

Evaluation of groundwater aquifers vulnerability in Ilorin Metropolis using electrical resistivity method of geophysics

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Abstract: An area of 321.97 km² in Ilorin Metropolis has been studied, using 312 Vertical Electrical Sounding data obtained in an intensive Electrical Resistivity Survey. The goal of the study is to evaluate the vulnerability of groundwater in the area to contamination with a view to advise Kwara State Government on the safe sites for locating the planned public water project in the different parts of Ilorin. VES data acquired in the area were subjected to manual and computer-aided interpretations to delineate the different geo-electric layers, their hydrogeological significance, and vulnerability of the aquifer. The area was divided into zones, namely, A, B and C. Results of the study revealed presence of five geo-electric layers and two groundwater aquifer layers. The first aquifer corresponds to weathered rock layer, has hydraulic conductivity ranging from 0.1 and 3.0 m/day, lies at shallow depths ranging between 2 and 36 m, and has overburden material whose protective capacity (s) against groundwater contamination is weak ($s \leq 0.19$), except in few places in zone C where protective capacity is moderate ($0.2 \leq s \leq 0.69$). The second aquifer layer corresponds to fractured basement rock, lies at depths ranging between 5.0 and 53 m, has overburden layer whose protective capacity against groundwater contamination ranges from moderate ($0.2 \leq s \leq 0.69$) to good ($0.7 \leq s \leq 4.9$). Groundwater in fractured basement rock aquifers is more protected against contamination from dumpsite leachates and anthropogenic wastes than the groundwater in the weathered rock aquifers. Joint interpretation of hydro-dynamic properties of the overburden and aquifer layers of the three zones showed that zone C has the highest groundwater protection capacity, while zone A has the least protection capacity against contamination. Different safe spots were identified for citing boreholes for portable water supply in the three zones. The study recommended that all boreholes for portable water supply, except in few places in zone C, should penetrate the fractured basement rock aquifers to avoid the supply of contaminated groundwater in the future.

Key words: Groundwater vulnerability; hydrogeology; protective capacity of overburden materials; longitudinal conductance; geo-electric layer; Electrical resistivity method

1. INTRODUCTION

This paper describes a study on the vulnerability or contamination potential of groundwater aquifer system in Ilorin Metropolis, using a set of Vertical Electrical Sounding data acquired in an intensive geophysical campaign. Ilorin falls within the basement complex of southwestern Nigeria. In the basement complex, the overburden material may consist of transported products or materials of *in situ* weathering of underlying rock. Overburden material is usually of limited thickness, thus making the water bearing system of basement complex lying at shallow depth, in contrast to the aquifer of sedimentary terrain, which may be as deep as hundreds of meters. The shallow nature of groundwater aquifers and the indiscriminate dumping of anthropological wastes in Ilorin area potentially exposed groundwater to contamination from anthropogenic sources and dumpsite leachates (Raji and Adeoye, 2017). In the local communities of Ilorin, dumpsites and latrines are sited without considering the hydrogeological settings of the area, thereby creating conditions that could make groundwater in shallow aquifers unsuitable for human consumption in the near future.

The suitability of groundwater for human, agricultural and industrial uses can be challenged by contaminants from salt-water intrusion, mining activities, oil spillages, sewages, leachates and other anthropogenic activities. The vulnerability of groundwater to pollution from any of these sources depends on a number of intrinsic conditions of the overburden material to protect the aquifers from

contamination. These intrinsic factors include composition of the overburden layer, depth of the aquifer (or thickness of overburden material), protective capacity of the overburden layer and hydraulic conductivity of the aquifer. During fluid flow through porous rocks, contaminant degradation may occur by mechanical, physicochemical and microbiological process (Vrba and Zaporozec, 1994; Robin et al., 2007), depending on the composition of the rock/soil and the hydro-dynamic forces. Generally, an effective protection against groundwater vulnerability is defined in terms of sufficient thickness of the overburden material and low hydraulic conductivity that leads to high resident time or monumental attenuation of the infiltrating contaminant (Doumal et al., 1990; Osborne et al., 1998; Ekwere and Edet, 2015).

A lot of research efforts have been dedicated to groundwater availability, groundwater volumetrics and exploitability, with little attention to studies on groundwater vulnerability. Predicting groundwater contamination potential is as important as locating sufficient quantity of potable groundwater. So, potable water project from groundwater sources should include studies on groundwater protection against contamination. Groundwater in the basement complex of Nigeria is usually hosted by weathered rock, fractured rock, or both (Olorunfemi and Fasuyi, 1993; Olasehinde et al., 1998; Olasehinde and Raji, 2007; Omosuyi, 2010). In each or both cases, the protective capacity of the overburden material on top of the groundwater aquifer is important, because it affects the extent and rate of transport of contaminants from surface sources into the groundwater. Development of groundwater resources for public water project in any geographical location depends, to a reasonable extent, on the knowledge of subsurface materials, its physical and chemical properties and their spatial distribution (George et al., 2014; Omoyoloye et al., 2008). The most effective non-destructive method of probing the subsurface layers for its physical properties and spatial distribution is the Electrical method of geophysics.

