Application of 2-D resistivity survey to groundwater aquifer delineation in a sedimentary terrain: A case study of south-western Nigeria

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Abstract: This study demonstrates an application of two-dimensional resistivity surveys to groundwater exploration in a problematic sedimentary terrain where thick clay layers impedes groundwater aquifer recharge. The objectives of the study are to (i) select locations for citing new boreholes and (ii) investigate causes of the failure of the two boreholes previously drilled in the area. Six profiles of 830 m length each were surveyed to probe the subsurface lithologies and their groundwater potentials. Data acquisition system comprised a Super Sting Resistivity Meter, 84 metallic electrodes, and their accessories. Data acquired from the survey were forward modeled and tomographically inverted, using finite difference techniques. Results of the study revealed the different rock layers beneath the survey lines, their spatial distribution and their resistivities. Two new boreholes, BH3 and BH4, drilled based on the inverted 2-D resistivity images are very productive and have respective yields of 46 l/s and 48 l/s in the dry season. The choice of the locations for the new boreholes was informed by the presence of low resistivity structures interpreted as saturated (wet) sand, good vertical and lateral extents of the saturated sands, the depth of the aquifer in relation to the water table, and the absence of impermeable (sandy clay) cover that could retard groundwater recharge and discharge. The resistivity images of the 2-D survey also show that the failed boreholes – BH1 and BH2 were located on low resistivity structures interpreted as aquifers. But the aquifers have limited vertical and lateral extents, and are adjacent to thick impervious sandy-clay layer. Overall, the study demonstrates the suitability and the superiority of 2D resistivity survey to the traditional 1D – four electrodes survey.

Key words: Groundwater aquifer; Sedimentary terrain; 2-D electrical resistivity survey; Finite difference techniques; Groundwater development

1. INTRODUCTION

The increased global drought condition has negatively impacted water availability for human, agricultural, and industrial uses. There is increased pressure on groundwater to meet the daily demand for water supply. The use of geophysical survey for water well and borehole pre-drill investigation in order to mitigate cases of 'dry wells' and failed boreholes is on the increase. The purpose of pre-drill survey is to understand the hydrologic properties and stratigraphic relationship of the different subsurface rock layers that can potentially yield water to the borehole or well. The use of one-dimensional (1D) Electrical Resistivity sounding (e.g., Vertical Electrical Sounding) employing four metallic electrodes – two potentials and two current electrodes – is gradually phasing-out. 1D resistivity survey is laborious, time-expensive, and does not account for the lateral variation in the hydrologic properties of the aquifer units (Merrick, 1997; O'Neill et al., 1984; Roy and Apparao, 1971). Having recognized the superiority of 2-deimesional to 1-dimensional resistivity survey for subsurface investigations, regularly spaced 1D VES surveys are mapped into 2D during data processing using interpolation techniques (Corriols et al., 2014; Adepelumi et al., 2008; Osinowo and Olayinka, 2012; Kaya et al., 2015). However, rocks properties and hydrogeologic parameters are non-linear properties. Often, interpolated data do not represent the true subsurface condition (McGillivray and Oldenburg, 1990). This often leads to incorrect hydrogeological interpretation of geological layers, especially in areas of complex geology where pinch-out structure and porosity heterogeneities are common.

Direct 2D Multi-electrodes resistivity survey is gaining more attention in groundwater

exploration. 2D survey provides excellent view of resistivity distribution of the rock in the depth and lateral axes, thus allowing reliable evaluation of the hydrogeological units in the subsurface beneath the profile line. The method is time inexpensive, has higher coverage, and gives deeper penetration compared to 1D survey. Because the data acquired are actual measurements of subsurface resistivity distribution, the uncertainties due to interpolation are removed. 2D resistivity survey have been successfully applied to groundwater exploration, dam seepage investigation, and other environmental studies in the different parts of the world (Benson and Mustoe, 1998; Bernston et al., 2000; Ayolabi et al., 2003; Olasehinde and Raji, 2007; Nyquist et al., 2008; Coriole et al., 2014; Raji, 2014; Naudet et al., 2014; Raji and Adeoye, 2017). Coriols et al. (2014) applied 2D electrical resistivity surveys to evaluate the groundwater aquifer dynamics in the Leon Chinandega plain in Nicaragua– Spain. The study revealed the presence of unconfined alluvial and consolidated volcanic aquifers, and concluded that 70% of the water used for irrigation in Leon Chinandega plain is sourced from the unconfined alluvial aquifer. 2-D resistivity survey method is operationally similar to multi-channel seismic survey where the arrival of seismic pulses generated at a shot point can be recorded at many receivers' points to construct the velocity image of the subsurface. In 2D resistivity surveying and imaging, the resistivities values recorded at multiple electrodes points are used to map the subsurface layers around and beneath the electrode points. The inversion process uses Finite element or finite difference techniques and the resulting resistivity image is called resistivity tomogram (Loke and Baker, 1996; Loke, 2001).

