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Geophysical Investigation of the Causes of Borehole Failure in the Crystaline Basement Complex: A Case Study of Kaura Area of Kaduna State, Nigeria

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Abstract
Vertical Electrical Soundings (VES) using Schlumberger array were carried out at different points along five (5) profiles. This research investigates the causes of massive borehole failure at Kaura area of Kaduna state using the resistivity tomography techniques. Terrameter SAS300 is the instruments used to acquire the data. A total of 19 boreholes are functioning, while 31 boreholes are non-functioning within the area. The investigation has portrayed the possible factors which are most probably causative to borehole failures in the area which involves the design and construction, groundwater potential/hydrogeological factors and operational and maintenance factors. It was found out that it is possible for one factor to lead to the other. For example, a borehole poorly designed, constructed and completed could result in sand/clay pumping and eventually affect the rubber seals in the hand pumps or the impellers in the case of submersible pumps. The boreholes tap the weathered and fractured basement aquifers of the area with yields ranging from 2litre/min to 20litre/min. However, yields from Sandy soil aquifers were found to be extensive. The survey shows that boreholes with initial recorded yield less than 10litre/min have failed over time. The survey reveals that the areas where wells and boreholes are drilled through sandy soil and fracture zones have sustainable aquifers for groundwater exploitation, while boreholes that are constructed through clayey formation usually fail.
Keywords: Resistivity1, Kaura2, Borehole failure

1. Introduction

In Nigeria as well as many other African countries, the provision of water for the teeming population is usually stated as one of the cardinal objectives of the Government. In Kaduna, specifically, many water provision initiatives have been undertaken over the years and although achievements have been recorded in certain areas, water provision in the state cannot, as is evident from the statistics below, be described as a complete success story. It is estimated that there are currently about 1805 boreholes constructed by the Ministry of Water Resources, covering all Kaduna's 23 LGAs. In addition, The Rural Water Supply and Sanitation Agency (WATSAN), Kaduna state, are believed to have constructed an additional 400 boreholes. However in 2011, it was reported that only 20% of the total boreholes are active while service coverage is estimated at 11% and 32% of the rural and urban population respectively (Eduvie et al, 2004).

Handpump-equipped boreholes are one of the most common water supply technologies adopted in the study Area, but often demonstrate low levels of sustainability (Akintorinwa et al, 2009). In addition to operational problems with the pump, the borehole itself may cease to provide adequate quantities of safe drinking water only a short time after construction. This can have a significant negative impact on poor rural communities, particularly in the dry season when alternative water sources are scarce.

2. Survey Area

Kaura area lies between latitudes $9^{o}30'$ N and $9^{o}45'$N and longitudes $8^{o}20'$E and $8^{o}35'$E. The area has an approximately landmass of 770 km^2 within the crystalline hydrogeological province of northern Nigeria (Figure1) belonging to the Younger Granite and Basement Complex suites. These rocks lack primary porosity where groundwater could accumulate for exploitation. For these rocks to store water there must exist in them secondary porosity, which invariably results from weathering and fracturing. However, the spatial distribution and depth of this kind of porosity vary from one location to another, hence the occurrence of groundwater in these rocks is sporadic and borehole siting for its abstraction in this geological terrain is often difficult (Alan et al, 2000), this is why for this study, to achieve high resolution images of the subsurface the resistivity tomography technique is employed.

The area is mainly accessible through the Jos –Kagoro Kaduna road that runs East-West. In the central part of the study area, Rail line traverses from Kafanchan-Kagoro to Jos Terminus in Plateau State.

There are fifty (50) boreholes within the survey area (Figure2). Out of the total of 50 schemes inspected, 19 are mechanized with submersible pumps, while 31 were fitted with hand pumps. A total of 15

boreholes are functioning, while 35 boreholes are non-functioning.
More details are presented in table 1.

Table 1. Status of boreholes inspected in the study area.

No. Of Pump	Functioning	%	Non-Functioning	%	Type of Scheme
31	7	22.6	24	77.4	Hand Pump
19	8	42.1	11	57.9	Motorized

Plate1. Picture of non-functional boreholes in the study Area.

