The groundwater potential evaluation at industrial estate Ogbomoso, Southwestern Nigeria

Ocena potenciala podtalnice na industrijskem območju Ogbomoso v jugozahodni Nigeriji

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Abstract: Vertical Electrical Sounding method was used to map Oyo State industrial estate Ogbomoso with a view to determining the groundwater potential of the study area. Ten Vertical Electrical Soundings (VES) were carried out across the area using the schlumberger electrode array configuration with current electrode separation (AB) varying from 130 m to 200 m. Nine out of the ten modeled curves were H-type where the remaining one was KH-type. The geoelectric sections obtained from the sounding curves revealed 3-layer and 4-layer earth models respectively. The models showed the subsurface layers categorized into the topsoil, weathered/clay, fractured layers and the fresh bedrock. The weathered basement and fractured basement are the aquifer types delineated for the area. Groundwater potential evaluated from the maps (i.e. overburden thickness, anisotropic coefficient, weathered layer isothickness, weathered layer isoresistivity, transverse resistance and bedrock relief maps) revealed that the Southern and Eastern parts of the study area are the most promising region for borehole development. However, Northeastern region of the study area can also be considered as fair for borehole development.

Original scientific paper

Izvleček: Z metodo vertikalnega električnega sondiranja so kartirali industrijsko območje države Oyo Ogmoboso v Nigeriji z namenom opredeliti potencial podtalnice. Opravili so sedem vertikalnih električnih sondiranj (VES) s Schlumbergerjevo razporeditvijo elektrod in razdaljami med tokovnima elektrodama (AB) od 130 m do 200 m. Devet izmed desetih modeliranih krivulj je bilo vrste H, preostala pa vrste KH. Geoelektrični profili, izdelani po krivuljah sondiranja, razkrivajo triplastne in štiriplastne modele. Zastopane so plasti vrhnjega nivoja tal, preperine/gline, razpokane kamnine in nepreperele kamnine. Vodonosnika na preiskovanem ozemlju sta v prepereli podlagi in razpokani podlagi. Potencial podzemne vode, ocenjen po izdelanih kartah (debeline pokrova, koeficienta anizotropnosti, navidezne debeline in navidezne upornosti in reliefa preperinske plasti), kaže, da so najperspektivnejši za vrtanje južni in vzhodni deli raziskovanega območja. Potencial vode v severovzhodnem delu je ocenjen kot povprečen.

Key words: vertical electrical sounding, groundwater potential, fractured basement, thick overburden, aquifer, industrial estate

Ključne besede: vertikalno električno sondiranje, potencial podtalnice, razpokana podlaga, debel pokrov, vodonosnik, industrijska lokacija

INTRODUCTION

The importance of groundwater as a supply source to the socio-economic development of a country is tremendous. Though, the state water corporations make use of some minor rivers as a means of water supply to the populace especially in the urban areas but this water is insufficient for domestic uses let alone its availability for industrial uses. Constant supply of water cannot be denied in any industrial settings, as it serves as one of the amenities to be available in industries. Therefore, groundwater has proved itself to be the only available source of water for industrial uses.

The use of geophysics for both groundwater resource mapping and for water quality evaluations has increased dramatically over the years. The Vertical Electrical Soundings (VES) has proved very popular with groundwater studies due to simplicity of the technique.

Groundwater has become immensely important for human water supply in urban and rural areas in developed and developing nations alike (Omosuyi, 2010). Using this method, depth and thickness of various subsurface layers and their water yielding capabilities can be inferred. Therefore, evaluation of groundwater potential at industrial estate Ogbomoso was done in order to know the groundwater yielding capabilities or groundwater conditions of the study area. In basement complex, unweathered basement rocks contain negligible groundwater. Significant aquifers however, develop within the weathered overburden and fractured bedrock. This research is particular to know feasibility of potable water borehole in the industrial estate (i.e. to know the promising areas for groundwater prospects within the study area). This was done in order to advise the building engineers and the users of the estate not to build factories, ware houses or administrative buildings on the available zones for groundwater exploration and to know the promising zones for groundwater exploration in the study area. However, the groundwater conditions of industrial estate when properly understood could be used as an effective tool in the planning of reliable water borehole in the study area.

The study area is underlain by Precambrian rocks of the Nigerian Basement Complex where aquifers are both isolated and compartmentalized. These rocks in their deformed state posses little or no primary intergranular porosity and permeability and thus the occurrence of groundwater is due largely to the development of secondary porosity and permeability by weathering and/or fracturing of the parent rocks (Acworth, 1987; Olorunfemi & Fasuyi, 1993; Olayinka et al, 1997). Groundwater localization in this region is controlled by a number of factors which include the parent rock type, the depth, extent and pattern of weathering, thickness of weathered materials, and the degree, frequency and connectivity of fracturing, fissuring and jointing, as well as the type and nature of the fillings in the joint apertures (Oluyide a& Udey, 1965; Bianchi & Snow, 1969; Asseez, 1972; Odusanya, 1989; Esu, 1993; Eduvie & Olabode, 2001).

Considering the limited characteristics of the groundwater reservoirs in the Basement Complex, the full benefit of the aquifer system can only be exploited through a well coordinated hydrogeophysical and geological investigation program of the prospective area. Geoelectrical techniques are powerful tools and play a vital role in groundwater investigations particularly in the delineation of the aquifer configuration in complex geological environments. A planned geoelectrical investigation is capable of mapping an aquifer system, clay layers, the depth and thickness of aquifers, fissure or fracture location, and qualitatively estimating local groundwater flow (Fitterman & Stewart, 1986; McNeill, 1987; Olasehinde, 1989) and has been adopted in this study. The most commonly used geophysical technique for groundwater exploration is electrical resistivity (Mazac et al, 1987) which is aimed at identifying high conductivity anomalies, normally thought to be due to deep weathering. Recent developments in geoelectrical data acquisition and interpretation methodology provide electrical images of subsurface features. A properly calibrated electrical image can be used to infer the aquifer configuration: depth, thickness, horizontal and vertical extent of the aquifers. Investigation involving detail geophysical study for groundwater potential in the area covered by this study is presently non-existence. This exigency inspired this study. Therefore, the primary objective of this study was to determine the groundwater potential and to identify suitable sites/locations for exploration of groundwater in industrial estate Ogbomoso, Southwestern Nigeria.

Site description

The studied area lies within the crystalline Basement Complex of Nigeria (MacDonald & Davies, 2000). It lies within latitude 08^{0} 06′ 07.4″ and 08^{0} 06′ 25.4″ and longitude 004^{0} 15′ 03.3″ and 004^{0} 15′ 49.0″. The study area is located at the outskirt of Ogbomoso South Local Government and shares boundary with Surulere Local Government Area along old Oshogbo road. The study area is accessible with network of roads that surrounds it and very close to Aarada market.

Hydrogeological setting

According to MacDonald & Davies (2000) who classified the hydrogeology of Sub-Saharan Africa into four provinces, these are: Precambrian basement rocks, volcanic rocks, unconsolidated sediments and consolidated sedimentary rocks (figure 1a). These four provinces are well represented in Nigeria (figure 1b). The study area is located on the Precambrian basement rocks of Southwestern Nigeria which comprise of crystalline and metamorphic rocks over 550 million years old (MacDonald & Davies, 2000).

Unweathered basement rock contains negligible groundwater. However, significant aquifers develop within the weathered overburden and fractured bedrock (MacDonald & Davies, 2000; Alagbe, 2005). In the soil zone (top soil) of Precambrian basement, permeability is usually high, but groundwater does not exist throughout the year and dries out soon after the rains end. Beneath the soil zone, the rock is often highly weathered and clay rich, therefore permeability is low. Towards the base of the weathered zone, near the fresh rock 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 for consumption (MacDonald & Davies).

Deeper fractures within the basement rocks are also an important source of groundwater, particularly where the weathered zone is thin or absent. These deep fractures are tectonically controlled and can sometimes provide supplies of up to 1 l/s or even 5 l/s. The groundwater resources within the regolith and deeper fracture zones depend on the thickness of the water-bearing zone and the relative depth of the water table. The deeper the weathering, the more sustainable the groundwater (MacDonald & Davies, 2000).

Geological setting

Regionally, the Study area lies within the South Western parts of the Basement rocks, which is part of the much larger Pan-Africa mobile belt that lies in between the West Africa Craton and Congo Craton, suspected to have been subjected only to a thermotectonic event (Alagbe, 2005).

In general, the southwestern Nigeria crystalline Basement (figure 1c) can be grouped into three:

- **The Migmatite-Gneiss Complex**: It compose of Migmatite and gneiss of various composition. Relics of sedimentary rocks such as quartzitic rocks occurring within the group with ages ranging from Pan-Africa (600 million years) to Leonian (Russ, 1957).They have been metamorphosed in the middle to upper amphibolite facies (Ajibade et al, 1988).
- **Metasedimentary and Metavolcanic Rocks:** (This is also known as Low grade sediment dominated schist belt) trending N-S which are considered to be Upper Proterozoic (Birimian) in age. The Northwestern basement has well developed schist belts(Green Schist facies) comprising mainly of phyllite, Schist, quartzitic and banded iron formation(BIF).The rocks are considered to be Upper Proterozoic that has been infolded into Migmatite-gneiss complex (Trusswell & Cope, 1963).
- **The Pan-African Older Granite Series:** This intrude both into the Migmatite-gneiss-quartzite complex and the Low grade schist belts. They range widely in age and composition from true granite to grano-

diorite, adamalite and tonalities. Other rocks associated with it are highly hypersthenes bearing rocks called charnokites.

