

Study of aquifer characteristics in northern Paiko, Niger State, Nigeria, using geoelectric resistivity method

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Abstract Vertical electrical soundings technique was used to evaluate the aquifer characteristics and distribution in the northern part of Paiko in Nigeria. A total of thirty vertical electrical soundings were carried out using ABEM SAS4000 Terrameter, and the data was analyzed both manually and with software (Resist software). The result revealed the aquifer resistivity and thickness to vary from 10.9 to 80,368 Ωm , and 1.06 to 72 m, respectively. Also, hydraulic conductivity ranges from 0.010267 to 41.61928 m/day while transmissivity values range from 0.035215 to 70.09302 m^2 . The hydrogeological maps (hydraulic conductivity and transmissivity image maps) showed the variations of these parameters in the study area and that the southwestern part of the area has prolific aquifer.

Keywords Vertical electrical soundings · Hydraulic conductivity · Transmissivity · Aquifer characteristics · Northern Paiko

Introduction

Paiko area falls within the Precambrian basement complex of Nigeria. This is composed mainly of granitic and migmatitic gneisses and granites. Nigerian basement complex

has many challenges as regards groundwater potential evaluation (Olasehinde and Amadi 2009). Both the older and younger granites of these areas are poor aquifers. However, over most of these areas occur thin, discontinuous mantle of weathered rocks or joint, and fracture systems in the unweathered basement provide secondary reservoir. The decomposed mantle is sometimes too thin to harbor large quantities of water and is usually too clayey to be highly permeable. The crystalline basement of Nigeria generally represents the deeper, fractured aquifer and is noted as a poor source of groundwater. This is partly overlain by a shallow, porous aquifer within the lateritic soil cover (Annor and Olasehinde 1996). Paiko is faced with increasing demands for water resources due to high population growth rate. The importance of groundwater in meeting a substantial percentage of this water need, and the overall development of the area's economy cannot be over-emphasized. In order to set the context for sustainable groundwater use and management options across the area, there is need to develop better predictive models, which are dependent on a thorough understanding of geological and hydrogeological settings.

The main economic activities in Paiko are agriculture and livestock rearing with about two-thirds of the population engaged in subsistence farming. Due to the ephemeral nature of surface water, groundwater abstraction is often the only realistic and affordable means of providing reliable water supply for the need of the people of Paiko. Development of the resource therefore depends on an accurate understanding of hydrogeology, and people with the skills to make informed decisions on how groundwater can best be developed and managed in a sustainable fashion. Development of groundwater supply involves a sequential process with three phases: exploration, evaluation, and exploitation. Often, groundwater supply projects

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concentrate on exploitation while the evaluation phase is neglected. Groundwater supply projects can fail if this sequential development process is not followed. Adequate data cannot be available for meaningful planning if no proper evaluation is carried out before exploitation. Many boreholes were and are still being drilled with little or no hydrogeological knowledge, hence the cause of many borehole failures and waste of human resources.

Groundwater is a major source of water required by man for domestic and industrial uses. To quantify and manage groundwater has been a challenge to researchers, compared to that of surface water. In the study area, groundwater is used commonly as a source of drinking water for individuals and stock watering. It is important that groundwater users should, before drilling, assess the groundwater potential of the area to find out the depth of groundwater quality and yield. The characteristics of aquifer are greatly influenced by formation strata and terrain type (Akpokodje and Etu-Efeotor 1987). These characteristics (hydraulic conductivity and transmissivity) are not known, and this has affected the aquifer exploitation in the study area negatively. This study will comprehensively and systematically help in establishing the nature and distribution of aquifers in the area. The knowledge of aquifer hydraulic parameters such as hydraulic conductivity and transmissivity is important in determining the natural flow of water through an aquifer and its response to groundwater extraction (Opara et al. 2012). Due to high cost of pumping test, which is used to estimate hydraulic conductivity, the resistivity method (non-invasive) which is cheaper in obtaining information on aquifer properties is employed. The spatial and temporal patterns of hydrological states can be retrieved from the geophysical parameters; thus, estimates of the hydrological and petro-physical parameters that determine flow and transport processes can be made (Aizebeokhai and Oyebanjo 2013).

