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Aquifer Vulnerability Studies using DRASTICA Model

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ABSTRACT:- *Groundwater in an area is vulnerable to the level of sanitation and hygiene of the populace. Next to air, water is considered as life's most basic need. The pattern and containable levels of life's development will largely depend upon the quantity, quality and variations in the supply of water made available to the population. The type of human activity going on in an area affects the water in terms of quality and quantity. The study identified hydrocarbon pollution, use of agrochemicals, industrial effluents and poor sanitation as contributors to the soil and water deterioration in the area. These are results of various anthropogenic activities domiciled in the area. DRASTICA model, a modification of DRASTIC model was developed and used in the construction of aquifer vulnerability map of the area. Owing to the monumental and devastating effects of hydrocarbon pollution in the area, the need to eradicate gas flaring and minimize oil spills in the area was advocated. Bioremediation and phytoremediation techniques were recommended to be applied in the clean-up of soils and water contaminated with hydrocarbon in the area. The effectiveness of DRASTICA model in evaluating water quality has been demonstrated successfully in this study.*

I. INTRODUCTION

The Niger Delta region of Nigeria has been experiencing high urbanization and industrialization as a result of exploration, exploitation, refining and marketing of the petroleum resources of the area. The impact of these human activities (Plates 1-6) on the largely unconfined, highly porous and permeable aquiferous unit in the area and the tendency of contaminants infiltrating into the shallow water table due to high hydraulic conductivity and transmissivity necessitated the present study. This research has provided hydrogeologically based aquifer vulnerability map of the area, which is vital in aquifer security, utilization and management, hence the justification. Stakeholders in the water sector will find the information provided by this study useful in their decision making.Crude oilexploration and exploitation have triggered adverse environmental impacts in the Delta area of Nigeria through incessant environmental, socio-economic and physical disasters that have accumulated over the years due to limited scrutiny and lack of assessment (Achi, 2003, Kar *et al.*, 2008; Amadi *et al*., 2010; Amadi, 2011; Amadi *et al.*, 2012).

The environmental pollution caused by anthropogenic factors domiciled in the region has affected weather conditions, soil fertility, groundwater, surface water, aquatic and wildlife (Olujimi, 2010, Plate 4). If this trend is allowed to continue unabated, it is most likely that the food web complexes in this wetland might be heading into extinction. This unhealthy situation continues to attract the interest of environmental observers and calls for evaluation of the impact of exploration and exploitation activities in the coastal areas of Nigeria and these were part of what this research intended to address.In many countries around the world, including Nigeria, groundwater supplies may have become contaminated through various human activities, which have impact on the health and economic status of the people. The discharge of untreated waste water, soakaway, pit-latrine as well as agricultural water runoff can lead to deterioration of groundwater in coastal aquifers (Abdel-Satar, 2001; Adams *et al*., 2008; Amadi and Nwankwoala, 2013; Karbassi et al., 2008; Ngah, 2002; Nwankwoala, 2011; Akoto *et al*., 2008; Etu–Efeotor, 1981; Etu–Efeotor and Akpokodje, 1990).

Plate 1: Land degradation due to leakage from crude oil pipeline in the area

Plate 2: A front-view of a dumpsite in the area

Plate 3: Surface water contaminated with crude oil in the area

Plate 4: Death of fishes and craps due to hydrocarbon contamination of rivers

Plate 5: Gas flaring at one of the stations in Southern Nigeria

Plate 6: Remnants of an Artisanal Refinery in Southern Nigeria

II. DESCRIPTION OF THE STUDY AREA

The study area lies within the eastern Niger Delta region of Nigeria between latitude 4°40'N and 5º40'N and longitude 6º50'E and 7º50'E (Figure 1). It covers parts of Port-Harcourt, Aba and Owerri and a total area of approximately 12,056 km^2. The area is low lying with a good road network system and is drained by Imo, Aba, Kwa-Ibo and Bonny Rivers and their tributaries. The topography is under the influence of tides which results in flooding especially during the rainy season (Nwankwoaloa and Mmom, 2007). The prevalent climatic condition in the area comprises of the rainy (March to October) and dry (November to February) seasons characterized by high temperatures, low pressure and high relative humidity throughout the year. A short spell of dry season referred to as the 'August break' is often felt in August and is caused by the deflection of the moisture-laden current. Due to vagaries of weather, the 'August break' sometimes occurs in July or September (Azeez, 1976; Etu–Efeotor, and Odigi, 1983).

