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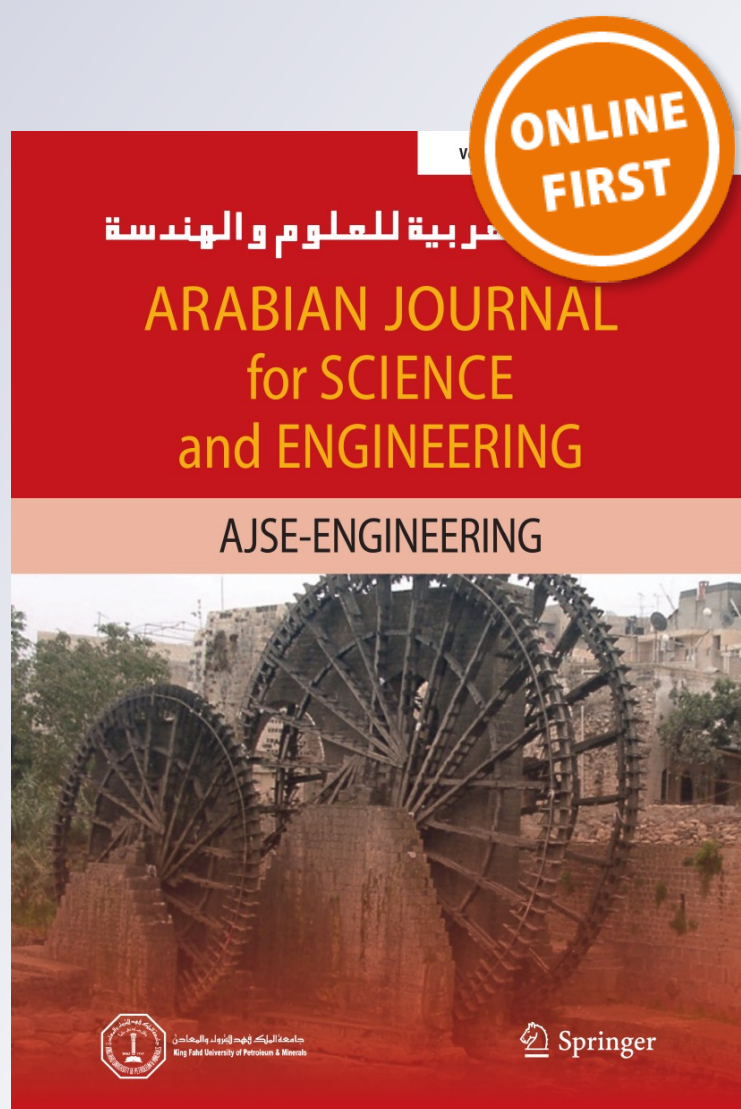
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Estimation of Aquifer Hydraulic Characteristics from Surface Geoelectrical Methods: Case Study of the Rima Basin, North Western Nigeria

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Abstract Forty vertical electrical resistivity soundings (VES) were acquired, using a Schlumberger array. Three soundings were additionally made at existing boreholes in the vicinity of the study area for comparison. Since the area is a basement complex terrain, a maximum current electrode spacing of 200 m which is believed to probe down to the fresh basement in the area was used. This is believed to enable fresh basement in the area to be observed. The concept of Dar Zarrouk parameters (transverse unit resistance and longitudinal conductance in porous media) was used to determine aquifer hydraulic characteristics in the sedimentary formation underlying the area. The results of the interpreted VES data using a combination of curve matching technique and computer iterative modeling suggest that the area is underlain by between 3–5 geoelectric layers. The geologic sections derived from the equivalent geoelectrical sections revealed lithologic sequence of mostly five layers. However, there are minor isolated cases of three layers. The geoelectrical sections showed that the resistivity of the aquifer varies between 14.1 and 128.8 Ω m. The thickness of the aquifer ranges from 1.0 to 48 m while its depth from the surface lies between 1.0 and 50 m. Relationships between aquifer characteristics and the geoelectrical parameters revealed the hydraulic conductivity K and transmissivity T variations to be 3.10–28.34 m/day and 10.0–796.6 m²/day, respectively. The maximum K and T occur around VES 4 and 14; thus the maximum yield could be expected around VES 4 and 14.

Keywords Electrical resistivity · Aquifer hydraulic characteristics · Rima Basin

الخلاصة

تم الحصول على أربعين سبر مقاومة كهربائية عمودية (VES)، وذلك باستخدام مصفوفة شلمبرجير. وتم عمل ثلاثة أسبار إضافية في الآبار الموجودة في المنطقة المجاورة لمنطقة الدراسة للمقارنة. وبما أن المنطقة هي تضاريس طابق سفلي معقدة استخدم تباعد قطب تيار من 200 متر كحد أقصى يُعتقد أنه يحقق وصولاً إلى الطابق السفلي الجديد في المنطقة، ويعتقد أن هذا يمكن من ملاحظة الطابق السفلي الجديد في المنطقة. وقد استخدم مفهوم معاملات دار زروق (مقاومة وحدة عرضية وتصرف طولي تصرف في الوسائط التي يسهل اختراقها) لتحديد الخصائص الهيدروليكية لطبقة المياه الجوفية في تشكيل الرسوبية التي تقوم عليها المنطقة. وتُشير نتائج بيانات VES التي تم تفسيرها باستخدام مزيج من تقنية مطابقة المنحنى ونمذجة تكرارية الكمبيوتر إلى أن المنطقة هي تحت وبين 3 و 5 طبقات جيوكهربائية. وكشفت المقاطع الجيولوجية المستمدة من المقاطع الجيوكهربائية المكافئة تسلسلاً صخرياً في معظم الطبقات الخمس. ومع ذلك، هناك حالات معزولة طفيفة من ثلاث طبقات. وأظهرت المقاطع الجيوكهربائية بأن المقاومة النوعية لطبقة المياه الجوفية تراوحت بين 14.1 و 128.8 Ω m، وسمك طبقة المياه الجوفية يتراوح بين 1.0 حتى 48 م، بينما عمقها من السطح يقع بين 1.0 و 50 م. وكشفت العلاقات بين خصائص طبقات المياه الجوفية والمعاملات الجيوكهربائية أن التوصيل الهيدروليكي والاختلافات النفاذية هي من 3.10 حتى 28.34 متر/يوم ومن 10.0 حتى 796.6 متر²/يوم على التوالي. وأقصى قيم للتوصيل الهيدروليكي والاختلافات النفاذية حدثت حول قيم VES 4 و 14، وبالتالي فإن الناتج الأقصى يمكن توقعه حول VES 4 و 14.

1 Introduction

Estimation of aquifer hydraulic characteristics involves assessing primarily the physical properties controlling ground water flow and transport. This includes the determinations of transmissivity, hydraulic conductivity and storage potentials of aquifers. However, [1–3] informed that it is difficult to design good management strategies for maximum

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exploitation of these aquifers. The problem could further be compounded by the poor knowledge of the geometry and hydraulic boundaries of an aquifer [4]. The River Matan fada, which is the major source of surface water in the area, serves not only for drinking and farming but more importantly also as a tourist attraction with the “Argungu International Fishing Festival” held annually in the vicinity of the study area. Although numerous boreholes were sited around the study area, there have not been any systematic and comprehensive studies to establish the nature and distribution of the aquifers in the study area.

