The use of geological-based geophysical surveys for groundwater distribution in crystalline basement terrain, SW Nigeria

K D Oyeyemi¹, A P Aizebeokhai¹, O A Sanuade², J M Ndambuki³, O M Olofinnade⁴, A A Olaojo⁵ and T A Adagunodo¹

¹Applied Geophysics Unit, Department of Physics, Covenant University, Nigeria
²Department of Geoscience, King Fahd University of Petroleum and Minerals, Saudi Arabia
³Department of Civil Engineering, Tshwane University of Technology, Pretoria, South Africa
⁴Department of Civil Engineering, Covenant University, Nigeria
⁵Department of Earth Sciences, Ajayi Crowther University, Nigeria

kdoyeyemi@yahoo.com, kehinde.oyeyemi@covenantuniversity.edu.ng

Abstract. This research involves the subsurface geological characterization for groundwater potential assessment within the campus of the Polytechnic of Ibadan, southwestern Nigeria. The study is directed towards groundwater resources exploration, development and management in the campus. Five 2D resistivity imaging traverses were conducted using Wenner array in addition to five VES surveys using Schlumberger array that provide layering information and geoelectrical parameters. Three geologic layers delineated from the 2D resistivity inversion models include predominantly clayey sand/ sandy clay top soil (overburden), partly weathered or fractured basement and fresh basement. Their inverse model resistivity values ranges 6.68 – 98.6 \( \Omega \text{m} \), 68.0 – 929 \( \Omega \text{m} \) and \( \geq 2252 \Omega \text{m} \) with bottom depths ranges 3.8 – 6.4 m and 6.4 – 10 m respectively. 1D model inversion from VES results also delineate three lithologies classifying both topsoil and some part of the partly weathered basement as overburden with resistivity and thickness range 483 – 1746.9 \( \Omega \text{m} \), 1.1 – 1.8 m; partly weathered or fractured basement 60.3 – 93.5 \( \Omega \text{m} \), 8.4 -12.9 m and fresh basement 984.6 – 2078.9 \( \Omega \text{m} \). The saturated portion of the partly weathered or fractured basement at depth will favour groundwater exploration and development in this area, while the relatively shallow overburden thickness would serve as the protective layer and recharge for the fractures.

Keywords: Geoelectrical resistivity, Basement terrain, Groundwater exploration, Subsurface characterization, Basement aquifer
1. Introduction
The heavy reliance on groundwater as a source of affordable water for both industrial and domestic use throughout the world demands that the water occurrence within the subsurface is of significant quantity and high quality. Subsurface geological characterizations using surficial geoelectrical resistivity technique are sufficient to address variety of problems related hydrological investigations in complex geological terrains such as crystalline basement. Several works have been carried out on the assessment, abstraction, development and management of groundwater within the hard rock terrain of Nigeria [1-14]. In this research, Electrical resistivity imaging (ERI) and vertical electrical soundings (VES) were combined for subsurface characterization as part of preliminary studies for groundwater resource evaluation and management in a basement complex, southwestern Nigeria.

2. Methodology

2.1. Geologic setting of the study area
The study site is located within the Polytechnic Ibadan Campus, Ibadan southwestern Nigeria. Most parts of Ibadan and other neighbouring towns within the southwestern Nigeria are underlain by gneiss-migmatites complex and the metasediments underlie [15]. The gneiss-migmatite complexes within this region include minor quartzites and calc-silicate bearing units. The major rock types present in the study area are predominantly granites and schists of metasedimentary scores (such as mica schist, quartzite and quartz-schist), biotite, biotite-hornblende gneiss, banded gneiss and granite gneiss, and migmatite gneiss (Figs 1a and b). The minor rock types within the area include augen-gneiss pegmatite and amphibolite. The gneisses that are rich in mafic minerals may undergo weathering, resulting to rigoliths and clayey soils overlying the coarse grained granitic components soil with more varying texture and lower clay contents [17].

2.2. Data acquisition and processing
The data acquisition were done manually using Omega resistivity meter in the investigation site within the Polytechnic of Ibadan campus, Ibadan southwestern Nigeria (Fig. 2). Five resistivity soundings were carried out along the five lines with maximum half-current electrode spread (AB/2) of 75.0 m using Schlumberger array, which is enough for the anticipated depth of investigation (DOI). Likewise, five 2D electrical resistivity profile lines in the West-East and North-South direction were conducted with each 2D resistivity profiles being 110 m length (Fig. 2). Wenner array with least electrode spacing of 5.0 m was adopted for the surveys reaching 5 data level of 5 for each profiles. The Wenner configuration was adopted for the 2D ERT survey due to its easy application, strongest signal strength, and greater sensitivity to vertical resistivity variation or structures lying horizontally with respect to the country rocks [18].