III. DRASTICA MODEL

The DRASTICA model is a modification of DRASTIC model (Aller*et al.*, 1987), was used for vulnerability studies in the Niger Delta region of Nigeria. It became necessary because the DRASTIC model of evaluating aquifer vulnerability makes use of intrinsic factors (physical factors) without considering the impact of human activities on safety of the aquifer. In the United States where it was first developed, there are good sanitary system and environmental security. The abuse arising from population, industrialization, urbanization and land-use typical of the Niger Delta region of Nigeria are not accounted for in DRASTIC model, hence the need for DRASTICA model to address the local challenges.As a result, anthropogenic factor 'A' was added to compliment the DRASTIC model considering the effect the various human activities in the area may have on the aquifer system. This gave rise to DRASTICA model, an improved version of DRASTIC model.

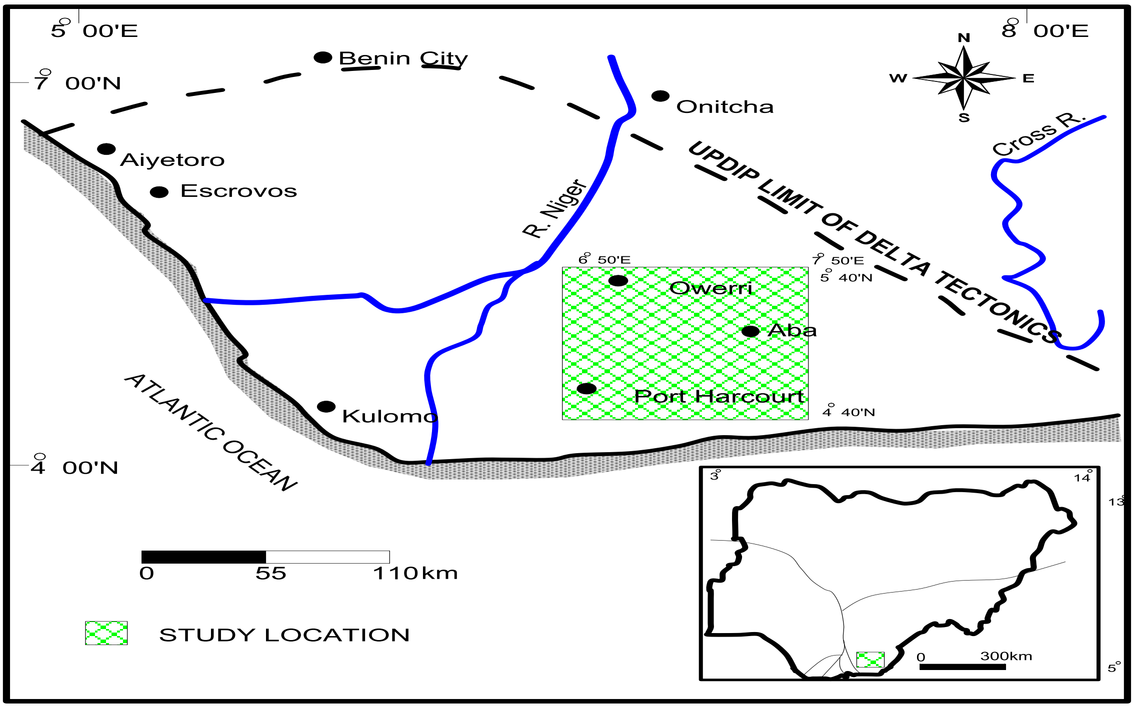

Figure 1: Map of the study area

DRASTICA index has been used to efficiently map aquifer vulnerability in porous and permeable aquifers of the Benin Formation in the Niger Delta region of Nigeria. DRASTICAindex is one of the mapping systems which provide a systematic way for planners, administrators, and managers to address the relative vulnerability of an area's water table aquifer to contamination when making decisions that may impact the groundwater resource especially places with huge environmental abuses. The name DRASTICA is derived from the eight factors that go into the maps, these are:

"D" Depth to water
"R" Recharge
"A" Aquifer Media
"S" Soil Media

"I" Impact of Vadose Zones
"T" Topography
"C" Hydraulic Conductivity
"C" Anthropogenic Factor

