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Delineating Crude Oil Impacted Zones Using Subsurface Modelling in Rivers State, Southern Nigeria

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***Abstract*— *Quick response in detecting crude oil spills using subsurface modelling helps in tracking oil spread. The study utilized subsurface models in delineating crude oil impacted zones in an oil-producing community within Niger Delta of Nigeria with the objectives of developing 3-D models of TPH distribution across the study area, detecting patches of oil and determining the levels of TPH. Rockwork software (v.2017) was utilized while the interval data of interest is TPH. Results showed that TPH values varied significantly (both vertically and spatially) across the study area ranging from 439 mg/kg at Location PA1 to 30,522 mg/kg at Location PA4. TPH values decreased with increasing depth intervals. The pattern of crude oil distribution in the study area suggests occurrence of a subsurface crude oil plume (at PA2), surface type of crude oil contamination (at PA3 to PA6) and areas with low crude oil impact (at PA7 to PA11). There is evidence of recent discharge of crude oil as well as historical discharge. Patches of hydrocarbon were found at both surface and subsurface. At Location PA2, oil plume was delineated at the depth interval of 2.0–2.5 m. Although patches of oil occurred at the surface around PA3, PA4 and PA5, the values decreased with depth. The study established significant crude oil contamination of the area under study. The distribution pattern of crude oil is uneven as high values occur near-surface in some areas and deeper within the subsurface in some other locations. The study delineated four zones of varying crude oil contamination including zones of non-impact or low-risk contamination (PA7 – PA9 and PA11), moderate contamination (PA1 and PA10), deeper contamination/subsurface plume (PA2) and surface contamination (PA3–PA6). Oil plume delineated at depth poses threat to groundwater resources within the study area. Therefore, groundwater quality assessment and periodic monitoring of water quality within the study area are recommended to ensure that the area around the zone of low-risk.*

***Keywords*— *Crude oil contamination; Subsurface modelling; TPH distribution.*

I. Introduction

Petroleum is a naturally occurring complex mixture made up predominantly of hydrocarbon compounds and frequently contains significant amounts of nitrogen, sulphur, and oxygen together with smaller amounts of nickel, vanadium, and various elements. Petroleum compounds can occur in solid form as asphalt, liquid form as crude oil and/or gaseous form as natural gas (Colwell *et al.,* 1977; Ite & Semple 2012). It is believed to have formed from decaying plant and animal material that has become incorporated in the sediments of shallow seas and later overlaid by a succession of strata. Over time these organic residues are converted by heat and pressure into petroleum, migrating upwards, sometimes over extensive areas, either to reach the surface or be occasionally trapped in what are to become oil reservoirs.

From its development phase to production phase (drilling and operations, transportation and distribution of crude oil, and storage), many disasters have occurred in the oil industries. Oil spill is the most important type of environmental disasters which usually occur. It is an accidental, intentional, or human-induced environmental disaster that occurs due to release of liquid petroleum into the environment (Tewari and Sirvaiya, 2015). It has negative impacts on humans as well as plants and wildlife, including birds, fish and mammals. Accidents resulting from drilling and production of crude oil, and anthropogenic-related activities are the main causes of oil spills. Crude oil is the major source of income to the Nigerian economy, which accounts for about 70% of government revenue and more than 83% of the country's total export earnings. (Nuhu *et al.,* 2021). Crude oil spills are frequent events in Nigeria and in the past 50 years, it is estimated that over 12 million tons of oil have been spilled into the environment and more than 77% of it have not been recovered (Nuhu *et al.,* 2021).

Discharges of petroleum hydrocarbon and petroleum–derived wastes have caused environmental pollution, adverse human health effects, detrimental impact on regional economy, socio-economic problems and degradation of host communities in the nine (9) oil-producing states in the Niger Delta region of Nigeria (Ite *et al.,* 2013). Major anthropogenic-related causes of oil spill are pipeline vandalization and illegal bunkering activities (Abrakasa, 2023). In some places, pipelines are laid on the surface of the earth, however, exceptions are made in other places where pipelines of six inches diameter are trenched four-six feet into the subsurface (Abrakasa & Douglas, 2022). Oil spill events have become a major source of environmental pollution in Nigeria, especially in the oil-producing communities. Assessment of hydrocarbon contamination within the subsurface is a complex program and requires both field-based measurement and geochemical analysis, to give a precise definition of the extent of pollution (Eze *et al.,* 2021).