Frequent flooding, which is an annual event since 1988 caused by uncontrolled release of water from the Bakolori and Goronyo dams upstream from Zamfara and Sokoto States, respectively, has caused devastation to croplands within the flood plains of settlements around the area and loss of lives. Persistent flooding washes away topsoil, which can cause soil infertility [5]. The contamination of the surface and ground water systems in the study area has led to the prevalence of water borne disease like guinea-worm, cholera, and typhoid fever. An acute water shortage in the study area is attributed to the utilization of Matan fada water for irrigation around the river and to its contamination by organic and inorganic chemicals applied as fertilizer in the nearby farms. The United Nations International Children Education Funds for Rural Water Sanitation, UNICEF-RUWATSAN project in 1988 in Nigeria reported that more than one million people are yearly affected by allied diseases such as guinea worm.

This work is therefore aimed at estimating the hydraulic parameters of the aquifers within the study area using an electrical resistivity method. Forty vertical electrical sounding (VES) points were occupied within the study area. The Schlumberger sounding array method was adopted in the work. The knowledge of hydraulic characteristics in a geologic formation plays vital roles in the groundwater control and management [6,7]. Hence, it is hoped that the results from the present study would help in improving the exploitation and management of water resources in the area, and will further compliment the hydrogeological activities such as test drilling and water analysis.

2 Location and Background Geology of the Area

The area (Fig. 1) is located in the northwestern part of Nigeria and lies in the northern part of Kebbi State. It is bounded by latitudes 12.7355°N to 12.7603°N and longitudes 4.5254°E to 4.5439°E, covering an area of about 2,265 km². Some of the notable inhabited settlements include Kabawa, Zabarumawa and Arewatawa. Two classes of soil can be identified in the area, namely the upland and fadama soils. The two soil groups are generally characteristic of the entire Sokoto Rima

Basin. The upland class is sandy and well drained while the fadama soil is generally clayey and hydromorphic especially in the back swamps. Availability of a passable road network and canoe eased data collection in this area.

The entire landmass lies within an area that constitutes rocks of the Gwandu, Illo, and Rima groups whose ages range from the Cretaceous to the Eocene. The Gwandu rock consists of massive clay grits, sandstones and clays, mudstone and siltstones, and some minerals like clay, quartz, kaolin, silica sand and salt, etc. The study area has a low landscape relief that forms part of the vast Sokoto plains which is a result of pediplanation (that is a planate erosion surface formed in the piedmont area of a desert, either bare or covered with a veneer of alluvium) [8]. It is monotonous lowland sedimentary in origin with an average elevation of about 300 m above sea level. The plain surface is interrupted by isolated flat-topped lateritic-capped hills ridges.

3 Materials and Methods

A four-electrode resistivity-meter (ABEM terrameter model SAS-300) was used to obtain apparent resistivity at VES points. Current from the inbuilt 12-V DC power source is passed to the earth through the current electrodes. There are four copper electrodes—two for electric current flow and the other two for electric potential measurement. A Schlumberger array (Fig. 2) was used for the resistivity measurement. Though the fieldwork was done during the driest period of the season in the area, the ground–electrode contact was fairly good. This was because the study area is in the vicinity of the Argungu River which provided enough saturation that ensured good electrical contact.

Starting from the northeast corner of the study area, a total of 40 VES stations were distributed evenly over the area (Fig. 14). The Schlumberger electrode configuration was adopted and the maximum current electrode spacing (AB) of 200 m was maintained throughout the survey. The choice of 200 m maximum spacing is based partly on the report by [3] that the possible depth probed in VES is around 0.19AB. The potential difference created within MN by the current through the electrodes was then measured. When the current electrode separation is large, at a particular potential electrode separation, the potential difference becomes small and almost immeasurable. This is signified by an error message on the digital readout screen of the instrument. On those occasions potential electrodes were expanded once for each case. However, poor or no contact between the electrodes and the ground could also be signified by the error message. This could be corrected by increasing the electrical contact by wetting the ground at the electrode locations.

The fundamental equation to get apparent resistivity is derived from Ohm's law [3]; that is

Fig. 1 Location of the study area

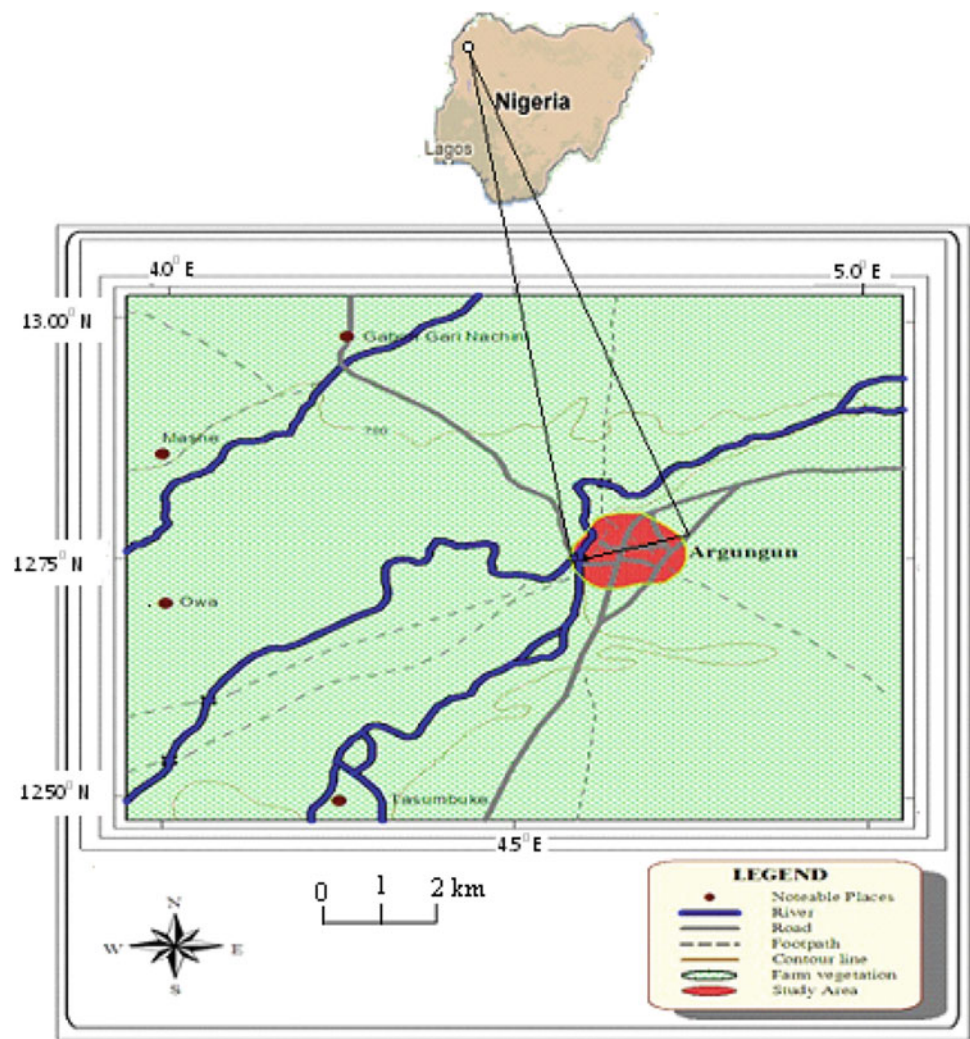
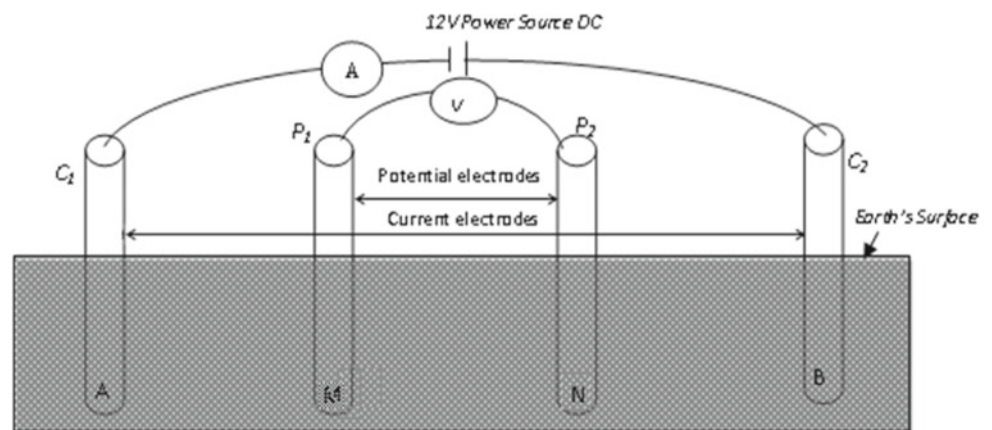