Groundwater exploration in the sedimentary terrain is straightforward when sedimentary layers are deposited in horizontal or near-horizontal pattern. Geophysical exploration for groundwater aquifer in sedimentary terrain can be challenging when clay sediments are deposited around the aquifer in dispersed or irregular pattern (Revil et al., 1998; Reynolds, 1997; Shevin et al., 2007). The presence of clay layers around aquifers impedes groundwater recharge and discharge (Longe et al., 1987) thereby reducing water volume accumulating in the boreholes or wells. Simawa, the study area, has zones of thick clay sediments that are deposited in irregular pattern (Adeoti et al., 2012; Aluko, 2014). Lenses of clay in porous sand units distort the expected resistivity pattern and makes interpretation of 1D resistivity data unreliable (Reynold, 1997) because 1D data does not account for lateral variation in lithology and resistivity. In this case, 1D resistivity survey cannot reveal the detailed geology needed to take informed decision on where to cite a borehole. A more detailed resistivity survey and *a priori* geological modelling are required to cite productive boreholes in such areas.

Simawa, the study area, is located on longitude 3° 50′ E and latitude 6° 76′ N with an altitude ranging from 15 m to 72 m above sea level. Simawa is one of the fastest developing communities in the outskirt of Lagos state. The availability of good roads and presence of an international church are contributory to its rapid population growth. Though located in Ogun state, Lagos workers who could not afford expensive housing in Lagos prefer to settle in Siwama and drive to Lagos everyday. The community has over 100 housing units as at the time of this study, but the residents suffer shortage of portable water. Two boreholes drilled in the area failed to yield sufficient water in dry season. The locations of the failed boreholes were cited by 1D vertical electrical sounding survey. This necessitated the use of 2D Electrical Resistivity Survey in this study. The goals of this study are to locate suitable places to drill new boreholes to supply portable water to the residents and investigate the failure of the previous boreholes. The current study took place in February 2013 in the peak of dry season.

2. GEOLOGY AND HYDROGEOLOGY

Simawa falls within the Nigerian sector of Dahomey Basin. The basin was formed by rifting and separation of the African and South American plates during the late Jurassic and early Cretaceous (Omatsola and Adegoke, 1981). Dahomey Basin stretches from south-eastern Ghana through Togo and Benin Republic to the western margin of the Nigerian Niger Delta. Seismic and drilling data show that the basement fracturing largely controlled the sedimentation and subsidence associated

with rifting. The basin is filled with sequence of argillaceous sediments underlain by basement complex rocks. The sedimentary rocks are soft and friable, but in some places are cemented by ferruginous and siliceous materials (Omatsola and Adegoke, 1981). The sedimentary sequence comprised sand and shale with some limestone intercalations. These sediments have been described and reviewed by many authors including Adegoke, 1977; Ako et al., 1980; Omatsola and Adegoke, 1981; Okosun, 1990; Nton, 2001. The five lithostratigraphic formations, from the oldest to the most recent are: Abeokuta Group (Cretaceous), Ewekoro Formation (Paleocene), Akinbo Formation (Late Paleocene - Early Eocene), Oshosun Formation (Eocene) and llaro Formation (Eocene). The Abeokuta Group un-comformably overlies the basement complex rocks.

