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Original Research Article

Time Lapse Resistivity Survey and its Implication on Aquifer Contamination: A Case Study of Aule Area Basement Complex Region, Akure, Ondo State, Nigeria

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ABSTRACT

This study was prompted by the need to carry out a follow-up study on an earlier work done ten years ago, which studied the depth extent of a contaminant plume in surrounding groundwater that originated from hydrocarbon leakage from an underground storage tank. Therefore, this follow-up study is an attempt to evaluate the extents to which the contaminant effects have either been reduced or completely removed, given a time-lapse of ten years. In this study, electrical resistivity method was engaged with the deployment of vertical electrical sounding (VES) within the study area. Nine (9) VES points were repeated at the exact location where similar measurements were carried out ten years ago. The information obtained gave useful and relevant information in terms of the correlation of geoelectric sequence and geophysical parameters between ten years ago and now. The contaminated layers resistivity and thickness ten years ago were at an average of 271 Ωm and 3.5 m which have reduced to an average of 95 Ωm and 0.49 m now. Findings revealed that time lapse has allowed the effects of the contaminant to be completely or partly removed along, VES 2, 6, 9, 10, 11, and 12. This study gave an insight into the minimum time lapse that may be required for the total or near-complete removable of the effect of contaminants of this nature in a typical basement Complex environment in Nigeria.

1. INTRODUCTION

Time-lapse geophysical study has an objective to gain insight into processes, and thus is different from traditional geophysical efforts which are focused on the characterization of properties. A time-lapse geophysical study requires what is typically referred to as a time-lapse survey. A time-lapse survey is made up of numerous individual geophysical datasets, each of which can have many individual geophysical measurements (Tso et al., 2020). In order to facilitate the interpretation of time-lapse surveys and driven by the need to avoid spatial aliasing, each individual dataset is typically collected at fixed time intervals. This interval is typically dictated by the need to avoid spatial aliasing of the processes being imaged (Versteeg and Johnson, 2008). In the case of time-lapse datasets which need to be collected manually, cost considerations provide a constraint on the number of datasets collected. However, if acquisition is fully automated the acquisition of continuous time-lapse geophysical data can be of very low cost. It should be noted that while time-lapse geophysics is well established and has been demonstrated numerous times, the process of interpreting changes in geophysical data in terms of changes in subsurface properties is complex (Doser et al., 2004).

Electrical resistivity surveys are now widely used in engineering and environmental investigations to map areas with complex geology (Griffiths and Barker, 1993; Ellis and Oldenburg, 1994; Dahlin, 1996). The many applications include mapping of groundwater contamination (Barker, 1996), bedrock topography (Ritz *et al.*, 1999), freshwater aquifers (Dahlin and Owen, 1998), and mapping of unconsolidated sediments (Christensen and Sorensen, 1994). Normally, the data from the surveys conducted at different times are inverted independently, and the changes in the subsurface resistivity values are determined by comparing the model resistivity values obtained from the inversions of an initial data set and the models for the other data sets.

Oil pollution is widespread and arises at all stages of the petroleum industry: extraction, transportation, refining and distribution. Natural processes that may act to reduce the severity of an oil spill or accelerate the decomposition of spilled oil are always at work in the terrestrial environment. These natural processes include weathering, evaporation, oxidation, bio-degradation, and migration. Under the influence of bio-degradation on the basis of earth as a filter, oil pollution in the ground changes the resistivity of the groundwater and the surrounding rocks, exhibiting as a zone of low resistivity.

Therefore, this work tends to look at the effect of time on the basis of earth as a filter especially over the deposited hydrocarbon contaminant that has find its way into the subsurface water (i.e. how long it will take the contaminant to be completely removed from the subsurface geology).

