SUBTERRANEAN EXPLORATION USING INTEGRATED GEOPHYSICAL TECHNIQUES TO DISCOVER AN ACCEPTABLE PLACE FOR SITING VIABLE GROUNDWATER WELL AT TAKOWANGWA AREA, NIGER STATE, NIGERIA

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Abstract
A subterranean exploration survey involving Electrical Resistivity (ER) and Induced Polarization (IP) techniques using Vertical Electrical Sounding (VES) by way of Schlumberger electrode configuration was carried out to locate acceptable place for siting viable well for the purpose of domestic groundwater demands within the study area (between latitudes 9°18.116′ N and 9°17.185′ N and longitudes 5°04.272′ E and 5°04.105′ E). The field data was inverted to produce Iterated Graphs, Log tables and models (phase pseudo-sections) representing subterranean resistivity and chargeability values. The IP was presented in the form of 2-D Phase Pseudo-cross sections and Chargeability cross-sections with their possible geologic meanings and the ranges in chargeability values, layer thickness and depth as well. The interpreted ER and IP values were obtained by iterative computer modelling (IPI2WIN) of the Apparent Resistivity and Chargeability data. The data were plotted as phase pseudo and chargeability cross-sections in order to locate viable places with satisfactory groundwater potentials to be sited well within the study area. The results suggested three geo-electric layers. Their equivalent geologic / lithological units suggested weathered and fractured basement as the aquiferous layer along the three profiles investigated. Profile 2 with resistivity variation of 354 to 755 ohm-metre and chargeability variation of 7.14 to 80.20 msec. was the suggested most preferred acceptable place for digging viable wells based on the estimated *aquifer quality, volume (thickness) (20.10 m) with economy of shallower watertable at 10 m. The recommended acceptable digging points were VES points 4 and 5 along the profile 2. The third Profile even though with thicker aquifer zone (21.82 m) was still suggested as the second priority place based on the economic challenge on the well digging at deeper watertable zones (30 m). However, the first profile was not viable despite all its favourable parameters of highest aquifer thickness (30.21 m) and shallower watertable (15 m) compared to profile 2. The proximity of this profile 1 to the dumpsite eroded its aquifer quality by the delineated traces of leachate contaminant up to the water table. Immediate ban and refill of all the wells along this bearing was among the recommendations.*

Keywords: *Aquiferous-layer, Iterated-graph, Chargeability, VES, IP*

Introduction
The groundwater quality has suffered some negative challenges from undesirable human activities, such as; indiscriminate dumping of refuse, wrong siting of locally hand dug wells, lack of treating underground water from such vulnerable groundwater sources before consumption and others. All these affect the original quality status. Groundwater is one of the necessary alternative to surface water sources in every community, most especially in the developing Countries like Nigeria and particularly, the study area. The groundwater existence and distribution over any given area is function of the local and regional geology, hydrogeological setting and the nature of the activities within the land (Akinlalu & Afolabi, 2018). Previous research at Kan Kurmi in north central basement complex of Nigeria also has it that groundwater is mostly found within subterranean areas of weathering and fracturing which often are not continuous in vertical and lateral extent (Arabi *et al.,* 2011).

In the study area also as observed in other similar areas by numerous researchers, unregulated landfills are commonly located adjacent to large residential settlements, releasing harmful contaminants into a leachate and thereby polluting underlying aquifers (Arabi *et al.,* 2011; Bello *et al.,* 2019; Folorunso, 2017 & Hasan *et al.,* 2019). Hence the need to explore the study area subterranean for locating viable groundwater sources far or free from such dumpsite effects.

The escalated rate of population increases in the study area due to the very lucrative agricultural and marketing activities has induced a growing demand for groundwater in Takowangwa areas of Niger State. This escalated groundwater demand within the study area and non-availability of sufficient boreholes or other sources of clean water either from government or any other source has also forced the poor community to site hand dug wells at wrong or vulnerable locations. David, (2013) identified rapid urbanization, agricultural and industrial activities as major contributors of pollutions to groundwater sources. In addition, unavailability of data such as geophysical information on groundwater quantity, hydrology, state of aquifer and withdrawal limits had also contributed to the unsustainable use of groundwater in Nigeria. The study area is underlain by rocks of the Nupe Basement Complex which is overlain by the sedimentary terrain consisting of essentially conglomerates, sandstones and claystones of Campanian to Maastrichtian age (Yusuf *et al.,* 2018). The major occupational activities of the settlers (who are mostly poor and peasant farmers) within the study area inducing such domestic demand for clean water is farming and agricultural produce marketing. Consequently, this lack of clean water supply thus restricted them to only such faulty or vulnerable groundwater sources, thereby exposing the entire community to descent health challenges. In an effort to improve the quality of health and the living standard of the affected community, provision of sustainable and clean water is an ultimate goal which must be pursued within the study area. There is therefore, every need to scrutinize the aquifer potential zones by way of considering its quality, quantity and economy of the well digging. In a bid to address such challenges, integrated geophysical techniques of Electrical Resistivity (ER) and Induced Polarization (IP) were carried out, at the study area to determine acceptable places for digging wells, which will serve as source of viable groundwater supply for the community for domestic usage purposes only.