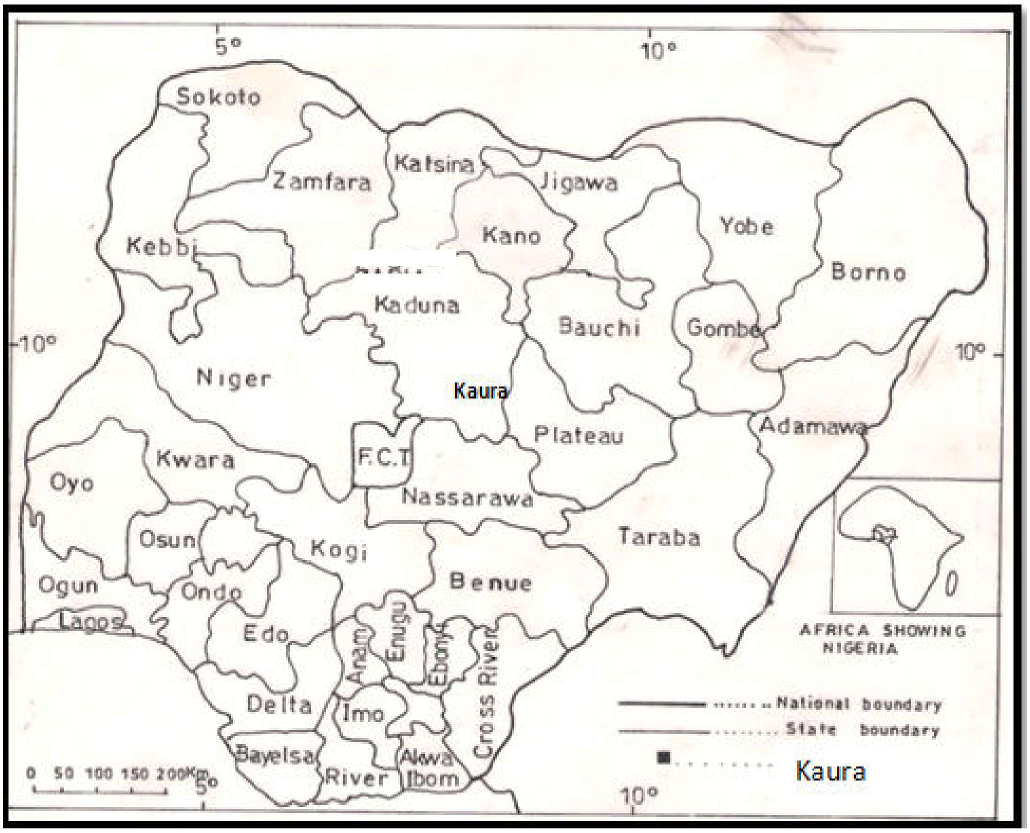


Figure1. Map of Nigeria showing Kaura Area of Kaduna state.

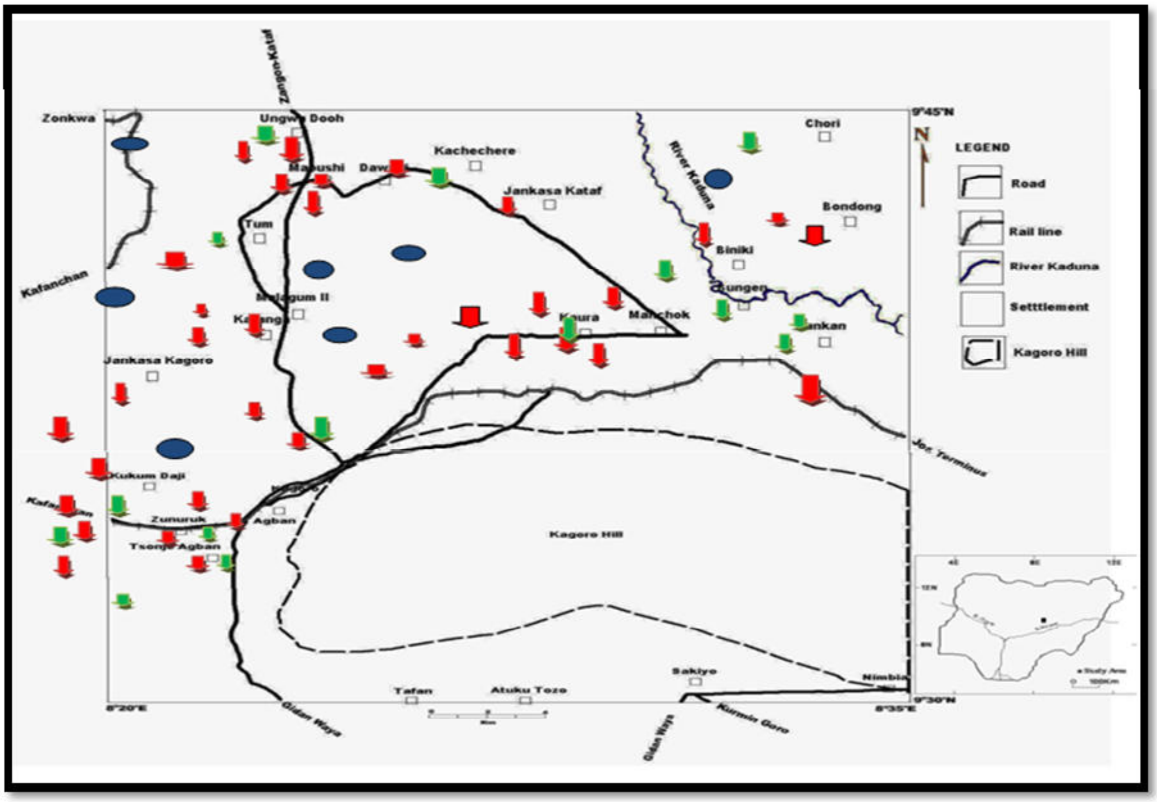


Figure2. Map of Kaura showing the functional (coloured green) and non-functional boreholes (coloured red).