A lot of authors in their research have established the relationship between electrical and hydraulic properties (Kelly 1977; Kosinki and Kelly 1981; Singh 2005; Sinha et al. 2009; Niwas et al. 2011). Since hydraulic and electrical properties of aquifers are related to pore space structure and heterogeneity, a correlation between these properties is possible (Niwas et al. 2006; Soupios et al. 2007). Though various studies have been done on the aquifer potentials of the north-central Nigerian basement complex (Dan-Hassan 2001; Amadi et al. 2012; Adeniji et al. 2013; Alhassan et al. 2015), no work had been done to ascertain the characteristics of the aquifer distribution parameters in the study area. Therefore, this paper is aimed at using the surface geoelectric sounding data to characterize and evaluate the distribution of aquifer parameters in the study area. The results of this study will help to reduce the cases of unproductive borehole and borehole failures.

Geomorphology and geology

The study area (Paiko) is located in the north-central part of Nigeria. It lies within latitudes 9°25'N and 9°27'N, longitudes 6°37'E and 6°39'E with an elevation of 304 m above sea level (Fig. 1). The vegetation in the area is of the Guinea savanna type which is characterized by annual rainfall variation of 1200–1300 mm. The mean annual temperature is between 22 and 25 °C. The area is drained by river Kaduna and its tributaries. The topography is fairly undulating with expanses of plain lands in the eastern part of the study area while the western part is characterized by very high steep-sided hills. Paiko hill is the highest hill within the vicinity of the study area, with an elevation of 60 m a.s.l. The study area falls within the basement complex of Nigeria and is underlain by four lithological formations as is evident from the rocks in the area. The rock types in this region include granites, gneisses, quartzites, as well as laterites. Most of the granites are older granites, and this distinguishes them from the younger granites found in Jos area. The mapped area is underlain by coarse- to medium-grained granite, and the rocks are well exposed at the northern part of Paiko. The main lateritic rock which occurred in all parts of the area is of two forms: the dark brown in appearance, hard, and spongy; and the light brown, soft, and less spongy, which is the oldest (Ajibade 1980).

Materials and methods

Electrical properties of the materials within the earth surface determine the choice of electrical resistivity method to be used. Also, the method that will make the field work faster, easier, and economical has to be considered. Thirty vertical electrical sounding (VES) points were taken, employing the Schlumberger electrode configuration. The potential electrodes remained fixed at a point while the current electrodes were expanded about the center of the spread. To maintain a measurable potential, the potential electrodes were increased where the current electrodes were too far apart. Artificially generated current was introduced into the ground through the two current electrodes (AB) and the resulting potential drops across the two potential electrodes (MN) were taken. This study was carried out using ABEM SAS4000 Terrameter. The maximum current electrode spacing ($\frac{AB}{2}$) was 100 m, and maximum potential electrode spacing ($\frac{MN}{2}$) was 15 m. The apparent resistivity (ρ_a) was computed using