It has been evident that the application of geophysical techniques such as VES and IP has been successfully utilized to measure aquifer properties that had led to the acceptable positioning of numerous important sources of clean groundwater for human consumption, agricultural purposes and other utilities (Mohammed *et al.,* 2012). The application of geophysical techniques on the search for groundwater and its quality status is based on the principle that certain physical properties of rocks change considerably with water content in them (Ibrahim *et al.,* 2019). The point of changes in the physical properties reveal a physical boundary characterized by variation in density, conductivity and elastic properties (Muhammad *et al.,* 2019). These variations make ER, gravimetric, IP and seismic methods of geophysical prospecting a useful tool in groundwater exploration. Each of these methods has varying degree of success in furnishing useful information regarding groundwater exploration (Yusuf, 2016). Out of all these geophysical methods, ER and IP has been reported to possess important attributes of responding to different materials than seismic and other methods specifically to overburden saturation and salinity of subsurface units (Olatunji *et al.,* 2017). All of these put into consideration, gave birth to this research which was aimed at exploring the subterranean to discover an acceptable place for siting viable well for the purpose of domestic groundwater demands using integrated geophysical techniques at Takowangwa area, Niger State, Nigeria. This was planned to be achieved through the below set down objectives:

(i) Delineation of the subterranean physical properties (resistivity and chargeability), which strongly influence groundwater yields, quality and quantity estimations
(ii) Detection of the dumpsite effects on the aquifer zone within the study area
(iii) Delineation of the variation in watertable, aquifer depths and thickness within the study area
(iv) Determination of the most viable place for digging groundwater well for the purpose of domestic usage within the study area.

Theoretical background of ER and IP

Electrical Resistivity: When the subterranean is in-homogenous, the resistivity will vary with relative positions of the electrodes and any computed value is called apparent resistivity (equation 1) and will be a function of the in-homogeneity (Olorunfemi & Oni, 2019).

$$\rho = \; = \frac{2\pi\Delta V}{I}\mathrm{K} \qquad (1)$$

The electric potential ΔV across electrodes at the surface of a uniform half-space (homogeneous ground) of resistivity **ρ** (referenced to a zero potential at infinity). The current **I** may be positive (if into the ground) or negative. For arrays, the potential at any voltage electrode is equal to the sum of the individual contributions from the current electrodes. In a four-electrode field survey over homogeneous ground the expression for the geometric factor (**K)** is as given by equation (2).

$$\mathrm{K} \;=\; \frac{1}{\frac{1}{AM}-\frac{1}{BM}-\frac{1}{AN}-\frac{1}{BN}} \qquad (2)$$

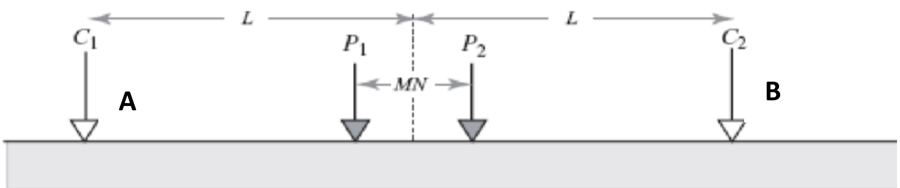


Fig. 1: Schlumberger array

Induced polarization (**IP**) is a Geophysical Imaging Technique used to identify the electrical chargeability of subterranean materials, such as groundwater, ore, etc., the polarization effect was originally discovered by Conrad Schlumberger when measuring the resistivity of rock (Olorunfemi & Oni, 2019).

The (IP) method is based on a current-stimulated electrical phenomenon observed as a delayed voltage response in subterranean materials. The IP effect is observed as a residual voltage decay after the current flow is interrupted (time domain IP) or as a frequency-dependent resistivity (frequency domain). In the time domain, the voltage decay is recorded during a time interval equation (1):

$$\Delta t = t_2 - t_1 \text{ (ms)} \qquad (3)$$

after the current flow is interrupted. The calculated parameter is the chargeability, given by equation (2);

$$\mathrm{m} \;=\; \int_a^b V_t(t)dt \qquad (4)$$

The first step in interpreting data in electrical tomography is to construct a pseudo cross-section. This is obtained by plotting the value of the apparent resistivity measured at the centre of the array and at a depth dependent on the spacing between the electrodes (Olorunfemi & Oni, 2019).

Study Area
The study area (Figure 2) is located at the eastern part of the Takowangwa Area behind the New Central Mosque specifically between latitudes 9°18.116′ N and 9°17.185′ N and longitudes 5°04.272′ E and 5°04.105′ E. It is situated along Lagos – Kaduna road in Mokwa Local Government Area of Niger State, Nigeria. It experiences two distinct seasons, the Dry and Wet seasons. The annual rainfall varies between 1,000 to 1,200 mm. the duration of the raining season ranges from 150 to 210 days. The mean maximum Temperature remains high throughout the year, hovering about 32^{o} F, particularly in March and June. However, the lowest minimum temperature occurs usually between Dec and Jan when most part of the state come under the influence of the tropical continental air mass which blows from the north. Dry season commences in October (Mohammed, 2018).

Fig. 2: Study location on the topographical map of Mokwa. (Google map 2020)

Material and Methods

Materials
The data acquisition for the two geophysical techniques (ER and IP) were achieved by the use of ABEM Terrameter SAS 4000 with its accessories during the field work.

Methodology
The survey methods for the two techniques (ER & IP) were combined utilizing the advantage of the terrameter capacitive facility of operating at multiple modes for an electrode layout. Electric current was transmitted into the subterranean through two current electrodes and the voltage was monitored through two other potential electrodes using Schlumberger electrode configuration. In this combined survey, resistivity, chargeability and other capacitive physical properties of the subterranean materials were measured. The IP technique provided additional information about the spatial variation in the lithology and grain-surface chemistry. The field procedure adopted for the combined ER and IP survey was VES with Schlumberger configuration of AB/2 maximum current electrode spacing of (1 – 100) m. The survey was conducted along 3 profiles containing 15 VES points with maximum profile length of 100 m. The first profile was taken at 150 m away from an existing dumpsite within the study area in order to determine the possible dumpsite effect on the watertable. The second profile was taken at a further distance of 700 m away from the dumpsite while the third profile was at 1000 m away from the dumpsite. The preference

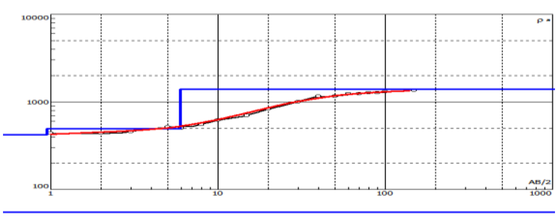
of the Schlumberger configuration over others was because of its sensitivity to subsurface in-homogeneities (Yusuf *et al.,* 2018). Coordinates of each profile, resistivity, chargeability and other parameters were recorded on the Datasheets. Necessary precautions were taken and most of the field challenges encountered were resolved on the spot instantly. Thereafter the field data was further processed using computer software, the output of which were the geophysical models of the subterranean resistivity and chargeability.

