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Vulnerability of Groundwater Contamination Due to Bitumen Exploration and Exploitation Site: Implication for Environmental Sustainability

Abstract

Groundwater is an essential resource, particularly in areas with industrial activities such as bitumen exploration. This study assesses groundwater vulnerability, groundwater-bitumen interaction, and baseline groundwater quality within the Southwest Bitumen proposed project area. The protective capacity of overlying geological materials was evaluated using longitudinal conductance values, revealing that aquifers with lower values are more vulnerable to contamination. Findings indicate that bitumen layers occur at varying depths, with some intercalated with groundwater-bearing zones, increasing the risk of hydrocarbon contamination. The groundwater quality assessment focused on physico-chemical and microbiological parameters from hand-dug wells across ten host communities, compared with control samples. Results showed seasonal variations in temperature (26.00 - 26.60°C in wet season vs. 28.80 - 31.2°C in dry season), electrical conductivity (142 - 263 µS/cm in wet season vs. 102 - 278 µS/cm in dry season), and total dissolved solids (TDS) (51 - 139 mg/L in dry season), though all remained within WHO potable water limits. However, turbidity (2.50 - 49.0 NTU) and pH (4.25 - 6.47) in some locations exceeded regulatory limits, indicating potential groundwater contamination risks. The study underscores the need for continuous groundwater monitoring, the implementation of mitigation measures, and sustainable management practices to prevent the degradation of this vital resource.

Keywords : Groundwater Vulnerability, Bitumen Exploration, Water Quality, Pollution Risk, Aquifer Protection

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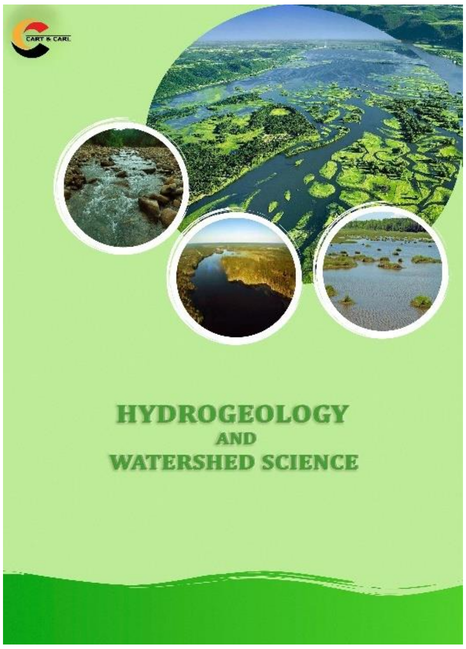

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Introduction

Water quality, both surface and underground, is particularly vulnerable in regions where mining and extraction activities take place. Extractive industries, such as bitumen mining, pose significant environmental risks due to their potential to introduce contaminants into local water systems (Adekoya, 2003; Akintunde et al., 2018). The methods used in the exploration and exploitation of bitumen often involve large-scale excavation, leading to increased exposure of underground water reservoirs to contaminants such as hydrocarbons, heavy metals, and other pollutants. In Nigeria, particularly in Agbabu, Ondo State, where substantial bitumen deposits are located, concerns regarding the vulnerability of groundwater to contamination have been growing. Understanding the extent of this vulnerability is critical for ensuring environmental sustainability and developing effective

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mitigation measures. The primary aim of this study is to assess the vulnerability of surface and groundwater to contamination in the event of large-scale bitumen mining in Agbabu, Ondo State, Nigeria. The research seeks to examine the impact of bitumen exploration on groundwater systems, evaluate the risks associated with contamination, and propose sustainable management strategies to mitigate these risks. Given the ecological and socio-economic of groundwater in the region, particularly as a primary source of drinking water for local communities, safeguarding its quality is essential.

Nigeria is home to one of the largest bitumen deposits in the world, with estimates suggesting that the country holds over 42 billion barrels of bitumen (Adegoke et al., 1991). The majority of these deposits are located in Ondo, Ogun, Edo, and parts of Delta States**, with** Agbabu in Ondo State being the most well-known and extensively studied bitumen deposit (Adeyemi & Olusola, 2015). Despite the vast reserves, commercial-scale mining has been largely undeveloped**,** with exploration activities remaining limited to pilot studies and feasibility assessments conducted over the years.

Bitumen extraction methods can be surface mining (open-pit mining) **or** in-situ extraction (thermal recovery techniques)**,** depending on the depth of the deposits. In Nigeria, most of the bitumen reserves are shallow deposits, making surface mining the most viable method of extraction. This approach involves the removal of large volumes of overburden, which can expose and disturb aquifers**,** leading to increased risks of contamination **(**Alagbe, 2002). Additionally, the use of hot water, solvents, and mechanical processes in bitumen separation increases the potential for leakage of hydrocarbons and other pollutants into groundwater systems.

The environmental concerns surrounding bitumen extraction in Ondo State are significant. Previous studies have shown that regions with bitumen deposits are prone to soil degradation, deforestation, air and water pollution (Fakayode et al., 2014). Specifically, groundwater contamination has been a major concern, as the excavation process can lead to hydrocarbon infiltration, heavy metal leaching, and alteration of the natural hydrological cycle (Olajire & Imeokparia, 2001). Groundwater vulnerability refers to the susceptibility of an aquifer system to contamination from surface and subsurface activities (Foster et al., 2006). This vulnerability is influenced by factors such as geology, depth to water table, soil permeability, and land use activities (Alley et al., 2002). In regions where bitumen mining occurs, groundwater is particularly at risk due to direct exposure of aquifers during excavation, infiltration of pollutants, and changes in groundwater flow patterns.

Several factors contribute to groundwater vulnerability in the Agbabu region**:** Shallow Aquifers**:** The groundwater table in the bitumen belt of Ondo State is relatively shallow, making it more susceptible to contamination from surface mining activities (Nwankwo et al., 2017). Hydrocarbon Contamination**:** Bitumen itself contains complex hydrocarbons, which can seep into underground water sources through fractures, cracks, or improper waste disposal practices (Oborie et al., 2015). Leaching of Heavy Metals: Bitumen deposits are often associated with heavy metals such as lead, arsenic, and cadmium, which, if mobilized through mining processes, can infiltrate groundwater supplies (Ogunleye et al., 2010). Alteration of Groundwater Flow**:** Large-scale excavation and the removal of overburden materials can change natural groundwater recharge and flow patterns, potentially leading to contamination of previously uncontaminated water sources (Badejo et al., 2019). Use of Chemicals in Processing**:** During bitumen extraction and processing, solvents, hot water, and other chemicals are often used, increasing the likelihood of chemical spills and leaks into the groundwater system(Akintunde & Olajide, 2013).

Studies have shown that similar concerns exist in other bitumen-rich regions worldwide**,** such as Canada's

Athabasca Oil Sands, where significant groundwater contamination has been linked to bitumen extraction processes (Kelly et al., 2010). The potential environmental risks in Nigeria are even more pronounced due to less stringent environmental regulations and limited enforcement capacity (Adeyemi et al., 2018).

