Near Surface Geophysics, 2014, **12**, 515-521 doi:10.3997/1873-0604.2014007

Integrated geoelectrical and structural studies for groundwater investigation in parts of Abuja, North Central Nigeria

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Received December 2012, revision accepted November 2013

ABSTRACT

Abuja, the capital city of Nigeria, West Africa, is underlain by Precambrian basement rocks consisting mainly of porphyroblastic gneisses, granitic-gneisses, migmatitic gneisses, amphibolites, Pan-African granites and undifferentiated schists. The geology of Abuja, therefore, makes the groundwater conditions in the area very unpredictable. Geophysical surveys were carried out at 12 locations within and around the Gosa area and the results integrated with 88 lineament (fractures) extracted from hill-shaded Shuttle Radar Topography Mission (SRTM) data. The dominant fracture trend for the area is NNE–SSW and N–S, which corresponds to the Pan-African trends in the basement complex of Nigeria. It is observed that in the Gosa area, whereas fractures exist, they do not possess sufficient interconnectivity; this may have adversely affected the permeability of the fractured zone, resulting in the incidence of dry wells in the area. Moreover, evidence from interpreted two-dimensional (2D) geoelectric sections reveals that in some parts of Abuja, the weathered overburden is not thick enough to support sufficient yield for a viable borehole. Interconnected fractures therefore become the desirable structural feature capable of improving the aquifer potential. This study demonstrates the usefulness of integrating conventional vertical electrical sounding (VES) surveys with structural data derived from enhanced SRTM imagery in a hydrologically complicated terrain.

INTRODUCTION

Basement rocks do not inherently make good aquifers (Acworth 1987; Manda, Mabee and Boutt 2006). The hydrogeologic characteristics of basement rocks are only enhanced when the rocks are fractured and/or when they are weathered (Clark 1985; Wright 1992). The conditions are better enhanced when the rocks are overlain by thick overburden, which could form considerable zones of weathered rock aquifer. Groundwater potentials of a basement complex area are often determined by geophysical means, which determines the thickness of the overburden and the network of fractures that may exist in the area (e.g. Mendoza and Dahlin 2008). Geophysical surveys are also important for groundwater investigation in basement areas in view of the discontinuous (localized) nature of basement aquifers (Satpatty and Kanugo 1976). The use of the vertical electrical sounding (VES) method is popular for groundwater investigation in both soft rock (sedimentary) and hard rock (igneous and metamorphic) terrains (De Beer and Blume 1985; Barongo and Palacky 1989; Mbonu *et al.* 1991; Shemang 1993). In the basement complex of Nigeria, extensive application of the geoelectrical method for groundwater investigation has been reported (e.g., Zohdy, Eaton and Mabey 1974; Pulawski and Kurth 1977; Acworth 1987; Olorunfemi and Okankune 1992; Olorunfemi and Fasuyi 1993; Edet and Okereke 1997; Nur and Ayuni 2004).

Application of remotely-sensed data for groundwater investigation is becoming increasingly popular, especially in areas where conventional methods are inadequate in accurately demarcating hydrologic zones. Examples include the works of Galnett and Gardner (1979), Edet *et al.* (1994), Bala (2001) and Bala, Batalan and De Smedt (2000). In a few case studies it has suc-

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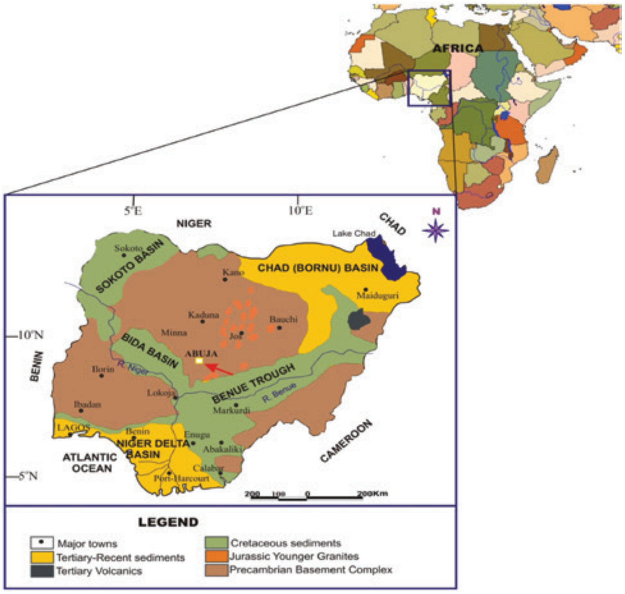

FIGURE 1

Geological map of Nigeria, showing the position of Abuja (see arrow) in the basement complex of north-central Nigeria.