When oil spill occurs, it could migrate or percolate into the subsurface while some will flow on the surface. The early detection of oil spill especially the use of subsurface modeling in determining the depth of occurrence, migration pathways, patterns and trends, and, in estimating the potential amounts of oil and its likely location, in addition to rapid response via remediation minimizes any environmental damages that would have been caused by crude oil-related environmental pollution. As a result, an accurate, rapid and remote spatial assessment of terrestrial crude oil pollution remains crucial for the implementation of any countermeasures employed to minimize and manage potentially irreversible damages to both human health and the environment.

Subsurface model is a tool employed in a scenario of an oil spill to delineate the depth and width of oil spread, and the volume of soil that have been heavily impacted (Wilson *et al.,* 2021). It is a quick approach to response to oil spills, and if applied to an oil spill site within the hours and weeks of occurrence, and actions taken immediately to remediate the delineated area, further spread and/or contamination is minimized. It estimates the amount of oil (concentration in ppm) and the volume of soil matrix requiring radiation. It is an accurate tool which specifies the exact location and environment that is heavily impacted (Barker *et al.,* 2020). If successfully delineated, an oil spill site becomes easy to remediate and restore.

A traditional method of oil spill detection and delineation is on-site soil excavation which provides vertical and lateral characteristics of oil within the subsurface (API, 2013). The ineffectiveness of this method is reflected in the time taken in mobilizing personnel to site, collection and analysis of soil samples in the laboratory, interpretation, reporting and recommendations. Timing is very important in oil spill response since, given longer period of time, the oil would move and spread across the depth and width of the site thereby impacting larger area. This prompted the development of cost-effective models that can quickly assess the spread of oil within minutes, hours and few days.

Subsurface modelling of an oil impacted site can be performed with the use of RockWares' Rockwork software (version 2017), employing iso-surface modelling. In subsurface modelling, the total petroleum hydrocarbon is the data of interest (Kuppusamy *et al.,* 2020). Iso-surface modelling is a complex modelling which enhances the detailed visualization of the distribution of hydrocarbons within the subsurface. It uses the interval data in portraying the crude oil impacted site (Rockworks & Wares, 2020). The subsurface modelling has many advantages as it provides useful information about the movement of oil after the occurrence of oil spills. It helps to generate the interval data (I-data) index map which makes it easy to view various orientations of the I-data vertical profile. As a 3-D model, it gives clues on the exact volume of soil matrix that have been impacted by specific petroleum concentration. One of the advantages of subsurface model over other techniques used in the delineation of oil spills including vertical electrical sounding (VES) method is that the volume of the entire soil matrix which houses the oil above a particular threshold of concentration can be visualized and represented (Abrakasa & Douglas, 2022).

Employing subsurface modelling in the delineation of oil spill impacted site enhances the ease with which the area and volume of heavily and/or lightly impacted site are delineated and presented. Currently, the two-dimensional (2-D) methods have been used, whereby contaminated soil samples are excavated on the surface and few depths into the subsurface without doing a model to know the exact location of patches of oil in the subsurface. In this study, a three-dimensional (3-D) subsurface model was used to ascertain the distribution of the spilled oil within the subsurface of a crude oil impacted site. The study therefore aimed at developing 3-D subsurface model of TPH distribution, identifying patches of oils in subsurface and evaluating TPH level using interval data.

Location of Study Area

This study was carried out in a crude oil impacted location in the Niger Delta Basin of Nigeria and lies between Latitudes 05^0 4' 0''N, 05^0 6' 0'' N and Longitudes 006^0 38' 0'' E, 006^0 39' 0'' E. The interval data profile index map of the study area (based on Eastings and Northings) is presented in Fig. 1.

