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Hydrogeophysical and Geotechnical Characterization of Soil and Groundwater at Two Crude Oil Spill Sites in Central and Eastern Niger Delta

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Abstract

Crude oil spills in the Niger Delta continue to impair shallow soils, groundwater quality, ecosystem services, and the geotechnical behaviour of near-surface sediments. This study presents an integrated geochemical, hydrogeological, geotechnical, and geoelectrical characterization of two spill-impacted communities, Agbura in Bayelsa State and Bodo in Rivers State. Five boreholes and nine vertical electrical soundings were established at each site to evaluate contaminant distribution relative to spill source, groundwater flow direction, depth of infiltration, and textural controls on contaminant mobility. Groundwater and soil samples were analysed for physicochemical parameters, total petroleum hydrocarbon (TPH), and selected heavy metals, while grain-size and Atterberg-limit tests were used to classify soils and infer hydraulic behaviour. Hydraulic-head contouring showed northeast–southwest flow at Agbura and northwest–southeast flow at Bodo, indicating preferential migration toward downslope receptors. Groundwater close to the spill centres recorded elevated turbidity, chemical oxygen demand, biochemical oxygen demand, and TPH, with the poorest quality at closest to spill sites in both communities. Water quality index status ranged from good to unsuitable, and heavy-metal pollution indices showed moderate to high pollution intensity near the impact points.The soils comprise clay, sandy clay, clayey sand, silty sand, and poorly graded sand, with average hydraulic conductivity of 3.11×10^{-6} m/s at Agbura and 8.53×10^{-6} m/s at Bodo. Correspondingly, spill-affected geoelectric layers displayed anomalously high resistivity, commonly between 500 and 2000 Ωm. The results demonstrate that the combined use of geochemical testing, geotechnical evaluation, and geoelectrical sounding provides a robust basis for site screening, vulnerability assessment, and remediation planning in coastal deltaic terrain.

Keywords: *crude oil spill; groundwater quality index; heavy metals; total petroleum hydrocarbon; electrical resistivity sounding; geotechnical characterization*

Introduction

One of the most enduring problems facing the environment in petroleum-producing areas is hydrocarbon contamination since its manifestations of the effects are manifested in soil, water, plants and the near-surface engineering products. In the Niger Delta of Nigeria, the tangled web of pipelines and ageing production facilities, tidal creeks, floodplains, shallow aquifers and heavy rainfall exacerbates this difficulty. However, oil spills seldom exist as single-surface incidents; additional distribution processes of oil include the run-off, infiltration, adsorption and capillary retention, and thus, they lead to multi-media contamination issues that impact agriculture, drinking-water systems, ecological wholesomeness and land developments (Nwilo &Badejo, 2005; Patin, 2004; Ugwu *et al.*, 2020). Niger Delta Crude oil spills relate to prescriptive and sedimentologic features of the basin, and are of significant environmental importance. To a large extent, the delta is supported by very permeable unconsolidated to slightly consolidated sand bodies in-between clayey layers of unstable persistence. These soils uphold shallow groundwater systems that are greatly depended upon to provide domestic and small community-scale supply (Etu-Efeotor & Akpokodje, 1990; Udom & Amah, 2006). The level of contamination where crude oil is discharged into such environments depends on the grain size distribution, clay content, hydraulic gradient, depth to water table and the physicochemical nature of the released hydrocarbon. As a result, a purely chemical definition of contamination would be inadequate; a technically convenient definition is also needed to determine the textural, hydraulic and geophysical constraints on contaminant mobility.

The documented cases of high levels of petroleum hydrocarbons and related heavy metals in soil, sediment, and shallow groundwater and observed degradation of agricultural lands, fisheries, mangroves, and community sources of water have been reported in the region previously (Osuji & Achugasim, 2007; Udoetok *et al.*, 2009; Nwankwoala and Mzaga Among the reported impacts are low productivity of plants, elevated health risk associated with water, ecosystem stress, and high levels of livelihood disruption in

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communities that rely on farming and fishing due to oil spillages (Aniefiong & Margaret, 2013; Bebeteidoh *et al.*, 2020). Added to these effects is that the response and remediation of spills are not swiftly addressed and the spill that is in the form of a hydrocarbon plume moves downslope or in a downwards direction into more permeable areas.

The Agbura and Bodo communities represent ideal case studies of affected coastal plain environments in the Niger Delta due to spills. In Bayelsa state, Agbura was affected by the Trans-Niger Pipeline corridor spill events related to the Nun RiverKolo Creek pipeline, and Bodo, in Rivers state, has been affected by the recurrence of spills in the corridor (Bamidele, 2021; Godwin, 2022). In either of these contexts, the interplay between hydrocarbon release, subterranean flowing, low land terrain, and fine- to coarse-grained mixed alluvial grains becomes of concern, not only regarding geochemical contamination but also the geotechnical and hydrostratigraphic behaviour of the affected soils.

The integrated site characterization is thus crucial. Geochemical studies determine the extent of the contamination, and correlate the concentrations with the regulatory or guideline levels. Geotechnical tests define the texture, plasticity, grading, and assumed permeability of the soils which precondition the retention and migration of contaminants. Geoelectrical sounding is considered to be a continuation of point sampling that is used to give overlaying information about the distribution of electro-anomaly of zones based on impact or lithologic contrast of hydrocarbons (Cassiani & Binley, 2005; Sauck *et al.*,1998; Egai &Oborie, 2021). The combination of such datasets gives a more compelling picture of the ways in which contaminants may move, and is more useful to guide the process of monitoring and remediation.

This paper thus explores geochemical and geotechnical nature of soils and groundwater on the two spill sites in Agbura and Bodo with special emphasis of (i) groundwater flow direction and areas susceptible to migrating contaminant, (ii) spatial variation in physicochemical parameters, TPH and heavy metals in groundwater and soil, (iii) geotechnical and hydraulic properties of the The more general objective is a combined approach to determining the behaviour of contaminants over spill-impacted deltaic land and to determine the comparative susceptibility of downslope receptors and shallow aquifers within individual communities.

Location and Geology of the Study Area

Location, Accessibility, and Environmental Setting

The study was carried out in two locations in the Niger Delta (Figure 1) in southern Nigeria. Agbura, in Yenagoa Local Government Area in Bayelsa State and Bodo, in Gokana Local Government Area in Rivers State, which are two sites of crude oil spill. Agbura is situated within approximately 15 km of Yenagoa, and it is located in a low-lying, fluvio-tidal plain, which is drained majorly by the Ikoli Creek and the Nun River.The area is located approximately between latitude 4°50'30″ and 4°52'00″ N and longitude 6°15'30″ and 6°17'30″ E. Bodo is an Ogoni community situated near latitude 4°37'00″ N and longitude 7°16'00″ E, roughly 53 km south-east of Port Harcourt, and is traversed by the 24-inch and 28-inch Trans-Niger pipeline corridors.

