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ORIGINAL PAPER

Contamination potential of tar sand exploitation in the western Niger-Delta of Nigeria: baseline studies

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Abstract Exploitation of the tar sands in Ondo State in the Niger Delta is likely to result in some environmental contamination and adversely affect the living conditions of the farmers and fishermen in the area. Three wells were established where samples were taken at 1, 2 and 3 m depth. Although no hydrocarbon contamination was detected in the water from the surface and boreholes, saline intrusion was recorded. This study produces a baseline against which future contamination can be monitored so that preventative measures can be taken to mitigate the effects.

Keywords Tar sands · Mining · Permeability · Groundwater vulnerability · Petroleum contamination

Introduction

The 3,600 km^2 study site is in Ondo State, in the western part of the Niger Delta, latitude 5°45′ and 6°30′, longitude 4°30′ and 5°15′ (Fig. 1). Mangrove and fresh water swamps cover the area, which also contains brackish lagoons. Rainfall in this equatorial zone is high, frequently exceeding 3 m per year (Ola 1983). The east–west outcrop of the tar sand extends for some 55 km while the north–south width is some 4.5 km (Fig. 2). The likely reserves of bitumen and heavy oil in Ondo State alone amount to some 43 billion barrels (Adegoke 1980).

The Niger Delta consists of a series of old beach sand ridges with interdune depressions, both of which run parallel to the coastline, having accumulated as a result of long shore drift. Results from ecological studies and borehole logs suggest an interbedded sequence of continental and marine sediments. The most important formations are the Coastal Alluvium, Coastal Plain Sands (Benin Formations), Agbada Formations and the very deep Akata Formations. The Quaternary deposits are saturated and unconsolidated. The underlying Tertiary deposits are up to 12,000 m thick in some places. The delta is still extending both seawards and to some extent in elevation (Ebisemiju 1985). Profiles from three boreholes are given in Fig. 3, which demonstrates the variation in the material relative to depth over a 20 km distance.

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Background to the study

General overview

The Federal Government of Nigeria has licensed two firms to exploit the bitumen, starting in the southern areas of Ondo State. The operations of the two firms are expected to affect close to a hundred communities inhabited predominantly by farmers and fisher–folk; people whose sources of livelihood are closely tied to the environment. The foreseeable problem of hydrocarbon contamination of the

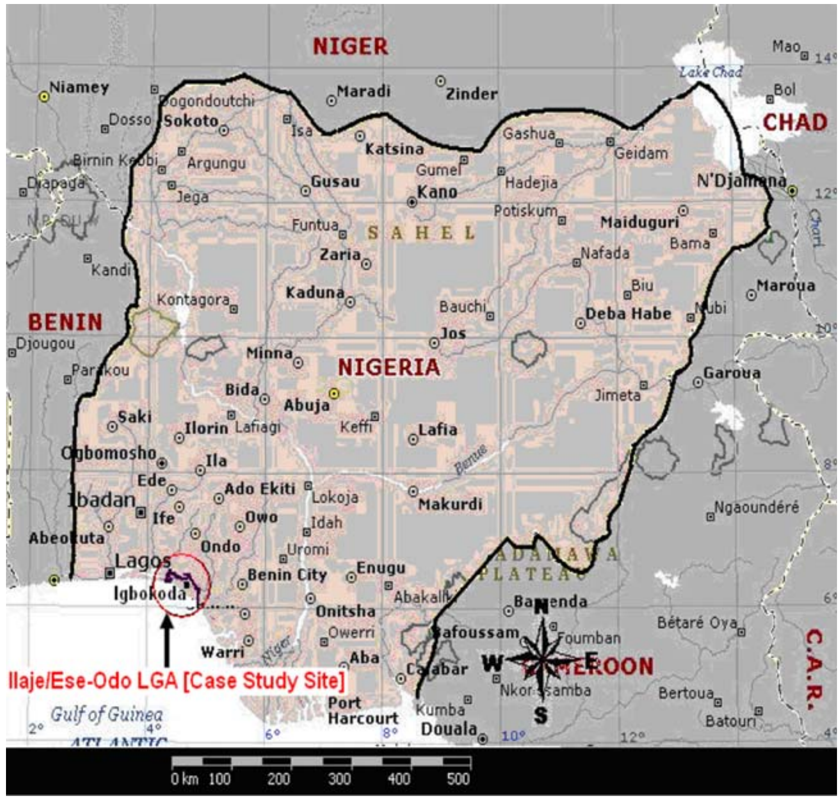

Fig. 1 Map of Nigeria showing Ilaje/Ese-Odo local government area in Ondo State, Nigeria