Application of Electrical Resistivity Method to the study of protective capacity of overburden materials against groundwater contamination has been reported in some literature (Kalinski et al., 1993; Rottger et al., 2005; Sahid, 2000; Isiorho, 2004; Vias et al., 2005; Casas et al., 2005; MacDonald et al., 2012). Results of the studies show that the material composition and thickness of the overburden play significant role in the protection of underlying groundwater aquifers. Abiola et al. (2009) applied electrical method of geophysics to the study of groundwater potential and aquifer protective capacity of overburden material in Ado Ekiti. They classified the area into good, moderate, weak and poor aquifer protective capacities. Lenkey et al. (2005) and Omosuyi (2010) used the resistivity depth sounding to assess the degree of imperviousness or the non-vulnerability of the unsaturated layer(s) capping the aquifers zones based on their resistivity parameters. Overall, Electrical method is a suitable and dependable geophysical method for studying subsurface layers for groundwater related subjects.

The aim of this study is to identify areas of well protected groundwater aquifers in Ilorin Metropolis in order to advise the state government on safe spots for siting its planned community water project using industrial boreholes and overhead tanks. The objective of the study is to use electrical resistivity method of geophysics to determine overburden thickness and its longitudinal conductance, thickness and hydraulic conductivity of the aquifer layer (s) and rate the vulnerability of the different aquifer zones in the study area. Although there has been a number of published work on the groundwater potential of Ilorin, to the best of our knowledge, there is no known published research work on groundwater vulnerability covering the entire Ilorin Metropolis. Findings from this study will contribute to the knowledge of groundwater in Ilorin and basement complex of Nigeria, and will bring a large body of groundwater data to the public domain.

2. DESCRIPTION AND GEOLOGY OF THE STUDY AREA

Ilorin, the capital of Kwara State is lying at the geographical boundary of southwestern and north central geopolitical zones of Nigeria. Ilorin falls in the Savana region of Nigeria, has two main seasons – rain season and dry season. Rain season usually starts in April and ends in October, while dry season usually commences in November and ends in March. The annual rainfall ranges between

75 and 112 cm, humidity and mean annual temperature range from 60-89% and 27-30 °C, respectively (Sule et al., 2013). Ilorin area is drained by many rivers, including rivers Asa, Oyun, Osere, Aluko and Alalubosa. The drainage pattern is dendritic with river Asa being the main river. The study area lies within latitudes 8°24.50'N and 8°35.00'N and longitudes 4°27.50'E and 4°41.00'E, covering an approximate area of 485 km².

Geologically, Ilorin falls in the basement complex of south western Nigeria, which is of Precambrian to lower Paleozoic age (Rahaman, 1976). The Precambrian crystalline basement complex consists of gneisses and migmatites; metasediments – schists, quartzites; meta-volcanics; Pan-African (older) granite and late-stage minor pegmatitic (Oluyide et al., 1998). The subsurface comprised the weathered, fractured and fresh crystalline basement rocks. The oldest rocks in the area comprise gneiss complex whose principal member is biotite-hornblende gneiss with intercalated amphibolites (Annor and Olasehinde, 1996). Other rock types are granite gneiss, banded gneiss, porphyritic granite and quartz schist. These rocks have been weathered and fractured in some places due to tectonic activities. The geological map of Nigeria showing the study area is presented as Figure 1a.

Two main types of aquifer in Ilorin are the weathered rock aquifer and the fractured rock aquifer. Fractured basement rock aquifer is deeper and overlain by weathered rock aquifers. Although the weathered rock aquifer is more porous than fractured rock aquifer, all basement rock aquifers have low porosity and permeability, depends on secondary porosity caused by weathering and fracturing to transmit fluids from one place to another (Olorunfemi and Fasuyi, 1993; Olasehinde, 1998; Dan-Hassan 2001; Casas et al., 2005; Olasehinde and Raji, 2007; Abubakar et al., 2014). Basement complex aquifer systems are localised, have limited extent and are mostly disconnected from one another except in places where regional fracture occurs. Weathered rock aquifers are shallower, have thin overburden and are more susceptible to contamination. Major source of groundwater recharge in Ilorin are surface runoff from rain and rivers.