The Abeokuta Group, Ewekoro Formation, Coastal Plain Sands, and recent sediments constitute different aquifers in the western part of Dahomey Basin upon which Simawa is seated. The aquifer can be classified into confined, semi-confined, and unconfined depending on the nature of the aquifer units and the adjoining rock layers (Longe et al. 1987). The coastal plain sands and recent sediment aquifers are unconfined aquifer found at shallow depth. They are prone to pollution from ground sources and run-off water, and their depths vary with topography and seasons. The aquifers in Ilaro formation are semi-confined aquifers due to the alternating sequence of sand and clay layers. The aquifers are confined where the sand unit is bounded at the top and bottom by the low-permeable clay layers. This aquifer is part of the aquifer system in Simawa residential area. At shallow depth, the marine sand aquifers are not confined but contain brackish water. Limestone is the aquifer in Ewekoro formation while the continental sands formed the aquifer in Abeokuta formation.

3. DATA ACQUISITION, MODELING AND RESISTIVITY IMAGING

Geophysical survey proceeded with a recognizance fieldwork to select suitable locations for data acquisition. The choice of survey location is guided by space availability, and the concentration of the houses that will use the borehole water. Resistivities were measured along six horizontal profiles as shown in Figure 1 using Supersting R8/IP Multi-electrodes Resistivity Meter. The equipment comprised 84 metallic electrodes, multi-core box, a D.C. battery, a resistivity meter, and 12 channel cables. Each channel cable comprised metallic clips for 7 electrodes. The 84 electrodes were arranged on a straight line following the Wenner Alpha Array with 10 m electrode spacing. Each profile length was 830 m. The schematic image of the survey layout and the electrical potential points at subsurface is shown in Figure 2 for twenty electrodes only. As shown in the Figure, for a single Wenner-alpha measurement with 20 electrodes, there are 17 (20-3) possible measurements at level n=1. In the case of this study where 84 electrodes were used per profile, there are 81 (84-3) possible measurement at the first level, n=1. This is equivalent to the data that will be recorded by 81 VES measurements using the common four electrodes system. Two of the six survey profiles were chosen to cover the areas where the failed boreholes were located so as to investigate the causes of their failure. The other four profiles are to delineate areas of prolific aquifers for citing new boreholes.

Data processing begins with plotting of the data for quality control. Resistivity data acquired along each profile lines were pre-processed to correct spurious data points and remove noise. 'bad' data point were eliminated and replaced with interpolation of the data at the neighbouring points. The interpolation method uses non-linear cubic spline technique. First, theoretical data is calculated using finite difference method and rectangular elements (Dey and Morrison, 1979; Loke, 1994). Next, Resistivity inversion is performed using a Finite difference based smoothness constrained least square technique (Loke and Barker, 1996; Loke, 2001). The resistivity inversion is based on the principle of geophysical tomography (Devaney, 1984; Bregman, 1989; Raji et al., 20016): where the inverted data is compared to the observed (or measured) data, and the misfit is used to adjust the inversion result for the next level of iteration. The inversion process continues until the maximum iteration number is reached, or the RMS error reaches the set minimum.
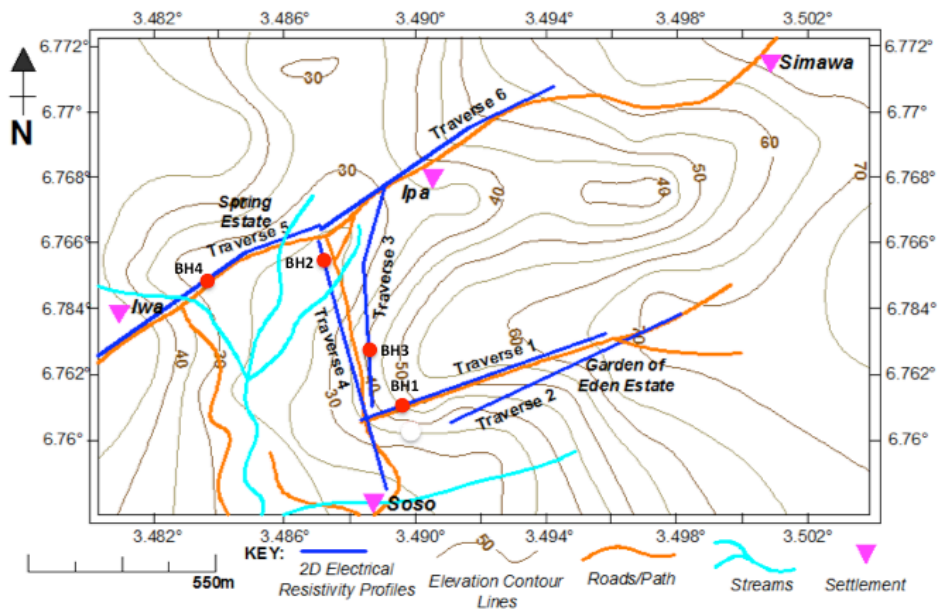
Figure 1. Topographic map of the study area showing the 2D survey profiles and the location of the boreholes
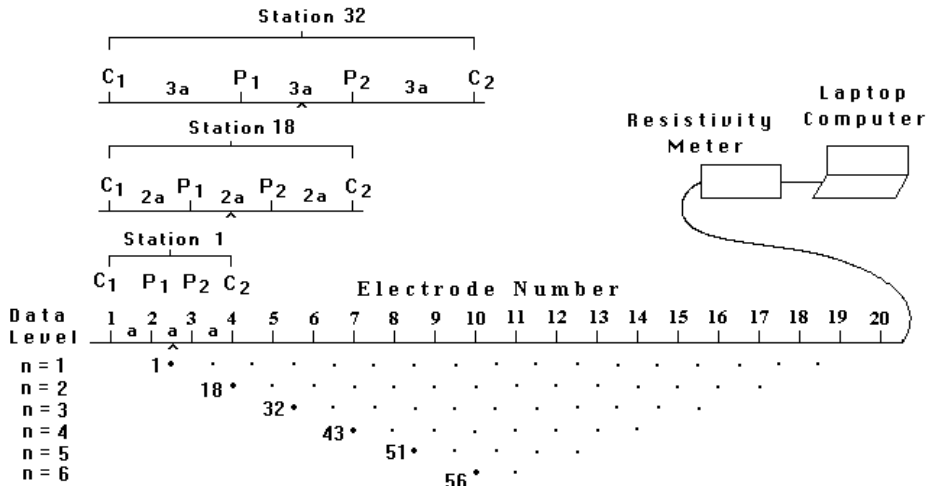

