Vertical electrical sounding as an exploration technique to improve on the certainty of groundwater yield in the fractured crystalline basement aquifers of eastern Uganda

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Arthur Batte
Makerere University

Andrew Muwanga
Makerere University

Michael Owor
Makerere University

Vertical electrical sounding as an exploration technique to improve on the certainty of groundwater yield in the fractured crystalline basement aquifers of eastern Uganda

A.G. Batte · A. Muwanga · P.W. Sigrist · M. Owor

Abstract Groundwater in eastern Uganda mostly occurs in fractures in the crystalline basement rocks and at the interface between the overburden and bedrock. The study was aimed at improving the success rate of boreholes through the use of complimentary geophysical siting procedures in 16 locations in Kamuli District, eastern Uganda. Boreholes that were sited after applying appropriate geophysical techniques yielded adequate quantities of water, whereas those sited where such procedures were not applied were out of service sooner than expected. Techniques to determine the precise location of resistivity anomaly and vertical electrical sounding (VES) models were used to locate water-bearing zones. VESs were undertaken to provide an overview of the geology. The apparent resistivities of the water-bearing zones both from VES and resistivity profiling data, had a relationship with the success rates of the boreholes. Electrical resistivities were correlated with hydrogeological parameters. The majority of successful boreholes had, within water-bearing zones, minimum apparent resistivity values less than 200 and 100 Ohmm, from the resistivity profiling anomalies and VES, respectively. The depth to bedrock was generally greater than 20m below ground level, which indicates potential for medium yielding boreholes.

Keywords Vertical electrical sounding · Geophysical methods · Groundwater exploration · Hydraulic properties · Uganda

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A. Batte (✉) · A. Muwanga · M. Owor
Department of Geology,
Makerere University,
P.O. Box 7062, Kampala, Uganda
e-mail: abatte@sci.mak.ac.ug
Tel.: +256-775-929921

P. Sigrist
GEO-RED Ltd.,
P.O. Box 71886, Kampala, Uganda

Introduction

The investigation was carried out in 16 locations (indicated as borehole locations) in Kamuli District, eastern Uganda (Fig. 1) with the objective of improving the certainty of locating successful boreholes in the district through the use of complementary geophysical siting procedures. Existing information (Aquatec Enterprises Uganda Ltd., unpublished data, 2003; GKO Trading Ltd., unpublished data, 2004) shows that many of the communities in Kamuli District are of limited spatial extent or are located where there is an absence of sand and gravel aquifers, which are favourable for constructing high-yielding boreholes. Boreholes that were constructed in the district after applying appropriate techniques yielded adequate quantities of water. Boreholes where these procedures were not followed due to high capital cost to the communities or preferred user locations among other factors had low yields and were out of service sooner than expected. Patton (1990) pointed out that the use of only one method was more vulnerable to errors linked to a particular method than studies that used multiple methods in which different types of data provide cross-data validity checks. Therefore, a proper desk study, the use of existing data, resistivity profiling and sounding procedures has been implemented to ascertain the reliability of the wells sited. Most of the district lies within the Victoria Nile catchment, downstream of Lake Victoria and discharges into Lake Kyoga. Kamuli District covers an area of 4,403 km^2, 23% of which is occupied by water (J. Okedi, National Environment Mangement Authority, unpublished data, 1998). The district lies at an average altitude of 1,083 m above sea level with distinct undulating wide ridges in the south but a generally gentle slope or flat terrain in Kidera towards Lake Kyoga to the north. A number of wide valleys with perennial rivers flow northwards, most of which are swampy. The consequence of the presence of a large wetland/swamp area in Kamuli District is the modification of what would otherwise be a continental climate similar to that of the Karamoja region (northeastern Uganda). The district experiences a bimodal type of rainfall with peaks in the main rainy season in March–June as well as in August–November with the main dry season experienced from December–March, and a shorter one during the June-July period. The predominant