Both areas are very low in relief, extensive floodplains, tidal creeks, wetlands, and seasonally flooded land common with the lowlands of the Niger Delta. Typically, elevations are lower than 10 m above sea level and the topographic gradient is mild. This is because these geomorphic conditions favour long period of surface ponding, shallow ground water occurrence and fast contaminant redistribution when they are released. On the Agbura axis, the drainage is primarily also dendritic, related to the Nun River system and the Bodo axis is more strongly influenced by tidal creek processes, which are related to the Bonny River system.

The climatic condition is humid tropical, the rainy season is long and is dry season is short. The rainfall is also adequate to sustain the year round recharge with a standard of relative humidity being high in most parts of the time. These conditions are significant to hydrocarbon behaviour since multiple wetting, infiltration, runoff, and recharge by groundwater offer efficient methods of plume transport and redistribution. Vegetation varies between freshwater swamp and wet rainforest assemblage of Agbura to mangrove and saltwater swamp, and freshwater swamp vegetation of Bodo.

Geologic and Hydrogeologic Framework

The areas of study are included in the Niger Delta sedimentary basin that is a significant regressive delta complex that is composed of fluvial and marine sedimentation between the Late Cretaceous to Recent

Fig. 1: Regional location framework of the study areas within the Niger Delta.

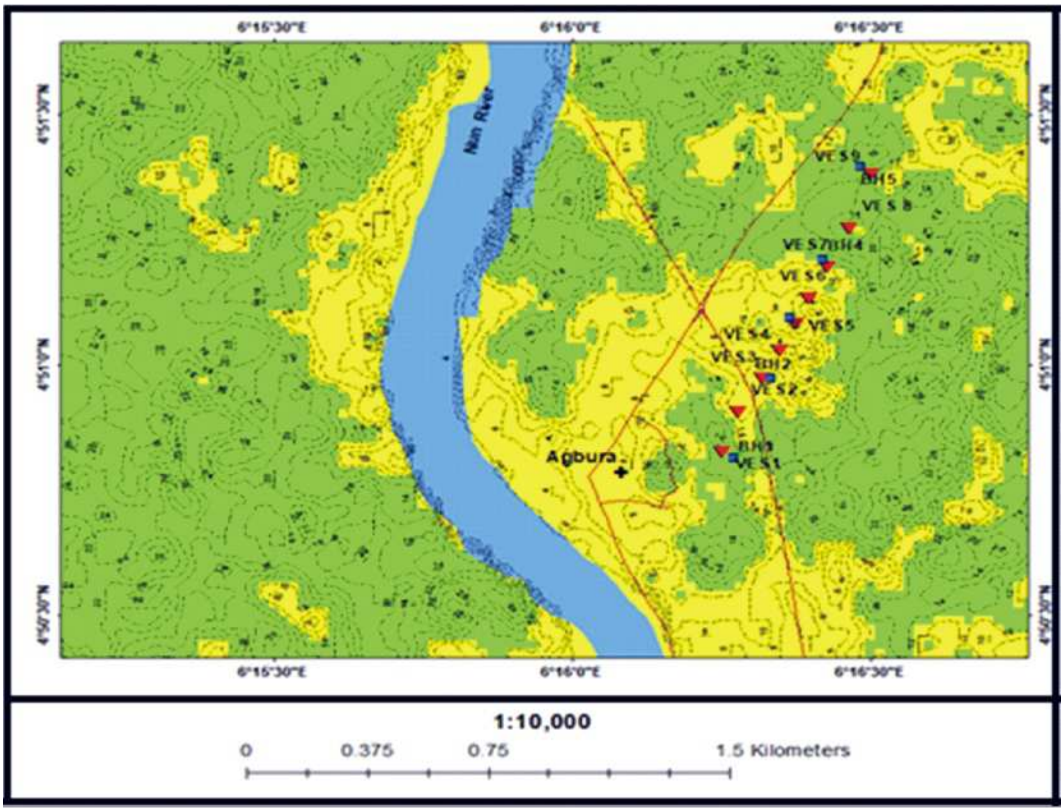

Fig. 2A:. Relative positions of boreholes and VES points in the sampling and geoelectrical stations at Agbura.

period (Doust & Omatsola, 1990; Short & Stauble, 1967). The basin is generally defined with three large lithostratigraphic units: the upper Benin Formation, the middle Agbada Formation as well as the lower Akata Formation. The major deep reaching-unit, the Benin Formation, in most on-shore areas of the delta, is composed of coarse- to medium-grained sand with minor silt and clay lenses. Near-surface alluvium comprising sand, clay, silt, peat, and swamp deposits overlies or interfingers with these units in many coastal lowlands (Allen, 1965; Weber, 1971).

