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INTEGRATED GEOPHYSICAL AND GEOCHEMICAL METHODS FOR ASSESSMENT OF HYDROCARBON CONTAMINATION OF THE WARRI-SOMBREIRO UPPER DELTAIC PLAIN DEPOSITS AQUIFER

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Abstract:

Oil spillage in oil-producing communities as a result of failure due to corrosion of aging pipelines has become a significant environmental menace in the Niger Delta. Groundwater resources at Afiesere, an oil-producing community, were evaluated with the view of assessing the quality of groundwater. This study involved in-situ and laboratory evaluation of physicochemical parameters at twenty-five (25) locations. Schlumberger configuration was also adopted in vertical electrical soundings at twenty (20) locations to delineate the sub-surface's lithological framework and protective capacity/vulnerability. Results from the study show pH (5.90 – 7.01), electrical conductivity (EC) (8.90 – 1247.3 µS/cm), total dissolved solids (TDS) (4.0 – 952.7 mg/l), K^+ (0.38 – 30.05 mg/L), Na^+ (0.09 – 16.34 mg/l), Ca^{2+} (0.29 – 65.80 mg/L), Mg^{2+} (0.02 – 6.14 mg/l), Cl^- (2.40 – 65.85 mg/l), HCO_3^- (1.07 – 77.2 mg/l), SO_4^- (0.05 – 7.16 mg/l), NO_3^- (0.00 – 0.07 mg/l), and total hydrocarbon content (THC) varied between 0.00 – 1.50 mg/l. The result shows that groundwater is fresh and weakly acidic. Cationic, anionic, and heavy metal concentrations were mostly below the acceptable standard for drinking water except for Ca^{2+}, HCO_3^-, Fe, Pb, TDS, and THC, which exceeded the permissible limits at 2 locations that were proximal to oil pipelines. This was adduced to hydrocarbon contamination due to leakages from oil pipelines. Electrical resistivity at these locations were characterized by low resistivity values (< 650 Ωm) which is due to degradation of hydrocarbon.

Keywords: Groundwater, contamination, hydrocarbon, corrosion, isoresistivity.

Introduction

The advent of crude oil production in the Niger Delta region has negatively impacted the environment; soils and groundwater have become contaminated with hydrocarbons from various routes: spills from corroded/vandalized pipelines and oil production operations. Unprecedented oil spillage, a persistent environmental problem for the past 5 decades, has made the region one of the most polluted in the world. The presence of petroleum hydrocarbons in soils is a problem that has caused concerns worldwide because it poses a considerable threat to human health and natural ecosystems (Hewelke *et al*., 2018). Once deposited on the surface, the hydrocarbon may persist, bioaccumulate (Alloway, 1992), and infiltrate into aquifers via leaching and surface runoff.

The Niger Delta, which covers about 20,000 km^2, is the largest wetland and the third-largest drainage basin in Africa. The region is Nigeria's crude oil and natural gas hub, with several networks of product pipelines dotting the entire landscape. These petroleum products remain one of the most prevalent contaminants (Atekwana *et al*., 2004a). The pipelines, which have an estimated life span of about fifteen years, are old and susceptible to corrosion because most of the pipelines are as old as twenty to twenty-five years. The activities of oil and gas industries pose a significant source of soil and water pollution (Hentati *et al*., 2013; Karr, 2013; Ohanmu and Bako, 2017). Corrosion which accounts for a high percentage of all spills, is due to the small size of the oilfields in the Niger Delta, which necessitated an extensive network of pipelines between oil fields and flow stations. These pipelines are old, susceptible to corrosion, and have narrow diameters, thus allowing many opportunities for leakage.

High concentrations of hydrocarbon has been reported groundwater in the Niger Delta by various studies (Karr, 2013; Akporido and Kadiri, 2014; Onojake *et al*., 2014; Imaobong and Prince, 2016; Onyegeme-Okerenta *et al*., 2017). It is the concern of crude oil seeping into the groundwater that necessitated the current investigation with the objective aimed at assessing the vulnerability of the aquifer to the activities of petroleum companies in the region. This is eminent to the availability of potable water resources both for present and future generation given the fact that aquifers in the Niger Delta region are generally shallow.