Their Rb/Sr ages range between 750 million years and 450 million years (AJIBADE et al 1988), which are considered to be ages of emplacement, classify these rocks as strictly belonging to Pan Africa. Notably among the granite series are Kusheriki granites (TRUSWELL & COPE, 1963). The above three division is largely based on lithology and does not in anyway reflect the range of Complex field relationship and structures displayed on the rocks.

Locally, the study area lies within Ogbomoso and is underlain by rocks of the Precambrian complex with Quartzite and Quartz-Schist and Undifferentiated Gneiss and Migma-

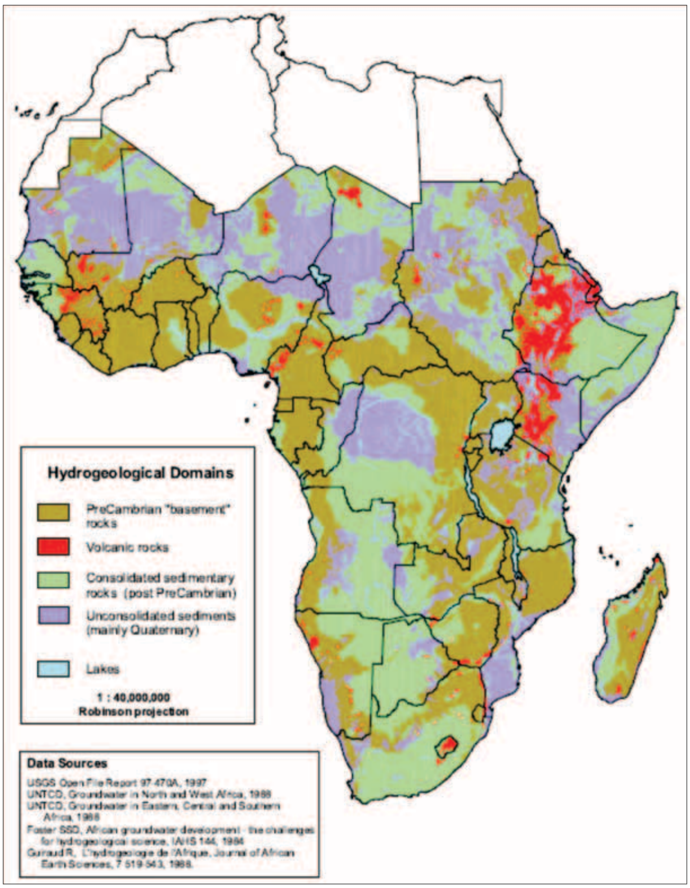


Figure 1a. The hydrogeological domains of Sub-Saharan Africa (MACDONALD & DAVIES, 2000).

tite (Ajibade et al., 1988). The rock groups in the area include quartzites and gneisses (Ajibade et al, 1988). Schistose quartzites with micaceous minerals alternating with quartzo-feldsparthic ones are also experienced in the area. The gneisses are the most dominant rock type. They occur as granite gneisses and banded gneisses with coarse to medium grained texture. Noticeable minerals include quartz, feldspar and biotite. Pegmatites are common as intrusive rocks occurring as joints and vein fillings (Rahaman, 1976; Ayantunji, 2005). They are coarse grained and weathered easily in to clay and sand-sized particles, which serve as water-bearing horizon of the regolith. Structural features exhibited by these rocks are foliation, faults, joints and microfolds which have implications on groundwater accumulation and movement (Ayantunji, 2005).

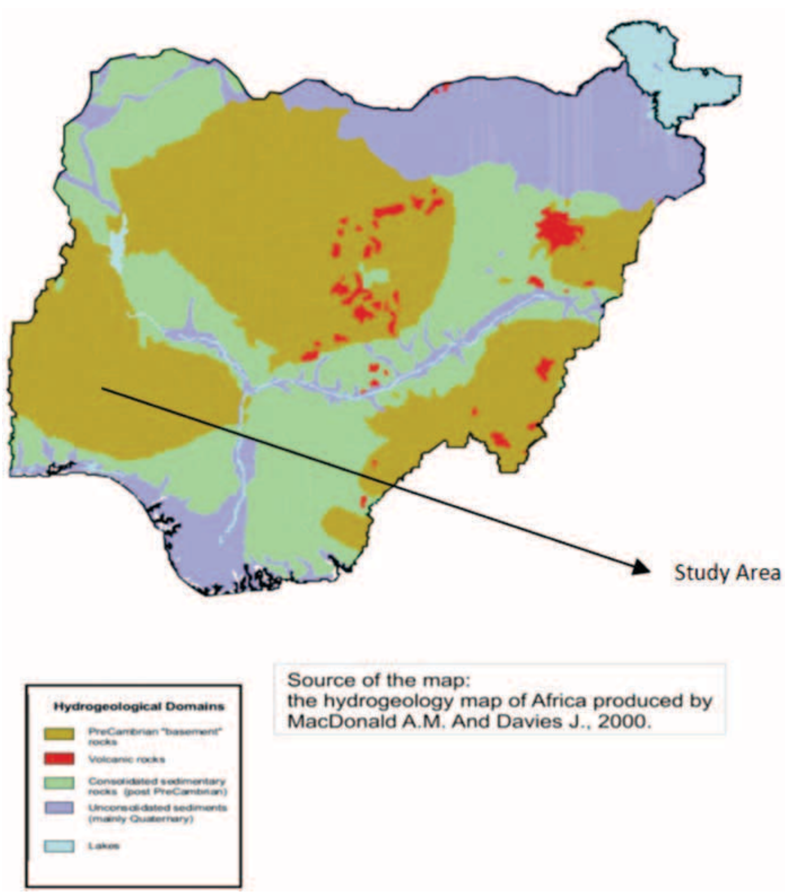


Figure 1b. The hydrogeological domains of Nigeria (extracted from MacDonald & Davies, 2000).

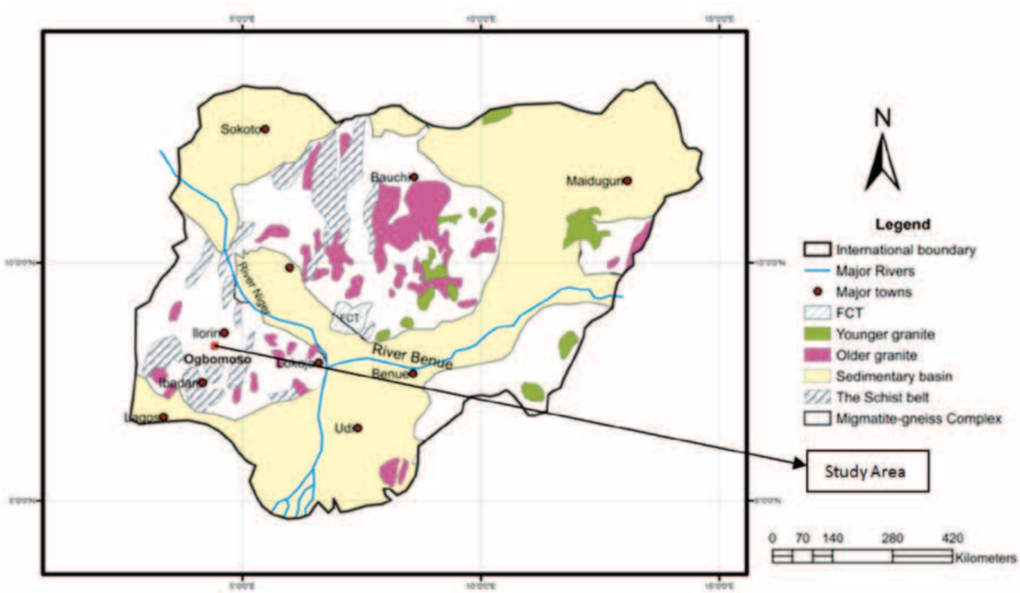


Figure 1c. Geological map of Nigeria showing the study area. (Modified after AJIBADE et al, 1988).

THEORY OF ELECTRICAL RESISTIVITY IN ROCKS

The foundation of electrical resistivity theory is the Ohm's law (GRANT & WEST, 1965) which states that the ratio of potential difference (V) between two ends of a conductor in an electrical circuit to the current (I) flowing through it is a constant.

$$V = IR \tag{1}$$

Where R is a constant known as resistance measured in ohms (Ω).

If the conductor is a homogeneous cylinder of length (L) and cross sectional area (A), the resistance will be proportional to the length and inversely proportional to the area (DUFFIN, 1979).

$$R = \frac{\rho L}{A} \tag{2}$$

Where ρ is the resistivity measured in ohm-meter (Ωm).

The earth's material is predominantly made up of silicate, which are basically non-conductors. The presence of water in the pore spaces of the soil and in the rocks enhances the conductivity of the earth when an electrical current (I) is passed through it, thus making the rock a semi-conductor.

If the electrical field generated by the current is E across the length when a potential difference (V) is applied, then the potential difference can be defined

(Evwaraye & Mgbana, 1993) as:

$$V = EL \quad (3)$$

where E is the electric field strength with dimension of volt per meter (V/m).

If the current electrode is taken to penetrate a small hemisphere of radius r, then the area of the hemisphere becomes $2\pi r^2$.