Figure 2. Pedagogic image of electrodes layout for 2D survey and the electrical potential points at subsurface (Loke, 2001). Only 20 electrodes are shown here.

The inversion process can be generally explained by the following equation:

$$\left(J^T J + \mu F\right)d = J^T g \qquad (1)$$

J is the partial derivatives of apparent resistivity with respect to the model parameters and J^T is the transposed of Jacobian matrix (size *m by n*); μ is the damping factor constraining the range of values the model perturbation vector, can take; F is an identity matrix, describing the layer structure, d is the discrepancy vector between the measured (pre-processed) data and calculated (modelled) data; and g contains the difference between the logarithms of the measured and the calculated apparent resistivity values. To improve the inversion results and optimise convergence time, d is defined as a Marquardt-Levenberg modification (Loke, 2001) that minimizes a combination of the magnitude of the discrepancy vector and the parameter change vector. Modelling and tomographic inversion were performed using Res2DInv software developed by Advanced Geosciences Incorporated. The RMS error in the inverted resistivity tomograms/images ranges from 7.2% to 14.3%. The measured, theoretical/calculated, and inverted resistivity model for

profile 1 are shown in Figure 3. The inverted resistivities tomograms for the six profiles are shown in Figures 4a-c.

4. DISCUSSION OF RESULTS

The basis for using electrical resistivity for groundwater exploration is electrolytic conduction where the fluid in the pore spaces of the rock acts as electrolyte. Dissolved ions in the pore fluid(s) carry electric charges from one electrode to another. The conductivity of the rock through which electric currents flow is determined from the current (I) and potential difference (dv). Conductivity (or resistivity) of rocks is related to various geological parameters such as the amount of dissolved ions in the saturating fluid, porosity of the rock media, and the nature and the degree of water saturation (Zohdy et al., 1980). In electrical methods of groundwater exploration, low resistivity (i.e. high conductivity) is often diagnostic of water-saturated rocks while high resistivity (i.e. low conductivity) can be interpreted as the absence of water saturated rocks or presence of non conductive fluid (e.g. oil). Low resistivity can also indicate high porosity since high water saturation implies good porosity. In groundwater exploration, a good aquifer corresponds to low resistivity layer that is sufficiently thick and porous, adjacent to and overlain by permeable rock units. These are the bases of our groundwater delineation in this study.
