Evaluation of aquifer vulnerability and the protective capacity in some oil producing communities of western Niger Delta

Edmund Aviedo Atakpo · Elijah Adebowale Ayolabi

Abstract Oil spills have become a major environmental hazard constituting serious social problems in Nigeria, especially in the oil producing communities. The spills contaminate the aquifer if the subsurface layers are not protected. Geoelectric technique of geophysical investigation has been used to evaluate the protective capacity of six oil producing communities: Oleh, Olomoro, Uzere, Afiesere, Ekakpamre and Uvwiamuge in the western Niger Delta. A total of 139 vertical electrical sounding (VES) using the Schlumberger electrode configuration were occupied in these communities. The longitudinal conductance maps delineated areas with poor (<0.1 mho), weak (0.1–0.19 mho), moderate (0.2–0.69 mho) and good protective capacity (0.7–4.9 mho). The study has shown that the protective capacity of most parts of the communities studied is poor with Uvwiamuge and Ekakpamre communities not protected hence the aquifer in these oil producing communities are vulnerable to contamination by hydrocarbon in the event of pollution. Hence proper environmental protection measures have been suggested to safeguard the aquifer from pollution by hydrocarbon in the event of spillage.

Keywords Protective capacity ·
Longitudinal conductance contamination

1 Introduction

The Niger Delta region is endowed with abundant oil and gas deposits which is the backbone of the Nigerian economy, contributing about 90% of the nation's foreign exchange earning and about 25% of the GDP. Oil spillage is the major environmental hazard caused by crude oil exploration in the Niger Delta constituting serious social problems in Nigeria, especially in the oil producing communities. Oil spills can occur due to a variety of reasons (Ozumba et al. 1999), including blowouts due to over-pressure; equipment failure; operators errors; corrosion; sabotage (vandalisation of pipelines); pigging operations; flowline replacement; flowstation upgrades; tank rehabilitation and natural phenomena such as heavy rainfall, flooding, falling of trees and lightening.

According to Directorate of Petroleum Resources (DPR 1997), over 6,000 spills had been recorded in the 40 years of oil exploitation in Nigeria, with an average of 150 per annum. In the period 1976–1996, 647 incidents occurred resulting in the spillage of 2,369,407.04 barrels of crude oil. With only 549,060.38 barrels recovered, 1,820,410.50 barrels were lost to the ecosystem. Similar report by Shell Petroleum Development Company (SPDC 2004) revealed that the company experienced a total of 457 number of oil spills in 2003 and 2004 in which a total of 18,219 barrels of oil were spilled. Pollution due to oil well blowout, corrosion of pipeline and vandalisation can lead to underground leakages which have an impact the environment in the form of groundwater pollution, soil pollution and destruction of vegetation. This may have a more direct impact on man if the subsurface pollution is not noticed on the surface but percolates to the aquifer which is an important source of potable water. The pollution of soil poses serious problems because it may take years for contaminated water to be flushed from an aquifer and replaced with clean water (Pipkin 1994).

As far as exploitation, production and transportation continue, oil producing communities will continue to face

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the consequent environmental effects such as pollution of the subsurface aquifer hence the need to have a picture of the subsurface protective capacity using geophysical methods. Geophysics is an effective non-invasive method that can be used to investigate the protective capacity. Henriet (1976) showed that the combination of layer resistivity and thickness in the Dar Zarrouk parameters *S* (longitudinal conductance) and *T* (transverse resistance) may be of direct use in aquifer protection studies, and for the evaluation of hydrologic properties of aquifers also the protective capacity of a clayey aquifer overburden is proportional to its longitudinal unit conductance *S* which, in terms of aquifer protection, gets a dimension of time (e.g. infiltration time). The protective capacity is considered to be proportional to the longitudinal unit conductance in mho. (Olorunfemi et al. 1998; Oladapo et al. 2004; Ayolabi (2005).

The area of study comprises six oil producing communities (Oleh, Olomoro, Uzere, Afiesere Ekakpamre and Uvwiamuge communities) rich in hydrocarbon deposits. These communities have over 200 producing oil wells, and four flowstations and many pipelines crisscrossing the area. The communities at one time or the other have experienced major oil spillage which destroyed plants and aquatic life thereby affecting the ecosystem and possibly the groundwater (Amaize 2006). This study is therefore, aimed at determining the protective capacity of these areas.