3. METHODOLOGY

312 Vertical Electrical Sounding (VES) data were acquired within the study area using Schlumberger Electrode Configuration. VES inter-station spacing ranges from 100 m to 500 m, depending on space availability and convenience – as tomography, houses, road and other engineering construction obstructed consistent VES spacing in some places. Maximum current electrode separation, AB, ranges from 100 to 200 m based on aquifer depth from previous study in the area and the reasons given above. 155 VES data were primarily acquired by the authors for the purpose of this study, while the rest were acquired by borehole drilling companies - Lower Niger River Basin and previous geophysical studies in the area (Raji, 2005; Olasehinde and Raji, 2007; Raji, 2014; Raji and Ibrahim, 2017). The geographic coordinates and height above sea level at each VES location were recorded. The area is subdivided into three, using community grouping and geographic information referencing (Figure 1b).

The data were processed and interpreted using manual techniques and computer iteration method. Resistivities measured on the field were plotted against the corresponding AB/2 on bi-logarithm papers to produce VES curves. The curves were carefully smoothened in some cases to suppress spurious values using a method developed by Raji and Adeoye (2017). The curves were interpreted using auxiliary curve matching techniques (Orellana and Mooney, 1966; Koefoed, 1979; Telford et al., 1990). Results from the manual interpretation were used as preset parameters to guide the computer interpretation process. IPI2Win software was used for the final interpretation. Some VES curves are presented in Figure 2. Zones A, B and C have 91, 83 and 138 VES data points, respectively.

Hydrogeological parameters of the geo-electric layers that are related to groundwater vulnerability were calculated. Thickness of the overburden material and the aquifer and their resistivities were estimated at every VES Point. Overburden material is defined as the soil and rock material present between the ground surface and the aquifer layer. The longitudinal conductance of

the overburden material was estimated as:

$$S = \sum_{i=1}^n \frac{h_i}{\rho_i} \quad (1)$$

where h is the overburden thickness and ρ is the layer resistivity. The hydraulic conductivity (k) of the aquifer layer was calculated at every VES point following the Kozeny-Carman-Bear equation (Domenico and Schwartz, 1990):

$$k = (d_w g / \mu) * (d^2 / 180) * (\phi^3 / (1 - \phi^2)) \quad (2)$$

where d is the grain size, d_w is the fluid density (1000 kg/m³), g is the acceleration due to gravity, ϕ is the porosity, and μ is the dynamic viscosity taken to be 0.0014 kg/ms (Fetter, 1994). The spatial distribution of the different parameters is presented in the form of maps in the next section.

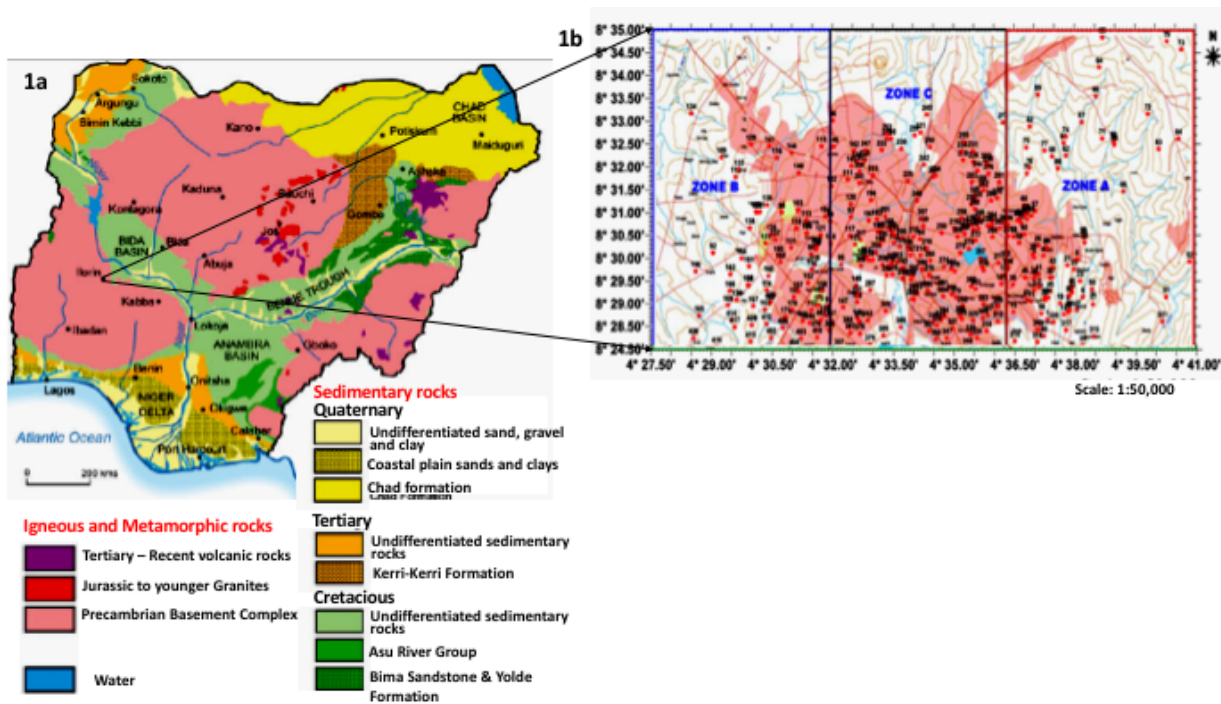


Figure 1. (a) Geological Map of Nigeria showing the study area (MacDonald et al. 2005); (b) Topographic Map of Ilorin showing VES points and the three zones.