Location and Geology

The study area, which lies within the Niger Delta, is situated approximately within longitudes 6° 00′ E, 6° 02′ E and latitudes 5° 30′ N, 5° 32′ N. The Warri-Sombreiro Upper Deltaic Plain deposits underlie the region. The stratigraphic sequence comprises of thin clay/sandy clay topsoil, underlain by fine to medium and coarse-grained sand (Aweto, 2018). The low-lying area does not usually exceed an elevation of 20 m and consists of an extensive plain exposed to periodical flooding when the rivers and creeks overflow their bank.

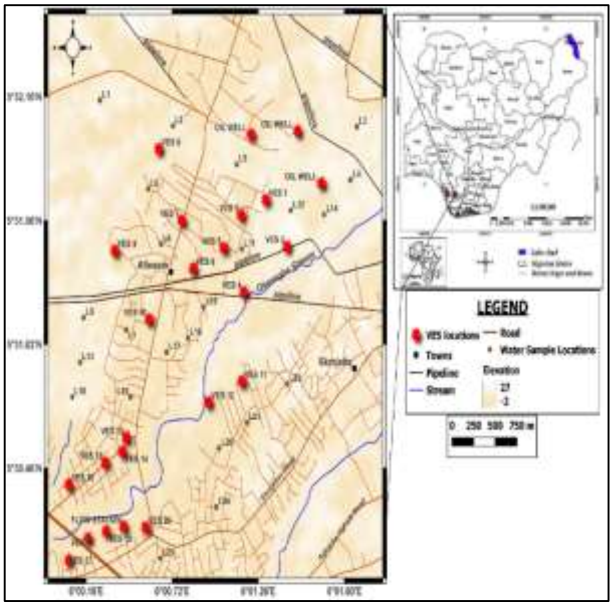


Fig. 1: Map of study area showing sounding and groundwater sampling locations

Methodology

Resistivity data

Geophysical electrical soundings with four electrodes Schlumberger configuration, were carried out at twenty (20) locations with current electrode spacing varying between 1 and 200 m. The ABEM SAS 1000 Terrameter was used to acquire the resistivity data. The processing, interpretation techniques, and application of resistivity data in protective capacity/vulnerability evaluation following the procedures of Orellana and Mooney (1996); Vander Valpen (2004); Oladapo *et al.* (2004); Aweto and Mamah (2014); Aweto (2019) were used in this study.

The vulnerability of the study area was evaluated based on longitudinal conductance using equation 1.

$$S = \sum_i^n \frac{h_i}{\rho_i} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

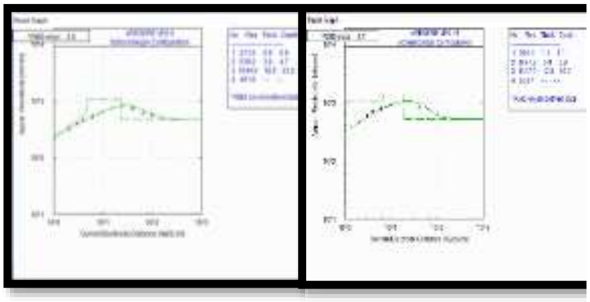
Groundwater sampling and analysis

Twenty-five (25) water samples were collected: thirteen (13) from boreholes and twelve (12) from hand-dug wells into sterile bottles that were tightly covered to minimize oxygen contamination and the escape of dissolved gases. The pH, electrical conductivity (EC), and total dissolved solids (TDS) were determined in-situ using Schott Gerate pH meter and HACH conductivity/TDS meter. Laboratory analysis was conducted to for THC, K, Na, Ca, Mg, Cl, HCO_3, SO_4, NO_3, Fe, Pb, Zn, Cu and Cr following standard methods as specified by APHA (2011).

Results and Discussion

Isoresistivity and Vulnerability maps of Afiesere

The sounding data obtained from the resistivity investigations are presented as sounding curves (fig. 2). The geoelectric parameters and vulnerability of the study are shown in Table 1. Isoresistivity at depths of 5 m, 10 m, 20 m and vulnerability maps was generated using SURFER (2002).