Interpretation Technique
Both the two adopted techniques (ER and IP) are very powerful tool for any subterranean exploration for hydro-geological mapping if properly interpreted (Singh *et al.,* 2009). The ER field data were inverted to produce Iterated Graphs and Log tables representing subterranean ER values. While the acquired IP field data were also inverted to produce the subterranean geophysical models presented in the form of 2-D Phase Pseudo-cross sections and Chargeability cross-sections. Their possible geologic meanings and the ranges in chargeability values, layer thickness and depth were also inferred as well. The field data iteration which led to the interpretations of ER and IP values were obtained by iterative computer modelling (IPI2WIN) (Olorunfemi & Oni, 2019). The field data were transformed into Iterated Graphs, Log tables, phase pseudo and chargeability cross-sections in order to image the most viable groundwater potential points within the study area. The entire results were presented in terms of layer numbers (N) and variations in resistivity values (p), chargeability (η), thicknesses (h) and depths (d) of the geo-electric section for all the three layers.

Results and Discussion
In order to obtain a better perception of the subterranean spatial quality of the studied area, the combined techniques of ER and IP were used. These allowed for the provision of the subterranean geophysical image for the investigated area and by inference revealed the location of a qualitative, quantitative and viable aquifer zones prospected for. This was achieved from the provided detailed information on the combined resistivity and chargeability responses based on depth across the study area. Tables 1 – 3 are the iterated curves with layered log table from the data acquired along profile 1 at VES points 1 - 5 for the ER survey for the area investigated.

Electrical Resistivity Response of the Subterranean Profile 1
From Tables 1 (a – e), it was revealed that the subterranean first layer resistivity along profile 1 varied between 72.60 to 418 Ωm with thickness ranged from 0.12 to 4.99 m and depth variations of 0.90 to 4.99 m. The second layer exhibited resistivity variations which varied from 48.70 to 497 Ωm with thickness ranges from 5.00 to 7.1 m and depth ranged was from 5.12 to 9.99 m. While for the third layer, the resistivity varied between 420 to 1417 Ωm, with thickness varied from 12.16 to 25 m and depth varied from 20.44 to 33.12.

Table 1 (a - e): Iterated field curve and Log Table for VES 1 - 5 of Profile 1 at the Study Area
(a): Iterated field curve and Log Table for VES 1



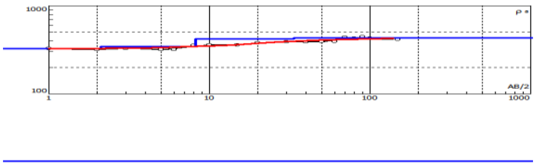
Iterated field Curve

N	1	2	3	4							
ρ	418	497	1391	1399							
h	0.12	5	14.9								
d	0.12	5.12	20.02								
Alt	-0.1200	-2.1100	-20.0200								

Log Table

Where, N is the layer number, ρ is the layer resistivity in Ωm, h is the layer thickness in meter d is the depth to the interface in meter

(b): Iterated field curve and Log Table for VES 2

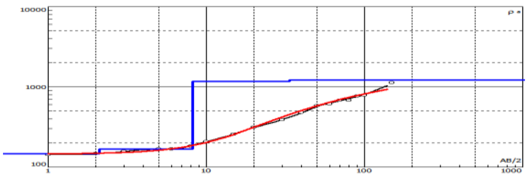


Iterated field Curve

N	1	2	3	4
ρ	326	345	420	432
h	2.11	6.01	25	
d	2.11	8.12	33.12	
Alt	-2.1100	-8.1200	-33.1200	

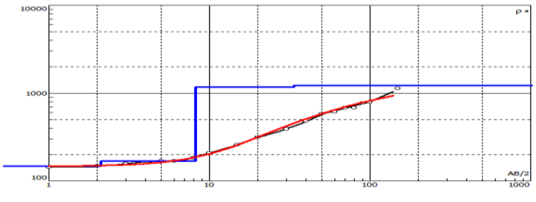
Log Table

(c): Iterated field curve and Log Table for VES 3



N	1	2	3	4
ρ	146.5	166.5	1193	1199
h	4.99	5	12.16	
d	4.99	9.99	22.15	
Alt	-0.7000	-8.1300	-21.1500	

(d): Iterated field curve and Log Table for VES 4

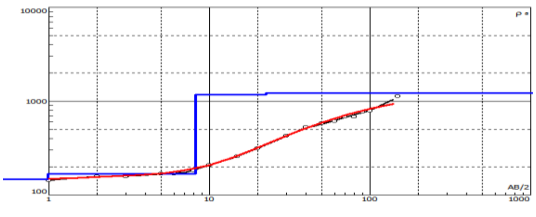


Iterated field Curve

N	1	2	3	4
ρ	151	171	1417	1423
h	2.1	5.94	12.4	
d	2.1	8.04	20.44	
Alt	-2.1000	-8.0400	-19.4400	

Log Table

(e): Iterated field curve and Log Table for VES 5



Iterated field Curve

N	1	2	3	4
ρ	72.6	48.7	1405	1422
h	0.9	7.1	14.23	
d	0.9	8	22.23	
Alt	-0.9000	-8.0000	-22.2300	

Log Table

Induced Polarization Response of the Subterranean Profile 1

Fig. 3 (a and b) revealed the corresponding IP Phase Pseudo cross-section and Chargeability Cross-section for the same VES points 1-5 with maximum electrode spacing of 1 – 100 m at the study area. The chargeability varied between 2.01 to 5.26 msec. with thickness ranged of up to 4.87 m, and depth range to a maximum of 3 m for the first layer.