2 Geomorphology and geology of the study area

The study areas (Oleh, Olomoro, Uzere, Afiesere, Ekakpamre and Uvwiamuge communities) are located in Isoko South, Ughelli North and Ughelli South Local Government areas of Delta State. They lie within longitude 5°52′ and 6°20′ East and latitude 5°15′ and 5°40′ North of the equator (Fig. 1) and average elevation of about 10 m above the sea level. The area under study falls within the Niger Delta which is characterised by nearly flat topography sloping very slightly seawards (Akpokodje and Etu-Efeotor 1987) and underlain by the quaternary sands of the Sombrero plain. This area lies in the sedimentary basin and is devoid of any outcrop. During the rainy season, the area is flooded while it is dry during dry season. Some parts of the areas are swampy. The vegetation of the areas is typical of the rainforest belt except along drainage stream where swampy areas exist as typical of the Niger Delta region.

The geologic sequence of the Niger Delta consists of three main tertiary subsurface lithostratigraphic units which are overlain by various types of quaternary deposits (Short and Stauble 1967). The base of the unit is the Akata formation and it comprise mainly of marine shales with some sand beds. The formation ranges in thickness from about 550 to over 6,000 m. Very little hydrocarbon has been associated with the formation. The Agbada formation is the overlying paralic sequence which consists of interbedded sands and shale with a thickness of 300 up to about 4,500 m, thinning both seawards and towards the Delta margin. The top most unit is the Benin formation. It is over 90% sandstone with shale intercalations. It is coarse grained, gravely, locally fine grained, poorly sorted, subangular to well rounded and bears lignite streaks and wood fragments (Asseez 1989). The unit is thickest in the central area of the Delta. The contact with the underlying Agbada formation is defined by the base of sandstones which also corresponds to the base of the fresh water bearing strata.
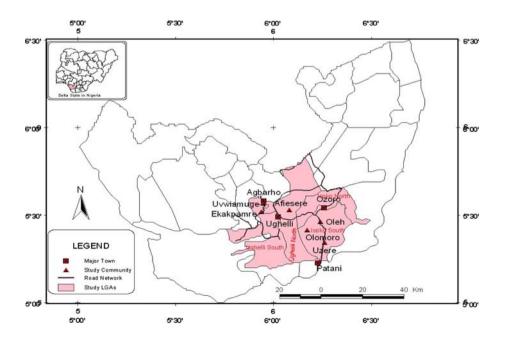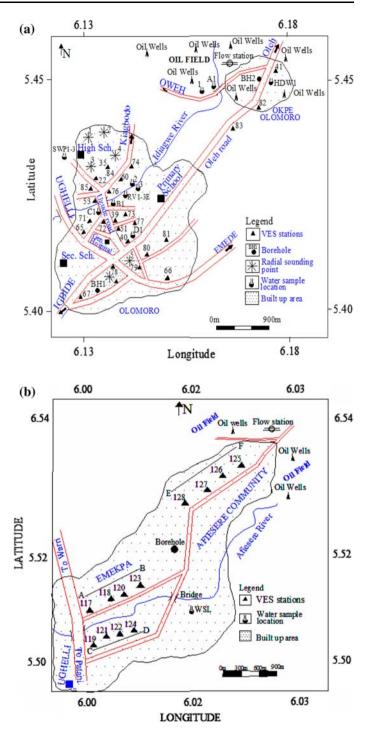
Fig. 1 Delta state showing the study area

Fig. 2 a Data acquisition map
of Olomoro. **b** Data acquisition
map of Afiesere

3 Methodology

The ABEM signal averaging system Terrameter (1000)
model was used for the resistivity data acquisition. It is
very portable to use and has high signal-to-noise ratio and
an inbuilt booster for greater depth of penetration.

The Schlumberger depth sounding technique which
is most preferred because of its sensitivity to surface
inhomogeneities was adopted for the data acquisition

(Sharma Prem 1997; Afolabi et al. 2004). This method
delineates contaminated zones of groundwater, capable of
clarifying subsurface structure distinctly, adequate depth of
penetration and it requires less labour. In this study the
maximum electrode separation varied from 50 m to
1,000 m in order to obtain shallow, deep and very deep
sounding.

A total of 139 vertical electrical sounding (VES) were
carried out in the six communities: twenty one VES

stations were occupied in Oleh, sixty four in Okpe Olomoro and Olomoro communities, thirty one in Uzere, twelve in Afiesere, three in Ekakpamre and eight in Uvwiamuge communities. The location of the VES in Olomoro, Afiesere are shown in the data acquisition maps (Fig. 2a, b).