$$\rho_a = G \frac{\Delta V}{I} \quad (1)$$

where G is the geometric factor given by

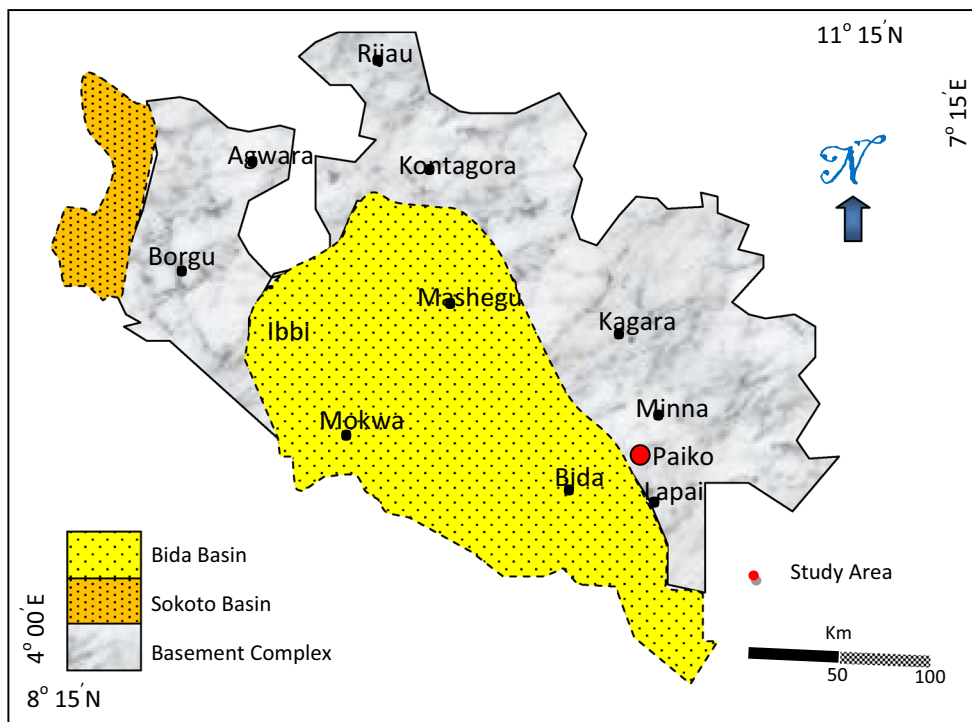


Fig. 1 Geological map of Niger State basement complex and sedimentary basin

$$G = \pi \left(\frac{\left(\frac{AB}{2}\right)^2 - \left(\frac{MN}{2}\right)^2}{MN} \right) \tag{2}$$

and

$$\frac{\Delta V}{I} = R, \text{ is the resistance} \tag{3}$$

where ΔV is the potential difference in volt, and I is the current in Ampere.

The computed apparent resistivity was plotted manually using a bi-logarithm graph, and the curves generated were smoothed to remove the effects of lateral inhomogeneities. The smoothed curves from the vertical electrical sounding data were quantitatively interpreted in terms of true resistivity, depth, and thickness by conventional manual curves and auxiliary charts (Orellana and Mooney 1966). The manually interpreted data was improved upon using Resist software which produces geological curve models from the field data, and the method of iteration was done. Hydraulic conductivity (K) was estimated using (Heigold et al. 1979):

$$K = 386.40\rho^{-.93283} \tag{4}$$

where ρ is the aquifer resistivity.

Maillet (1947) introduced the concept of Dar Zarrouk parameters. He defined the longitudinal unit conductance (S) and transverse unit resistance (R_T) for a sequence of horizontal, homogeneous, and isotropic layers as:

$$S = \frac{h}{\rho} \tag{5}$$

$$R_T = h\rho \tag{6}$$

where ρ is the resistivity, h is the thickness.

Analytical relationship between aquifer transmissivity and transverse resistance on the one hand and between transmissivity and longitudinal conductance on the other hand was established by Niwas and Singhal (1981). Taking into account, a prism of aquifer material having a unit cross-sectional area and thickness h , Niwas and Singhal (1981) combined Eqs. 5 and 6 to obtain the relationship given as:

$$T_r = KkR_T = \frac{KS}{k} \tag{7}$$

where K is the hydraulic conductivity, k is the aquifer conductivity, T_r is the aquifer transmissivity. These equations were used to determine the longitudinal conductance and transmissivity of aquifers in the study area.

Results and discussion

The results of the electrical resistivity survey of the area show a resolution of resistivities and thicknesses of the aquiferous zone from computer-modeled interpretation together with the estimated hydraulic parameters as

presented in Table 1. The geoelectrical sections for profiles G, H, and I (Fig. 2a–c) revealed 3–4 geoelectric layers within the study area. The VES results (VES G5 and VES H10) were correlated with the lithological logs from nearby boreholes as shown in Fig. 3. Hydrogeological maps (aquifer resistivity, aquifer thickness, aquifer hydraulic conductivity, and aquifer transmissivity maps) were generated using the resistivity data. The aquifer resistivity varies between 10.9 and 80,368 Ωm . The variation of aquifer resistivity values (Fig. 4a) indicates that the northeastern part of the study area is made of highly resistive materials, and this implies low concentration of conducting fluid and thus a high groundwater quality can

be inferred in these zones, while the northwest, southwest, and southeast shows the existence of low resistive fluid and thus a high concentration of conducting materials. Also, the zone underlain by high resistive aquifer materials may not be good for drilling boreholes with high yield expectation (Mbonu et al. 1991). The aquifer thickness ranges from 1.06 to 24.3 m, and its variation is shown in the image map (Fig. 4b). It can be observed from the image map that the northwest toward the southwest has very low aquifer thickness, but high thickness is observed in parts of the northeast and central part of the study area. It can be inferred that these zones with high aquifer thickness have high groundwater potential. The longitudinal conductance

