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Assessment of the Vulnerability of Aquifers at Artisanal Refining Sites in Parts of Ogu-Bolo LGA, Rivers State, Nigeria

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Abstract:

The spillage of crude oil from artisanal refineries poses critical environmental risks, significantly affecting aquatic ecosystems, soil, and groundwater. This study assesses aquifer vulnerability to contamination from artisanal refining activities. Water and soil samples were analyzed in the laboratory using standard methods. The ArcGIS version 10.3, ENVI version 4.7, Surfer 10, SPSS 22 and Microsoft Enterprise were used for the interpretation of contaminant pattern. The result shows the presence of BTEX, lead (Pb), Zinc (Zn), Copper (Cu), Chemical Oxygen Demand (COD), Oxygen Demand (DO) which are within NESREA limits. pH of water samples fell within the range of the stipulated standard. Also, there is high concentration of Fe and Zn in water and high hydrocarbon content in soils, deeming water sources unsuitable for consumption and soil unfit for agriculture. Water Quality index rating of 1 was measured in the study area which is an indication that the water is very bad. Also, the physiochemical analysis on soil and water revealed poor water and soil. The soil samples recorded high levels of crude content from 1m, with concentration reducing with depth up to 3m, highlighting the need for regular geochemical analysis of water samples to determine any future pollution of the water due to the activities in the area. This research also underscores the urgency of addressing artisanal refining and its associated environmental impacts, driven largely by socio-economic factors in Nigeria.

Keywords: *Vulnerability, Aquifers, Artisanal Refining, Crude Oil Spill, Rivers State Nigeria.*

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Introduction

Groundwater is widely considered the most significant component of the hydrological cycle, serving as a primary source of drinking water in many parts of the world, including Africa, and representing roughly two-thirds of the planet's freshwater reserves.

Groundwater has been described as the main source of potable water supply for domestic, industrial and agricultural uses in the southern part of Nigeria especially the Niger Delta, due to long retention time and natural filtration capacity of aquifers (Amangabara and Njoku, 2012). The contaminated Groundwater unlike surface water contamination is considered a more difficult problem because of the difficulty in its early detection and skill required for prediction of its rate and path of movement (Nwankwoala and Ngah, 2013).

Groundwater resources have been under increasing stress in many parts of the world due to pollution. Pollution is primarily the result of irrigated agriculture (Bartzas *et al*., 2015), industrialization and urbanization (Arshad and Umar, 2022; Sarkar *et al*., 2021; Zhang *et al*., 2019), which generates diverse wastes, with the attendant impact on the ecosystem and groundwater. Pollution of groundwater has gradually been on the increase especially in our cities with lots of industrial activities, population growth, poor sanitation, land use for commercial agriculture and other factors responsible for environmental degradation (Lin *et al*., 2022). The concentration of contaminants in the groundwater also depends on the level and type of elements introduced to it naturally or by human activities and distributed through the geological stratification of the area (Agbalagba *et al*., 2011).

It has been reported that petroleum refining contributes solid, liquid, and gaseous wastes in the environment (Adebiyi, 2022; Shahbaz *et al*., 2023; Ogbuagu, *et al*., 2011). Some of these wastes could contain toxic components such as the polynuclear aromatic hydrocarbons (PAHs) (Varjani *et al*., 2017; Howard *et al*., 2021), which have been reported to be the real contaminants of oil and most abundant of the main hydrocarbons found in the crude oil mixture (Gbarakoro and Bello, 2022). Once introduced in the environment, PAHs could be stable for as short as 48 hours (e.g. naphthalene) or as long as 400 days (e.g. fluoranthene) in soils (El-Deeb and Emara, 2005). They thus, resist degradation and, remain persistent in sediments and when in organisms, could accumulate in adipose tissues and further transferred up the trophic chain or web (Martens and Frankenberger, 1995; Mandal *et al*., 2024).

The Niger Delta region of Nigeria is the crude oil and natural gas hub of Nigeria with several networks of product pipelines (both surface and subsurface) dotting the entire landscape which has created a social problem of vandalization of product pipelines and artisanal refining and the associated environmental hazards. Artisanal refining typically involves primitive illegal stills – often metal pipes and drums welded together – in which crude oil is boiled and the resultant fumes are collected, cooled and condensed in tanks to be used locally for lighting, energy or transport (Amangabara and Njoku, 2012). The distilleries are heated on open fires fed by crude oil that is tipped into pits in the ground. As part of the oil burns away, some seeps into the ground. Apart from the high risk of self harm from artisanal refining – a large number of accidents, fires and explosions on refining sites claim dozens of lives every year, quite apart from the longer-term health effects of ingestion, absorption and inhalation of hydrocarbons. The crude which is usually stored in open containers or open pits increases the risk of fire and the contamination of the environment and possibly impacting the underground aquifer.

It is this concern of crude oil seeping to the groundwater that necessitated the current study with the aim of assessing the vulnerability of the aquifer to the activities of artisanal refining which is eminent to the availability of potable water resources both for present and future generation given the fact that aquifers in the Niger Delta zone and the study area are near to the surface.

Materials and Methods

Study Area

The area under study is located in Ogu-Bolo local government area of Rivers State, Nigeria. It is readily accessible by a network of roads and footpaths and accessible to ships, boats, and canoes through the bonny river and its tributaries. There are two principal towns with their satellite communities namely Ogu and Bolo which make up the Ogu/Bolo Local Government Area (Fig. 1).