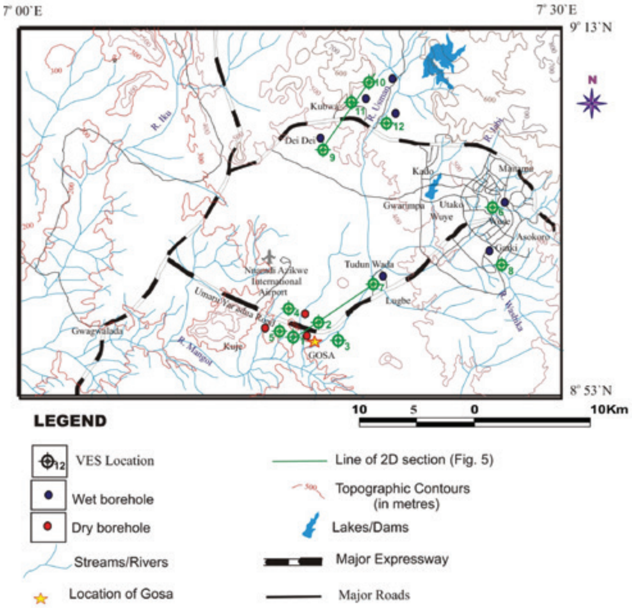

FIGURE 2

Accessibility map of the study area, showing positions of boreholes and VES locations (see key).

cessfully complemented conventional geophysical investigations (Goki *et al.* 2010; Anudu *et al.* 2011). The use of Shuttle Radar Topography Mission Digital Elevation Model (SRTM-DEM) data for hydrogeologic studies has been reported in other parts of the world (Valeriano *et al.* 2006; Wright *et al.* 2006; Grohmann, Riccomini and Machado-Alves 2007; Abdullah, Sarfaraz and Shadab 2012). In this study, lineaments extracted from hill-shaded SRTM-DEM data were subjected to statistical analysis and integrated with VES data in an attempt to explain the absence of aquiferous zones around the Gosa area of south-western Abuja. Figure 1 shows the position of Abuja in the basement complex of north-central Nigeria.

The area of study includes most parts of Abuja main city, and western suburbs. It includes areas around Maitama, Asokoro, Wuse, Garki, Gwarimpa, Kado, Jabi, Kubwa, Dei-Dei, Lugbe and Gosa (Fig. 2). Gosa has become important because of the increasing population of the suburbs of Abuja. Many residents of the area embark on the development of private boreholes to augment inadequate public water supplies. However, most private boreholes here are unsuccessful and so counter the intentions of the owners, who also lose capital. This work presents a case study aimed at establishing the groundwater conditions in the Gosa area of Abuja, Nigeria, which will help in adequate planning and future drilling of boreholes in the area.

GEOLOGY AND HYDROGEOLOGY OF THE AREA

The area of study forms part of the basement complex of north-central Nigeria. Lithologic units fall under three main categories, which include: (1) undifferentiated migmatite complex of Proterozoic to Archean origin, (2) metavolcano-sedi-