The contamination of groundwater in bitumen mining areas has serious environmental and socio-economic implications. Water pollution can lead to health risks for local communities, including exposure to carcinogenic hydrocarbons, heavy metals, and waterborne diseases (Adebanjo et al., 2015). In addition, groundwater contamination can negatively impact agriculture, fisheries, and biodiversity, leading to reduced livelihoods and economic losses.

From a policy perspective, the sustainability of bitumen exploration in Ondo State will depend on the implementation of environmentally sound mining practices, including proper waste management, groundwater monitoring, and remediation measures. The application of geospatial and hydrogeological modeling techniques to assess groundwater vulnerability and predict potential contamination pathways is essential for effective environmental management.

This study is essential in assessing the vulnerability of groundwater to contamination at a bitumen mining site in Agbabu, Ondo State. Given the significant risks associated with bitumen extraction, there is a need for sustainable exploration practices that minimize environmental degradation and protect water resources. The findings from this research will provide critical insights into the potential impacts of bitumen mining on groundwater quality and offer policy recommendations for mitigating contamination risks. By examining hydrogeological conditions, pollution pathways, and contamination risks, this study will contribute to ongoing discussions on balancing economic development with environmental sustainability in Nigeria's extractive sector.

Material and Methods

Study Area

Agbabu area, located in Ondo State, Nigeria, is an area of significant interest due to its natural bitumen deposits (Figure 1). Understanding its environmental characteristics is crucial, especially considering potential impacts from bitumen exploration. Below is an overview of Agbabu's soil, climate, water quality, and vegetation, supported by relevant literature. The soils in Agbabu are predominantly sandy loam, characterized by moderate fertility. A geochemical study of the Agbabu soils revealed that they are rich in silica, with moderate amounts of alumina and iron oxides. The presence of bitumen in the area has led to increased organic carbon content in the soils, which can influence their physical and chemical properties. However, the extraction of bitumen poses a risk of soil contamination, potentially altering soil pH and reducing its fertility. Agbabu experiences a tropical climate with distinct wet and dry seasons. The wet season typically spans from March to October, characterized by heavy rainfall, while the dry season occurs from November to February. The area receives an average annual rainfall of approximately 2,000 mm, with temperatures ranging between 24°C and 32°C throughout the year. Humidity levels are generally high, especially during the wet season. The presence of bitumen deposits in Agbabu raises concerns about water quality, particularly regarding potential contamination from mining activities. Studies have indicated that surface and groundwater in the area may be susceptible to pollution from hydrocarbons and heavy metals due to bitumen extraction processes. Regular monitoring of water sources is essential to ensure the safety and health of local communities.

The vegetation in Agbabu is typical of the tropical rainforest ecosystem, comprising a diverse array of plant species. Common tree species include Milicia excelsa (Iroko), Terminalia superba (Afara), and Triplochiton scleroxylon (Obeche). The dense canopy and rich biodiversity are characteristic of such ecosystems. However, bitumen exploration and exploitation activities pose a threat to this vegetation, leading to deforestation and habitat degradation. Conservation efforts are necessary to preserve the ecological balance of the area.

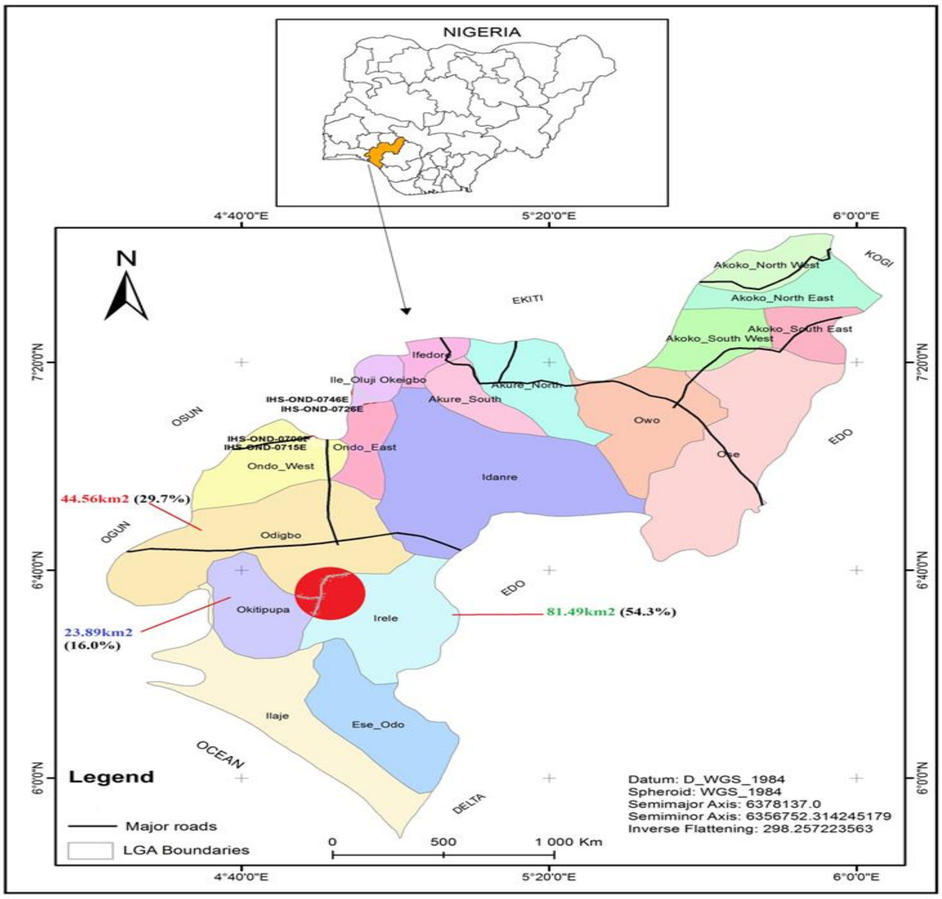


Figure 1: Overview of the Study Area Indicating the Proposed Exploitation Site (Area Marked In Red Circle)

Data Collection

Geophysical Study

The geophysical investigation conducted in this study employed the electrical resistivity method to assess subsurface properties. This technique involves passing an electric current (I) into the ground through a pair of current electrodes, while the resulting potential difference (V) is measured across another pair of potential electrodes positioned within the current electrode pair. For this study, the Vertical Electrical Sounding (VES) technique was adopted using the Schlumberger array configuration. The electrode spacing (AB/2) was varied from 1 meter to 225 meters, with a maximum spread length of 450 meters to obtain detailed resistivity data of the subsurface layers. The Omega Resistivity Meter was used for data acquisition, ensuring accuracy and consistency in measurements.

A total of 13 VES tests were conducted across selected communities in the study area. Of these, 12 soundings were carried out within sedimentary terrain, while one (1) sounding was conducted in the basement complex terrain to compare subsurface variations. The VES data were presented as sounding curves, which were analyzed using preliminary quantitative interpretation techniques, including the conventional partial curve matching method (Patra & Nath, 1998). The models derived from manual interpretation were further refined interactively using computer-based software to enhance the accuracy of the geophysical interpretations.