Fig. 2 Field array



$$V = IR$$

and

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

- (1) where R is electric resistance, ρ is electrical resistivity, A is area, and L is the length defined by the radius r .

- (2) The equipotential surface set up by the current flowing into the subsurface rocks is semispherical. So the area A in Eq. 2 could be that of a semi-sphere. Thus, the electric poten-

tial V at any point at a distance r from a surface point electrode emitting an electric current I in an infinite homogenous and isotropic semispherical medium of resistivity ρ is given by

$$V = \frac{\rho I}{2\pi r} \quad (3)$$

Irrespective of surface location and electrode spread, the resistivity is constant in a homogenous and isotropic ground. However, it does vary with the relative positions of electrodes in the presence of subsurface inhomogeneities and any computed value is known as the apparent resistivity ρ_a , given by

$$\rho_a = \frac{\Delta V}{I} (2\pi r). \quad (4)$$

So, for the Schlumberger technique used here (Fig. 2) the geometric factor G is thus given as:

$$G = \pi \frac{\left[\left(\frac{AB}{2} \right)^2 - \left(\frac{MN}{2} \right)^2 \right]}{2 \left(\frac{MN}{2} \right)^2} \quad (5)$$

that is

$$\rho_a = \pi \frac{\Delta V}{I} \times G = R \times G. \quad (6)$$

The resistance obtained from current and potential difference data at a given electrode spacing is applied in Eq. 6 to compute the apparent resistivity at that point. In this way, VES data at each sounding stations were computed and recorded.

The qualitative interpretations of the vertical electrical sounding curves were carried out in two stages, namely:

- (a) Curve matching and
- (b) a computer iteration technique using the software called WinResist.

The curve-matching technique employed in this study involves the use of two-layer master (standard) curves and the corresponding auxiliary curves. The field curves were interpreted segment by segment starting from the portions with shorter electrode spacing and moving towards those with larger spacing.

The VES data were plotted as depth-sounding curves. The results obtained were interpreted both qualitatively and quantitatively. The qualitative interpretation was done by noting the shape of the apparent resistivity sounding curves and then characterizing the curves according to their signatures. The quantitative interpretation of the curves was done through partial curve-matching and computer-iteration techniques. The interpretation was controlled by the limited borehole information available from the contractors on site. The resistivity ratio (K_1) and resistivity (ρ_1) of the first layer were obtained by reading the horizontal and vertical coordinates

Table 1 Location of the VES points

VES point	Longitude (°E)	Latitude (°N)
1	4.5201	12.7603
2	4.5201	12.7710
3	4.5112	12.7603
4	4.5403	12.7710
5	4.5500	12.7814
6	4.5304	12.7814
7	4.5112	12.7814
8	4.5112	12.7291
9	4.5002	12.7291
10	4.4925	12.7217
11	4.4731	12.7217
12	4.5002	12.7291
13	4.5002	12.7411
14	4.4925	12.7291
15	4.4925	12.7411
16	4.5112	12.7411
17	4.5002	12.7491
18	4.4925	12.7411
19	4.4925	12.7411
20	4.4807	12.7291
21	4.4731	12.7291
22	4.4807	12.7411
23	4.4807	12.7491
24	4.5002	12.7603
25	4.4731	12.7603
26	4.4925	12.7603
27	4.4925	12.7710
28	4.4731	12.7710
29	4.5500	12.7603
30	4.5411	12.7603
31	4.5304	12.7491
32	4.5304	12.7491
33	4.5224	12.7491
34	4.5304	12.7411
35	4.5304	12.7411
36	4.5304	12.7411
37	4.5224	12.7291
38	4.5304	12.7217
39	4.5403	12.7291
40	4.5403	12.7411

of the first origin. Following [9–11], the resistivity of the second layer was obtained from the relationship

$$\rho_2 = \rho_1 \times K_1 \quad (7)$$

where K_1 is the reflection coefficient at the interface between the two layers. The horizontal and vertical coordinates of