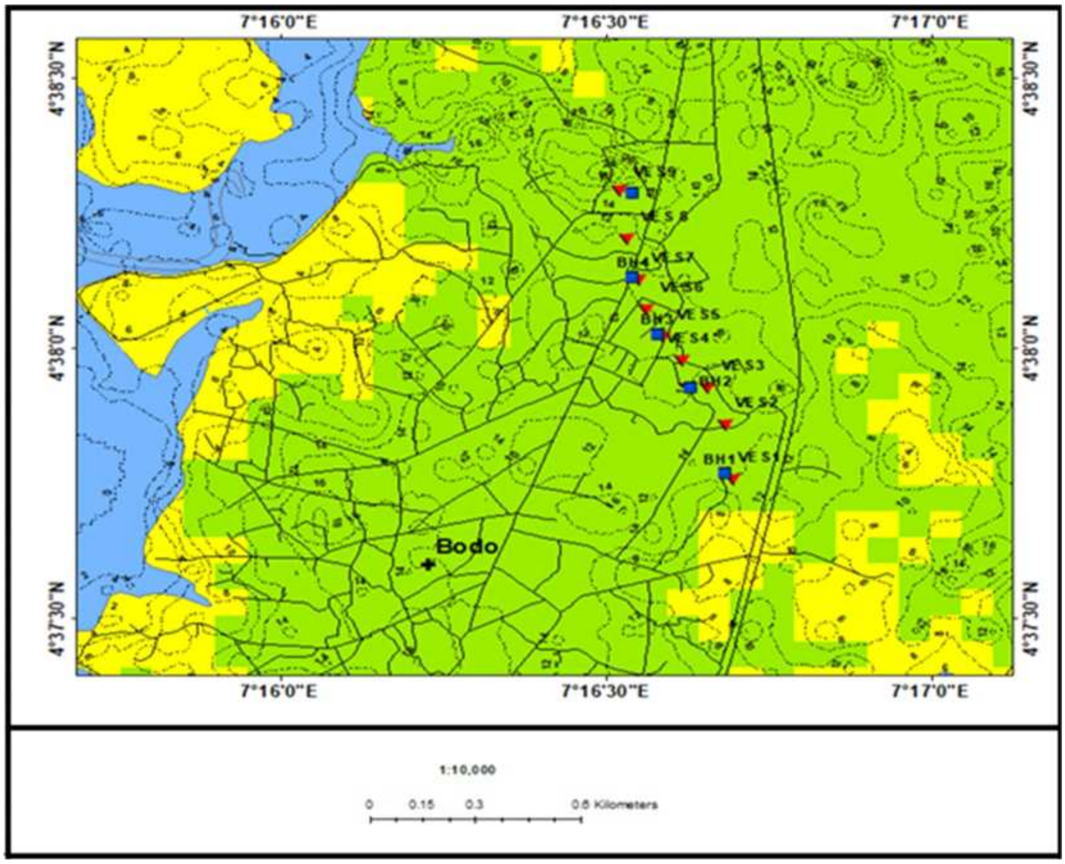

Fig. 2B: Sampling and geoelectrical stations at Bodo showing relative positions of boreholes and VES points.

In both Agbura and Bodo (Figure 2A and 2B), the shallow subsurface is dominated by coastal plain sand and alluvial materials, including clayey topsoil, sandy clay, clayey sand, silty sand, and poorly sorted sand bodies. The alternation of these materials is critical from a contaminant-transport perspective. Fine-grained and plastic horizons retard vertical movement and may temporarily trap or perch hydrocarbons, whereas sandy horizons provide the more transmissive pathways through which contaminants may migrate laterally or downward

Hydrogeologically, the Benin Formation is a prolific groundwater reservoir because of its generally high porosity and permeability, although the system is complicated by discontinuous clay intercalations that produce layered and locally heterogeneous aquifer conditions (Amajor, 1989; Etu-Efeotor & Akpokodje, 1990; Udom & Amah, 2006). Recharge occurs mainly from direct precipitation, and groundwater in the shallow subsurface is commonly under unconfined or semi-confined conditions. In low-lying deltaic communities where hand-dug wells and shallow boreholes are widely used, contamination of the upper aquifer horizon is therefore a major environmental and public-health concern.

Crude oil migration in the study areas will not be chemically controlled; this is because of the geological and hydrogeological setting of the study areas. Instead, the behaviour of the plumes is predicted to be a combined effect of hydraulic gradient, depth to water table, textural contrast, pore continuity, and the relative location of the spill source with regard to local downslope receptors. The premise lies at the heart of the integrated approach which has been taken in the present study.

Materials and Methods

The experiment used an integrated field and lab design whereby data of hydrochemical, geotechnical, hydrogeologic and geoelectrical was measured and interpreted collectively. Reconnaissance visits were initially undertaken to determine areas of spill impact, gain access to community, and choose representative

Table 1: Streamlined geologic structure of the study regions and hydrogeologic value.

Unit	Typical lithology	Age/setting	Hydrogeologic implication
Recent alluvium	Sand, clay, silt, swamp deposits, peat, organic-rich floodplain material	Quaternary deltaic and floodplain deposits	Controls shallow infiltration, localized perched conditions, and near-surface contaminant storage
Benin Formation (coastal plain sand)	Coarse- to medium-grained sands with subordinate clay and silt lenses	Miocene Recent upper delta plain succession	Main freshwater aquifer unit; generally high porosity and permeability
Agbada Formation	Alternating sandstone and shale	Eocene–Recent paralic succession	Important regional petroleum-bearing unit; not the primary shallow aquifer target
Akata Formation	Predominantly shale	Paleocene deep marine setting	Basinal shale unit forming the deeper regional foundation

survey lines, borehole points, and control stations. Fieldwork at Agbura was done in detail in early March 2022, the Bodo investigation in early November 2022.

Five boreholes and nine vertical electrical sounding (VES) stations along the spill corridor were set up at every community. The reference spill point was the borehole/VES pair (BH3/ VES5), the 50 m, 100 m, 150 m, 500 m boreholes and VES points located at the same location presented the upslope and downslope near-field observations. This layout as depicted in Table 2 was created to investigate the effects of the direction in which the groundwater flowed and the distance between the source and contaminants.

Direction of groundwater flow (Figure 2) was calculated based on the hydraulic heads (Figure 3) at existing wells by the difference of measured ground-surface elevation and measured static water level. Measurements of coordinates and elevation were made with a handheld global positioning system and hydraulic-head contours were drawn to estimate the likely flow and the relative susceptibility of the receptors nearby. The method adheres to conventional groundwater-flow mapping practices whereby flow lines are sketched at right angles to equipotential lines (Freeze and Cherry, 1979; Fetter, 2001).

Hand-augered depth of soil boreholes was 6 m. These recovered strata were logged and some representative samples were taken at the deep impacted horizon and at the deeper subsurface and geochemical analysis at the laboratory was primarily conducted at 0.5 m and 2.0 m. BH1-BH5 Groundwater samples were taken at every site. The in situ pH and electrical conductivity were measured using a calibrated meter, EZ9910, and other physicochemical parameters were measured through the normal laboratory procedures, which included; turbidity, dissolved oxygen, chemical oxygen demand, and biochemical oxygen demand. The USEPA 8015 gas chromatographic technique was applied in analysing total petroleum hydrocarbon in water whereas the atomic absorption spectrophotometry method was used in analyzing the heavy metals.

Table 2: Summary of sampling design and principal monitoring points in the two study areas.