Surface Water Sampling

During the field data collection campaigns, six (6) surface water bodies were identified within the study area. Water samples were collected from the following rivers: Lita River; Lamudifa River; Oghon River (which includes tributaries named Oghon Leja, Oghon Woli, and Oghon Akarigbo); Omifun River; Oluwa River; Ominla River, the sample sites are shown in **Figure 2a.** Several of these rivers merge at different points to form larger water bodies. For example, the Oluwa and Ominla Rivers converge at Seba River, with the resulting water body retaining the dominant name, Oluwa River. Similarly, Oghon River changes its name based on the local community through which it flows, being referred to as Oghon Leja, Oghon Woli, and Oghon Akarigbo at different locations. It was observed that Oghon Akarigbo experiences seasonal drying, particularly during the dry season, as noted during the dry season field campaign.

In addition to these, water samples were collected upstream and downstream of the Ogian River at Lowo community and Agbabu, respectively. Samples from outside the study area were collected to serve as control samples for comparative analysis. The majority of these rivers eventually drain into the Oluwa River downstream and continue their flow into Ondo State's coastal waters.

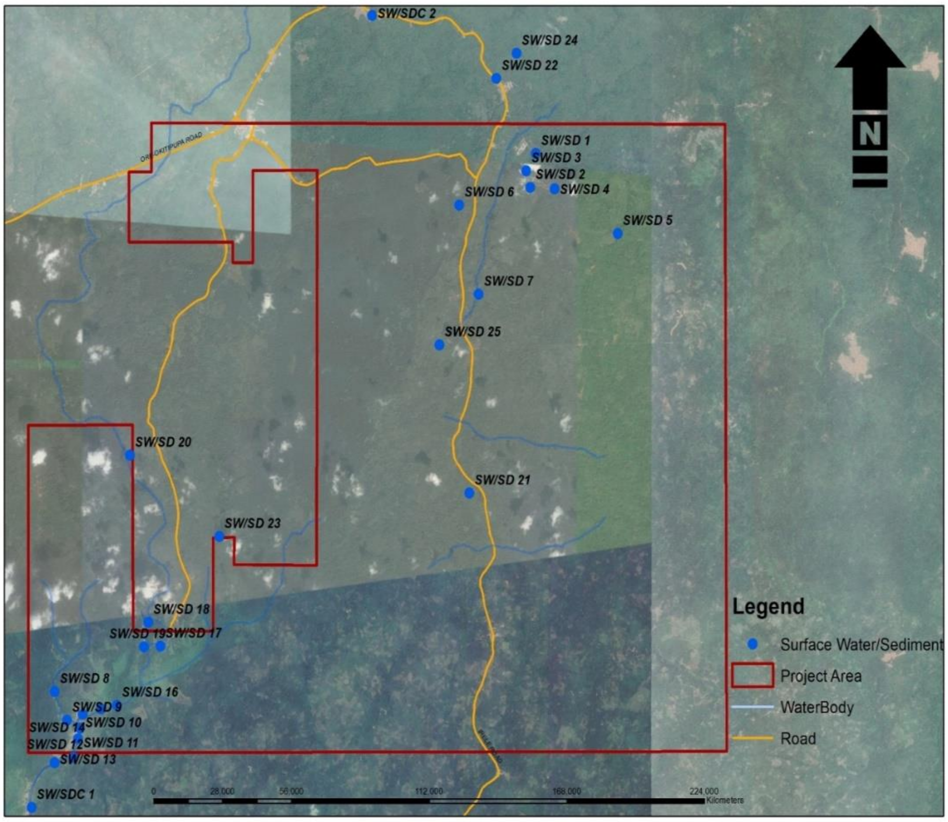


Figure 2a: Sampling Map for Surface Water and Sediment

Water Sample Collection Procedure

At each sampling station, grab water samples were collected just below the water surface at three different time intervals (every 5 minutes) and then composited to obtain a representative sample. The collected samples were preserved according to standard laboratory procedures:

i. General Physico-Chemical Parameters: Samples were collected into 2-liter pre-cleaned polyethylene bottles, which were first rinsed with the surface water before sampling.
ii. Heavy Metals Analysis: Samples were collected in 1-liter pre-cleaned polythene bottles and preserved using 2 mL of Analar grade concentrated nitric acid to maintain a pH <2.

iii Oil and Grease / Hydrocarbons: Samples were collected in 1-liter pre-cleaned glass bottles and preserved by adding 2 mL of concentrated sulfuric acid.

iv Chemical Oxygen Demand (COD): Samples were collected in 500 mL pre-cleaned glass bottles and treated with Analar grade H_2SO_4 to stabilize the organic content.

v Biochemical Oxygen Demand (BOD): Samples were collected in 300 mL amber-colored BOD bottles to prevent light interference.

vi Microbiological Analysis: Samples were collected in sterilized McCartney bottles to ensure contamination-free storage. All samples were immediately stored in a cooler with ice packs in the field and later transferred to the laboratory for further storage at 4 ±2 °C. before analysis. Several physico-chemical parameters such as water temperature, pH, dissolved oxygen (DO), electrical conductivity, and total dissolved solids (TDS) were measured in situ using portable hand-held measuring devices for real-time assessment.

Bottom Sediment Sampling

Sediment samples were taken from the bed of the surface water bodies using a hand trowel for shallow rivers and a 0.1sqm Eckman grab for the deep rivers. Twenty seven (27) sediment samples (25 + 2 controls) were collected at the same points where surface water samples were collected. Samples for physico-chemistry study were kept in polythene bags, while those for hydrocarbons and microbiology analyses were kept separately in aluminium foil. All samples were preserved in a cooler with Ice packs and transported to the laboratory for analysis.

Groundwater Sampling

Groundwater samples from existing hand-dug wells in communities within the field were sampled to represent the groundwater system in the study area shown **Figure 2b.** A hand-dug well at Lowo village, outside the project area was sampled as control station. Samples were collected and preserved as described for surface water. Also, all *in situ* measurements were conducted as described for the surface water.

