RMS) errors vary between 1.7–3.9 % for six iterations. This indicates high accuracy in data collection (Aleardi, et al., 2021; Alao, et al., 2024b). The volumetric block of the survey area was generated utilizing a 3D visualization program called Slice Dicer for the three-dimensional representation of the inverted model. The 3D ERI was selected to provide spatial resolution, providing a more comprehensive subsurface image and visualization of HCCs (Joseph, 2025), which essentially enhances precise delineation of plume morphology, depth variability, and migration pathways. This method improves accuracy in detecting contamination hotspots for effective remediation planning.

2.2.3. Electrical resistivity theory

The electrical resistivity data acquisition techniques relied on the principle of Ohm's law, which can be given by Eq. (1).

$$\Delta V = IR \quad (1)$$

The response of materials under the surface to the subterranean current was documented by the resistivity meter (Terrameter SAS 4000), which was converted into the "electrical apparent resistivity (ρ_a), and can be articulated in Eq. (2).

$$\rho_a = K \frac{\Delta V}{I} = RK \quad (2)$$

Where K is a k-factor, that was contingent upon the electrode design, as delineated in Eq. (3). The equation can be used to calculate the k-factor when (AC) = (BD) and (BC) = (AD) (Fig. 2)

$$K = \pi \left[\frac{(AC)(AD)}{CD} \right] \quad (3)$$

3. Results and discussion

The findings of the hydro-chemical analysis and geophysical research are demonstrated in Tables 2 and 3, together with Figs. 3, 4, and 5. The hydro-chemical analysis indicated the levels of

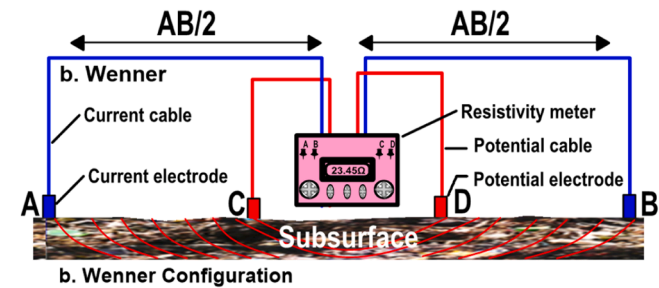


Fig. 2. Electrical resistivity configurations.

Table 2
The results of the groundwater hydrochemical water analysis of hand-dug wells (HDWs) from the spill site, all measured in $\mu\text{g/l}$.

HCCs	HDW1	HDW2	HDW3	HDW4	HDW5	HDW6
TPH	472.1	451.7	571.6	401.2	342.1	413.3
PAHs						
Chrysene	0.0092	0.0089	0.0572	0.0093	0.0512	0.0511
Naphthalene	0.2149	0.4645	0.1877	0.4161	0.6952	0.7121
Pyrene	0.0887	0.0701	0.0077	0.1091	0.1292	0.1233
Fluoranthene	0.0382	0.0081	0.0862	0.0086	0.0083	0.0094
Fluorene	0.0099	0.0089	0.0087	0.0093	0.0897	0.0901
Phenanthrene	0.0189	0.0077	0.0092	0.0497	0.0085	0.0085
Acenaphthylene	0.0091	0.0088	0.0085	0.0097	0.0079	0.0088
Acenaphthene	0.1987	0.0089	0.1110	0.2799	0.2852	0.2911
Anthracene	0.0099	0.0087	0.0094	0.0089	0.0097	0.0081
Benzo (b) fluoranthene	0.0083	0.0078	0.0820	0.0087	0.1433	0.1415
Benzo (k) fluoranthene	0.0082	0.0079	0.0081	0.0082	0.0073	0.0087
Benzo (a) pyrene	0.0085	0.0088	0.0087	0.0085	0.0076	0.0091
Dibenz (a,h) anthracene	0.0099	0.0089	0.0074	0.0094	0.009	0.0087
Indeno (1,2,3-cd) pyrene	0.0069	0.0090	0.0077	0.0103	0.0093	0.0085
Benzo (g,h,i) perylene	0.0111	0.0719	0.0077	0.0101	0.0087	0.0087
Total	0.6504	0.7089	0.6072	0.9558	1.4701	1.4877

Note: Polycyclic aromatic hydrocarbons and all contaminants are measured in $\mu\text{g/l}$.

concentrations of HCCs in water samples, reflecting the condition of regional groundwater. Additionally, resistivity data were employed to identify and delineate the depth and distribution of HCCs in both surface and subsurface environments, thereby offering a thorough understanding of the environmental ramifications of HCCs.