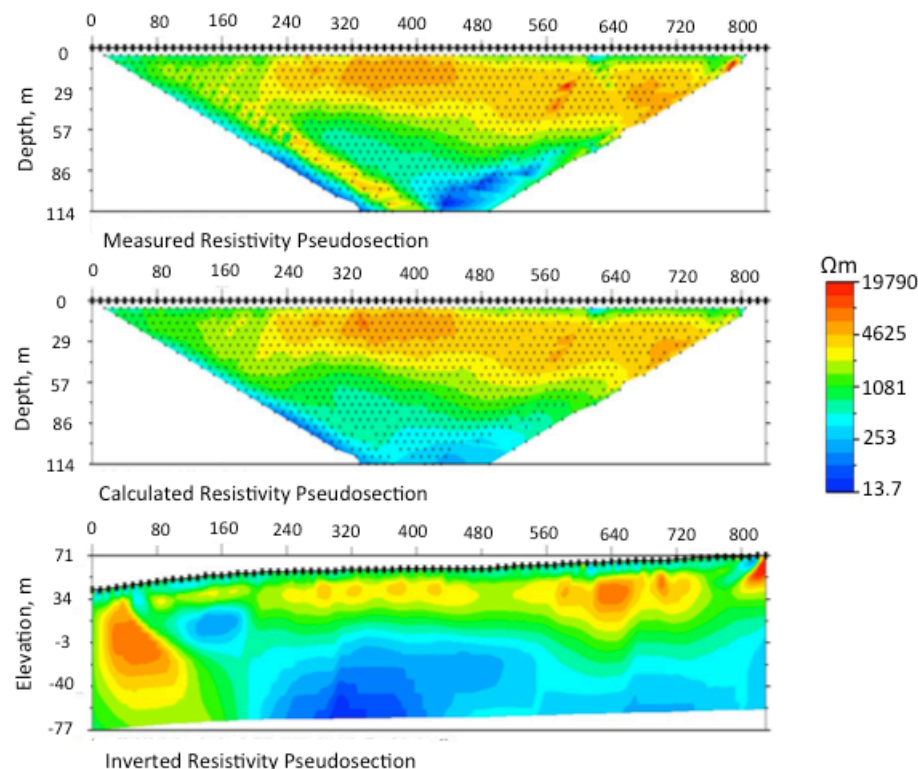

Figure 3. Resistivity pseudo-sections for the measured, calculated, and inverted Resistivities for Profile 1.

The measured resistivity data is processed to eliminate noise and spurious values. Theoretical data is forward modeled using finite difference technique; theoretical and measured data are compared iteratively to obtain the model that best represents the subsurface geology beneath the survey lines. As shown in Figure 4, the subsurface presents heterogeneous resistivity distribution. The resistivity ranges from 13.7 Ωm to 19,790 Ωm. Based on the resistivity signature and the geology of the area, four distinct lithology units were established. Geological interpretation of these units is based on the descriptions of the sediments in Dahomey basin by Omatsola and Adegoke (1981), Longe (1987), and others.

(i) The dark blue very low resistivity structure is interpreted as saturated/wet sand (see also,

Osinowo and Olayinka, 2012; Adeoti et al., 2012). Resistivity of the saturated sand ranges from 13.7 to 253 Ωm. This saturated sand corresponds to the interbeded sand units of the Afowo Formation in the Abeokuta Group which are characterised by high porosity and high permeability (Adegoke et al., 1980). Where the saturated sand is found to be sufficiently thick and located at depths below water table, it is delineated as groundwater aquifer.

(ii) The red-coloured resistivity structure is interpreted as unsaturated (dry) sand. This dry sand unit has characteristic high resistivity that ranges from 4625 Ωm – 19790 Ωm due to the absence of pore water. The sand particles are in some places cemented by ferruginous and siliceous materials (Adegoke et al., 1980) which reduced its porosity and water storage capacity.

(iii) The green-coloured resistivity structure is interpreted as the sandy clay. Resistivity of the sandy clay ranges from 506 to 1081Ωm. This unit contains higher proportion of clay particles than sand particles, and has been previously identified by Osinowo and Olayinka (2012), in a resistivity survey of a section of Dahomey Basin around Ijebu Ode. The presence of high proportion of clay particles in sandy-clay unit reduces it aquifer potential. Its moderate resistivity property is attributed to the availability of mobile ions in clay minerals.