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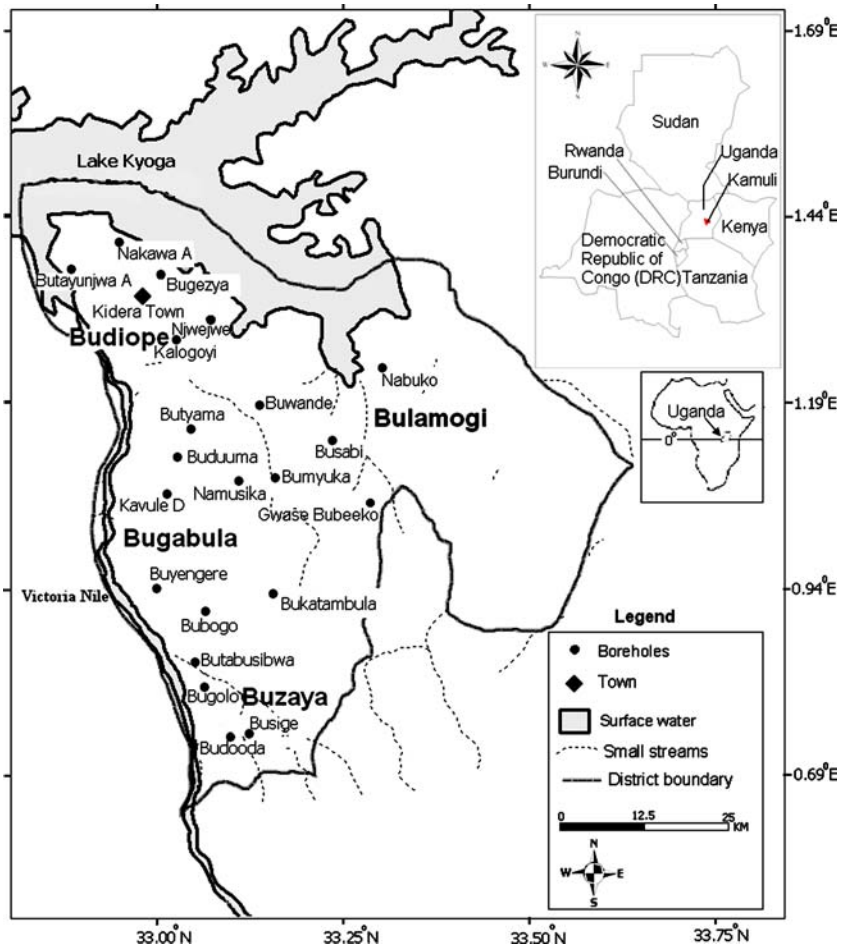

Fig. 1 Location of study areas in Kamuli District, eastern Uganda

soils in the district are dark brown clays (grumosolic soils; Regional Soil Conservation Unit, unpublished data, 1997; Lands and Survey Department, unpublished data, 1959). Bugabula and Buzaya counties have deep sandy loams of high to medium fertility, which progressively change into shallow sandy loams of medium to low fertility in Budiope and Bulamogi counties. The soils are underlain by Precambrian rocks of the basement complex. These rocks are mostly exposed in remote areas and have been subjected to a long history of overprint and alteration. The basement complex of Uganda, which is part of the Archean Congo craton, occupies most of the country; the metamorphic grade varies mainly between amphibolite (dominant) and granulite-facies (Geological Survey and Mines Department, unpublished data, 1966). Groundwater generally occurs in the weathered basement, or regolith, and in the fractured rock. The yields of many boreholes in the district are low (not more than 0.4 m^3/h) and the potential for groundwater is apparently poor because of the unfavorable geomorphologic and geological conditions. Traditionally, boreholes have been drilled into the bedrock to tap the fractured crystalline rock aquifers where replenishment is provided by the overburden aquifers. Recharge of the shallow aquifers, found in the overburden or in the fractured upper part of the bedrock, is generally dependent on the size of the catchment area and the lithological character of the overburden. The presence of weathered and fractured quartzites and granites, generally associated with weathered zones, may enhance the chances of high yielding boreholes. In the overburden, the aquifers are predominantly clayey sand with limited groundwater potential. Most of the water is, however, encountered at the interface between the regolith and the fractured bedrock (Aquatec Enterprises Uganda Limited, unpublished data, 2003; G.K.O. Trading Ltd., Water and Sanitation Development Programme, unpublished data, 2004). The regolith thickness is highly variable depending on the topography of a particular area but ranges from 20–50 m and consists mainly of laterites, clay, and sandy-clay with some gravel. The boreholes drilled in the regolith have yields ranging from 1.0–1.5 m^3/h with an average yield of 1.35 m^3/h. The electrical resistivities of the encountered aquifers in the district vary between 1,300–3,000 Ohm-metres (Ohmm) for the fractured basement, 80–180 Ohmm for the weathered rock, 180–250 Ohmm for the fractured quartzites, and 50–300 Ohmm for the sand layer.