3.1. Hydro-chemical analysis

The laboratory findings of PAHs and TPH in water samples are displayed in Table 2 and Fig. 3. PAHs and TPH are two primary categories of hydrocarbons that raise significant concern due to their toxicity and potential health hazards. This study examined the amounts of PAHs and TPH in groundwater samples from the suspected hydrocarbon spill

location to evaluate the environmental effects and related health hazards. The quantities of PAHs in the groundwater samples varied from $0.6072 \mu\text{g/l}$ to $1.4877 \mu\text{g/l}$, whereas the values of TPH ranged from $0.3421 \mu\text{g/l}$ to $0.5816 \mu\text{g/l}$ (Table 1). All measured values of PAHs and TPH surpassed the permitted limit of $0.5 \mu\text{g/l}$ established by the NDPR for drinking water quality. The heightened concentrations of PAHs and TPH signify substantial groundwater contamination in proximity to hydrocarbon extraction facilities. PAHs are a category of organic compounds produced from the incomplete combustion of organic materials, including fossil fuels. They are recognized as carcinogenic and may present significant health hazards to persons and ecosystems (Madia, et al., 2019). Prolonged exposure to PAHs via contaminated drinking water can elevate the risk of cancer, respiratory issues, and other detrimental health impacts. Elevated levels of PAHs in groundwater tests near hydrocarbon extraction facilities underscored the environmental consequences of hydrocarbon activities and the potential health hazards linked to exposure to these harmful substances.

Similarly, TPH is a broad category of hydrocarbons that includes various compounds found in petroleum products. TPH contamination in groundwater can result from spills, leaks, or improper disposal of petroleum products, leading to environmental degradation and health

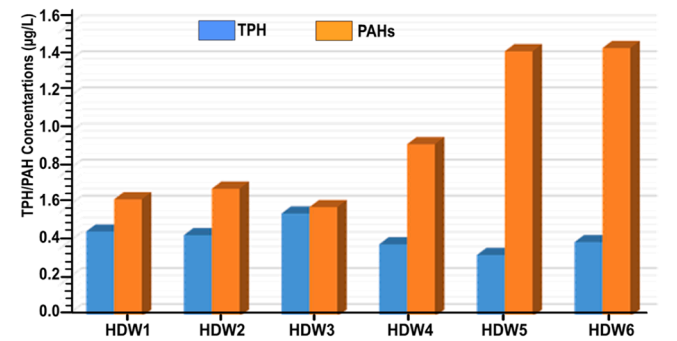


Fig. 3. The concentration of TPH and PAHs in groundwater from the six investigated HDWs.

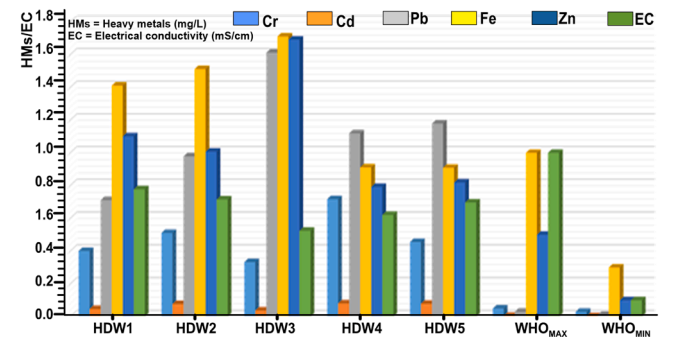


Fig. 4. Heavy metal levels and electrical conductivity in the regional groundwater systems.

Table 3
Hydro-chemical examination of water samples from six hand-dug wells (HDWs) for heavy metals (HMs) utilizing atomic absorption spectrometry (AAS).

Parameters	HDW 1	HDW 2	HDW 3	HDW 4	HDW 5	HDW 6	(WHO, 2017)
Cr	0.401	0.511	0.333	0.717	0.456	0.398	0.030 – 0.050
Cd	0.047	0.077	0.038	0.081	0.079	0.079	0.003 – 0.005
Pb	0.711	0.978	1.612	1.119	1.179	1.089	0.010 – 0.030
Fe	1.411	1.512	1.711	0.911	0.909	1.322	0.300 – 1.000
Zn	1.101	1.007	1.692	0.792	0.819	1.333	0.100 – 0.500
EC	0.777	0.715	0.524	0.621	0.697	0.598	0.100 – 1.000
pH	5.700	6.300	5.300	7.100	6.700	4.800	6.500 – 8.500

Note: HDW = Hand-dug well, and all parameters are in mg/l , except EC is in mS/cm , and pH is dimensionless.