The VES data obtained from the electrical resistivity survey are presented as VES curves (Fig. 3). The VES curves were interpreted quantitatively by computer iteration using the Resist Software based on the work of Vander Velpen 1988 to obtain the first-order geoelectric parameters (the layer resistivity ρ_i and the layer thickness h_i, (Table 1) for the ith layer ($i = 1$ for the surface layer).

These first-order geoelectric parameters were utilised in deriving the longitudinal unit conductance (S_i), which is a second-order geoelectric parameter or the Dar Zarrouk parameter (Maillet 1947).

The total longitudinal unit conductance

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} \tag{1}$$

The overburden protective capacity in an area was evaluated by utilising the total longitudinal unit conductance values of Eq. 1 (Henriet 1976; Oladapo et al. 2004).

Table 1 shows the longitudinal conductance values of the study area.

4 Results and discussion

The longitudinal conductance values were used to generate protective capacity maps with the aid of SURFER 8 Terrain and 3D Surface modeling software (2002). The protective capacity was interpreted based on the modified (Oladapo et al. 2004) longitudinal conductance/protective capacity rating in Table 2.

5 Longitudinal unit conductance maps

The longitudinal conductance maps showing the overburden protective capacity of the six communities are shown in Fig. 4. The red colour depicts areas with poor protective capacity having longitudinal conductance of <0.1 mho, the green colour depicts areas with weak protective capacity having longitudinal conductance of 0.1–0.19 mho, the yellow colour depicts areas with moderate protective capacity having longitudinal conductance value of 0.2–0.69 mho and the blue colour for areas with good protective capacity with longitudinal conductance values of 0.7–4.9 mho.

6 Protective capacity of study areas

The longitudinal conductance map showing the overburden protective capacity of Oleh is shown in Fig. 4a. The poor
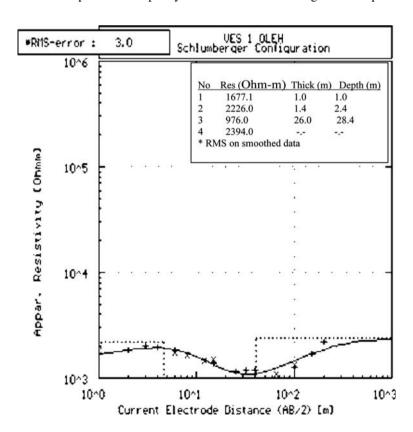
Fig. 3 Computer iterated field curves

Table 1 VES interpreted results and longitudinal conductance values

VES stn.	Resistivity ($h_1/h_2/h_3/.../h_n$)	Thickness ($\rho_1/\rho_2/\rho_3/.../\rho_n$)	$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$
Oleh			
1	1677/2227/97	1/3.6/36.4……	0.03759
2	1709/2416/964/2338	1/2.1/7.2/87	1.00146
3	383/1065/444	0.9/6.7/42.2	0.0087
4	274/615/134	0.8/1.9/18.5	0.146
5	137/24/428	1.5/11.6/29.4	0.49
6	23/644/95	0.5/4.7/12.7	0.163
7	1525/1484	1.7/14.4	0.0097
8	233/629/215/805/278	1.1/6/9.2/38/52	0.0573
9	426/2653	0.9/16.5	0.08
10	403/1163	0.8/8.1	0.09
11	535/245	1.7/12.0	0.502
12	467/51	1.8/8.4	0.1679
13	153/1018/403	0.6/2.1/30	0.0060
14	150/35	1.9/9.4	0.283
15	998/3217/2421	1.6/4.3/29.8	0.0029
16	55/22/112	2.1/6/14.9	0.444
17	54/200/46	0.9/4/14	0.339
18	110/537/184	0.9/12.5/35.5	0.0312
19	129/312/165	0.9/5.8/18.5	0.1375
20	78/54/231	1.9/34.6	0.665
21	75/170/404	1.5/33	0.214
Olomoro			
22	1614/862/2201/1121	0.9/4.8/30.6/104	0.0112
23	5370/2857	1.6/8.8	0.0034
24	6004/1844	2.6/8.9	0.00523
25	5812/2797	1.9/5.3	0.00223
26	5916/2118	2.1/9.0	0.00460
27	5238/2610	1.5/7.6	0.00319
28	5867/2109	1.9/9.0	0.00462
29	5871/2443	2.1/8.6	0.00386
30	6515/2257	2.1/8.8	0.00421
31	1794/63	1.7/8.9	0.0074
32	1493/1420	1.5/8.9	0.0073
33	1841/1784	2.1/7.4	0.00534
34	1556/1330	2.0/9.8	0.0087
35	3101/1468/1875	2.3/12.0/57	0.0089
36	2746/1484	2.6/8.9	0.00685
37	2859/1367	2.8/8.2	0.00698
38	2706/1574	2.5/11.5	0.05792
39	58/515/81	0.8/7.2/27.3	0.365
40	267/161/333	0.8/15/32.5	0.009
41	173/30/32	2/10.6/17.2	0.3646
42	345/135	0.8/3.4	0.0273
43	445/154	0.6/4.1	0.0280
44	501/148	0.7/4.3	0.0304
45	331/136	0.9/4.2	0.0337
46	664/386	0.9/5.5	0.01568
47	584/341	0.7/4.1	0.0132