Substituting for E and integrating Equation 3 gives:

$$\Delta V = \int E.dr. \quad \text{(Duffin, 1979)} \quad (4)$$

$$\text{or} \quad \Delta V = \frac{I\rho}{2\pi r} \quad (5)$$

$$\text{and} \quad \rho = \Delta V.2\pi r \quad (6)$$

Since the earth is not homogeneous, Equation 6 is used to define an apparent resistivity ρ_a which is the resistivity the earth would have if it were homogeneous (Grant & West, 1965). Equation 6 can be written in a general form as:

$$\rho_a = \frac{\Delta V}{I}.G \quad (7)$$

where G is a geometrical factor fixed for a given electrode configuration.

The Schlumberger electrode configuration has been used in this study. In this arrangement, current is injected into the earth through two electrodes which create a potential field which is detected by another pair of electrodes. The geometrical factor for the schlumberger electrode configuration is given by:

$$G = \frac{\pi((\frac{AB}{2})^2 - (\frac{MN}{2})^2)}{2(\frac{MN}{2})} \quad (8)$$

where AB is the distance between two current electrodes, and MN is the distance between two potential difference.

Materials and methodology

A four day geophysical survey was carried out from 13th to 16th October, 2011 using the electrical resistivity method. The survey was conducted with R 50 Resistivity meter. A total of 10 Vertical Electrical Sounding (VES) stations were occupied randomly to cover the area of study (Figure 2). The schlumberger array with maximum electrode spacing (AB) of 130 m to 200 m was used for the field resistance measurements. The resistivity values were determined and plotted on a double logarithmic graph paper for quick check on the field. The VES curves were generated by applying the conventional curve matching (Zohdy, 1973; Zohdy & Maboy, 1974; Patra & Nath, 1999).

Parameters such as apparent resistivity and thickness obtained from partial curve matching were used as input data for computer iterative modeling using the WinResist software (VANDER VELPEN, 2004). The VES curves generated gives the thickness and the resistivities of different layers. The depth sounding curves were then classified according to the resistivity contrasts between the layers as H, K, A, Q or multiples thereof, following the classification by KELLER & FRISCHNECHT (1970) and PATRA & NATH (1999). The modeling produced series of curves as shown in figure 3(a–b). Nine out of the ten curves were H-type ($\rho_1 > \rho_2 < \rho_3$) while the remaining one showed KH-type ($\rho_1 < \rho_2 > \rho_3 < \rho_4$). Surfer 8 software (Surfer 8, 2002) was further used on personal computer to produce 3-dimensional view of Overburden isopach map, overburden anisotropic coefficient map, weathered layer isothickness map, weathered layer isoresistivity map, weathered layer transverse resistance map, and bedrock relief map in order to evaluate the groundwater potential of the study area. Surfer 8 program is software that helps to produce 2-Dimensional and 3-Dimensional images. Geoelectric layers parameters was input into this software to produce 3-Dimensional images of subsurface in order to determine the groundwater potential of industrial estate Ogbomoso.

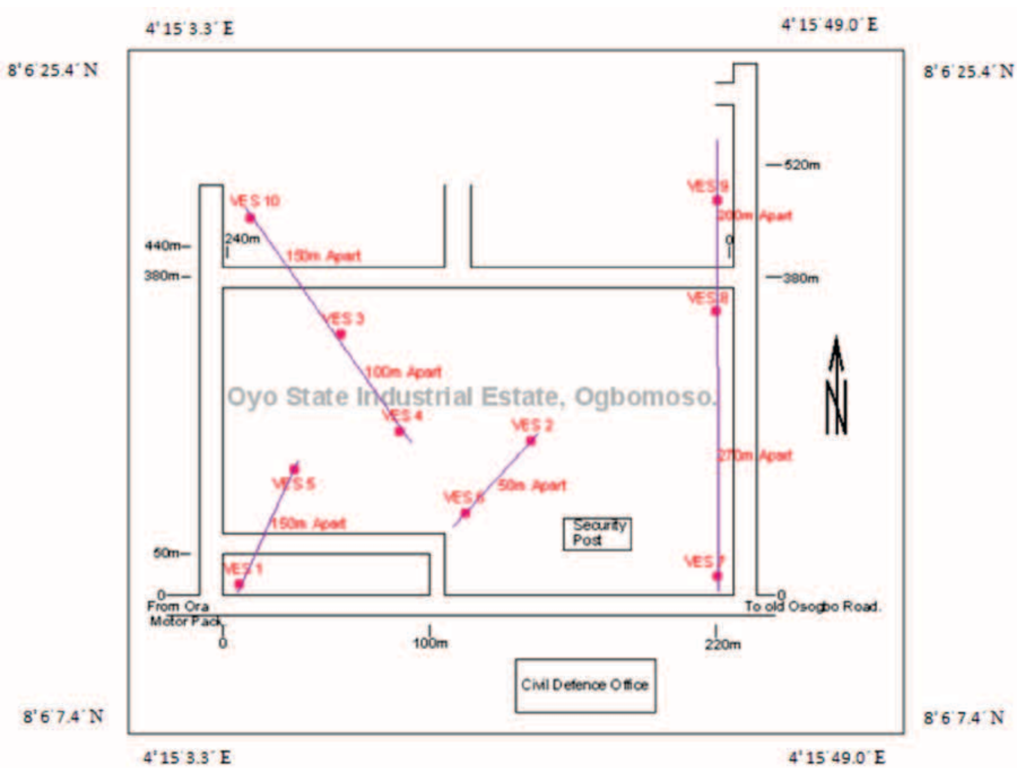


Figure 2. Layout map of Vertical Electrical Sounding stations.

Results and discussion

The presence of groundwater in any rock presupposes the satisfaction of two factors: adequate porosity and adequate permeability. On account of their crystalline nature, the metamorphic and igneous rocks of the Basement Complex satisfy neither of these requirements. Basement complex rocks are thus considered to be poor aquifers because of their low primary porosity and permeability necessary for groundwater accumulation (Davis & De Weist, 1966). However, secondary porosity and permeability imposed on them by fracturing, fissuring, jointing, and weathering through which water percolates make them favourable for groundwater storage (Omorinbola, 1979).