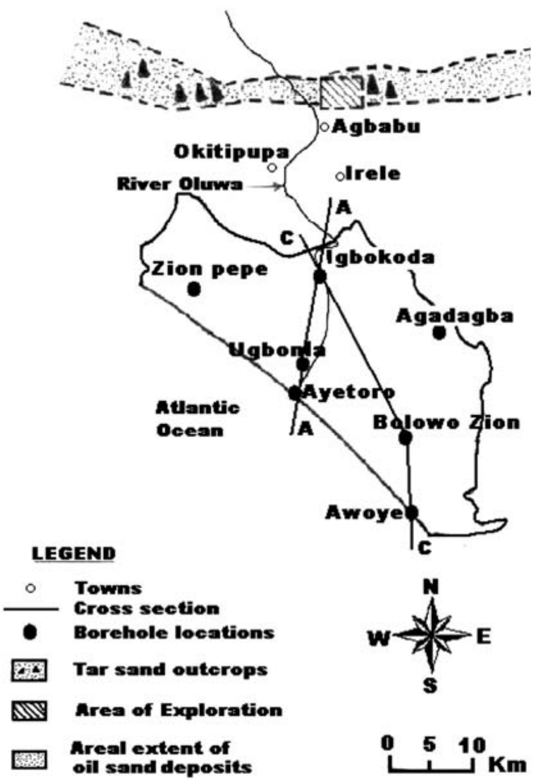

Fig. 2 Site layout (Ilaje/Ese-Odo LGA) showing areal extent of oil sand deposits (Adegoke 1980)

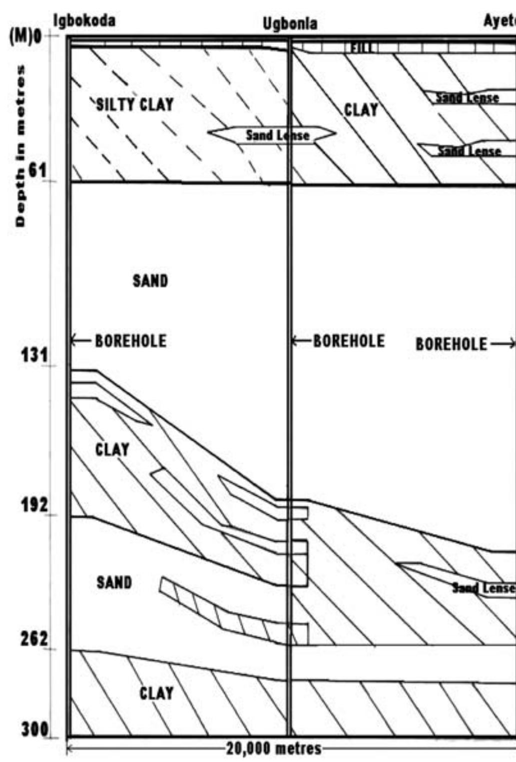

Fig. 3 Simplified borehole logs on cross-section showing stratigraphy along A–A for study area NN–SS (source ODSWC)

groundwater from tar and oil sand exploitation activities necessitates this baseline study. Indiscriminate dumping of waste oil from the terminal harbours and marine transport vessels, together with the influx of seawater is also a concern. This is pertinent as an increase in economic activities during the bitumen exploitation period would obviously lead to an increase in river transportation in the study area.

The layout of the study area is shown in Fig. 2, which indicates the proximity of the site to Agbabu (tar sand and oil sand deposits), the River Oluwa and the terminal harbour at Igbokoda. These profiles were compiled from existing Ondo State Water Corporation borehole logs from Aiyetoro, Agadagba, Ugbonla, Zion Pepe, and Bolowo Zion, together with soil and material investigation borehole logs for the construction of the Igbokoda–Ayetoro Road (Figs. 3, 4). The cross-sections indicate a less permeable stratum of silty clay overlies a more permeable sandy formation.