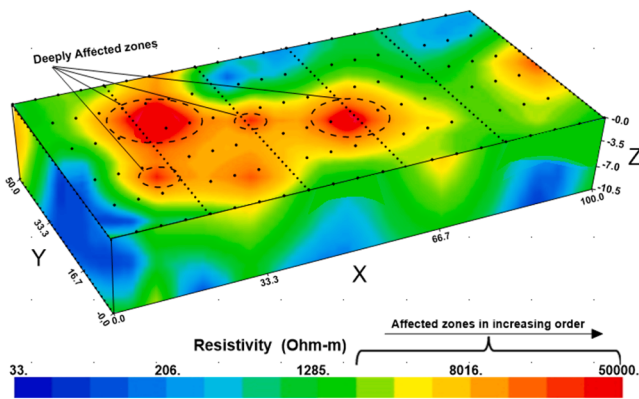


Fig 5. The 3D ERI volumetric data inversion of the suspected spill site.

hazards. Exposure to TPH through drinking water can cause skin irritation, respiratory issues, and other health problems (Logeshwaran, et al., 2018; Fei-Baffoe, et al., 2024). The detected quantities of TPH in the groundwater samples surpassing allowed limits signified a substantial risk to the environment as well as human health. The pollution of groundwater with PAHs and TPH adjacent to hydrocarbon extraction sites can have significant repercussions for human populations and ecosystems. The migration of these toxic compounds through the soil and water can lead to long-term pollution of water sources, affecting not only drinking water quality but also aquatic life and vegetation in the surrounding areas (Alao, et al., 2024a). The persistence of PAHs and TPH in the environment can result in bioaccumulation in food chains, further amplifying the health risks for humans and wildlife. This study's results underscore the environmental repercussions of hydrocarbon activities on groundwater quality, as indicated by the increased levels of PAHs and TPH in samples obtained near extraction sites. The surpassing of thresholds of the allowable limits highlighted the immediate necessity for cleanup and mitigation strategies to safeguard the environment and human health from the detrimental impacts of PAHs and TPH pollution. Effective monitoring, enforcement of regulations, and implementation of best practices in hydrocarbon extraction are essential to prevent further pollution and safeguard water resources for present and future generations support by previous investigations (Srivastava, et al., 2019; Venkatraman, et al., 2024). In addition, the groundwater hydraulics data showed that the direction of groundwater movement is towards the north, heightening the risk of HCCs compromising the groundwater supplies. Based on the regional hydrological and groundwater hydraulics data, the gradient of the water table significantly promoted the understanding of the direction of groundwater movement (Alao and Abubakar, 2025). Groundwater flowed in a downward direction relative to the total head.

The laboratory results from the physicochemical examination of HMs are displayed in Table 2 and Fig. 4. HMs persist as prevalent hazardous components that can accumulate in the environment, posing significant health concerns to individuals and ecosystems (Alao, 2024). The content of HMs was examined in groundwater samples near the probable hydrocarbon spill location to evaluate the environmental effect and related health hazards. The amounts of HMs in the groundwater samples were quantified as follows: Zinc (Zn) varied from 0.792 mg/l to 1.692 mg/l, Iron (Fe) varied from 0.909 mg/l to 1.711 mg/l, Cadmium (Cd) varied from 0.038 mg/l to 0.081 mg/l, Lead (Pb) varied from 0.711 mg/l to 1.612 mg/l, and Chromium (Cr) varied from 0.333 mg/l to 0.717 mg/l. The EC of the groundwater samples ranged from 0.598 to 0.777 mS/cm, and the pH varied from 4.6 to 6.7. The EC derived from the water samples is significantly lower than that of leachate plume pollutants, hence verifying the existence of hazardous chemical compounds. It is crucial to observe that almost all heavy metal concentrations beyond the World Health Organisation (WHO) acceptable threshold for drinking

water indicate substantial contamination.