Fig. 3 Resistivity curve for VES 1

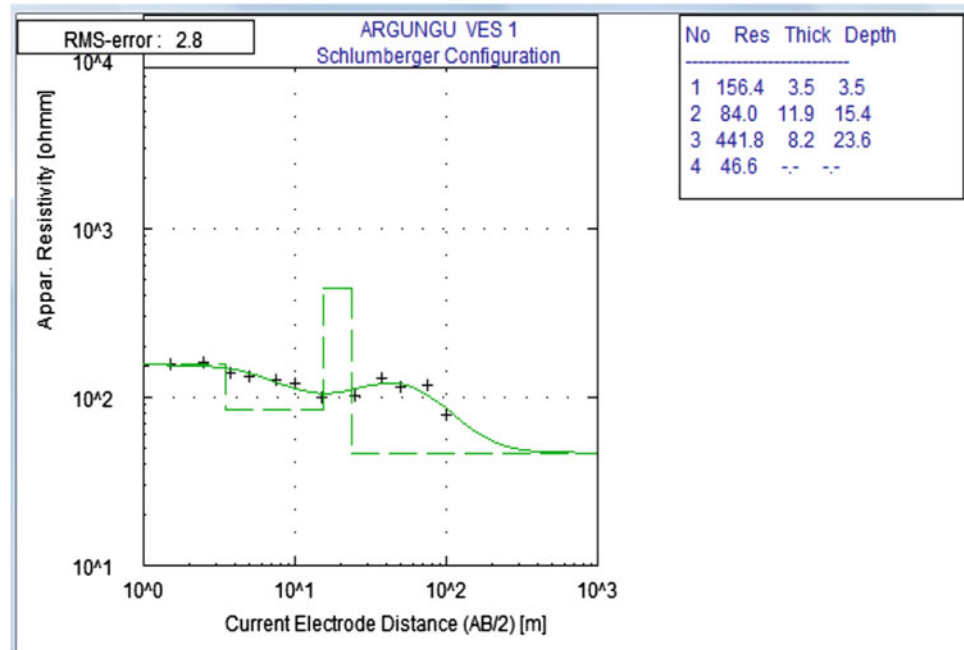
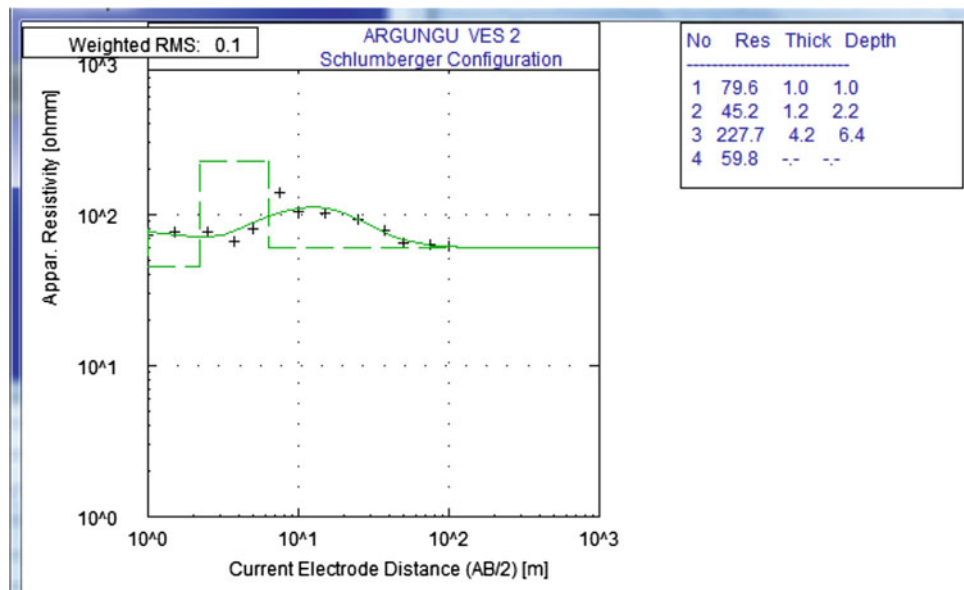


Fig. 4 Resistivity curve for VES 2



the second origin gave the replacement resistivity. Hence, the resistivity of the third layer (ρ_3) was obtained from the relationship

$$\rho_3 = \rho_2 K_{2r} \quad (8)$$

The depth ratio value (D_n/D_{r1}) was read at the location of the second cross-point. The thickness of the second layer was then obtained from the relationship

$$h_2 = (D_n/D_{r1})h_1 \quad (9)$$

These procedures were repeated for depth-sounding curves with more than three layers until the curves were completely

matched. Computer iterations were carried out with the aid of the 'Interpret VES' computer software. The results of the final interpretation were used to generate the geoelectric sections.

3.1 Aquifer Hydraulic Parameters from VES Data

To derive a formula in determining layer parameters, a unit square cross sectional area in a vertical direction is assumed. So, from Ohm's law transverse resistance of the layer can be

$$R = h\rho \quad (10)$$



Fig. 5 Resistivity curve for VES 3

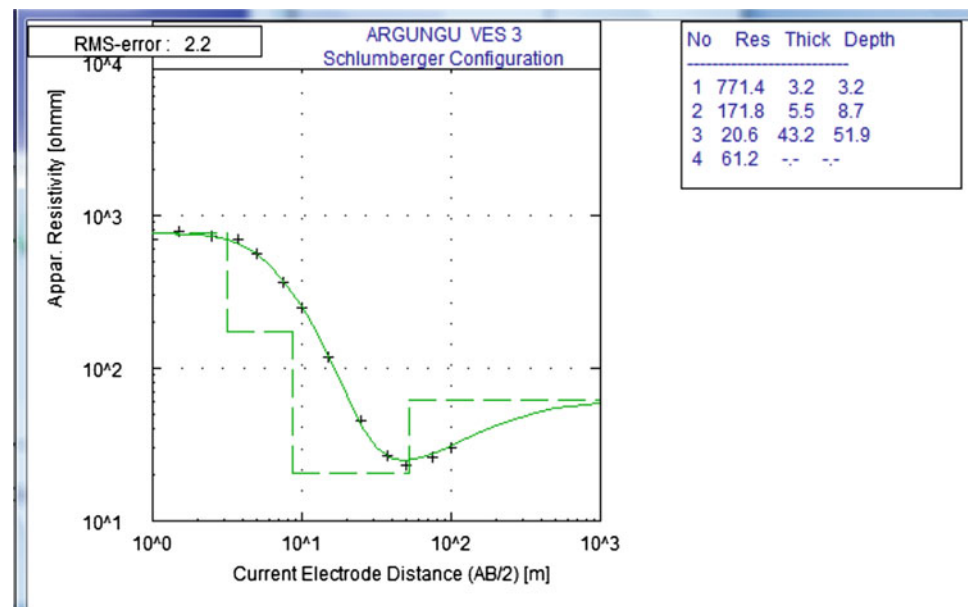
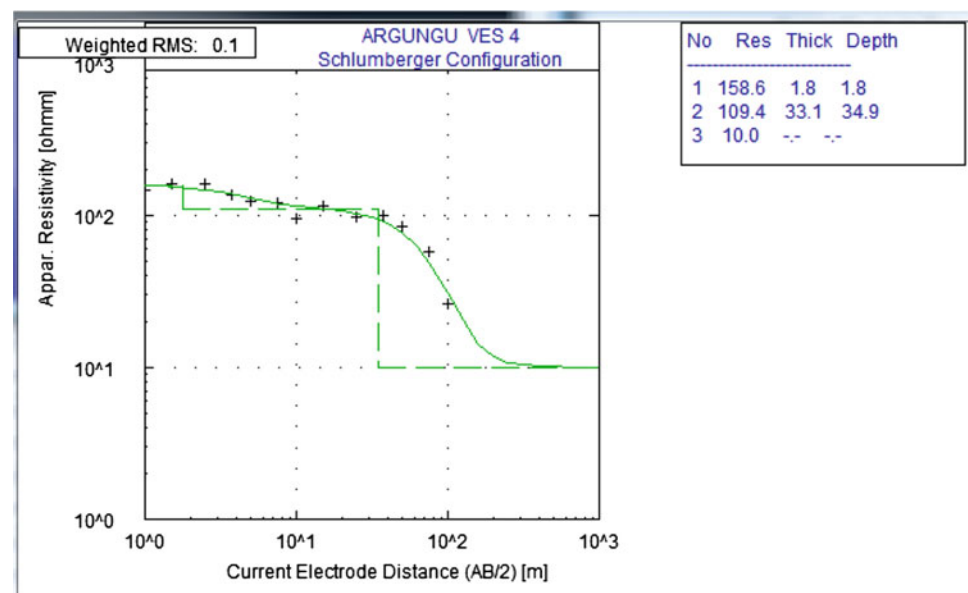