The processing of the acquired soundings (VES) data were done by plotting the apparent resistivity against half–current electrode spacing (AB/2) on a log–log graph sheets. The estimated geoelectric parameters (resistivities and thicknesses) from the partial curve matching were later adopted as the initial inputs for several iteration on a Win-Resist software program to get final model parameters for subsurface geoelectric layers. Also, apparent resistivity data observed for the 2D electrical resistivity tomography (ERT) were processed and inverted using RES2DINV inversion code [19] [20].
3. Results and Discussion

3.1. Vertical electrical sounding
The derived geoelectric parameters from several iterations of the resistivity vertical electrical soundings are shown in Figs. (3 and 4) and Table 1. Three geoelectrical layers were identified from the iterated curves. Large consistency of the geoelectric parameters were observed in the VES curves.

Fig. 1: Map showing the Nigeria relief and adjoining areas with extracted and modified Ibadan, using ETOPO1 global relief model [16]. b. Geological map of Ibadan (After NGSA, 2009).

Fig. 2: Satellite imagery map of the study site in Ibadan indicating the 2D resistivity profile lines (blue) and VES points (yellow arrows)
Based on the local geology of the area and the information available from the boreholes and hand-dug wells, the delineated subsurface strata are: overburden layer (mainly sandy clay units) with model apparent resistivity ranging between 1746.3 (Ωm) and 483.3 (Ωm) and thickness range 1.1 – 1.8 metres; intercalation of partly weathered and fracture basements with model resistivity range of 60.3 – 93.5 (Ωm) as well as thickness range of 8.4 – 12.4 metres; fresh basement with model resistivity ranging from 784.6 to 2078.9 (Ωm). The second layer is interpreted as the water-saturated aquiferous zone in the area of study. The fresh portion of the basement is inferred to be the lowermost infinitely thick layer with very high resistivity values. The outcomes of the VES surveys serve as great input to better understanding the hydrogeological setting in the study area. The water saturated fractured and weathered basement should be the target for sustainable water supply in the study area.

3.2. Interpretation of 2D resistivity models

The 2D inverse models of the apparent resistivity distribution within the subsurface with depths obtained from the smoothness constrained inversion are presented in Figs. 5 and 6. The inversion models reveal a range of both relatively low resistivity and high resistivity zones within the area of study. The 2D inverse models resistivity values range from about 9.18 – 10133 Ωm, 6.68 – 40441 Ωm, 17.7 – 7219 Ωm, 15.1 – 20382 Ωm, and 10.1 – 19610 Ωm for traverses 1 – 5 respectively. The variations in inverse models resistivity values 2D geoelectrical imaging to the tune of tens of thousands Ohm-metre higher than those of the 1D VES points denote the greater sensitivity and resolution of 2D electrical resistivity imaging [21]. The geoelectrical parameters for the three identified geoelectric layers such as the inverse resistivity models values and thicknesses obtained from the soundings agree reasonably with those obtained from the 2D resistivity imaging.

| Layer | Resistivity (Ωm) | VES 1 | VES 2 | VES 3 | VES 4 | VES 5 | Lithology               |
|-------|------------------|-------|-------|-------|-------|-------|-------------------------|
| 1     | Resistivity (Ωm) | 483.3 | 739.7 | 723.3 | 973.9 | 1746.9 | Overburden (Sandy Clay) |
|       | Thickness (m)    | 1.8   | 1.4   | 1.2   | 1.1   | 1.1   |                         |
|       | Bottom Depth (m) | 1.8   | 1.4   | 1.2   | 1.1   | 1.1   |                         |
| 2     | Resistivity (Ωm) | 603.3 | 846.4 | 832.2 | 93.5  | 71.3  | Weathered /Fractured basement |
|       | Thickness (m)    | 8.9   | 12.9  | 10.5  | 11.4  | 8.4   |                         |
|       | Bottom Depth (m) | 10.8  | 14.3  | 11.7  | 12.5  | 9.4   |                         |
| 3     | Resistivity (Ωm) | 784.6 | 1928.4| 909.1 | 2078.9| 1532  | Fresh Basement           |

Depth-to-base of the geoelectric layers reveals quick assessment of their lateral thickening.
Fig. 3: VES curves and geoelectrical parameters obtained for (a) VES 1, (b) VES 2 and (c) VES 3.

Fig. 4: VES curves and geoelectrical parameters for (d) VES 4 and (e) VES 5.
4. Conclusion

Geoelectrical resistivity surveys involving vertical electrical soundings and ERT have been used to evaluate the groundwater potential in a crystalline basement terrain and to delineate target locations for siting boreholes in the study area. The analyses of the soundings resistivity models and the 2D inversion models clearly shows three geoelectric layers; top layer, which is inferred to be sandy clayey/clay; water-saturated weathered and fractured basement with clayey materials serving as the aquifer unit, and fresh basement. The electrical soundings delineate higher bottom depth for the water-saturated aquiferous unit, however with little or low lateral resolution. Lateral heterogeneity of clay content within this layer was evident in the 2D electrical resistivity imaging. The rigoliths (weathered basement) unit within the area with bottom depth up to 10 metres from 2D imaging but about 14.1 metres from the VES results. Thus, groundwater exploration and development in the area should target the weathered and fractured basement layer.
Acknowledgements
The authors wish to appreciate the management of the Polytechnic of Ibadan for permission to carry out this research. We are equally very grateful to the Covenant University Centre for Research, Innovation and Discovery for the conference support sponsorship.