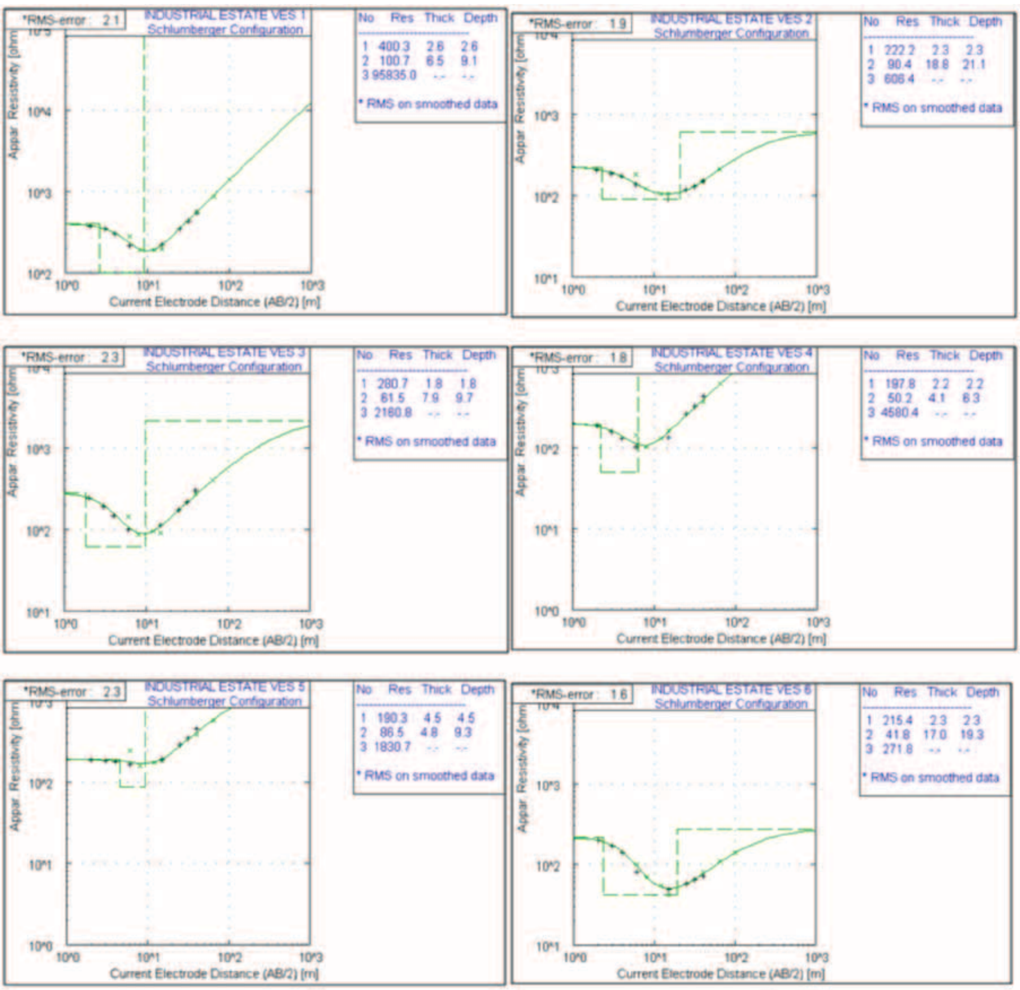


Figure 3(a). The modeled curve for VES 1 to VES 6

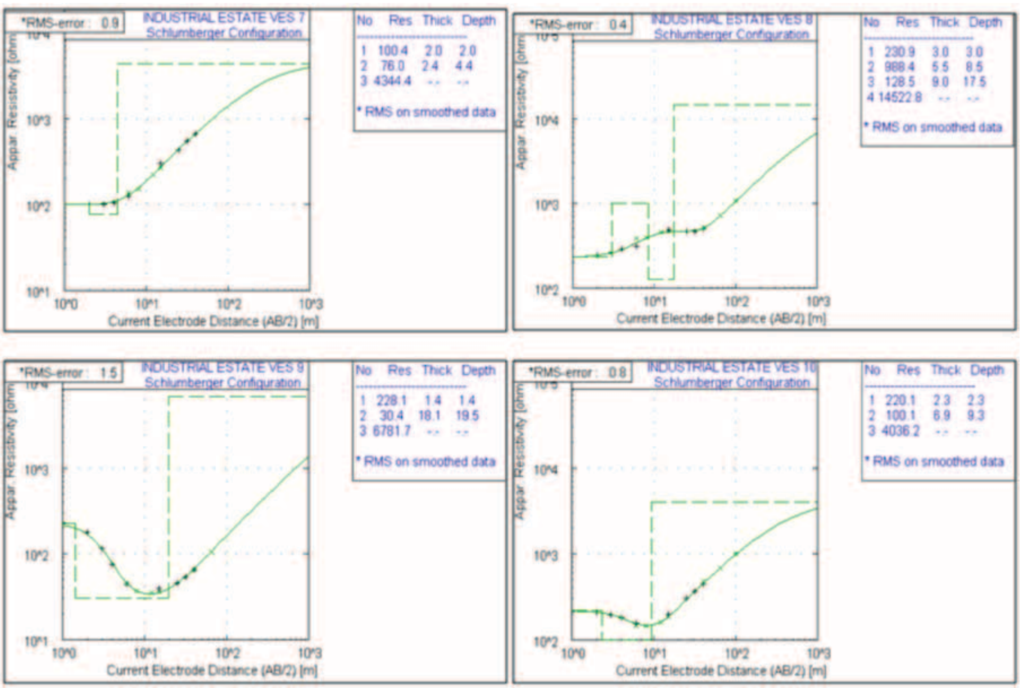


Figure 3(b). The modeled curve for VES 7 to VES 10.

The modeled curves showed three layers in nine of the VES stations (i.e. VES 1, 2, 3, 4, 5, 6, 7, 9 and 10) and four layers in the remaining one (i. e. VES 8) (figure 3a–b). The result showed that 60 % of the VES stations have thin overburden and fresh basement rocks (i.e. VES 1, 3, 4, 5, 7 and 10), 20 % of the VES stations have thick overburden and fresh basement rocks (i.e. VES 8 and 9) while the remaining 20 % of the VES stations have thick overburden and fractured basement rocks (i. e. VES 2 and 6).

From the results, VES 2 and 6 are the best location for groundwater prospect because of the thick overburden and fracture in the basement (Wright, 1990; Meju et al., 1999). VES 8 and 9 could be considered as another location for groundwater exploration because Benson & Jones (1988) and Lenkey et al. (2005) reported that boreholes should be sited where the regolith is thickest.

Summary of the formation of the layer parameters is presented in table 1 while summary of classification of the resistivity sounding curves is presented in table 2.

Table 1. Summary of the formation of layer parameters.

Location	Layer 1		Layer 2		Layer 3		Layer 4	
	ρ_1/(Ω m)	h_1/m	ρ_2/(Ω m)	h_2/m	ρ_3/(Ω m)	h_3/m	ρ_4/(Ω m)	h_4/m
VES 1	400.3	2.6	100.7	6.5	95835.0	-	-	-
VES 2	222.2	2.3	90.4	18.8	606.4	-	-	-
VES 3	280.7	1.8	61.5	7.9	2160.8	-	-	-
VES 4	197.8	2.2	50.2	4.1	4580.4	-	-	-
VES 5	190.3	4.5	86.5	4.8	1830.7	-	-	-
VES 6	215.4	2.3	41.8	17.0	271.8	-	-	-
VES 7	100.4	2.0	76.0	2.4	4344.4	-	-	-
VES 8	230.9	3.0	988.4	5.5	128.5	9.0	14522.8	-
VES 9	228.1	1.4	30.4	18.1	6781.7	-	-	-
VES 10	220.1	2.3	100.1	6.9	4036.2	-	-	-

Table 2. Classification of the resistivity sounding curves.

Curve types	Resistivity model	Model frequency	VES Locations
H	$\rho_1 > \rho_2 < \rho_3$	9	1, 2, 3, 4, 5, 6, 7, 9, 10
KH	$\rho_1 < \rho_2 > \rho_3 < \rho_4$	1	8
Total		10	

Groundwater Potential Evaluation

The groundwater potential of a basement complex area is determined by a complex inter-relationship between the geology, post emplacement tectonic history (fractures), weathering processes and depth, nature of the weathered layer, groundwater flow pattern, recharge and discharge processes (Olorunfemi et al, 1999). The groundwater potential of the study area was evaluated based on maps (i.e. overburden thickness, anisotropic coefficient, weathered layer isothickness, weathered layer isoresistivity, transverse resistance and bedrock relief maps) generated from the VES interpretation results. The characteristic geoelectric parameters enabled the groundwater potential rating at each VES location. These maps are as presented below.

Overburden Thickness Isopach Map

The depth to the basement (overburden thickness) beneath the sounding stations were plotted and contoured at 1m interval as shown in figure 4. This was done to enable a general view of the aquifer geometry of the surveyed area. The overburden is assumed to include the topsoil, the lateritic horizon and the clay/weathered rock. The values range from 4.4 m to 21.1 m. Areas with thick overburden corresponding to basement depression and are known to have high groundwater potential particularly in the basement complex area (WRIGHT, 1990; OLORUNFEMI & OKHUE, 1992; MEJU et al., 1999).

The Southern (i. e. VES 6), Northeastern (i. e. VES 8 and VES 9) and Eastern (i. e. VES 2) side of the study area has thick overburden thickness while the Western and Southeastern side of the study area showed thin overburden thickness. The Southern, Northeastern, and the Eastern side of the study area are the promising locations for groundwater prospect.

Since the yield of a well in the Basement Complex is expected to have a positive correlation with the depth

Table 3. Aquifer potential as a function of the depth to bedrock (OLAYINKA et al., 1997).

Overburden Thickness (m)	
Range	**Weighting**
<5	2.5
5–10	5
10–15	7.5
>15	10

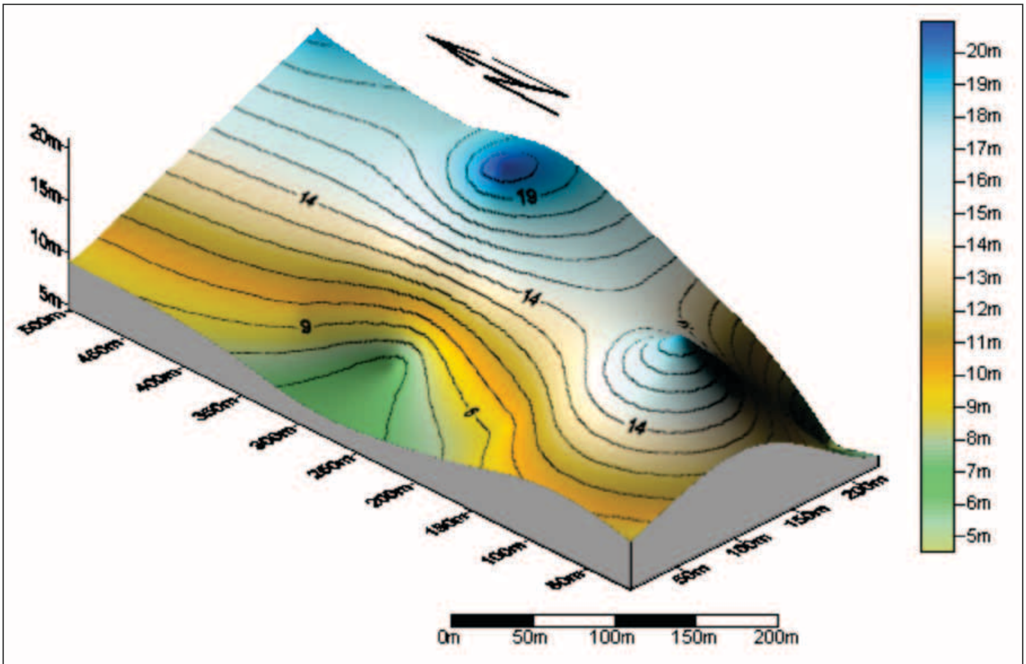


Figure 4. Overburden thickness isopach map

to bedrock, weights that are directly proportional to the overburden thickness have been assigned (Olayinka et al., 1997). These weights range from a minimum of 2.5 for thickness less than 5 m to a maximum of 10 for overburden thickness exceeding 15 m (table 3).

Coefficient of Anisotropy of the Overburden

The overburden's coefficient of anisotropy (λ) was calculated for each VES station using the layer resistivities and thicknesses (Olorunfemi & Okhue, 1992);

$$\lambda = \sqrt{\frac{\rho_t}{\rho_l}} = \sqrt{\frac{\sum_{i=1}^{n-1} h_i \rho_i \sum_{i=1}^{n-1} \frac{h_i}{\rho_i}}{(\sum_{i=1}^{n-1} h_i)^2}} \qquad (9)$$

where ρ_t is the transverse resistance, ρ_1 is the longitudinal resistance, i is the summation limit varying from 1 to $n - 1$, h_i is the ith layer thickness and ρ_i is the i-th layer resistivity.