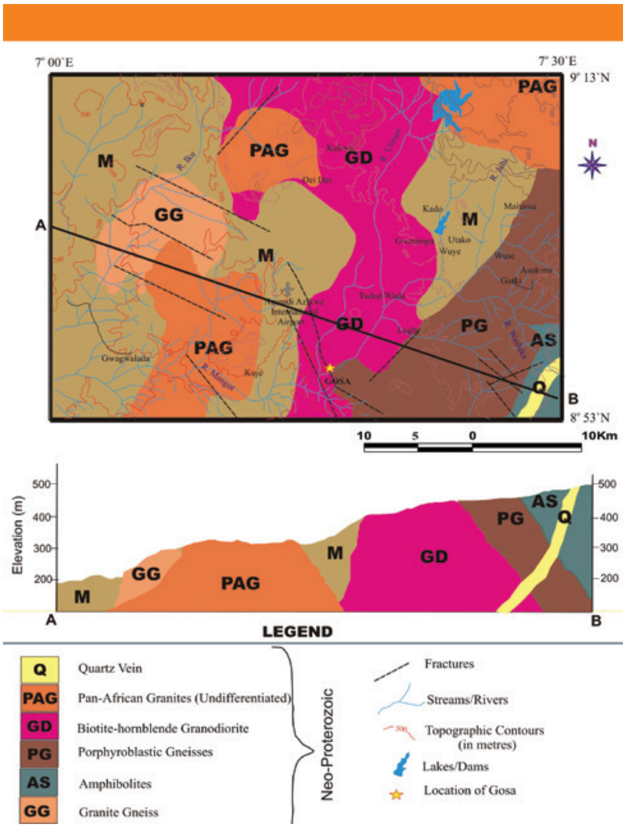

FIGURE 3

Geological map of the study area (top) with schematic cross section (bottom).

TABLE 1

Summary of results obtained from the computer output of twelve (12) VES in the area.

VES No.	Location	Resistivities (ohm-m) $\rho1$ $\rho2$ $\rho3$ $\rho4$ $\rho5$ $\rho6$	Thickness (m) h1 h2 h3 h4 h5	Depth (m)	Curve Type	Lithology
VES1	Gosa	410.6, 130.5, 47.7, 4869, 164.4	0.4, 1.2, 3.3, 4.9, , ∞	9.9	AK	Sandy clayey topsoil, fresh basement
VES 2	Gosa	212.2, 82, 122, 54.3, 1140, 82043	0.6, 2.0, 2.9, 6.0, 12.5, ∞	23.9	HQ	Sandy topsoil, weathered basement, fresh basement
VES 3	Gosa	1580, 332.8, 47.6, 19369, 72.7	0.5, 1.3, 4.4, 6.9, ∞	13.1	AK	Sandy topsoil, clayey weathered zone, fresh basement
VES4	Gosa	184.3, 1104, 37.9, 1473	0.2, 2.5, 13	15.6	KH	Sandy topsoil, weathered basement
VES5	Gosa	83, 438, 62, 236, 68,2067	3.4, 39.3, ∞	42.7	KH	Lateritic topsoil, weathered basement, fresh basement
VES 6	Wuse zone 5	94, 171, 677, 298	1.0, 2.8, 2.2, ∞	6.0	QK	Sandy topsoil, clayey sand, weathered basement
VES7	Lugbe	231, 59, 297	1.7, 3.4, ∞	5.1	H	Sandy clayey topsoil, weathered and fractured basement
VES8	Area 11	691, 181, 388, 69, 2770	1.2, 5.0, 3.7, 8.7, ∞	18.6	HQ	Lateritic topsoil, fractured basement
VES 9	Dei-Dei	320, 100, 493	1.1, 9.7, ∞	10.8	H	Sandy clay topsoil, weathered basement
VES 10	Phase 4	42, 1323, 217, 39, 444	0.9, 0.3, 4.6, 16.4, ∞	22.2	KH	Lateritic clay topsoil, weathered and fractured basement
VES11	Kubwa	257, 1219, 530, 100000	0.8, 0.9, 13.9, ∞	15.6	KH	Sandy clay topsoil, weathered basement
VES 12	Brick City Estate	69, 1451	3.1, ∞	3.1		Sandy clay topsoil, fractured basement

mentary rocks of Late Proterozoic age and (3) older granite complex of Late Precambrian – Lower Paleozoic age, also known as Pan-African granites. All these rocks were affected and deformed by the Pan-African thermotectonic event. Detailed reports of the lithological description, age, history, structure and geochemistry of the basement complex of Nigeria are given in Oyawoye (1972), Black *et al.* (1979), Ajibade, Woakes and Rahaman (1987), Rahaman (1988), Caby (1989) and Dada (2008).