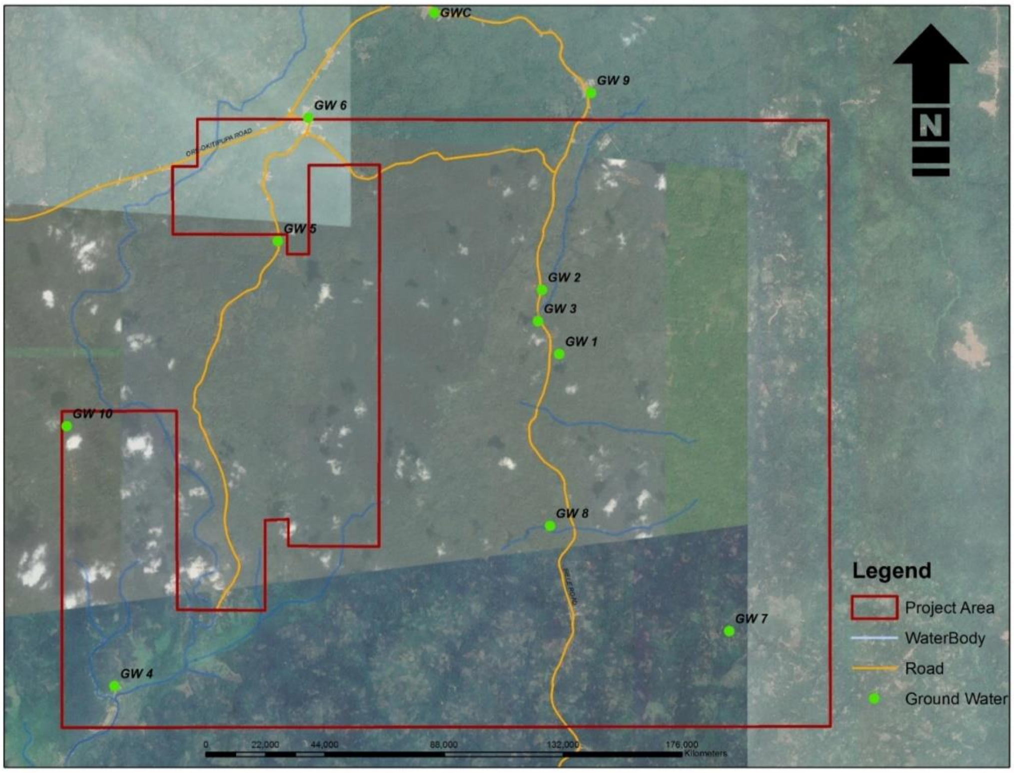


Figure 2b: Sampling Map for Groundwater

Results and Discussion

Regional Geologic Setting

The landmass of Nigeria is underlain by both the Basement Complex and Sedimentary rocks, occurring in almost equal proportion (**Figure 3**). The Basement Complex of Nigeria consists largely of Precambrian crystalline igneous and metamorphic rocks which either occur as outcrops or are concealed by variably thick superficial materials. The rocks of the Basement Complex of Nigeria have been described in detail in various publications (Oyawoye, 1972, Ajibade, 1976, Rahaman, 1976, Oluyide, 1988, Obaje, 2009). About ten sedimentary basins are present in Nigeria, including the Dahomey basin underlying the southwestern segment of Nigeria.

Local Geologic Setting

The sedimentary rocks of Eastern Dahomey Basin or the Nigeria sector of the basin contains extensive wedge of Cretaceous to Recent sediments, up to 3000 m, which thicken towards the offshore. The basin consists of conglomerates and grits at base and in turn overlain by coarse-to-medium sediments. Omatsola and Adegoke (1981) proposed the Cretaceous sequence in the eastern Dahomey basin as beginning with the Abeokuta Group, made up of three formations: Ise, Afowo and Araromi Formations. The Ise Formation unconformably overlies the basement complex of southwestern Nigeria and consists of conglomerates, and grits at base and in turn overlain by coarse-to-medium grained sands with interbedded Kaolinite. The conglomerates are unimplicated and at some locations contain ironstones. The age is Neocomian to Albian.

Overlying the Ise Formation is the Afowo Formation, which composed of coarse to medium grained sandstones with variable but thick interbedded shales, siltstones and claystones. The sandy facies are tar-bearing, while the shales are organic-rich (Enu, 1990). The lower part of this formation is transitional with mixed brackish to marginal horizons that alternate with well-sorted, sub-rounded sands indicating a littoral or estuarine near-shore environment of deposition. Using palynological assemblage, Billman (1992) assigned a Turonian age to the lower part of this Formation, while the upper part ranges into the Maastritchian.

Araromi Formation overlies the Afowo Formation and has been described as the youngest cretaceous sediment in the eastern Dahomey basin (Omatsola and Adegoke, 1981). It is composed of fine to medium-grained sandstone at the base, overlain by shales, siltstone with interbedded limestone, marl and lignite. This Formation is highly fossiliferous containing abundant planktonic Foraminifera, Ostracods, pollen and spores. Omatsola and Adegoke (1981) assigned a Maastritchian to Paleocene age to this formation, based on faunal content. The bitumen belt in Ondo State is underlain by the sedimentary rocks of Dahomey basin (**Figure 4**). This portion of the basin is often referred to as the Eastern Dahomey basin.

The Ewekoro Formation overlies the Araromi Formation in the eastern Dahomey basin. It is an extensive limestone body, which is traceable over a distance of about 320 km from Ghana in the west, towards the eastern margin of the Dahomey basin in Nigeria (Jones and Hockey, 1964). Elueze and Nton (2004), has reported that the limestone is of shallow marine origin, owing to abundance of coralline algae, gastropods, pelecypods, echinoid fragments and other skeletal debris. It is Paleocene in age. Overlying the Ewekoro Formation is the Akinbo Formation, which is made up of shale and clayey sequence (Ogbe, 1972). The claystones are concretionary and are predominantly Kaolinite (Elueze and Nton, 2005). The base of the Formation is defined by the presence of glauconitic band with lenses of limestone (Ogbe, 1972; Nton, 2001). The Formation is Paleocene to Eocene in age.