Site	Representative codes	Reference spill point	Distance from spill	Interpretive significance
Agbura	BH1/VES1 to BH5/VES9	BH3/VES5	0, 50, 100, 150 and 500 m	Allows comparison of central spill point, downslope stations and upslope/control stations
Bodo	BH1/VES1 to BH5/VES9	BH3/VES5	0, 50, 100, 150 and 500 m	Captures impact gradient along the Trans-Niger pipeline corridor and contrast with control positions

Results

Groundwater flow pattern and hydrogeologic position of monitoring points

The hydraulic-head mapping indicated that the groundwater flow at Agbura is directed mostly in the northeast to southwest direction, as compared to the Bodo site that is dominated by northwest southeast direction. The importance of these results lies in the fact that the sampling transects were chosen to cross the flow path, meaning that at least a few of these points were

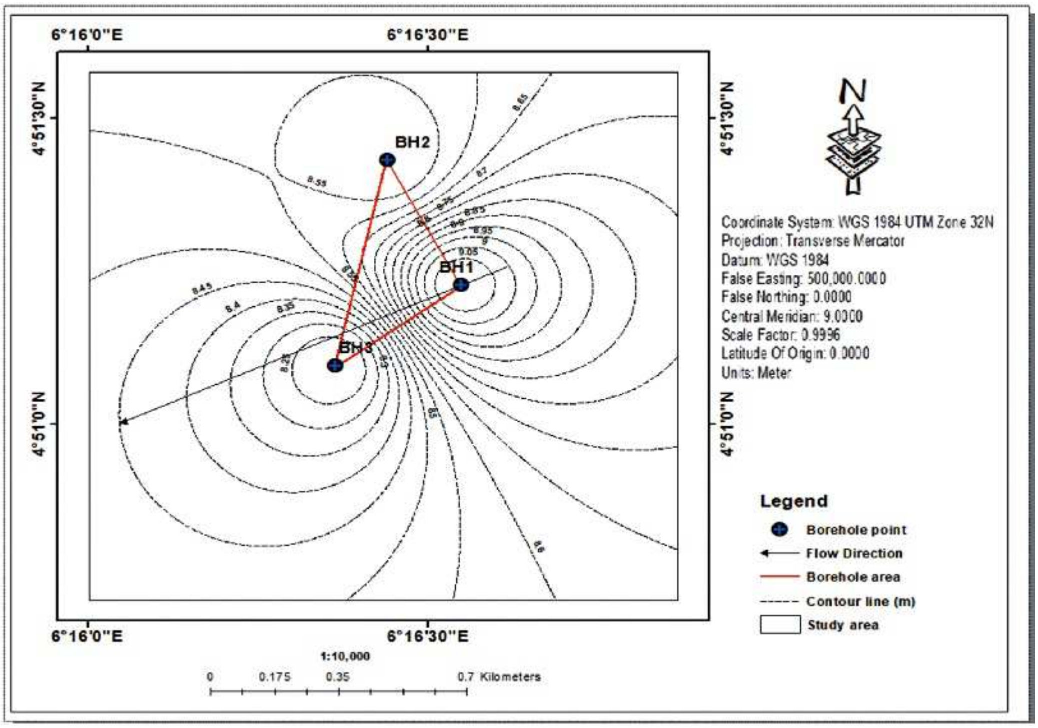

Fig. 3A: Groundwater flow direction in Agbura

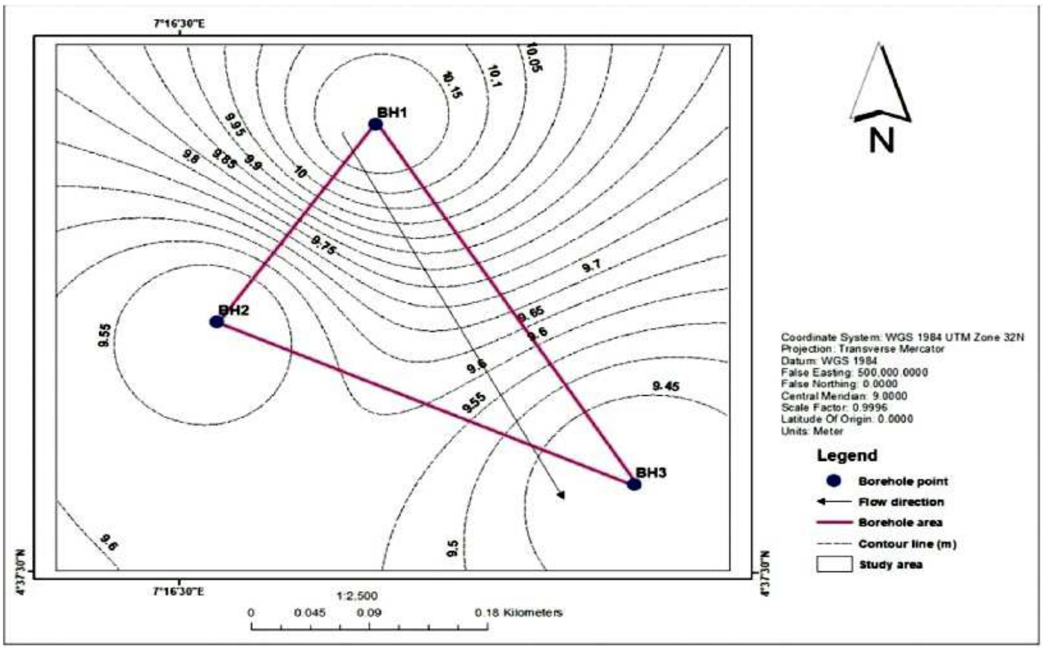

Fig. 3B: Groundwater flow direction in Bodo

either downslope of the location of the spill or was upslope. Practically, it would indicate that the points on the downgradient path are more apt to record plume migration as opposed to the points on the hydraulic upgradient side.

In Agbura, the hydraulic head estimate dropped to approximately 8.2 m (instead of 9.1 m) through the change in control wells, which were employed to contour across the wells, which was also in line with a southwestward trend. Hydraulic head at Bodo remained about 12.7 m and then reduced to 10.9 m along the contoured surface with signs of southeastward movement of groundwater (Table 3). The most vulnerable locations of groundwater and soil influence were thus considered to be the boreholes and the VES points nearest to the spill centres and those which followed the downgradient trend.

Table 3: Observations of hydraulic-head with which to interpret groundwater-flow.

Site	Well	Longitude (°E)	Latitude (°N)	Static water level (m)	Hydraulic head (m)
Agbura	Well 1	6.2758	4.8538	2.5	9.1
Agbura	Well 2	6.2740	4.8572	2.4	8.5
Agbura	Well 3	6.2727	4.8516	2.1	8.2
Bodo	Well 1	7.2763	4.6269	3.2	12.7
Bodo	Well 2	7.2753	4.6256	3.1	12.2
Bodo	Well 3	7.2742	4.6285	3.6	10.9

Groundwater physicochemical quality

The ground water in the two communities is slightly acidic to a near neutral with pH ranging between 6.1 and 6.9 at Agbura and between 6.3 and 7.2 at Bodo. The electrical conductivity was mostly lower than the WHO limit of 1000 µS/cm which means low or moderate dissolved ionic content. The most effective evidence of contamination, however, was found in the samples nearest to the main spill points, according to the high turbidity, oxygen-demand variables, and TPH.