Table 1 Summary of results of interpreted layer parameters from the study area

VES station	Longitude (°)	Latitude (°)	Layer no	Aquifer resistivity ρ (Ωm)	Aquifer thickness (h) (m)	Hydraulic conductivity (K) m/day	Longitudinal conductance S (Ω^{-1})	Transmissivity Tr (m^2/day)
G ₁	6.6533	9.3372	3	184	4.60	2.981	0.025	13.712
G ₂	6.6536	9.3370	3	526	5.89	1.119	0.011	6.591
G ₃	6.6545	9.3366	3	126	2.92	4.244	0.023	12.392
G ₄	6.6540	9.3368	3	70.8	3.47	7.266	0.049	25.212
G ₅	6.6548	9.3363	4	1021	24.4	0.603	0.024	14.707
G ₆	6.6552	9.3360	3	8244	2.04	0.086	0.0003	0.175
G ₇	6.6554	9.3357	3	132	1.06	4.064	0.0083	4.307
G ₈	6.6557	9.3353	3	968	19.40	0.633	0.020	12.289
G ₉	6.6560	9.3350	3	11,184	4.75	0.065	0.0004	0.307
G ₁₀	6.6564	9.3347	3	351	7.88	1.632	0.023	12.860
H ₁	6.6552	9.3377	4	750	22.10	0.804	0.030	17.762
H ₂	6.6556	9.3376	3	124	2.24	4.308	0.018	9.649
H ₃	6.6560	9.3375	3	130	1.86	4.122	0.014	7.667
H ₄	6.6560	9.3375	3	136	5.23	3.952	0.039	20.669
H ₅	6.6560	9.3375	3	60,825	72.00	0.013	0.001	0.959
H ₆	6.6565	9.3374	3	80,368	3.43	0.010	0.00004	0.035
H ₇	6.6569	9.3372	3	941	24.30	0.650	0.026	15.805
H ₈	6.6573	9.3369	3	700	10.90	0.857	0.016	9.343
H ₉	6.6577	9.3367	3	28	2.17	17.262	0.078S	37.458
H ₁₀	6.6580	9.3364	4	263	14.60	2.136	0.056	31.188
I ₁	6.6543	9.3380	3	46.4	1.96	10.776	0.042	21.121
I ₂	6.6548	9.3379	3	110	2.86	4.817	0.026	13.776
I ₃	6.6515	9.3366	3	153	3.23	3.541	0.021	11.437
I ₄	6.6517	9.3362	3	32	4.31	15.240	0.135	65.685
I ₅	6.6520	9.3358	3	27.7	4.02	17.436	0.145	70.093
I ₆	6.6522	9.3355	3	154	2.60	3.519	0.016	9.150
I ₇	6.6526	9.3352	3	34.1	1.12	14.363	0.033	16.086
I ₈	6.6528	9.3348	3	131	6.06	4.092	0.046	24.800
I ₉	6.6531	9.3344	3	27	2.36	17.857	0.087	42.144
I ₁₀	6.6534	9.3341	3	10.9	1.67	41.619	0.153	69.504