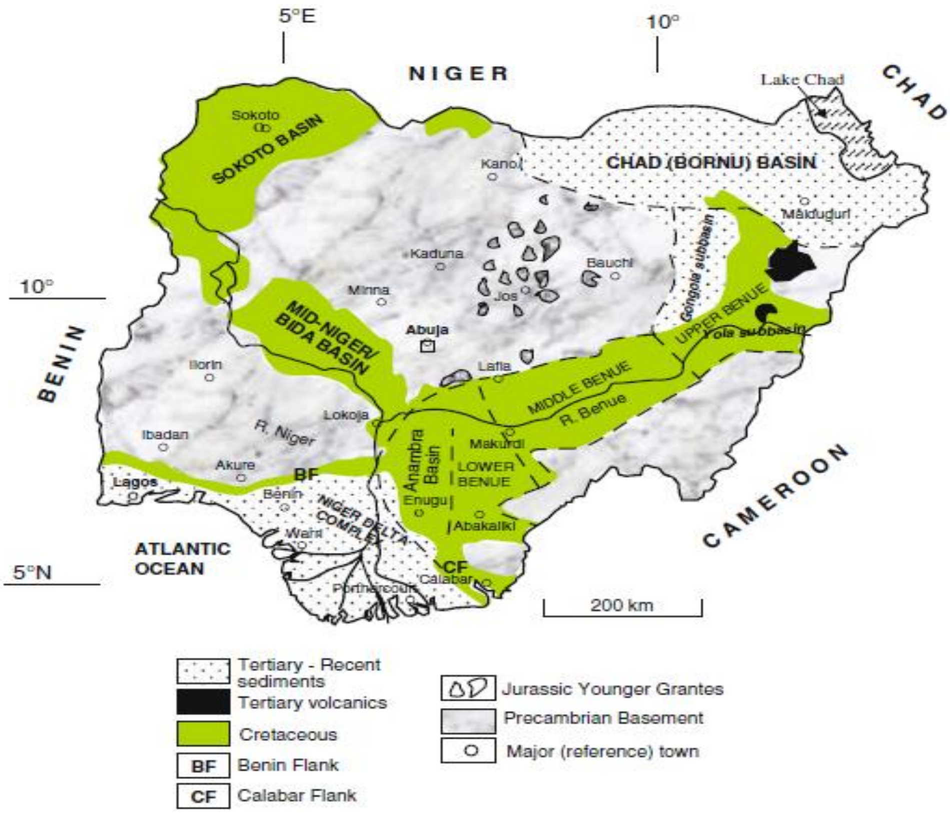


Figure 3: Simplified Geological Map of Nigeria (*Source: Obaje, 2009)*

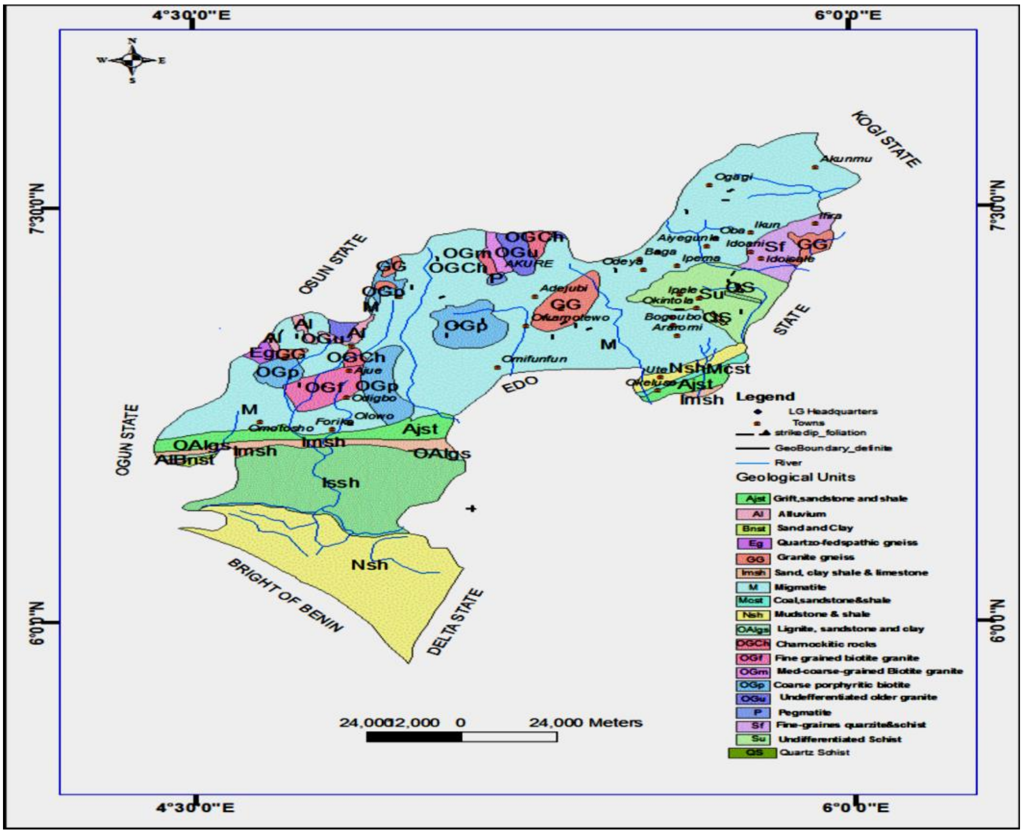


Figure 4: Geological Map of Ondo State

The Oshosun Formation overlies the Akinbo Formation and consists of greenish grey or light brown clay, and shale with interbeds of sandstones. The shale is thickly laminated and glauconitic. According to Okosun (1998), the basal beds consist of the following facies: sandstones, mudstones, claystones, clay-shale or shale. This Formation is phosphate-bearing (Jones and Hockey, 1964; Nton, 2001). The Ilaro Formation overlies conformably the Oshosun Formation and consists of massive yellowish, poorly consolidated, cross-bedded sand stones. The youngest stratigraphic sequence in the eastern Dahomey basin is the Benin Formation. It is also known as the Coastal Plain Sands (Jones and Hockey, 1964) and consists of poorly sorted sands with lenses of clays. The sands are in parts cross-bedded and show transitional to continental characteristics. The age is from Oligocene to recent.

Hydrogeologic Setting

The subsurface geology in the sedimentary terrain reveals two major lithologies: sand and clay deposits. These major deposits are interbedded in places with sandy clay or clayey sand. Studies, including litho-stratigraphic correlation of recently drilled boreholes in parts of the basin (Longe et al., 1987, Omosuyi et al., 1999) delineated similar sequence of alternating succession of sand and clay horizon. The sand layers are considered the aquifer units while the clay constitutes impermeable barriers (aquiclude). Jones and Hockey (1964), Omatsola and Adegoke (1981) and Ako (1982) believe that the basal Abeokuta Group, the sands of the Benin Formation and the Coastal Alluvium equally constitute important aquifers in the area. Borehole lithostratigraphic correlation of some existing boreholes in the area (Omosuyi et al., 1999) delineated alternating sequence of sand and clay with variable thicknesses in the upper 300 m of the subsurface geology. The study also delineates three major aquifer horizons in the zone underlain by the Benin Formation and two major aquifers in the area underlain by Alluvium. Groundwater exists under artesian and sub-artesian conditions in the area. The extensive Coastal Plain Sands or the Benin Formation is frequently believed to be a valuable reservoir of groundwater in the Dahomey basin.

Hydraulic Parameters

Information relating to hydraulic parameters in the area is very scanty. Ako (1982) reported that borehole yields range between 45 – 92 m^3/h in the area underlain by the Benin Formation. Transmissivity also varies between 3.0 x 10^{-4} m^2/sec and 1.2 x 10^{-3} m^2/sec. In the area underlain by Alluvium, borehole yields vary between 3.9 m^3/h and 114.8 m^3/h (Ako, 1982).

Static Water Level and Groundwater Head

Borehole production data from the area show static water level varying between 23 m and 35 m in the area underlain by the Benin Formation, and 0 m (ground level) and 20 m in the area underlain by coastal Alluvium. This indicates that static water level generally varies between 0 m and 35 m across the area. Recent studies show that groundwater head levels are higher in the transition zone and lower in the southern parts underlain by Alluvial deposits. Since groundwater generally flows from high to low hydraulic head (Freeze and Cherry, 1979), it follows that the overall groundwater flow direction in the area is North-South.

Geophysical Investigation

Vertical Electrical Soundings (VES) were conducted across thirteen (13) communities in the area (**Table 1**). ***Geophysical (Geoelectric) Characteristics;*** The VES curves are the KQH, AK, QQH, KQQ, AKQ, AAA, AKH and HKH types. The KQH and AK curves constitute 30.8% and 23.1% respectively while each of the remaining type constitutes 7.6%. The AK curve type reflects four layer subsurface sequence, while the remaining types reflect five-layer subsurface sequence in which there is either progressive decrease in resistivity from the first to the second/third layer and subsequent increase in the resistivity of 4th layers (as in QQH), while in KQQ, there is increase in resistivity of the 1st, 2nd and 3rd layers but a decrease in resistivity of the 4th and 5th layers respectively.

Geoelectric Parameters/Columnar Sections.