(iv) The topsoil is a mix of unsaturated (dry) sand particles and laterites. This unit overlies most parts of the study area and has a wide range of resistivity values represented by light green (1081 – 2062) and yellowish-red (2062 – 4625) colours.

The first failed borehole, BH1 is located at distance 160 m along profile 1 (Figure 4b). Actually, the bottom of the borehole corresponds to a low resistivity structure (saturated sand) that could be interpreted as an aquifer, but the saturated sand has limited horizontal and lateral extents, is at shallow depth, and it's surrounded by impervious sandy-clay which has poor recharge and discharge potentials. The second failed boreholes, BH2 is located at 822 m on profile 4 (Figure 4b). Although, the subsurface resistivity image indicates the presence of saturated sand below the top-soil, the depth of the saturated sand is shallow and the overburden is not thick enough. Given that depth, we speculate that run-off from rain is the only means to recharge the aquifer –A combination of poor recharge mechanism, shallow depth, and limited extent of aquifer (saturated sand), and the presence of sandy-clay around the aquifers contributed to the poor performance of BH1 and BH2. BH2 may do well during raining season but would yield low water in dry season. The resistivity curves from the 1D survey used for citing BH1 and BH2 are shown in Figure 5. The data is sourced from a report submitted to the landlord association.
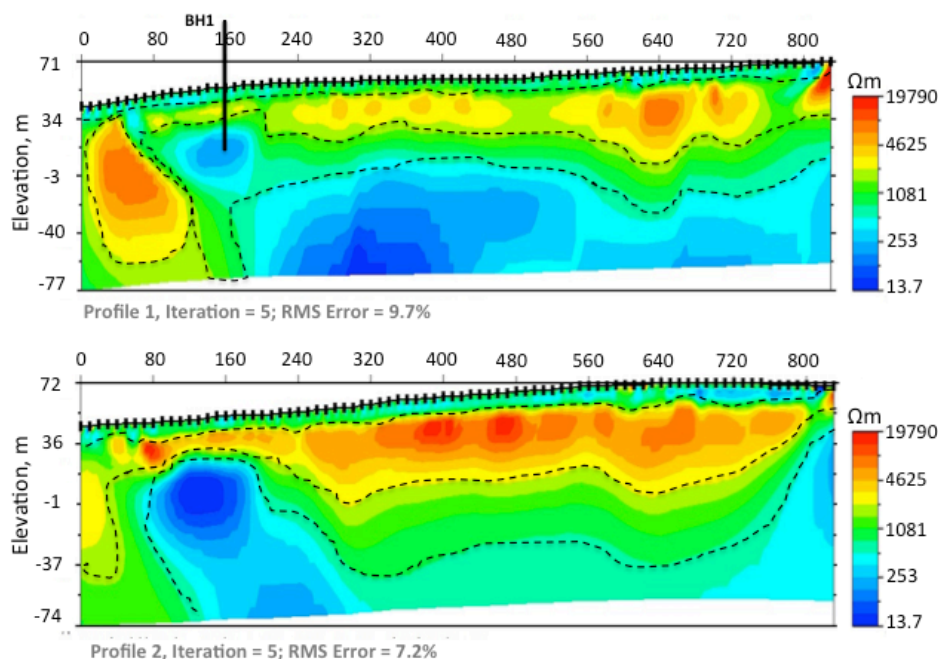