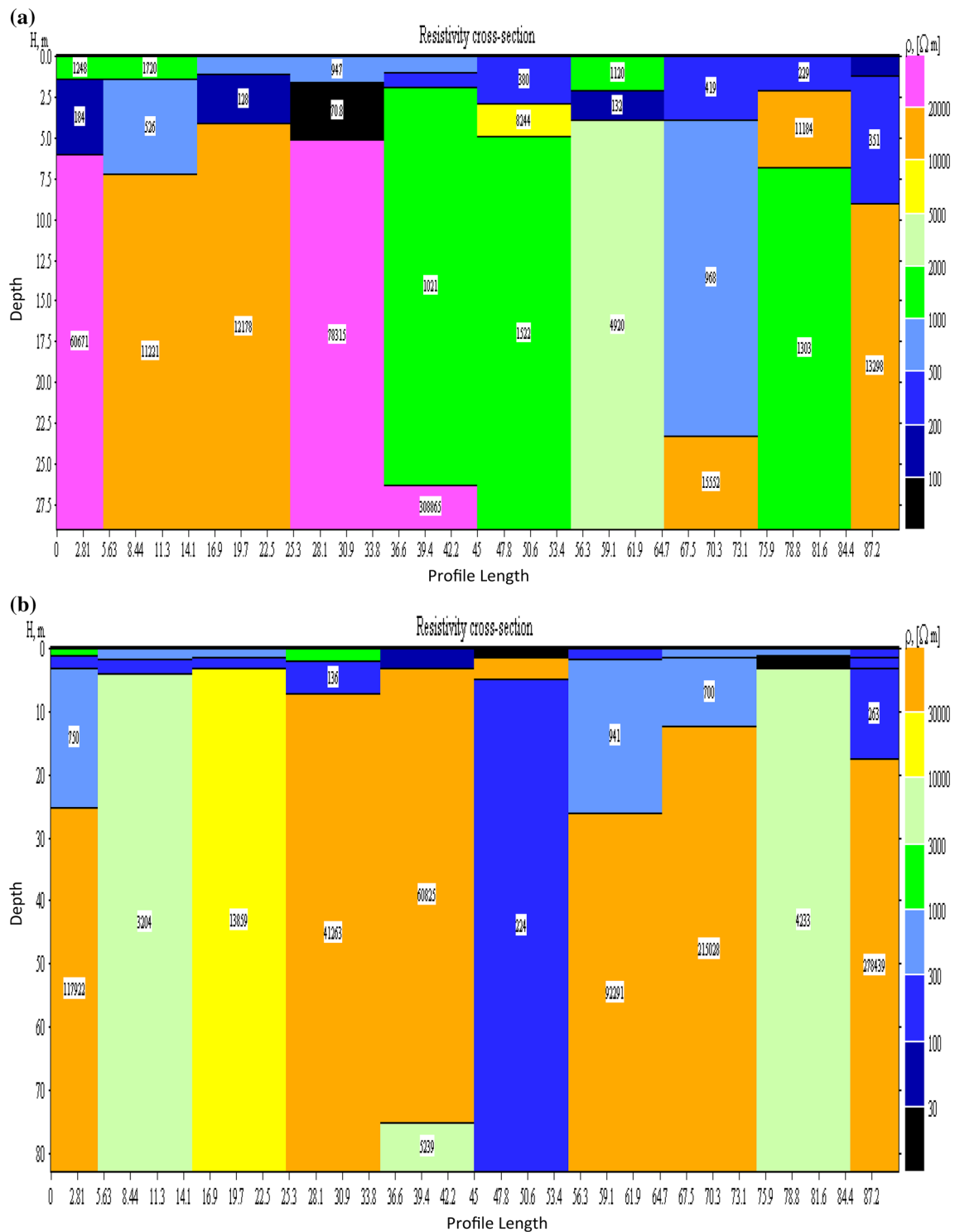


Fig. 2 a Geoelectric section for profile G. b profile H. c profile I

calculated for the aquifer unit is generally very low ranging between 0.00004 and $0.153 \Omega^{-1}$. This shows that the study area has high permeability and low volume of clay thus

rendering the aquifer vulnerable to contamination as a result of infiltration of surface contaminant liquid into the aquifer (Barker et al. 2001; Ibuot et al. 2013). Figure 4c