The turbidity of BH1 to BH4 at Agbura was 6.2 to 11.8 NTU and that of BH5 was 6.3 NTU; the turbidity of BH1 to BH4 at Bodo was 4.2 to 12.4 NTU. The dissolved oxygen was relatively low at various points especially at the main spill points. Chemical oxygen demand was higher in Agbura BH3 (15.2 mg/L) and Bodo BH3 (22.1 mg/L), whereas biochemical oxygen demand was greater in all boreholes sampled (maximum of 10.2 mg/L and 15.7 mg/L, respectively). The maximum TPH in ground water at BH3 was recorded in both communities, which were 0.9382 mg/L at Agbura and 1.255 mg/L at Bodo and the values were high in the range of about 100-150 m of the source of the spill.

Heavy metals, groundwater quality index, and pollution indices

In Agbura, the iron level was between 0.20 and 0.35 mg/L and in Bodo, it was between 0.15 and 0.27 mg/L. The Agbura results show that the 0.30 mg/L guideline was exceeded in three sites and that copper, zinc, and nickel were below the WHO guideline in the two communities. The study considered lead as a contaminant of interest, and its values were above the recommended limit in most samples, and the values of manganese were only above the recommended limit in the locality.

The weighted water quality index (Figure 4) clearly distinguishes between the central spill corridor and the more distal stations. Agbura found good-quality groundwater at BH1, BH4, and BH5, poor water at BH2, and water that cannot be drunk at BH3. At BH4 and BH5, Bodo registered good groundwater, at BH1, poor water, at BH2, very poor water and at BH3, unsuitable water. The indices of the heavy-metal pollution support this reading by showing that the nearest indices to the spill points are moderate to high in terms of pollution burden, and the highest values of HPI, HEI, and CI values are found at BH3 in both locations.

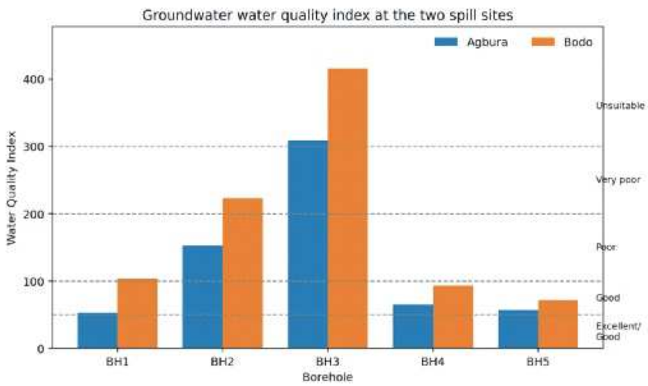

Fig. 4: Water quality index values showing progressive deterioration toward the spill centres, especially at BH3.

Soil geochemistry

Soil geochemistry confirms that the most intense hydrocarbon impact is centred on the spill point and diminishes outward from it, although the vertical expression differs between Agbura and Bodo (Figure 5). At Agbura, TPH at 0.5 m depth across the boreholes ranged from 4.9 to 106.6 mg/kg and at 2.0 m depth from 32.6 to 101.8 mg/kg. The maximum concentrations were at BH3 and BH2 was also greater than the EGASPIN target value at depth. The deeper average of Agbura is marginally greater than the shallow average indicating that there is a significant downward redistribution of oil or retention in a less permeable intermediate horizon.

The shallow horizon at Bodo is more contaminated than the deeper one with TPH of 18.9-140.2mg/kg at a depth of 0.5m and 12.4-111.6mg/kg at depth 2.0m. At both levels, BH2 and BH3 surpass the EGASPIN target, whereas BH4 maintains high TPH but at lower concentrations than that at the center of the spill. The Bodo results hence suggest a high near surface contamination core, with diminishing concentration further out of source as well as depth, but vertical penetration is still high.

The heavy-metal concentration of the soils exhibits local enrichment of nickel and lead at the more affected stations, and iron and manganese are used to indicate both the natural composition of the sediments and redistribution associated with spills. Zinc and copper do not exceed the intervention levels applied to make comparisons but the spatial distribution of the two still reflects the general hydrocarbon footprint.

Geotechnical characteristics and hydraulic estimates

According to the geotechnical data (Table 4 and Figure 6), there is significant lithologic heterogeneity in the shallow subsurface. Agbura has soils that are largely dominated by CL, CH, SC, MH and SM, but Bodo has soils that are dominated by SC, CL, CH, SP-SM and SC-SM. Plasticity tends to be greater in the clay-bearing horizons and less in the sands.

In Agbura, liquid limit values are between 28 percent and 73 percent and plasticity index between 12 percent

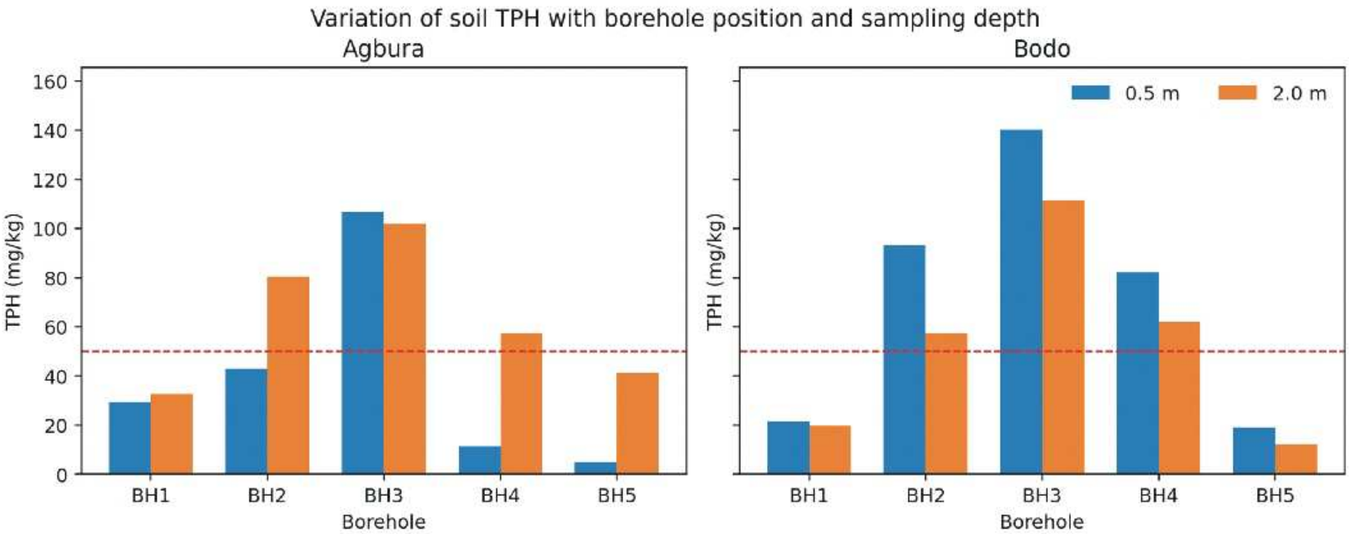

Fig. 5: Soil TPH, borehole scale depths (0.5 m and 2.0 m) at Agbura and Bodo.