3. Geology of the Study Area

The study area is made up of the rocks of the Migmatite-Gneiss Complex, Gneiss, Younger Metasediments, Older Granites, Younger Granites and Newer Basalts. The distribution of the various rock types is as shown on the geological map of the area (Figure 3). Basement rocks that occur in the study area could be classified into:

1. Migmatites-Gneiss Complex
2. Schists
3. Older Granites
4. Younger Granites
5. Newer Basalts.

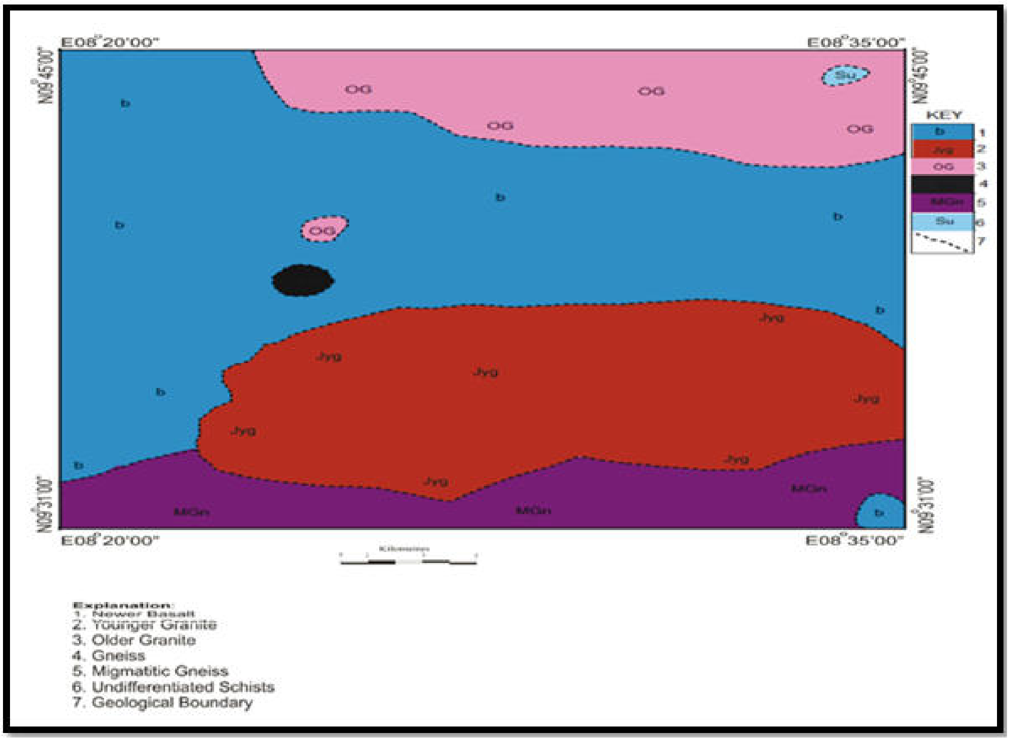


Figure3. Geological map of the Kaura.

4. Objectives of the Survey

The goals of this study are:

- To identify the primary causes of borehole failure within the survey area and recommend appropriate solution.
- To analyse borehole logs collected during borehole drilling and development in order to determine the relationship, if any, between each data variable and subsequent failure of boreholes, and so determine whether these data can be used to predict or mitigate against failure.
- Identifying existing field practice(s) that may have a detrimental effect on borehole sustainability, in order to recommend any appropriate adjustments to field procedures.
- To map out the subsurface layers along the selected profiles in the survey area.

5. Materials and Method

The method of study includes geophysical investigation using resistivity method and analysis of records on boreholes located within the area. In the DC resistivity surveying, using the Schlumberger array (figure4), an electric current is passed into the ground through two outer electrodes (current electrodes), and the resultant potential difference is measured across two inner electrodes (potential electrodes) that are arranged in a straight line, symmetrically about a centre point. The ratio of the potential difference to the current is displayed by the Terrameter as resistance. A geometric factor (G) in metres is calculated as a function of the electrode spacing. The resistance reading obtained by the Terrameter is multiplied by this factor to give an apparent resistivity value. The electrode spacing is progressively increased, keeping the centre point of the electrode array fixed. Schlumberger arrays are relatively sensitive to vertical variations in the subsurface resistivity below the centre of the array but less sensitive to horizontal variations in the subsurface resistivity (Barker, 2001). The arrays have moderate depths of investigation and generally strong signal strength which is inversely proportional to the geometric factor used in calculating the apparent resistivity values (Afuwai, 2014). The major limitation of these arrays is the relatively poor horizontal coverage with increased electrode spacing.

Vertical Electrical Soundings (VES) using Schlumberger array were carried out at different points along five (5) profiles. Each profile has its azimuth N-S, E-W, NW-SE or NE-SW (guided by the emplaced structures). The largest Current electrode spacing AB used was 200m, that is, $\frac{AB}{2}$=100m. The principal instrument used for this survey is the ABEM Signal Averaging System, (SAS 300) Terrameter. The resistance readings at every VES point were automatically displayed on the digital readout screen and then written down on paper. The geometric factor, K, was first calculated for all the electrode spacings using the formula; $K = \pi (L^2/2l - b/2)$, for Schlumberger array with $MN=2l$ and $\frac{AB}{2}=L$. The values obtained, were then multiplied with the resistance values to obtain the apparent resistivity, ρ_a, values. Then the apparent resistivity, ρ_a, values were plotted against the electrode spacings $(\frac{AB}{2})$ on a log-log scale to obtain the VES sounding curves using a computer software *IPI2win+IP*.