4. INTERPRETATION AND DISCUSSION OF RESULTS

Interpretation of the VES data revealed the presence of three, four and five geo-electric layers. The percentage composition of the three, four and five geo-electric layers are 17%, 72% and 11%, respectively. Interpretation of geo-electric layers from VES curves was guided by borehole lithologic logs provided by Lower Niger River Basin for the area. In places where we have three geo-electric layers, the first, second and third layers correspond to top soil layer, weathered rock layer and the basement rock, respectively. In places delineated for four geo-electric layers, the geo-electric layers correspond the top soil layer, weathered rock layer, fractured rock and the fresh basement rock. The geo-electric layer in places delineated for five layers correspond to top soil layer, lateritic soil layer, weathered rock layer, fractured basement rock and the fresh basement rock.

Two aquifer layers were delineated – the weathered rock aquifer and the fractured basement rock aquifer. The two aquifers were separately evaluated for groundwater vulnerability using the

overburden protective capacity. For the weathered layer aquifer, the overburden consists of the top soil and the lateritic layer. For the fractured basement rock aquifer, the overburden was taken to be the top soil, lateritic layer and the weathered rock layer. The plots of overburden thickness above the weathered rock aquifers and its longitudinal conductance are shown in Figure 3. Figure 3a shows that overburden thickness above weathered rock ranges between 0.4 and 36 m. The highest overburden thicknesses in zones A, B and C are 18.6 m, 24.8 m and 36 m, respectively. The corresponding longitudinal conductance of the overburden material ranges from 0.004 to 0.23 in zone A, 0.05 to 0.14 in zone B, and 0.04 to 0.40 in zone C (Figure 3b). According to the longitudinal conductance and protective capacity rating shown in Table 1, most places in Ilorin have weak protective capacity against groundwater contamination. Only few places within zone C have moderate protective capacity.