The λ values were plotted and contoured. This was done in order to know the areas that are good for groundwater prospects. Areas which show ridges on the map will be promising zones for groundwater prospects while areas which show depressions on the map will not be suitable for groundwater prospects. The resulting overburden coefficient of anisotropy map (figure 5) shows λ values ranging from 1.0 to 1.45 with a mean value of 1.16. Vividly, the Northeastern and to the base

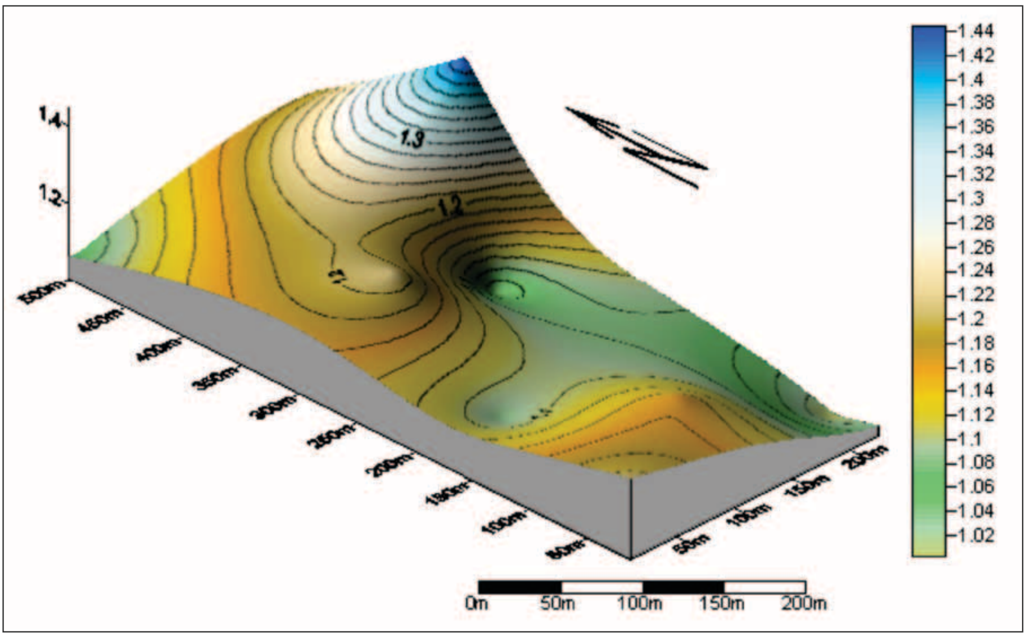


Figure 5. Overburden anisotropy coefficient map.

Table 4. Aquifer potential as a function of overburden anisotropic coefficient.

Anisotropy Coefficient (λ)	
Range	**Weighting**
<1	2.5
1–1.5	5
1.5–2	7.5
>2	10

of the Eastern side of the study area showed that overburden's coefficient of anisotropy (λ) is high. Also, some peaks were observed at Southern to the Southwestern part of the study area. These areas with peaks are the promising locations for groundwater prospect.

Olorunfemi et al, (1991) gives the mean coefficient of anisotropy of igneous and metamorphic rocks of the Basement Complex of southwestern Nigeria as 2.12 and 1.56 respectively and that groundwater yields increase linearly with increase in λ (Olorunfemi & Olorunniwo, 1985; Olorunfemi et al, 1991; Olorunfemi & Okhue, 1992). All the values of λ obtained fall within the range of areas underlain by metamorphic rocks in the southwestern Nigeria.

Since the yield of a well in the Basement Complex is expected to have a positive correlation with the value of the overburden anisotropic coefficient, weights, ranging from a minimum of 2.5 for λ less than 1 to a maximum of 10 for λ exceeding 2 have been assigned (table 4).

Weathered Layer Isothickness Map

The weathered layers as defined in this work are materials constituting the regolith, straddled in between the topsoil or laterite and fractured or fresh bedrock. The thickness of these lithological materials varies between 2.4 m and 18.8 m. This was determined from the layer interpretation of the sounding results. The weathered layer isopach map was produced using a contour interval of 1 m (figure 6). The map was produced with a view to observing how the weathered basement layer considered to be the major component of the aquifer in the study area varied from place to place.

The weathered layer is seen to be thickest at Eastern, some part of the Northeastern region and Southern part of the study area, groundwater potential is most prominent here. The Western and peak of the Southeastern part of the study area showed a very thin weathered layer.

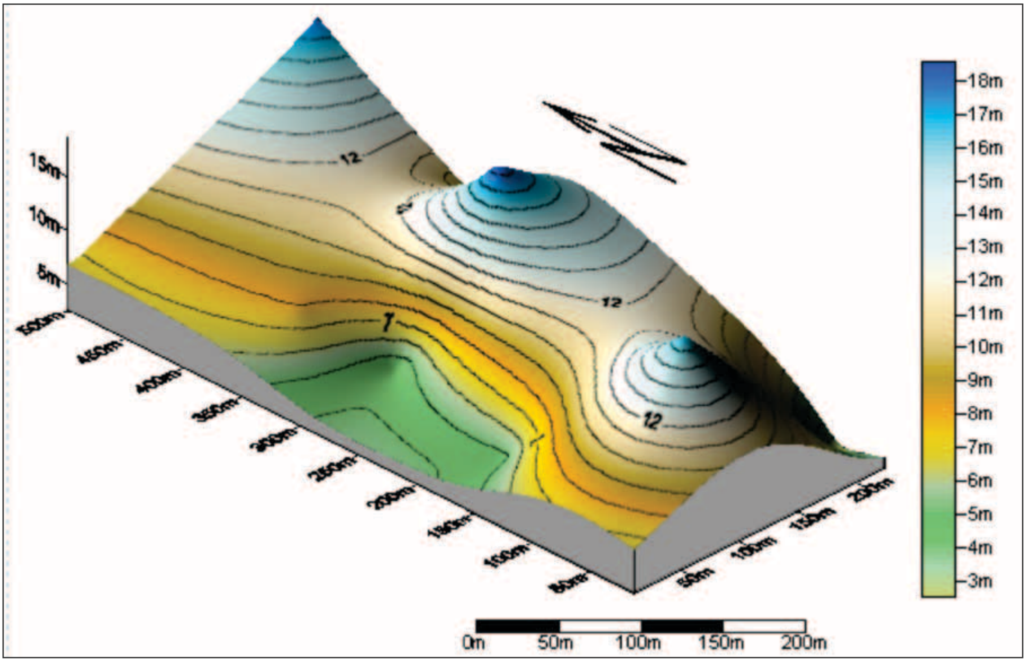


Figure 6. Weathered layer isothickness map

Weathered Layer Isoresistivity Map

In order to have an insight to the groundwater potentials of the study area, an aquifer resistivity map (figure 7) was produced from the interpreted VES data results of this work. The resistivity value of the aquifers at each VES site location was plotted and contoured at 5 Ω m. The map was produced in order to distinguish high water-bearing weathered layer from low water-bearing ones, and to find out whether or not the degree of weathering /saturation varies from point to point in the study area.

As shown on the map, the resistivity value of the aquifer is highest at the Northeastern (i. e. VES 8 and VES 9) part of the study area which falls within medium potential condition (table 5). However, the Southern part (i. e. VES 6) and the Western part (i. e. VES 4) of the study area showed low resistivity values. The Southern part might be the most promising location for groundwater prospect because of the results from VES curve 6 (Wright, 1990; Meju et al., 1999). The Western part (i.e. VES 4) could be considered as another promising area for groundwater prospect but because of its thin overburden (Lenkey at al., 2005), the water present in the aquifer might not be able to serve the industrial purposes in the time of prolonged dry season.

The electrical resistivity of the saprolite layer overlying the basement is controlled by the parent rock type, climatic factors, as well as the clay content. A low resistivity of the order of less than 20 Ω m is indicative of a clayey regolith (CARRUTHERS & SMITH, 1992; Olayinka et al, 1997). This reduces the permeability and thus lowers the aquifer potential. Weights are assigned to the weathered layer resistivity values according to WRIGHT, (1992). Table 5 summarized the optimum aquifer potentials associated with the saprolite resistivities.

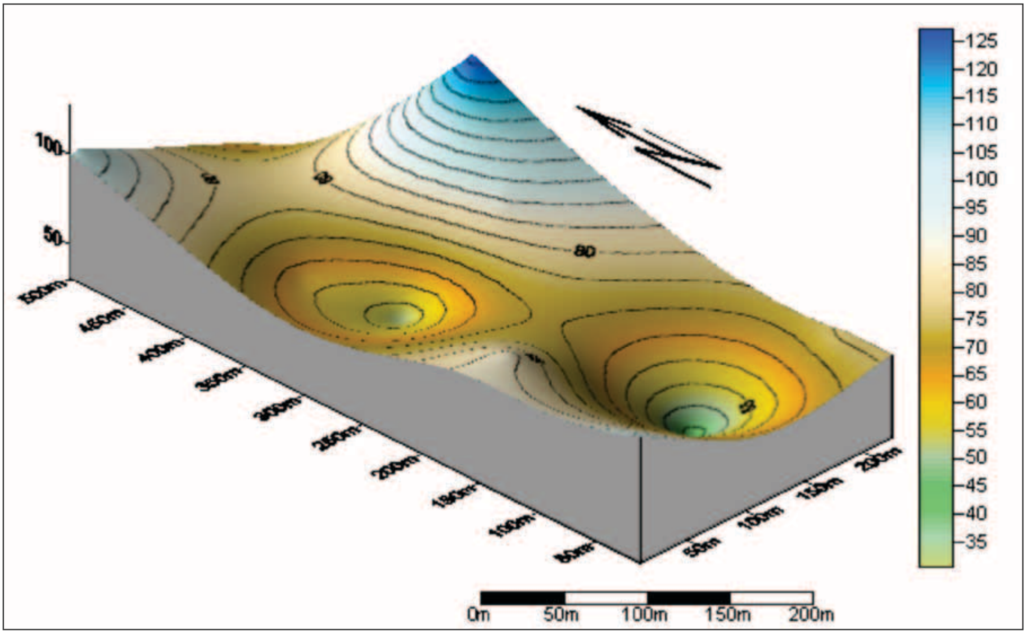


Figure 7. Weathered layer isoresistivity map

Table 5. Aquifer potential as a function of the weathered layer resistivity (modified after WRIGHT, 1992).