Table 1 continued

VES stn.	Resistivity ($h_1/h_2/h_3/.../h_n$)	Thickness ($\rho_1/\rho_2/\rho_3/.../\rho_n$)	$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i}$
48	510/342	0.9/4.3	0.01144
49	579/415	0.9/5.1	0.01405
50	385/121/27	0.9/3.8.15	0.615
51	443/53/125	1.1/6.1/6.9	0.2523
52	70/14/86	0.7/3.1/10.1	0.397
53	1377/1029/1368	1/4.2/20.8	0.0114
54	3399/4483	1.0/7.4	0.0046
55	2800/7587	1.1/10.2	0.0052
56	3684/57278	1.0/11.4	0.00476
57	2092/5493	1.0/7.8	0.00188
58	2000/3014	1.0/15.0	0.0085
59	1257/361/2441	0.7/3.8/19.2	0.01156
60	3780/1573/3807	1.3/7.8/23.9	0.00521
61	1043/1151	1.0/9.4	0.00916
62	1213/926/2451	1.0/3.3/23.4	0.00442
63	1271/985/2510	1.0/4.0/20.4	0.00489
64	1577/814/2776	1.1/6.0/19.2	0.00810
65	945/617/1744	1.2/2.7/36.7	0.00567
66	310/939/152/1402/621	0.6/1.0/3.6/50.4/64	0.02674
67	178/1439/327/2491	0.5/2.0/4.7/38.7	0.00419
68	58/80/326	1.0/6.1/28.9	0.0935
69	325/140/837/318	0.6/2.0/34/44	0.16
70	97/189/672/362	1.0/4.8/32/48	0.036
71	44/239	1.4/11.3	0.079
72	365/204/44	0.8/1.9/16.7	0.37
73	53/48	1.7/19.3	0.425
74	2147714/2791	0.9/4.5/76	0.00672
75	3345/1334/2452	1.2/6.6/38	0.0053
76	109/315/179	0.6/2.3/4.7	0.039
77	1379/448/45/590	2.0/2.3/11/27	0.253
78	58/45/324	0.9/3.4/18.1	0.091
79	142/562/193	0.6/16.3/12.1	0.004
80	67/86/469/185	11/2.6/12.6/21	0.07
81	445/261/711/290	1.7/3.4/14/23	0.0168
82	1222/922/1953/900	1.2/3.2/11.3/20.1	0.0045
83	1331/1299	1.7/7.1	0.0068
84	299/2391	0.9/5.2	0.0044
85	2684/4803	0.8/3.8	0.0011
Uzere			
86	241/874/272	0.8/4.6/11.7	0.00862
87	608/287/2146	1.4/5.1/41.7	0.0201
88	625/892/4517	1.0/3.1/25	0.0051
89	480/953/3368	0.8/7.1/30.4	0.00912
90	428/2075/4091	1.0/3.5/18.1	0.004
91	404/85/19	1.0/4.7/14.7	1.33
92	155/34/19	1.9/6.1/18	1.14
93	87/13	0.9/15	1.165
94	331/17	1.1/20.7	1.221
95	2553/688/7114	2.5/8.2/56	0.013