The motivation for this work is against the background that the earth is a filter (Bawallah *et al.*, 2019) and to find out if the effect of the hydrocarbon has been reduced or removed completely. Therefore, a follow up study was carryout to evaluate how time lapse has allowed the earth filtering process to remove the effect of the contaminant ten years later. In view of this, the electrical resistivity method used in the baseline study was engaged using resistivity profiling, as well as the vertical electrical sounding. This is to allow the evaluation of lateral variation and determine the depth extent.

2. MATERIALS AND METHODS

2.1. Description and Geology of the Study Area

The study area is located along Akure-Ilesha, expressway, Akure, southwestern Nigeria. The location lies between the UTM coordinates of Eastings 738600 to 739300 m and Northings 804100 to 804500 m as shown in Figure 1. The Southwestern basement complex of Nigeria lies within the rest of the Precambrian rocks in Nigeria as shown in Figure 2. The rocks in this region were grouped as migmatite-gneiss complex comprising largely of sedimentary series with associated minor igneous rock intrusions which have been altered by metamorphic, migmatitic and granitic processes (Rahaman, 1988). Odeyemi et al. (1999) suggested that almost all the foliation exhibited by rocks of southwestern Nigeria excluding the intrusives are tectonic in origin, because pre-existing primary structures have been obliterated by-subsequent deformation. The joints ranging from minor to major ones are found in all the rock types, some of which are filled with quartz, feldspar or a combination of both which lie generally in the NE-SW direction (Anifowose, 2004), while Boesse and Ocan, (1992) reported that the southwestern basement complex of Nigeria has been affected by two phases of deformation namely D1, D2, the first phase D1 produces tight to isoclinals fold while the second phase D2 is characterized by more open folds of variable style and large vertical NNE-SSW trending fault. Oluyide, (1988) gave evidence that within the basement complex, tectonic deformation has completely obliterated primary structures except in a few places where they survived deformation (Okonkwo, 1992).

