Evaluation of aquifer protective capacity and soil corrosivity in Okerenkoko, Warri-Southwest, Delta State, using one-dimensional resistivity inversion

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***Abstract*: Thirty (30) Vertical electric soundings (VES) were acquired in Okerenkoko community Warri-Southwest, Delta State, to evaluate the protective capacity and soil corrosivity of the area which falls within the oil producing communities in the Niger Delta. Evaluation of longitudinal conductance of the area showed areas with poor (< 0.1 mho), weak (0.1-0.19 mho), good (0.7-4.9 mho), very good (5-10.0 mho) and excellent (> 10.0 mho) protective capacities. The study has shown that the protective capacity of most parts of the community were rated excellent, very good and good, hence aquifers in these areas are protected from contamination by oil spillage in the event of pollution, while areas with weak and poor protection capacity are susceptible to groundwater contamination from surface spills and other near surface phenomena. Soil corrosivity evaluation from VES data indicated the presence of slightly corrosive, moderately corrosive and practically noncorrosive materials in the subsurface. The areas with slight and moderate corrosivity are prone to pipeline failure. Therefore, environmental management programs should be considered in the area for the protection of the aquifer system in the community. This study serves as a useful guide for location of subsurface aquifers and their protection capacity distributions throughout the study area. This will assist in planning of exploration programs for sitting of groundwater production wells in the area.**

***Keywords:* Aquifer protection; longitudinal unit conductance; Corrosivity; Vertical electrical sounding (VES); Resistivity inversion.**

I. INTRODUCTION

Groundwater is water in a saturated cavity beneath the surface of the earth. The source of groundwater is mainly derived from the precipitation and humidity that percolates and permeates the subsoil [1]. This is only available if the rocks in the vadose/saturated zone are permeable enough to drain large amounts of water into wells, springs, or streams. Its availability, amount, and exploitability depend on the porosity and permeability of the host rock containing it. Both parameters play important roles in the practice of groundwater extraction [2]. Water is one of the most important natural resources on earth that support the existence of life. For this reason, the world has celebrated World Water Day every year on March 22nd since 1993, emphasizing the importance of freshwater [3]. While there is a strong demand for groundwater exploration and mining, the current social demand is not only to discover new groundwater resources but also to protect them. The drinkability/usability of groundwater can be contaminated by leachate from landfills, saltwater intrusion, oil pollution, mining activities, and wastewater (from toilets, oil-lined pipelines, and septic tanks) [4]. Landfills and toilets are often constructed without consideration of the hydrogeological conditions of the area, thereby jeopardizing the fate of groundwater [5]. In the Niger Delta region, oil spillage is a major environmental hazard caused by crude oil exploration in the region and constitutes serious social problems in Nigeria, especially in the oil-producing communities. Oil spills are caused by vandalism of pipelines and storage facilities, pipeline corrosion, human error, equipment failure, and sabotage, pigging operations; flowline replacement; flow station upgrades; tank rehabilitation, and natural phenomena such as heavy rainfall, flooding, falling of trees and lightening [6, 7]. Oil spills on land have resulted in the loss of arable land and soil fertility, loss of biodiversity, and contamination of surface and groundwater resources. The study area `Okerenkoko` in Gbaramatu kingdom Warri south in Delta State which hosts the famous Nigeria Maritime University, is an oil-producing community in the Niger Delta, has had its own share of environmental pollution/degradation caused by ceaseless exploration and oil embezzlement (bunkering) activities. Whether intentionally disposed of or accidentally spilled to the ground, some of these oil spills can eventually infiltrate into the groundwater and contaminate it, and because of their relative stability in groundwater, such contamination can pose a serious threat to public health. Today, the number of wells drilled by governments, non-governmental organizations and individuals is increasing. This clearly shows that groundwater is effectively a supplement to other sources of water in the country. Therefore, this study aims to use one-dimensional resistivity inversion to assess the protective capacity of aquifer units and soil corrosivity of buried metal pipelines and concrete in the study area.

Soil corrosivity is a geological hazard that affects buried metals and concrete in direct contact with soil and bedrock. It leads to the failure of underground oil and gas transmission lines, which are the main cause of hydrocarbon pollution in oil-producing areas.

Conventional methods for characterizing a protective layer include drilling test holes and analyzing drill logs solely for the purpose of characterizing the thickness and/or lateral spread of the protective layer. The disadvantage of such inspections is that they can be labor intensive and costly [8].