In the study area, all the three major rock categories mentioned above are well represented (Fig. 3). The rocks are generally weathered into reddish micaceous sandy-clay to clay materials, capped by lateritic soils. The hydrogeology of the basement area is simple since there is an inherent limitation to the occurrence of groundwater. However, where the soil is thick, about 15 m, and there is a dense network of fractures, the potentials for the accumulation of groundwater in basement complex rocks may increase. Limitations of yield may be due to the fact that the aquifers are often localized. This makes the search for a feasible borehole site imperative in such areas.

MATERIALS AND METHODS

The search for groundwater was carried out through the use of integrated structural interpretation from remotely-sensed data and electrical methods of near surface geophysical surveys. The Schlumberger configuration in VES with 5 m spacings was used to obtain field data. VES probes the vertical variation in resistivity of the subsurface, thereby indicating the presence of fluid and ionic concentration in the subsurface materials (Reynolds 2011). It is also applied to determine the depth to bedrock, delineate the various units that constitute the overburden (soil), and determine the degree of fracturing of the bedrock, all of which would help in making the choice of a feasible site for constructing a successful borehole. VES data for this work were obtained using the Allied OmegaC2 Terrameter. The field data obtained are presented as curves of apparent resistivity values against half of the current electrode separation (AB/2) in metres on a log-log scale. Figure 4 shows representative one-dimensional (1D) VES profiles based on curve types (see Table 1). A 3-mode filter was employed to remove associated noise due mostly to electrical signals and interference from adjacent power transmission lines. The VES data obtained were analysed using the WINRESIST

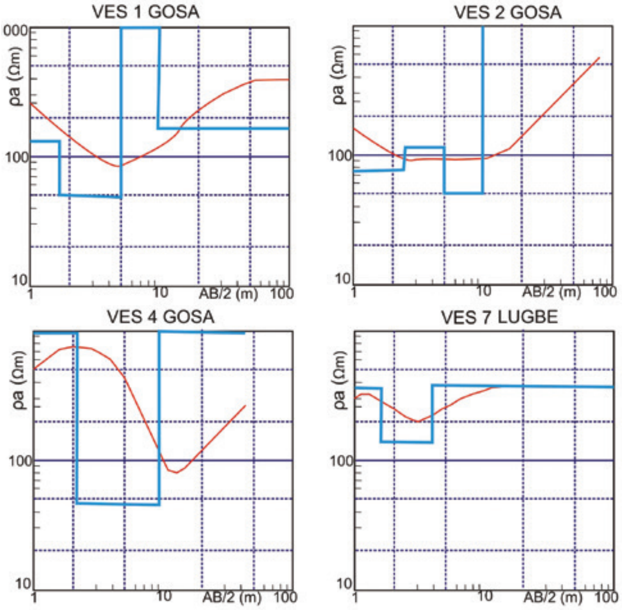

FIGURE 4
1D profile plots of representative curve types.

2004 computer software to improve the quality of the interpretation by iteration and modelling to goodness of fit.

The SRTM, a single pass interferometry mission flown in February 2000, generated digital elevation data at 90 m resolution for 80% of the Earth's surface in C-band. The SRTM-DEM data were downloaded from the website http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1 and subjected to hill shading using Idrisi 32 software to enhance linear features that could be major regional fractures. The analytical hill shading was used to create the hill-shading image with the Sun azimuth angle set to 315° (NW) and the Sun elevation angle set to 30°. The identified lineaments were extracted and digitized on screen to create a lineament map, and the lineament directions were plotted on a rose diagram using GEOrient 9.5.0 software.

DATA INTERPRETATION AND RESULTS

VES data analysis and interpretation

Twelve VES data sets were studied in this work – five from areas around Gosa and seven from other parts of Abuja (Fig. 2). The five points in the Gosa area were close to dry borehole sites (Fig. 2). Table 1 shows a summary of the results. The table shows that at the location of VES 1, there is an interpreted thick lateritic topsoil of up to 3.4 m, underlain by a thin micaceous sandy-clay layer of weathered basement rock that cannot sustain boreholes. This is directly underlain by unweathered, unfractured basement. VES 2 shows an area with thicker lateritic topsoil underlying fresh basement at a very shallow depth. At the location of VES 3, the unweathered basement is encountered at a deeper depth, yet the area does not sustain a borehole. At the location of VES 4 and VES 5, the fresh basement is encountered at shallow depth. The lithology around the other VES points is similar to that of the Gosa area described above; however, all the wells are productive.