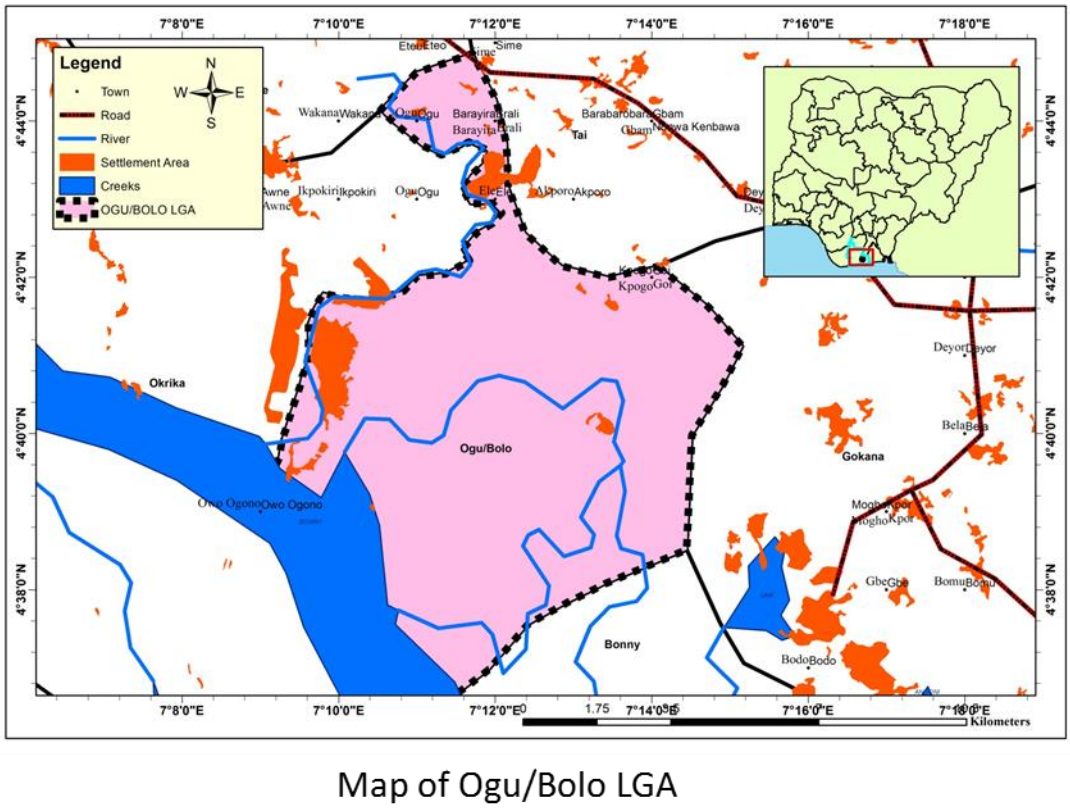

Figure 1. Map of Ogu/Bolo Local government Area

Bolo is geo referenced on Lat 4°34´ S to Lat 4°45´ S and Long 7°10´E to Long 7°15´E, is in the South-Eastern part of Ogu/Bolo Local Government Area, sharing boundaries with Tai, Gokana, and Bonny Local Government Areas of Rivers State, in the Niger Delta of Nigeria. Ogu/Bolo is an Island settlement with several archipelago types of villages and fishing ports straddled along its numerous and dense network of creeks. Bolo is host to two oilfields: Bodo West and parts of Bomu II oilfields with the associated product pipelines including the Trans Niger Pipeline. These pipelines have not been maintained and have led to equipment failure in some cases leading to spills and fires. Ogu & Bolo as at the 2006 census had a population of 75,282 with 16,468 Households. As at today, the population is estimated to be 105,300

Geology of the study area

The formation of the present-day Niger Delta started in the early Paleocene era and resulted in the built-up of fine-grained sediments eroded and transported by the River Niger and its tributaries. The subsurface geology of the Niger Delta consists of three lithostragraphic units (Akata, Agbada and Benin formations) which are in turn overlain by various types of quaternary deposits. The Benin Formation (2,100m thick) is made up of over 90% massive, porous, coarse sands with clay/shale inter-beds (Short and Stauble, 1967). This Formation is the most prolific aquifer in the region. The quaternary deposits (40-150m thick) generally consist of rapidly alternating sequences of sand and silt/clay with the latter becoming increasingly more prominent seawards. The recent Niger Delta can be subdivided into major inter-gradational geomorphologic units from land to sea (north to south) and these are:

i. Dry deltaic plain with rare freshwater swamps
ii. Extensive freshwater swamps and meander belts
iii. Salt water mangrove swamps, estuaries, creeks and lagoons (to which Ogu/Bolo LGA falls)

The sediment of the area, which are indicative of the Holocene geomorphic units are underlain by the Benin, Agbada and Akata formations. The Benin Formation, which is the continental mega-facie of the tertiary Niger Delta, comprises about 6000m thick succession of unconsolidated sands with thin clay and lignite interbeds. The Benin formation grade very gently downwards into the paralic delta front mega-facies. The underlying Akata Formation is the marine pro-delta facies of the tertiary Niger Delta. Consequently, it is dominated by shales of more than 1,380m thick. Sands constitute the major aquiferous layer in the Niger Delta and are dominated by sands, and gravelly sands (Andersen, 1967)

Table 1. *Geological and Lithological Units of the Niger Delta*

Geologic Unit	Lithology	Age
Alluvium	Grave, Sand, Clay Silt	**Quaternary**
Freshwater Back Swamp Meander Belt	Sand, clay, some silt and gravel	
Mangrove and Salt water/back swamp	Medium-fine sand, clay and some silt	
Active/abandoned beach ridges	Sand, clay and some silt	
Benin Formation (Coastal Plain Sand)	Coase to medium sand with subordinate silt and clay lenses	**Tertiary**
Agbada Formation	Mixture of sand, silt and shale	
Akata Formation	Shale, sandy in some place	

Source: Niger Delta Environmental Survey, 1995.

Hydrometeorology

There is no hydrometeorogical information that is readily available about Ogu/Bolo LGA, but because of its proximity in both distance and latitude to Port Harcourt City, hydro meteorological parameters for Port Harcourt are generally adopted for the area. Hydro meteorological parameters are important in this case because they determine the water balance of the impacted area. The water balance accounts for how water (surface, rainfall or groundwater) is expended and the interaction among the different phases.

The study area is confined within the humid-hot equatorial climate, (Ojo, 1977). The average temperature is 27^0C. It is characterized by two major seasons the dry seasons and wet seasons. The dry seasons begins from November and end at about March, while the Raining (Wet) season stretches from mid-March to October. Fresh water is generally supplied by heavy precipitation estimated to have net annual rainfall of more than 2600mm (Seams, 1999; Foodie, 2002). Rainfall in the area varies over a wide range in temporal context because of the occurrence of wet and dry season. The mean annual rainfalls within the past ten years, from 1997 to 2007, in Port Harcourt have shown notable variation. However, the highest rainfall recorded with the years under review was in September 2006, with the mean annual rainfall for this period (1997- 2007) estimate to be 4455mm. The peaks of the rains occur in the months of June/ July and September /October. The most important factor that influences rainfall in this area is the tropical marine air mass, moisture. Laden air that blows from the sea at least for ten mouth of the year that is, stretching from February to November. The counter air mass is the tropical continental air mass that blows from the Sahara Desert with dry and dusty characteristics. It is usually felt in the area during the months of December and January. The relative humidity is very high all year round, greater than 80% (Offodile, 2002). Bonny River and its tributaries and the creeks are responsible for the drainage around.

Soil

The superficial soils in the area fall under the geomorphic classification of coastal Plain sands, although described as sands; they contain substantial amounts of clay at the upper horizon which impede effective drainage within the vadose zone. Some researchers refer to the coastal plain sands as the surface expression of the Geologic Benin Formation but in the context of engineering applications, they are referred to as lateritic soils. They are rich in iron content; this imbues them with reddish brown coloration. At the impacted site, the reddish colour was suppressed by the very high antecedent soil moisture content and almost submerged condition.

The soil falls into the major groups of hydromorphic soils, that is they are poor to imperfectly drained soils. This is principally due to the low flood plain relief. The sediments become progressively finer in texture from the hinterland to the tidal zone. In terms of degree of profile development, the soils generally classified as young and weakly developed soils (lentisols and inceptisols in the USDA system and Cambisols in the FAO system). The poor ground drainage encourages the accumulations of raw organic matter (litter from trees) on the soil surface which decay slowly to form peat.