The heightened concentrations of HMs in the groundwater tests adjacent to the probable hydrocarbon spill location raised concerns regarding environmental repercussions and potential health hazards linked to hydrocarbon operations. Zn, Fe, Cd, Pb, and Cr are recognized as harmful to persons and ecosystems, even in minimal amounts (Agbasi, 2023; Alao, et al., 2024a). Prolonged exposure to these HMs via contaminated drinking water can result in various health issues, including neurological diseases, renal damage, and cancer. The high EC encountered in the regional groundwater samples is indicative of the presence of dissolved salts and minerals, which can further exacerbate the environmental impact of hydrocarbon activities. Increased salinity in water sources can harm aquatic organisms, disrupt ecosystems, and reduce water quality for human consumption and agricultural use. The low pH levels in the groundwater samples indicated acidity, which may facilitate the leaching of HMs from adjacent rock formations and soil into the water (Alao, 2024). Acidic water can also corrode pipes and infrastructure, leading to further contamination of the water supply. The study's findings demonstrated that hydrocarbon activities have substantially affected groundwater quality in the area, with increased levels of HMs presenting a grave risk to the ecosystem and human health. The significant HM pollution in groundwater samples adjacent to hydrocarbon extraction sites underscored the environmental consequences and related health hazards of hydrocarbon operations. The elevated levels of Zn, Fe, Cd, Pb, and Cr, along with high EC and low pH, indicated significant pollution of the water sources. Immediate measures are required to mitigate this contamination, safeguard human health, and maintain the integrity of ecosystems in the impacted region. Additional study and monitoring are crucial to comprehend the complete scope of the environmental damage and to formulate effective remediation and preventative efforts.

3.2. Electrical resistivity

The subsurface resistivity data acquired from the alleged spill site exhibited notable anomalies in resistivity values, suggesting potential environmental effects of hydrocarbons on the soil, which adversely affect the nearby groundwater. The resistivity anomalies observed in the overloaded topsoil varied from 5000 Ω m to 50000 Ω m at depths ranging from 0.0 m to 3.5 m (Fig. 5), contrasting with the region's subsurface resistivity values of 300 Ω m to 3000 Ω m from the previous studies (Dogara, et al., 2017; Omeiza and Dary, 2018), and the outcome of the unforeseen spillage of silt. These anomalies indicated the presence of HCCs in the soil, which may impact the groundwater quality in the region. The high resistivity values observed in the topsoil layer (5000 Ω m to 50000 Ω m) are indicative of HCCs due to their insulating properties. Hydrocarbons are non-conductive materials that resist the flow of electrical current through the soil because their presence in the soil displaces water and other conductive ions, reducing the overall conductivity of the soil (Aydi, et al., 2020). These high resistivity contrasts encountered at the overburdened topsoil decrease with depth, confirming that the vertical impact of the HCCs also decreases with depth. Hydrocarbons are known to increase the resistivity of soil due to their insulating properties (Delgado-Rodríguez, et al., 2018; Aydi, et al., 2020), which impede the flow of electrical currents through the subsurface. The rise in resistivity was due to the presence of petroleum-derived chemicals in the soil, which modify its EC qualities.

The contrast between the resistivity values in the topsoil layer and the region's subsurface resistivity values further supported the hypothesis of HCCs. The reduced resistivity values in the subsurface layer (300 Ω m to 3000 Ω m) are characteristic of unpolluted soil and groundwater, signifying a distinct separation between the impacted zone and the adjacent environment. The existence of HCCs in the soil can adversely affect the environment, leading to soil degradation, groundwater contamination, diminished microbial activity, and potential threats to human health. Contaminants from hydrocarbons can leach into the

groundwater, posing a threat to drinking water sources and aquatic ecosystems in the vicinity (Truskewycz, et al., 2019; Alden, et al., 2024). In addition, it was noted that as the depth of the HCCs increases, the electrical signals generated by the ERI system may weaken or attenuate as they travel through the subsurface materials, which slightly reduces signal strength and resolution. In conclusion, the subsurface resistivity data obtained at the suspected spill site offer substantial evidence of hydrocarbon contamination in the soil and significant implications for groundwater quality, raising alarms regarding public health risks. The 3D ERI is not commonly deployed for HCC assessment, however, this study shows that 3D ERI can provide detailed activities of HCCs in soil, which occurred within the overburdened topsoil. Therefore, investigating HCCs with 3D ERI and geochemical data has great potential to improve our knowledge of landfill contamination and increase our capacity to safeguard sensitive ecosystems and communities. However, the technique could not provide a detailed concentration of HMs, PAHs, and TPH, which was complemented by the sampling technique. Additional investigation and remedial actions are required to alleviate the environmental impacts of this contamination and safeguard the adjacent ecosystem and human health.