The interpretation results of the VES data (according to Location) are presented in Table 1. Columnar sections showing geoelectric layers relating geoelectric parameters across the VES locations in the area are shown in **Figure 5**. The sections display subsurface sequence of five geoelectric layers across the surveyed locations. The geoelectric parameters are described as follow:

1st Layer: Topsoil
Resistivity range: 45 - 1378 ohm-m
Thickness: 0.6m - 2.6m

2nd Layer: Layer underlying the topsoil
Resistivity range: 153 - 863 ohm-m
Thickness range: 0.9m - 14.5m

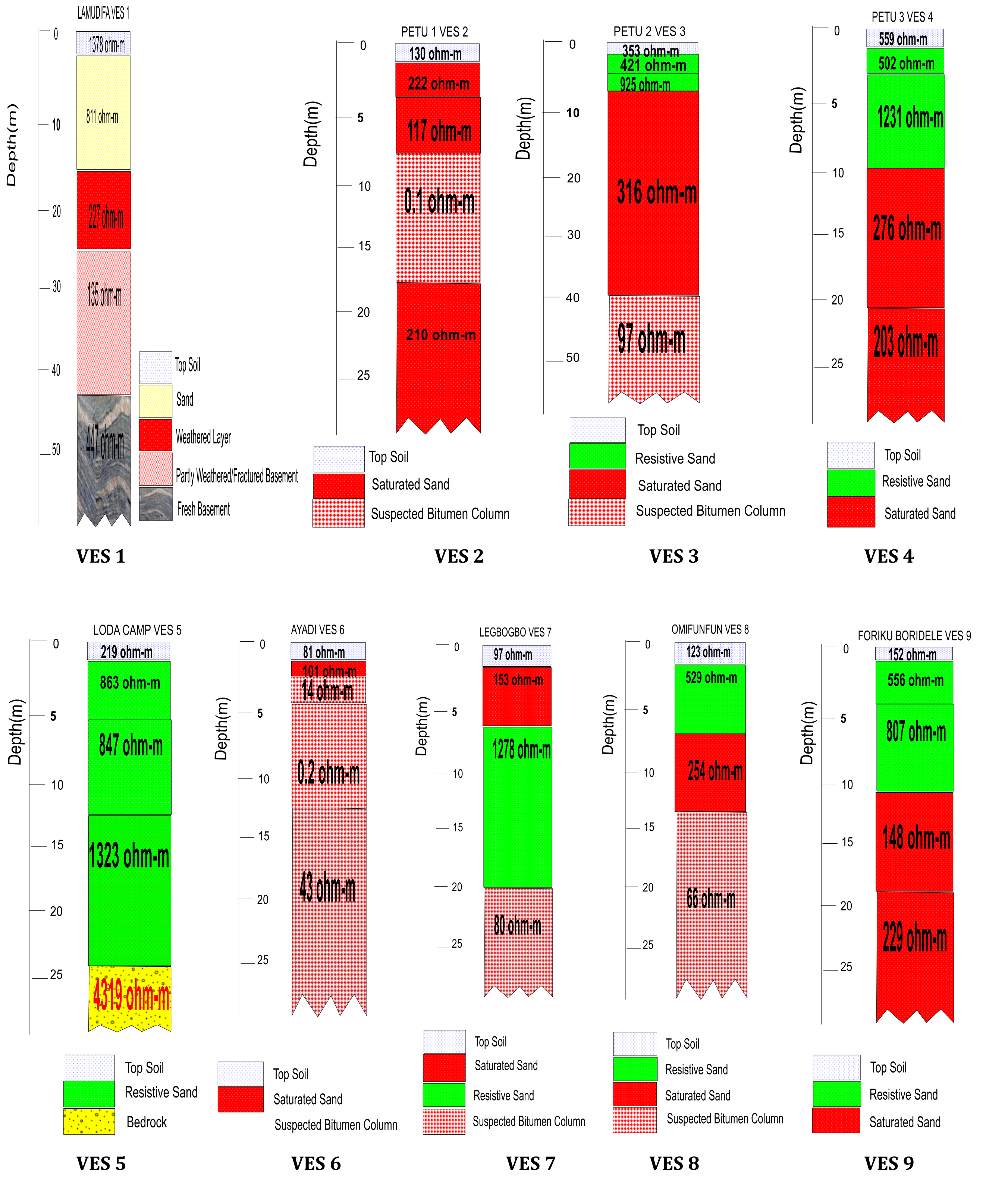
3rd Layer: Sand Layer/Suspected Bitumen in some locations
Resistivity range: 96 - 2491 ohm-m
Thickness range: 1.7m - 14.9m.

4th Layer: Sand Layer/Suspected Bitumen in some locations
Resistivity range: 3.2- 1323 ohm-m
Thickness range (where delineated): 6.4m - 33.5m.

5th Layer: Sand/Bitumen (in some locations):
Resistivity: 30- 506 ohm-m

Table 1: VES Interpretation Results

VES NO	LOCATION	COORDINATES	THICKNESS (m) $D_1/d_2/d_3/\ldots\ldots d_n$	RESISTIVITY (Ω m) $\rho_1\rho_2\ \rho_3\ldots\ldots\rho_n$
1	Lamudifa	N06⁰ 40.523' E004⁰ 54.159'	0.8/14.5/14.9/13.2	**1377.7/811.3/226.5/134.8/446.7**
2	Petu 1	N06⁰ 39.611' E004⁰ 54.678'	1.0/2.4/3.5/10.9	**130.1/222.3/117.0/88.4/209.6**
3	Petu 2	N06⁰ 39.508' E004⁰ 54.630'	0.6/0.9/4.4/33.5	**302.9/420.7/920.1/315.0/97.2**
4	Petu 3	N06⁰ 39.657' E004⁰ 54.662'	0.7/1.4/8.1/18.1	**558.9/592.0/1231.1/276.0/203.1**
5	Loda Camp	N06⁰ 39.795' E004⁰ 53.519'	1.0/4.4/12.7/6.4	**219.4/862.9/846.8/1323.5/4318.6**
6	Ayadi	N06⁰ 38.300' E004⁰ 53.556'	0.5/1.1/1.7/9.0	**80.5/91.1/13.9/3.2/42.7**
7	Legbogbo	N06⁰ 35.180' E004⁰ 5.731'	2.8/3.1/14.0	**97.3/153.3/1277.7/79.7**
8	Omifunfun	N06⁰ 33.748' E004⁰ 53.858'	2.1/4.6/6.4	**123.8/528.5/253.5/66.6**
9	Boridele (Forikun)	N06⁰ 40.103' E004⁰ 50.344'	0.9/3.7/5.7/8.2	**152.2/556.0/807.0/148.4/229.1**
10	Mulekangbo	N06⁰ 39.409' E004⁰ 50.492'	0.9/4.1/12.1/7.5	**418.8/759.2/86.4/43.8/136.1**
11	Likaju	N06⁰ 36.864' E004⁰ 48.176'	2.2/2.1/7.0	**44.9/238.0/826.0/11.6**
12	Arefun	N06⁰ 34.656' E004⁰ 56.173'	Noisy data	
13	Lonla Camp	N06⁰ 38.334' E004⁰ 54.807'	0.8/3.4/6.9/10.6	**57.7/382.8/18.6/10.5/29.5**