Fig. 6 Resistivity curve for VES 4



Also, longitudinal layer conductance can be expressed as

$$S = \frac{1}{R} = \frac{h}{\rho} = h\sigma \quad (11)$$

This can be compared with a relation given as

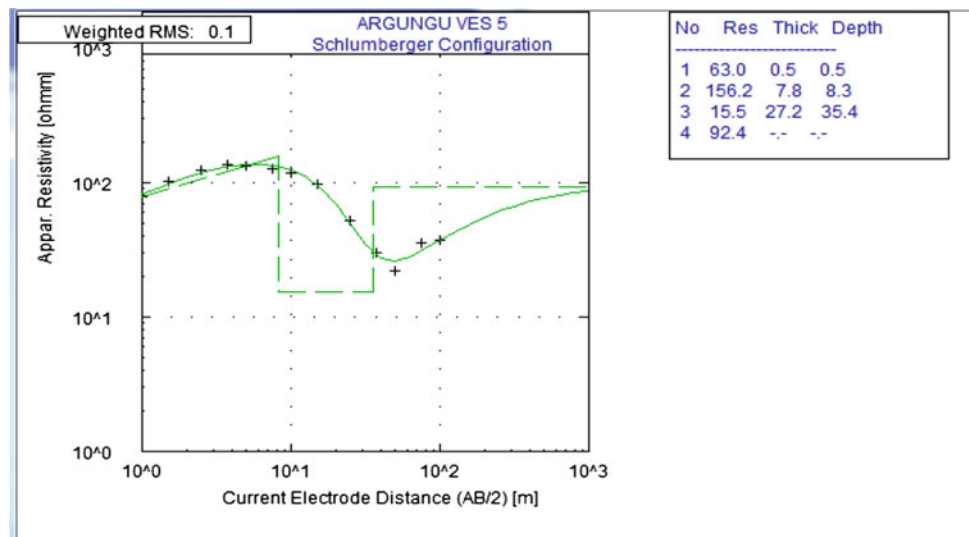
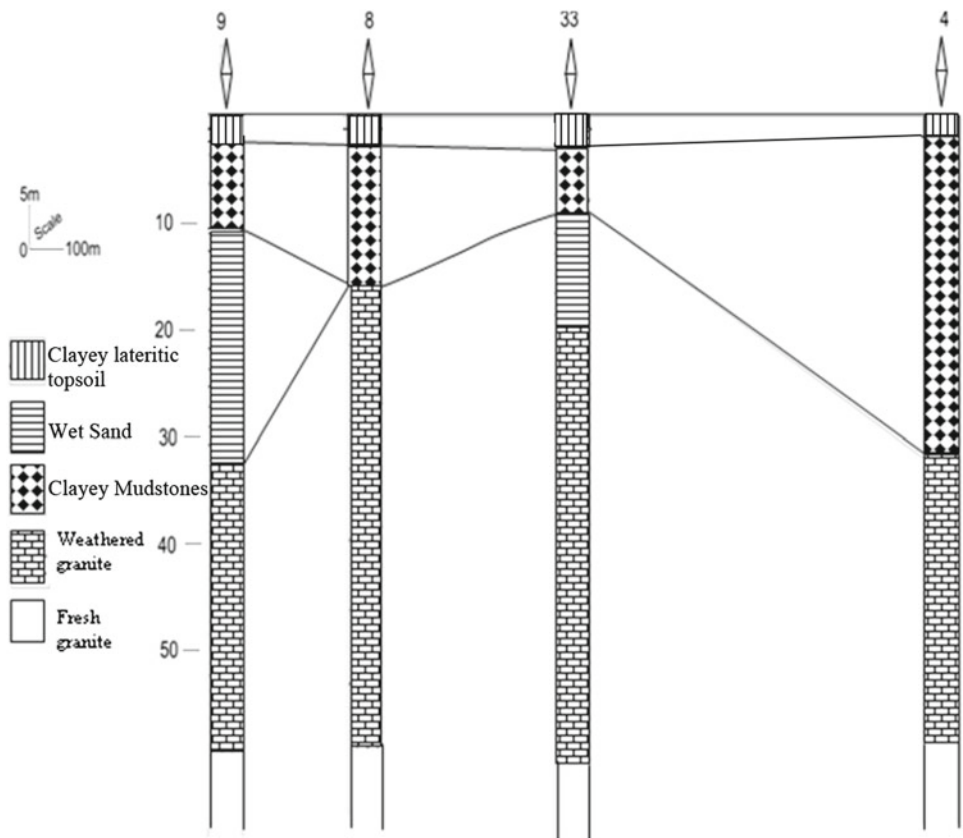
$$T = Kh \quad (12)$$

For aquifer material having unit cross-sectional and thickness h , according to [11], Eqs. (10), (11) and (12) can be combined to give

$$T = K\sigma R = \frac{KS}{\sigma} = Kh \quad (13)$$

where σ is the electrical conductivity, which is analogous to the hydraulic conductivity K of the layer, S is the longitudinal conductance which is analogous to layer transmissivity T and h is the thickness of the layer. R and S are called Dar Zarrouk parameter.

Further, [11] confirmed that the product $K\sigma$ is fairly constant for the same geologic formation and water quality. Thus, knowing K from borehole information and σ from VES soundings $K\sigma$ can be estimated for the same geologic zone. Hence, the aquifer hydraulic conductivity and transmissivity for the entire area can be estimated. This relationship forms the basis for the determination of aquifer hydraulic parameters.

Fig. 7 Resistivity Curve for VES 5**Fig. 8** Geological interpretation of a NE–SW geoelectrical section

4 Results and Discussions

4.1 Field Curves and Cross-Sections from VES Data

The sounding data were analyzed with the WinResist software to delineate the sub-surface layering as well as their depths, thickness and the resistivity values. Sample field curves at sounding locations (Table 1) across the study area

are shown in Figs. 3, 4, 5, 6, 7. In each of these diagrams both the variations of apparent resistivity with electrode spacing as well as the modeled layer resistivity versus depth are plotted. These curves suggest that the area is mostly underlain by five (5) geoelectric layers of various lithologies. However, there are minor isolated cases of three layers.

The NE–SW geoelectrical section in Fig. 8 is through VES points 9, 8, 33, 4 and the NW–SE section in Fig. 9 is through