Surface geophysical measurement is an inexpensive, non-invasive method that can be used to study the protection capacity of an area. Henriet [9] found that the combination of layer resistivity and thickness of Dar Zarrouk variables S (longitudinal conductance) and T (transverse/lateral resistance) can be used directly for aquifer protection studies and evaluation of aquifer hydrological properties. The ability of a clayey aquifer to protect the load of overburden sediments is proportional to its longitudinal conductance S, which has a temporal dimension (such as permeation time) in terms of aquifer protection. The protection capacity is believed to be proportional to the unit longitudinal conductivity in Mho [10, 11, 12, 13]. The use of surface geophysical measurements in both groundwater resource mapping and water quality assessment has recently been dramatic due to the rapid advances in numerical modeling software programs associated with microprocessors used to simulate large volumes of geophysical data. [14, 15]. The 1D electrical method, commonly known as Vertical Electrical Exploration (VES), has proven to be very popular in groundwater conservation studies due to the simplicity of the technique.

II. LOCATION AND GEOLOGICAL SETTING OF THE STUDY AREA

Okerenkoko community is located in the Kingdom of Gbaramatu in the Warri-south local government area of Delta State (Ijaw-ethnic group). Okerenkoko is sited between latitude 05^{0}37’39.22” to 05^{0}37’10.12”N and longitude 005^{0}23’30.64” to 005^{0}23’08.79”E. It is located within the coastal creeks between the Benin River and the Escravos River (Figure 1) that links Warri and Escravos. Vegetation is characterized by mangrove forests and rainforests. The Mangrove swamps are low, generally less than about 5 m above sea level, with tides and crisscrossed tides. Politically, the Ijaw ethnic group is made up of four oil-producing communities (Gbaramatu, Isaba, Ogbe-ijoh, and Oporoza). This local government boasts of the largest proven oil and gas reserves in Delta State and in the Niger Delta. The permanent campus of Nigeria Maritime University is located in Okerenkoko, and also has a take-off campus at Kurutie community also in Gbaramatu Kingdom.

Given the abundance of natural resources, the local governments have been heavily affected in recent years by resource depletion and community conflicts. The communities at one time or the other have experienced major oil spillage due to pipeline vandalization and other causes that destroyed plants and aquatic life thereby affecting the ecosystem and possibly the groundwater [16]. The local population protested against oil spill allegedly from the facilities of a multinational oil-giant in the area, adding that it should among other things provide the communities with portable drinking water, relief materials and adequately compensate the people for their loss [17]. However, in recent times, it has emerged a safe place for business and development. Warri South-West local government has an estimated land area of 1,722 km^2 (665 sq mi) and is the home to the Itsekiri and Ijaw ethnic groups in Delta State.