The second layer chargeability varied between 17.80 and 31.30 msec. with thickness ranged of up to 30.21 m and depth ranged of up to 26.99 m. An IP anomaly indicated by a sharp jump of chargeability values from 5.26 to 17.80 msec. was observed between the first and second layers across VES points 4 and 5. This implied weathered / fractured zone which is favorable to aquifer prospecting (Singh *et al.,* 2009) & (Yusuf *et al.,* 2018). This zone is represented by horizontal horizon made up of green, grey and yellow colors delineated around VES points 1, 2,3, 4 and 5 in (Fig. 3). However, the lower resistivity zone < 49 Ωm with its corresponding chargeability < 18 msec. observed in this layer could be due to dumpsite effect on this reasonable aquifer thickness of 30.21 m.

The third layer exhibited highest chargeability zone in this profile 1. The chargeability varied from 28.30 to 76.00 msec. with maximum thickness of 31.60 m and depth of 13.10 m. The highest exhibited chargeability here which also correlated with the delineated resistivity was inferred to be basement.

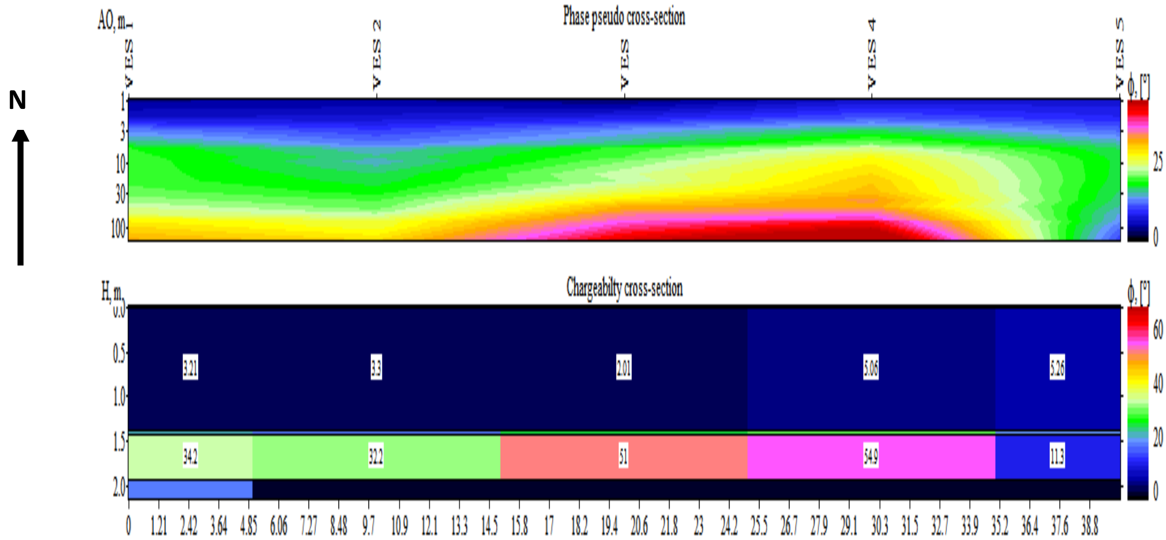


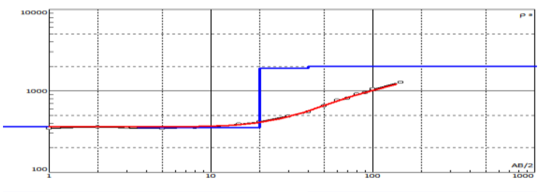
Fig. 3: Phase Pseudo cross-section and Chargeability Cross-section at VES points 1-5 along profile 1 of the Study Area.

Electrical Resistivity Response of the Subterranean Profile 2

Tables 2 (a – e), revealed that the subterranean first layer resistivity along profile 2 varied between 319 to 488 Ωm with thickness ranged from 1.13 to 4.99 m and depth variations of 1.13 to 4.99 m. The second layer exhibited a resistivity variation which ranged from 354 to 755 Ωm with thickness ranged of up to 5.56 m and depth ranged of up to 8.04 m. For the third layer, the resistivity varied between 950 to 1920 Ωm, while thickness varied from 2.97 to 22.47 m and depth varied from 15.03 to 40.11.