(a) (b)

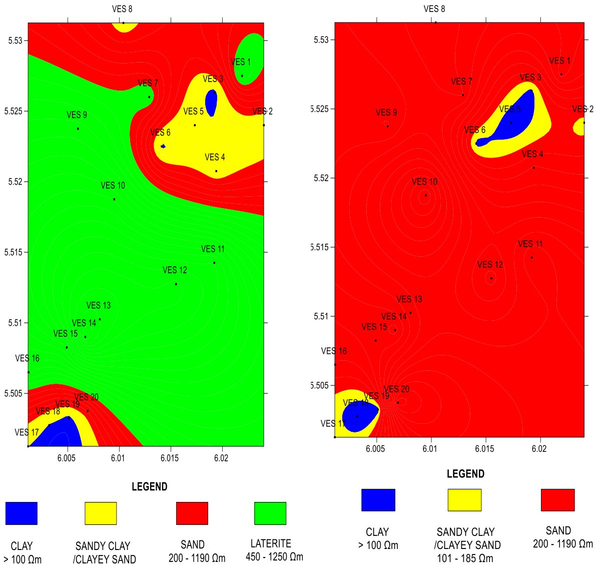
Fig. 2: Computer generated model data curves for Afiesere VES 6 and 16.

Table 1: Summary of geoelectric parameters and protective capacity/vulnerability rating

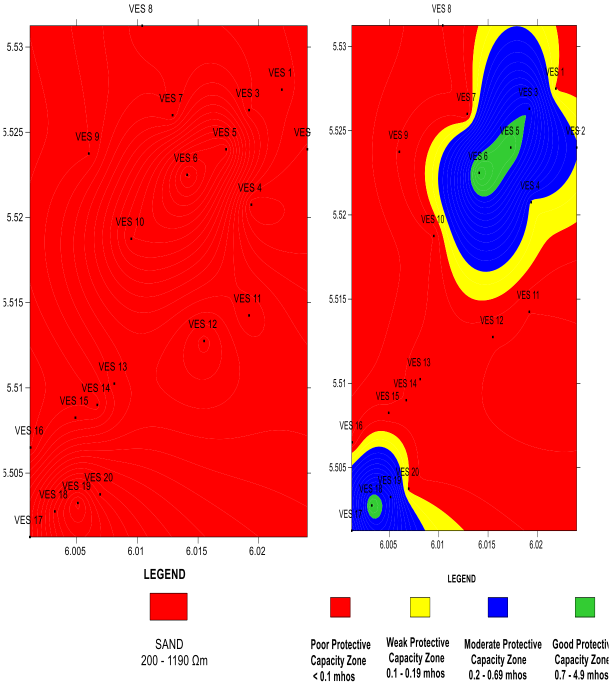
VES Location	Resistivity (Ωm)	Thickness (m)	$S = \sum_i^n \frac{h_i}{\rho_i}$	Protective capacity/ vulnerability Rating
1	268/855/637/109	1.1/6.3/18.7	0.012	Poor Protective Capacity
5	118/22/428/925	0.5/16.5/10.4	0.754	Good Protective Capacity
10	1152/605/450/975	1.5/1.9/21.8	0.004	Poor Protective Capacity
15	508/872/647/228	1.9/5.4/12.6	0.02	Poor Protective Capacity
20	816/356/405/1175	1.8/9.5/11.4	0.03	Poor Protective Capacity

The Isoresistivity maps generated for Afiesere at 5 m, 10 m, and 20 m are shown in fig. 3a - 3c. At 5 m, about 65% of the area is underlain by laterite, 20% is underlain by sand while the remaining 12% of the area is underlain by clayey regolith. At depths of 10 m, 80% of the subsurface is sand; the aquifer is located within this depth where it is mostly unconfined. At depths of 20 m, the lithology is wholly sand and constitutes part of the aquifer in the area.

The vulnerability map of Afiesere (fig. 3d) shows that about 70% of the area has poor protective capacity. This is consistent with the isoresistivity map that shows that the vadose at 5 m is made up of sand in about 85% of the community. A concentric pattern of vulnerability ranging from weak to good protective capacity was observed in the northeastern and southwestern parts. This vulnerability pattern is consistent with the lithology of clay/sandy clay that underlie these regions. The aquifer is shallow and not adequately protected except the northeastern and southwestern parts where the aquifer is given moderate to good protection by clayey horizon. Thus, the aquifer is vulnerable to contamination in the event of oil spill. According to Aweto and Mamah, 2014; Ohwoghere-Asuma *et al*., 2019, aquifers are given protection and are less vulnerable when the vadose zone is comprised primarily of clayey regolith, which retard infiltration of contaminants.