Materials and methods

The study included assessing existing reports from the area and topographic (1:250,000), soil (1:250,000) and geology maps (1:250,000; Lands and Survey Department, unpublished data, 1963; Lands and Survey Department, unpublished data, 1959; Geological Survey and Mines Department, unpublished data, 1966). Identification of appropriate target sites was done by means of a hand-held Garmin eTrex Summit global positioning system (GPS) receiver. Mapping of groundwater sources was carried out (existing boreholes, springs, etc), including taking note of surface features such as topography, drainage, and location of possible areas of groundwater recharge, and a general appraisal of the geology, soils and hydrological characteristics of the area was made. Aerial photographs (1:40,000) were analyzed to obtain information on the drainage, general geomorphologic and structural features as well as lithology. Fracture trace analysis of the aerial photograph that covers the study area revealed five major fractures and three minor fractures in the area and these yielded important hydrogeological information. These predominant fractures trend in a NW–SE direction. This is related to a regional folding episode which resulted in the formation of folds whose axes strike in a NW–SE direction. The minor fracture system trends in a NE–SW direction and these fractures are related to a cross folding episode (Fig. 2). The NW–SE folding episode suggests a compressive stress with the principal axis oriented in a NE–SW direction (King and Swardt 1970). Therefore, the predominant fractures that trend in the NW–SE direction are normal to the direction of the regional stress field and are likely to be poorly yielding while the minor fractures that are parallel to the direction of the regional stress field are likely to be high yielding. Borehole yields depend largely on the presence of these fractures in which relatively large volumes of water are stored. During the resistivity profiling exercise, it was these fractures that were being targeted.

Sixteen geo-electric line profiles implementing the ‘precise location of resistivity anomaly’ were run using a resistivimeter (ABEM Terrameter SAS 300C). ‘Precise location of resistivity anomaly’ is a technique used to accurately locate a resistivity value(s) that deviates from the background resistivity of the area. This involves keeping the electrode spacing constant but the array is