Hydrogeology and the Aquifer systems

The bulk of groundwater in the Niger Delta is contained in very thick and extensive sediments of Benin Formation. The exploited aquifers including Bolo are derived from the

Benin Formation. Based on geophysical and borehole data collected over the years, the Niger Delta hydro geological set up can be classified into:

a. Impermeable/Semi permeable horizons from ground level to 10m below mean sea level.
b. A permeable/gravel sand layer up to 80m below sea level.
c. From 80m to 225m below sea level, the formation consists of a permeable sand/gravel layer with thin impermeable/semi permeable clay/silt layers.

The water levels measured in the area fluctuate between 3m below ground level and 8.3m above sea level. In this aquifer more than 1500 wells are sunk in various part of Rivers State by private developers. Most of the boreholes are shallow (less than 70m deep) except a few constructed near coastal zones where there is threat of salt water intrusion. In general the hydrogeological data in the upland areas of the Niger Delta have very broad similarities not only on the subsurface lithology but also in the overall aquifer characteristics, for example the producing aquifer in Bodo (80m), kono (55m) have approximately the same features as the boreholes drilled in Trans Amadi in Port Harcourt and Umuayagu in Etche (Obinna 2010) similarly producing wells in Sakpenwa are quite similar to the boreholes in Ahoada and Ikwerre Local Government areas.

The exploited aquifers in the Niger Delta including Ogu/Bolo are derived from the Benin Formation. The ground water levels respond to seasonal variations in rainfall and recharge. Groundwater level Monitoring at the site of the Bonny Export Terminal at the Port Harcourt Refinery revealed a lag in response time of a little over two months during the wet season; groundwater level is considerably close to the ground surface, thereby making groundwater highly vulnerable to pollution. In general, the higher values are obtained from the north and the lower values in the southern part. The general direction of groundwater flow is southwards (Abam, 2011).

Vegetation

The vegetation of the area is mainly mangrove swamp forest. About 5 species of tree plants, 2 species each of ferns and hydrophytes are common in the mangrove swamp forest. The commonest trees were Rhizophora mangle and Rhizophora racemosa (red mangrove).

Data Acquisition

The data-set that were acquired for this study include primary and secondary data of both spatial and non-spatial attributes.

The primary dataset includes: The X&Y coordinates of the selected public boreholes and communities wells obtained with a handheld GPS in the study area.

The secondary data includes: SRTM (Short Radar Thematic Mapper) Images, administrative map, demographic data and digital elevation model (DEM).

Software packages include; ArcGIS version 10.3, ENVI version 4.7, Surfer 10, SPSS 22 and Microsoft Enterprise. A quick summary of the data type acquired, date of acquisition their sources and scale are presented in tabular form in table 2 below.

Table 2. *Data Description*

DATA	NAME	SHEET/ FORM/PR	DATE	FORM	SOURCE	SCALE/ RESOLUTION /QUANTITY	PREPARATIONS
•Boundary •River •Contour •Settlement	Administrative Map	Ogu-Bolo and Okrika	1968	Digital	Federal Surveys	1:100,000	•Import •Georeference •Digitize •Shape file
Soil type	Soil Map	Rivers State Soil map	2000	Digital	Geological Surveys	1:100,000	•Import •Georeference •Digitize •Shape file
Lithological Type	Geological map	Rivers state Geological map	1965	Digital	Geological Surveys of Nigeria	1:250,000,	•Import •Georeference •Digitize •Shape file
•Elevation •DEM •TIN	SRTM		2005	Digital	GLCF	28m	•Import •Georeference •Digitize •Shape file

Selection of Sampling Points

A total number of eight (8) sampling points were selected using random sampling techniques used in selecting the water points (wells, boreholes) and soil samples within Ogu Bolo. The map required for this study was acquired with the use of GIS. The coordinates of the sample points location for soil is presented in Table 3 while Table 4 is the location of water samples, Figure 2 is the map showing the locations where water and soil samples were collected.

Table 3. *Location of the Collection of Soil Samples*

s/n	Easting	Northing	LGA	Location	Sample type
1	7.20369	4.67842	OGU-BOLO	OB1	Soil
2	7.215291	4.691593	OGU-BOLO	OB2	Soil
3	7.11932	4.700406	OGU-BOLO	OB3	Soil
4	7.219415	4.76656	OGU-BOLO	OB4	Soil

Table 4. *Location of Collection of Water Samples*

s/n	Eastings	Northings	LGA	Location	Sample type
1	7.203478	4.678651	OGU-BOLO	OG1	GWATER
2	7.215175	4.691741	OGU-BOLO	OG2	GWATER
3	7.275823	4.681742	OGU-BOLO	OG3	GWATER
4	7.275823	4.67005	OGU-BOLO	OG4	GWATER