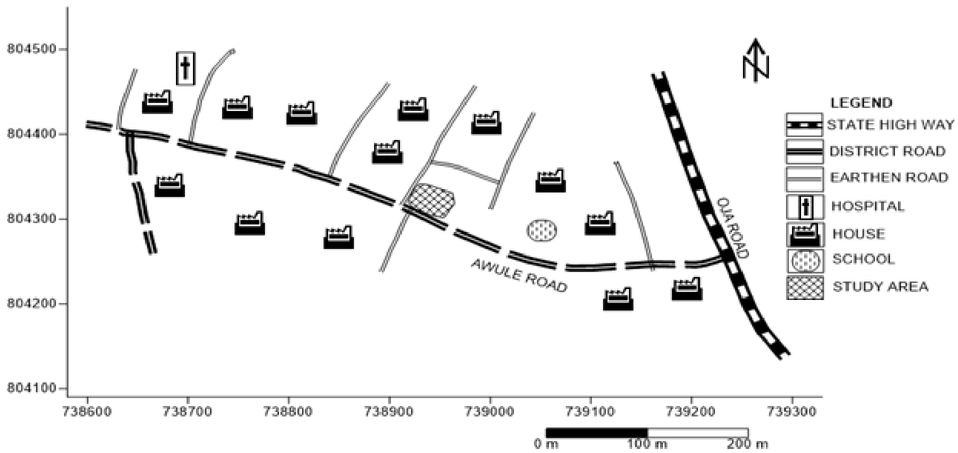

Figure 1: Map of the study area

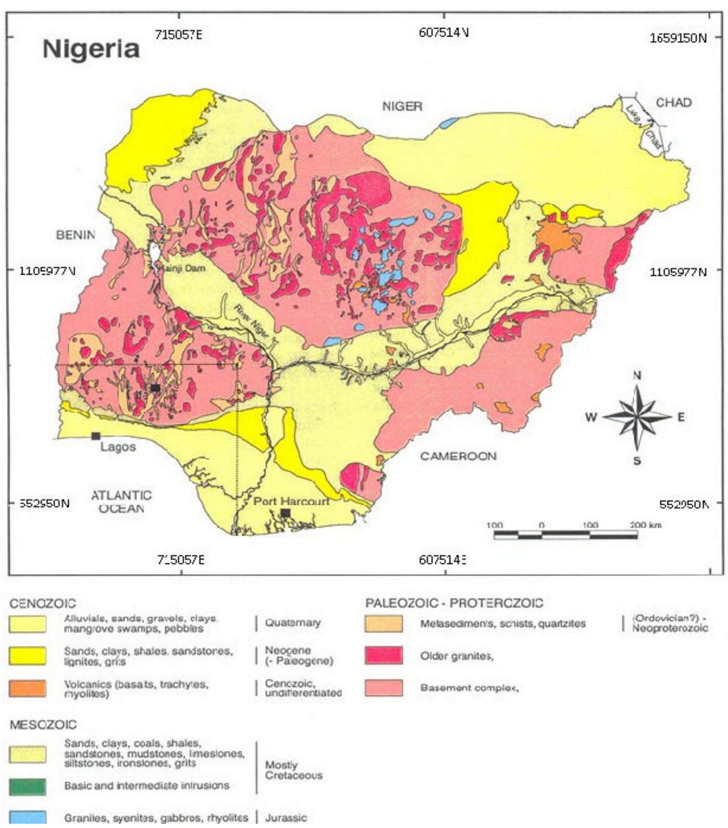

Figure 2: Geological Map of Nigeria (Rahaman, 1988)

2.2. Methods

The vertical electrical sounding (VES) is in accordance with the lectrical methods done by Adelusi *et al.* (2013) where all VES points where repeated. WINRES inversion software was used to generate pseudo-sections from the resistivity data. The number of the curve obtained by sounding over a horizontal medium is a function of the number of layers, the resistivity and thickness of each layer as well as the electrode array used. Nine (9) VES points (namely VES 2, 3, 5, 6, 8, 9, 10, 11 and 12) out of twelve (12) VES points acquired by Adelusi *et al.* (2013) ten years ago from the study area were repeated as shown in Figure 3.

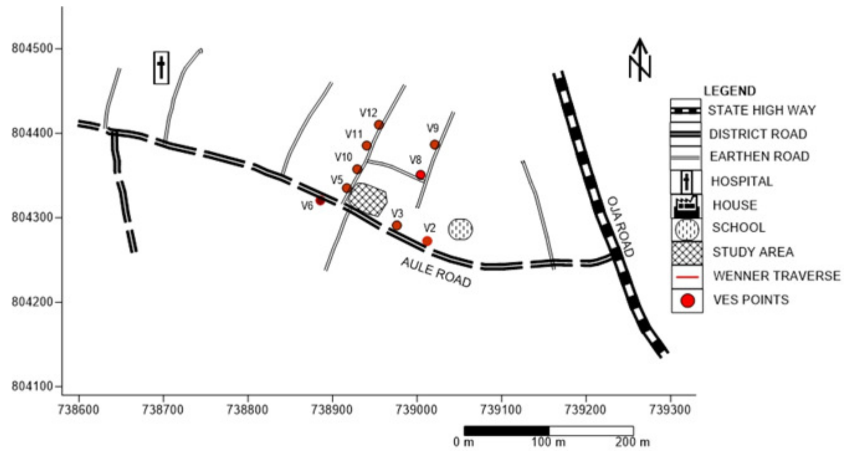

Figure 3: Vertical electrical sounding points of the survey

The geoelectric parameters were used to determine the contamination reduction variation per month is with the following equations as done by Bawallah *et al.* (2019).

$$A = \frac{Ai + Aii + Aiii}{3} \quad (1)$$

$$B = \frac{Bi + Bii + Biii}{3} \quad (2)$$

$$C = \frac{Ci + Cii + Ciii}{3} \quad (3)$$

$$\text{Traverse average (TRA)} = \frac{A+B+C}{3} \quad (4)$$

Therefore:

$$\text{Average local weathering trend/rate per year} = \frac{TRA1+TRA2+TRA3}{3} \quad (5)$$

Where

A= First block on each traverse. B= second block on each traverse. C= third block on each traverse. Ai= First section of Block A. Aii= Second section of Block A. Aiii= Third section of block A. Bi= First section of Block B. Bii= Second section of Block B. Biii= Third section of block B. Ci= First section of Block C. Cii= Second section of Block C. Ciii= Third section of block C.