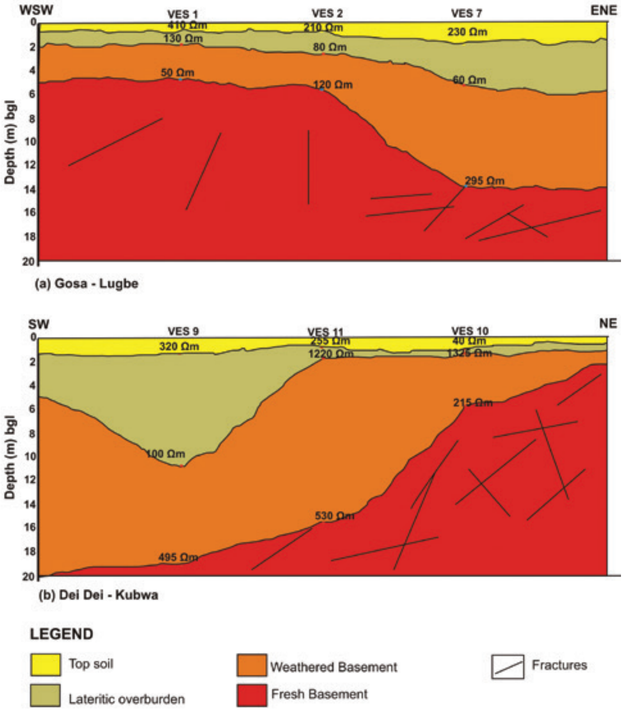

FIGURE 5
2D schematic cross sections of interpreted VES layers across the survey area (a) Gosa – Lugbe (b) Dei-Dei – Kubwa (see Fig. 2 for location).

Two-dimensional (2D) geoelectric sections were then generated by combining any three VES data falling along distinct trends. Figure 5 shows 2D lithological characterizations obtained from VES data combinations around Gosa and Dei-Dei. In the Gosa area, VES 1, VES 2 and VES 7 fall within a WSW–ENE trend and extend from Gosa to Lugbe. A similar trend (SW–NE) is assumed by VES 9, VES 11 and VES 10 around the Dei-Dei–Kubwa axis. It is observed from Fig. 5(a) that the weathered zone is thin around Gosa and becomes considerably thicker around Lugbe. This explains why the groundwater condition is less problematic around Lugbe. In the Dei-Dei–Kubwa area, the top layers which correlate with the weathered layers exhibit considerable thickness. Although the interpreted weathered layer thins out around Phase 4 (VES 10), it is still much thicker than that obtained around Gosa.

Schematic representation of two well logs, from Gosa and Dei-Dei (Fig. 2), correlates well with the interpreted VES data and reveals the absence of thick weathered basement around Gosa. In areas around Dei-Dei, depth to bedrock is thicker (about 20 m) and the water table in the area is about 6 m (Fig. 6).

SRTM data analysis and interpretation

A total of 88 interpreted structural lineaments were digitized on screen and displayed on the lineament map of the study area (Fig. 7). Visual interpretation of the lineament distribution shows that the eastern part of the map, which falls within the Abuja Municipal Council, has a higher concentration of lineaments than the western part. Moreover, it is observed that many of the lineaments around Gosa (south-western part) are not intersecting, whereas those in the eastern part are intersecting, thereby showing a higher promise of fractured basement aquifer potential. This may explain why all the boreholes in the eastern part of the map are productive, whereas those in the south-western part (around Gosa) are not. It is also observed from the rose diagram (Fig. 7) that the dominant fracture trends (NNE–SSW and N–S) coincide with the dominant Pan-African trend in the basement complex of Nigeria (Ajibade *et al.* 1987; Caby 1989; Dada 2008). This indicates that the fractures are regional in scale; hence their intersections could potentially form large zones of brecciation with more pronounced porosity and permeability, which are desirable in regions where boreholes need to intersect significant groundwater.