Table 4: Representative geotechnical and hydraulic properties of selected soil samples.

Sample	USCS class	LL (%)	PL (%)	PI (%)	D10 (mm)	Porosity	Hydraulic conductivity (m/s)
A3	SC	28	16	12	0.044	0.3806	2.38×10^{-6}
A4	SC	32	18	14	0.052	0.4035	4.04×10^{-6}
A10	SM	34	21	13	0.046	0.3929	2.90×10^{-6}
B1	SC	27	18	9	0.072	0.4242	9.09×10^{-6}
B2	SC	26	14	12	0.058	0.4063	5.20×10^{-6}
B8	SP SM	33	24	9	0.080	0.3981	9.19×10^{-6}
B9	SC-SM	26	20	6	0.086	0.4121	1.18×10^{-5}
B10	SC	22	16	6	0.070	0.4035	7.36×10^{-6}

and 41 percent; at Bodo, liquid limit is between 22 percent and 61 percent and plasticity index is between 6 percent and 34 percent. The values suggest that the near-surface stratigraphy has moderately to highly plastic fine-grained materials that can retard vertical movement in addition to coarser sandy layers that can easily transmit fluids.

Sandy units which were selected gave a D10 value of approximately between 0.044 and 0.086 mm and uniformity coefficient of approximately between 2.2 and 4.0 representing mainly poorly graded to marginally well-graded materials. The approximate values of porosity are between 0.38 and 0.42 and the hydraulic conductivity of Hazen and Kozeny-Carman relationships are between 2.38 x -6 to 1.18 x -5 m / s. The site-average conductivity is approximately 3.11 x 10 - 6 m/s at Agbura and 8.53 x 10 - 6 m/s at Bodo meaning the sandy fractions are more transmissive at Bodo.

These findings indicate that the Bodo site provides better hydraulic characteristics of downward and lateral mobility of hydrocarbons through sandy routes under similar exposure periods, compared to Agbura that has more areas where the movement of contaminants could be retarded, trapped or reallocated by clay-rich intermediate layers..

Geoelectrical characteristics

The VES results as presented in Table 5, and Figures 7 and 8, show a consistent distinction between control

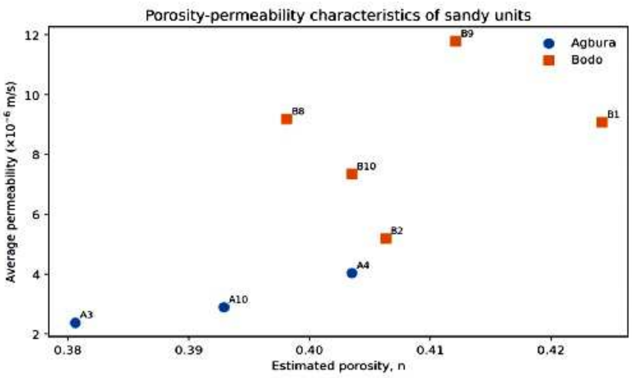

Fig. 6: Relationship between porosity and estimated hydraulic conductivity for selected sandy units.

locations and spill-affected stations. Control sites in both communities typically display near-surface resistivity values compatible with natural unconsolidated clayey sand, sandy clay, and sand deposits. Conversely, resistivity enhancement is observed to be intense at stations near and at the spill centres particularly the shallow and intermediate subsurface. The control site topsoil resistivity on Agbura is approximately 54106 Om and the data at the spill-centre station are 1584, 769, 325, 680, and 2171 Om, successively on top. Control stations in Bodo show good resistance of the topsoil, about 81158 Ohms/M and those of spill-centre station is 1326 ohms.

After correlating the sounding interpretations with the lithology of the borehole and geotechnical observations, three wide resistivity domains are revealed. Originally, values between 50-200 0m is associated to unaffected clay, silty clay, sandy clay and natural sandy units. Second, the measurements between 500-1000 Ωm of the values are indicative of an intermediate layer which is likely to be affected by infiltration of hydrocarbons. Third, values above approximately 1000 Ωm, and occasionally near 2000 Ωm are found in only the shallow, and heavily affected, horizon, nearest to the source of a spill. The interval that is usually localized is that which is in the range of 0.8-3.2 m depth.

The geoelectrical results also show increased vertical penetration at Bodo compared to Agbura and this is in agreement with the increased average hydraulic conductivity that is determined in the geotechnical investigation. The VES results thus offer a good subsurface bridge to the single point chemical data and the overall hydrogeologic task.

Table 5: Summary of control and spill-centre station representative VES resistivity signature.

Site/station	Resistivity sequence (Ωm)	Interpretive lithology	Hydrocarbon implication
Agbura VES1 (control)	106, 78, 124, 192, 401, 1270	Clayey sand–sandy clay–sand succession	Essentially background condition
Agbura VES5 (spill point)	1584, 769, 325, 680, 2171	Highly resistive impacted topsoil over mixed sands and clays	Strong hydrocarbon imprint
Bodo VES1 (control)	158, 112, 191, 284, 501	Natural clayey sand and sandy layers	Background condition
Bodo VES5 (spill point)	1703, 1314, 786, 502, 1326	Strongly resistive spill-impacted profile	Pronounced hydrocarbon impact