3. RESULTS AND DISCUSSION

3.1. Results from Traverse One

Four VES points namely VES 2, VES 3, VES 5 and VES 6 cut across traverse one. Four subsurface geologic layers were delineated as shown in Figures 4(a) and 4(b), from the geoelectric section, the topsoil, contaminated layer, weathered layer and fresh basement respectively. The thickness of the contaminated layer was 1.9 m, 6.7 m, 3.1 m and 4.7 m in VES 2, VES 3, VES 5 and VES 6 respectively in the previous study as shown in Figure 4(a) but it could not be seen in the recent study as shown in Figure 4(b), that is, the effect of the contaminant plume could be seen to have reduced to the barest minimum or has been completely removed between VES 2, 3 and 6. Meanwhile, little traces of it could be seen in VES 5 with a thickness of 1 m in the recent study. However, the resistivity of the contaminated layer ranged between 33 Ωm to 311 Ωm in the recent survey as shown in Figure 4(b), so therefore the resistivity range of the contaminated layer has reduced from 84 Ωm - 398 Ωm of the baseline study to 33 Ωm – 311 Ωm of the recent study which shows that the contaminant has been reduced or removed almost completely.

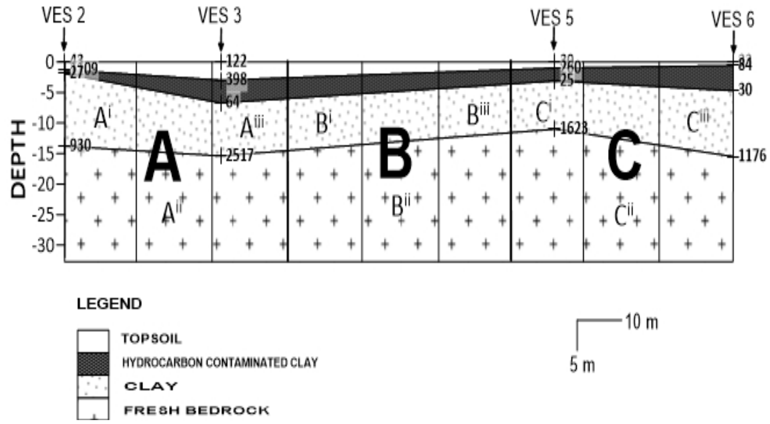

Figure 4(a): Traverse 1 of previous study (geoelectric section)

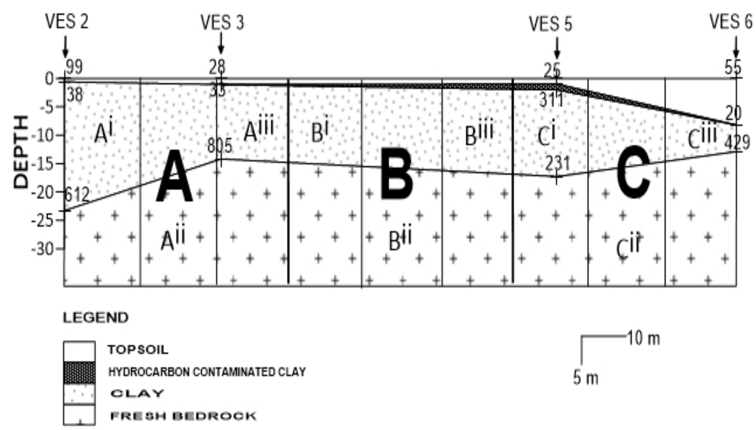

Figure 4(b): Traverse 1 of recent study (geoelectric section)