Weathered Layer Resistivity (Ω m)		
Range	**Aquifer Characteristics**	**Weighting**
<20	Clay with limited potential	7.5
21–100	Optimum weathering and good groundwater potential	10
101–150	Medium conditions and potential	7.5
151–300	Little weathering and poor potential	5
>300	Negligible potential	2.5

Weathered Layer Transverse Resistance Map

Aquifer transmissivity has been found to be a very powerful means of confirming zones of prolific aquifers. This parameter is defined in hydrogeology, as the product of aquifers hydraulic conductivity (or permeability) and its thickness.

$T = K \times \mathrm{h}$ (10)

where T is transmissivity, K is hydraulic conductivity and h is the thickness of the aquifer (Todd, 1980).

According to Maillet, 1974 transverse resistance (R_T) of a layer as of the Dar-Zarrouk parameters, is defined as:

$R_T = h \times \rho$ (11)

Where, h and ρ are thickness and resistivity respectively, of the layer.

The relationship between transmissivity (T) and transverse resistance (R_T) is meaningful, simply because hydraulic conductivity (K) and resistivity (ρ) have a direct linear relationship (Niwas & Singhal, 1981). Combining the two equations, we have

$$T = \frac{K}{\rho} \times R_T = K\sigma \times R_T \quad (12)$$

This relationship is suitable for determination of aquifer transmissivity, as the ratio $K/\rho = K\sigma$ is assumed to be constant in areas with similar geologic setting and water quality (Niwas & Singhal, 1981; Aderinto, 1986; Onuoha & Mbazi, 1988; Onu, 2003). Thus knowing the value of K for some existing boreholes and the value of σ extracted from the sounding interpretation for the aquifers at the borehole locations, the transmissivity of the aquifer can be computed.

These established relationships were utilized with the hydraulic conductivity (K) values of boreholes near Northwestern side (i.e. some metres away from VES 10), near Northeastern side (i. e. some metres away from VES 9), and the other two boreholes were located towards the Southern part of the study area (i. e. behind the Civil defence office). The hydraulic conductivity (K) were determined to be (6.62, 11.99, 11.42 and 15.54) m/d respectively after pumping test by D' Strata Drilling Company and the $K\sigma$ of these points were found to be 0.097, 0.097, 0.1164 and 0.1034 respectively. An average of 0.10344 was used for the entire study area. The transmissivity at each VES station was determined by multiplying average $K\sigma$ with corresponding transverse resistance, R_T and the variation of transmissivity across the aquiferous zone of the investigated area is shown in figure 8.

On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance (Henriet, 1975). Therefore, transverse resistance maps is used in determination of zones with high groundwater potential (TOTO et al, 1983: BRAGA et al, 2006) and suitable for drilling wells.

The Eastern flank of the study area has transverse resistance corrensponding to high transmissivity which in turn means greater water potential. Also, a little peak is experienced at the Southern part of the study area, this location is another promising area for groundwater prospect in the study area. However, the Western and the Southeastern flank generally has low transmissivity.

On a purely empirical basis, it can be admitted that the transmissivity of an aquifer is directly proportional to its transverse resistance (HENRIET, 1975; HADI, 2009). Hence, there exists a lin-

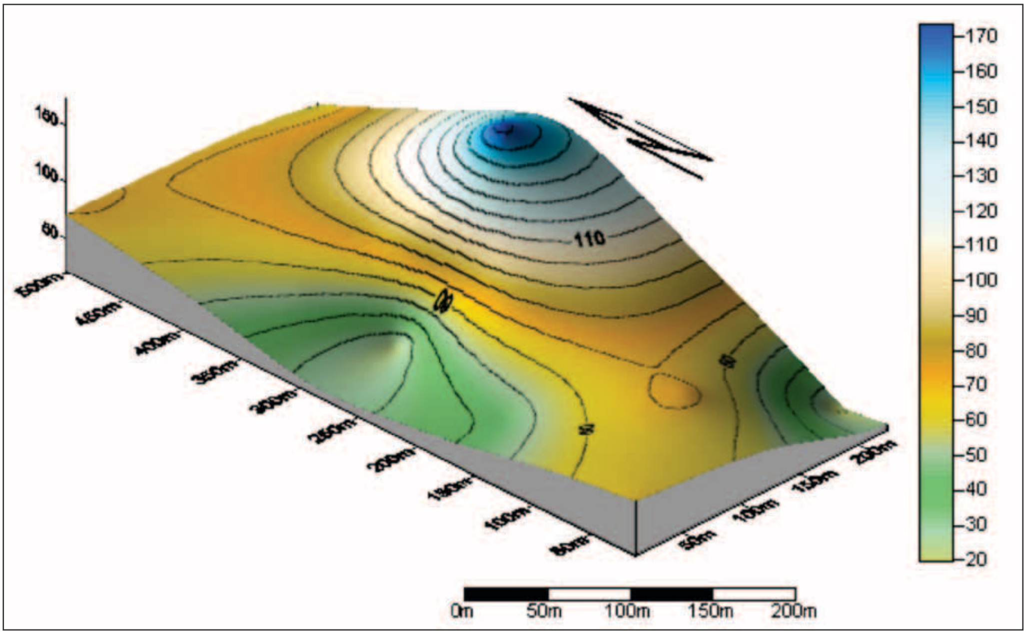


Figure 8. Weathered layer transverse resistance map.

Table 6. Aquifer potential as a function of the weathered layer transverse resistance.

Transverse Resistance (Ω m^2)	
Range	**Weighting**
<400	2.5
400–1000	5
1000–2000	7.5
>2000	10

ear relationship between groundwater potential and the transverse resistance of an aquifer (Aderinto, 1986). Table 6 gives a summary of the variation of aquifer potential with transverse resistance.

Bedrock Relief Map

The bedrock relief map (figure 9) is a contoured map of the bedrock elevations beneath all the VES stations. These bedrock elevations were obtained by subtracting the overburden thicknesses from the surface elevations at the VES stations. The bedrock relief map generated for the locations shows the subsurface topography of the bedrock across the surveyed area. Bedrock relief map helps to see vividly the suspected areas for groundwater prospects. Areas with basement depressions on the map serve as collecting trough for groundwater which will be the best zones for groundwater prospects. Bedrock relief has been used by Okhue & Olorunfemi (1991), Olorunfemi & Okhue (1992), Dan–Hassan & Olorunfemi (1999), Olorunfemi et al, (1999) and Bala & Ike (2001) to investigate into groundwater prospects at Ile- Ife SW, Kaduna North Central, Akure SW and Gusau NW part of Nigeria respectively. Procedures used by them have been adopted under this subsection in order to get the promising areas for groundwater prospects at Industrial Estate Ogbomoso SW Nigeria.

The map shows series of basement lows/depressions and basement highs/ridges. Southern, Eastern and Northeastern part (i. e. VES 2, 6, 8 and 9) are the designated areas for the depressions while Northwestern, Western, Southwestern and Southeastern part (i. e. VES 1, 3, 4, 5 and 7) are ridges zones. The depression zones are noted for thick overburden cover while the basement high/ridge zones are noted for thin overburden cover. Omosuyi & Enikanselu (1999) findings revealed that depressions zone in the basement terrain serves as groundwater collecting trough especially water dispersed from the bedrock crests. Thus, the zones with basement depressions are priority areas for groundwater development in the study locations.

If the bedrock has a low resistivity, a high aquifer potential could be inferred as result of expected high fracture permeability. Bedrock resistivities of the study area from figure 3a–b are as given below: VES 1 = 95835.0 Ω m, VES 2 = 606.4 Ω m, VES 3 = 2160.8 Ω m, VES 4 = 4580.4 Ω m, VES 5 = 1830.7 Ω m, VES 6 = 271.8 Ω m, VES 7 = 4344.4 Ω m, VES 8 = 14522.8 Ω m, VES 9 = 6781.7 Ω m and VES 10 = 4036.2 Ω m. The maximum weight of 10 is therefore assigned to cases where the resistivity of the bedrock is less than 750 Ω m. As the resistivity of the bedrock increases, there would be a reduction in the influence of weathering, with a corresponding lowering of the aquifer potential (OLAYINKA et al, 1997). Table 7 gives a summary of the variation of aquifer potential with bedrock resistivity.