(a) 5 m (b) 10 m



(c) 20 m (d)

Fig. 3: Isoresistivity map at depths of (a) 5 m, (b) 10 m, (c) 20 m. (d) vulnerability map

Hydrogeochemistry of Groundwater

The results of the physical and chemical characteristics of groundwater samples in the study area are presented in Table 2. The pH values ranged between 5.90 – 7.01, electrical conductivity (EC) ranged from 8.90 – 1247.3 µS/cm, and total dissolved solids ranged from 4.0 – 952.7 mg/l. The range concentration of major cautions: K^+, Na^+, Ca^{2+}, and Mg^{2+} are: 0.38 – 30.05 mg/l, 0.09 – 16. 34 mg/l, 0.29 – 65.80 mg/l and 0.02 - 6.14 mg/l. the range concentration of major anions: Cl^-, HCO_3^-, SO_4^- and NO_3^- are 2.40 – 65.82 mg/l, 1.07 – 77.2 mg/l, 0.05 – 7.16 mg/l and 0.00 – 0.07 mg/l. heavy metals concentration range of Fe, Pb, Zn, Cu, and Cr are 0.01 – 0.52 mg/l, 0.00 - 0.05 mg/l, 0.00 – 0.12 mg/l, 0.00 – 0.08 mg/l and 0.00 – 0.01 mg/l while total hydrocarbon content (THC) ranged between 0.00 – 1.50 mg/l.

Table 2: Summary of physicochemical parameters in groundwater

Parameters	Min.	Max.	Mean	Std.	WHO
pH	5.90	7.01	6.45	0.29	6.5 – 8.5
TDS (mg/l)	4.0	952.7	36.16	37.92	500
EC (µS/cm)	8.9	1247.3	73.97	72.86	1000
THC (mg/l)	0.00	1.50	0.06	0.29	1.0
K (mg/l)	0.38	30.05	7.62	6.86	-
Na (mg/l)	0.09	16.34	5.15	4.64	-
Ca (mg/l)	0.29	65.80	5.80	6.38	75
Mg (mg/l)	0.02	6.14	1.01	1.36	50
Cl (mg/l)	2.40	65.92	17.49	16.51	200
HCO_3 (mg/l)	1.07	77.2	8.82	7.26	-
SO_4 (mg/l)	0.05	7.16	1.38	1.62	200
NO_3 (mg/l)	0.00	0.07	0.017	0.026	50
Fe (mg/l)	0.01	0.52	0.13	0.12	0.3
Pb (mg/l)	0.00	0.05	0.01	0.015	0.01
Zn (mg/l)	0.00	0.12	0.02	0.03	5.0
Cu (mg/l)	0.00	0.08	0.006	0.017	1.0
Cr (mg/l)	0.00	0.01	0.004	0.002	-

The physical description of groundwater is clear and fresh. The pH values of groundwater samples were low and indicated that the water is mostly weakly acidic; the low pH may be due to gas flaring from the flow station in the study area. Olobaniyi and Efe (2007); Akpoborie and Aweto (2015); Ohwoghere-Asuma *et al*. (2020), have documented similar observations of low pH in the Niger Delta. Electrical conductivity is an indicator of the presence of ions and concentration of dissolved solids. The results of EC, TDS, major cations, and anions in groundwater samples were below the permissible limits set by WHO (2011) except at 2 locations (9 and 15). The concentrations of total hydrocarbon content at these locations, which lie proximal to oil pipelines, were above the WHO recommended limits of 1.0 mg/l. These locations also show remarkably high EC and TDS, thus an indication of possible hydrocarbon contamination.