In summary, the hydro-chemical analysis shows that the PAH levels ranged from 0.65 to 1.47 $\mu\text{g/l}$, exceeding the NDPR limit of 0.5 $\mu\text{g/l}$ for drinking water. TPH concentrations ranged from 0.3421 to 0.5716 $\mu\text{g/l}$, also exceeding the NDPR limit, while the HMs levels were found to be above WHO guidelines for drinking water, with Zn, Fe, Cd, Pb, and Cr exceeding the recommended limits. Similarly, ERI data revealed significant resistivity anomalies in the topsoil, with values ranging from 5000 to 50000 Ωm , much higher than the typical regional range of 300–3000 Ωm (Aboh, 2009). This indicates a high concentration of HCCs near the surface. On the other hand, the environmental and health implications of HCCs were heightened in soil degradation, groundwater, and public health risks. The HCCs, particularly PAHs and TPH, have contaminated groundwater sources, posing risks to human health and aquatic ecosystems, while the elevated levels of HMs in groundwater indicate a significant threat to human health, potentially leading to neurological disorders, organ damage, and developmental issues. In addition, the HCCs have altered soil structure and microbial activity, impacting nutrient cycling and soil respiration, while constant exposure to HCCs through contaminated water and soil can lead to various health problems, including cancer, respiratory issues, and developmental complications. Regular monitoring of HCC levels in soil and groundwater is crucial to track contamination trends and prevent long-term impacts, and effective remediation strategies are needed to address the contamination and mitigate the associated health risks. Stricter regulations and enforcement are essential to prevent further HCC spills and leaks are also required, while involving local communities in monitoring, remediation, and decision-making processes is also vital for ensure their safety and well-being.

However, the study is not without limitations, as it primarily focused on groundwater and soil contamination, leaving the impact on surface water bodies and air quality behind. Involving the local community in the research process to understand their concerns, gather valuable local knowledge, and ensure that research findings are communicated effectively is essential (Alao, et al., 2025). Therefore, future research should consider a more holistic approach to assess the overall environmental impact to provide a deeper understanding of the environmental and health impacts of HCCs and develop more effective strategies for mitigation and remediation. However, the study uniquely integrates 3D ERI with hydrochemical analysis to assess hydrocarbon contamination, offering high-resolution spatial mapping of pollutants. Unlike conventional studies focusing solely on geophysical assessments, this approach enhances contamination detection accuracy to provide local insights into the environmental risks of HCCs due to the presence of KRPC. In conclusion, a comprehensive approach involving monitoring, remediation, and community engagement is crucial to protect public health and ensure environmental sustainability. The study highlights the urgent

need for proactive measures to address HCC contamination at KRPC and similar sites.

4. Environmental and health implications of HCCs and future directions

Hydrocarbon contamination can have significant impacts on the environment (groundwater systems, soil, and microbial activity) and public health, altering the region's geochemical, and hydrochemical signatures, which inversely affect the region's health status and soil microorganism performance. The HCCs, especially aromatic compounds such as benzene, toluene, ethylbenzene, and xylene (BTEX), can be toxic to soil microorganisms (Gao, et al., 2022; Venkatraman, et al., 2024) because these compounds can inhibit microbial growth, reduce microbial diversity, and disrupt metabolic processes essential for microbial activity (Fig. 6). The presence of HCCs characterized by elevated levels of PAHs, TPH, HMs, and high subsurface resistivity anomalies, poses significant health risks to human populations exposed to these pollutants. PAHs are recognized carcinogens that can adversely affect human health (Logeshwaran, et al., 2018; Fei-Baffoe, et al., 2024). Concentrations between 0.65 $\mu\text{g/l}$ and 1.47 $\mu\text{g/l}$ were above the recommended limits set by the NDPR, thereby elevating the risk of cancer, respiratory disorders, and other severe health complications for persons or communities exposed to these levels. TPH levels ranging between 0.34 $\mu\text{g/l}$ and 0.57 $\mu\text{g/l}$ provided health risks, since extended exposure may result in respiratory issues, skin irritation, and possible prolonged health ramifications. These elevated levels highlighted the importance of addressing contamination sources to protect public health. HMs, with concentrations between 0.038 mg/l and 1.711 mg/l, beyond WHO guidelines of (0.01 mg/l - 1.00 mg/l), present significant health hazards. Exposure to HMs can lead to neurological abnormalities, organ damage, developmental complications, and other detrimental health effects. Individuals or communities exposed to these contaminants may experience a range of health issues, emphasizing the urgent need for remediation efforts (Agbasi, 2023; Gogoi, et al., 2024). The abnormal subsurface resistivity distribution across the suspected oil spill site overburdened topsoil, with values of 5000 Ωm to 50000 Ωm compared to the normal regional range of 300 to 3000 Ωm , indicated potential groundwater and soil contamination. This may result in the leaching of deleterious compounds into water sources, endangering human health via contaminated drinking water and agricultural products.