Final Groundwater Potential Map of the Study Area

Final groundwater potential map of the study area was produced in order to draw the final conclusion from the evaluated maps. The weights that have been assigned in Table 1 – Table 7 were used to get the weights of Overburden Thick-

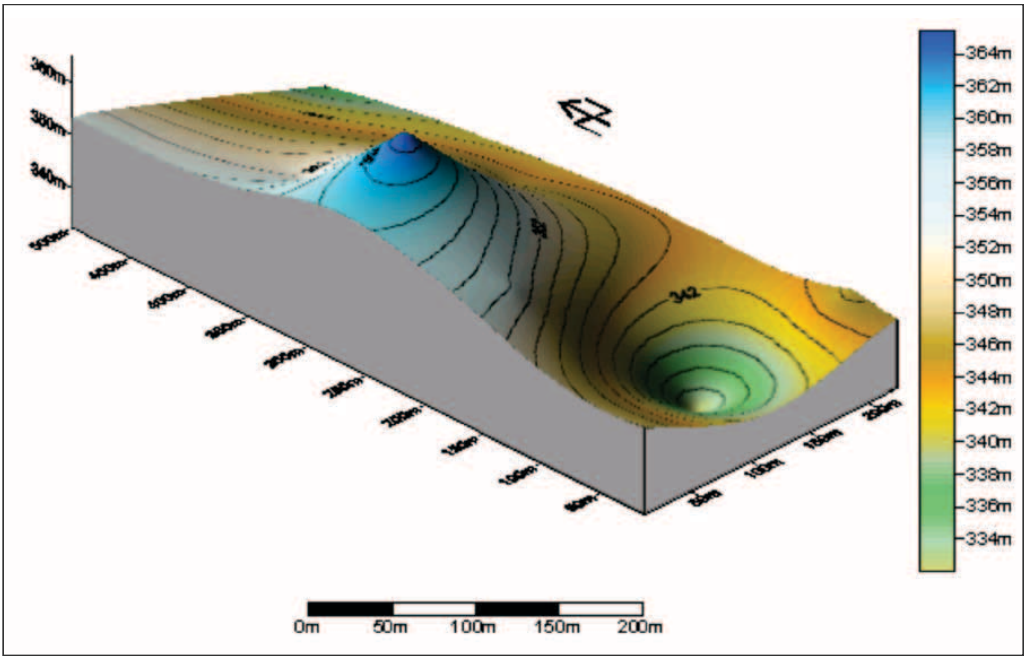


Figure 9. Bedrock relief map.

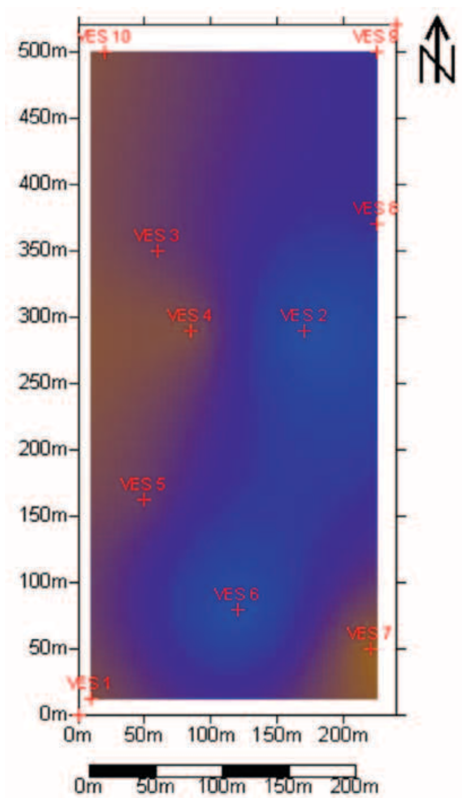
Table 7. Aquifer potential as a function of bedrock resistivity.

Bedrock Resistivity (Ω m)		
Range	**Aquifer Characteristics**	**Weighting**
<750	High fracture permeability as a result of weathering; high aquifer potential	10
750–1500	Reduced influence of weathering; medium aquifer potential	7.5
1500–3000	Low aquifer potential	5
>3000	Little or no weathering of the bedrock; negligible potential	2.5

ness, Anisotropy Coefficient, Weathered Layer Resistivity, Transverse Resistance and Bedrock Resistivity of the study area.

A single weighted average is then determined from the geometric mean of the five weights to produce the 2-Dimensional groundwater potential map of the investigated area (figure 10). The map presents local groundwater prospects of the study area which is zoned in to high, medium and low groundwater potentials.

Area with colour brown on the map constitute the low groundwater potential zone (i. e. VES 1, VES 3, VES 4, VES 5, VES 7 and VES 10) while area with colour blue constitute the high groundwater potential zone (i. e. VES 2 and VES 6). Medium groundwater potential zone share its colour between brown and blue, this is noted at the Northeastern side of the study area (I .e. VES 8 and VES 9). The Southern (VES 6) and the Eastern (VES 2) part of the study area are seen to have relatively higher groundwater potential than the Northeastern (VES 8 and VES 9) region of the study area. Southwestern, Southeastern, Western, Northern and Northwestern (i. e. VES 1, VES 3, VES 4, VES 5, VES 7 and VES 10) regions are seen to have low groundwater potential in the study area. These zones with low groundwater potential will be good for engineering purposes (i.e. construction of factories).



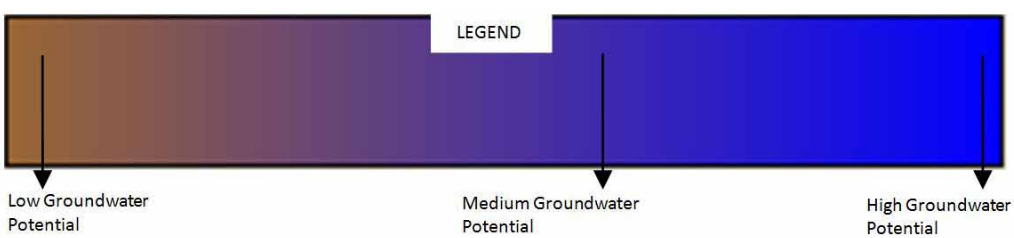


Figure 10. Final groundwater potential map of the study area

Conclusion

Though the study area was assigned as an industrial estate, as long as water still remains one of our essential amenities in life, the groundwater potential evaluation in the industrial estate Ogbomoso cannot be overlooked. Ignorantly without carrying out geophysical survey, the building contractor might have decided to build on the promising areas for groundwater exploration which will lead to scarcity of groundwater in the study area. Also, building of factories on promising areas for groundwater exploration is even disastrous to the users in the future.

The study has been able to highlight the importance of resistivity method in effective hydrogeologic characterization and groundwater exploration. This study has proved to be quite successful for mapping outrock types, structural formations and fractures which would not have been observed at the surface. The presence of weathered layer and fractured basement are key components of aquifer system and zone of groundwater accumulation in industrial estate, Ogbomoso. A multidimensional approach to this study (that is modeled curves and the maps presented for groundwater potential evaluation) has made the study both very qualitative and quantitative as information missed by any of the methods is revealed by the other and thereby necessitating justifiable conclusions.

It can be concluded that the low resistivity and significantly thick weathered rock/clay and the fractured basement constitute the aquifer in this area. Results from this study have revealed that the Southern and Eastern parts of the study area are the most promising region for borehole development. However, Northeastern region of the study area can also be considered as fair for borehole development as it has been shown from Figure 10.

It is recommended that detailed work be done in this industrial estate using other relevant geophysical methods so as to confirm the fractures predicted and to elucidate the patterns of the fractures.

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References

ACWORTH, R. I. (1987): The development of crystalline basement aquifers in a tropical environment. *Quarterly Journal of Engineering Geology*, Vol. 20, 265–272.

Aderinto, I. O. (1986): Estimating aquifer transmissivity in the Basement Complex using Dar-Zarrouk parameters, *Unpublished M. Sc Thesis, University of Ibadan, Nigeria*.

Ajibade, A. C., Rahaman, M. A. & Ogezi, A. E. O. (1988): The Precambrian of Nigeria, a Geochronological Survey. *Publication of the Geological Survey of Nigeria*.

Alagbe, O. A. (2005): Integration of Electrical Resistivity Techniques and Lineament analysis in Hydrogeological investigation of parts of Ogbomoso, South – Western Nigeria. *M.Tech Thesis, Ladoke Akintola University of Technology, Ogbomoso, Nigeria*.

Asseez, L. O. (1972): Hydrogeology of Southwestern Nigeria. *The Nigerian Engineer*, Vol. 7, (1), 22–44.

Ayantunji, B. G. (2005). Integrated use of electrical and electromagnetic (VLF) method in the delineation of the fault pattern of Odokoto, Ogbomoso, Southwestern Nigeria. *M.Tech Thesis, Department of Pure and Applied Physics, Ladoke Akintola University of Technology, Ogbomoso, Nigeria.*

Bala, A. N. & Ike, E. C. (2001): The aquifer of the crystalline basement rocks of Gusau area, Northwestern Nigeria. *Journal of Mining and Geology*, Vol. 2, (37), 177–184.

Benson, S. & Jones, C. R. C. (1988): The combined EMT geophysical method for sitting boreholes. *Groundwater*, Vol. 26, 45–63.

Bianchi, L. & Snow, D. T. (1969): Permeability of crystalline rocks from measured orientations and apertures of fractures. *Annals of Arid zones*, Vol. 8, (2), 231–245.

Braga, A. C. O., Filho, W. M. & Dourado, J. C. (2006): Resistivity (DC) method applied to aquifer protection studies. *Revista Brasileira Geofysica*, Vol. 24, 573–581.

Carruthers, R. M. & Smith, I. F. (1992): The use of ground electrical survey methods for siting water supply boreholes in shallow crystalline basement terrains. In: WRIGHT, E. P. & BURGESS, W. G. (eds). The hydrogeology of crystalline basement aquifers in Africa. *Geological society special publication,* No. 66, pp. 203–220.