LAMUDIFA VES 1
Depth(m)
0
10
20
30
40
50
1378 ohm-m
811 ohm-m
227 ohm-m
135 ohm-m
447 ohm-m
Top Soil
Sand
Weathered Layer
Partly Weathered/Fractured Basement
Fresh Basement
VES 1
PETU 1 VES 2
Depth(m)
0
5
10
15
20
25
130 ohm-m
222 ohm-m
117 ohm-m
0.1 ohm-m
210 ohm-m
Top Soil
Saturated Sand
Suspected Bitumen Column
VES 2
PETU 2 VES 3
Depth(m)
0
10
20
30
40
50
353 ohm-m
421 ohm-m
925 ohm-m
316 ohm-m
97 ohm-m
Top Soil
Resistive Sand
Saturated Sand
Suspected Bitumen Column
VES 3
PETU 3 VES 4
Depth(m)
0
5
10
15
20
25
559 ohm-m
502 ohm-m
1231 ohm-m
276 ohm-m
203 ohm-m
Top Soil
Resistive Sand
Saturated Sand
VES 4
LODA CAMP VES 5
Depth(m)
0
5
10
15
20
25
219 ohm-m
863 ohm-m
847 ohm-m
1323 ohm-m
4319 ohm-m
Top Soil
Resistive Sand
Bedrock
VES 5
AYADI VES 6
Depth(m)
0
5
10
15
20
25
81 ohm-m
101 ohm-m
14 ohm-m
0.2 ohm-m
43 ohm-m
Top Soil
Saturated Sand
Suspected Bitumen Column
VES 6
LEGBOGBO VES 7
Depth(m)
0
5
10
15
20
25
97 ohm-m
153 ohm-m
1278 ohm-m
80 ohm-m
Top Soil
Saturated Sand
Resistive Sand
Suspected Bitumen Column
VES 7
OMIFUNFUN VES 8
Depth(m)
0
5
10
15
20
25
123 ohm-m
529 ohm-m
254 ohm-m
66 ohm-m
Top Soil
Resistive Sand
Saturated Sand
Suspected Bitumen Column
VES 8
FORIKU BORIDELE VES 9
Depth(m)
0
5
10
15
20
25
152 ohm-m
556 ohm-m
807 ohm-m
148 ohm-m
229 ohm-m
Top Soil
Resistive Sand
Saturated Sand
VES 9

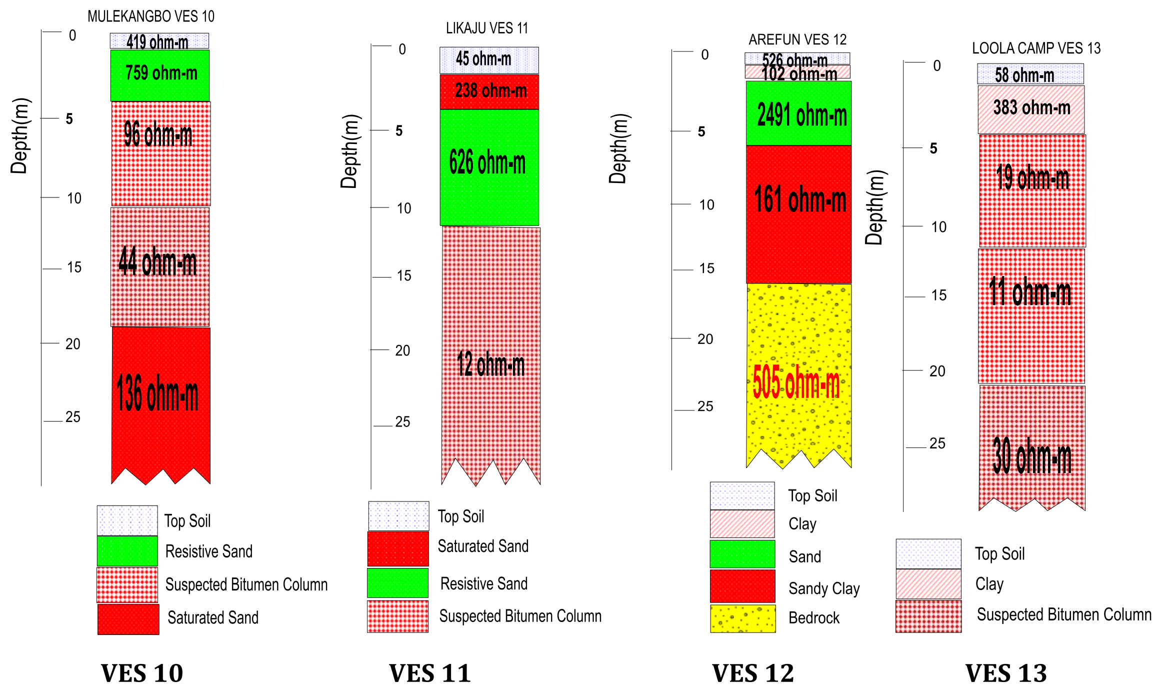


Figure 5: Columnar sections showing geoelectric layers in part of the Bitumen Belt (VES 1-13)

Aquifer Delineation

Electrical resistivity methods primarily reflect variations in ground resistivity. The electrical resistivity contrasts existing between lithological sequences in the subsurface are often adequate to enable the delineation of geoelectric layers and identification of aquifer and non-aquifer units in the area. Studies across Okitipupa/Irele/Odigbo sedimentary area (Omosuyi et al., 2008) have shown that two/three aquifer horizons occur across the area- the upper/superficial, the intermediate and the lower aquifers. The depth to the top of the upper aquifer varies from 16 m to 62 m (**Figure 6a**) while that of the intermediate aquifer ranges from about 28 m to 97 m across the area (**Figure 6b**). The two aquifer horizons generally deep southward in the area.

Groundwater Vulnerability

In the evaluation of aquifer vulnerability, the thickness, the nature of lithological and the geoelectric parameters of the materials overlying the aquifer unit are of important consideration. If the overlying materials are significantly thick, then the underlying aquifer may be significantly protected and consequently not vulnerable to contaminants. If the lithology is lateritic (near nil porosity, low permeability), or clayey (not porous), the aquifer is equally protected and not vulnerable. In addition, the protective capacity of the materials overlying the aquifer(s) is assumed to be proportional to its thickness and inversely proportional to its hydraulic conductivity (Henriet, 1976). However, high clay contents generally correspond with low resistivities and low hydraulic conductivities. Hence, the protective capacity of the materials overlying the aquifer(s) can be considered as being proportional to the longitudinal unit conductance (S), defined as the ratio of the thickness of material overlying the aquifer to the resistivity. In essence, the higher the longitudinal conductance value, the higher is the protective capacity, while low values suggest that the underlying aquifer is vulnerable. The longitudinal conductance value(s) of the materials overlying the aquifer units (where delineated) in the area are shown in **Table 2**.