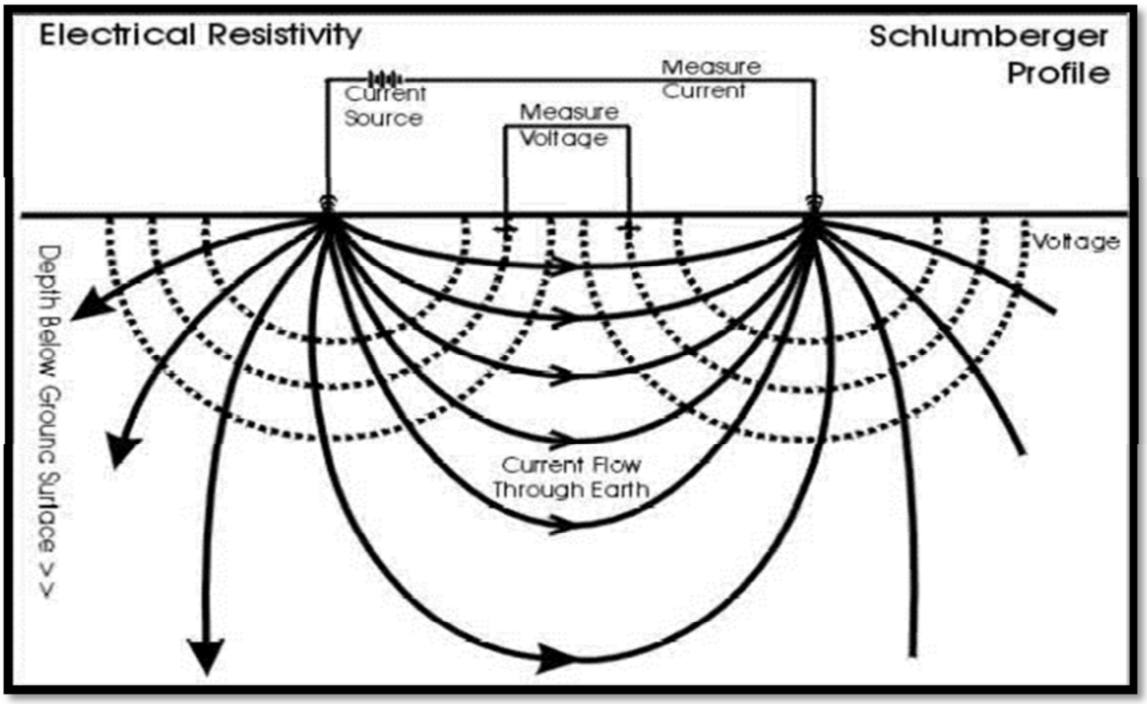


Figure4. The Full-Schlumberger Array

6. Variables Investigated

In order to determine the possible causes of borehole failure, the following variables were analysed for each borehole.

These are:

- Initial recorded yield of borehole.
- Borehole depth when drilled.
- Season during which drilling took place.
- The recorded static water level of the area when the borehole was drilled.

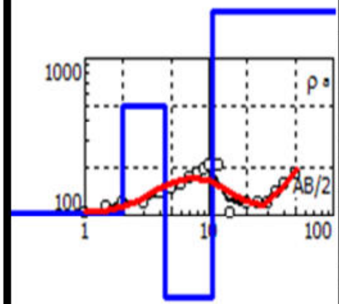
7.0 Results and Discussions

The data analysis was performed using IPI2Win+IP method for the automatic interpretation of schlumberger vertical electrical sounding. This method was used to obtain the model for the apparent resistivity of each sounding point. The true resistivity models at every sounding point along each profile were used to produce the geoelectric Pseudo section for that profile.

Three resistivity sounding curve types were obtained from the studied area and these are the H ($\rho1>\rho2<\rho3$), A ($\rho1< \rho2<\rho3$) and KH ($\rho1>\rho2< \rho3>\rho4$) type curves. The VES profiles were correlated and merged with respect to the direction of the profile line and the closeness of the individual VES stations. On the pseudo sections, the top horizontal scale represents the names of the sounding points, while the bottom horizontal ruler represents the coordinates of the sounding points. Vertical lines mark the sounding point given as *AO (m)* being equivalent to half the current electrode spacing, *AB/2*.

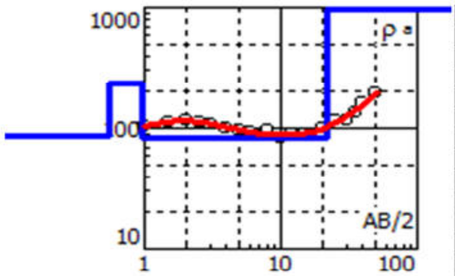
The interpretation made for each tomogram is placed by its side. A log of the borehole along each profile and the geology of Kaura Area aided the interpretation.

Based on the IPI2Win's method, the field curves were found to be averagely four layers (figure5). Below are some examples of resistivity models obtained in the survey.



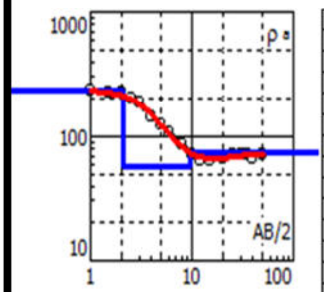
N	ρ	h	d	Alt
1	103	2.02	2.02	-2.019
2	498	2.33	4.35	-4.353
3	26.6	6.42	10.8	-10.77
4	13056			

Where,
N is the number of layers,
ρ is the apparent resistivity,
h is the thickness and
d is the depth to interface of each layer.