Fig. 9 Geological interpretation of a NW–SE geoelectrical section

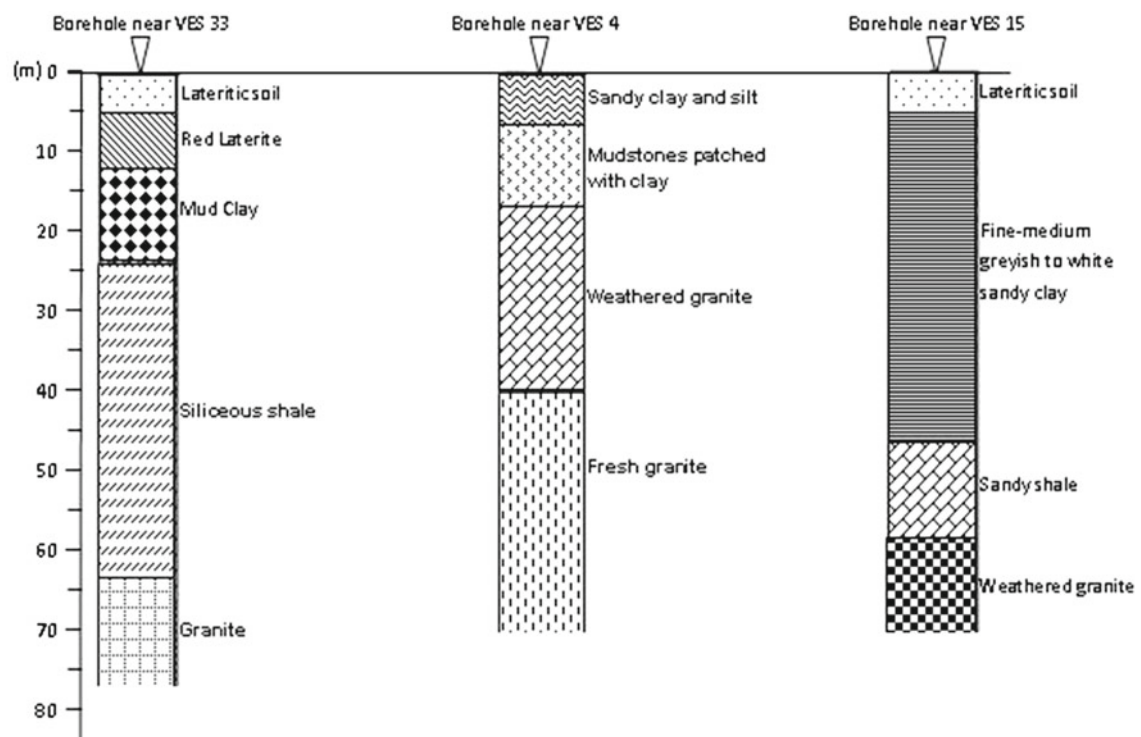
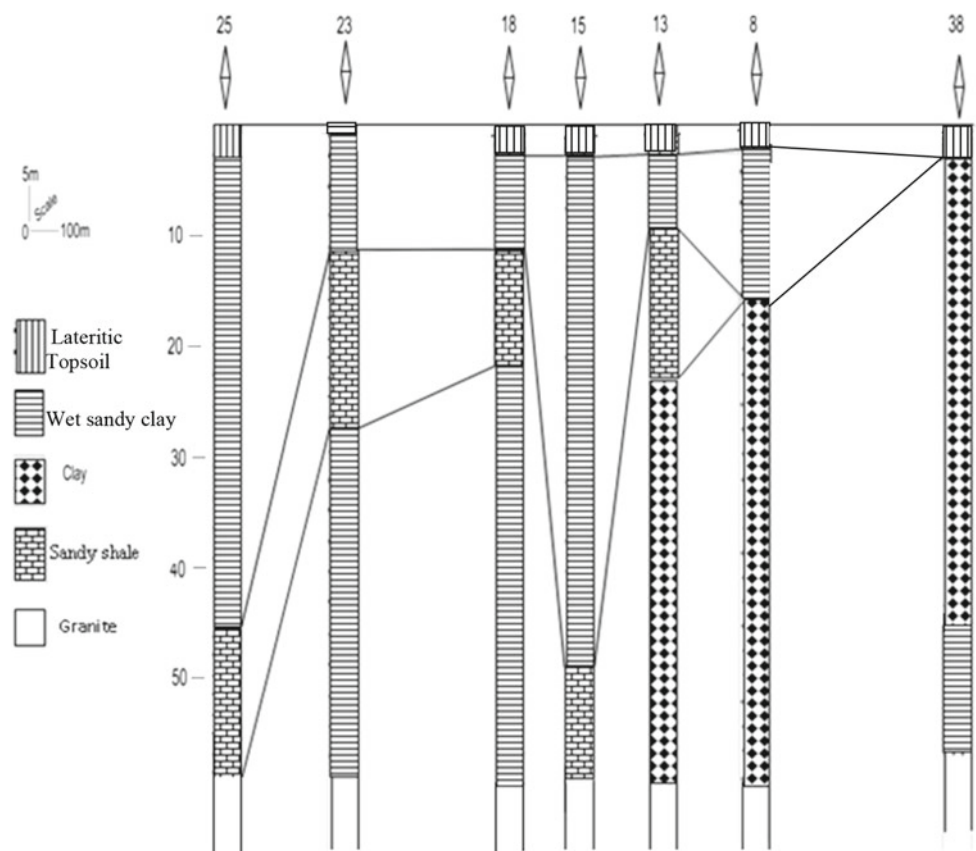


Fig. 10 Lithologies for some boreholes around the survey area (Courtesy: Batcaves Geo-Technical Services Nigeria Limited, 1992)

Table 2 Determination of layer parameters of the study area

VES no.	Depth to water table (m)	Aquifer thickness, h (m)	Apparent resistivity of aquifer ρ_a (Ω m)	$K\sigma$ (Ω^{-1})	Transverse resistance $R = h\rho$ (Ω m ²)	Hydraulic conduct. K (m/day)	Transmissivity $K\sigma R$ (m ² /day)
1	15.4	11.9	85.2	0.21699	1013.9	18.48	219.9
2	2.2	1.2	45.2	0.21940	54.2	9.92	11.9
3	51.9	43.2	20.6	0.22002	889.9	4.53	195.8
4	34.9	33.1	109.4	0.21999	3621.1	24.07	796.6
5	35.4	27.2	15.5	0.22011	421.6	3.41	92.8
6	2.8	1.2	38.0	0.21930	45.6	8.33	10
7	8.9	6.8	57.7	0.21995	392.4	12.69	86.3
8	15.6	13.5	71.8	0.21996	969.3	15.8	213.8
9	10.1	8.8	52.9	0.21997	465.5	11.64	102.4
10	27.5	23.9	43.9	0.21998	1049.2	9.66	230.8
11	38.0	36.3	37.4	0.22002	1357.6	8.23	298.7
12	44.6	33.5	24.5	0.22003	820.8	5.39	180.6
13	8.8	6.2	75.5	0.22004	468.1	16.61	103.0
14	10.6	8.6	128.8	0.22001	1107.7	28.34	243.7
15	49.9	46.7	56.0	0.22001	2615.2	12.31	572.3
16	8.4	7.1	48.9	0.22005	347.2	10.76	76.4
17	6.7	4.7	30.7	0.21968	144.3	6.74	31.7
18	11.2	8.5	59.4	0.22004	504.9	13.07	111.1
19	30.7	28.9	63.3	0.22002	1829.4	13.93	402.5
20	6.5	4.9	40.1	0.21985	196.5	8.82	43.2
21	6.7	4.9	24.9	0.21967	122.0	5.47	26.8
22	37.6	33.2	56.2	0.22001	1865.8	12.36	410.5
23	11.7	10.4	57.0	0.21997	592.8	12.54	130.4
24	2.9	2.5	23.6	0.21992	59.0	5.18	129.6
25	46.5	43.5	54.6	0.21999	2375.1	12.01	522.5
26	5.7	3.8	38.5	0.22010	146.3	8.47	32.2
27	34.1	29.4	40.9	0.22004	1202.5	9.00	264.6
28	14.1	12.1	63.0	0.21999	762.3	13.86	167.7
29	33.6	27.3	38.0	0.21997	1037.4	8.36	228.2
30	35.5	26.4	14.1	0.22004	372.2	3.10	81.9
31	52.5	45.5	53.1	0.21998	2416.1	11.68	531.5
32	11.9	10.3	89.4	0.22003	920.8	19.67	202.6
33	8.0	5.8	69.1	0.22006	400.8	15.21	88.2
34	12.6	10.6	94.5	0.21998	1001.7	20.81	220.6
35	8.2	6.2	30.6	0.21982	189.7	6.73	41.7
36	46.6	44.2	34.1	0.22001	1507.2	7.50	331.6
37	5.9	4.5	34.4	0.22022	154.8	7.36	33.1
38	2.7	1.9	18.7	0.21997	35.5	4.11	174.0
39	43.2	20.1	31.2	0.22006	627.1	6.87	138.0
40	39.2	32.0	19.8	0.22001	633.6	4.36	139.4