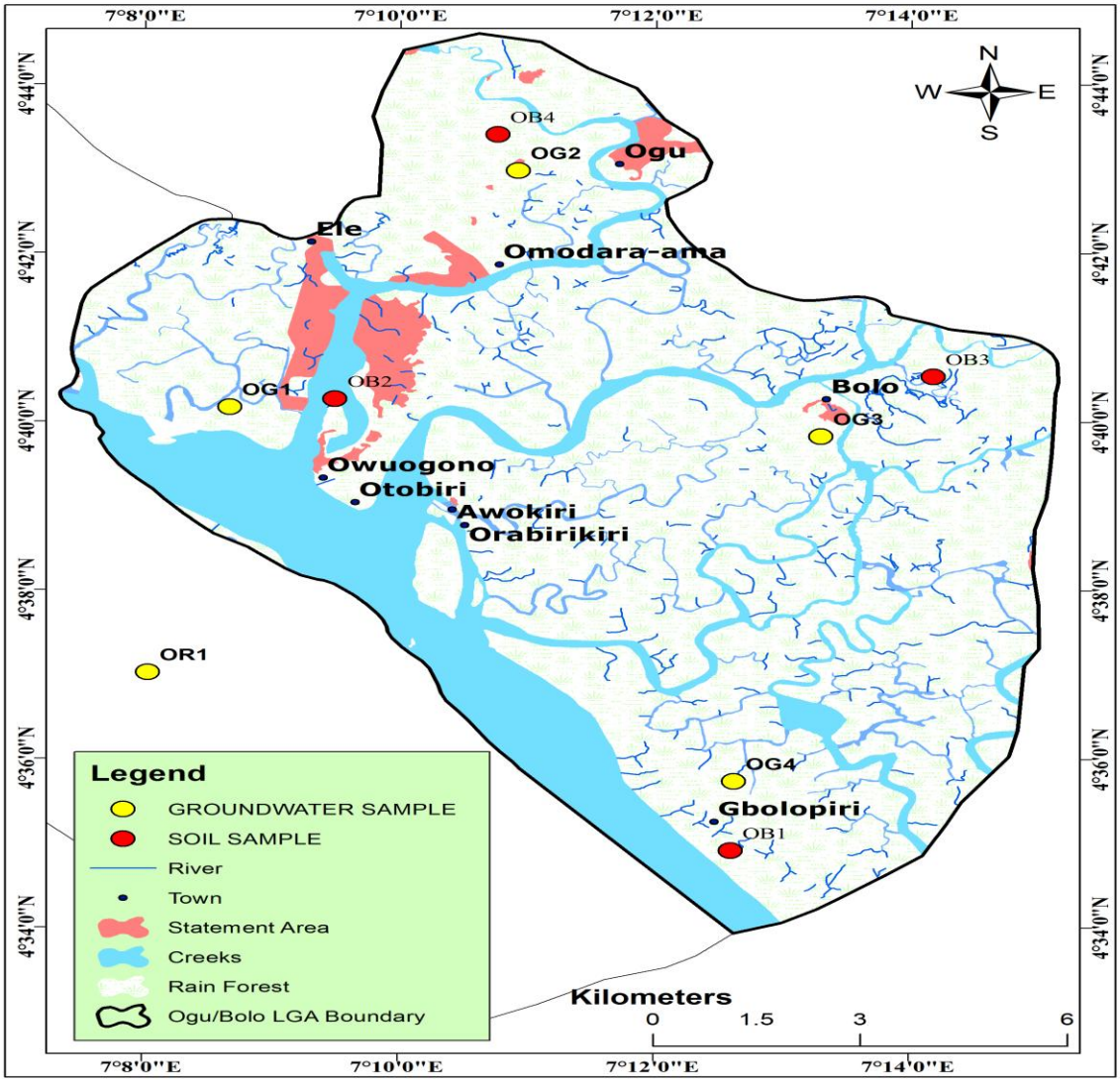

Figure 2. Ogu/Bolo Sample Location

Data Collection, Preparations and Analysis

The Digital Elevation Model was created from the elevation data obtained from SRTM (Short Radar Thematic Mapper) satellite image and contour extracted from the topographic map. This was achieved by turning on hill shading in the layer properties dialog box by choosing the Stretched renderer and checking use hill shade effect (color ramp) to represent various elevation ranges. Triangulated Irregular Network (TIN) were generated from contour (with Z attribute value) and used to generate digital elevation model (DEM).Slope, Flow accumulation, flow direction was generated from the DEM using the ArcGIS 10.3 3D analyst tool function of ArcGIS Version 10.3. Watershed and other drainage morphometric analysis were generated from the drainage map while land use/land cover and its class statistics were generated from the classification of the Landsat image covering. The slope of the study area was derived and modelled from the digital elevation model data data-set using create slope tool, the percentage (%) units were used to display the slope.

Field Data Collection

Each of the selected facilities was visited and detailed inspection carried out. Physical condition such as topography, land use, present condition of the water points and latrines

were noted. Instrument and materials used for field data collection are: a map of Ogu/Bolo local Government Area, Geographic positioning systems (GPS), measuring rope, mercury-in-glass thermometer, litmus paper and questionnaires.

The GPS model MAP 76CSx GARMIN was used to obtain coordinates of each sample location. The data forms were designed to cover issues relating to water sources and supply such as private and public well water, private and public borehole water, public tap water, and water from stream. The following criteria were assessed:

i. Water quantity – convince of water points – water quality
ii. Reliability of the water supply – proportion of households using the facilities

Physical conditions of each facility were assessed including location within the buildings and construction material used. The distance between the water supply facilities and the sanitary wells (soak away and pit latrines) were also estimated taking into consideration the direction of water flow relative to the facilities (upstream or downstream). Camera snapshot of the environment was obtained for each of the facilities for easy identification during analysis

Results

Water Quality: Physicochemical Results Water Samples

Water quality is the study of the suitability of the water for the intended use. Therefore, it is a function of the percentage of both the physical and chemical characteristics (parameters) present in the water which to a very large extent depends on the geology of the area as well as anthropogenic activities of human in the area (Ezeigbo, 1989). Summary of the results of water chemistry (physico-chemical properties, cation and anion content and trace metal content) of water samples are presented in Tables 5 below. The result shows the presence of BTEX, lead (Pb), Zinc (Zn) and Copper (Cu) are within NESREA limits while Iron (Fe) is elevated across all sampling locations.

Table 6 is a table showing the minimum, maximum and mean values of various parameters obtained from analysis of the samples from the study area with stipulated standards for water i.e. the Nigeria Environmental Standards and Regulations Enforcement Agency (NESREA) standards for drinking and public health purposes except for Iron and Chlorine. The descriptive statistics show that min value for Iron (fe) is 0.17, maximum 0.466 and the mean value 0.826. Another parameter of slightly elevated value is chlorine (Cl^-) min (7.08), Max (10.88) with mean value of 8.34 (Table 6)

Cu in all samples was far less than the value of the stipulated standards of NESREA. Fe in all samples was far higher in value than stipulated value for standardization. pH of water samples fell within the range of the stipulated standard. Dissolved Oxygen value were far less than 40 which is the stipulated value by NESREA. Also, Chemical Oxygen Demand values for all samples in the study area far below recommended values by NESREA.
The high values of Fe and Zn present in the analyzed water sample indicates that such water is not suitable for human consumption as well as other domestic use. The high concentration of Fe may be due to the anthropogenic activities in the area.

Table 5. *Result of Heavy metals & some Physico-chemical Parameters in Ogu/Bolo Water Samples*

Sample Identity	Pb (mg/l)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)	BTEX (mg/l)	Cl^- (ppm)	Temp (^{o})	pH	DO	Turbidity (NTU)	COD (ppm)
G/water 1 (Agakien Ama)	<0.1	<0.1	0.466	<0.1	<0.001	7.08	28.9	4.9	1.7	<1.0	2.5
G/water 2 (Nonju Ama)	<0.1	<0.1	0.17	<0.1	<0.001	7.08	29.0	5.1	1.6	<1,0	1.7
G/water 3	<0.1	<0.1	0.190	<0.1	<0.001	10.88	30.0	5.8	1.9	2.5	1.9
Control 4	<0.1	<0.1	0.17	<0.1	<0.001	106.2	30.0	6.9	3.1	<0.0	3.6
NESREA LIMITS	0.001	1	0.5	0.05				6.50-8.50	40		30

Table 6. *Descriptive Statistics of Water Sample*

Chemical parameter	Min	Max	Mean	NESREA LIMIT
Pb	**-**	**-**	**-**	**0.001**
Cu	**-**	**-**	**-**	**1**
Fe	**0.17**	**0.466**	**0.826**	**0.5**
Zn	**-**	**-**	**-**	**0.05**
Temp	**28.8**	**30.0**	**29.3**	**-**
BTEX	**-**	**-**	**-**	**-**
Cl^-	**7.08**	**10.88**	**8.34**	**-**
pH	**4.9**	**5.8**	**5.2**	**6.50-8.50**
DO	**1.6**	**1.9**	**1.7**	**40**
Turbidity	**-**	**2.5**	**-**	**-**
COD	**1.7**	**2.5**	**2.0**	**30**

Note: COD- Chemical oxygen demand
DO – Dissolved oxygen

Total Petroleum Hydrocarbon (TPH) and Polycyclic Aromatic Hydrocarbon (PAHs) in Soil in the Study Area

The average Total Petroleum Hydrocarbon (TPH) at various sample locations is presented as Table 7. At location OGB L.1, average TPH is 8,663.41mg/kg, at location OGB L.2, 4,998.41. At location OGB L. 3 is 2,406.33mg/kg while the least was recorded at Location OGBL.13 994.59mg/kg

The corresponding values for Polycyclic Aromatic Hydrocarbons (PAHs) are presented as Table 8. At Sample location OGB 1 (25.99mg/kg). The highest value was obtained at OGB 2 (106.40mg/kg).