Studies have shown that certain microorganisms may be more sensitive to hydrocarbons than others, resulting in shifts in microbial populations and a decline in overall microbial diversity (Orcutt, et al., 2010; Alrumman, et al., 2014; Kebede, et al., 2020; Wu, et al., 2024). Nevertheless, soil microbes are essential for nutrient cycling processes, including decomposition, mineralization, and nitrogen absorption by plants. The elevated levels of HCCs encountered in this study can disrupt these processes by inhibiting the activity of key microbial groups involved in nutrient cycling, leading to nutrient imbalances in the soil. Soil microbial activity is intricately connected to soil respiration, the process through which microorganisms decompose organic materials and emit carbon dioxide (Gao, et al., 2022). Therefore, the encountered HCCs can reduce soil respiration rates by inhibiting microbial respiration and metabolic activity, impacting soil carbon dynamics. The potential HCCs can affect enzyme activity in the soil, leading to reduced enzymatic degradation of organic compounds and impaired nutrient availability for plants. The soil microorganisms generate enzymes that facilitate crucial biochemical reactions essential for organic matter decomposition and nutrient cycling. Moreover, the most perilous consequences of HCC in soil and groundwater are the enduring repercussions that influence both environmental integrity and public health (Mao, et al., 2016; Wu, et al., 2024). The effects on the ecosystem can endure longer than anticipated, even following the initial contamination event. Chronic exposure to HCCs can result in microbial adaptation or acclimation, where certain microbial species develop tolerance

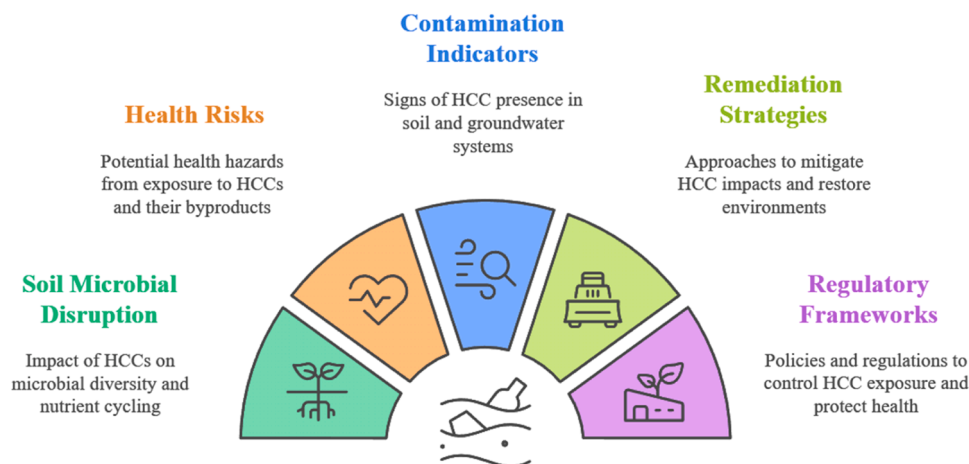


Fig. 6. Environmental and health implications of hydrocarbon contaminations.

to hydrocarbons but at the expense of overall microbial diversity and ecosystem functioning.