The first 7 acronymswere derived from DRASTIC modelwhile the eight acronym differentiates it from DRASTICA model. A set of basic assumptions concerning the DRASTICA model are:
1) Material introduced at the land surface as a soluble solid or liquid travels to the aquifer with recharge waters derived from precipitation.
2) The mobility of the contaminant is assumed to be equal to that of the groundwater.
3) Attenuation processes are assumed to go on in the soil, Vadose zone and aquifer.
Scientific DRASTICA index was used here to estimate the sensitivity of the groundwater against pollution. In order to develop the vulnerability map, the following steps were followed:
i) Divide the survey area into cells, each cell must be given a node, and coordinates.
ii) Translate aquifer rocks, unsaturated zone rocks, permeability, groundwater recharge, groundwater depth and topography (slope) into digital forms according to DRASTICA index rates.
iii) Multiply the resulted numbers, which is related to every cell by the importance of the variety according to DRASTICA index equation.
iv) Gathering the results of the multiplication which comes from every cells, and the degree of sensitivity will be obtained, and classified according to DRASTICA index. Each parameter is subdivided into ranges and is assigned different ratings in a scale of 1 (least contamination potential) to 10 (highest contamination potential) based on importance of the parameter (Table 1). The weighting factors ranges from 1 (least significant) and 5 (most significant). The linear additive combination of the above parameters with the ratings and weights was used to calculate the DRASTICA Vulnerability Index (DVI). Therefore chemical and bacteriological analyses of geomaterials are used in the determination of DRASTICA Vulnerability Index (DVI).

$$DVI = DrDw + RrRw + ArAw + SrSw + TrTw + IrIw + CrCw + ArAw$$

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 assigned to topography
Ir = Ratings assigned to vadose zone
Iw = Weights assigned to vadose zone
Cr = Ratings for rates of hydraulic conductivity
Cw = Weights given to hydraulic conductivity
Ar = Ratings for anthropogenic factor
Aw = Weights assigned to anthropogenic factor

Table 1: Weights of the different components in DRASTICA Model

Components	Weight
Depth to water	5
Net recharge	4
Aquifer media	3
Soil media	2
Topography	1
Unsaturated zone media	5
Hydraulic conductivity	3
Anthropogenic factor	5

Good knowledge of the local geology and hydrogeology of the research area is a prerequisite to determine rating ranges of the parameter. The procedure for mapping the study area according to DRASICA index was clarified for every component. Dealing with a big data set calls for the use Surfer technique specifically Minimum Curvature gridding method, and GIS ARC-View to produce the vulnerability map of the area.

(i) Depth to Water Table

The top of the saturated zone is called the water table. The water table rises and falls according to the season of the year and the amount of rain that occur. It is usually higher during the rainy season and lower in dry season. Heavy rainfall or drought conditions may cause fluctuations in the groundwater table. Water table depth determines the depth which a contaminant must travel before reaching the aquifer. Rates for groundwater depths are given in Table 2.

Table 2: Ratings of water table depth

Water Table Depth (m)	DRASTICA Rating
0.00 – 1.23	10
1.23 – 4.58	9
4.58 – 9.15	7
9.15 – 15.25	5
15.25 – 22.88	3
22.88 – 30.50	2
>30.50	1

(ii) Vadose Zone

This is the zone above the water table which is unsaturated or discontinuously saturated. It determines the attenuation characteristics of the material below the typical soil horizon and above the water table. It is the region above the water table where pores and fractures are partially filled with water and partly by air. The pressure in the unsaturated zone is atmospheric. Conditions are usually highly oxidizing due to the presence of free oxygen from the air and highly reactive due to the presence of water. The unsaturated zone forms an important buffering zone for hazardous wastes before reaching the water table. Understanding the mechanisms and rates of movement of pollutants in rocks is an important step in the process of groundwater protection. It plays an important role in many modeling applications, e.g. for recharge estimation, surface-groundwater interaction and agricultural pollution. The unsaturated zone refers here to the mostly-unsaturated soil profile extending from the land surface down to the groundwater table. The profile is usually heterogeneous, consisting of horizons with distinct differences in the physical properties of the soil. The unsaturated zone is characterized by cyclic fluctuations in the soil moisture as water is replenished by rainfall and removed from the soil profile by evapo-transpiration and percolation. The geological map of the study area, and the available borehole data were used in defining this zone. Digitizing the different sub-zones and giving them the special rates using (Table 3) were carried out.