Table 9 shows the level of BTEX in soil samples. The highest elevated amount was found in soil samples obtained at Sample location 2 – Nonju Ama (32.11mg/kg), closely followed by Yayo Ama (Sample location OGB L3) with values averaging 30.69mg/kg.

Table 7. *Total Petroleum Hydrocarbons (TPH) in Soil Samples*

SAMPLE IDENTITY	TPH AVERAGE (mg/kg)
OGB L1 (Gbolopiri)	8,663.41
OGB L2 (Nonju Ama)	4,998.41
OGB L3 (Adokiye Ama)	2,406.33
OGB L11 (Orabere Kiri)	5,432.22
OGB L12 (Owu ogono)	3,879.37
OGB L13 (Yayo Ama)	994.59

Table 8. *Polycyclic Aromatic Hydrocarbon (PAHs) in Soil Samples*

SAMPLE IDENTITY	PAH AVERAGE (mg/kg)
OGB L1 (Gbolopiri)	25.99
OGB L2 (Nonju Ama)	106.40
OGB L3 (Adokiye Ama)	37.5
OGB L11 (Orabere Kiri)	41.91
OGB L12 (Owu ogono)	88.45
OGB L13 (Yayo Ama)	57.8

Table 9. *BTEX in Soil Samples*

SAMPLE IDENTITY	PAH AVERAGE (mg/kg)
OGB L1 (Gbolopiri)	18.49
OGB L2 (Nonju Ama)	32.11
OGB L3 (Adokiye Ama)	10.00
OGB L11 (Orabere Kiri)	15.98
OGB L12 (Owu ogono)	12.83
OGB L13 (Yayo Ama)	30.69

Results of PAHs in water (Table 10 and Table 11) showed sample L2 had the highest value of PAH at 1m depth for both Ogu and Bolo Axis of the LGA. With greater depth of 2m, sample L2 still had the highest value of PAH for both Okrika and Ogu-bolo and at 3m depth, sample L2 also had highest value for PAH.

TPH vales were highest for sample L1 at 1m, as well as for 2m. But with further depth of 3m, sample L2 for Ogu-bolo hid highest values of TPH and sample L1 had highest values for Ogu.

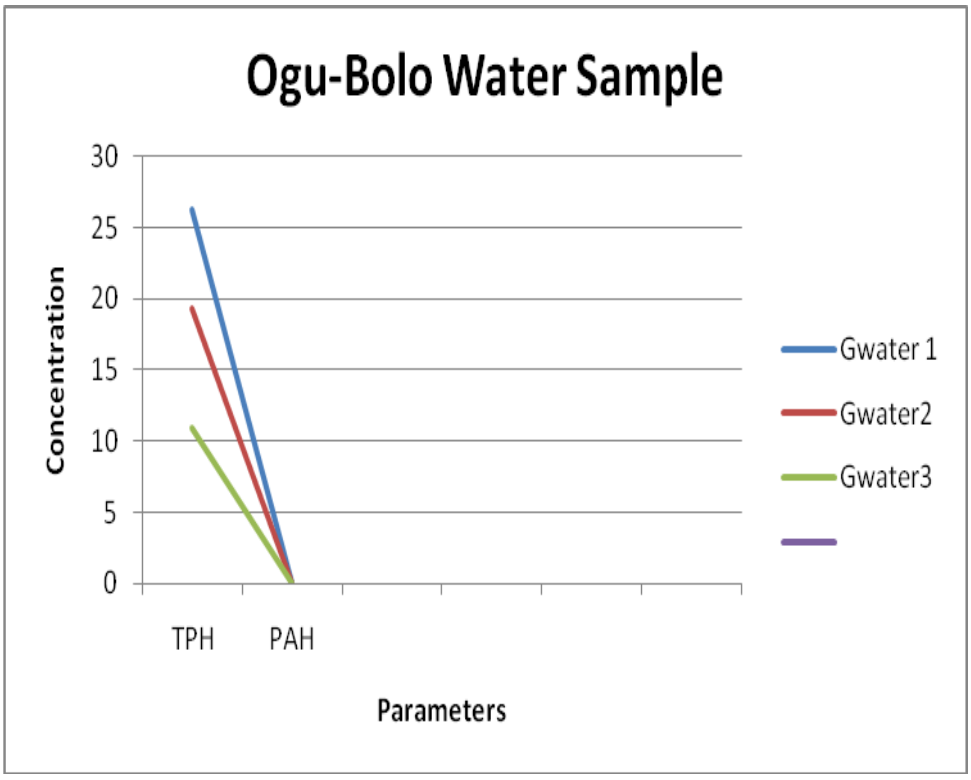

Figure 3. Line plots of TPH and PAH of water sample

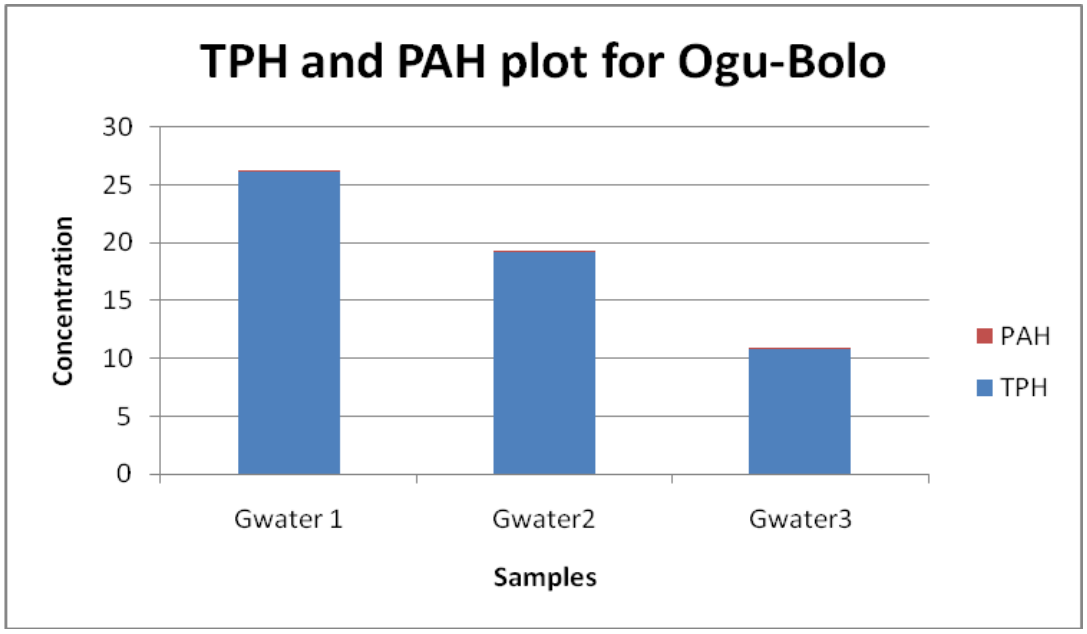

Figure 4. TPH and PAH of water sample for Ogu-bolo

Table 10. Results of TPH in the Study Area

S/N	Sample Identity	GPS	TPH Results (mg/kg)		
			1.0m	2.0m	3.0m
1.	**OGB L1**	**N4.678420 E7.203690**	**13,125.23**	**8,432.00**	**4,433**
2.	**OGB L2**	**N4.691593 E7.215291**	**7,521.22**	**4,487.00**	**2,987.00**
3.	**OGB L3**	**N4.700406 E7.119320**	**3,121.00**	**2,098.00**	**2,000.00**
4.	**OGB CONTROL**	**N4.766560 E7.219415**	**65.11**	**60.08**	**49.22**