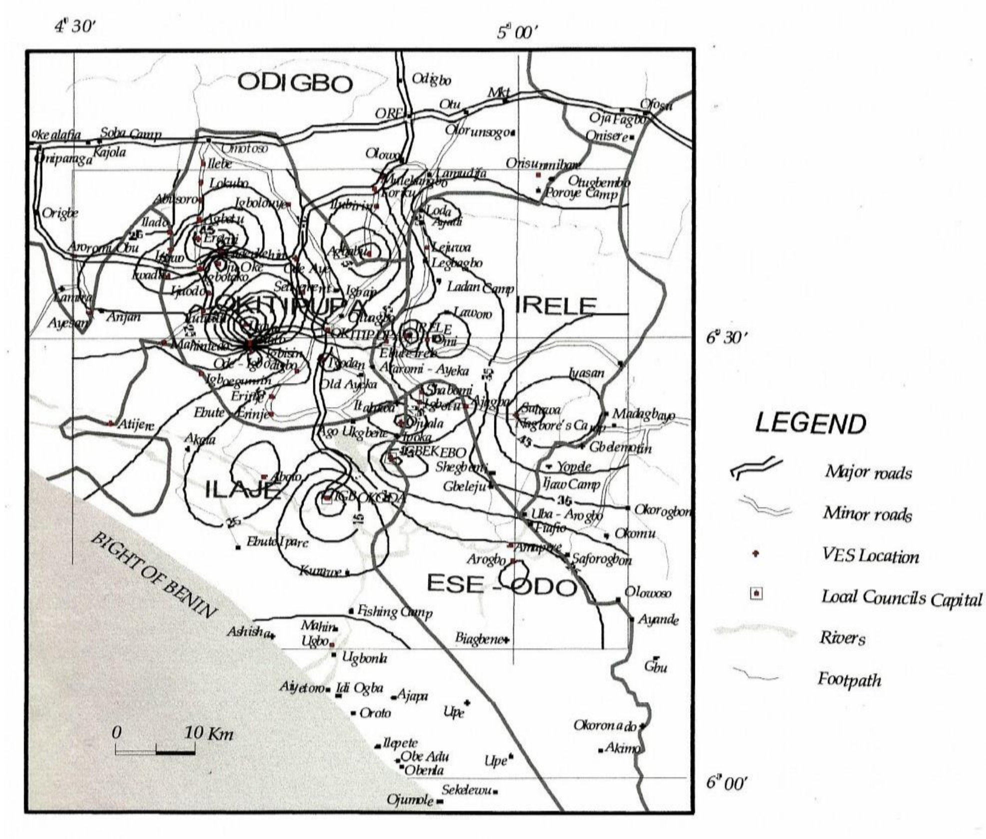


Figure 6a: Depth to the Top of Upper Aquifer in the Area (Omosuyi et al., 2008)

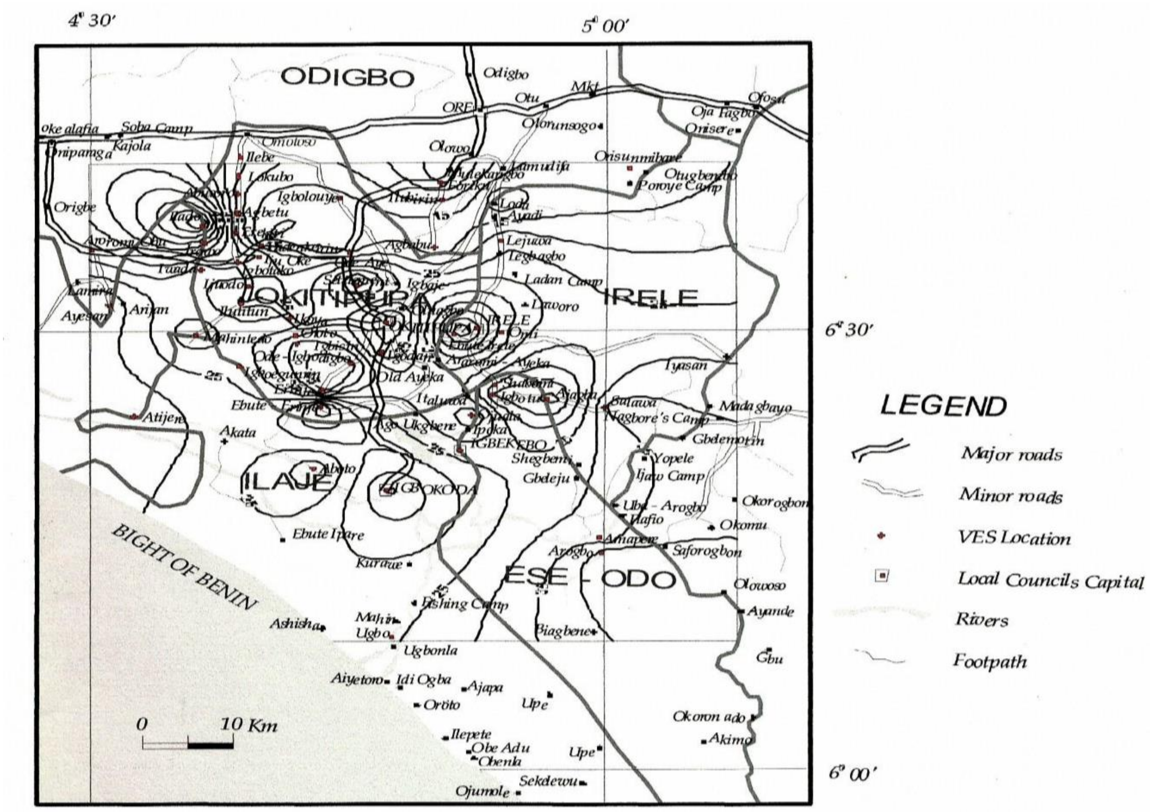


Figure 6b: Depth to the Top of Intermediate Aquifer in the Area (Omosuyi et al., 2008)

Table 2: Table showing Longitudinal conductance values and aquifer protective capacity at the VES locations

VES No	*Longitudinal Conductance (mhos)*	*Protective Capacity*
Lamudifa	0.08424	Fair
Petu 1	0.12031	Fair
Petu 2	0.11524	Fair
Petu 3	0.01020	Weak
Boridele	0.02253	Weak
Legbogbo	0.05790	Poor

The aquifer systems in the area are weakly to fairly protected as shown in **Table 2**, based on the rating of Henriet (1976). Consequently, the aquifer units in the area are not significantly protected from pollutants or contaminants entrained by fluids infiltrating from the surface.

Groundwater-Bitumen Interaction

Investigations have shown that bitumen occurs at both shallow and greater depths in the area. It has also been observed that the upper aquifer layer occurs mostly above the bitumen layers, although bituminous shale has been delineated at shallow depths of about 1.2 m (at Ode Aye). This suggests intercalation of aquifer and bitumen horizons in the area. Where there is interaction of bitumen with groundwater, the groundwater and the sand containing the groundwater are vulnerable to contamination.

Conclusion

This study highlights the potential vulnerability of groundwater in bitumen-rich areas due to geological conditions and human activities. The protective capacity of overlying materials was assessed, revealing that areas with low longitudinal conductance values are highly vulnerable to contamination. Findings indicate that bitumen deposits and groundwater-bearing units are intercalated, increasing the risk of hydrocarbon migration into aquifers. Given these findings, regular groundwater monitoring is crucial to track contamination risks and ensure safe drinking water for local communities. Future research should focus on hydrocarbon migration patterns, the impact of bitumen extraction on groundwater chemistry, and the implementation of mitigation strategies such as well casing, water treatment, and sustainable mining practices. To protect groundwater quality in the long term, strict environmental regulations, community awareness programs, and the adoption of best mining practices must be enforced in bitumen exploration regions.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Credit Authorship Contribution Statement

All authors contributed equally.

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