VES points 25, 23, 18, 15, 13, 8, 38. The traverse directions are shown in Fig. 15. They both depict that the area is mostly being underlain by four geoelectric layers and five layers in some areas. Based on the available geolog-

ical information, borehole data and the known resistivity values of some rocks used as a standard in the geological interpretation, the rock units are identified mostly to consist of the clayey lateritic topsoil, sand, clay, weathered granite



Fig. 11 Aquifer thickness map

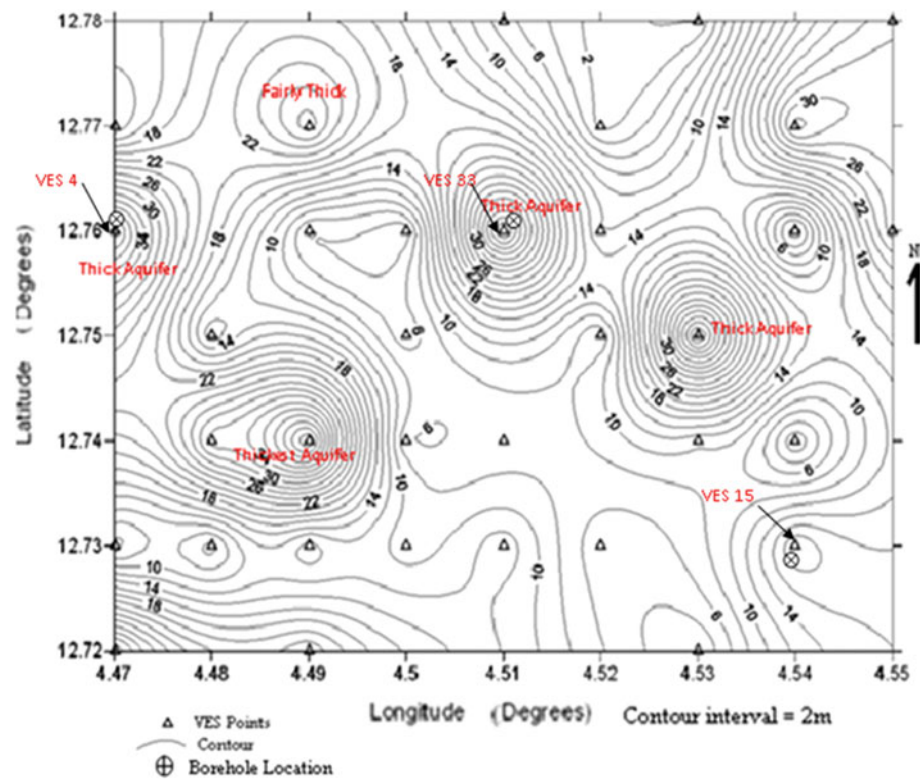
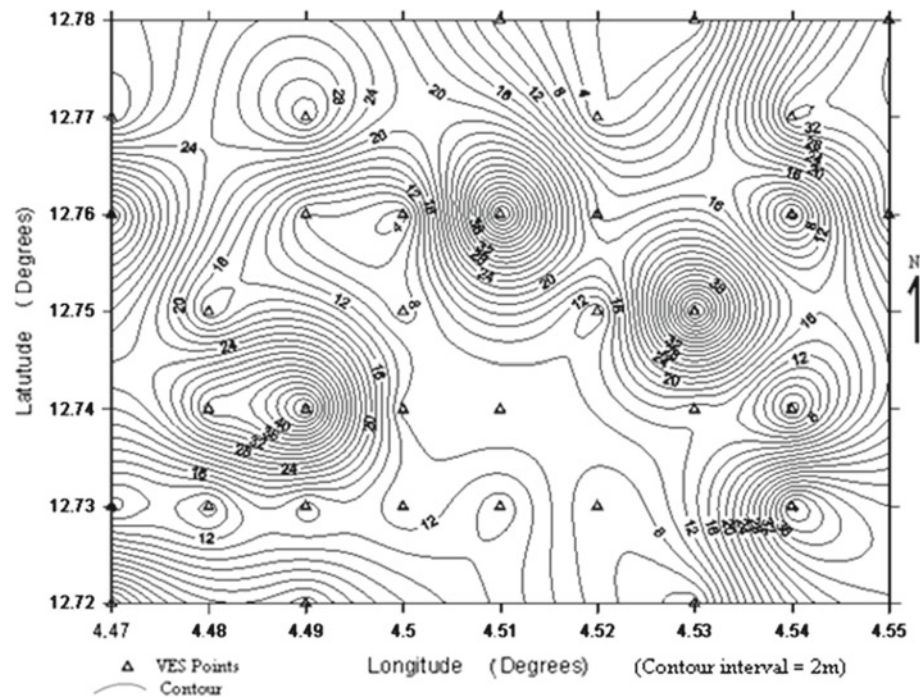


Fig. 12 Map of depth to the water table



and fresh granite. Shale appears on the NW–SE profile section. Section of NE–SW (Fig. 8) shows that aquifer zone lies within the second and third layers (i.e., sand and weathered granite) while NW–SE profile shows that water exists partly in shale and clay layers around VES 18, 23 and 38. The

aquifers around VES 4 and VES 33 lie within the weathered granite with thickness of 34–40 m, at depths ranging 30–46 as shown. This is similar to the boreholes log data (Fig. 10) obtained around the area. The last layer in both cases is granite which is the bedrock. Aquifers in the area