The environmental and health ramifications of HCC pollutants, indicated by the heightened concentrations of PAHs, TPH, and HMs, emphasize the urgent necessity for prompt measures to reduce exposure hazards and safeguard public health (Fig. 6). Confronting the intricate issues presented by these pollutants necessitates a comprehensive approach that includes rigorous monitoring, remedial techniques, and strict regulatory frameworks. Prioritizing efforts to alleviate the detrimental impacts of PAHs, TPH, HMs, and irregular resistivity levels is essential to protect human health, preserve ecosystems, and foster sustainable environmental practices. Effective monitoring, remediation, and regulatory measures are also essential to minimize the adverse health effects associated with HCCs to ensure the well-being of communities exposed to HCCs. Also, developing a real-time sensor for possible identification of linkages of hydrocarbon into the environment through advanced sensor technologies and remote monitoring systems, which also enable proactive mitigation strategies and regulatory compliance (UNEP, 2019). This is challenging and a difficult task, but is possible at KRPC, which will incorporate renewable energy sources into oil and gas operations in the grid integration techniques and hybrid energy systems to improve energy resilience, lessen environmental effects, and advance sustainable development in the energy sector. In conclusion, proactive measures against the HCCs spillage or linkage identification, and community engagement are essential in fostering a comprehensive response to the environmental hazards posed by HCCs. Additionally, the research informs groundwater protection policies, guiding stricter environmental regulations and monitoring frameworks. Public health outreach can leverage these insights to educate communities on contamination risks, exposure mitigation, and safe water consumption practices. Collaborative efforts among stakeholders, including government agencies, industries, researchers, local communities, and environmental agencies, are crucial in implementing effective solutions and ensuring long-term ecological resilience.

5. Conclusion

The findings presented in this study underscore the frightening environmental impact of HCC and the associated health risks posed by elevated levels of PAHs, TPH, and HMs, which varied from 0.6504 µg/l to 1.4701 µg/l, 0.3421 µg/l to 0.5716 µg/l, and 0.038 mg/l to 1.711 mg/l, respectively. The statistics indicated a troubling divergence based on WHO, (2017) thresholds, signifying a substantial risk to public health. The overloaded topsoil at the alleged spill location has subsurface resistivity values between 5000 Ωm and 50000 Ωm, signifying significant resistivity anomalies. The elevated resistivity anomaly values detected

in the topsoil layer at depths ranging from 0.0 m to 3.5 m suggest the presence of HCCs, as their non-conductive characteristics impede current flow through the soil by displacing water and other conductive ions, thereby diminishing overall soil conductivity. Also, it was observed that HCCs decrease with depth, while the electrical resistivity signals were attenuated with depth. Based on these outcomes, HCCs disrupt ecosystems and harm wildlife, aquatic organisms, crops, and human beings, vulnerable to the toxic effects of HCCs. The presence of potential HCCs in the investigated suspected spill site had altered the region's soil structures, geophysical signatures, hydro-chemical structures, and public health status. Overall, the 3D ERI proves to be a powerful geophysical tool for imaging subsurface structures and HCCs. However, the accuracy of the imaging results can be affected by the depth of HCCs. In conclusion, this study underscored the pressing necessity for coordinated efforts towards addressing the environmental impact of HCCs. By implementing evidence-based interventions and fostering a culture of environmental stewardship to ensure healthier, ecological sustainability, and future generations. Prioritization of environmental protection and security of public health through decisive steps is recommended to combat the detrimental effects of HCCs. Regulatory authorities and environmental and industry stakeholders should implement measures to mitigate HCCs to protect groundwater resources from further degradation.

Ethical approval

I declare that this research is original work carried out by all the authors and that no part of this work has been previously published in any journal. All information provided in this work has been duly acknowledged in the text and the references provided.

Consent to publish

I have read, understand, and agree with the provided information and the terms of the Journal.

CRediT authorship contribution statement

Joseph Omeiza Alao: Writing – review & editing, Writing – original draft, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ahmed M. Saqr:** Writing – review & editing, Visualization, Validation, Supervision, Software, Methodology, Investigation, Formal analysis. **Daniel A. Ayejoto:** Writing – review & editing, Visualization, Validation, Software, Formal analysis. **Oche Joseph Otorokpa:** Writing – original draft, Validation, Supervision, Funding acquisition, Conceptualization. **Fahad Abubakar:**

Writing – review & editing, Validation, Supervision, Software, Resources, Methodology, Investigation. **Musaab A.A. Mohammed:** Writing – review & editing, Visualization, Validation, Methodology, Investigation, Formal analysis. **Amarachukwu A. Ibe:** Writing – review & editing, Validation, Supervision, Resources, Investigation, Formal analysis, Data curation.

Declaration of competing interest

The author has no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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