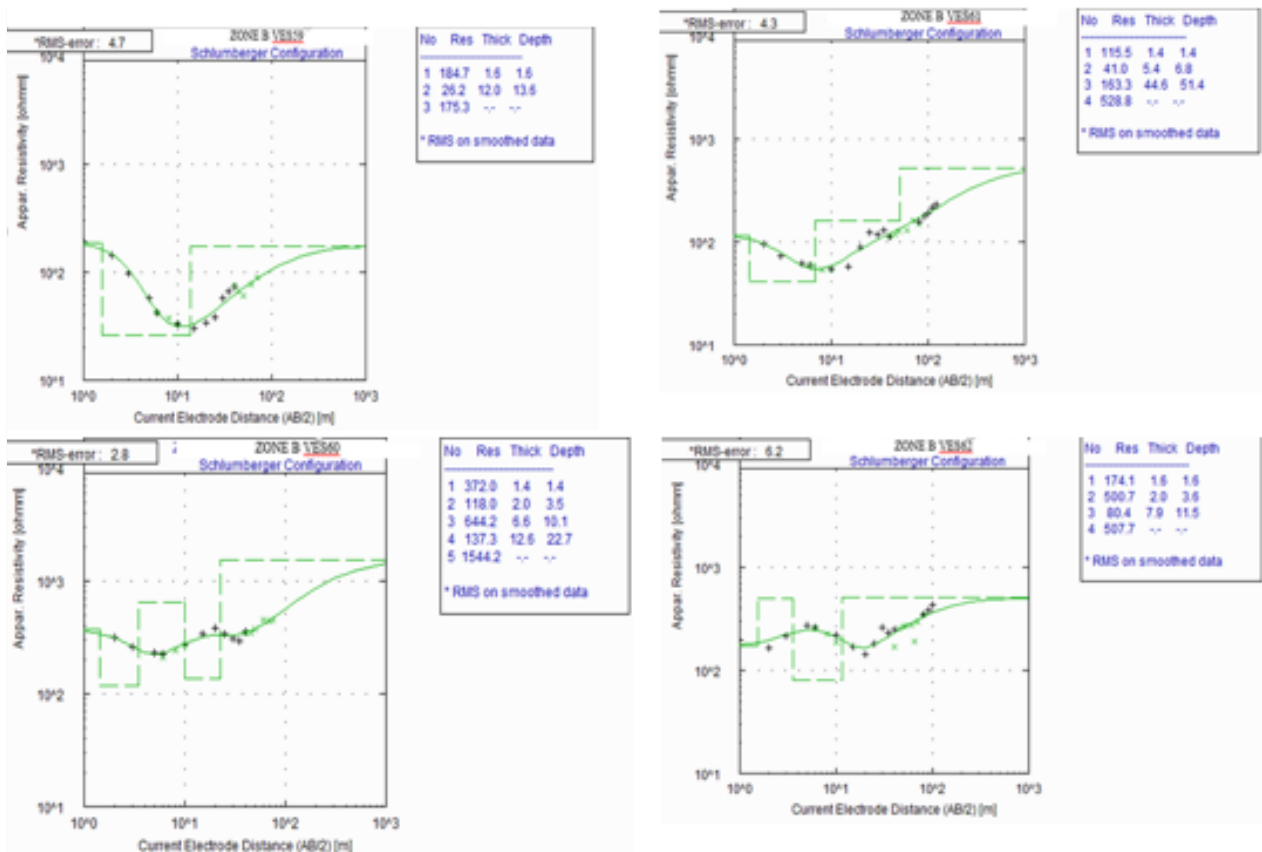


Figure 2. Some VES Curves and their interpretations showing apparent resistivity, thickness and depth of different geo-electric layers.

Table 2. Modified longitudinal conductance/protective capacity rating (Henriet 1976; Oladapo et al. 2004).

Longitudinal conductance (mhos)	Protective capacity rating
> 10	Excellent
5 – 10	Very good
0.7 – 4.9	Good
0.2 – 0.69	Moderate
0.1 – 0.19	Weak
< 0.1	Poor

Thickness of overburden material above fracture rock aquifer ranges from 3.1 to 37 m in zone A, 2.55 to 52.9 m in zone B, and 3 to 39.8 m in zone C (Figure 4a). The corresponding longitudinal conductance / groundwater protective capacity of the overburden material range from 0.02 to 0.95 (mhos) in zone A, 0.01 to 1.92 in zone B, and 0.1 to 2.86 (mhos) in zone C (Figure 4b). The

protective capacity of the overburden material above the fractured aquifer has rating that ranges from moderate to good. The weathered layer aquifer has thickness that ranges from 1.2 to 55 m (Figure 5a). The thickness of the fractured layer aquifer ranges from 3.8 to 34 m, 5 to 75.6 m, and 4.5 to 68 m in zones A, B and C, respectively (Figure 5b). The hydraulic conductivity of weathered rock aquifer ranges from 0.10 and 2.95 m/day (Figure 6). In some places, the weathered rock aquifers are thick enough to store substantial volume of groundwater, have good hydraulic conductivity for recharge and discharge groundwater to wells/boreholes, but protection against groundwater contamination is generally weak.