Table 1 continued

VES stn.	Resistivity $(h_1/h_2/h_3/\ldots/h_n)$	Thickness $(\rho_1/\rho_2/\ \rho_3/\ldots/\ \rho_n)$	$S = \sum\limits_{i=1}^{n} \frac{h_i}{\rho_i}$
96	1481/434/3408	0.8/3.4/18.6	0.0083
97	787/1192/3314	1.0/6.3/26.4	0.0065
98	975/1491/936/2886	0.9/3.2/5.4/17.7	0.0091
99	1105/1896/2121	0.6/3.9/25.6	0.00264
100	1259/2896/2551	0.9/4.1/41.8	0.0021
101	1290/323/1189/202	1.0/3.4/16.7/40	0.0113
102	1140/20/74	1.0/1.4/21.3	0.3587
103	805/367/737/109	1.2/5.3/8.2/16.2	0.01593
104	698/210/731/101	1.7/2.9/6.6/30	0.032
105	677/1260/2532	0.8/5.3/34.5	0.0054
106	1383/437/2144	1.5/8.7/47.2	0.0210
107	1353/599/3174	1.1/6.2/43	0.0112
108	1007/662/1980/937	0.9/3.5/17.5/28.4	0.00618
109	1129/636/3390	1.2/3.5/32.7	0.0066
110	533/2686	0.8/11.3	0.0571
111	2300/1497/7957	0.8/2.3/26	0.014
112	1734/629/1651	0.9/2.1/8.8	0.00854
113	355/1612	1.0/13.2	0.01
114	1929/1198/2835	1.1/3.2/22.1	0.00324
115	268/714	3.0/9.5	0.0111
116	2533/334/655	1.2/5.0/12.7	0.015
Afiesere			
117	1128/1032/2722/559	0.8/1.4/5.8/23	0.0042
118	1154/506	0.9/14.1	0.0293
119	49/562/2759	0.9/1.9/18.6	0.022
120	62/558/359	1.3/18.7/5.2	0.0545
121	41/158/118	0.8/3.3/2.4	0.061
122	32/247/84	0.8/2.5/4.9	0.093
123	180/568/965	1.9/15.5/21.7	0.035
124	45/270/2413	0.8/1.2/14.8	0.022
125	74/126/2003	0.8/4.2/42	0.043
126	12/224/61	0.5/2.3/5.1	0.0136
127	30/246/80	0.9/5.9/10.4	0.0184
128	57/70/627	0.9/6.5/13.2	0.011
Ekakpamre			
129	37/124/335	0.9/4.7/21.9	0.05
130	309/983/426/1539	0.5/4.8/3.3/21	0.0065
131	37/124/335	0.9/4.7/22	0.0579
Uvwiamuge			
132	926/669/1540/302	1.0/1.4/26/43	0.0032
133	681/198/715/342	1.3/3.6/25/148	0.02
134	836/149/1667	0.6/3/10.7	0.021
135	914/196/2225/471	1.5/0.4/16/58	0.004
136	188/395/1583	1.3/2.8/28	0.014
137	78/22/418/947	0.5/1.3/4.1/7.1	0.066
138	103/55	0.7/2.3	0.055
139	106/70	0.7/1.6	0.0295

Table 2 Modified the longitudinal conductance/protective capacity rating (Oladapo et al. 2004)

Longitudinal conductance (mho)	Protective capacity rating
>10	Excellent
5–10	Very good
0.7–4.9	Good
0.2–0.69	Moderate
0.1–0.19	Weak
<0.1	Poor

and weak protective zones are prone to hydrocarbon pollution. The following VES locations fall within the area of poor protective capacity; VES 1, 2, 3, 7, 8, 9, 10, 11, 13 and 15 while VES 4, 12, 19 and 6 are in the weak protective capacity zones. The data acquisition map of Oleh (Fig. 2) shows that VES 8, 9 and 10 are very close to oil wells and pipelines (about 50 m), hence the aquifer in this residential area is not protected and is prone to contamination by hydrocarbon. The central part of the community lies in the moderately protected zone; these include VES 5, 20, 14, 17 and 18. The aquifer in this area is protected from percolating fluid.