References
[1] Edet A E and Okereke C S 1997 Assessment of hydrogeological conditions in basement aquifers of the Precambrian Oban Massif, southeastern Nigeria. Journal of Applied Geophysics 36 pp 195–204.
[2] Olorunfemi M O and Fasuyi S A 1993 Aquifer types and geoelectric/hydrogeologic characteristics of part of central basement terrain of Nigeria (Niger State). Journal of Africa Earth Science 16(3) pp 309–317.
[3] Edet A E (1990) Applications of Photogeologic and Electromagnetic Techniques to Groundwater Exploration in Northwestern Nigeria. Journal of African Earth Sciences 11(3–4) pp 321–328.
[4] Olayinka, A I and Weller A 1997 The inversion of geoelectrical data for hydrogeological applications in crystalline basement areas of Nigeria. Journal of Applied Geophysics 37 (2) pp 103–105.
[5] Adepelumi A Ako B and Ajayi T 2001 Groundwater contamination in the basement-complex area of Ile-Ife, southwestern Nigeria: A case study using the electrical-resistivity geophysical method Hydrogeology Journal 9(6) pp 611–622.
[6] Ehinola O A Opoola A O and Adesokan H A 2006 Empirical analysis of electromagnetic profiles for groundwater prospecting in rural areas of Ibadan, southwestern Nigeria. Hydrogeology Journal 14(4) pp 613–624.
[7] Aizebeokhai A P and Oyeyemi K D 2014 The use of the multiple gradient array for geoelectrical resistivity and induced polarization imaging. Journal of Applied Geophysics 111 pp 364–375 doi:10.1016/j.jappgeo.2014.10.023.
[8] Oyeyemi K D Aizebeokhai A P and Oladunjoye M A 2015 Integrated Geophysical and Geochemical investigation of saline water intrusion in a coastal alluvial terrain, Southwestern Nigeria. International Journal of Applied Environmental Sciences 10(4) pp 275–1288.
[9] Aizebeokhai A P Oyeyemi K D and Joel E L 2016a Groundwater potential assessment in a sedimentary terrain southwestern Nigeria. Arabian Journal of Geoscience 9 pp 110–117. doi.org/10.1007/s12517-016-2524-5
[10] Aizebeokhai A P Oyeyemi K D and Joel E L 2016b Electrical resistivity and induced polarization imaging for groundwater exploration. SEG International Exposition and Annual Meeting, Texas.
[11] Oyeyemi K D and Olofinnade O M 2016 Geoelectrical –Geotechnical studies for near surface characterization, case history: Lagos, SW Nigeria. Electronic Journal of Geotechnical Engineering 21(10) pp. 3735–3750.
[12] Aizebeokhai A P Oyeyemi K D Noiki F R Etete B I Arere A U E Eyo U J and Obiuehi V C 2017 Geoelectrical resistivity data sets for characterization and aquifer delineation in Iyesi, southwestern Nigeria. Data in Brief, 15 pp 828–832 doi:10.1016/j.dib.2017.10.057.
[13] Aizebeokhai A P and Oyeyemi K D 2017 Geoelectrical characterization of basement aquifers: the case of Iberokodo, southwestern Nigeria. Hydrogeology Journal 1–14 doi.org/10.1007/s10040-017-1679-9.
[14] Oyeyemi, K D Aizebeokhai A P Adagunodo, T A Olofinnade O M Samuade O A and Olaojo A A 2016 Subsoil characterization using geoelectrical and geotechnical investigations: Implications for foundation studies. International Journal of Civil Engineering and Technology 10(8) pp 302-314.
[15] Oyinloye O A 2011 Geology and geotectonic setting of the basement complex rocks in South Western Nigeria: implications on provenance and evolution. In: Earth and Environmental Sciences, I. A. Dar IA (Ed.), chapter 5, InTech, Rijeka, Croatia

[16] Amante C and Eakins B W 2009 ETOPO1 1 arc-minute global relief model: procedures, data sources and analysis. NOAA Technical Memorandum NESDIS NGDC – 24, 19p

[17] Oyawoye M O 1970 The Basement Complex of Nigeria, In: T. F. J. Dessauvagie, and Whiteman (Eds), African Geology. Ibadan University Press. Nigeria.

[18] Dahlin T and Zhou B 2004 A numerical comparison of 2-D resistivity imaging with 10 electrode arrays. Geophysical Prospecting 52 pp 379–398.

[19] Griffiths D H and Barker R D 1993 Two dimensional resistivity imaging and modelling in areas of complex geology. Journal of Applied Geophysics 29 pp 211–226.

[20] Loke M H and Barker R D 1996 Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. Geophysical Prospecting 44 pp 131–152.

[21] Loke MH (2001) Electrical Imaging Surveys for Environmental and Engineering Studies: A Practical Guide to 2D and 3D Surveys, (Available at www.geoelectrical.com), 62 pp.