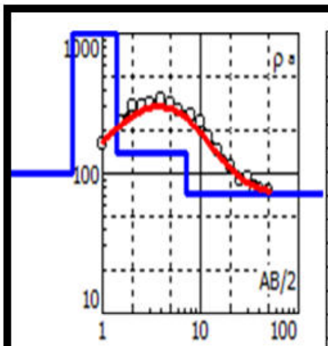
N	ρ	h	d	Alt
1	87	0.549	0.549	-0.5492
2	236	0.405	0.954	-0.9542
3	82.3	20.6	21.6	-21.58
4	1000			

Where,
N is the number of layers,
ρ is the apparent resistivity,
h is the thickness and
d is the depth to interface of each layer.



N	ρ	h	d	Alt
1	239	2.09	2.09	-2.089
2	56.7	7.4	9.49	-9.491
3	75.6			

Where,
N is the number of layers,
ρ is the apparent resistivity,
h is the thickness and
d is the depth to interface of each layer.



N	ρ	h	d	Alt
1	98.8	0.5	0.5	-0.5
2	1012	0.895	1.39	-1.395
3	138	5.81	7.2	-7.202
4	70.5			

Where,
N is the number of layers,
ρ is the apparent resistivity,
h is the thickness and
d is the depth to interface of each layer.

Figure5. Samples of VES curves and interpretations obtained in the survey. Most of the curves show four layer models consisting of the subdivided regolith layer and the basement rock

7.1.0 Interpretations of Pseudo Sections along Profiles

7.1.1 Garaje Profile

The Borehole at Garaje is located at latitude $8^{0}19^{I}53.10^{II}$E, longitude of $9^{0}35^{I}46.91^{II}$N and Elevation of 771m. **The Borehole is functional**. A total of ten (10) VES Points were sounded along a profile of 200m length in the N-S direction across the Borehole location. The Borehole was constructed in the year 2005; it was drilled to a depth of 42m. The recorded sufficient yield of the borehole at the point of commissioning was 15litre/min (KSWB, 2006) which is above the minimum guideline value for a successful borehole. The Pseudo section shows that along the Profile where the borehole is located has an aquifer with thickness of approximately 60m (Figure6). The overburden with a resistivity range of 50-140Ωm constitutes of wet brown sand and sandy clay which correlates well with the borehole log. The weathered basement which is the second layer constitutes of coarse/medium grain sand which slightly differs from that of the Borehole log which is fine grain sand. The resistivity value of the weathered basement layer ranges from 100-250Ωm. The depth to basement varies along the profile; however, averagely it is about 65m. Generally, the geophysical results revealed that the high yielding aquifer is a heterogeneous unconfined aquifer with a good yielding potential which have thick overburden deposition of weathered sand.

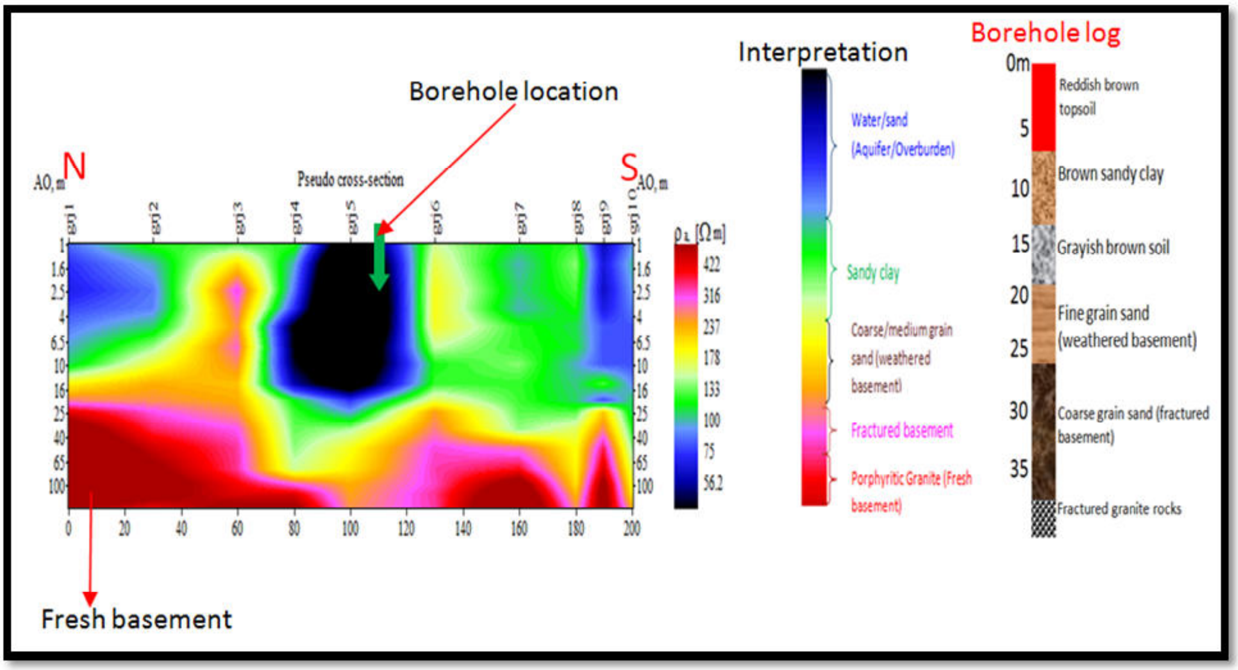


Figure6: Resistivity tomography section for Garaje Profile.