Tables 1 and 2 show the physical and chemical analyses of water from the surface and from boreholes. It can be seen that the chloride and total iron concentration in the borehole water and the oil/grease and lead concentrations in the surface waters exceed the maximum contaminant level (EPA 1999) at several locations. Benzene, toluene, ethlybenzene and xylene (BTEX) are the main organic (hydrocarbon) pollutants associated with crude oil and its products (Bekins et al. 2002). The level of benzene

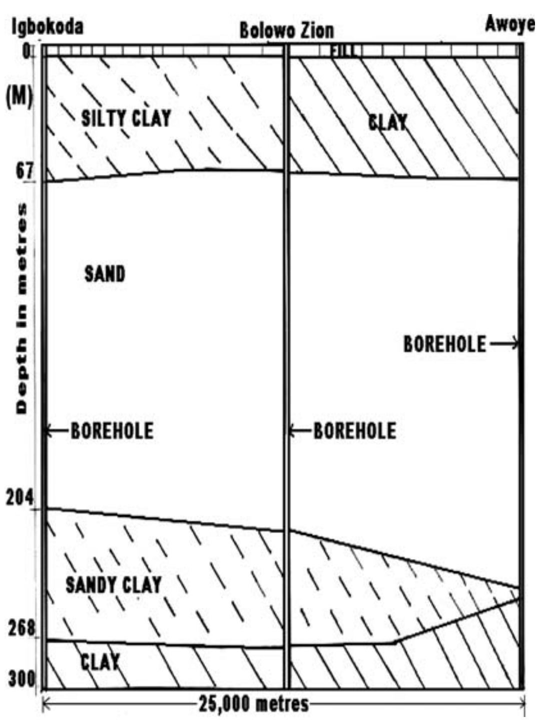

Fig. 4 Simplified borehole logs on cross-section showing stratigraphy along C–C for study area NW–SE (source ODSWC)

(1,780 mg/L) is much greater than the established drinking water limit (DWL) of 5 ug/L while naphthalene (a polycyclic aromatic hydrocarbon) is also considered to be of concern (Suarez and Rifai 2004). Naphthalene, although of lower solubility than benzene and non-carcinogenic, is a major constituent of tar sands. Acute toxicity is rarely reported in humans, fish or wildlife as a result of exposure to low levels of a single polycyclic aromatic hydrocarbon (PAH) although complex mixtures of aromatics (e.g. PAHs, alkyl PAHs, benzenes and alkyl benzenes) are known to be associated with chronic illnesses such as cancer (Irwin 1996). The high chloride and total dissolved solids concentration in the borehole and surface waters due to the impact of saline waters is also a cause of concern for the communities along the shoreline in the study area. Indeed, during the dry season, people have to travel by canoes for many kilometres to collect unpolluted water (ODSWC 1991). Water supply wells exist at Agadagba, Ugbonla, Aiyetoro, Bolowo Zion, Zion Pepe, Agerige and Atijere, but those at Aiyetoro, Agerige, and Atijere have had to be abandoned due to salinity and their excessive iron compound content (ODSWC 1991).

Vulnerability/GIS studies

Groundwater vulnerability is defined as an intrinsic property of a groundwater system which depends on the sensitivity of that system to human and/or natural impacts. As this is a relative, non-measurable, dimensionless property, the results of a groundwater vulnerability assessment are normally portrayed on a map showing various homogeneous areas, sometimes called cells or polygons, which have different levels of vulnerability. The differentiation between cells is, however, arbitrary because vulnerability maps only show relative vulnerability rather than absolute values (Zaporozec and Vrba 1994).

Materials and methods

Baseline studies and preliminary data analysis

An extensive literature search was undertaken into the impact of soil/groundwater contamination from tar sands (bitumen), crude oil, seawater, and petroleum products (boats/ship fuel) on the geo-environment in the study area. The topography was determined based on spot heights for 30 locations within the study area, taken from the existing topographic maps and aerial photography and a Digital Elevation Model (Fig. 5) constructed using the software GRIDBUILDER (Mclaren 2004) and Tecplot 10.

The Point Count System Model (PCSM) (Vrba and Civita 1994), a parametric method for groundwater

Table 1 Physical and chemical analysis of borehole waters in the riverine areas of Ondo State (ODSWC 1991)

Location	Predominant soil type	Ground water level (m)	Colour (Hazen)	Temperature (°C)	pH	Total solids (mg/l)	Methly alkalinity (mg/l $CaCo_3$)	Total hardness (mg/l $CaCo_3$)	K (mg/l)	Cl (mg/l)	Total Fe (mg/l)	SiO (mg/l)	Mg (mg/l)
Agadagba	Gravelly sand	3.05	100.0	25.0	7.5	250	80	10	10	95	1.0	14	0
Ayetoro	Medium sand	0.00	70.0	25.0	7.5	3,800	4	70	70	2,500	0.8	12	–
Bolowo Zion	Medium sand	0.00	80.0	25.0	7.1	2,700	100	40	25	1,800	1.0	15	15
Okitipupa	Sand	34.80	25.5	25.5	6.3	160	64		12	50	0.1		
Ugbonla	Coarse sand	0.58	26.0	26.0	7.8	3,500	348	134	85	2,500	0.4	15	–
Zion Pepe	Med. sand	1.0	25.0	25.0	7.0	4,500	50	700		3,500	2.0	20	20
Agbabu				26.0	7.2		69		12		0.1		
Igbekebo				26.5	7.0		65						