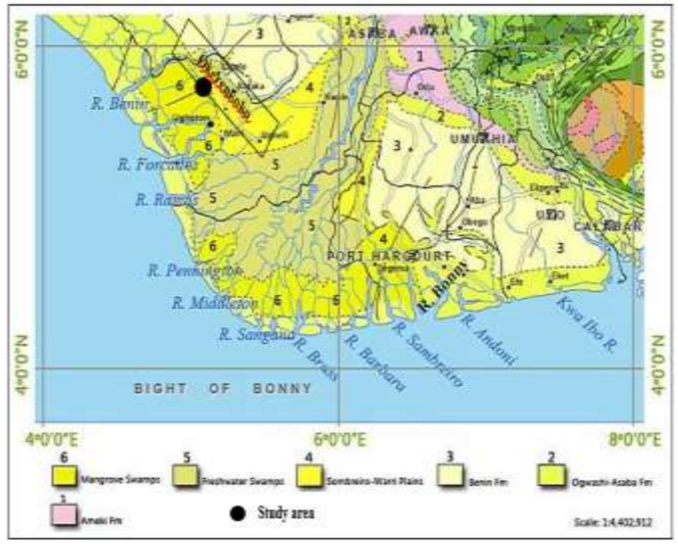


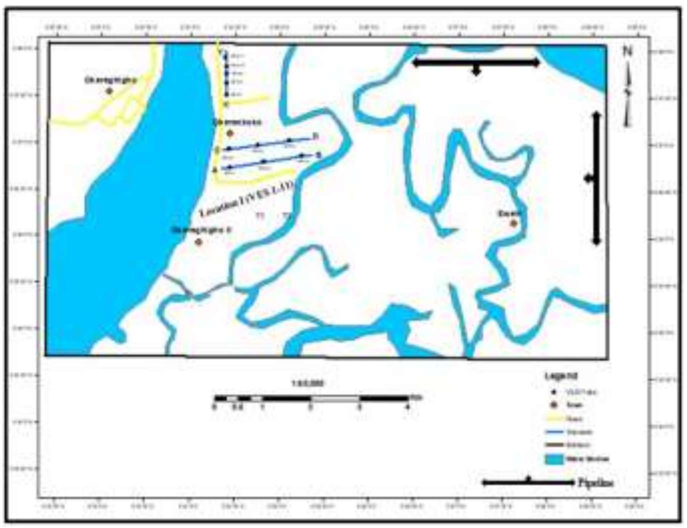
Figure 1: Geological map of the Niger Delta region showing the areal distribution of mangrove swamps and the Benin Formation (Adapted from NGSA [18]).

The geology of the area Okerenkoko in Warri-south is located in the Niger Delta, and the geology of this area has been studied by a number of researchers [19, 20, 21]. The Stratigraphic formations in the Niger Delta basin comprises of Benin, Agbada and Akata formations. Typical sections of these formations are summarized in [21] and other reports such as [22, 23]. The Akata Formation comprises mostly of marine shale and sand layer, and its subsoil consists of dark gray sand and shale. The thickness of this Formation is estimated to be more than 7,000 m [22]. The upper Agbada Formation is a series of sandstone and shale-deposits [24]. It consists of the upper part mainly sand with a small number of shale and lower end containing shale. The thickness is over 3,700 m. The upper layer of Benin is covered in many places by thin laterite layers of varying thickness, but is much more exposed near the coast.

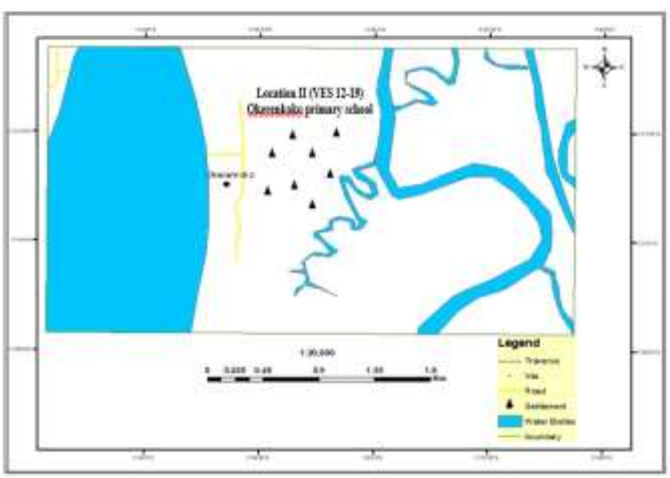
III. METHODOLOGY

Electrical resistivity method adopting the one-dimensional resistivity technique was employed in this study. The technique measures vertical changes in resistivity as a function of depth. The PASI-16GL model resistivity meter was employed for field data acquisition. The Schlumberger-depth sounding technique was adopted for data collection because of its susceptibility to near-surface inhomogeneities [25, 26]. This method delineates contaminated zones of groundwater, capable of discriminating subsurface structures' precisely (in terms of their resistivity and thickness) with respect to depth, profound depth of penetration and it requires less labour.

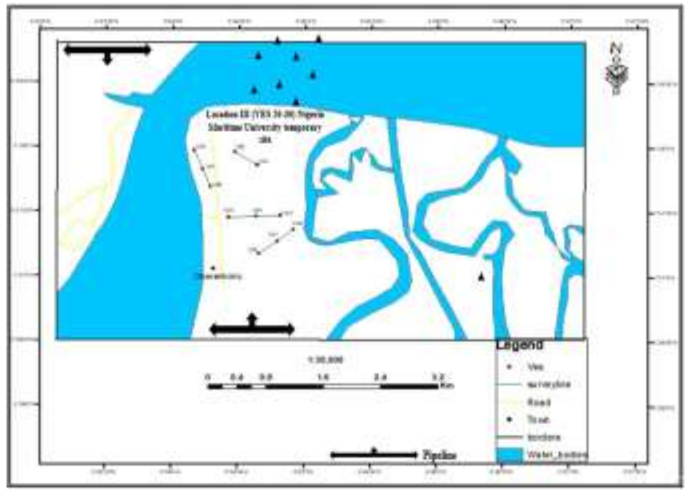
In this study the maximum current electrode spacing varied from 300 m to 500 m in order to obtain shallow and deep layers. A total of thirty (30) vertical electrical sounding (VES) were carried out in three different locations within the community: eleven (VES 1 to 11) in location I within the community, eight (VES 12 to 19) in location II in Okerenkoko primary school and eleven (VES 20 to 30) in location III inside the Nigeria Maritime University temporary site in Okerenkoko. In each case the GPS (geographical positioning satellite) of each sounding point was recorded in degree, minute and second (DMS). The data acquisition maps for locations I, II, and III are shown in (Figure 2a, b, c).