Niger Delta region is within the southern part of Nigeria, and it is bounded in the south by the Atlantic Ocean and in the east by Camerooon. Its surface area has been estimated to be approximately 112,110 km^2, with a large area covered by mangrove forest (Nwobi *et al.,* 2020). Within the Niger Delta area, rainfall is experienced almost in all the months of the year with a mean annual amount of rainfall reaching about 2,000 mm in the inland towns and peaking to about 4,000 mm in the coastal communities. The Niger Delta area is characterized with a tropical monsoon type of climate. Generally, an equatorial climate is experienced on its southern coast and subequatorial climate in the north on the basis of koppen's Af classification. There are two major seasons namely the dry season which kick-starts from the month of November and stretches into the month of March and the wet season which kick-starts in the month of April and terminates in the month of October. Despite that dry season of November to March, there is nearly a month without rainfall in Niger Delta of Nigeria.

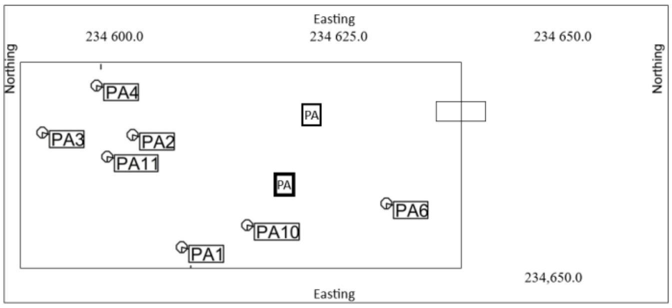

Fig. 1. The Interval Data Profile Index Map (based on Eastings and Northings)

A little break in the amount of rainfall commonly referred to as 'August break'' occurs between late July and early September. The monthly temperature is variable and ranges from 26 °C to 30 °C. January is the warmest month with an average temperature of 27.6 °C while August is the coldest month with a temperature averaging 25.5 °C. Agumagu and Agumagu (2010) in a projection study of the changes in the precipitation and temperature within the Niger Delta area showed that both temperature and precipitation displayed an overall increasing trend. The humidity is high and slightly decreases in the dry season. This alongside the long-lasting wet season of about six to ten months together maintain enough supply of water and moisture thereby promoting the growth and consequent thriving of perennial shrubs and trees (Salawu, 1993). The water table depths in the area increase seawards, varying from about 5 m (inland) to 0.5 m at the coast (Salawu, 1993). The high-water table in the Delta resulting from the high rainfall, swampy and flat topography of the area accounts for the high-water content of soil in the region.

In the Niger Delta, the drainage system consists of an upper braided belt above Obiafu and meander belt region with distributaries. These distributaries drain and criss-cross the delta through a network of Rivers and Creeks with a least 18 major river systems directly connected to the sea. These rivers are mostly turbid during the wet season possibly due to the discharge of clay and silt into the drainage channel during this time (Nwankwo *et al.,* 2013, Amadi *et al.,* 1996). The freshwater aquifers in the Niger Delta occur in three zones; (1) a northern zone of shallow aquifers generally less than 100 m deep and made up mainly of continental deposits, (2) a transitional zone of marine and continental deposits located southwards towards the coast, and (3) a third aquifer zone that occurs within the sand bars and beaches of the coastal areas and at depths of 200 m and more (Amadi *et al.,* 1996).

Geology of the Study Area

The study area lies within the Niger Delta region which is situated in the Gulf of Guinea. Guiraud and Maurin (1991) traced the origin of the Niger Delta Basin to the Cretaceous period. Staring from the Eocene to the present time, Doust and Omatsola (1989) observed that the basin has prograded in the south-westward direction, forming depositional sinks (depo-belts) which could be described as the most active part of the basin at each phase of its development. According to Burke and Whiteman (1973), and Whiteman (1982), the Niger Delta basin is bounded at both at the north-western edge and the north-eastern edge by some rift faults.