7.1.2 LGEA ZAKWA PROFILE

The Borehole at LGEA Zakwa is located at a latitude of 09^{0}36'35.04"N and longitude of 08^{0}19'31.62"E. The Borehole is non-functional. A total of eight (8) VES Points were sounded along a profile of 200m length in the N-S direction across the Borehole location. The Borehole was constructed by Kaduna State Water Board (KSWB) in the year 1998; it was drilled to a depth of 36m. The recorded initial yield of the borehole at the point of commissioning was 9.5litre/min (KSWB, 2006) which is slightly below the minimum guideline value for a successful borehole. The Pseudo section of this profile (figure7) shows a top layer resistivity value range of 100-1000 Ωm. This variation in the resistivity value from one point to another along the profile is an indication that the degree of weathering of the area varies within the subsurface and also may composed of partly saturated but compacted materials. This layer is underlain by a homogenous low resistivity layer (100Ω m to 180Ωm) at a depth ranging from approximately 4m at the southern part of the profile to about 16m to the northern part. The layer is interpreted as rich in clay. This clay which characterized the layer is a poor aquifer. This suggests that the borehole was drilled through clayey formation which is prone to seasonal volumetric changes (Sands, 2002). Therefore the degree to which a soil expands or contracts is a critical cost factor, particularly for the Borehole sustainability. The clay soil shown on the section occurs at various levels of consolidation. This is in agreement with the interpretation provided in the Borehole log which suggests that the depths to which the borehole is sited are clayey and that the clay formation is significantly active. According to Egwuonwu et al. (2012) and the Council for Geosciences, South Africa (2006), moisture changes lead to swelling and shrinkage of clays, and affect shallow boreholes and foundation of buildings. It has been stated earlier that the Borehole was drilled to a depth of 36m with an initial yield of 9.5litre/min which is relatively shallow and low to sustain the Borehole. Towards the base of the clayey zone (approximately 46m deep), near the fresh basement interface, the proportion of clay significantly reduces. This horizon, which consists of fractured rock, is often permeable, allowing water to move freely. Wells or boreholes that penetrate this horizon can usually provide sufficient water. These facts suggest that the active clayey soils, insufficient depth of drilling and low initial yield most probably have contributed to the failure of the borehole.