(a). Map of study location-I in Okerenkoko, showing the eleven (11) VES stations occupied along three (3) traverses which were is close to the coastline.



(b). Map of study location-II in Okerenkoko, showing the eight (8) VES stations occupied within the primary school premises.



(c). Map of Study location-III at Nigeria Maritime University temporary site in Okerenkoko. Eleven (11) VES stations (VES 20 to 30) were sounded within the university premises and at the staff quarters.

Figure 2 (a, b, c): Data acquisition maps of study locations I, II, and III in Okerenkoko, Warri South, Nigeria.

Geophysical data processing and inversion

VES data was processed using the manual-curve fitting method to obtain curves of resistivity models, that were later curve-fitted to the auxiliary and master curves and layer parameters obtained was entered into Win-Resist computer program [27] and interpreted quantitatively to obtain the one-dimensional resistivity model parameters (which are thickness and layer resistivity), from which the curve type for each VES point were inferred from the four (4) standard curves: **A**-curve ($\rho1<\rho2<\rho3$), **Q**-curve ($\rho1>\rho2>\rho3$), **K**-curve ($\rho1<\rho2>\rho3$) and **H**-curve ($\rho1>\rho2<\rho3$).

Quantitative interpretation of VES data generated the layer parameters (thickness and layer resistivity) also known as the first-order geoelectric parameters (the layer thickness hi and the layer resistivity ρ_i) for the i_{th} layer. These first-order geoelectric parameters were utilized to derive longitudinal unit conductance (S_i) of all the geoelectric layers, also known as a second-order geoelectric parameter [28].

The total longitudinal conductance was computed using the expression:

$$\sum_{i=1}^{n} \frac{h_i}{\rho_i} \qquad (1)$$

The overburden protective capacity of the area was deduced using the total longitudinal unit conductance values obtained in Eqn. 1 for each VES point [9, 11]. The protective capacity of the area was evaluated using Oladapo and Akintoriwa [29] rating (in Table 1) which enables the classification of aquifer protective capacity into poor, weak, moderate, good, very good or excellent. Areas in the community rated poor, weak or moderate, are susceptible to contamination from near surface pollution events.

Table 1. Longitudinal conductance / protective capacity rating (after Oladapo and Akintoriwa [29]).

Total longitudinal unit conductance (mhos)	Overburden protective capacity classification
<0.10	Poor
0.1-0.19	Weak
0.2-0.69	Moderate
0.7-4.9	Good
5-10	Very good
>10	Excellent

The soil corrosivity in the study area was also determined using the first layer resistivity values (top-soil) and evaluation based on [11, 30, 31] classification scheme shown in Table 2.

Table 2. Classification of soil resistivity in terms of corrosivity (Baeckmann and Schwenk [30]; Agunloye [31]; Oladapo et al., [11]).

First layer soil resistivity (Ω-m)	**Soil corrosivity rating**
< 10	Very strongly corrosive (**VSC**)
10-60	Moderately corrosive (**MC**)
60-180	Slightly corrosive (**SC**)
≥ 180	Practically non-corrosive (**PNC**)