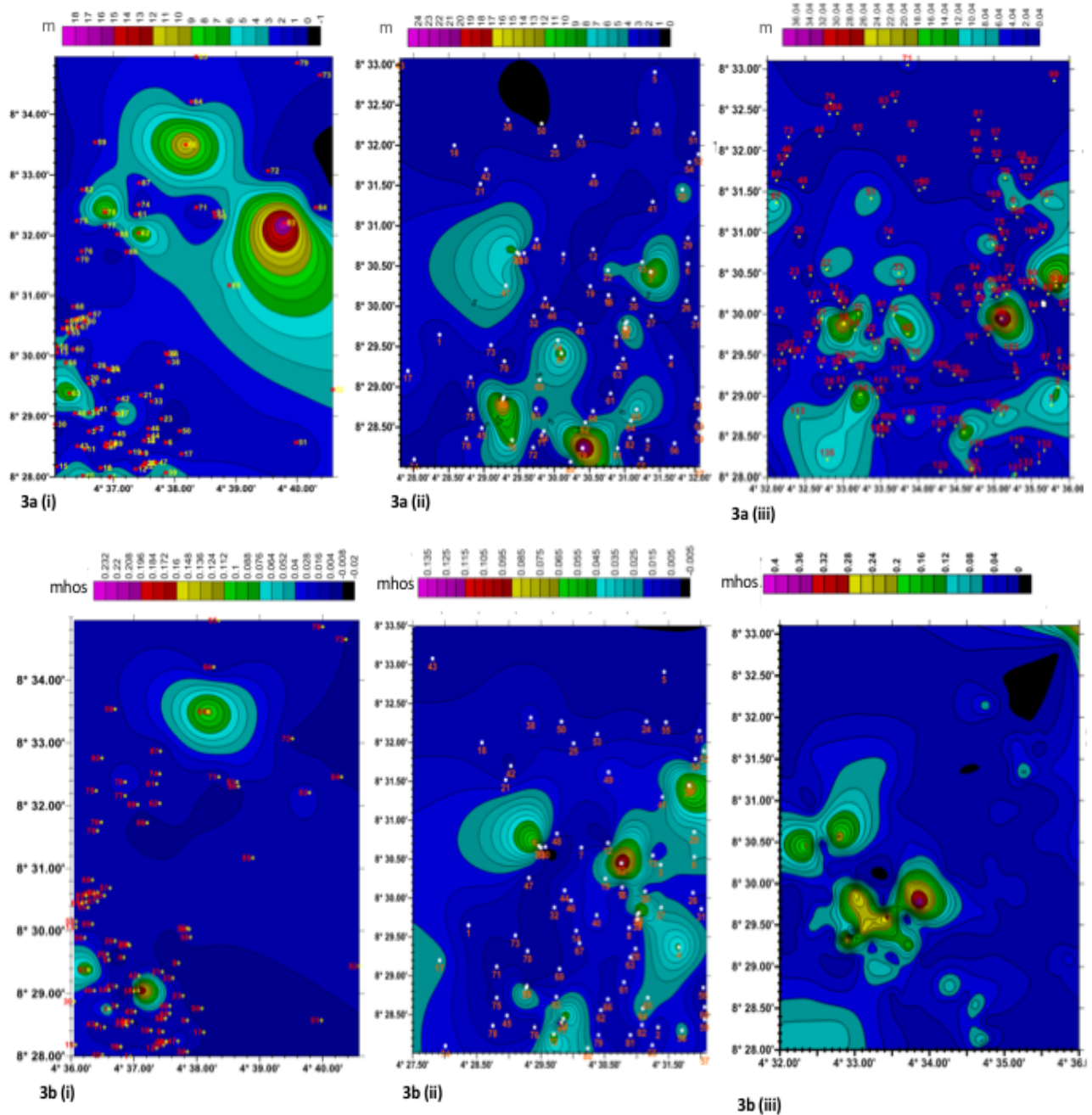


Figure 3. (a) Thickness of overburden materials above the weathered rock aquifer, (i) Zone A, (ii) Zone B, and (iii) Zone C. (b) Longitudinal conductance of overburden materials above the fractured rock aquifer, (i) Zone A, (ii) Zone B, and (iii) Zone C.

Generally, the two aquifer layers delineated in the study area are sufficiently thick to store economic quantity of groundwater that can be tapped through borehole and wells. The weathered rock aquifer is shallow, its head lies at a depth less than 2.0 m from the surface in some places and

Only about 5% of the VES points show moderate protective capacity against groundwater contamination. However, the hydraulic conductivity of the weathered rock aquifer, an important parameter for groundwater discharge and recharge, is good. The protective capacity of the overburden layer above the fracture rock aquifer ranges between moderate and good. 65% of the area has protective capacity rating in the range of moderate and good. This shows that the groundwater in the fracture aquifer is less vulnerable to contamination. The fractured rock aquifers are thick but its storage potential, being crystalline rock, is low. Putting these parameters together, groundwater in fractured rock aquifer is less vulnerable to contamination than the groundwater in the weathered rock aquifer.