Table 2 Physical and chemical analysis of surface waters in the riverine areas of Ondo State (Kinga 2001)

S. n	Location	Temperature (°C)	pH	Tot. susp. solids (mg/l)	Tot. dissolv. solids (mg/l)	Salinity (%)	Dissolv. oxygen (mg/l)	Biochem. oxygen demand (mg/l)	Chem. oxygen demand (mg/l)	Oil and grease (mg/l)	Tot. hydro carbon (mg/l)	Phosphorous (mg/l)
1.	Aiyetoro sea water	33.8	7.8	1.08	14.10	1.83	7.13	9.0	696.0	1630.0	12.59	0.12
2.	Awoye sea water	34.5	7.5	2.22	17.76	2.43	6.53	668.0	1,500.0	1302.0	29.55	0.18
3.	Ori Oke Iwamimo sea water	30.8	7.7	0.90	17.82	2.52	6.79	124.0	748.0	740.6	70.80	0.11
4.	Ori Oke Iwamimo creek	30.8	7.6	0.02	1.64	0.17	7.63	30.0	142.0	605.6	15.55	0.12
5.	Ogogoro Creek	31.1	7.7	0.58	14.80	1.90	6.85	76.0	647.0	1441.8	20.69	0.17
6.	Ilepete creek	33.8	7.6	0.02	3.06	0.32	7.36	52.0	201.0	452.0	36.91	0.18
7.	Araromi seaside	32.1	7.8	0.24	12.40	2.08	7.65	42.0	590.0	882.0	42.42	0.16
8.	Mahin water	31.1	7.8	0.03	7.74	0.19	7.01	172.0	240.0	1103.0	55.20	0.15
9.	Abereke fish pond	31.1	7.7	0.51	3.40	2.36	6.71	502.0	190.0	452.0	54.99	0.12
10.	Oke Siri sea water	31.1	7.8	1.05	2.22	2.63	7.59	32.0	720.0	1302.0	64.39	0.17

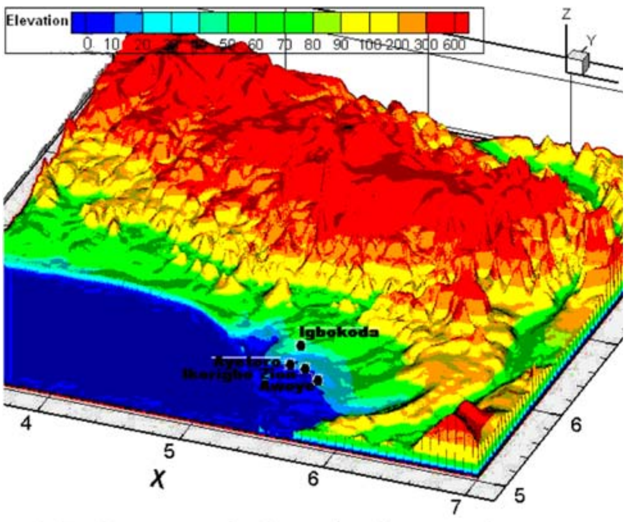

Fig. 5 South-Western Nigeria, regional topography

vulnerability assessment, has been used to assess the sensitivity of the groundwater system to human and natural impacts. A number of parameters, judged to be representative for the vulnerability assessment, are selected and weighted to reflect the relationship between them and their relative importance as regards vulnerability/impact. Each of the selected parameters has a given range, which is subdivided into discrete hierarchical intervals. Each interval is assigned a value reflecting the relative degree of vulnerability, and the rating points are summed. The final numerical score is divided into segments (mapping) expressing a relative vulnerability degree.

The Geographic Information System (GIS) (ESRI, Arcview GIS 3.2) was combined with the DRASTIC model (Aller et al. 1987), a point count system model, to produce intrinsic and specific vulnerability maps for the study area. DRASTIC is a groundwater quality model for evaluating the pollution potential of large areas using mappable units with common hydrogeological characteristics (hydrogeologic settings). This model also employs a numerical ranking system that assigns relative weights to various parameters which influence groundwater vulnerability to contamination. The hydrogeologic settings (which make up the acronym DRASTIC) are: [**D**] depth to water table, [**R**] recharge (net), [**A**] aquifer media, [**S**] soil media, [**T**] topography (slope), [**I**] impact of vadose zone, [**C**] conductivity (hydraulic). Typical ratings range from 1 to 10 and weights from 1 to 5. The results are summarised in Table 3.