IV. RESULT AND DISCUSSION

Table 3 summarizes the results of VES interpretation, longitudinal conductance of the overburden aquifer unit calculated for VES 1-30, soil corrosivity and curve type in the study area. The curve types are K and Q dominant (Table 3). The longitudinal conductance values in Table 3 were used to generate a protective capacity map using SURFER-13 terrain and 3-D surface modeling software [32] using the advanced contour level option. In the advanced contour level option of SURFER-13 program, the contour lines are made invisible and filled with diagnostic colors used to distinguish the various longitudinal conductance/protective capacity rating based on Oladapo and Akintoriwa [29] as shown in Table 1. Figure 3 is the 3D distribution map of longitudinal conductance of the study area (Okerenkoko), it shows the 3D surface distribution of the longitudinal conductance values computed for the study area (Table 3). The longitudinal conductance map was color coded in Figure 4 to distinguish areas with excellent protective capacity (>10 Mho), very good protective capacity (5-10 Mho), good protective capacity (0.1-4.9 Mho), weak protective capacity (0.1-0.19 Mho) and poor protective capacity (< 0.1 Mho) for VES 1 to 30 (Table 3). The following VES locations fall within the area of excellent protective capacity; VES 1, 2, 3, and 4 (Table 3) and are indicated in the blue color zone in Figure 4, VES location 5 falls within the very good protective capacity zone and is indicated by a yellow color in Figure 4, while VES locations 6, 7, 8, 9, 10, 11, 21, 22, 23, 24, 25, 26, 29 and 30 fall within the good protective capacity zone and are indicated by the green color in Figure 4. The longitudinal conductance map of Okerenkoko (Figure 4) shows that parts of the community which fall under the aforementioned VES locations are adequately protected from oil spillage or from other near surface phenomena such as leachate contamination from landfills, sewage and septic tanks, chemical spills and waste materials from agriculture e.t.c., having excellent, very good to good protection capacities (Table 3). The earth's medium acts as a natural filter to percolating fluid. The ability of the earth to hold back or hasten and filter percolating fluid into the subsurface is a measure of its protective capacity [33]. VES locations 12, 13, 14, 15, 16, 17, 18, 19, 20, 23, 27 and 28 fall within weak to poor protective capacity as indicated by the ash and red colors' in Figure 4, and show that these areas in the community are unprotected and are susceptible to aquifer contamination due to hydrocarbon pollution or other near surface phenomena. The study also revealed that areas with aquifer protective capacity ranging from excellent to good coincide with zones of sizeable overburden thickness with clayey columns, which are thick enough to protect the aquifer in the area from surface polluting fluid.

Table 3. Summary of VES Interpretation showing the model resistivity parameters (layer resistivity and thickness), calculated longitudinal conductance values, soil corrosivity classification and curve type.

VES Stn.	**Layer resistivity (ρ_1/ ρ_2/ ρ_3/…./ ρ_n)**	**Layer thickness (h_1/ h_2/h_3/…./ h_n)**	$\sum_{i=1}^{n}\frac{h_i}{\rho_i}$	**protective capacity rating**	**Soil Corrosivity**	**Curve type**
VES 1	102.6/93.9/24.5/4.5/1.6	0.6/2.3/7.4/23.2/31.3	25.0504	Excellent	Slightly corrosive	**QQQ**
VES 2	67.9/49.5/6.7/1.5	0.7/3.3/12.5/62.5	43.6093	Excellent	Slightly corrosive	**QQ**
VES 3	266.2/36.2/92.3/5.7/2.3	0.5/2.3/2.8/20.8/22.1	13.3536	Excellent	Practically Noncorrosive	**HKQ**
VES 4	41.2/20.0/78.5/7.2/1.4	0.4/2.1/1.7/24.9/39.9	32.0947	Excellent	Moderately corrosive	**HKQ**
VES 5	388.8/58.7/14.8/5.6	0.7/3.2/8.3/47.0	9.0100	Very Good	Practically Noncorrosive	**QQ**
VES 6	64.5/30.2/213.8/15.0	0.5/1.6/2.4/29.5	2.0386	Good	Slightly corrosive	**HK**
VES 7	96.0/169.1/23.7/8.4	0.6/3.3/17.7/15.8	2.6536	Good	Slightly corrosive	**KQ**
VES 8	202.8/349.6/61.8/14.2	0.7/1.9/8.3/30.0	2.2559	Good	Practically Noncorrosive	**KQ**