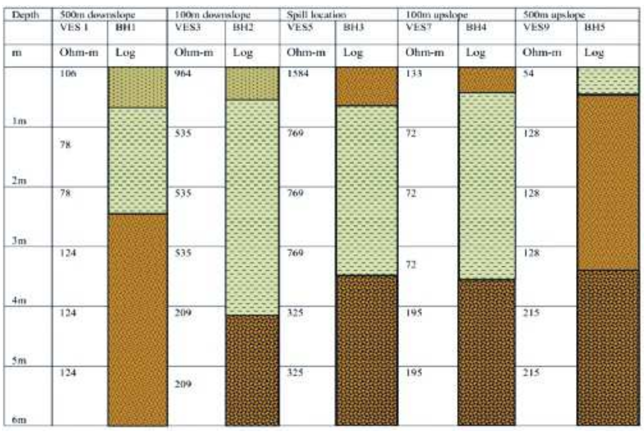

Fig. 7: Borehole lithology-Agbura VES interpretation/correlation

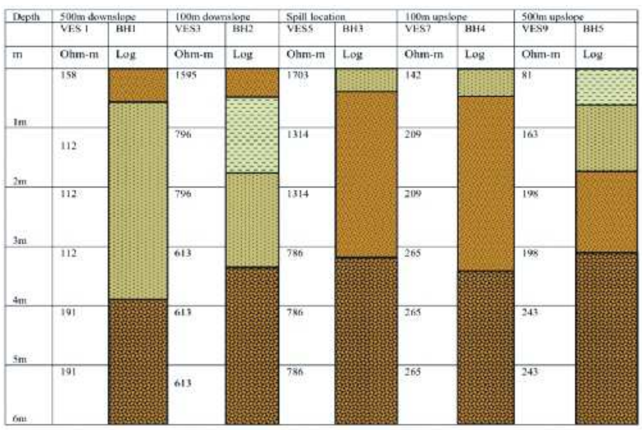

Fig. 8: Correlation of Bodo VES interpretation with borehole lithology.

Discussion of Results

The integrated data implies that the three mutually reinforcing controls that control the environmental behaviour of the crude oil at the two sites of investigation are: hydraulic gradient, textural heterogeneity and the hydraulic capacity of the shallow sediments. The spill point contaminants that leaked have not a uniform likelihood of spreading in one direction or the other, as demonstrated by the ground water-flow maps. Rather, the downgradient sector is the most vulnerable sector in each community. That is why the boreholes situated along the supposed flow reveal more water-quality degradation and why the control stations which are some distance away or on the hydraulic upgradient side appear to reveal some low contamination signatures.

These hydrochemical findings show that the most severe degradation of the ground water takes place at and around the areas of the major spills. The references at BH2 and BH3 were lower than TPH values in ground water at both communities and at BH4 in Bodo where the contaminants persistently exist in the shallow aquifer system. The resulting growth in turbidity, COD and BOD indicates that the spill has changed the physical and oxygen demand properties of the groundwater. These alterations agree with petroleum contamination since the loading of hydrocarbons can cause the introduction of suspended solids, use of oxygen when exercising biodegradation, and alteration in biogeochemical equilibrium of shallow water (Patin, 2004; Rostami & Juhasz, 2011).

These changes can be conveniently summarized by the water quality index. At both locations, BH3 has the poorest water quality, and BH2 is still severely undermined, proving the fact that the closeness to the spill source is a highly influential factor of groundwater degradation. The overall reduction in WQI at BH1-BH3 is higher in Bodo, as compared to Agbura. This can indicate a synergy in multiple spills along the Bodo corridor and the relatively greater hydraulic conductivity of sandy materials there, which would preferential transferrin of contaminants. The same conclusion is justified by the heavy-metal pollution indices that reveal an overall pollution burden with maximum in BH3 and a downward trend.

The vertical and lateral structure of the hydrocarbon footprint is explained with the help of soil geochemistry. The maximum TPH concentrations are invariably concentrated on BH3, and at BH2, and in Bodo, BH4, the contamination remains noticeable. The dissimilarity in the two neighborhoods is on the partitioning of the oil in depth. In Agbura, TPH is greater at 2.0 m compared to 0.5 m, implying that some of the spilt hydrocarbon must have washed down and be trapped or held in a lower less permeable layer. In Bodo, however, the shallow horizon is bearing the higher burden of hydrocarbons meaning it has a more pronounced near-surface core of contamination although there is still clear evidence of downward migration. The differences between these contrasting profiles are in line with the variations in proportional abundance and persistence of clay-rich and sandy horizons at the two locations.

These observed differences can be explained in a mechanistic manner by the geotechnical data. Clay and high plasticity clay layers are less permeable with high adsorptive potential, which retains the amount of hydrocarbons and helps to reduce downward movement. The transitional behaviour is given by sandy clay and clayey sand, with preferential migration being given by poorly graded sands and silty sands. The greater site-average hydraulic conductivity of the sandy units at Bodo means that the hydrocarbon will travel faster in the transmissive units once it has traversed or broken through the young fine-grained cover. Lower average conductivity, at Agbura, and increased plastic strata support the retardation, temporary storage and redistribution in the shallow subsurface. The calculated travel distances obtained in the dissertation indicate the fact that oil may horizontally travel about 3.5 m in depth, within 30 days in favourable conditions, underlining the limited time that one has to respond to a spill event.

Of special significance is the geoelectrical evidence that indicates that spill footprint is not restricted to the small number of sampled points. The anomaly of strong resistivity of the affected stations in such deltaic sediments is best attributed to the replacement of the pore-fluid matrix that is normally conductive in the shallow soil by hydrocarbons. The natural range of resistivity of the clayey and sandy alluvium is characterised by the control stations, and the affected ones display the sudden jump to significantly high values. The 5001000 ohms (especially 500 1000 ohms) intermediate zone is particularly important as it likely represents the depth range in which migrated hydrocarbon builds either above or within a less permeable horizon. This interpretation concurs with the vertical TPH distribution of the soils that is observed and agrees with the geotechnical evidence of mixed fine and coarse-grained layering.

Combined outcomes suggest that Bodo is a bit less susceptible to fast vertical and lateral migration, whereas Agbura presents greater manifestations of subsoil entrapment and redistribution, according to an environmental management perspective. However, the sites have groundwater and soils which would take priority in removal in the area surrounding the spill centre and the path of downgradient. The statistics also suggest that the remedial interventions are not merely to be directed at the spill area that is visible at the surface.

They also have to consider the vulnerability of the shallow aquifers, its hydraulic direction of contaminant movement, and the probability of having a storage of the hydrocarbons in the middle geoelectric layers where it might remain as a long-term source.

The current paper also reveals the usefulness in practice of applying chemical, geotechnical and geophysical approaches to spill-site appraisal. Laboratory chemistry is sufficient to tell the contaminated points but not to sufficiently tell the geometry of the impact of the underground. On the other hand, geophysics does not have enough confidence to define the regulatory significance and type of contaminant unless it is combined with other tests. Integrating both methods and grounding them onto the basis of hydrogeologic measurement and geotechnical measurements, the study creates a more justifiable model of screening an area of impact and prioritizing areas of intervention and remediation monitoring programmes on the Niger Delta.