The DRASTIC Index, a measure of contamination potential is computed by summation of the products of ratings and weights for each factor as follows:

$$\text{DRASTIC Index} = \mathbf{DrDw} + \mathbf{RrRw} + \mathbf{ArAw} + \mathbf{SrSw} + \mathbf{TrTw} + \mathbf{Ir\,Iw} + \mathbf{Cr\,Cw}$$

Table 3 **DRASTIC** rating system and weights (Aller et al. 1987)

Range	Rating	Weight
D, depth to water table (m)		
0–1.5	10	5
1.5–4.6	9	
4.6–9.1	7	
9.1–15.2	5	
15.2–22.9	3	
22.9–30.5	2	
30.5+	1	
R, recharge (net) (m)		
0–0.5	1	4
0.5–1.0	3	
1.0–1.8	6	
1.8–2.5	8	
2.5+	9	
A, aquifer media		
Massive shale 1	2	3
Metamorphic/igneous 2–5	3	
Weathered metamorphic/igneous 3–5	4	
Glacial Till 4–6	5	
Bedded sandstone, Limestone and shale		
Sequences 5–9	6	
Massive sandstone 4–9	6	
Massive limestone 4–9	8	
Sand and gravel 4–9	8	
Basalt 2–10	9	
Karst limestone 9–10	10	
S, soil media		
Thin or absent	10	
Gravel	10	
Sand	9	2
Peat	8	
Shrinking and/or aggregated clay	7	
Sandy loam	6	
Loam	5	
Silty loam	4	
Clay loam	3	
Muck	2	
Nonshrinking and nonaggregated clay	1	
T, topography (slope)		
0–2	10	1
2–6	9	
6–12	5	
12–18	3	
18+	1	
I, impact of vadose zone		
Confining layer 1	1	5
Silt/clay 2–6	3	
Shale 2–6	3	

Table 3 continued

Range	Rating	Weight
Limestone 2–5	3	
Sandstone 2–7	6	
Bedded limestone, sandstone, shale 4–8	6	
Sand and gravel with significant silt and clay 4–8	6	
Sand and gravel 4–8	8	
Basalt 2–10	9	
Karst limestone 8–10	10	
C, conductivity (hydraulic) (m/s)		
4.7e-7–4.7e-5	1	3
4.7e-5–1.4e-4	2	
1.4e-4–3.3e-4	4	
3.3e-4–4.7e-4	6	
4.7e-4–9.4e-4	8	
9.4e–4+	10	