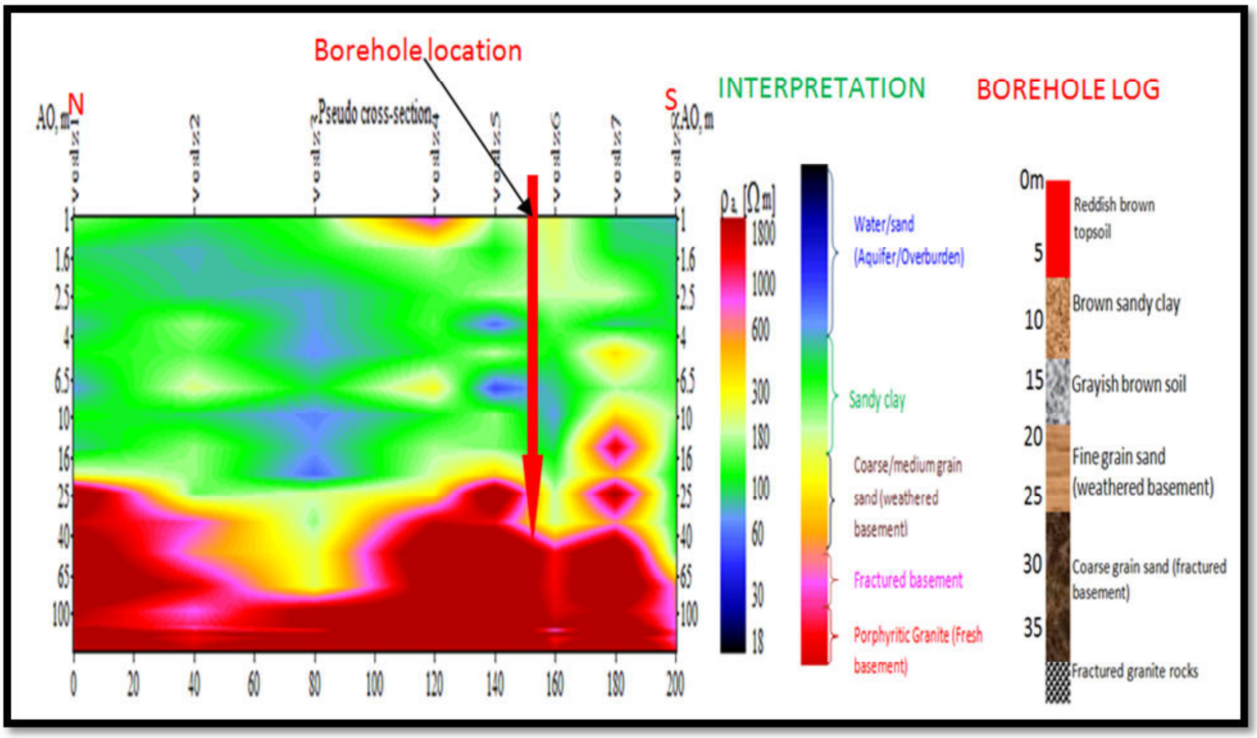


Figure7: Resistivity tomography section for LGEA Zakwa Profile

7.1.3 LGEA TECHARAK PROFILE

The Borehole at LGEA Techarak Primary School is located at latitude of 09^{0}38^{I}28.92^{II}N and longitude of 08^{0}26^{I}24.42^{II}E. The borehole is non-functional. It was drilled to a depth of 25m, the initial recorded yield was 8litre/min and the static water level was 10m (Yanet, 1996). The borehole was drilled by National livestock development project, Kaduna. Eight (8) VES Points were sounded along the Techarak Profile of 200m length. The calculated apparent resistivities of these VES Points are then inverted using the IPI2win+IP software to produce a tomogram of the profile. The image (figure8) produce shows that the underlying layers where the borehole was drilled is predominantly clay and of sand/water. Generally, the subsurface structures as shown on the tomogram seem to be highly weathered. The borehole most have failed because it was drilled through a clayey layer of resistivity range of 100-300Ωm. Other factors may include hydrogeological failures due to the problems of boreholes tapping aquicludes and seasonal water level fluctuations (Afuwai et al., 2013). This could result from poor siting of a borehole due to the absence of proper pre-drilling investigations. The problem of water level fluctuations in aquifers arise when over-pumping may result in dynamic water levels dropping below the pump intake, leading to temporary failures. This situation is quite common when borehole drilled in the basement complex terminate only at the overburden without tapping the fractured basement rocks.

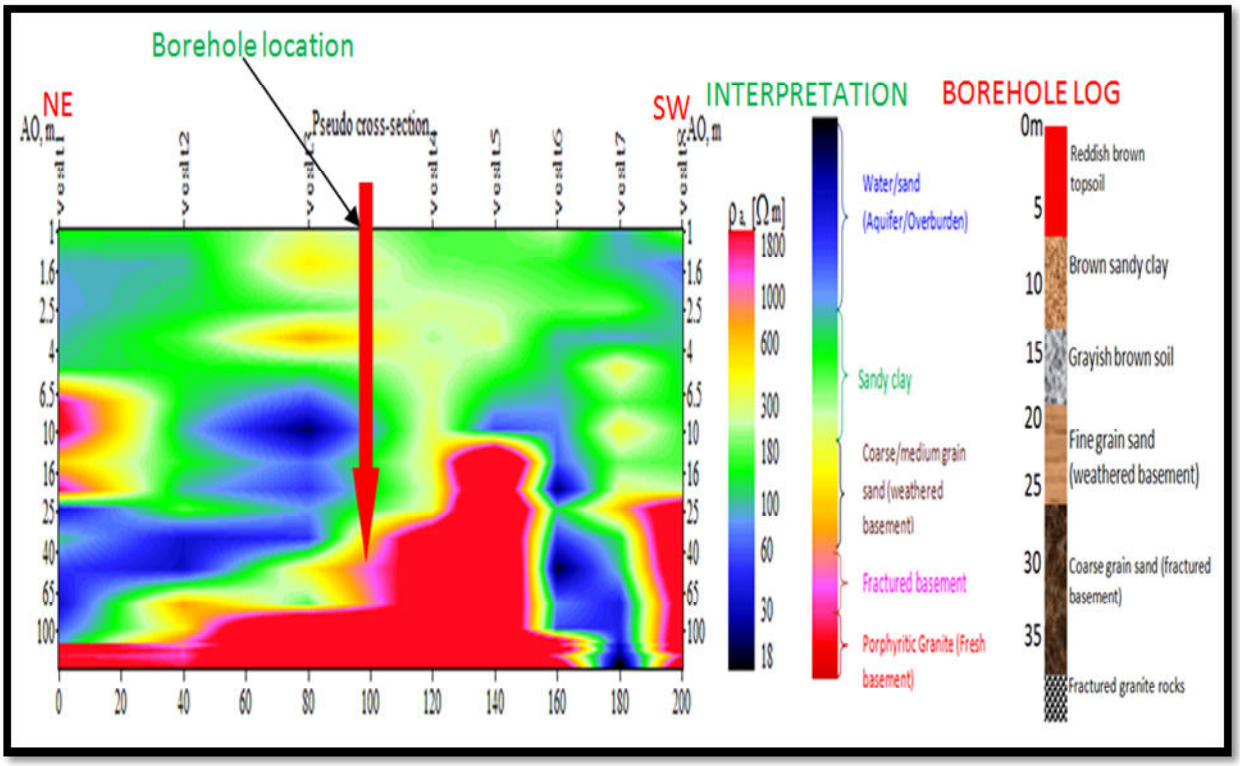


Figure8: Resistivity tomography section for LGEA Techarak Profile

7.1.4 LGEA Madamai Profile

The LGEA Madamai profile is 160m long in the W-E direction. The borehole is non-functional. It is located at latitude 09^{0}40^{I}23.58^{II}N and longitude 08^{0}24^{I}11.80^{II}E. five (5) VES Points were sounded along the profile at 40m interval. The calculated apparent resistivities at all the VES points along the profile were inverted to produce an image using IPI2win+IP software. The image (figure9) shows that there is a high resistivity anomaly at VESma4 which may be as a result of protrusion of granites around that point. The layers underlain the boreholes around VESma2 composed of water and sandy soil which is a good and promising aquiferous layer. The borehole was drilled to a depth of 48m, the recorded initial yield was 11.5litre/min, and the static water level was 10m (KSWB, 2006). The plausible causes of the borehole failure can be attributed to design, construction, operation and maintenance factors. It is possible for one factor to lead to the other. For example, a borehole poorly constructed and completed could result in clay/silt pumping and eventually affect the rubber seals in the handpumps or the impellers in the case of submersible pumps.