Table 11. Result of PAHs in the Study Area

S/N	Sample Identity	GPS	TPH Results (mg/kg)		
			1.0m	2.0m	3.0m
1.	**OGB L1**	**N4.678420 E7.203690**	**31.12**	**26.32**	**20.54**
2.	**OGB L2**	**N4.691593 E7.215291**	**121.21**	**100.00**	**98.00**
3.	**OGB L3**	**N4.700406 E7.119320**	**19.00**	**56.00**	**<0.001**
4.	**OGB CONTROL**	**N4.766560 E7.219415**	**<0.001**	**<0.001**	**<0.001**

Crude Oil sample Analysis of the Study Area

Crude oil sample collected from artisanal refinery sites and analysed for density, kinetic viscosity and presence of iron, nickel and Na is presented as table 12.

Table 12. *Characteristics of Crude Oil Sample Analysis in Ogu-bolo*

Sample Identity	DENSITY ($kg/m^{3)}$	KINETIC VISCOSITY (mm^2/sec)	Fe(mg/l)	Ni(mg/l)	Na(mg/l)
Bolo crude oil	$862.5kg/m^3$	$3.59cst(mm^2/sec)$	15.1	17.9	30.9
Ogu crude oil	$881.3kg/m^3$	$7.08cst(mm^2/sec)$	15.3	17.0	31.2

Analysis shows density of 862.5kg/m^3 for Bolo crude sample and 881.3kg/m^3 for Ogu crude sample. Also, the kinetic energy for Bolo and Ogu are 3.59cst (mm^2/sec) and 7.08cst (mm^2/sec) respectively. For Bolo crude oil sample, analysis also shows the following Fe 15.1, Ni 17.9 and Na 30.9 and Ogu Fe 15.3, Ni 17.0 and Na 31.2.

It simply implies that crude oil samples from artisanal refinery sites at Ogu have a higher kinetic viscosity compared to those found at Artisanal refinery sites at Bolo axis and also Fe, Ni and Na were found to be slightly higher. An indication that the sources of crude oil at these locations may be different.

Geologic Formation/Soil of the Study Area

The geologic characteristics of the study as generated by the Geographic Information System (GIS) are presented as Fig 5. There are major features. The northern of the study area (Ogu) is the coastal Plain sands while the rest of the area is principally the Basement complex.

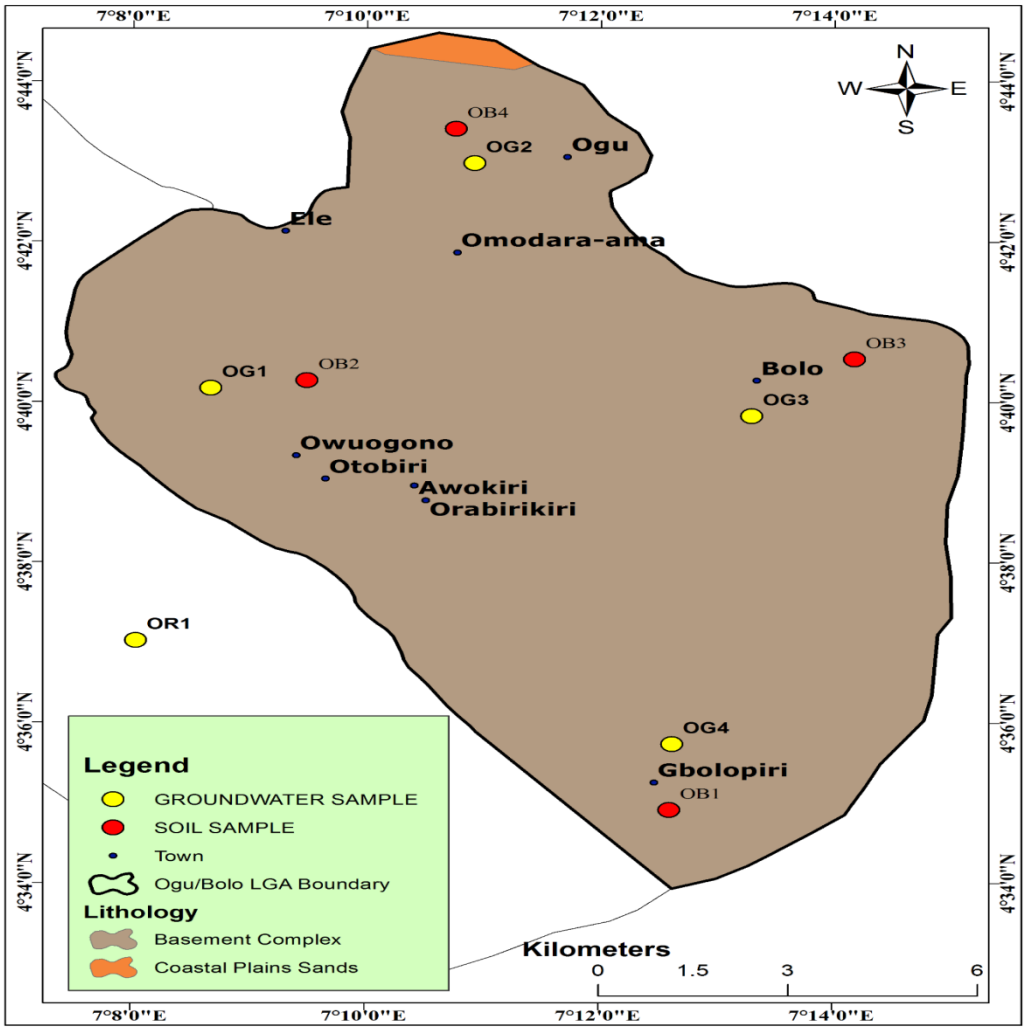

Figure 5. Ogu/Bolo Geology map

The soil also reflects the geologic features. Figure 6 shows that, there also two dominant soil type. Fluvisols to the northern part and Ferralsols which is the most widespread in the rest part of the LGA