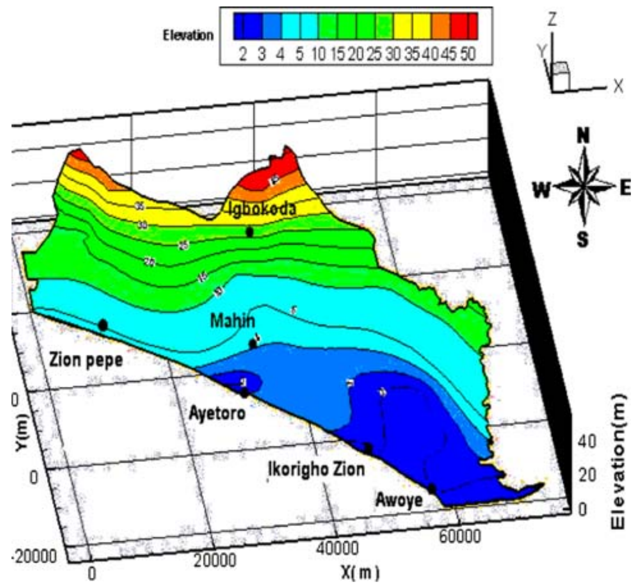

Fig. 6 Western Niger-Delta (Ilaje/Ese-Odo): topography

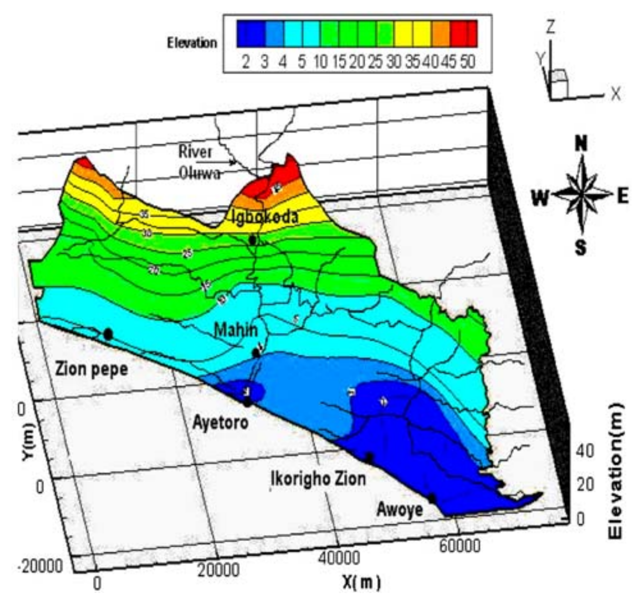

Fig. 7 Western Niger-Delta: hydrological network on topography

where

Dr ratings to the depth to water table
Dw weights assigned to the depth to water table
Rr ratings for ranges of aquifer recharge
Rw weights for the aquifer recharge
Ar ratings assigned to aquifer media
Aw weights assigned to aquifer media
Sr ratings for the soil media
Sw weights for soil media
Tr ratings for topography (slope)
Tw weights for topography
Ir ratings assigned to vadose zone
Iw weights assigned to vadose zone
Cr ratings for rates of hydraulic conductivities
Cw weights given to hydraulic conductivity

The higher the DRASTIC index, the greater the relative contamination potential. The DRASTIC index can be further divided into four categories: low, moderate, high, and very high.

Geochemical sampling, testing and analysis

The three sampling locations were:

1. Mahin (N06 10 27.2; E 04 47 55.2): about 40 km from the shore line;
2. Ayetoro (N05 57 27.2; E 04 55 42.1): close to the shore line and central to the study area and
3. Ikorigho-Zion (N06 06 20.3; E 04 47 09.3): on the eastern side of Ayetoro.

Piezometers were installed at depths of 1, 2 and 3 m within a 0.6 m radius of each sampling location. Each pipe was properly screened at the bottom of the well. Groundwater samples were also collected at 1, 2 and 3 m depth from a 75 mm diameter auger. Analyses were undertaken to determine the presence/abundance of benzene, toluene, ethylbenzene and xylene (BTEX), light-end components of petroleum hydrocarbons, naphthalene, tar sand component, dissolved oxygen (DO), nitrate (NO_3), sulphate (SO_4), (electron acceptors); Ferrous iron (Fe^{+2}) and methane (CH_4).

At least three well volumes of water were purged from the installed piezometers before sampling, using a low-rate

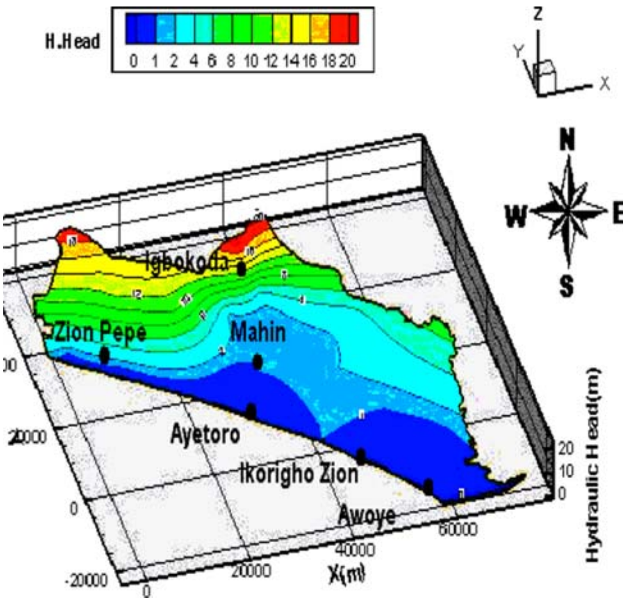

Fig. 8 Water table Map: Western Niger-Delta, Nigeria

Table 4 DRASTIC Index computation for Area 1

Factor	Data	Rating × weight = number
D (depth)	0–1.5 m	10 × 5 = 50
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Thin	10 × 2 = 20
T (topography)	0.5%	10 × 1 = 10
I (impact of vadose zone)	Absent	10 × 5 = 50
C (conductivity)	E-05 m/s	9 × 3 = 27
		208

Table 5 DRASTIC Index computation for Area 2

Factor	Data	Rating × weight = number
D (depth)	0–1.5 m	10 × 5 = 50
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Thin	10 × 2 = 20
T (topography)	2%	9 × 1 = 9
I (impact of vadose zone)	Absent	10 × 5 = 50
C (conductivity)	E-05 m/s	9 × 3 = 27
		207

submersible pump attached to a polyethylene (PE) hose. Water samples for BTEX and naphthalene analysis were collected directly from the water stream in 40 mL amber glass vials ensuring the vials were completely full. They were kept in ice packs at below 4°C during shipment to the