Table 2 (a - e): Iterated field curve and Log Table for VES 1 - 5 of Profile 2 at the Study Area

(a): Iterated field curve and Log Table for VES1

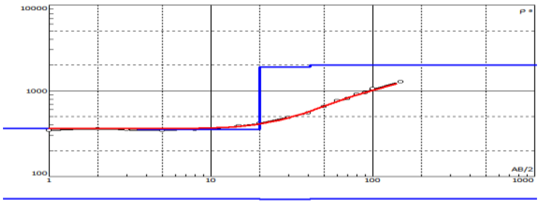


Iterated field Curve

N	1	2	3	4								
ρ	319	354	1894	1899								
h	3.55	14.08	22.47									
d	3.55	17.63	40.1									
Alt	-3.5500	-17.6300	-40.1000									

Log Table

(b): Iterated field curve and Log Table for VES 2

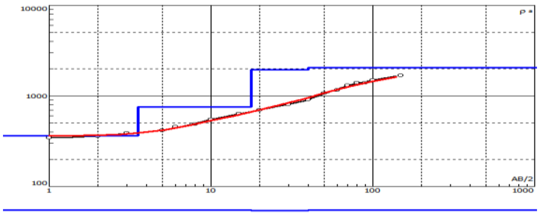


Iterated field Curve

N	1	2	3	4
ρ	428	454	1920	1971
h	3.61	16.49	19.03	
d	3.61	20.1	39.13	
Alt	-3.6100	-20.1000	-39.1300	

Log Table

(c): Iterated field curve and Log Table for VES 3

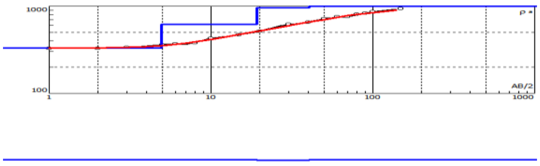


Iterated field Curve

N	1	2	3	4
ρ	415	755	1920	1971
h	3.99	14.1	22.02	
d	3.99	18.09	40.11	
Alt	-3.9900	-18.0900	-40.1100	

Log Table

(d): Iterated field curve and Log Table for VES 4

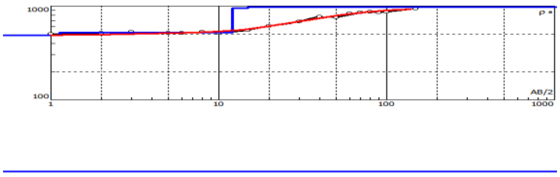


Iterated field Curve

N	1	2	3	4
ρ	330	613	963.18	1017
h	4.99	14.1	21.02	
d	4.99	19.09	40.11	
Alt	-4.9900	-19.0900	-40.1100	

Log Table

(e): Iterated field curve and Log Table for VES 5



Iterated field Curve

N	1	2	3	4
ρ	488	523	950	1011
h	1.13	10.93	2.97	
d	1.13	12.06	15.03	
Alt	-1.1300	-12.0600	-15.0300	

Log Table

Induced Polarization Response of the Subterranean Profile 2

Fig. 4 (a and b) Indicated the Phase Pseudo cross-section and Chargeability Cross-section for VES points 1-5 with maximum electrode spacing of 1 – 100 m for the second profile investigated at the study area. The chargeability varied between 4.96 to 62.00 msec. with thickness ranged of up to 4.99 m, and depth ranged of up to 5 m for the first layer. This low chargeability zone implied claystones and when compared with that of the profile 1 first layer, it is higher than that of dumpsite effect thus could be due to the high subterranean moisture content.

While second layer chargeability varied between 7.14 to 80.20 msec. with thickness ranged of up to 20.10 m and depth ranged of up to 9.69 m. The higher resistivity zone > 319 Ωm with its corresponding chargeability > 4.96 msec. observed in this layer was inferred to be weathered basement. There was also an exhibited IP anomaly indicated by a sharp drop of chargeability values from 62.00 down to 7.14 msec. between the first and second layers. This anomaly inferred fractured zones which are evidences of the aquifer potential of this profile with aquifer thickness of 20.10 m which is free from dumpsite effects. This also correlated well with that of ER anomaly which also dropped from 488 down to 354 Ωm. These well correlated anomalies indicated by sharp variations at layer boundary values usually implied weathered / fractured zones where groundwater are banked (Yelwa, 2015). Considering this reasonable thickness of 20.10 m, the quality and the shallower depth of 9.69 m, this profile could be inferred as the prospected aquifer zone viable for siting well Yusuf *et al.,* (2018) and Olatunji *et al.,* (2017). This zone is represented by horizontal horizon made up of green, grey, yellow and pink colors delineated around VES points 4 and 5 in (Fig. 3).

The chargeability variation delineated varied from 29.70 to 55.70 msec. with maximum thickness range of 37.23 m and depth range of 40.11 m for the third layer. This highest resistive and chargeability zone was inferred to be weathered basement Yusuf *et al.,* (2018).