3.2. Results from Traverse Two

Three VES points namely VES 10, VES 11, and VES 12 cut across traverse two. Four subsurface geologic layers were also delineated as shown in Figures 5(a) and 5(b), from the geoelectric section, the top soil, contaminated layer, weathered layer and fresh basement respectively. The thickness of the contaminated layer is 3.3 m, 6.5 m and 6.0 m in VES 10, VES 11, and VES 12 respectively in the previous study as shown in Figure 5(a) but it could not be seen in the recent study as shown in Figure 5(b), that is the effect of the contaminant plume could be seen to have reduced to the barest minimum or has been completely removed between VES 10, 11 and 12. The resistivity range of the contaminated layer was in the range of 109 Ωm – 509 Ωm in the previous study as shown in Figure 5(a), but the recent study has no contaminated layer as shown in Figure 5(b) which shows that the contaminant plume has been reduced or removed almost completely.

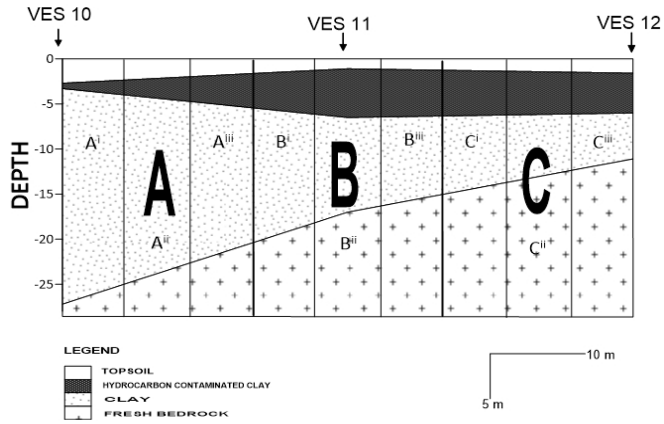

Figure 5(a): Traverse 2 of previous study (geoelectric section)

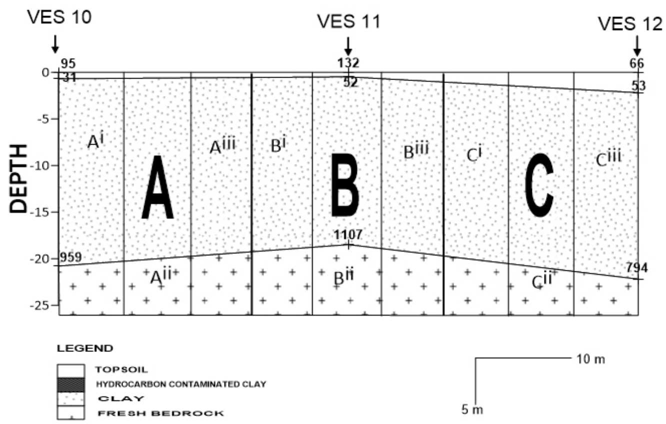

Figure 5(b): Traverse 2 of recent study (geoelectric section)

3.3. Results from Traverse Three

Two VES points namely VES 8, and VES 9 cut across traverse three. Four subsurface geologic layers were also delineated as shown in Figures 6(a) and 6(b), from the geoelectric section, the topsoil, contaminated layer, weathered layer and fresh basement. The thickness of the contaminated layer in VES 8 is 5.7 m in the previous study as shown in Figure 6(a) and little traces of it could be seen with a thickness of 2.9 m in the recent study as shown in Figure 6(b). Meanwhile in VES 9, the thickness of the contaminated layer is 4.4 m in the previous study as shown in Figure 6(a) but it thinned out in the recent study as shown in figure 6(b), that is the effect of the contaminant plume could be seen to have reduced to the barest minimum or has been completely removed in VES 9. However, the resistivity of the contaminated layer in VES 8 is 96 Ωm in the recent survey as shown in Figure 6(b), showing that the resistivity range of the contaminated layer has reduced from 152 Ωm - 179 Ωm in the baseline study to 96 Ωm of the recent study which shows that the contaminant has been reduced or removed almost completely.