Obaje (2009) identified and described five main depositional belts (depo belts) within the Niger Delta basin. These depo belts include Offshore, Coastal Swamp, Central Swamp, Greater Ughelli and Northern Delta. Researches have shown that the depositional belts of the Niger delta basin constitute one of the largest regressive basins in the world, having an area of about 300,000 km^2, a thickness that is more than 10 km at the centre of the basin and a sediment volume that reaches about 500,000 km^3 (Kaplan *et al.,* 1994; Hospers, 1965; Kulke, 1995). The depositional points show a successive stage of well-developed delta which have layers of thick sequences of sediments separated by series of faults (Obaje, 2009). These sedimentary deposits within the basin of Niger Delta occurred as a result of the transgressive and regressive sequences that took place during the Paleocene - Eocene period. The sediments constitute a body of marine, continental and transitional deposits accruing from the sediment supplies emanating mainly from River Benue and River Niger during the Tertiary and Quaternary times.

Layers of sands and layers of shale alternate within the sedimentary units and the two lithological units are bounded at both adjoining ends by growth-related faults. The thickness of the sediments within the Niger Delta Basin was estimated by Evamy *et al.,* (1978) to be about 12,000 m. The study stated that the regression that yielded to such sediment thickness started in the Paleocene period. Over the time, the Niger Delta basin has experienced stress from some geologic structures which has led to the deformation of sediments. Obaje (2009) identified some geologic structures in the Niger Delta Basin and recognized three most striking of all the structures. These structures include the popular and very common syn-sedimentary growth faults, the rollover anticlines and the diapirs of shale.

The Akata Formation constitutes the basal lithostratigraphic unit of the Niger Delta basin and it plays an important role in its petroleum system. Weber and Daukoru (1975) noted that the deposits of Akata Formation are marine in origin and are composed of thick sequences of shale, although interbedded occasionally with turbidite sandstones, and then with minor quantities of siltstone and clay deposited in slope and deep marine environments. Akata Formation acts as both a source rock and a cap/seal rock within the Niger Delta petroleum system as hydrocarbons generated within the formation migrate upward into the Agbada Formation (overlying it), while the over-pressured shales abundance in the formation provide an effective seal for trapping and accumulation hydrocarbons (Weber, 1987). The Agbada Formation, which overlies the Akata Formation, is a key lithostratigraphic unit in the Niger Delta and is integral to its hydrocarbon system. According to Doust and Omatsola (1990), it is characterized by a complex interplay of deltaic and shallow marine depositional processes. The Benin Formation conformably overlies the Agbada Formation with a deposit of alluvial or upper coastal plain sands depositional environment having a thickness exceeding 2,000 m within some places (Avbovbo, 1978). The Benin Formation also referred to as the Coastal Plain Sands contain loose ill-sorted sands and clays of Oligocene to Pleistocene age (Tatam, 1943; Rayment, 1965). The coarse-grained nature of Benin Formation could have resulted from its proximal relationship with the sediment source areas. The formation covers a large area extending from the western part of Niger Delta to the entire Niger Delta basin, and to the south even beyond the present shoreline.

The quaternary sediments which are the structural foundation materials in the Niger Delta were deposited in a wide variety of hydrologic conditions resulting in unique geomorphologic units which have rendered them both vertically and laterally heterogeneous in form and engineering properties. Akpokodje (1989) classified the Niger Delta region into five main geomorphologic including dry flatlands and plains, deltaic plains with abundant fresh water back swamps, fresh water swamps, saltwater or mangrove swamps and active/abandoned coastal ridges, and active/abandoned coastal beaches.

Hydrogeology of Study Area

The Niger Delta is characterized by a complex multilayered aquifer system hosted in the Benin Formation with the main body of freshwater, with increasing occurrence of intercalating clay units towards the coast. Lithological analysis indicates the pre-valence of unconsolidated sand and sandy gravels in the aquiferous horizons, presenting them as previous and prolific aquifers. Reported hydro-chemical data gathered from wells drilled suggest that the quality of groundwater in the Niger Delta is considered generally very good and compares favorably with the World Health Organization standards for drinking water although relatively high iron/manganese and chloride values are localized in time and space. In the coastal areas however, seawater intrusion has been identified asone of the major influences on hydrochemistry of groundwater in shallow unconfined aquifers (Abam and Nwankwoala, 2020).