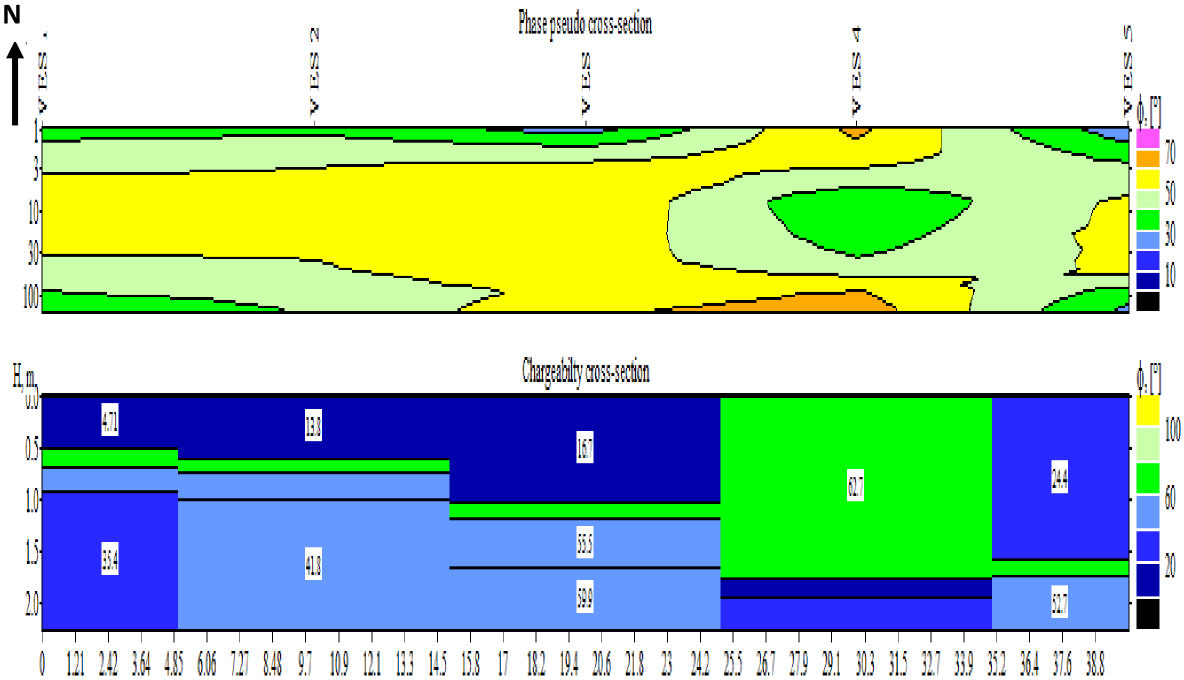


Fig. 4. Phase Pseudo cross-section and Chargeability Cross-section at VES points 1-5 along profile 1 of the Study Area.

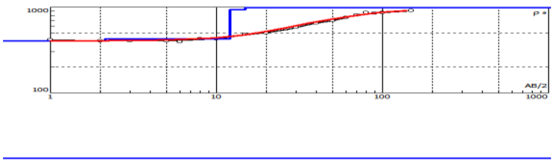
Electrical Resistivity Response of the Subterranean Profile 3

Tables 3 (a – e) are the iterated curves with layered log tables for the data acquired along profile 3 for VES points 1 – 5 assessed within the College farm site.

Tables 3 (a – e), revealed that the subterranean first layer resistivity along profile 3 varied between 400 to 427 Ωm with same thickness and depth variations of 0.23 to 2.97 m. The second layer exhibited a very slight resistivity variation which ranged from 420 to 525 Ωm with maximum thickness ranged of 9.75 m and depth ranged of 9.72 m. The higher resistivity zone here deduced weathered conglomerates with fractured zones Yusuf *et al.,* (2018). For the third layer, the resistivity varied between 925 and 1618 Ωm, while thickness varied from 2.98 to 12.35 m and depth varied from 12.35 to 15.72. The highest resistivity zone here implied weathered basement Yusuf *et al.,* (2018).

Table 3 (a - e): Iterated field curve and Log Table for VES 1 - 5 of Profile 3 at the Study Area

(a): Iterated field curve and Log Table for VES1

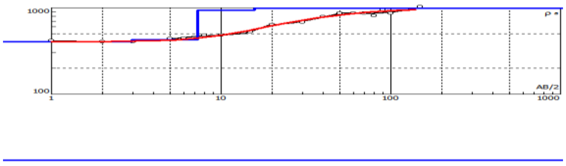


Iterated field Curve

N	1	2	3	4
ρ	400	423	925	956
h	2.11	9.94	2.98	
d	2.11	12.05	15.03	
Alt	-2.1100	-12.0500	-15.0300	

Log Table

(b): Iterated field curve and Log Table for VES2

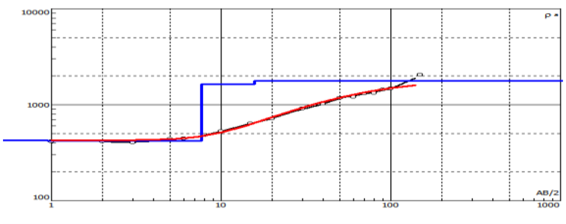


Iterated field Curve

N	1	2	3	4
ρ	423	525	982	988
h	2.97	4.28	8.47	
d	2.97	7.25	15.72	
Alt	-2.9700	-7.2500	-15.7200	

Log Table

(c): Iterated field curve and Log Table for VES3

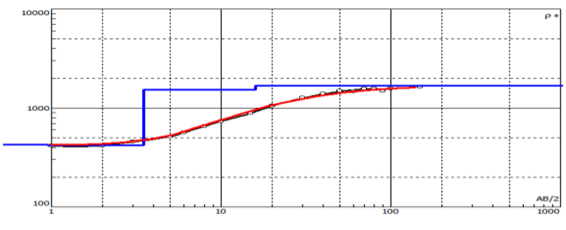


Iterated field Curve

N	1	2	3	4
ρ	412	420	1618	1623
h	0.55	6.66	7.91	
d	0.55	7.21	15.12	
Alt	-0.5500	-7.2100	-15.1200	

Log Table

(d): Iterated field curve and Log Table for VES4

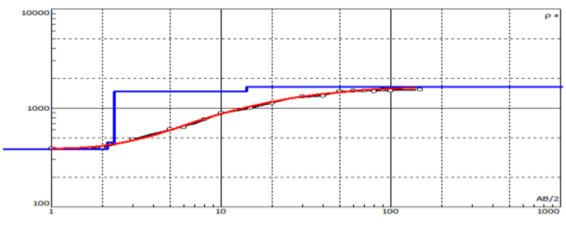


Iterated field Curve

N	1	2	3	4
ρ	419	443.98	1520	1561
h	0.23	2.54	12.35	
d	0.23	2.77	15.12	
Alt	-0.2300	-2.7700	-15.1200	

Log Table

(e): Iterated field curve and Log Table for VES5



Iterated field Curve

N	1	2	3	4
ρ	427	448	1464	1466
h	2.14	0.19	11.82	
d	2.14	2.33	14.15	
Alt	-2.1400	-2.3300	-14.1500	

Log Table

Lithology and Resistivity logs

In Figure 5, the summary results of the electrical resistivity study are presented as geo-sections for the three profiles. The geo-sections enabled the identification of the various lithological units within the study area. These were utilized to determine the pollution and its depth along profile 1, the quality of groundwater and viable acceptable place for siting viable well among the rest two profiles across the study area. The geophysical VES data obtained showed that there is massive dumpsite effect on aquifer along profile 1 affecting the portability of the groundwater from sources along that profile. Table 1(e) shows that the pollution is seen to occur as indicated by very low resistive anomaly of 48.7 ohm-m up to an average depth of 15 m. The result of the data agrees with a similar assessment of another neighborhood area by Yusuf *et al.* (2018), who discovered dumpsite effects on groundwater by applying electrical resistivity and geochemical methods to monitor soil and groundwater pollution at Tifinmadza, Mokwa Town, Niger State, Nigeria.