Summary and Conclusion

In this work, we have shown that the combinations of the proximity of the sources to crude oil, the direction of the groundwater flow, and the textural-hydraulic characteristics of the shallow subsurface help to control crude oil pollution at Agbura and Bodo. The flow of groundwater has an agbura east- northeast southwest direction and Bodo northeastsouthwest meaning downgradient receptors are more susceptible than upgradient location. The quality of groundwater is significantly reduced around the spill centres as indicated by high levels of TPH, turbidity, COD, and BOD and WQI of good and unsuitable. Soil geochemistry proves that the spill footprint is concentrated at the reference points spills and decreases away and the way it is expressed varies at both sites. Agbura records a significant downward redistribution of TPH to deeper subsoil as compared to Bodo which records a stronger near-surface redistribution of TPH, but with a higher accumulative transmissivity of the sandy units. Geotechnical classification reveals interbedded clay-sandy clay- clayey sand- silty sand and poorly graded sand with the estimated hydraulic conductivity of 3.11 × 10 -6 m/s in Agbura and 8.53 × 10 -6 m/s in Bodo. These values provide the greater implied susceptibility of Bodo to swift migration of contaminants.

The geoelectrical data further extrapolate the chemical findings to the depths by distinguishing between unalterable natural sediments and those that were altered by spills. Background soils normally lie in the range of 50- 200 O m and the affected layers lie in the range of 500- 2000 O m. The shallow to intermediate subsurface usually contains most of the contamination, usually in a depth of about 0.832m. The results include, in general, that the spill sites need contact planning of the remediation of the sites with emphasis on the core of the spill corridor and downgradient flow routes. The situation requires immediate action, since within a few days after the release, migration of hydrocarbons into the sandy beds is possible due to the shallow, sands-based level of the reservoir. To match the conditions of the deltaic environments, a combination of groundwater-flow mapping, geochemical tests, geotechnical analysis, and electrical resistivity sounding is suggested to a powerful system of screening, delineation, and post-remediation monitoring.

Comparative environmental diagnosis and importance of remediation.

The two sites can be directly compared to demonstrate that poorer groundwater quality, high average hydraulic conductivity, and strong resistivity-determined vertical penetration are also observed in Bodo, whereas the effects of subsoil trapping and redistribution in an intermediate layer are evident in Agbura (Table 6). This is a significant difference to remediation design. In the case of Bodo, monitoring and recovery efforts must focus on the shallow transmissive routes and down gradient water receptors due to the ability exhibited by the hydrocarbon plume to move at high speed in the event that it moves through sandy formations. At Agbura, the presence of retention of contaminants in clay-based or mixed-texture horizons where petroleum could remain as a secondary delayed source should also be taken into account, to facilitate remedial measures.

The combined evidence indicates a realistic remediation sequence of such spill affected deltaic environments: instant containment on the spill source, expedite safeguarding of downstream wells and creeks, superficial retrieval of soil in the main spill segment, and subsequent subsurface research based on the 0.8-3.2 m range, where geoelectrical anomalies and soil chemistry reflect the highest retention. In the case of a community water supply relying on shallow aquifers, it follows that groundwater monitoring must initially be focussed at the boreholes situated along the hydraulic gradient, rather than just being by radial distance to the spill point.

Table 6: Comparative environmental syntheses between Agbura and Bodo

Diagnostic factor	Agbura	Bodo
Groundwater-flow direction	Northeast–Southwest	Northwest-Southeast
Worst groundwater quality location	BH3 (unsuitable)	BH3 (unsuitable)
Average hydraulic conductivity of sandy units	~3.11 × 10^{6} m/s	~8.53 × 10^{6} m/s
Dominant contamination style	Downward redistribution with intermediate trapping	Strong near-surface enrichment with greater transmissive potential
Resistivity expression	High anomaly at spill centre; impacted layer concentrated at shallow intermediate depth	Stronger vertical resistivity anomaly and deeper effective penetration
Priority remediation focus	Source control plus subsoil retention zone	Source control plus downgradient shallow aquifer pathway

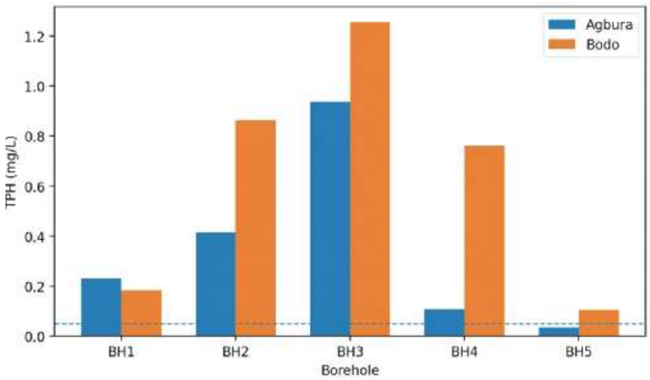

Fig. 9: Table of distribution of groundwater TPH at the boreholes, where it is innocent at the spill-centre stations.

Ground water TPH pattern with respect to the spill centres

The TPH pattern of ground water (Figure 9) resembles the level of diagnostic outcomes of the WQI and the geoelectrical interpretation. Within the two communities, the concentrations peak rapidly toward the distal points but decrease once more at the further, more distant stations. Nevertheless, Bodo has higher TPH than Agbura more distant to the centre especially at BH4 which contributes to the assumption that Bodo site provides a better system of hydraulic connection to spread contaminant by means of the shallow aquifer system.

These other comparisons combined give support to the major conclusion of the paper that groundwater-flow direction, shallow stratigraphy and the response of impacted soils to hydraulic influence are essential in determining spill response in low-lying coastal populations. Strategies that do not consider these controls may underestimate the tenacity of remaining contamination and susceptibility of receptors that are down-gradient of the spill footprint being visible.

Another implication of the findings is that the spill evaluation of the Niger Delta must differentiate between the presence and absence of the visible surface cleanup and the risk mitigation at the subsurface level. The most prominent hydrocarbon signature at Agbura and at Bodo is not restricted to the visibly stained surface of the ground, but also extends deep into the subsurface to the shallow ground and in some cases to groundwater used to supply household needs. This implies that one cannot determine the remediation success on the basis of clean topsoil or survival of vegetation. The follow-up monitoring should involve shallow groundwater chemistry, repeat geophysical screening of the spill area, and selective verification sampling in the intermediate depth area where the hydrocarbons can be trapped.

The research is also relevant to the engineering field other than environmental chemistry. The foundation of low-lying deltaic settlements, excavation work, buried utility services and water-supply networks all come in direct contact with the same poorly-strengthened and variably- contaminated soils which are described here. Contaminated soil with sufficient clay content can be soft, plastic, water retentive, and the sandy impacted materials can still be functioning as sources of residual hydrocarbons to the neighboring buildings and wells. For this reason, future spill-response protocols in similar terrains should integrate environmental geoscience with geotechnical appraisal from the earliest stage of site investigation.

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