VES 9	316.6/511.1/64.1/14.5	0.6/1.3/6.5/12.8	0.9886	Good	Practically Noncorrosive	**KQ**
VES 10	92.1/124.6/24.9	0.7/4.0/48.2	1.9754	Good	Slightly corrosive	**K**
VES 11	164.8/295.4/31.0/7.9	0.7/1.9/2.6/26.2	3.4110	Good	Slightly corrosive	**KQ**
VES 12	469.3/1190.2/145.8	0.9/2.6/6.1	0.0459	Poor	Practically Noncorrosive	**K**
VES 13	605.2/881.2/189.7	0.8/2.4/8.2	0.0473	Poor	Practically Noncorrosive	**K**
VES 14	670.2/649.9/84.2	0.7/4.4/7.4	0.0957	Poor	Practically Noncorrosive	**Q**
VES 15	738.1/820.8/314.2	0.7/2.3/7.2	0.0267	Poor	Practically Noncorrosive	**K**
VES 16	618.0/1594.4/206.9	0.8/2.2/8.9	0.0457	Poor	Practically Noncorrosive	**K**
VES 17	642.2/1518.6/121.8	0.8/2.6/7.4	0.0637	Poor	Practically Noncorrosive	**K**
VES 18	790.6/1162.1/197.3	1.0/2.6/6.8	0.0380	Poor	Practically Noncorrosive	**K**
VES 19	635.6/1435.4/252.8	0.7/2.4/7.2	0.0313	Poor	Practically Noncorrosive	**K**
VES 20	443.7/1078.3/199.6	1.1/3.5/21.2	0.1119	Weak	Practically Noncorrosive	**K**
VES 21	1150.3/961.2/170.9/24.1	0.7/4.8/14.2/39.7	1.7360	Good	Practically Noncorrosive	**QQ**
VES 22	1867.5/467.8/63.8	1.3/9.1/61.1	0.9778	Good	Practically Noncorrosive	**Q**
VES 23	645.7/864.0/148.9	0.8/3.4/23.6	0.1637	Weak	Practically Noncorrosive	**K**
VES 24	266.4/760.7/138.5/16.5	0.8/3.2/14.8/48.6	3.0595	Good	Practically Noncorrosive	**KQ**
VES 25	230.8/817.4/118.4/21.2	0.9/3.4/4.8/19.8	0.9826	Good	Practically Noncorrosive	**KQ**
VES 26	86.9/214.6/18.2	0.8/5.9/24.8	1.3993	Good	Slightly corrosive	**K**
VES 27	61.3/250.2/103.0	1.0/3.9/9.2	0.1212	Weak	Slightly corrosive	**K**
VES 28	13.8/43.0/262.8	1.0/5.1	0.1911	Weak	Moderately corrosive	**A**
VES 29	162.7/631.4/298.7/29.4	0.9/3.2/6.7/49.1	1.7031	Good	Slightly corrosive	**KQ**
VES 30	951.4/2258.5/200.8/27.6	0.8/2.5/13.0/53.0	1.9870	Good	Practically Noncorrosive	**KQ**

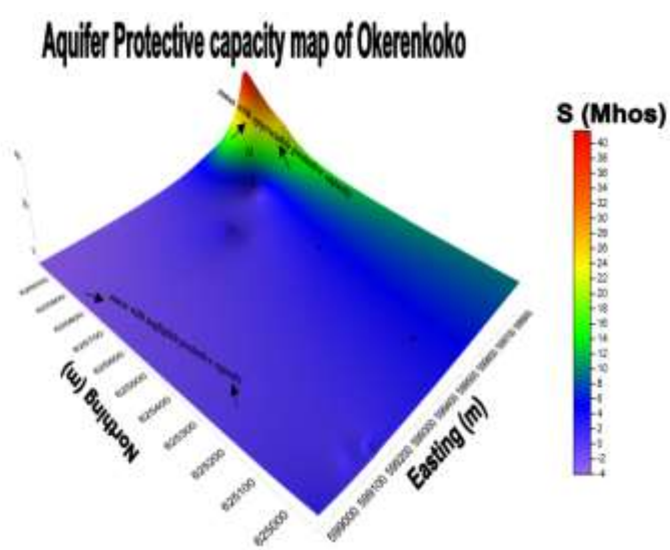


Figure 3: 3D distribution map of the longitudinal conductance of the study area Okerenkoko, Warri-South, showing the protection capacity distribution in the area (as indicated).

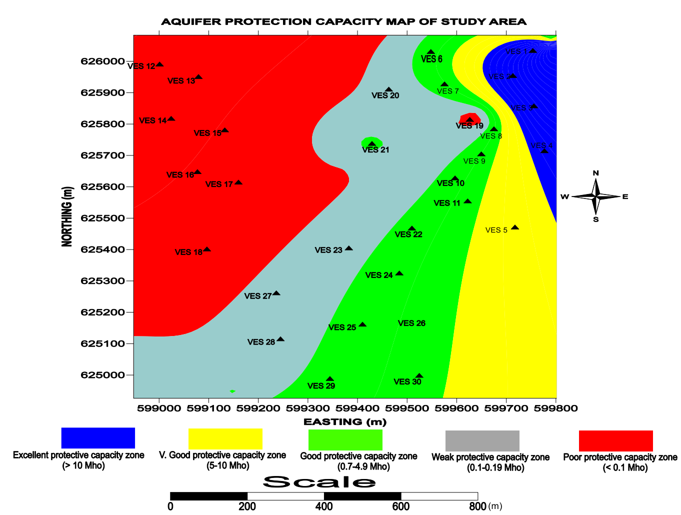


Figure 4: Longitudinal conductance map of Okerenkoko, showing the overburden protective capacity. The contour lines were color coded with **SURFER-13** advanced contour program to distinguish the various protection capacities obtained in the area study.