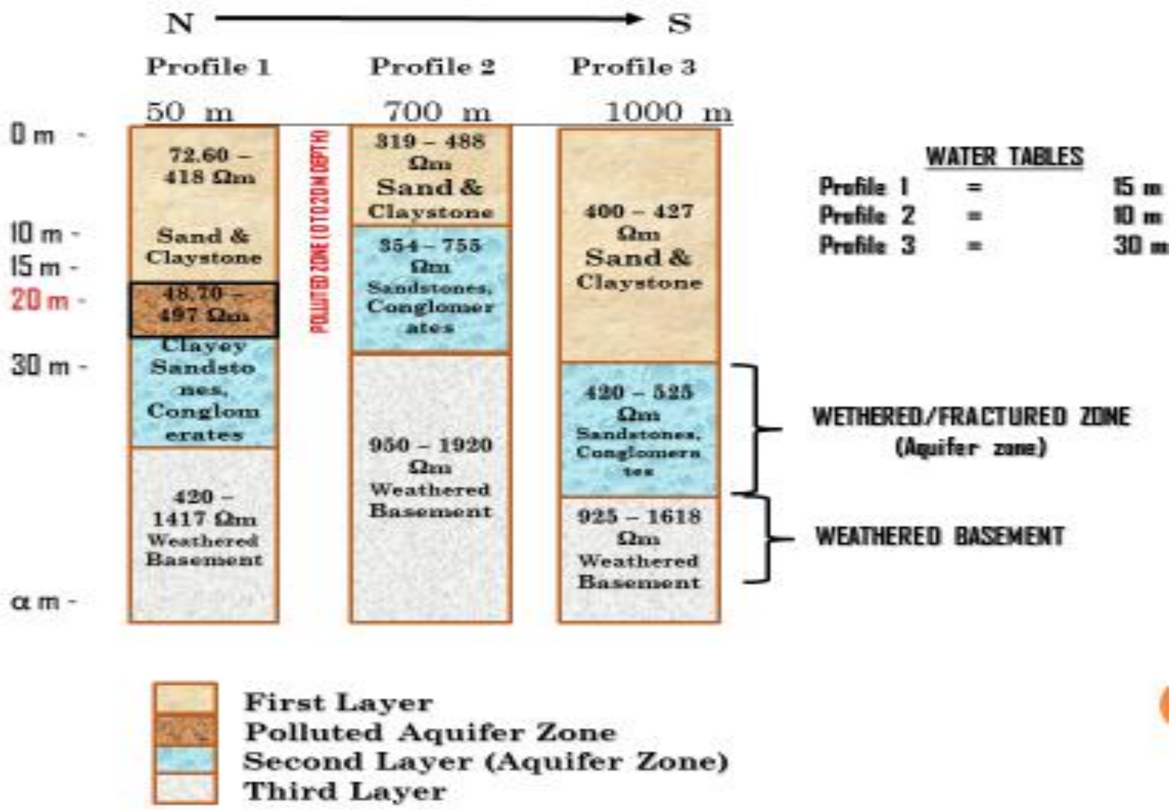


Figure 5: The Subterranean Lithological geo-electric section of the study area

Induced Polarization Response of the Subterranean Profile 3

Fig. 6 (a and b) Indicated the Phase Pseudo cross-section and Chargeability Cross-section for VES points 1-5 with maximum electrode spacing of 1 – 100 m at the study area. The chargeability varied between 0.01 to 90.00 msec. with maximum of both thickness and depth ranged of 5 m for the first layer. The very low IP anomaly could be due to dumpsite effect as evident by its proximity to the dumpsite area.

The second layer chargeability varied between 2.67 and 55.20 msec. with thickness ranged of up to 21.82 m and depth ranged of up to 91.05 m. Higher chargeability > 0.01 msec. was observed in this layer as equally revealed by its corresponding resistivity zone > 400 Ωm. This and the evidence of an IP anomaly exhibited by sharp drop in chargeability values from 55.20 down to 8.69 msec. between the second and third layers inferred prospected aquifer zone free from dumpsite effect. This delineated IP anomaly also correlated with that of ER anomaly which also dropped from (925 down to 525) Ωm between the same layers. These anomalies indicated by sharp variations in resistivity and chargeability values usually implied weathered / fractured zones favorable to groundwater reservoir (Olorunfemi & Oni, 2019). This profile has a very reasonable aquifer thickness (21.82 m) however, considering the economy of digging to the depth of the watertable (30 m) compared to that of the second profile (10 m), this could be recommended to be the second viable place. The prospected aquifer zone was represented by horizontal horizon made up of green, grey and yellow colors delineated around VES points 3 in (Fig. 3).

The chargeability variations delineated varied from 8.69 to 32.40 msec. with maximum thickness range of 21.82 m and depth range of 91.05 m for the third layer. This zone exhibited the highest resistivity and chargeability implied weathered basement complex for the subterranean investigated. This was observed around VES points 2 and 5.