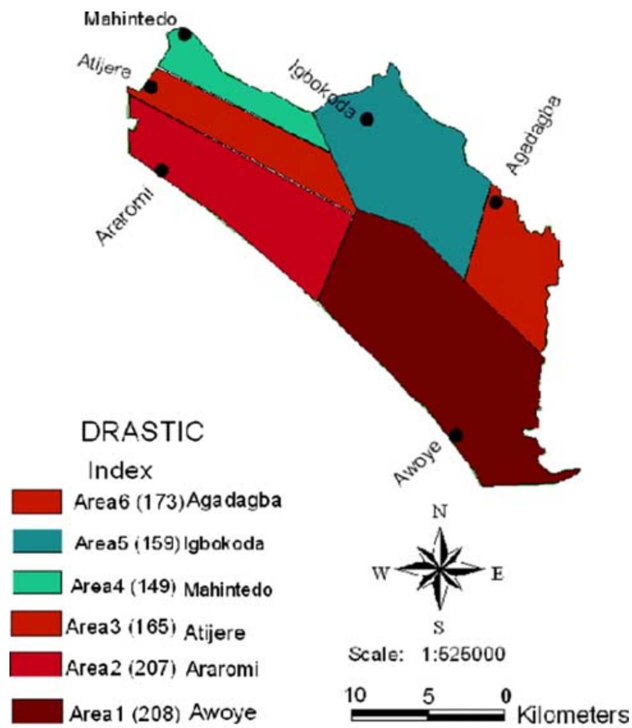

Fig. 9 Intrinsic vulnerability map (Western Niger-Delta, Nigeria)

Table 6 DRASTIC Index computation for Area 3

Factor	Data	Rating × weight = number
D (depth)	3.0 m	9 × 5 = 45
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Sandy loam	6 × 2 = 12
T (topography)	2.5%	9 × 1 = 9
I (impact of vadose zone)	Silt/clay	6 × 5 = 30
C (conductivity)	E-04 m/s	6 × 3 = 18
		165

Table 7 DRASTIC Index computation for Area 4

Factor	Data	Rating × weight = number
D (depth)	7.1 m	7 × 5 = 35
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Loam	5 × 2 = 10
T (topography)	6%	5 × 1 = 5
I (impact of vadose zone)	Silt/clay	6 × 5 = 30
C (conductivity)	E-04m/s	6 × 3 = 18
		149

Table 8 DRASTIC Index computation for Area 5

Factor	Data	Rating × weight = number
D (depth)	4.0 m	9 × 5 = 45
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Loam	5 × 2 = 10
T (topography)	6%	5 × 1 = 5
I (impact of vadose zone)	Silt/clay	6 × 5 = 30
C (conductivity)	E-04m/s	6 × 3 = 18
		159

Table 9 DRASTIC Index computation for Area 6

Factor	Data	Rating × weight = number
D (depth)	1.5 m	10 × 5 = 50
R (recharge)	250 mm	9 × 4 = 36
A (aquifer)	Alluvium	5 × 3 = 15
S (soil)	Thin	10 × 2 = 20
T (topography)	2%	10 × 1 = 10
I (impact of vadose zone)	Silt/clay	3 × 5 = 15
C (conductivity)	E-04 m/s	6 × 3 = 18
		173

laboratory. Distilled water was used for rinsing the sampling and portable testing devices after each sampling and testing. During the sampling periods, there was no rainfall. At least 10% of the samples were control/duplicate samples (Fetter 1991).

A portable Horiba U-10 Water Quality Checker and laboratory analysis in the Ondo State Water Corporation laboratory were used for the inorganic analyses. Organic compounds including BTEX were analyzed by gas chromatography–mass selective detection (GC–MSD) with a purge-and-trap system (HP5890, Tekmar3000; Hewlett-Packard, Palo Alto, CA) at the Organic Geochemistry laboratory, Department of Earth Sciences, University of Waterloo, ON, Canada.