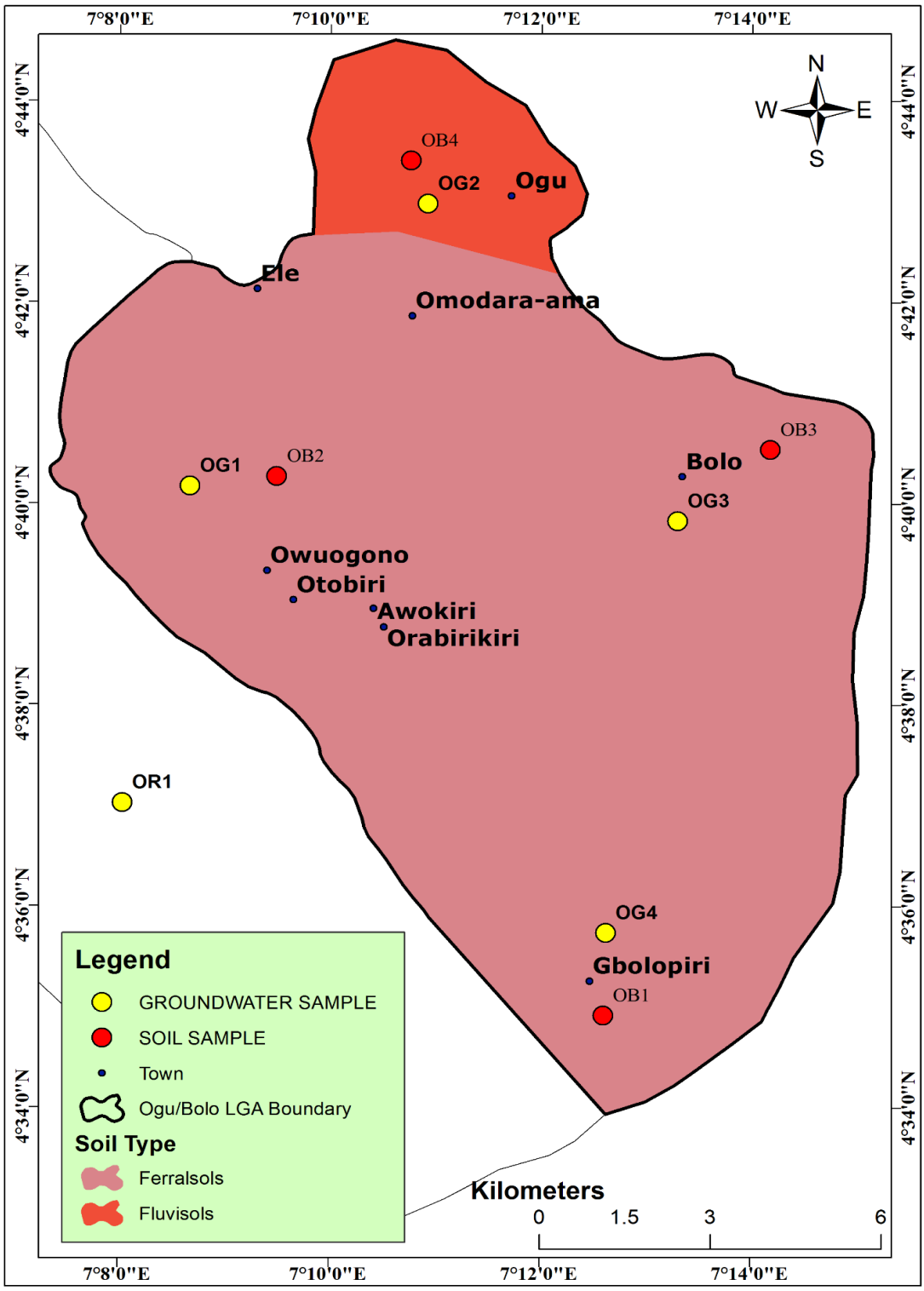

Figure 6. Ogu/Bolo Soil map

Vulnerability of Aquifers at the Study Area

The assessment of aquifer vulnerability at artisanal refining sites involves evaluating the risk of crude oil seeping into groundwater and contaminating the water supply. This is important because contaminated water is a threat to the availability of potable water. Risk originates from type of spills and volume of spills. Risk reach aquifer depending river proximity,

drainage density, precipitation, landuse/land cover, percentage sandiness elevation, slope, and depth to water table.

The water quality analyses on water samples from the study area showed that groundwater is already being impacted upon by crude oil related activities. Considering the cavalier attitude of this bunkers to the environment upon which they operate, groundwater is highly vulnerable to severe hydrocarbon pollution in Bolo and Environs and mostly likely all Niger Delta areas where the activities of artisanal refining and oil bunkering takes place, given that the surface of the Niger delta is dissected by a dense network of rivers and creeks, which create a condition of delta-wide hydrological continuity.

The water levels measured in the boreholes within the study area seem to fluctuate between 3m below ground level and 8.3 meters above sea level. Published records of water levels of shallow wells of the upper aquifer which are the most exploited indicate the general structure of the groundwater surface. During the wet season, groundwater level is considerably close to the ground surface, thereby making groundwater highly vulnerable to pollution. Artisanal oil refining activities including the waste generated from such activities affect the environment as well as the groundwater system. This finding agrees with Amangabara and Njoku, (2012) who adopted an empirical method in estimating permeability and the Kozeny – Carman equation for deriving the coefficient of permeability and estimated infiltration rate of 1.15 x 10-8cm/s can be expected and posited that crude oil contaminant plume or wetting front has intercepted the groundwater table

Influence of Local Geology

The superficial soils in the area fall under the geomorphic classification of coastal Plain sands, although described as sands; they contain substantial amounts of clay at the upper horizon which impede effective drainage within the vadoze zone. Some researchers refer to the coastal plain sands as the surface expression of the Geologic Benin Formation (Short and Stauble, 1967) but in the context of engineering applications, they are referred to as lateritic soils. They are rich in iron content.

The bulk of groundwater in the Niger Delta is contained in very thick and extensive sediments of Benin Formation. The exploited aquifers including Bolo are derived from the Benin Formation. Based on geophysical and borehole data collected over the years, the Niger Delta hydro geological set up can be classified into:

a) Impermeable/Semi permeable horizons from ground level to 10m below mean sea level.

b) A permeable/gravel sand layer up to 80m below sea level.

c) From 80m to 225m below sea level, the formation consists of a permeable sand/gravel layer with thin impermeable/semi permeable clay/silt layers.

The water levels measured in the area fluctuate between 3m below ground level and 8.3m above sea level. The ground water levels respond to seasonal variations in rainfall and recharge. The area's high porosity and permeability allow metals to easily move into the groundwater system under acidic conditions. There is no hydro-meteorological information that is readily available on Bolo Community, but because of its proximity in both distance and latitude to Port Harcourt City, hydro meteorological parameters for Port Harcourt are generally adopted for Ogu-Bolo LGA. Rainfall in the area varies over a wide range in temporal context because of the occurrence of wet and dry season.

Influence of Soil

The influence of soil in mass movements cannot be underestimated. Soils play a dual role because it is a by-product of the Groundwater process and at the same time it is an important affective factor. The most important properties in soil stability are those that influence the rate of water movement in the soils and the capacity of the soil to hold water (Sidle *et al*., 1985). The types of soil found in the study area include Fluvisols, Nitisols, Ferralsols and Sedbeds (Figure 5 and 6).