The interpretations of these Iterated curves, log tables, phase Pseudo cross-sections and the Chargeability cross-sections enabled the derivation of three geologic sections (Mohammed *et al.,* 2012). These geologic sections were the topmost layer which consists mainly of sands and claystones followed by a formation of clayey sandstones, conglomerates, and a weathered / fractured layer, and the third section consisting of fresh basement. The qualitative interpretation indicated that the weathered/fractured basements constituted the main aquifer units delineated within the study area.

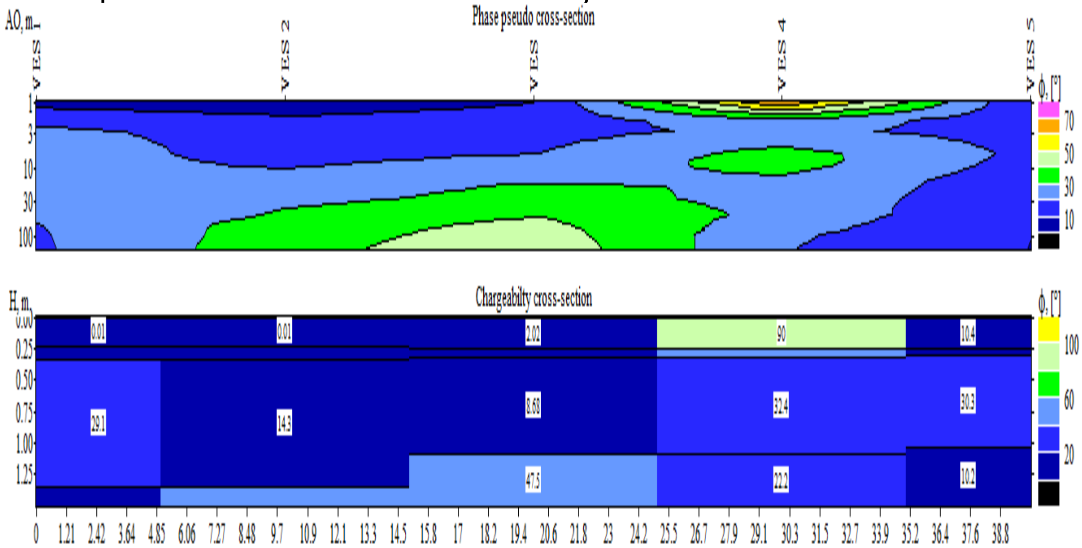


Fig. 6, Phase Pseudo cross-section and Chargeability Cross-section at VES points 1-5 along profile 1 of the Study Area

Table 4 revealed the summary of some of the powerful delineated aquifer parameters which will influence the discovery of an acceptable place for siting viable wells within the study area. Profile 1 appeared to possess the highest potential considering its highest aquifer thickness of 30.21 m when compared to profiles 2 and 3. However, both the ER and IP responses were not favorable for the profile due to the revealed leachate invasion up to aquifer zone. This has ruled out its consideration based on the aquifer quantity parameter. The second profile therefore carried the first priority place when compared to the third profile. This is because although the third profile has higher aquifer thickness but economically the variations (1.72 m) in the thickness compared to the cost of digging the well gave profile 2 (shallower 10 m) an edge over the third profile (deeper 30 m). However, if the demand shifted to commercial viability, profile 3 might be better in terms of the overburden thickness and other parameters.

Table 4: Aquifer parameters across the three profiles within the study area

Profile	Watertable (M)	Aquifer Thickness (M)	Aquifer Depth (M)	Remark
1	15	30.21	26.99	Not viable due to leachate invasion
2	10	20.10	9.69	Most Acceptable Place
3	30	21.82	91.05	Second Option Place

Conclusion and Recommendations

The groundwater prospection in ER and IP conducted at the study area, Takowangwa area, made it possible to provide information on the different heterogeneities present in the surrounding subterranean prospected, in this case the acceptable places for siting wells. Indeed, it was able to highlight the places with the highest aquifer potential (profile 2) based on the residents' economy status, the estimated aquifer quality, volume (thickness) (20.10 m) and cheaper well digging cost at shallower watertable (10 m). The recommended digging acceptable places are VES points 4 and 5 along profile 2. The third Profile carried the second priority place based on the quality, thickness and the well digging cost.

Of all the three geologic layers, the weathered basement and the fractured basement were considered as the main aquifer components because of their importance as water bearing units in basement Complex (Akinlalu & Afolabi, 2018). From the result of the interpretations, it became conclusive that groundwater, in part of the study area, is accessed mainly in form of shallow (hand-dug) wells. Also, the well water withdrawal activities in this area are mostly un-regulated thereby subjecting the groundwater sources to avoidable abuses and pollutions. Therefore, the acceptable places recommended with highest priority for consideration when digging the well was profile 2 at VES points 4 & 5 based on the aquifers quality (free from dumpsite effect), thickness and watertable depth/well digging cost in relation to the economic status of the resident of the study area. The order of preferential hierarchy based on the same considerations were: P2 > P3. However, if the need arises for the groundwater exploration to be extended beyond domestic usage to commercial purpose (larger groundwater volume demand), the higher cost of well digging at deeper watertable (30 m) might give way for the higher aquifer thickness (21.82 m). In which case the most viable place should be at VES point 3 along profile 3. (P1 = 0) - Not Acceptable/Noneviable profile. Consequently, based on the eroded quality of groundwater along this profile, all wells that fall within such bearings (Profile 1) should be banned and refilled immediately and any further well digging along the profile / bearing should be disallowed by the relevant authorities. Proper adherence to the regulation of groundwater resources and its protection under the land use act and other relevant legislations should be considered very instrumental to any sustainable groundwater exploitation.

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