II. Materials and Methods

TPH Modeling: The modeling of the subsurface of the crude oil impacted area was carried out using a subsurface modeling software (Rockwork Software version 2017). The coordinates of the site which were obtained from GPS in a unique format (sexagesimal format) were converted to the appropriate format (Universal Transverse Mercator –UTM) before carrying out data modeling. The modeling was visualized using slices which show the distribution of specific concentration of crude oil (TPH) within the subsurface. The interval data profile (I-data) showing the distribution pattern of TPH across the crude oil impacted area was then generated. The distribution pattern and trend of crude oil (TPH), its migration and changes depth-wise and lateral-wise were analyzed and interpreted.

Modelling of Groundwater Flow Direction: The groundwater flow direction was modeled by using the spacing of contours to show high and low areas, along with the elevation values gathered by the GPS.

III. Results and Discussion

The data obtained were analyzed and the results presented and discussed here. These include geospatial distribution of elevation and depths of boreholes, groundwater flow direction, total petroleum hydrocarbon (TPH) distribution and the three-dimensional (3-D) models of crude oil impact.

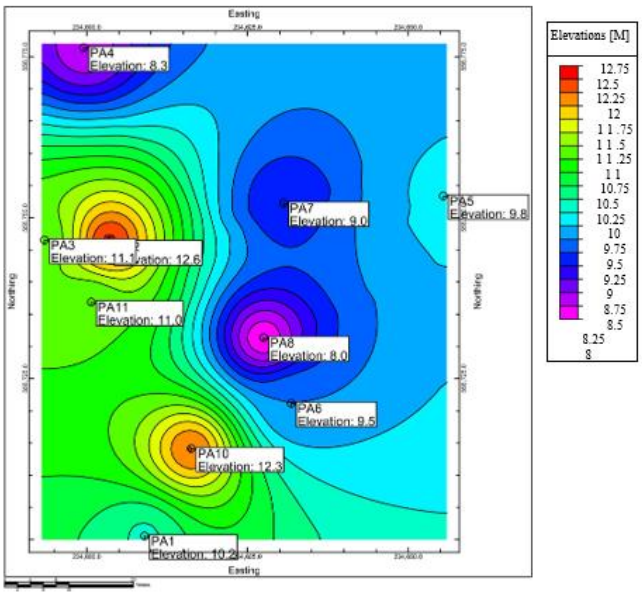

Fig. 2. Geospatial Distribution of Elevation across the Study Area

The geospatial map showing the spatial distribution of elevation is presented in Figure 2. The entire central part of the study area has deeper penetration values ranging from 2.0 m to 2.5 m but the western, eastern, northern and some parts of southern areas have low penetration values of 1 m to 1.9 m. The geospatial map showing the spatial distribution of depth of penetration is presented in Fig. 3. There are two spot heights in the study area- one is located at the northwestern part of the study area while the other is located at the central part.