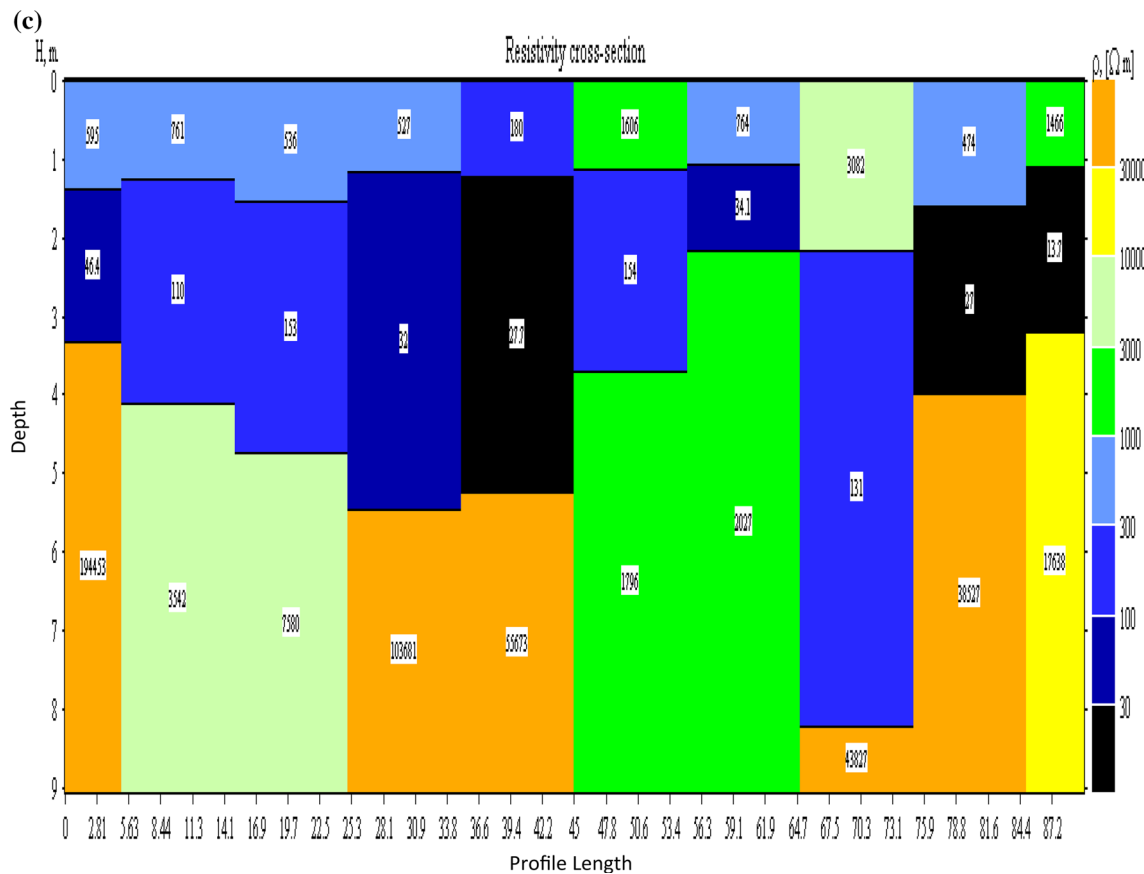
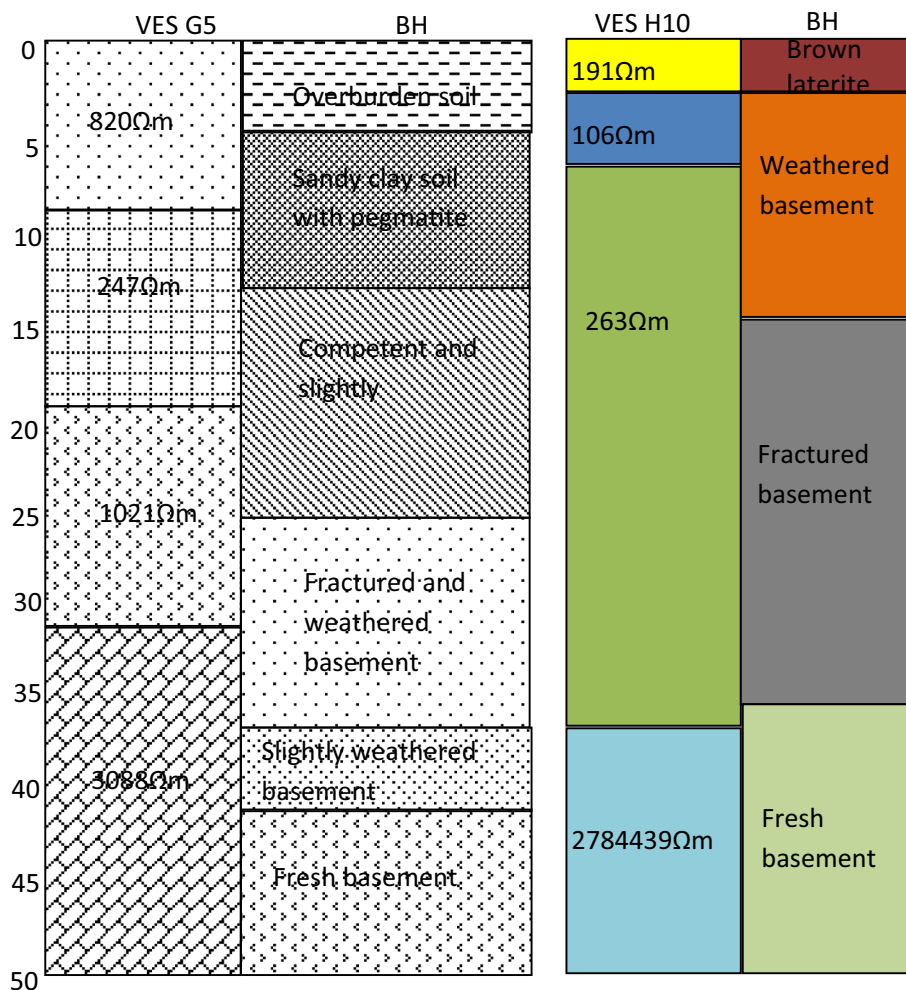