Table 3: Ratings of the unsaturated zone material

Unsaturated Zone Material	DRASTICA Rating
Confining layer	1
Silt/clay	3
Shale	3
Limestone	6
Sandstone	6
Bedded limestone, sandstone shale	6
Sand and gravel with significant silt and clay	6
Metamorphic/igneous	4
Sand and gravel	8
Basalt	9
Karst limestone	10

(iii) Aquifer Media

This refers to the consolidated or unconsolidated rocks serving as aquifers (sand and gravel or limestone). The route and path length which a contaminant must follow are governed by the flow system within the aquifer. The aquifer media also influences the amount of effective surface area materials which contaminants may come into contact with. The larger the grain size and the more fractures or openings within the aquifer, the higher the permeability and the lower the attenuation capacity of the aquifer media. The geological map of the study area and the wells data were used as the data source in specifying the media of the aquifer all over the study area. The rates were given for every media type depending on Table 4.

Table 4: Ratings of the aquifer material

Aquifer Material	DRASTICA Rating
Massive shale	2
Metamorphic/igneous	3
Weathered metamorphic/igneous	4
Glacial till	5
Bedded sandstone, limestone, shale sequences	6
Massive sandstone	6
Massive limestone	6
Sand and gravel	8
Basalt	9
Karst limestone	10

(iv) Topography

This refers to the slope and slope variability of the land surface. It controls the likelihood that a pollutant will run off or remain on the surface long enough to infiltrate. Topography also influences soil development and has an effect on pollutant attenuation. Zero-two percent slope provides the greatest opportunity for a pollutant to infiltrate. Neither the pollutant nor precipitation exits the area as runoff. On the other hand, 18+ percent slope provides a high runoff capacity and a lesser probability of contaminant infiltration (high erosion and contamination of surface water). A digital elevation model of the study area –100 meter spacing- has been used in generating the slope. IDRISI (2000) was used in modeling the percent slope of the study area, and in converting the produced raster model into (X,Y,Z) type of data. The produced data was put in an ascending order, and the rates were given depending on Table 5. Rates were found to range from 1 to 10. The gridding method of Minimum Curvature was used.

Table 5: Ratings of slope percent

Slope (%)	DRASTICA Rating
0-2	10
2-6	9
2-12	5
12-18	3
>18	1

(v) Soil Material

This refers to the uppermost portion of the vadose zone characterized by significant biological activity. Soil has a significant impact on the amount of recharge which infiltrates into the ground. The presence of fine-textured material such as loam and clay loam can decrease soil permeability and restrict contaminant movement. The pollution potential of a soil is largely affected by the type of clay present, the shrink/swell potential of that clay and the grain size of the soil. The less clay shrinks and swells and the smaller the grain size, the less pollution potential. The geological map of the study area, besides some sieve analyses results were used as the data source for the soil media in the study area. The produced different zones were grouped after the special rates as in Table 6.

Table 6: Ratings of soil material

Soil Material	DRASTICA Rating
Thin or absent	10
Gravel	10
Sand	9
Peat	8
Shrinking and or aggregated clay	7
Sandy loam	6

Loam	5
Silt loam	4
Clay loam	3
Muck	2
Non-shrinking and non-aggregated clay	3

(vi) Hydraulic Conductivity

This is the ability of the aquifer materials to transmit water. It controls the rate at which ground water will flow under a given hydraulic gradient. The rate at which the groundwater flows also controls the rate at which a contaminant moves away from the point it entered the aquifer. High conductivities are associated with higher pollution potential. Values for hydraulic conductivity are calculated and modeled from the pumping tests and permeameter tests carried out. Zones of hydraulic conductivity were defined and accordingly the special rates depending on Table 7.