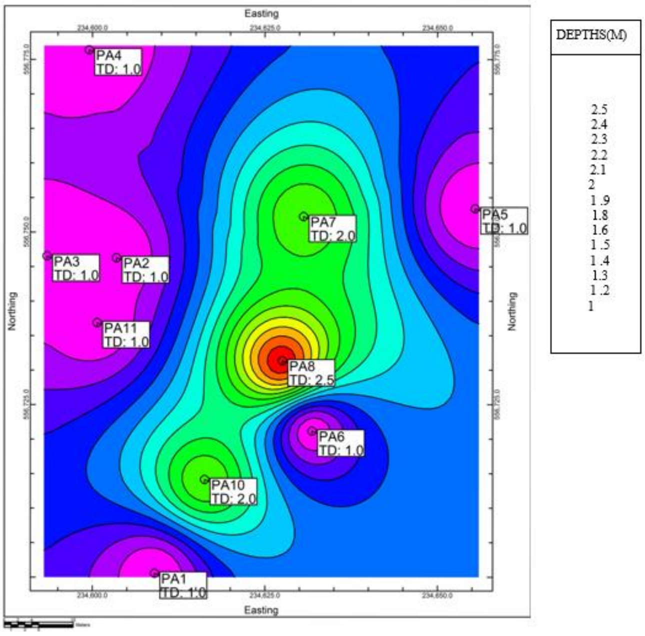

Fig. 3. Geospatial Distribution of Depth across the Study Area

Water flows from the higher elevation to the lower elevation. Fig. 4 is a map that shows the direction of water flow. Subsurface model was used to create the distribution of the Total Petroleum Hydrocarbon (TPH) concentration level at the crude oil impacted location. A 3-D subsurface model of the area of study impacted by crude oil spill as shown in the eleven borehole is presented in Fig. 1.6. The areas across the crude oil impacted site where TPH concentration levels exceeded 2,000 mg/kg, 3,000 mg/kg, 3,059 mg/kg, 4,000 mg/kg, 5,000 mg/kg, 6,055 mg/kg, 8,007 mg/kg, 11,000 mg/kg, 12,171 mg/kg and 16,542 mg/kg are shown in Figs. 1.7 to 1.11. The 3-D model showed hydrocarbon distribution both vertically and spatially. Hydrocarbon hotspot was found at Borehole 2 (PA2) within the depth interval of 1.5 m – 2.0 m. This corresponded to the high TPH value of 22,199 mg/kg obtained from laboratory analysis of soil samples.

The results of TPH showed that the hydrocarbon distribution across the study area is unevenly distributed. This pattern of variation in TPH distribution occurred both spatially (lateral-wise) and vertically (down the depth). This might be as a result of subsurface crude oil migration, oil weathering process and multiple sources of oil spills. The site does not show a widespread occurrence of hydrocarbon but a localized type of occurrence. Although the concentrations of TPH varied between 439 mg/kg and 30,522 mg/kg, the impact ranged from minimal or no impact to high and very high impact.

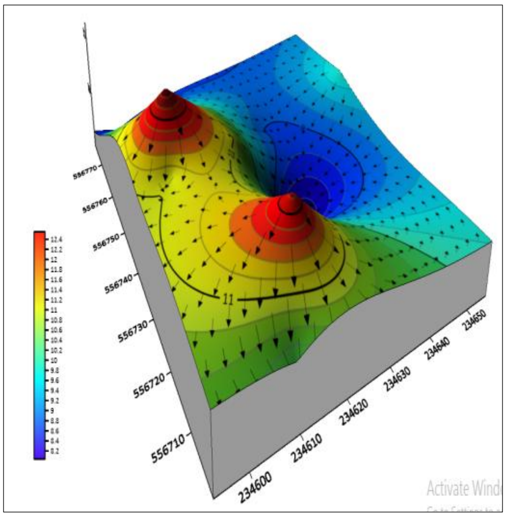

Fig. 4. The Map showing Groundwater Flow Direction

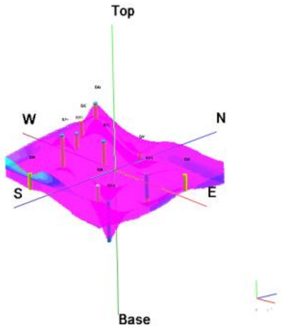

Fig. 5. The 3-D block Model showing Area of Oil Spill Impact

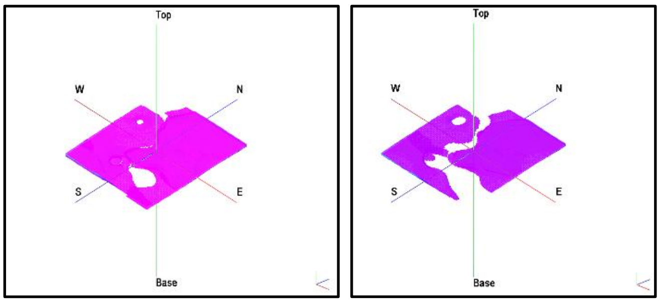

Fig. 6. The Areas where TPH Concentration is greater than 2,000 mg/kg and 3,000 mg/kg