The longitudinal conductance map of Olomoro (Fig. 4b) shows that a large extent of the Olomoro is not protected. Only a small area of the community is moderately protected (VES 73, 77, 51, 39, 52, 53 and 41). Hence the aquifer in Olomoro community is prone to contamination in the event of hydrocarbon pollution. A part of the Okpe Olomoro community around VES 82 is also not protected This community stands a higher risk groundwater contamination because oil wells are located less than 10 m from the community as can be seen from the data acquisition map (Fig. 2).
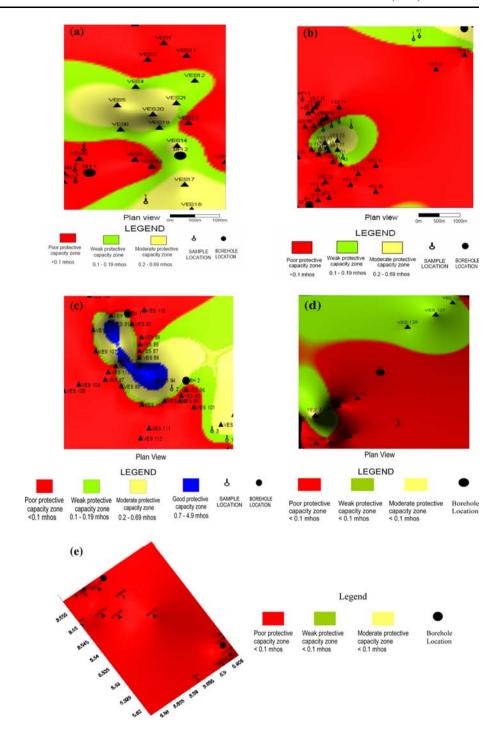
The longitudinal conductance map of Uzere (Fig. 4c) shows that parts of the Uzere community are protected; VES 91, 92, 93 and 94 are located in areas having good protective capacity zone with longitudinal conductance value between 0.7 and 4.9 mho (blue colour). The areas having poor protective capacity are towards the oil field in the outskirts of the community.

In Afiesere (Fig. 4d) the longitudinal conductance map shows almost the whole of the community is not protected. Apart from VES 112 area which is moderately protected the rest of the area have weak and poor protective capacities thereby exposing the aquifer to contamination in the event of hydrocarbon pollution.

The longitudinal conductance map of Uvwiamuge and Ekakpamre showing the overburden protective capacity is as presented in Fig. 4e. The red colour depicts areas with

Fig. 4 **a** Longitudinal conductance maps of Oleh, showing the overburden protective capacity. **b** Longitudinal conductance maps of Olomoro showing the overburden protective capacity. **c** Longitudinal conductance maps of Uzere showing the overburden protective capacity. **d** Longitudinal conductance maps of Afiesere showing the overburden protective capacity. **e** Longitudinal conductance maps of Ekakpamre and Uvwiamuge showing the overburden protective capacity

poor protective capacity having longitudinal conductance of <0.1 mho. The protective capacity of the whole of Uvwiamuge and Ekakpamre area is poor. The area has very little or no clay and lateritic overburden to protect the aquifer. The Uvwiamuge and Ekakpamre communities are the least protected of the five communities studied and the aquifer most prone to contamination.

7 Conclusion

This paper describes the determination of the overburden protective capacity using the electrical resistivity survey. The survey involve a total 139 Schlumberger vertical electrical soundings (VES) distributed in the six communities comprising the survey area. In this study the

maximum electrode separation varied from 50 to 1000 m in order to obtain shallow, deep and very deep sounding. The VES data were presented as VES curves interpreted quantitatively by partial curve matching computer iteration using the Resist Software to obtain the first-order geo-electric parameters (the layer resistivity ρ and the layer thickness h. These first-order geoelectric parameters were utilised in deriving the longitudinal unit conductance (S). The overburden protective capacity in an area was evaluated by utilising the total longitudinal unit conductance values. The longitudinal conductance maps delineated areas with poor (<0.1 mho), weak (0.1–0.19 mho), moderate (0.2–0.69 mho) and good protective capacity (0.7–4.9 mho). The protective capacity of most parts of the communities studied is poor with Uvwiamuge and Ekakpamre communities not protected, hence the aquifer in these oil producing communities are prone to contamination by hydrocarbon in the event of pollution. Management of the water quality must be given top priority in these oil producing communities since they experience frequent spillages. Some of the measures that can be taken for the protection of the aquifer include: (i) Drilling 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) pipelines should be frequently monitored for corrosion and in the event of spillage either by sabotage or otherwise remediation measures should be done immediately to prevent the contamination of the aquifer which is vulnerable, (iii) groundwater monitoring wells should be provided in these communities and constant water quality analysis conducted.

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