Fig. 13 Hydraulic conductivity anomaly map

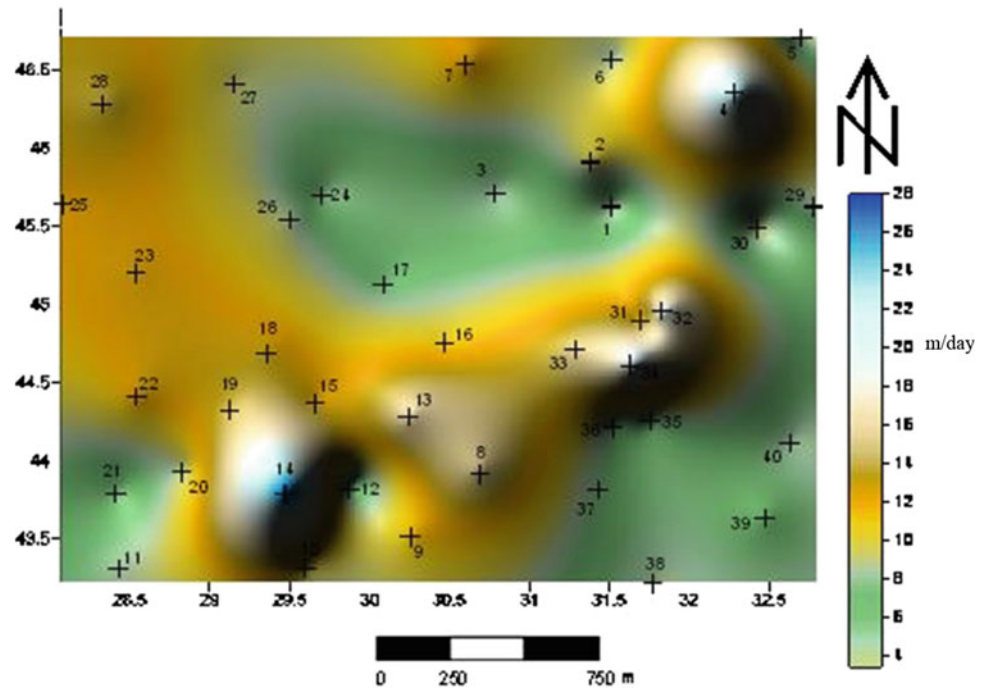
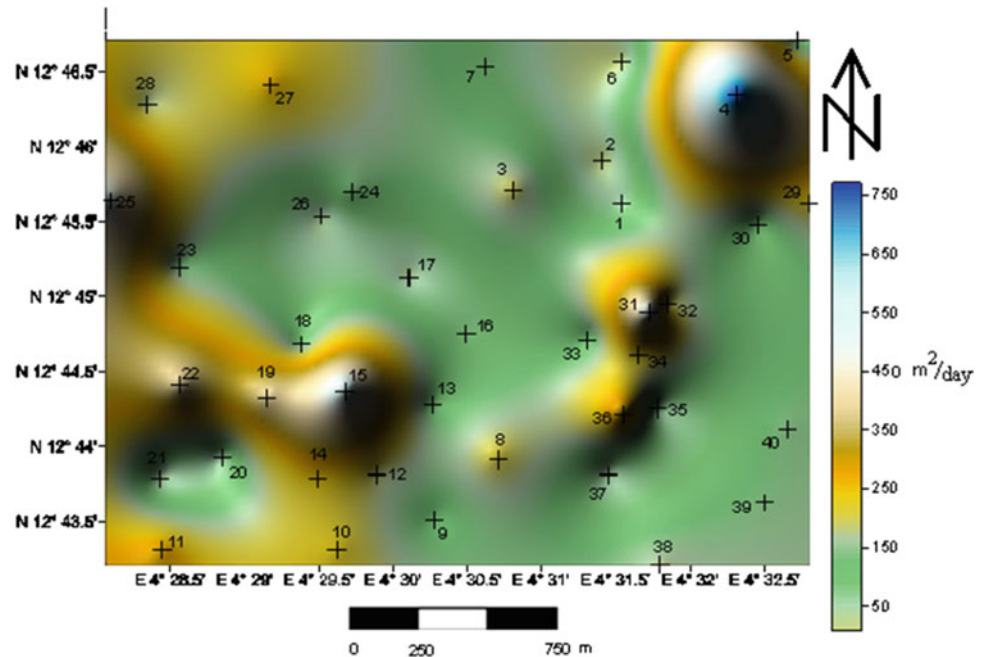


Fig. 14 Transmissivity anomaly map



are mostly located within sandy clay, shale and weathered granites.

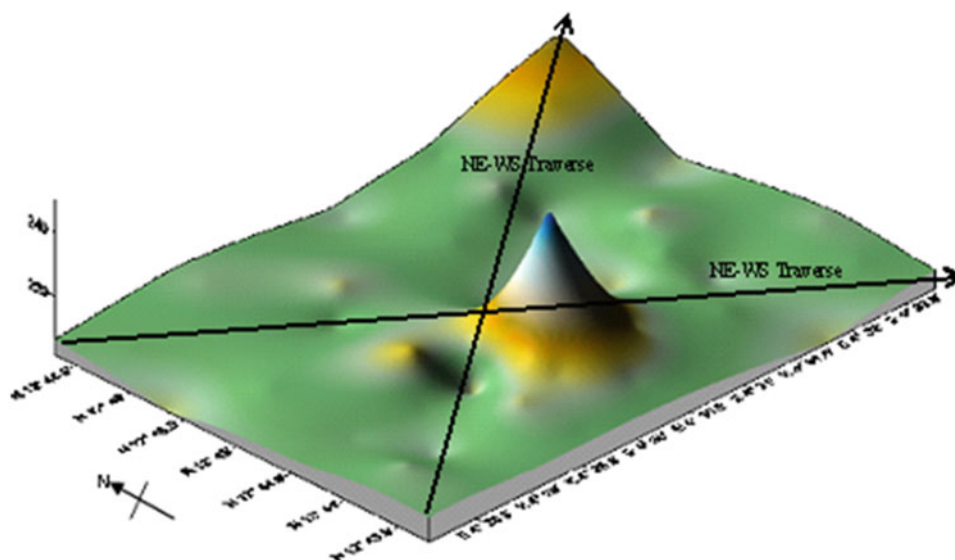
4.2 Aquifer Depth and Thickness in the Study Area

The aquifers in the area are categorized as thickest, thick and fairly thick as shown in Fig. 8 obtained from Table 2. The thickest aquifer, about 42 m thick, is located close to the southwestern corner of the area. VES numbers 4, 5, 14, 15,

17, 19, 21, 22, 25, 26, 28 and 29 are situated around the area. Thick aquifers are found trending west–east around the middle part in the area. Depth to the water-table is shallow around VES 2, 6, 14, 24 with an average depth of around 7 m. The deepest aquifers at about 50 m depth lie coincidentally around the location of the thickest aquifer. The thickest aquifer in the area appears suitable for the groundwater exploitation due to its greater depth and is presumably free from sewage and surface contaminations. However, chemical analysis of the



Fig. 15 3-D topographic map of the study area



underground water is still required to determine its suitability for consumption (Figs. 11, 12).

4.3 Hydraulic Characteristics of the Aquifer Systems

The hydraulic characteristics of the several aquifer types within the study area were established using the concept of Dar-Zarrouk parameters, the results are shown in Table 2. The $K\sigma$ product is homogeneous hydrologically for some VES locations with the values varying between $0.21930 \Omega^{-1}$ at VES 6 and $0.22006 \Omega^{-1}$ at VES 38 with average value of $0.21988 \Omega^{-1}$.

The mean of the hydraulic conductivity $K = 10.9345$ m/day, while the mean of the transmissivity $T = 197.965$ m²/day. The maximum $K = 28.34$ m/day at VES 4, while the minimum $K = 3.10$ m/day. The maximum $T = 796.6$ m²/day at VES 14, while the minimum $T = 10.0$ m²/day. Low values for K and T imply low potential for aquifer productivity. Thus maximum yield could be expected around VES 4 and 14.

The variations of transmissivity and hydraulic conductivity are shown in Figs. 13 and 14. The highest transmissivity and hydraulic conductivity values trend NW–SE, with the peak in the NE corner of the area. In addition, a 3D topographic image obtained from the elevations at all VES points is shown in Fig. 15. The area is a relatively flat plain with isolated uplifts along the NE–SW direction.

5 Conclusion

Vertical electrical sounding had been carried out within the study area with the principal aim of evaluating and comparing the primary and secondary aquifer parameters including the resistivity, thickness, hydraulic conductivity and trans-

missivity of the layers of the aquifer. The VES data interpreted and from the information obtained from borehole in the area has been used to produce the geoelectric section at each of the VES sites investigated. From the analysis of the VES data and curves, the formations identified are all sandy and this indicates the nature of the aquifer. This study successfully evaluates the secondary aquifer parameters such as hydraulic conductivity and transmissivity from the primary aquifer parameters which are resistivity and thickness. The results could help in the exploitation and management of ground water in the area.

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