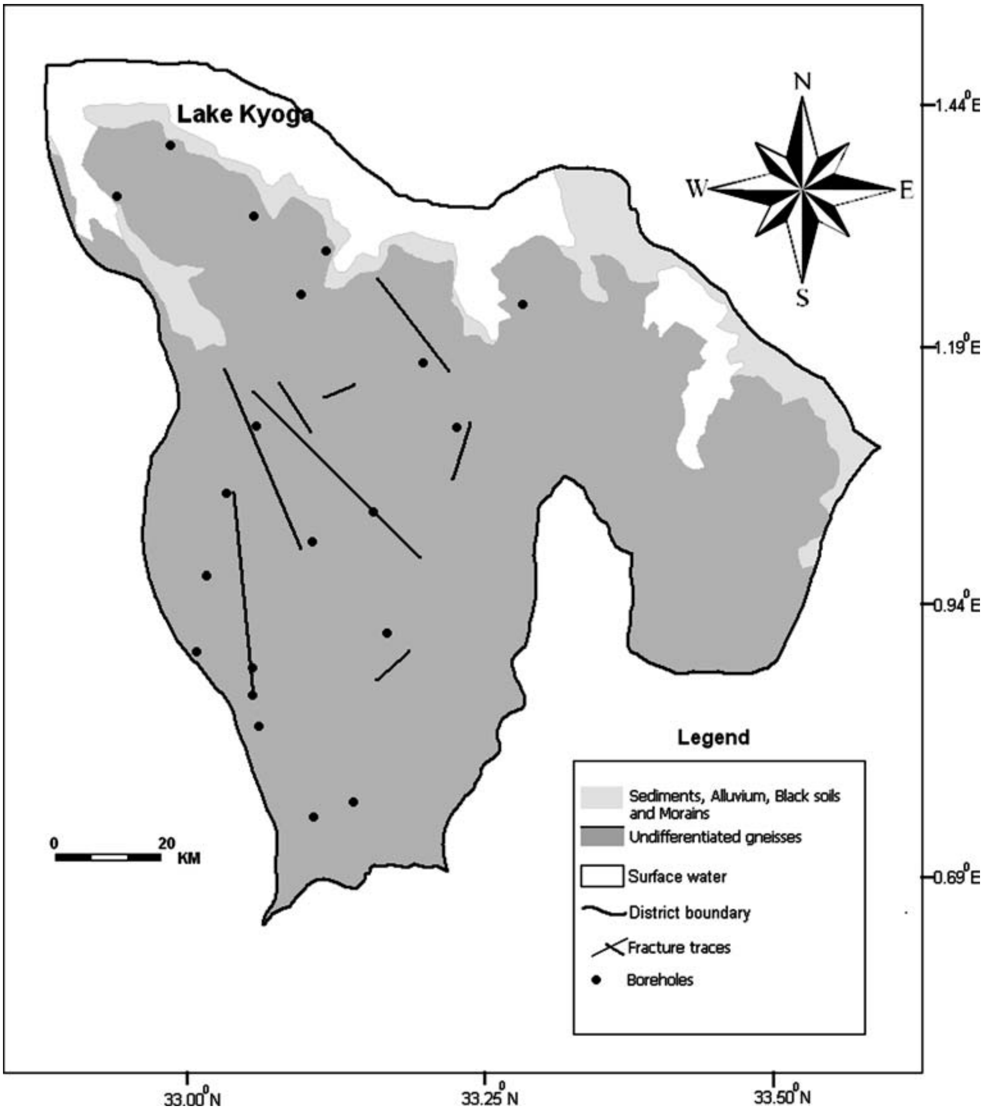

Fig. 2 Fracture traces in the study area from an aerial photograph

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moved to various points along a transect of interest (Directorate of Water Development, unpublished data, 1994). The technique requires that a small station interval (in this case 10 m) be used in order to map the anomaly. Fig. 3 shows the Schlumberger array used. Four electrodes were placed along a straight line on the ground surface in the same order as in the Wenner array, AMNB, but with AB≥MN. For any linear, symmetric array AMNB of electrodes, the resistivity ρ is give by: (Zohdy et al. 1974)

$$\overline{\rho} = \pi \left[\frac{\left(\frac{\overline{AB}}{2}\right)^2 - \left(\frac{\overline{MN}}{2}\right)^2}{\overline{MN}} \right] \frac{\Delta V}{I}$$

However, if MN→0, then the above equation can be written as

$$\overline{\rho} = \pi \left(\frac{\overline{AB}}{2}\right)^2 \frac{E}{I}$$

where $E = \lim\limits_{MN \to 0} \frac{\Delta V}{MN}$

ρ = apparent resistivity, AB = distance between the current electrodes (metres), MN = distance between the potential electrodes (metres), ΔV = potential difference measured between the potential electrodes (volts), E = electric field (volts per metre, V/m) and I = applied current strength (milliampere, mA).

A profile configuration of 10/90 (i.e. 10 m for 1/2 MN and 90 m for 1/2 AB) was initially used (AB = 180 m, MN = 20 m, I = 10 mA). An increase in the success rate of the boreholes was achieved by using simple geophysical investigations to target the thickest zones of weathering. The vertical electrical soundings (VES) were based on the modeling of the resistivity properties of horizontally layered ground by measuring the apparent resistivities at the surface using a geometric factor k expressed by the equation below.

$$k = \pi \frac{[(AM) \times (AN)]}{MN}$$

where, AM = distance between the first current electrode and first potential electrode (meters) and AN = distance between the first current electrode and second potential electrode (metres).