Dan-Hassan, M. A. & Olorunfemi, M. O. (1999): Hydrogeophysical investigation of a basement terrain in the north central part of Kaduna State, Nigeria. *Journal of Mining and Geology*, Vol. 2, (35), 189–206.

Davis, S. N. & De Wiest, R. J. M. (1966): Hydrogeology. *Wiley, New York*.

Duffin, W. J. (1979): Electricity and Magnetism. 3rd Ed. *The English Book Society*, 58–61, 155–156.

Eduvie, M. O. & Olabode, O. T. (2001): Evaluation of aquifer potential in the crystalline basement using geoelectric sounding data from the southern part of Kaduna State, Nigeria. *Water Resources-Journal of NAH*, Vol. 12, (2), 56–61.

Esu, O. E. (1993): Fracture Mapping-Scientific basis for well siting in hard rocks. *Water Resources-Journal of Nigerian Association of Hydogeologists (NAH),* Vol. 4, (1&2), 25–35.

Evwaraye, A. O. & Mgbanu, E. N. (1993): Electromagnetism and Modern Physics for physical sciences. *Spectrum* *books Ltd*, 86–88.

FITTERMAN, D. V. & STEWART, M. T. (1986): Transient electromagnetic sounding for groundwater. *Geophysics*, Vol. 51, 995–1005.

GRANT, F. S. & WEST, G. F. (1965): Interpretation theory in applied geophysics. *McGraw Hill Book Company*, 385–443.

HADI, T. N. (2009): Geoelectric Investigation of the Aquifer Characteristics and Groundwater Potential in Behbahan Azad University Farm, Khuzestan, Iran. *Journal of Applied Sciences*, Vol. 9(20), 3691–3698.

HENRIET, J. P. (1975): Direct applications of the Dar-Zarrouk parameters in groundwater surveys. *Geophys. Prospect.,* Vol. 24, 344–353.

KELLER, S. & FRISCHNECHT, N. (1970): An interactive computer/graphic – display-terminal system for interpretation of resistivity soundings. *Geophysics prospect*, Vol. 23, 449–458.

LENKEY, L., HAMORI, Z. & MIHALFFY, P. (2005): Investigating the hydrogeology of a water-supply area using direct-current vertical electrical soundings. *Geophysics*, Vol. 70(4), H1–H19.

MACDONALD, A. M. & DAVIES, J. (2000): A brief review of groundwater for rural water supply in Sub-Saharan Africa. *B.G.S. Technical Report*. W.C./00/33.

MAILLET, R. (1974): The fundamental equations of electrical prospecting. Geophysics, Vol. 12: 529–556.

MAZAC, O., KELLY, W. E. & LANDA, I. (1987): Surface geoelectrical methods for groundwater pollution and protection studies. *Journal of Hydrology*, Vol. 93, 277–287.

MCNEILL, J. D. (1987): Advances in electromagnetic methods for groundwater studies. *Proceedings of Exploration ’87–Applications of Geophysics and Geochemistry*, 678–702.

MEJU, M. A., FONTES, S. L., OLIVEIRA, M. F. B., LIMA, J. P. R., ULUGERGER, E. U. & CARRASQUILLA, A. A. (1999): Regional aquifer mapping using combined VES-TEM-AMT?EMAP methods in the semiarid eastern margin of Parnaiba Basin, Brazil. *Geophysics*, Vol. 64(2), 337–356.

NIWAS, S. & SINGHAL, D. C. (1981): Estimation of aquifer transmissivity from Dar-Zarrouk parameters in porous media. *J. Hydrol*. Vol. 50, 393–399.

ODUSANYA, B. O. (1989): An empirical resistivity model for predicting shallow groundwater occurence in the Basement Complex. *M.Sc. thesis, University of Ibadan, Nigeria.*

OKHUE, E. T. & OLORUNFEMI, M. O. (1991): Electrical resistivity investigation of a typical Basement Complex area. The Obafemi Awolowo University campus case study. *J. Mining Geol*., Vol. 2, (27), 63–69.

OLASEHINDE, P. I. (1989): Elucidating fracture patterns of the Nigerian Basement Complex using electrical resistivity method. *Z. Angew. Geowiss. Heff.,* Vol. 8, (5), 109–120.

OLAYINKA, A.I., AKPAN, E. J. & MAGBAGBEOLA, O. A. (1997): Geoelectric sounding for estimating aquifer potential in the crystalline basement area around shaki, southwestern Nigeria. *Water Resources- Journal of NAH*, Vol. 8, (1 & 2), 71–81.

OLORUNFEMI, M. O. & FASUYI, S. A.

(1993): Aquifer types and the geoelectrical/hydrogeologic characteristics of part of the central basement terrain of Nigeria. *Journal of African earth sciences*, Vol. 16, 309–317.

Olorunfemi, M. O., Ojo, J. O. & Akintunde, O. M. (1999): Hydrogeophysical evaluation of the groundwater potential of Akure metropolis, Southwestern Nigeria. *J. Mining Geol*., Vol. 2 (35), 207–228.

Olorunfemi, M. O. & Okhue, E. T. (1992): Hydrogeologic and Geologic Significance of a Geoelectric Survey at Ile-Ife, *Nigeria Journal of Mining and Geology*, Vol. 28, (2), 221–229.

Olorunfemi, M. O., Olanrewaju, V. O. & Alade, O. (1991): On the electrical anisotropy and groundwater yield in a Basement Complex area of South Western Nigeria. *Journal of African Earth Sciences*, Vol. 12, No. 3, pp. 467–472.

Olorunfemi, M. O. & Olorunniwo, M. A. (1985): Geoelectric parameters and aquifer characteristics of some parts of southwestern Nigeria. *Geologia Applicata E, Idrogeologia*, XX, part 1, pp. 99–109.

Oluyide, P. O. & Udey, A. N. (1965): Preliminary comments on the fracture system of Nigeria. *Paper presented at the national seminar on earthquakes in Nigeria, A.B.U., Zaria, Nigeria*.

Omorinbola, E. (1979): A quantitative evaluation of groundwater storage in Basement Complex regoliths in southeastern Nigeria. *Ph.D Thesis, University of Ibadan*, 254.

Omosuyi, G. O. & Enikanselu, P. A. (1999): Direct Current Resistivity Sounding for Groundwater Potential in Basement Complex of North-Central Nigeria. *J. Sci. Eng. Tech.,* Vol. 1, (2), 331–334.

Omosuyi, G. O. (2010): Geoelectric assessment of groundwater prospect and vulnerability of overburden aquifers at Idanre, South Western Nigeria. *Ozean Journal of Applied Sciences*, Vol. 3(1), 19–28.

Onu, N. N. (2003): Estimates of the relative specific yield of aquifers from geo-electrical sounding data of the coastal plains of Southwestern Nigeria. *J. Technology. Educ. Nig.,* Vol. 8, 69–83.

Onuoha, K. M. & Mbazi, F. C. C. (1988): Aquifer transmissivity from electrical sounding data: the case of Ajali sandstone aquifers, Southeast of Enugu, Nigeria. In: C. O. Ofoegbu (editor), Groundwater and Mineral resources of Nigeria, *Friedr. Vieweg & Son Publishers*, pp. 17–30.

Patra, H. P. & Nath, S. K. (1999): Schlumberger Geoelectric Sounding in Groundwater (Principle, Interpretation and Application). *Published by A. A. Balkema/Rotterdam/Brookfield.*

Rahaman, M. A. (1976): Review of the Basement Geology of Southwestern Nigeria. In: Kogbe, C. A. (ed.) Geology of Nigeria. *Elizabethan Pub. Co., Lagos*. 41–58.

Russ, W. (1957): The Geology of part of Niger, Zaria and Sokoto Province *.Bull. Geological Surv Nigeria*, Vol. 27, pp. 42.

Surfer 8, (2002). Version 8.01. Surface mapping system. Golden Software Inc, Colorado.

Todd, D. K. (1980): Groundwater Hydrology. 2nd Edn., *John Willey Sons Inc., New York*, pp. 539.

TOTO, E. A., KERROURI, C., ZOUHRI, I., EL BASRI, M., IBENBRAHIM, A., TURNER, D. C. (1983): Upper Proterozoic Schist Belts in the Nigerian Sector of the Pan-African Province of West Africa. *Precamb. Res*. 21, 55–79.

TRUSSWELL, J. F. & COPE, R. N. (1963): The Geology of Part of Nigeria and Zaria province. *Northern Nigeria Bull. Geological Surv Nigeria*, Vol. 29, pp. 42.

VANDER VELPEN, B. P. A. (2004): WinRESIST Version 1.0. Resistivity Sounding Interpretation Software. *M.Sc. Research Project, ITC, Delft Netherland.*

WRIGHT, E. P. (1990): Basement aquifers in Africa. *Commonwealth Science Technical Paper*, Vol. 273, (2), 363–394.

WRIGHT, E. P. (1992): The hydrogeology of crystalline basement aquifers in Africa. In: Wright, E. P. & Burgess, W. G. (eds). The hydrogeology of crystalline basement aquifers in Africa. *Geological society special publication* No. 66, pp. 1–27.

ZOHDY, A. A. R. (1973): The use of schlumberger and equatorial in groundwater investigation near EL Paso, Texas. *Geophysics,* Vol. 34 (5), 713–728.

ZOHDY, A. A. & MABOY, D. R. (1974): Application of surface geophysics to groundwater investigation. *U.S. Geol. Surv.* Book 2 Ch D1, 304–320.