Myriads of investigations by Sauck (2000); Atekwana *et al*. (2000), Werkema *et al*. (2003); Atekwana *et al*. (2004b) have reported TDS up to 810 mg/l for groundwater contaminated by hydrocarbon. This assertion is consistent with the findings of this study at these contaminated sites, which reported TDS of 834.2 and 952.7 mg/l, respectively. Ca and HCO_3 ions at these locations were also relatively high; concentrations of Ca were 50.6 and 65.8 mg/l, while those of HCO_3 was 38.4 and 77.2 mg/l. These values were significantly higher than those reported by Akpoborie and Aweto (2012); Ohwoghere-Asuma *et al*. (2014); Ofomola, (2018). Legal (2002) showed that Ca and HCO_3 in groundwater may have accounted for the increase in TDS. A study by McMahon *et al*. (1995) also reported a similar trend of higher concentrations of dissolved ions in aquifers contaminated with hydrocarbon. Geochemical analysis revealed the presence of Pb at the hydrocarbon-impacted sites with concentrations above 0.01 mg/l. According to Onojake *et al.* (2014); Wilberforce (2016), hydrocarbon-impacted areas are characterized by increased levels of heavy metals such as Cd, Cr, and Pb. The resistivity values of the second layer (fig. 2a) close to a pipeline (VES 6) which coincided with normal depth of burial of pipelines (1.5 – 2.5 m), were significantly low (< 650 Ωm). Resistivity investigations at hydrocarbon-impacted sites have documented high resistivities due to the replacement of conductive pore water by highly resistive hydrocarbon (Schneider and Greenhouse; De Ryck, 1993). This is true as long as the hydrocarbon is fresh; signatures at aged hydrocarbon sites indicate lower resistivity due to biodegradation (Sauck, 2000; Shevnin, 2003).

The spike in THC was observed only in the vicinity of oil pipelines, thus indicating that hydrocarbon contamination is localized, the source of hydrocarbon is leakages from pipelines due to corrosion. According to Atakpo and Ayolabi (2008); Ukobah *et al*. (2011), groundwater contamination by hydrocarbon can result from leakages in corroded pipelines. The isoresistivity and vulnerability map show that the area impacted by hydrocarbon is underlain by porous, permeable sand and has a poor protective capacity, as a result, prone to contamination by hydrocarbon in the event of spills. Corrosion usually leads to a reduction in the thickness of pipelines and, in some cases, breaches and finally results in leakages reported as spillages. Studies carried out by Afa and Ngobia (2013); Ngah and Abam, (2014), reported that soil resistivity in some parts of the Niger Delta was found to be slightly and strongly corrosive with few localized non-aggressive soils. Their findings indicated a spatial variation in soil corrosivity that increases across geomorphic zones of the Niger Delta in an N-S trend. Corrosivity increases from the coastal plain in the North to the mangrove and estuary in the South. Okiongbo *et al*. (2019) observed that corrosivity in the coastal plain, generally drier and at a higher elevation, is less corrosive compared to the mangrove swamps and estuarine environments, which are wet and at lower elevations. The fact that the study area lies in a less corrosive sub-environment explains why spillage due to corrosion is not widespread.

Conclusion

This study describes the distribution pattern of groundwater chemistry and the overburden protective capacity around Afiesere, an oil-producing community in the Niger Delta. Results from the study show that most parameters are within the maximum contamination limits except at 2 locations that lie in the vicinity of oil pipelines. TDS, EC, Ca^{2+}, HCO_3^- and THC at the 2 locations were above the maximum permissible limits for potable water, indicating hydrocarbon contamination. Resistivity values at the hydrocarbon-impacted zones were significantly low (< 650 Ωm). This is contrary to the general assumption that hydrocarbon-impacted zones are characterized by high resistivity; this is true only if the hydrocarbon is fresh or has not been altered. The impacted zone in this study is aged, and the hydrocarbons have undergone degradation leading to an increase in TDS due to enhanced weathering of minerals from acids which are byproducts of the degradation process. The possible source of hydrocarbon is from leakage of aging pipelines. The poor protective capacity of the vadose zone around the vicinity of the pipelines further accentuated the spread; as hydrocarbon migrated through the interconnected pore spaces within the sand underlying the area. Monitoring of pipelines for corrosion should be done frequently and in the eventuality of spillage, remediation measures should be put in place immediately to prevent the contamination of the aquifer which is highly vulnerable.

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