The principle is that current was introduced into the ground by means of two current electrodes and the potential drop between a second pair of electrodes (potential electrodes) placed in line in between the pair was measured. A proportion of the current penetrated deeply into the ground and the depth of penetration increased with increasing electrode spacing. In heterogeneous ground in which there exists a vertical variation in resistivity with depth, the apparent resistivity rather than the true resistivity is measured. The flow of the current in such ground is influenced by the density, porosity and salinity of the fluid contained in the ground (Mohammed et al. 2007). For some localities, parallel profiles were conducted, at a 30 m separation from the original profile, traversing in the same direction in order to confirm the anomalies obtained on the original profile. This was done in order to ascertain the strike of the inferred geological structure. This helped in the alignment of the VES array, which should preferably be parallel to the strike of the lineament (Fig. 4) based on the fact that the technique is used to obtain measurements of apparent resistivity along the vertical section, thereby allowing geological boundaries to be identified. A VES array is an ordered arrangement of electrodes about a resistivimeter to simulate the characteristics of the ground in terms of the thickness of individual layers together with their respective apparent resistivity values along vertical profile. This requires that the array is centered at one location with measurements being made for incremental increases in electrode spacing. The rationale of applying this technique is to obtain measurements of apparent resistivity along the vertical section, thereby allowing geological boundaries to be identified. A maximum 1/2 AB of 120 m was used with a 1/2 MN of 0.5 and 5 m. Three VES spots were selected for each of the 16 localities from which the best site for drilling was chosen depending on the geophysical analysis and accessibility of the sites by the drilling team. The down tool hammer method was employed during the drilling procedure. Lithological borehole samples were collected at intervals of 1 m. Yield estimates were made for all the measurable water strikes using a bucket of known volume (10 L) and a stopwatch every time a new strike of water was observed during the drilling. The water level in the borehole was allowed to stabilize first before pumping tests were begun. An electrical submersible pump (Grundfos SP3A-30) was installed into the borehole and positioned several metres below the deepest water levels expected during the test. Water level measurements were made using an electrical groundwater level meter—Comet-Anschlubspan Gardena (24V). The wells were constantly pumped until the drawdowns stabilized and then recovery was monitored over a similar period to that of pumping.

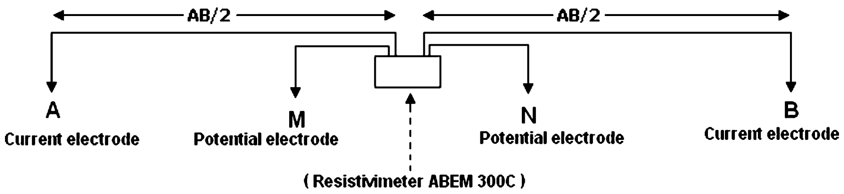

Fig. 3 The Schlumberger configuration

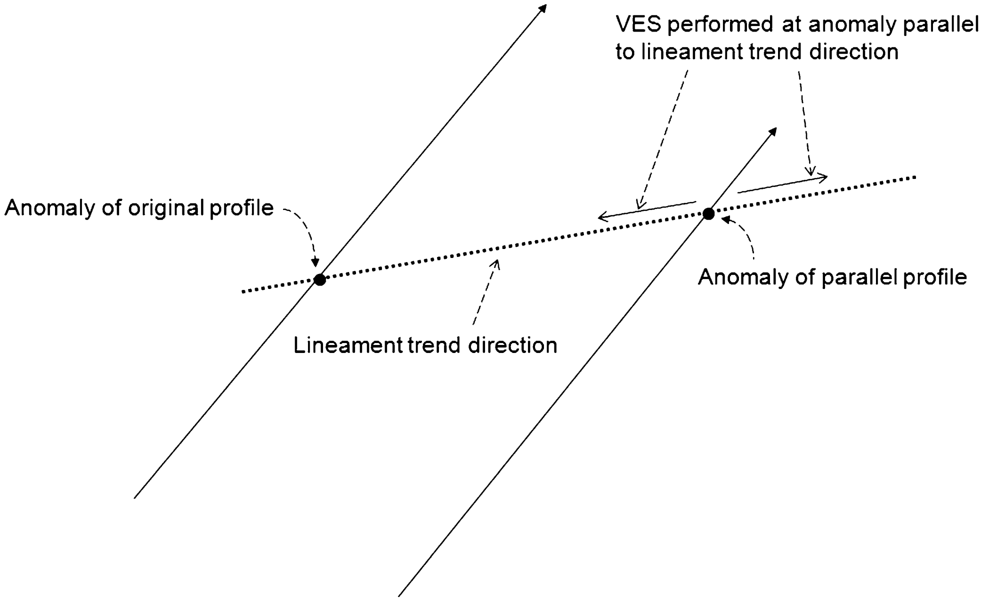

Fig. 4 Showing how the trend of the linear structure can be obtained in order to align the VES