Fig. 2 continued

shows the variation of hydraulic conductivity, with maximum hydraulic conductivity observed in the extreme southwestern part of the study area while minimum value is observed in the northeast down to the southeast. The values of hydraulic conductivity range from 0.010267 to 41.61928 m²/day. The zones with high hydraulic conductivity are associated with low clay and would be highly permeable to fluid flow. The estimated hydraulic conductivity values can be useful in correlating and determining the rate of groundwater flow in the aquifer formation and similar formations within the study area (George et al. 2011). Figure 4d shows the variation of aquifer transmissivity in the study area. The transmissivity values range from 0.035215 to 70.09302 m²/day, which represent very low to intermediate groundwater potential (Krasny 1993). The map revealed that the southwestern part of the study area has high aquifer transmissivity; as such, these zones will have good water-bearing potential. The zone from northwest to the southeast is observed to have low transmissivity values, which is an indication of poor aquifer productivity prospect. VES stations with transmissivity values between 1 and 10 m²/day are designated as low,

from 0.1 to 1 m²/day are very low while those from 10 to 100 m²/day are intermediate (Krasny 1993). It can be seen that most of the VES stations in the study area fall within the intermediate zone. This indicates that the well yield will meet the local water supply of the area. The knowledge of transmissivity helps in determining the natural flow of water through an aquifer and its response to groundwater extraction. The results suggest that the groundwater potential in the southwestern part of the study area is high, since the aquifer transmissivity is high and thus suitable for development of productive boreholes. Table 2 shows the result of pumping test from two boreholes in the study area: one (borehole 1) situated around G5 and the other (borehole 2) around H10. The difference in the borehole yield values (Table 2) shows the variation of aquifer characteristics of the area. Based on results in Table 2, Borehole 1 and Borehole 2 have yields that could be classified as moderate (MacDonald et al. 2005). In highly weathered and/or fractured basement, average yields of 0.1–1 L/s are considered to be moderate, which shows that the area has intermediate aquifer transmissivity, an indication of good aquifer productivity.

Fig. 3 Correlation of VES lithology with nearby borehole logs



Conclusion

Useful estimation of hydraulic conductivity and transmissivity of the aquiferous layer is obtained from the result, and the maps showed the lateral and longitudinal distribution of these parameters within the study area. The estimated aquifer parameters revealed that the hydraulic conductivity values range from 0.010267 to 41.61928 m/day while transmissivity values range from 0.035215 to 70.09302 m²/day, and the wide range observed may be due to high inhomogeneity of the basement area. The transmissivity map delineated the southwestern part of the study area to have good groundwater potential. The low

values of longitudinal conductance indicate high permeability in the area. The hydrogeological knowledge obtained from this study is a significant tool for effective development and management plan for abstraction of groundwater in the study area. It will also help for further study of the groundwater flow in the area. Development of the groundwater resources depends on an accurate understanding of hydrogeology, and people with the skills to make informed decisions on how groundwater can best be developed and managed in a sustainable fashion. Careful and appropriate data collection during project implementation, together with data interpretation and knowledge dissemination, can prevent past mistakes being repeated

Fig. 4 Image map of the study area showing **a** variation of resistivity, **b** variation of thickness, **c** variation of hydraulic conductivity, and **d** Image map showing the distribution of transmissivity in the study area