The overburden thickness map of the first, second and third geoelectric layers are presented in the 3D surface map shown in (Figure 5a, b and c). From the vertical and lateral extents of the maps, it show that the overburden thickness is highly variable in the study area and comprising of areas with sizeable/appreciable thickness and areas with negligible overburden thickness (as indicated). The maps shown in Figures 3, 4 and 5, and Table 3 serve as useful guides for location of subsurface aquifers and their protection capacity distributions throughout the entire study area. This will assist in planning of exploration programs for sitting of groundwater production wells in the area.

The soil corrosivity in the study area was also appraised from Table 3, using the first layer resistivity values and comparing with that of Table 2 after Baeckmann and Schwenk, (1975); Agunloye, (1984) and Oladapo et al., (2004). VES 1, 2, 6, 7, 10, 11, 26, 27 and 29 suggest that the subsurface (soil) is slightly corrosive with first layer resistivity in the order (ρ between 60-180Ωm). VES 3, 5, 8, 9, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, and 30 indicate that the subsurface (soil) is practically noncorrosive with first layer resistivity in the order (ρ ≥ 180 Ωm), while VES 4 and 28 suggest moderately corrosive material (first layer resistivity between 10-60 Ωm). Figure 6 shows the soil corrosivity distribution contour map of the study area.

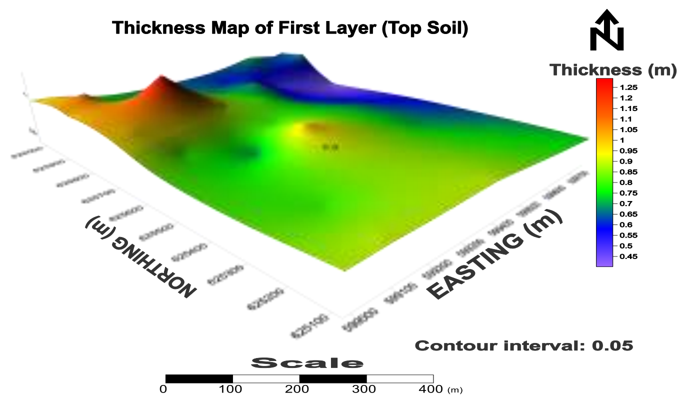


Figure 5(a): Overburden thickness map of first layer top soil

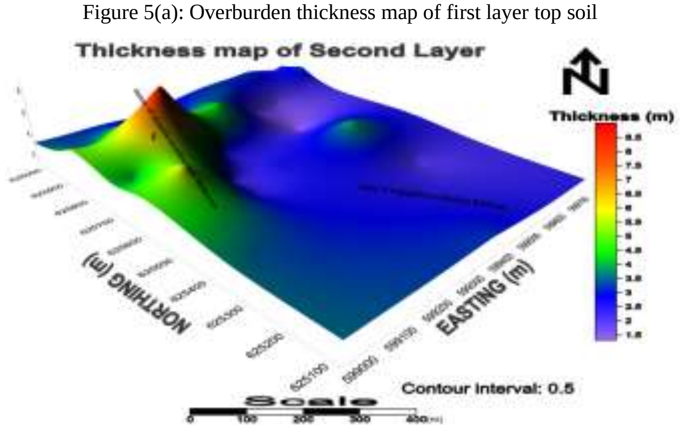


Figure 5(b): Overburden thickness map of second layer

The contour lines in the map (Figure 6) were made invisible and filled with different colors to distinguish areas with practically noncorrosive materials (yellow color), slightly corrosive materials (blue color) and moderately corrosive materials (red color). The map shows that the study area is underlain predominantly by practically noncorrosive materials, while areas with moderate and slight corrosivity will be susceptible to pipeline failures. This explains the incessant oil spills often observed at disseminated locations in the study area.