Fluvisol is one of the 30 soil groups in the classification system of the Food and Agriculture Organization (FAO). Fluvisols are found typically on level topography that is flooded periodically by surface waters or rising groundwater, as in river floodplains and deltas and in coastal lowlands. They are cultivated for dryland crops or rice and are used for grazing in the dry season. Fluvisols in Ogu Bolo are technically defined by a weak or non-existent surface horizon (uppermost layer) and by parent material derived from river, lake, or marine sediments that have been deposited at regular intervals or in the recent past. These soils exhibit a stratified profile that reflects their depositional history or an irregular layering of humus and mineral sediments in which the content of organic carbon decreases with depth. Wide variations in texture and mineral composition are observed.

Ferralsols in Ogu/Bolo are technically defined by a fine-textured subsurface layer of low silt-to-clay ratio, high contents of kaolinite clay and iron and aluminium oxides, and low amounts of available calcium or magnesium ions. When crude oil content is spilled they easily are infiltrated into the groundwater system which is close to the top

Water Quality Index (Wqi) Model Result

Water quality index is a 100 point scale that summarizes results from a total of different measurements when complete. It is a dimensionless number that combines multiple water-quality factors into a single number by normalizing values to subjective rating curves (Miller *et al*., 1986). Factors to be included in WQI model could vary depending upon the designated water uses and local preferences. Some of these factors based on this study includes PAH= POLYCYCLIC AROMATIC HYDROCARBON, TPH =(total petroleum hydrocarbon), BTEX (Benzene Toluene Ethylbenzene Xylene, Fe (Iron), Zn (Zinc), Cu (Copper), Pb (lead),Hub (Hydrocarbon utilizing Bacteria), Cl (Chloride), Nitrate, SO_4 (sulphate), pH, BOD (Biological Oxygen Demand), COD (Chemical Oxygen Demand), Turbidity, DO (Dissolved Oxygen) and Temperature etc. These parameters occur in different ranges and expressed in different units. The WQI takes the complex scientific information of these variables and synthesizes into a single number. Graphs are used to convert field data to a Q or Quality Value. The Q value is then multiplied by Weighing Factor to get the Water Quality Index for that Chemical. The results are then totalled to get the Overall Water Quality Index. The index equation generates a number between 1 and 100, with 1 being the poorest and 100 indicating the best water quality. Within this range, designations have been set by CCME (2005) to classify water quality as poor, marginal, fair, good or excellent.

WQI Development Process

The process of developing a WQI involves the following steps:

- Identification of water quality parameters of interest and their ranges of acceptability for the intended uses of the water. In this study the emphasis is consummation quality of the water.

- The measured values were compared with the subjective rating curve chart of the participating element (see appendix) where a numerical value also known as the Q-value is obtained. Subsequently the Q-value is multiplied by a weighting factor. The weighting factor sets the relative importance of the parameter to overall water quality. For a given participating parameter, the weighting factor value falls between 0 and 1. The weighting factors for different participating parameter are shown in Table 13.

- The results generated from the Q-value and weighting factor computation is further computed using the weighted arithmetic mean models in accordance to Cude (2001).

WQI Interpretation

The index equation generates a number between 1 and 100 with 1 being the poorest and 100 indicating the best water quality. Within this range, designations have been set by CCME (2005) to classify water quality as poor, marginal, fair, good and excellent. The designations are presented in Table 13.

Table 13. *Weighting Factors for Different Participating Parameter*

Factor	Weight
DO (Dissolved Oxygen)	0.1
Fecal coli form	0.1
Ph	0.09
BOD (Biological Oxygen Demand)	0.09
Turbidity	0.08
TPH =(total petroleum hydrocarbon)	0.07
Temperature	0.07
PAH= POLYCYCLIC AROMATIC HYDROCARBON	0.05
Fe (Iron)	0.05
COD (Chemical Oxygen Demand)	0.05
Pb (lead)	0.04
Cl (Chloride)	0.04
BTEX (Benzene Toluene Ethylbenzene Xylene	0.03
Zn (Zinc)	0.03
Cu (Copper)	0.03
Hub (Hydrocarbon utilizing Bacteria)	0.03
Nitrate	0.03
SO4 (sulphate)	0.02
	1

Table 14. *Water Quality Rating*

Water Quality Index Range	Water Quality Rating
90-100	Excellent
70-89	Good
50-69	Medium
25-49	Bad
0-24	Very Bad

The spillage of crude oil from artisanal refineries is a critical environmental issue with profound implications for aquatic ecosystems. Artisanal refining activities contaminate water through multiple channels, such as discharges from nearshore operations, industrial effluents, accidental spills during loading, and leaking pipelines. Further contamination arises from illegal well tapping, rudimentary refining processes, and ballast water from oil tankers. These activities introduce harmful substances, including polycyclic aromatic hydrocarbons (PAHs), benzene, and other carcinogenic compounds, which pose severe risks to both the environment and public health.

Furthermore, crude oil pollution drastically affects soil and water quality by altering their physicochemical properties and destroying vegetation cover, resulting in the release of toxic hydrocarbons into the environment. Contamination severely impacts the microbiological properties of soil and water, disturbing the growth dynamics of microorganisms that play essential roles in nutrient cycling and ecosystem functioning. These changes compromise the delicate balance of aquatic ecosystems, leading to a decline in biodiversity and creating long-term disruptions in ecological stability.

Oil spills are frequent due to rudimentary refining processes and a lack of containment measures. These spills release crude oil into rivers, streams, and wetlands, contaminating surface and groundwater systems. Groundwater aquifers, which are crucial sources of drinking water for many communities, are particularly vulnerable to seepage contamination. This not only renders the water unfit for human consumption but also increases the bioaccumulation of harmful chemicals in aquatic organisms.

The impact of water pollution from artisanal refining is compounded by seasonal flooding, which disperses contaminants across broader regions, affecting farmlands and residential areas. The widespread contamination threatens the region's already fragile food and water security, perpetuating health challenges and socio-economic disparities. During the artisanal refining process, crude oil often seeps into the ground, contaminating soil with hydrocarbon residues and hazardous pollutants. This contamination significantly alters the soil's physical and chemical properties, including raising soil pH levels and reducing phosphorus content. These changes create an environment unsuitable for agriculture, as persistent organic pollutants and heavy metals penetrate several meters deep, rendering the soil toxic and unfit

for cultivation. Additionally, the penetration of oil can contaminate groundwater sources over large areas, posing severe health risks to local communities.

Conclusion

Artisanal refining in the Niger Delta area of Nigeria poses severe environmental and health challenges due to the lack of regulation and hazardous refining methods. The practice results in significant air pollution, water contamination, and soil degradation, which adversely impact respiratory health, increase cancer risks, and harm biodiversity and traditional livelihoods. Socioeconomic factors, regulatory weaknesses, and community dynamics perpetuate these challenges

The assessment of vulnerability of aquifer due to artisanal crude oil refining in the Ogu/Bolo LGA reveals alarming levels of contamination and degradation of groundwater resources. The widespread practice of artisanal refining characterized by inadequate processing techniques and improper waste disposal leads to significant challenges and subject the groundwater in the area vulnerable due to constant spills, porous soil media and the characteristics of the crude with high viscosity. The soil in the study area is predominantly of the coastal plain sands which allows for quick infiltration of the pollutant to the water table.

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