Figure 4a. Inverted resistivity Images (or tomograms) for profiles 1 and 2. Profile 1 shows the location of failed borehole, BH1.
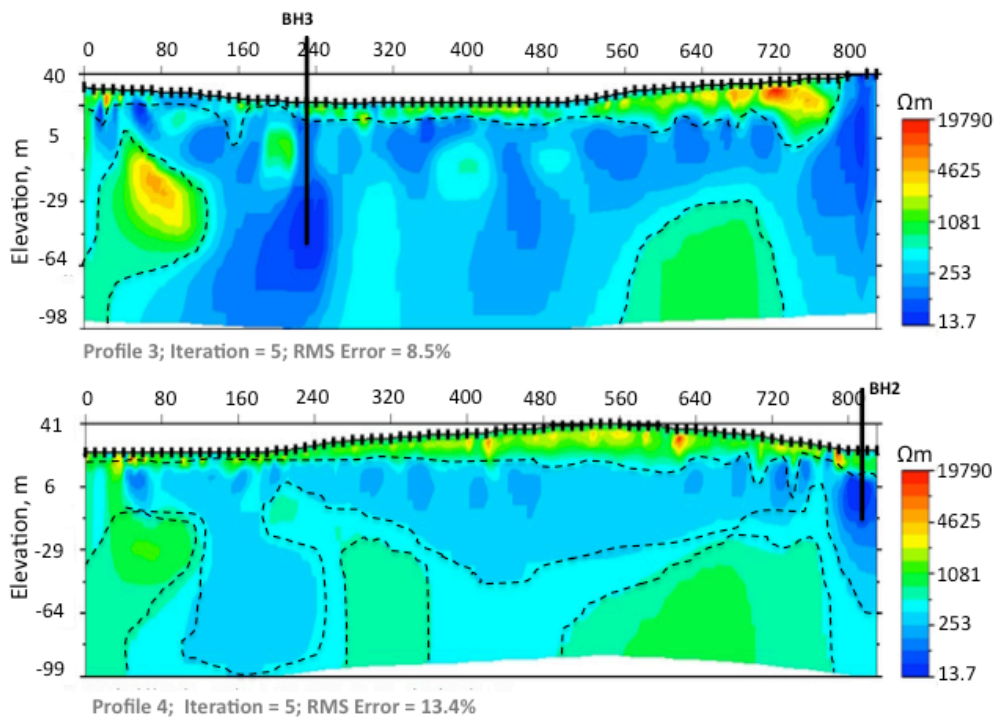
Figure 4b. Inverted resistivity Images (or tomograms) for profiles 3 and 4. Profile 4 shows the position of failed borehole BH2, while profile 3 shows the position of the new borehole BH3 drilled base on 2D resistivity survey.
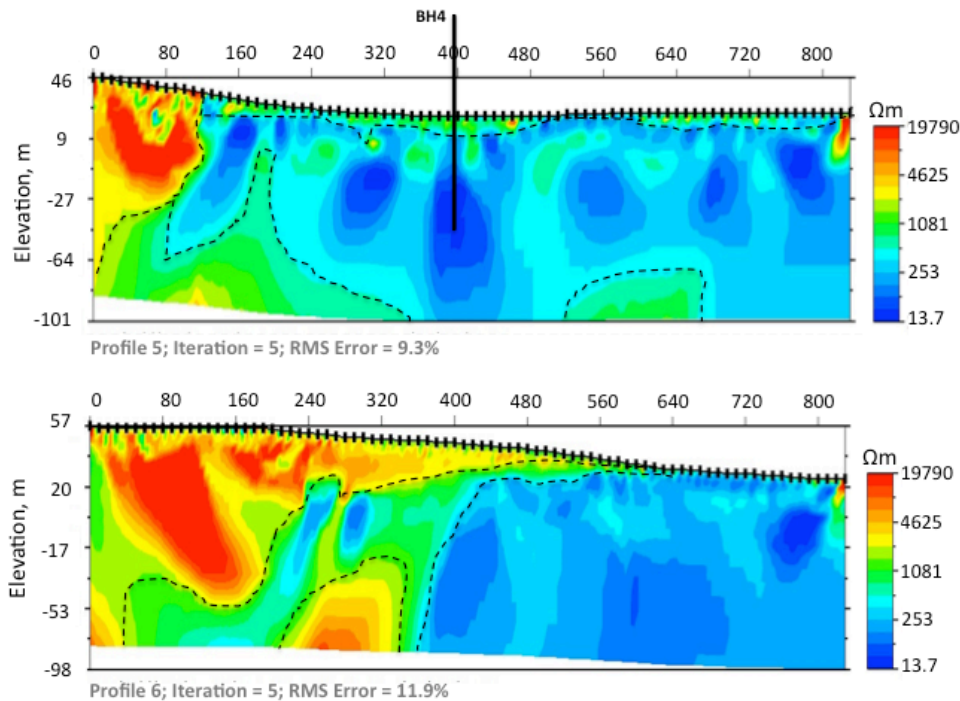

Figure 4c. Inverted resistivity Images (or tomograms) for profiles 5 and 6. Profile 5 shows the location of the new borehole BH4 drilled on 2D resistivity survey.