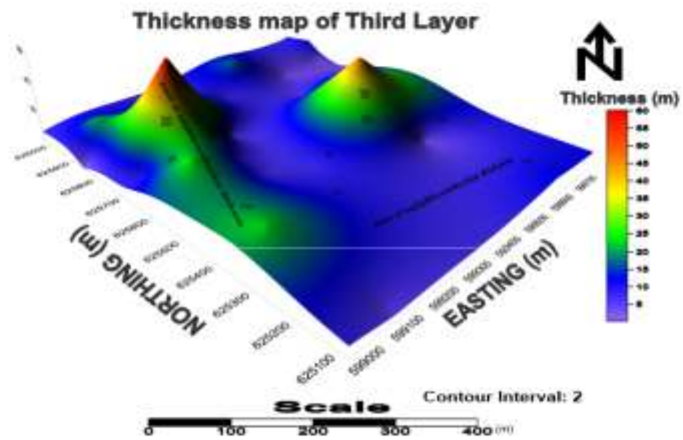


Figure 5(c): Overburden thickness map of third layer

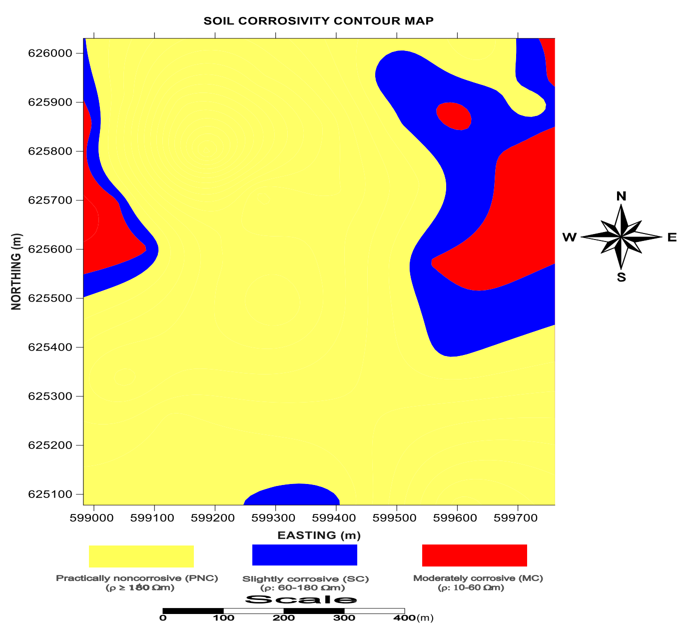


Figure 6: Soil corrosivity map of the study area

V. CONCLUSION

The electrical resistivity sounding (VES) technique has been applied to determine the overburden protective capacity, corrosivity of subsurface soil materials and overburden thickness in Okerenkoko community in Warri-Southwest, Delta State. The survey involved a total of thirty (30) Schlumberger vertical electrical soundings (VES) distributed in three locations within the community in the survey area. In this study, the electrode separation varied from 300 m to 500 m in order to obtain shallow and deep soundings. The VES data were interpreted quantitatively using the Resist-Software platform to obtain the first-order geoelectric variables (the layer resistivity and the layer thickness). The frequency of the curve types indicates predominance of **K** and **Q** curves. The first-order geoelectric variables were utilised in determining the longitudinal unit conductance (S), from which the overburden protective capacity of the area was evaluated by utilising the total longitudinal unit conductance values. The longitudinal conductance map delineated areas with poor (< 0.1 mho), weak (0.1-0.19 mho), good (0.7-4.9 mho), very good (5-10.0 mho) and excellent protective capacity (> 10.0 mho). The protective capacity of most parts of the community surveyed as shown in the VES interpretation were rated excellent, very good and good, hence the aquifer in these areas are protected from contamination by hydrocarbon in the event of pollution, while areas with weak and poor protection capacity are susceptible to groundwater contamination from surface spills and other near surface phenomena. Soil corrosivity evaluation from VES data indicated the presence of slightly corrosive, moderately corrosive and practically noncorrosive materials in the subsurface. Areas with slight and moderate corrosivity are prone to pipeline failure. Therefore, management of water quality must be given top priority in these areas of the community since they experience incessant spillages. In view of the results obtained in this study, the following considerations are thereby recommended for the protection of aquifer system in the community: (i) Drilling of deep boreholes in the area and awareness should be created by discouraging the inhabitants from drinking water from hand dug wells which can be easily polluted, (ii) petroleum pipelines should be frequently monitored for corrosion and in the event of spillage either by pipeline failure, sabotage or otherwise, remediation programs should be done immediately to prevent the contamination of the aquifer which is vulnerable, (iii) monitoring wells for groundwater should be provided in these communities and water quality analysis conducted on a regular basis.

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Code availability (Software used)

Arc-GIS, Microsoft Excel, Sufer-13 and Winresist-Suite.

Conflicts of interest/Competing interests

We declare that this research work has never been submitted previously by anyone to any journal for peer review and publication, hence it is an original work. The authors declare no competing interests.

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