Results and discussion

Geo-electric line profiles are presented as original (solid line) and corresponding parallel (dotted line) profiles where traverses were made in order to intersect the underlying water-bearing geological structures. Plots of apparent resistivity with the distance traversed for different sites are given in Fig. 5a and b. Where the water-bearing structures were intersected is reflected by an anomaly. According to existing reports, the anomalies that depict water-bearing zones in the area are negative anomalies with apparent resistivities ranging between 50–250 Ohmm. It is at these anomaly spots that VES were performed. VES were performed to simulate a one-dimensional depth profile of resistivity beneath the midpoint of the survey. Log-log plots of apparent resistivity against $\frac{AB}{2}$ were made (Fig. 6a and b). The advantages of the log-log plot are that it emphasizes near-surface resistivity variations and suppresses variations at greater depths simply because interpretation of the results depends largely on the small variations in resistivity occurring at shallow depths. Additionally, if at two different sites the resistivities of the underlying layers (or their thicknesses) increased or diminished by the same constant multiple, the two resistivity curves would look alike, although they may be shifted horizontally or vertically with respect to one another. Mohamed (1975) reported that the basement complex or the presence of an electric basement was readily determined on the log-log plot by a 45° sloping straight line.

Relationship between lithology and electrical resistivity

The electrical properties of rocks depend on composition (bulk properties of the constituents), micro structure (geometrical arrangement of the constituents) and interfacial effects (Ruffet et al. 1995). The alteration of cracks and pores in rocks produces a local reduction of the strength of the electric field in the vicinity of the mineral surface (surface conductivity) (Revil and Cathles 1999; Ruffet et al. 1995) which modifies the contribution of the interfaces to the total electrical conductivity. In low permeability environments controlled by secondary and accessory minerals (e.g. clay minerals), electrical properties are significantly affected by surface conductivity (Perrier and Froidefond 2003). Therefore, there is no direct connection expected between the electrical resistivity and permeability of the aquifer materials. In many of the cases in this study, the suitability of a site for a borehole largely depended on confirmation of the thickness of the regolith and fractured bedrock. It is therefore important that the inferred depth to bedrock from the sounding should be close to that found during drilling. White et al. (1988) showed that most soundings gave depth to the bedrock within ±25% of that indicated by drilling. If allowance was made for the difficulty in identifying this depth accurately during drilling, especially where there were very large boulders within the regolith, then this assumption was adequate for siting decisions. In order to assess the potential of a site before drilling, the minimum thickness of regolith that could be inferred from a resistivity sounding was generally given. Significant improvements in the interpretation of the depth to bedrock as determined by the soundings could always be achieved after controlled logging from drilling became available. Figure 7 shows an average borehole log that consists of eight different types of geological formation together with their respective apparent resistivity values. Telford et al. (1976) came up with approximate average resistivity values associated with rocks and water types in the basement complex layers that were obtained from VES data (Table 1).