DISCUSSION

The similarity in the VES sections suggests a relatively homogenous aquiferous setting for the area. However, after subsequent intensive investigations, it was found that this was not the case, as out of a total of ten boreholes drilled in the study area, seven had good water yield with static water level ranging from 4–6 m below ground level (bgl), while three boreholes all around the Gosa area were dry, even when drilled to depths of over 120 m bgl. Geoelectrical surveys also indicated the existence of both weathered and fractured basement, which ideally could form good aquifers in the study area. The soil over the unweathered basement is, however, clayey, and so does not constitute a good aquiferous material, as indicated by borehole records (Fig. 6a). These observations agree with previous research in the basement complex of central Nigeria (e.g., Olorunfemi and Okankune 1992; Okogbue and Omonona 2013). Okogbue and Omonona (2013) identified three aquifer potential types in the Mopa-Egbe basement area of central Nigeria. They included relatively high (> 2.0 L/s), medium (1.0 – 2.0 L/s) and low (< 1.0 L/s) productivity types. The high productivity aquifers constitute the weathered aquifer layers and weathered/fractured aquifer.

Omeje *et al.* (2013) attempted to map aquiferous zones around the Gosa area using only VES data. They inferred that the groundwater problems around the area were as a result of the presence of dense intrusive bodies. This differs remarkably with results from the present study, which suggests that in addition to the absence of a thick overburden, low fracture densities and absence of interconnected fracture zones most probably constitute the reasons for unsuccessful boreholes in the Gosa area (Fig. 2).

In order to overcome the challenge of drilling dry wells in the study area, structural data generated from hill-shaded SRTM data, in combination with VES data, constitute a powerful tool

FIGURE 6

Lithological logs of representative boreholes drilled around (a) Dei-Dei and (b) Gosa areas (above) with respective photographs (below).

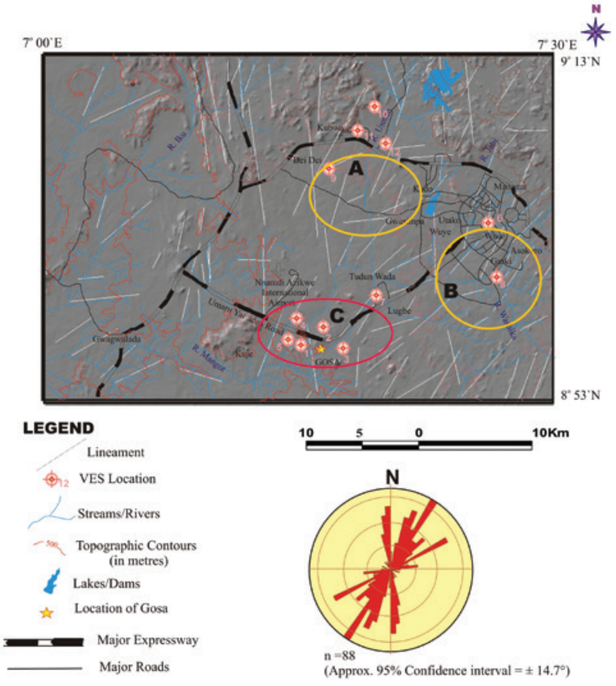

FIGURE 7

(a) Lineament map draped on hill-shaded SRTM-DEM image of the study area. Yellow ellipses show zones of higher fracture density and intersection; red ellipse shows the Gosa area with low fracture density and no intersection. (b) Rose diagram showing the distribution of fracture orientations in the study area.

for delineating potential aquifers in basement rocks. Figure 7 shows the spatial distribution of lineaments (fractures) digitized from enhanced SRTM data. It is observed that in most parts of the study area, large-scale fractures exist, many of which extend for distances in excess of 2 km. These regional features would usually undergo intense brecciation at points of intersection, resulting in widespread shattering of unweathered rocks, which leads to enhanced porosity and permeability.

CONCLUSION

Results from the 12 VES surveys carried out in the study area indicate the presence of lateritic or sandy topsoil, weathered basement and fractured basement. Geoelectric surveys indicate the existence of both weathered and fractured basement, which ideally could form good aquifers in the study area. The regolith over the unweathered basement is, however, clayey, and so does not constitute a good aquiferous material. The major aquiferous zones in the study area are zones of brecciation developed by the intersection of regional fractures detectable on hill-shaded SRTM-DEM images. The lineament map generated from the hill-shaded SRTM-DEM image shows the presence of large regional fractures around the Gosa area; however, the fracture density is relatively low and the fractures do not intersect. This explains the reason why boreholes found around the Gosa area are dry. It is pertinent to note that most of the successful boreholes in the study area terminate at depths of approximately 60 m bgl in fractured zones that are interconnected.