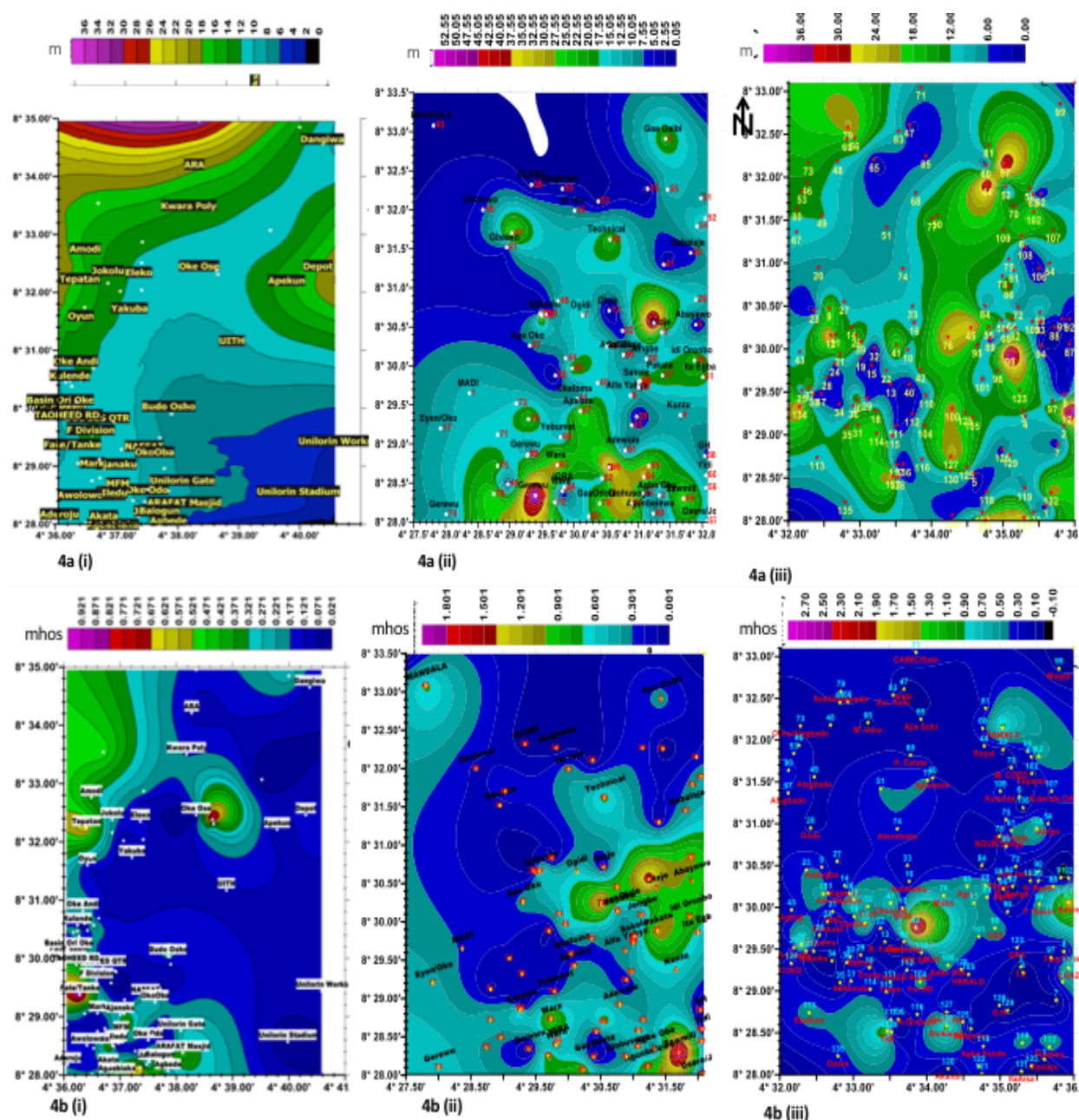


Figure 4. (a) Thickness of overburden material above fractured rock aquifer (i) Zone A, (ii) Zone B, and (iii) Zone C. (b) Longitudinal conductance of the overburden material above fractured rock aquifer (i) Zone A, (ii) Zone B, and (iii) Zone C.