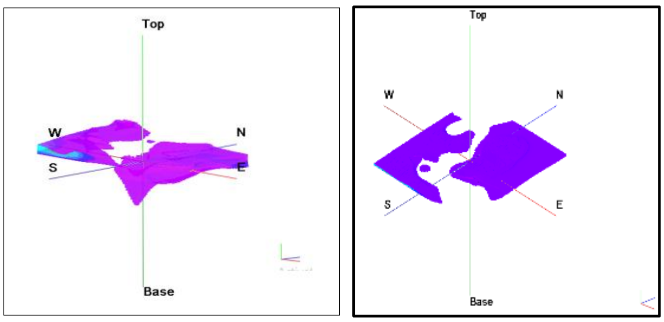

Fig. 7. The Areas where TPH Concentration is greater than 3,059 mg/kg and 4,000 mg/kg

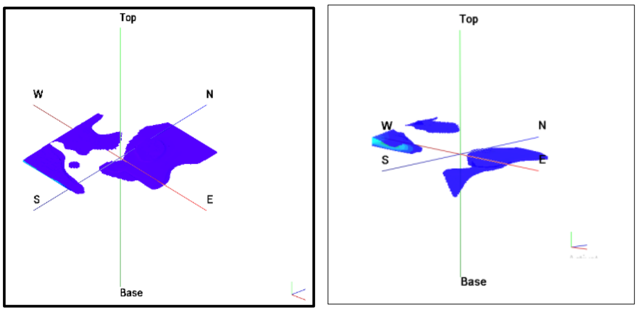

Fig. 8. The Areas where TPH Concentration is greater than 5,000 mg/kg and 6,055 mg/kg

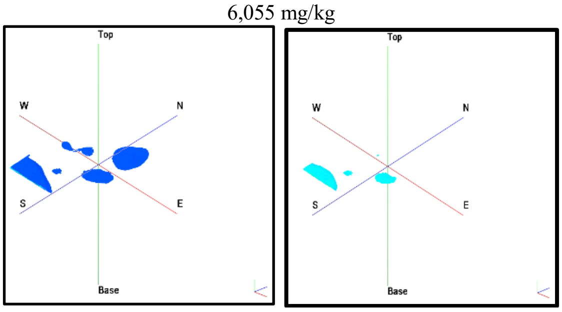

Fig. 9. The Areas where TPH Concentration is greater than 8,007 mg/kg and 11,000 mg/kg

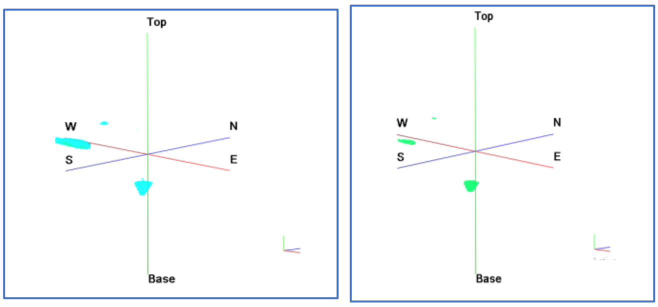

Fig. 10. The Areas where TPH Concentration is greater than 12,171 mg/kg and 16,1542 mg/kg

Modeling of the TPH concentrations Locations PA1, PA2 and PA3) show that the main crude oil contamination hotspot (with a strong red-coloured zone) is at the depth interval of 1.5 – 2.0 m near Location 2 (PA2) (Figure 11). The milder red/yellow zones showing a light crude oil spread are found near the surface at Locations 1 and 3 (PA1 and PA3). The contour gradients show vertical crude oil migration from mid-depth at Location 2 (PA2) and surface oil impact at PA1 and PA3 respectively. Within areas affected by crude oil, some authors have used subsurface modeling to identify hydrocarbon distribution. In their separate works carried out at different regions, Nixon and Michel (2015), Prasad *et al.,* (2017), Low *et al.,* (2021) and Abrakasa and Douglas (2022) showed that subsurface modeling remains an effective tool in hydrocarbon detection, delineation of impacted zones and in predicting the trajectory of oil spill.