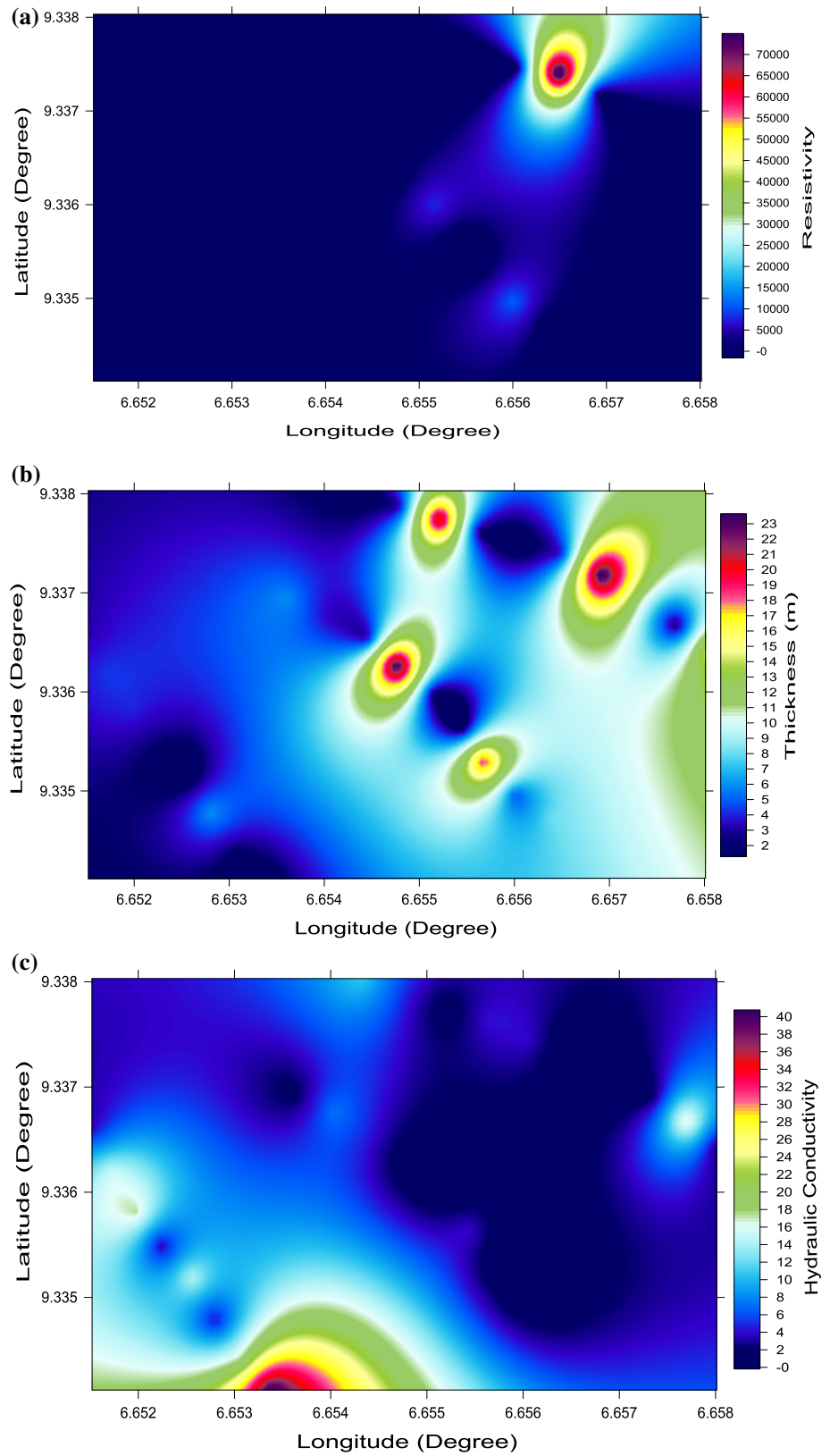


Fig. 4 continued

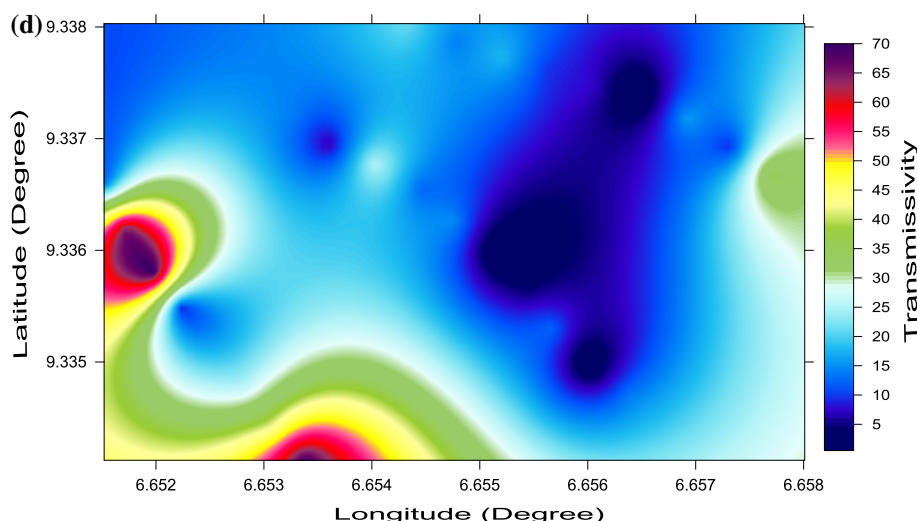


Table 2 Nearby boreholes pumping test

Parameters	Borehole 1	Borehole 2
Borehole depth	50 m	50 m
Static water level	4.78 m	8.09 m
Pump type and capacity	Same	Same
Top of casing above ground level	0.2 m	0.25 m
Pump setting	40 m	34.5 m
Borehole yield	16 L/min	60 L/min
Water level	37.11 m	21.24 m
Drawn down	32.33 m	13.15 m
Recovery drawn down	32.33 m	13.15 m

and reduce the ultimate cost of water supply schemes both from a human and a financial point of view.

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