ACKNOWLEDGEMENTS

The authors would like to thank the Ministry of Higher Education (MOHE) for their funding through Universiti Teknologi Malaysia Research Grant Scheme Project number: Q.J130000.2526.03H28. The authors gratefully acknowledge the Nigerian Geological Survey Agency and Federal Ministry of Water Resources for their support in this work. The authors wish to thank SYB Sinyoung Borehole Limited for providing the Rig and Compressor used in drilling the boreholes, and Maxico Hydrosolution consult for providing the Campus Ohmega terrameter. We would also like to thank two anonymous reviewers whose suggestions went a long way in improving the quality of the initial manuscript.

REFERENCES

Abdullah K., Sarfaraz A. and Shadab K. 2012. Geology and geomorphology of the Manipur Valley using digitally enhanced satellite image and SRTM DEM in the eastern Himalaya, India. *International Journal of Geosciences* **3**, 1010–1018.

Acworth R.I. 1987. The development of crystalline basement aquifers in a tropical Environment. *Quarterly Journal of Engineering Geology* **20**, 265–272.

Ajibade A.C., Woakes M. and Rahaman, M.A. 1987. Proterozoic crustal development in the Pan-African regime of Nigeria. In: *Proterozoic Lithospheric Evolution Geodynamics* **17**, 259– 271.

Anudu G.K., Essien B.I., Onuba L.N. and Ikpokonte A.E. 2011. Lineament analysis and interpretation for assessment of groundwater potential of Wamba and adjoining areas, Nassarawa State, northcentral Nigeria. *Journal of Applied Technology in Environmental Sanitation* **1,** 185–198.

Bala A.E. 2001. *An evaluation of Landsat 5 Thematic Mapper data as a tool for groundwater investigation in Basement Complex rocks of Nigeria*. Unpublished Ph.D Thesis, Ahmadu Bello University, Zaira, Nigeria.

Bala A.E., Batalan O. and De Smedt F. 2000. Using Landsat5 imagery in the assessment of groundwater resources in the crystalline rocks around Dutsin-Ma, northwestern Nigeria. *Journal of Mining and Geology* **36**, 85–92.

Barongo J.O. and Palacky G.D. 1989. Investigation of electrical properties of weatherlayers in the Yale area, Western Kenya, using resistivity soundings. *Geophysics* **56**, 133–138.

Black R.R., Caby R., Moussine-Pouchkine A., Bayer R., Bertrand J.M., Boullier A.M. *et al*. 1979. Evidence for Late Precambrian plate tectonics in West Africa. *Nature* **278**, 223–227.

Caby R. 1989. Precambrian terrains of Benin, Nigeria and Northeast Brazil and the Late Proterozoic South Atlantic fit. *Geologic Society of American Special Paper* **230**, 145–158.

Clark L. 1985. Groundwater abstraction from basement complex areas of Africa. *Quartenarly Journal of Engineering Geology* **18**, 25–34.

Dada S.S. 2008. Proterozoic evolution of the Nigeria – Boborema province. *Geologic Society London Special Publications* **294**, 121–136.

De Beer J.H. and Blume J. 1985. Geophysical and hydrogeological investigation of the groundwater resources of western Hereroland, southwest African/Namibia. *Trans. Geol. Soc. S. Africa* **88**, 483-493.

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**, 195–204.

Edet A.E., Teme C.S., Okereke C.S. and Esu E.O. 1994. Lineament analysis for groundwater exploration in Precambrian Oban Massif and Obudu Plateau, S.E Nigeria. *Journal of Mining and Geology* **30**, 87–95.

Galnett R.H. and Gardner J.V. 1979. Use of radar for groundwater exploration in Nigeria, West Africa. *Proceedings of the 14th International Symposium on Remote Sensing of Environment*, Ann Arbor, Michigan, USA.

Goki N.G., Ugodulunwa F.X.O., Ogunmola J.K., Oha I.A. and Ogbole J.O. 2010. Geological controls for groundwater distribution in the basement rocks of Kanke, central Nigeria from geophysical and remotely sensed data. *African Journal of Basic and Applied Sciences* **2**, 104–110.