Table 7: Ratings of hydraulic conductivity

Hydraulic Conductivity (m)	DRASTICA Rating
$0.50*10^{-6}$ – $0.50*10^{-4}$	1
$0.50*10^{-4}$ – $0.15*10^{-3}$	2
$0.15*10^{-3}$ – $0.36*10^{-3}$	4
$0.36*10^{-3}$ – $0.51*10^{-3}$	6
$0.51*10^{-3}$ – $0.10*10^{-2}$	8
$>0.10*10^{-2}$	10

(vii) Aquifer Recharge

Precipitation is the primary source of groundwater because it infiltrates through the surface of the ground and percolates to the water table. Net recharge represents the amount of water per unit area of land which penetrates the land and reaches the water table. Recharge water is the principle vehicle for leaching and transporting contaminants vertically to the water table and horizontally within the aquifer. The greater the recharge, the greater the potential for ground water pollution (measured in mm/year). Other sources include irrigation, artificial recharge and wastewater application. No maps were found to represent the net natural recharge in eastern Niger Delta. However, rainfall and evaporation data for the area was obtained from the Federal Ministry of Environment while slope, soil media, vegetation cover and infiltration rates were studied to estimate the groundwater recharge values. Relative similarity of climate in eastern Niger Delta allowed the assumption that rainfall and evaporation amounts are virtually the same all over the area. Accordingly, soil and slope were the major factors to deduce a primary estimation of natural recharge values to the area taken from recharge rates of the aquifer due to DRASTICA model (Table 8).

Table 8: Ratings of groundwater recharge

Recharge (mm/year)	DRASTICA Rating
0.00 – 50.8	1
50.8 – 101.6	3
101.6 – 177.8	6
177.8 – 254.0	8
>254.0	9

(viii) Anthropogenic Factor

This refers to the various human activities that affect the hydrologic cycle. Such activities in the area includes petroleum exploration, exploitation, refining and marketing as well as gas flaring, oil spillage, sewage, soakaway, industrial and domestic waste. These human endeavours offer the greatest threat to aquifer and groundwater contamination and very expensive to ignore (Table 9).

Table 9: Ratings of anthropogenic factor

Anthropogenic Factor	DRASTICA Rating
Oil spillage/gas flaring	**9**
Effluents/sewage/industrial waste (untreated)	**9**
Cementary/soakaway/pitlatrine (unlined)	**7**
Open dumpsites (non-sanitary landfill)	**8**
Effluents/sewage/industrial waste (treated)	**5**

Emissions from automobiles/generators	**8**
Domestic waste (organic/degradable)	**6**
Fertilizer/agro-chemicals	**7**
Cementary/soakaway/pit-latrine (lined)	**4**
Sanitary landfill	**5**
Bush burning	**4**
E-wastes	**9**

IV. GROUNDWATER VULNERABILITY MAP FOR EASTERN NIGER DELTA

The knowledge of the local geology and hydrogeology of the area, coupled with the information obtained through geophysical survey, borehole logging, sieve analysis, permeability test, pumping test and laboratory analysis, employed in this study were used to develop the vulnerability mapfor the aquifer system in the area (Figure 2). The entire area was categorized into three region based on pollutant dominance: areas of high vulnerability, moderate vulnerability and low vulnerability. The high vulnerability area are domiciled by high profile anthropogenic activities and have witnessed long term environmental degradation arising from gas flaring, oil spills, open dumpsites, urbanization and industrialization. The local geology and the hydraulic properties of the southern portion may be also a contributing factor. The low vulnerability area (northern sector) is dominated by fishing and subsistence farming.The medium vulnerability region sharesthe characteristics of both high and low vulnerability region.