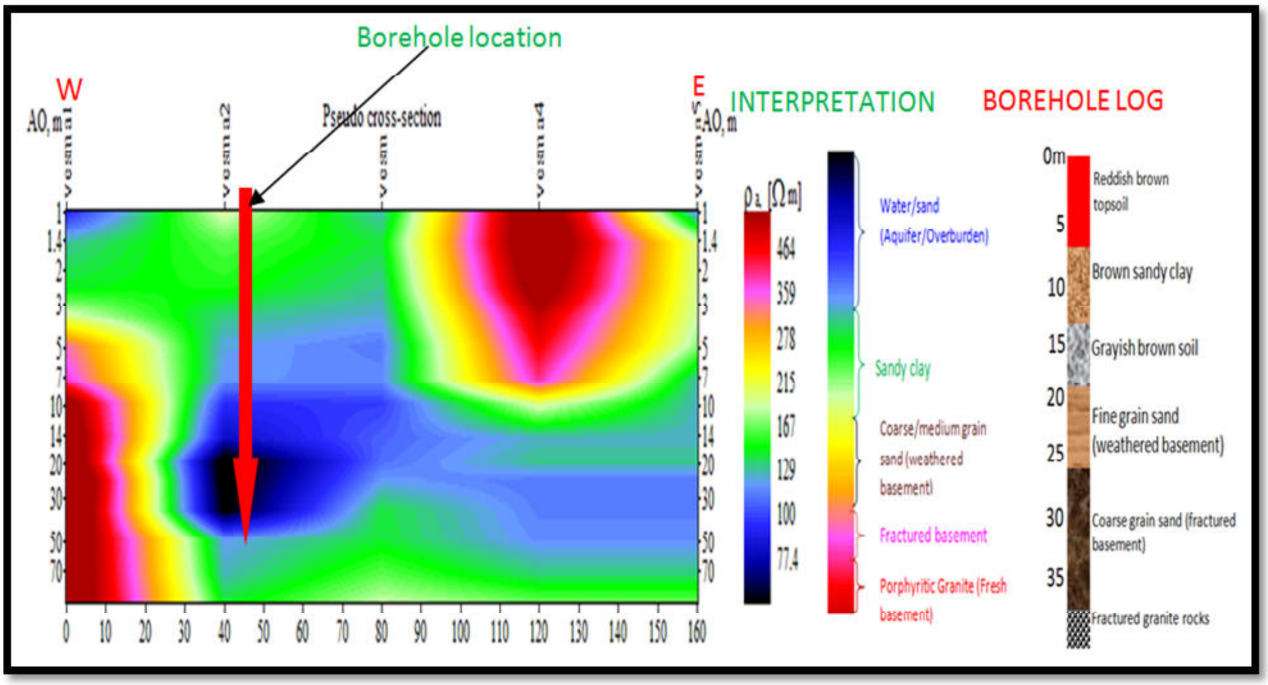


Figure9: Resistivity tomography section for LGEA Madamai Profile

8. Conclusion and Recommendations

Geophysical survey, supported by borehole logs provides a valuable key to resolving the problems of borehole failures. This investigation has portrayed the possible factors which are most probably causative to borehole failures in the area. The following can be concluded from the study:

1. The most plausible causes of these borehole failures can be attributed to (i) design and construction (ii) groundwater potential/hydrogeological consideration and (iii) operational and maintenance factors. It is possible for one factor to lead to the other. For example, a borehole poorly designed, constructed and completed could result in sand/clay pumping and eventually affect the rubber seals in the hand pumps or the impellers in the case of submersible pumps.
2. The boreholes tap the weathered and fractured basement aquifers of the area with yields ranging from 2litre/min to 20litre/min. However, yields from Sandy soil aquifers are extensive. The survey shows that boreholes with initial recorded yield less than 10litre/min have failed over time.
3. Rainfall intensity during the month of drilling has a direct influence on failure rates. It is essential that where drillers operate throughout the year, they should develop compensation strategies for seasonal drilling. This is likely to involve drilling to greater depth in wet season, but groundwater levels must be recorded in order to develop appropriate strategies for different geological environments.
4. The survey reveals that the areas where wells and boreholes are drilled through sandy soil and fracture zones have sustainable aquifers for groundwater exploitation, while boreholes that are constructed through clayey formation usually fail.

On the basis of this study, it is important that drillers develop field practices which take full account of seasonal groundwater variations and low borehole yields. The people involved in groundwater development must have the skills and knowledge required to be effective, so that they can acquire a real understanding of the environment in which they operate, rather than just follow rigid operational guidelines. The required yield should be matched to forecast water demand for each specific borehole, based on the population and water usage, rather than using a fixed arbitrary guideline value.

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