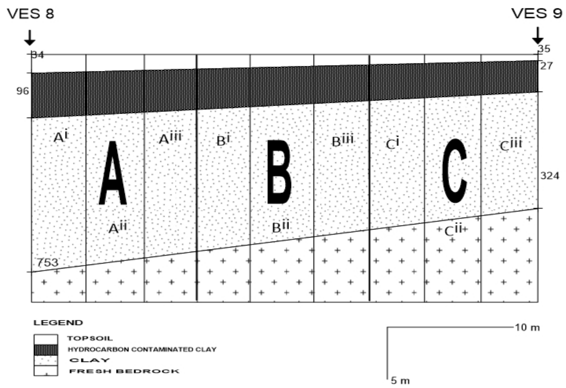

Figure 6(a): Traverse 3 of previous study (geoelectric section)

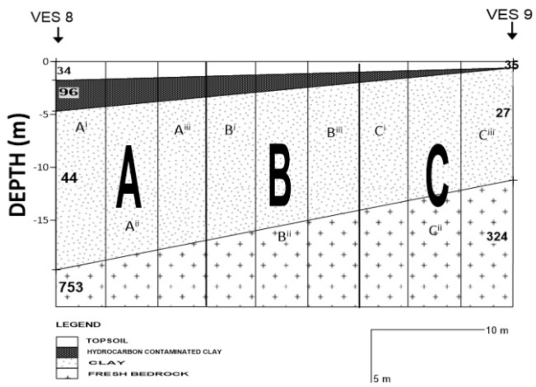

Figure 6(b): Traverse 3 of recent study (geoelectric section)

3.4. Reduction Characteristics

The geoelectric section was divided into three blocks (A, B and C) along the three traverses for a better evaluation and correlation of datasets of the previous and recent survey, and there have been reduction in the thickness of the contaminated layer in all three traverses over the period of years in consideration as shown in Figures 7, 8, and 9 respectively.