Overall, we attributed the failure of the two boreholes to poor borehole citing. Results of 1D VES survey only presented limited vertical overview of resistivity distribution below the survey point. It does not give the lateral stratigraphic relationship of the different layers that can potentially yield water to the borehole. For an example, BH1 is located at a low resistivity structure– saturated sand. But, the saturated sand is deposited in sandy clay which has poor recharge and discharge capacities. Although the location of the borehole represents the best point at that depth level

throughout profile 1, but it has limited vertical and lateral extents, and cannot be considered as a good aquifer in a strict hydrogeological sense.
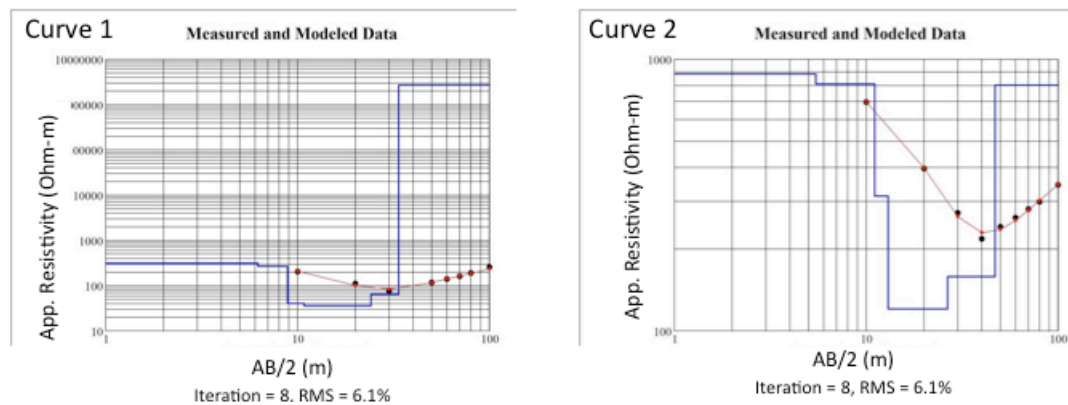

Figure 5. Resistivity Curves for the 1D survey for the failed boreholes BH1 and BH2. The data is sourced from the report submitted to Simawa Landlords Association

Based on the 2-D survey presented in this study, two boreholes, BH3 and BH4 were drilled at the location indicated on profiles 3 and 5 respectively. The choice of these locations is informed by the (i) presence of low resistivity structures interpreted as saturated sand, (ii) good vertical and lateral extents of the saturated sand, (iii) aquifers fall below the water table and has thick overburden materials, and (iv) the absence of impermeable cover– sandy clay that could retard groundwater recharge. Pumping test on BH1 and BH2 shows that the borehole yields are 46 l/s and 48 l/s respectively. Good vertical and lateral view of the stratigraphic relationship of the different geological units and their resistivity distribution played a major role in the interpretation of the 2D resistivity results and the citing of BH3 and BH4. The absence of lateral view and limited vertical views of resistivity distribution and stratigraphic structures are the problems of 1D resistivity data interpretation.

5. CONCLUSION

Groundwater aquifers have been delineated in the sedimentary terrain of Simawa Community using 2-dimentional multi-electrodes resistivity surveys. The inverted subsurface resistivity image revealed heterogeneous lithologic units whose resistivity values range from 13.7 Ωm to 19790 Ωm. The four geo-electric units delineated correspond to top-soil unit, consolidated dry sand unit, sandy-clay unit, and saturated (wet) sand unit. Thick saturated sand units measuring low resistivities (17.3 Ωm - 253 Ωm) values are delineated as the groundwater aquifers. Boreholes BH3 and BH4 drilled on these aquifers are very productive and have yields of 46 l/s and 48 l/s respectively. 2D resistivity image inverted from the study showed that the two boreholes previously drilled in the study area were not productive because they were located on aquifers having limited vertical and horizontal extents, and bounded by impervious sand-clay units. Overall, the study demonstrates the superiority of 2D resistivity survey to the traditional 1D – four electrodes survey for groundwater exploration.

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