The environmental implication as interpreted from the solid model is that Location 1 (PA1) has moderate crude oil contamination which occurred at the surface. This moderate contamination can respond well to natural attenuation process or simple soil washing. The soils at Location 2 (PA2) have been impacted by oil spill and therefore requires detailed remediation

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probably via soil excavation method or in-situ bioremediation technique. This is due to occurrence of high TPH values within the subsurface. Soils at Location 3 (PA3) present no serious risk as it can be seen as a likely minor contamination limited to surface zone

A heavy impact of hydrocarbon at the surface occurred at Locations PA3, PA4, PA5 and PA6 with TPH values of 13,452 mg/kg, 30,522 mg/kg, 9,861 mg/kg and 20,013 mg/kg) respectively. These high concentrations of TPH which exceeded the intervention value of DPR (5,000 mg/kg) in soil occurred at the depth interval of 0.0 – 0.1m. High TPH occurrence at the surface is usually caused by operational discharges of oil, on-land oil spills or oil leakages from aboveground facilities.

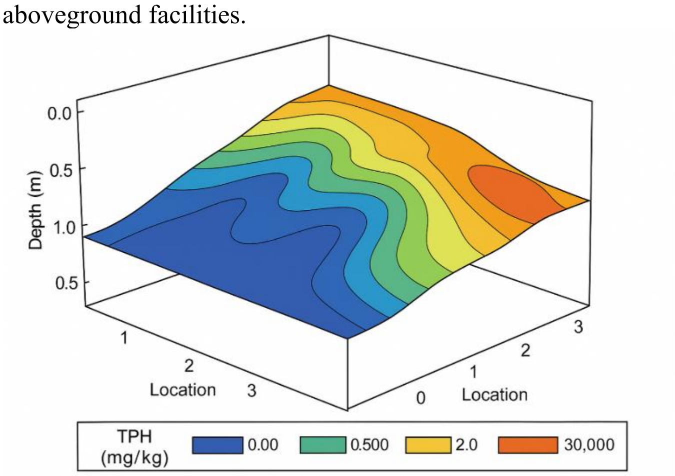

Fig 11: Hotspots of TPH Concentration within the Subsurface

Hydrocarbon occurrence and distribution in PA2 shows a strikingly different pattern as TPH values increased with increasing depth. This pattern could be attributed to one of the three scenarios: that oil drained from overlying permeable layer and accumulated within a soil layer that impeded further downward movement, downward oil migration triggered by groundwater flow, and/or oil spills from buried oil facilities. Researches have shown that upon oil spill incidence, hydrocarbon migrates vertically and laterally although the extent of migration is highly influenced by the nature, type and characteristics of the soil. For instance, Okop and Ekpo (2012) determined the concentrations of TPH in soil after three months of crude oil spill within a site at the Niger Delta of Nigeria and found high TPH values near surface, which decreased with depth. A study by Iwegbue *et al.,* (2007) which was carried out in a crude oil impacted community in Niger Delta of Nigeria revealed high values of TPH within the top soil. Also, Abrakasa and Douglas (2022) employed subsurface modeling of crude oil impacted site to determine the distribution of hydrocarbon. The study showed very high values of TPH which reached 54,236 ppm at the surface. The study reported a decrease of TPH value with increasing depth.

The study delineated crude oil plume within the subsurface at Location PA2. This poses a threat to groundwater resources within the study area. It is therefore recommended that groundwater quality assessment be carried out in further research to find out whether the water has been impacted by crude oil before carrying out site remediation. Also, appropriate remediation techniques suitable for the different zones of contamination delineated are to be employed to tackle crude oil contamination. There should be periodic monitoring of water quality within the study area is recommended. This is to ensure that the area around the zone of low-risk (Locations PA7 to PA9, and PA11) is not affected in the nearest future.

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