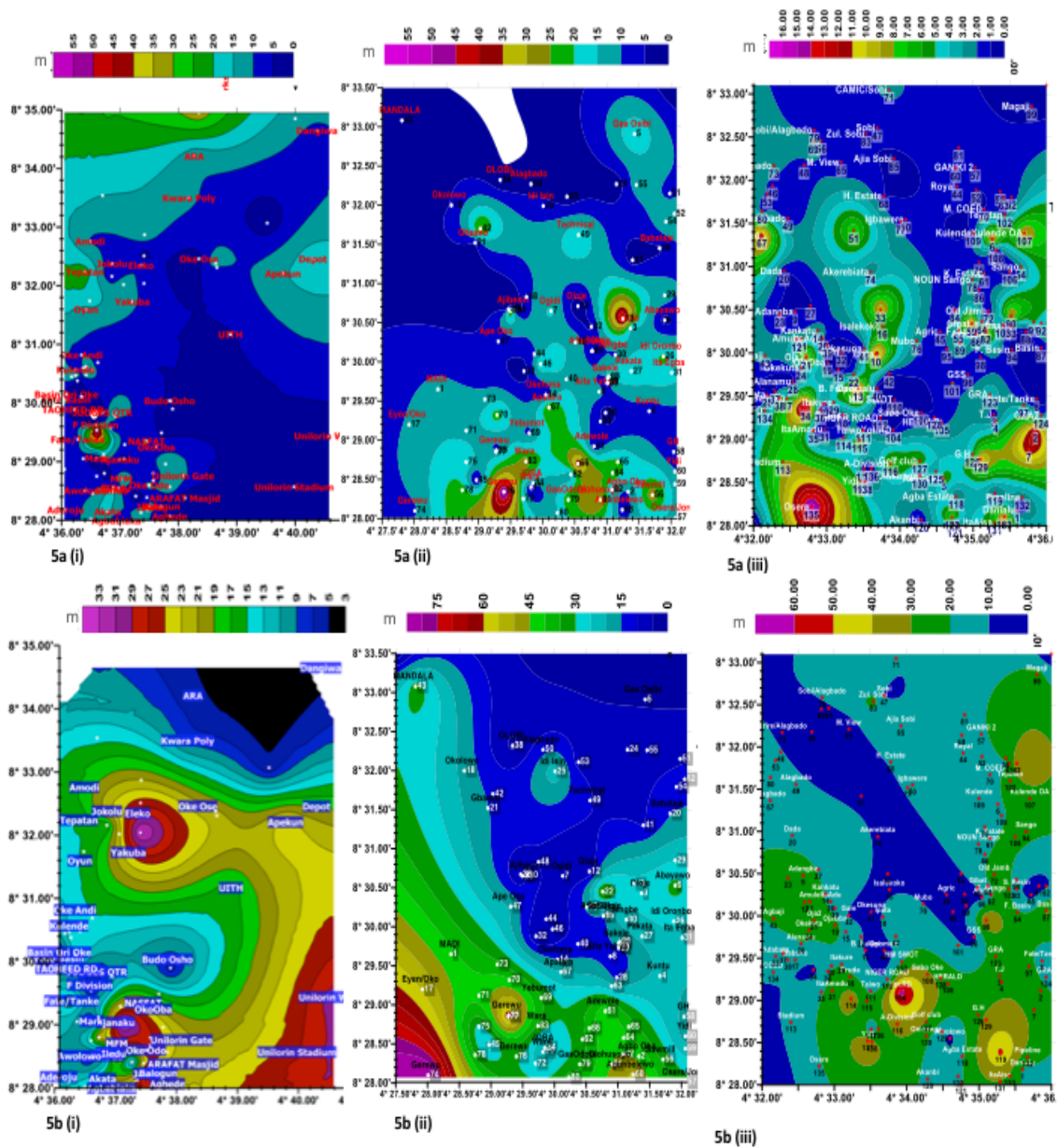


Figure 5. (a) Thickness of weathered layer aquifer (i) Zone A, (ii) Zone B, and (iii) Zone C. (b) Thickness of fractured layer aquifer (i) Zone A, (ii) Zone B, and (iii) Zone C.

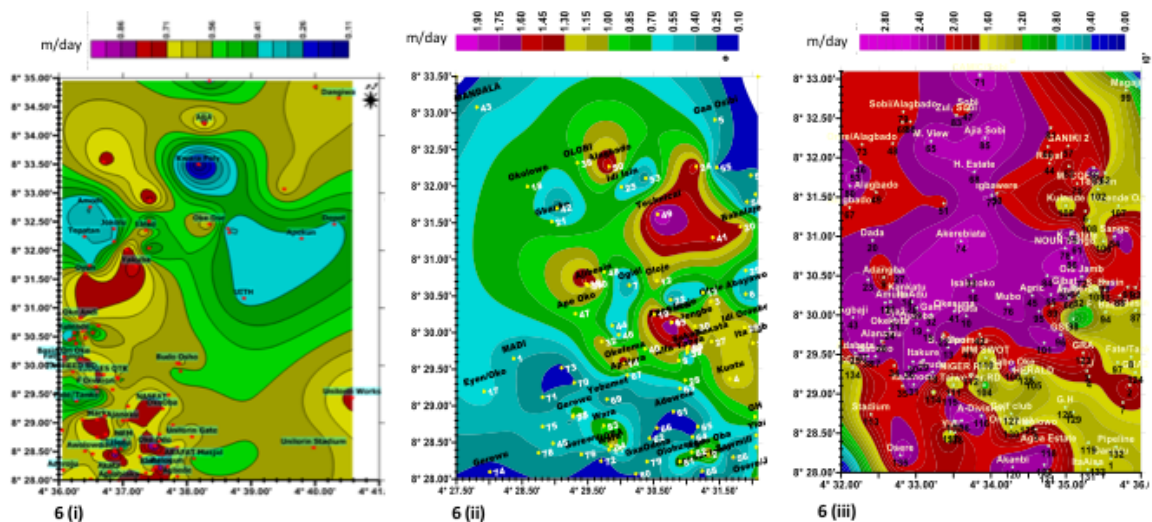


Figure 6. Hydraulic conductivity of weathered rock aquifer (i) Zone A, (ii) Zone B, and (iii) Zone C.

5. CONCLUSION

Ilorin Metropolis is underlain by three to five geo-electric layers that corresponds to the top soil layer, lateritic later, weathered rock later, fractured basement rock layer and the fresh basement rock. There are two aquifer zones in the area and they correspond to weathered rock and the fractured basement rock. Groundwater in the fractured rock aquifer is less vulnerable to contamination compared to the groundwater in the weathered rock aquifer. The weathered rock aquifer has good hydraulic conductivity, good groundwater recharge potentials, lies at shallow depths, and has weak protection against contamination. The fractured rock aquifers are thick, deep seated and well protected against contamination. Therefore, it is recommended that water well and boreholes in the areas should be drilled to penetrate the fractured rock aquifers. Pumps should be installed in the fractured rock aquifers. It is surmised that if the boreholes are producing from fractured aquifers, contaminants in the groundwater infiltrating through the weathered rock aquifers would be attenuated before reaching the fractured rock.

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