Grohmann H.C., Riccomini C. and Machado-Alves F. 2007. SRTM-based morphotectonic analysis of the Pocos de Caldas Alkaline massif, Southern Brazil. *Computers & Geosciences* **33**, 10–19.

Manda A.K, Mabee S.B. and Boutt D.F. 2006. Characterizing fractured crystalline bedrock aquifers using hydrostructural domains in the Nashoba terrane, Eastern Massachusetts. In: *Proceedings of 2006 Annual Meeting of the Geological Society of America,* Philadelphia, Pennsylvania USA, 22–25 October 2006.

Mbonu P.D.C., Ebeniro J.O., Ofoegbu C.O. and Ekine A.S. 1991. Geoelectrical Sounding for the determination of aquifer Characteristics in part of Umuahia area of Nigeria. *Geophysics* **56**, 284–291.

Mendoza J.A and Dahlin T. 2008. Resistivity imaging in steep and weathered terrains. *Near Surface Geophysics* **6**, 105–112.

Nur A. and Ayuni N.K. 2004. Hydrologeolectrical study in Jalingo Metropolis and environs of Taraba State, Northeastern Nigeria. *Global Journal of Geological Science* **2**, 101–109.

Okogbue C.O. and Omonona O.V. 2013. Groundwater Potential of the Egbe-Mopa basement area, central Nigeria. *Hydrological Sciences Journal* **58**, 1–15.

Olorunfemi M.O. and Fasuyi S.A. 1993. Aquifer types and geoelectrical/hydrogeologic characteristics of the central basement terrain of Nigeria. *Journal of African Earth Sciences* **16**, 309–317.

Olorunfemi M.O. and Okankune E.T. 1992. Hydrogeological and geological significance of geoelectrical survey of Ile-Ife. *Nigerian Journal of Mining and Geology* **28**, 221–222.

Omeje M., Husin W., Noorddin I., Oha I.A., Onwuka O.S., Ugwoke P.E. and Meludu O. 2013. Geolectrical investigation of aquifer problems in Gosa area of Abuja, North Central Nigeria. *International Journal of Physical Sciences* **8**, 549–559.

Oyawoye M.O. 1972. The basement complex of Nigeria. In: *African Geology, Ibadan*, (eds T.F.J. Dessauvagie and A.J. Whiteman), 66–102.

Pulawaski B. and Kurth K. 1977. Combined use of resistivity and seismic refraction methods in groundwater prospecting in crystalline areas. *Study Project, Kenya, DANIDA* 5-33.

Rahaman M.A. 1988. Recent advances in the study of the Basement Complex of Nigeria. *Precambrian Geology of Nigeria, Geological Survey of Nigeria Publication*, 11–43.

Reynolds J.M. 2011. *An Introduction to Applied and Environmental Geophysics*. John Wiley & Sons Ltd., England, vol. 2, 712 pp.

Satpatty B.N. and Kanugo B.N. 1976. Groundwater exploration in hard rock terrain; a case study. *Geophysical Prospecting* **24**, 725–736.

Shemang E.N. 1993. Groundwater potentials of Kubami River Basin, Zaria, Nigeria, from D. C Resistivity study. *Water Resources* **2**, 36–41.

SRTM. Accessible online at: http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1 (Date of access 06/09/2010).

Valeriano M.M., Kuplich T.M., Storino M., Amaral B.D., Mendes J.N. and Lima D.J. 2006. Modelling small watersheds in Brazilian Amazonia with Shuttle Radar Topographic Mission 90 m data. *Computer & Geosciences* **32**, 1169–1181.

Wright E.P. 1992. The hydrogeology of crystalline basement aquifers in Africa. *Geological Soceity, London, Special Publications* **66**, 1–27.

Wright R., Garbeil H., Baloga S. and Mougin-Mark P. 2006. An assessment of Shuttle Radar Topographic Mission digital elevation data for studies of volcano morphology. *Remote Sensing of Environment* **105**, 41–53.

Zohdy A.A., Eaton C.P. and Mabey D.R. 1974. Application of surface geophysics in groundwater investigation. In: *Technical Water Resources Investigation*, Washington, USGS.