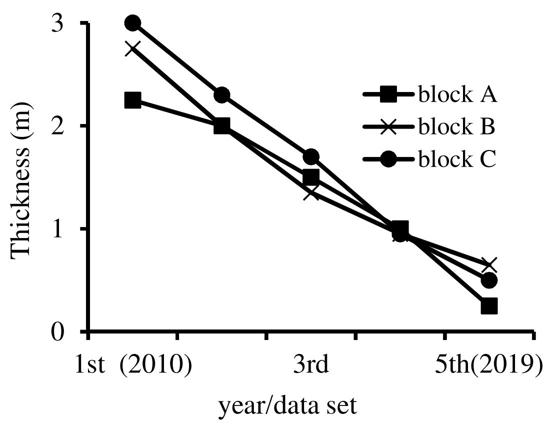

Figure 7: Reduction evaluation along Traverse 1

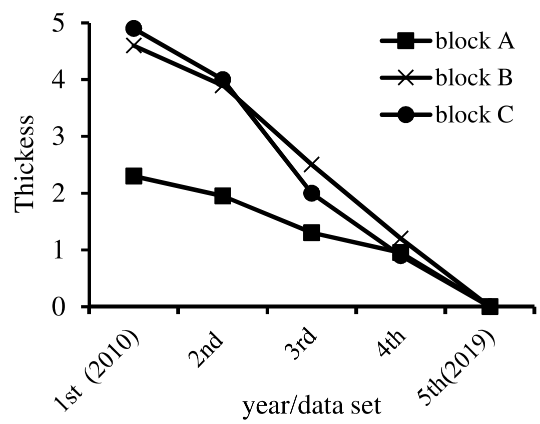

Figure 8: Reduction evaluation along Traverse 2

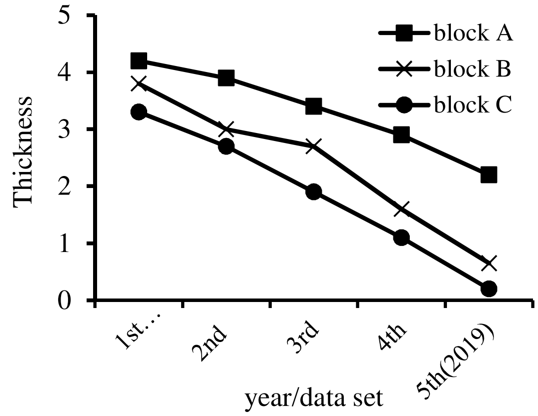

Figure 9: Reduction evaluation along Traverse 3

The average contaminated layer thickness while considering the variations over a space of ten years ranged between 13.73 to 15.48 m (Figures 4a and 4b, 5a and 5b, 6a and 6b).

3.5. Time Lapse Variation

As done by Bawallah *et al.* (2019) to allow a fair statistical analysis, each transverse was further partitioned into A = Ai + Aii + Aiii, B = Bi + Bii + Biii and C = Ci + Cii + Ciii respectively and averaged after which the totality of it was subjected to another overall average of A, B, and C along the traverses. The previous depth was subtracted from the recent depth, to represent the reduction in thickness in the last decade. These were divided by ten (10), and further divided by 12 months which represents the reduction rate per month (Tables 1, 2, and 3). Therefore, the average local reduction rate per month was determined to be 0.02 m per month.

Traverse 1 (VES 2, 3, 5 and 6) geoelectric section

Previous study (2009) Traverse 1:

Using Equations (1) to (3):

$$\frac{0.9 + 2.0 + 4.0\ \text{m}}{3} = \frac{6.9}{3} = 2.30$$

$$\frac{3.8 + 3.0 + 2.9\ \text{m}}{3} = \frac{9.7}{3} = 3.23$$

$$\frac{2.5 + 3.5 + 4.5\ \text{m}}{3} = \frac{10.5}{3} = 3.50$$

$$\frac{2.3 + 3.23 + 3.5\ \text{m}}{3} = \frac{9.03}{3} = 3.01$$

Present study (2019) Traverse 1

Using Equations (1) to (3):

$$\frac{0 + 0 + 0\ \text{m}}{3} = \frac{0}{3} = 0$$

$$\frac{1 + 1 + 1\ \text{m}}{3} = \frac{3}{3} = 1$$

$$\frac{1 + 0.5 + 0\ \text{m}}{3} = \frac{1.5}{3} = 0.8$$

$$\frac{0 + 1 + 0.8\ \text{m}}{3} = \frac{1.8}{3} = 0.61$$

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Table 1: Reduction rate per month along traverse one

Zone	Average past (2009)	Average present (2019)	Reduction (R) = 2019 - 2009	Reduction rate per year (RRpY) = $\frac{R}{10}$	Reduction rate per month (RRpM) = $\frac{RRpY}{12}$
A	2.30	0.00	2.30	0.23	0.02
B	3.23	1.00	2.23	0.23	0.02
C	3.50	0.83	2.67	0.27	0.02

Note: All parameters are in meters

Using Equation (4):

Traverse average 1 (TRA) = $\frac{0.02+0.02+0.02}{3} = 0.02$ m

Traverse 2 (VES 10, 11 and 12) geoelectric section

Previous study (2009) Traverse 2:

Using Equations (1) to (3):

$$\frac{1.7+ 2.8+3.8 \text{ m}}{3} = \frac{8.3}{3} = 2.8$$

$$\frac{5+ 5.3+5 \text{ m}}{3} = \frac{15.3}{3} = 5.1$$

$$\frac{4.7+ 4.4+4.4 \text{ m}}{3} = \frac{13.5}{3} = 4.5$$

$$\frac{2.8 +5.1+ 4.5 \text{ m}}{3} = \frac{9.03}{3} = 4.13$$

Present study (2019) Traverse 2:

Using Equations (1) to (3):

$$\frac{0 +0+ 0 \text{ m}}{3} = \frac{0}{3} = 0$$

$$\frac{0 +0+ 0 \text{ m}}{3} = \frac{0}{3} = 0$$

$$\frac{0 +0+ 0 \text{ m}}{3} = \frac{0}{3} = 0$$

$$\frac{0+0+ 0 \text{ m}}{3} = \frac{0}{3} = 0$$

Table 2: Reduction rate per month along traverse two

Zone	Average past (2009)	Average present (2019)	Reduction (R) = 2019 - 2009	Reduction rate per year (RRpY) = $\frac{R}{10}$	Reduction rate per month (RRpM) = $\frac{RRpY}{12}$
A	2.8	0	2.8	0.28	0.02
B	5.1	0	5.1	0.51	0.04
C	4.5	0	4.5	0.45	0.04

Note: All parameters are in meters

Using Equation (4):

Traverse average 2 (TRA) = $\frac{0.02+0.04+0.04}{3} = 0.03$ m

Traverse 3 (VES 8 and 9) geoelectric section

Previous study (2009) Traverse 3

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Using Equations (1) to (3):

$$\frac{4.3+4.0+3.7\text{ m}}{3}=\frac{12}{3}=4$$

$$\frac{3.7+3.5+3.3\text{ m}}{3}=\frac{10.5}{3}=3.5$$

$$\frac{3.2+3+2.8\text{ m}}{3}=\frac{10.5}{3}=3$$

$$\frac{4+3.5+3\text{ m}}{3}=\frac{10.5}{3}=3.5$$

Present study (2019) Traverse 3

Using Equation (1) to (3):

$$\frac{2.9+2.5+2.3\text{ m}}{3}=\frac{7.7}{3}=2.6$$

$$\frac{2.1+1.7+1.3\text{ m}}{3}=\frac{5.1}{3}=1.7$$

$$\frac{0.8+0.6+0.4\text{ m}}{3}=\frac{1.8}{3}=0.6$$

$$\frac{2.6+1.7+0.6\text{ m}}{3}=\frac{4.9}{3}=1.6$$

Table 3: Reduction rate per month along traverse three

Zone	Average past (2009)	Average present (2019)	Reduction (R) = 2019 - 2009	Reduction rate per year (RRpY) = $\frac{R}{10}$	Reduction rate per month (RRpM) = $\frac{RRpY}{12}$
A	4.1	2.6	1.8	0.18	0.01
B	3.5	1.7	1.9	0.19	0.02
C	3.0	0.6	2.4	0.24	0.02

Note: All parameters are in meters

Using Equation (4):

Traverse average 3 (TRA) = $\frac{0.01+0.02+0.02}{3}=0.02$ m

Therefore, average local reduction trend/rate per month in the study area =

$\frac{0.02+0.03+0.02}{3}=0.02$ m

4. CONCLUSION

This study reveals that time lapse has shown the effect of the contaminant to be completely or partly removed along VES 2, 6, 9, 10, 11, 12 and also given an insight of the rate of biodegradation of contaminant of this nature in a typical basement complex of this nature. The rate of biodegradation of the contamination in traverse 1, 2, and 3 is on average 0.02 m, 0.02 m and 0.02 m per month. Generally, the finding reveals that overtime time lapse will allow the gradual removal of hydrocarbon, as revealed in this study an average of ten years is enough to completely remove or near completely remove the effect of hydrocarbon contaminant of this nature, and that the rate of biodegradation of the contamination in the study area and areas of like geological strata is averagely 0.02 m per month.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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