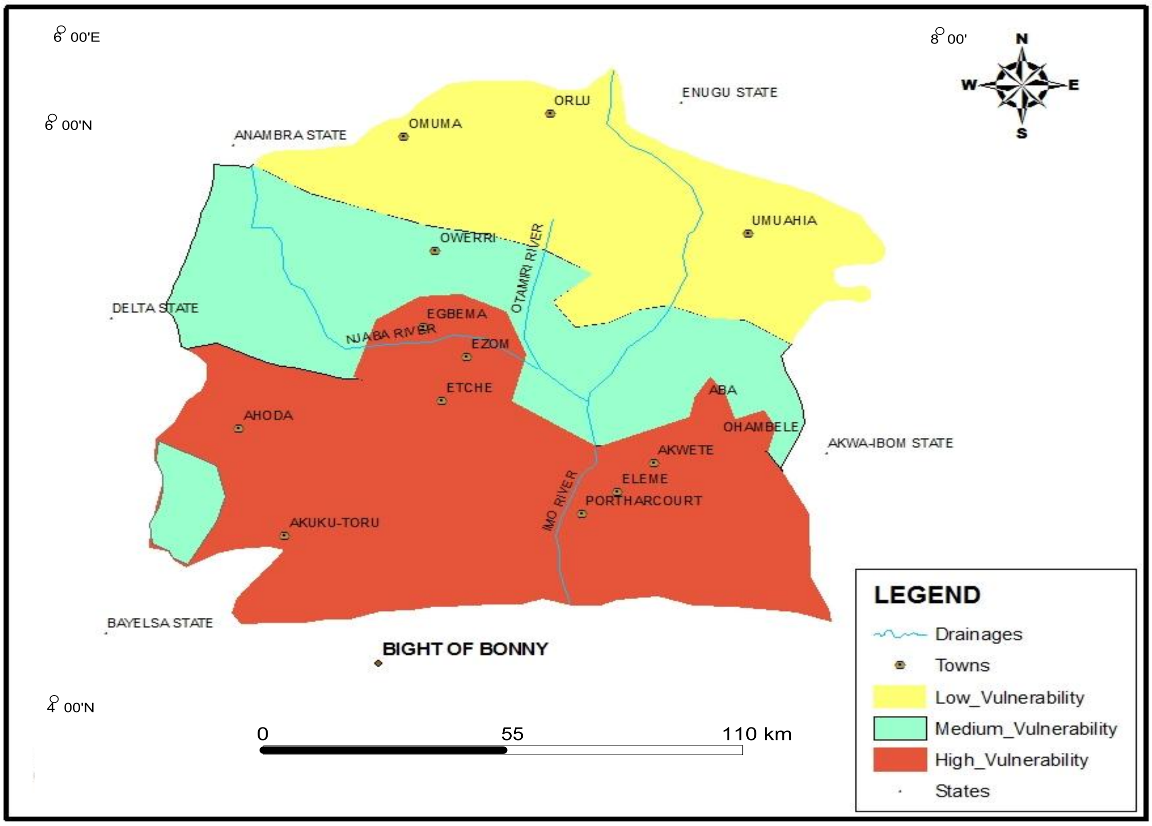

Figure 2: Groundwater Vulnerability Map of part of Eastern Niger Delta

V. CONCLUSION

This study has clearly established that gas flaring, oil spill and indiscriminate dumping of wastes constitute a major source of soil and water pollution in the oil producing region of Niger Delta region of Nigeria.The study has revealed that the various anthropogenic activities domiciled in the area have constituted serious soil and water quality problems which have resulted to classic environmental and health challenges in their host communities.

Apart from anthropogenic interference in the groundwater system in the area due the huge human activities going on in the area, salinity and high iron content constitutes the major natural sources of groundwater pollution in the area. Many boreholes in the area have been abandoned solely due to the problem of salt water intrusion and or high iron content. The impact of salt intrusion is more on the southern part of the area than the northern part of the area while the reverse was the case for high iron content. The sea water from the Atlantic Ocean that bounds the southern portion of the area may be responsible for the problem of salt intrusion while the leaching of thick porous and permeable lateritic overburden in the northern part of the may be attributed to the high iron content of the groundwater from the area.

5.2 Recommendations

The following recommendations are suggested:

[1] The government should without any further delay, put an end to artisanal crude oil refining.

[2] With respect to the degree and extent of hydrocarbon pollution in the area, a multi-purpose approach, aimed at cleaning up the polluted top soil, surface water and replanting of the vegetation as a way of restoration is advocated.

[3] The use of all drinking water wells where crude oil has been detected should be discontinued and the community informed on the health implications associated with drinking water polluted with hydrocarbon.

[4] Host communities where the surface water is polluted with hydrocarbon should be cautioned on the danger of fishing, swimming, bathing and drinking such water.

[5] All government agencies saddled with the responsibility of cleaning up oil spill and other environmental challenges should be monitored to ensure compliance.

[6] Public lectures, workshops and seminars should be organized to create the awareness on the danger of hydrocarbon pollution on the environment and how to minimize it.

[7] Oil companies should henceforth ensure industry best practices are employed in their operations in the region

[8] Periodic environmental assessment by all stake holders in the oil sector (Government, oil companies and host communities) should be constituted to ensure no future abuse of the ecosystem.

[9] Sequential evaluation of the soil and water from the area should be carried out to ensure that the water and soil from the area are free any form of pollution..

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