Table 10 Groundwater geochemical analysis for inorganics

Location		1: Mahin 06 10 27.2 E 04 47 55.2	2: Ikorigho N05 57 27.2 E 04 5542.1	3: Ayetoro N06 06 20.3 E 04 47 09.3
Elevation (m) a.s.l.		3.1	1.8	2.5
Conductivity (mS/cm)	Top	0.031	3.02	3.31
	Middle	0.036	4.70	3.39
	Bottom	0.038	8.24	3.72
DO (mg/l)	Top	5.92	6.15	6.14
	Middle	5.78	6.10	6.12
	Bottom	5.70	5.92	6.11
Temperature (°C)	Top	27.4	27.5	26.7
	Middle	28.4	26.8	26.8
	Bottom	28.1	26.6	26.6
pH	Top	4.42	6.29	6.3
	Middle	3.95	6.16	6.2
	Bottom	4.10	6.25	6.25
Chloride (mg/l)	Top	550	1,200	1,250
	Middle	700	2,150	1,200
	Bottom	800	2,000	1,500
Nitrate NO_3^- (mg/l)	Top	2.0	ND	2.2
	Middle	1.5	2.0	ND
	Bottom	1.5	ND	1.0
Sulphate SO_4^{2-} (mg/l)	Top	–	72.2	87.3
	Middle	31.4	61.9	81.7
	Bottom	30.5	48.3	69.0
Iron Fe^{2+} (mg/l)	Top	1.9	1.0	0.1
	Middle	1.8	1.5	0.1
	Bottom	2.7	1.6	0.2

Results and discussion

Results of baseline studies and preliminary data analysis

As seen in Figs. 5 and 6, the topography is almost flat, rising gently inland to a maximum elevation of about 50 m a.s.l. close to Mahintedo, Shabomi and Ojuala (a distance of about 30 km from the shoreline). The hydrological network is shown in Fig. 7 and the depth to ground water in Fig. 8, which also shows the hydraulic head contours. Alluvial deposits form the most productive aquifers. In this sedimentary rock area, aquifers are multi-layered and occur as permeable (sands and gravels) and semi-permeable horizons (clayey and silty sands and gravels) separated by less permeable (clay and shale) horizons.

The computations of the DRASTIC indices for the six delineated zones are shown in Tables 4, 5, 6, 7, 8 and 9. Figure 9 shows the plot of the resulting intrinsic vulnerability map obtained using the Arcview GIS 3.2. Area 1 (consisting of the Awoye, Jinrinwo, and Bolowo Zion communities) has the highest vulnerability index (208), and therefore has the greatest contamination potential while Area 4 (consisting of Atijere, Akata and Bawa communities) has the lowest vulnerability index (149).

The results of the soil/groundwater sampling and analysis for inorganics (terminal electron acceptors and natural attenuation byproducts) and organics (priority hydrocarbon pollutants from tar sand and crude oil) for three locations are given in Tables 10 and 11. It can be seen that benzene, toluene, ethyl benzene and xylene (BTEX) and naphthalene

Table 11 Groundwater geochemical analysis for organics

Units are μg/L (ppb)

	Benzene	Toluene	Ethylbenzene	*p,m*-xylene	*o*-xylene	1,3,5-Trimethyl-benzene	1,2,4-Trimethyl-benzene	1,2,3-Trimethyl-benzene	Naphthalene
MDL	2.08	1.72	1.05	2.34	1.10	1.40	1.41	1.91	1.83
Sample ID									
G1-M	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL
G2-M	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL
G3-M	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL	<MDL
TB	0	0	0	0	0	0	0	0	0
FB1	0	0	0	0	0	0	0	0	0
FB2	0	0	0	0	0	0	0	0	0
FB3	0	0	0	0	0	0	0	0	0

Sample identification: *G1-M* middle groundwater sample in Mahin, *G2-M* middle groundwater sample in Ikorigho-Zion, *G3-M* middle groundwater sample in Ayetoro, *MDL* method detection limit, *TB* trip blank sample (quality assurance/quality control sample), *FB1* field blank sample for Mahin (quality assurance/quality control sample), *FB2* field blank sample for Ikorigho (quality assurance/quality control sample), *FB3* field blank sample for Ayetoro (quality assurance/quality control sample)

were not detected in the groundwater, indicating that the subsurface is at the moment free of hydrocarbon contamination from tar sands and crude oil spills. However, salt water intrusion into the fresh water is indicated by the chloride and conductivity levels (Table 10). The results also suggests that the sea water intrusion could be a source of transport for dissolved petroleum hydrocarbon derived from offshore/onshore oil spills.

Conclusions

Dissolved hydrocarbon concentrations in the groundwater were below the detection limit. This indicates that at present, natural processes are adequate to assimilate the low levels of petroleum hydrocarbon contamination arising from occasional oil spills and water transportation related to anthropogenic activity in the study area.

This study provides a baseline against which the effects of the massive mining of the tar sands can be assessed. Continual monitoring is necessary as exploitation of the tar sand progresses in order to avoid/mitigate contamination of groundwater and prevent the environmental pollution, economic disempowerment and social dislocation which so often occurs in the Niger Delta areas when oil and gas are exploited.

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