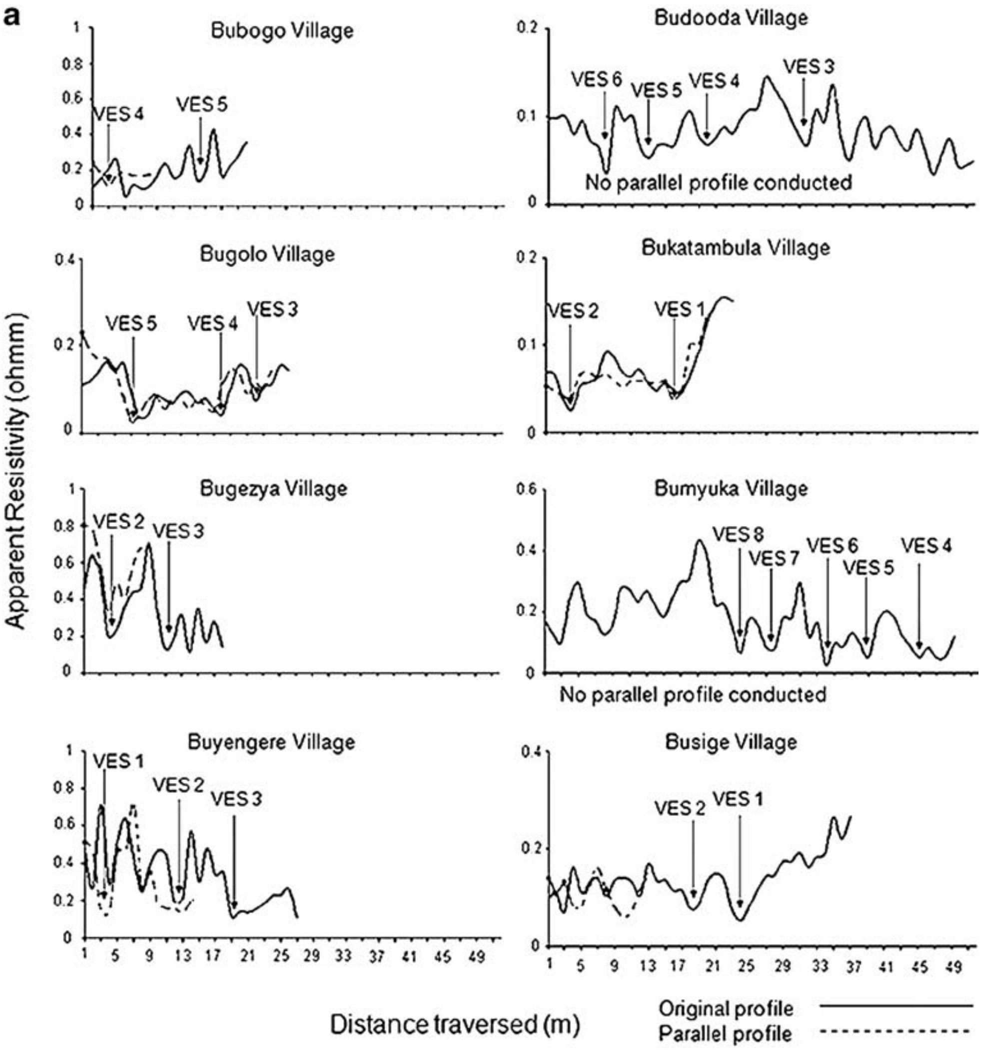

Fig. 5 **a** Curve characteristics of the original and parallel geophysical profiles for some boreholes. **b** Curve characteristics of the original and parallel geophysical profiles for some boreholes

The discrepancy in the number of layers obtained from the log and VES data, however, is due to the large contrast in resistivity between bedrock and regolith which often masks the presence of suppressed layers of intermediate resistivity, representing fractured bedrock that often contains significant quantities of water, encountered on drilling (Ghosh 1971). The aquifer system is partly composed of lake sand layer and the highly fractured weathered granites. Among the geological formations overlying the aquifer system, the clay layer displays the lowest resistivity range. Clay minerals have a high cation exchange capacity and because of their proportion in weathered crystalline rock terrains, yield a low electrical resistivity. This is because of the effect of the so-called surface conductivity which corresponds to an electrical conduction mechanism located in the close vicinity of the pore water/mineral interface in the electrical double layer coating the mineral-water interface (Revil and Leroy 2001). The electrical double layer contributes to the enhancement of the electrochemical properties of clay minerals (Leroy and Revil 2004). The lake sand formation within the aquifer system had a slightly higher resistivity range compared to the weathered and the clay formations because of the water between the sand grains that picked up only small amounts of charged ions from the very small surface area of the sand grains and enabled it to acquire a slightly lower ionic conductivity resulting in a relatively higher electrical resistivity. The low resistivity of the mineralized water between the sand grains almost completely overshadowed the higher resistivity of the lake sand formation. The fractured altered basement in the aquifer system had the lowest apparent resistivity. Weathering processes lead to the dissolution of the unstable minerals within the granite basement resulting in a highly conductive solution and, hence, a lower apparent resistivity. Below the water-bearing formations was the slightly fractured basement (granitic gneiss) with a very high resistivity range which was ascribed to the fact that granite

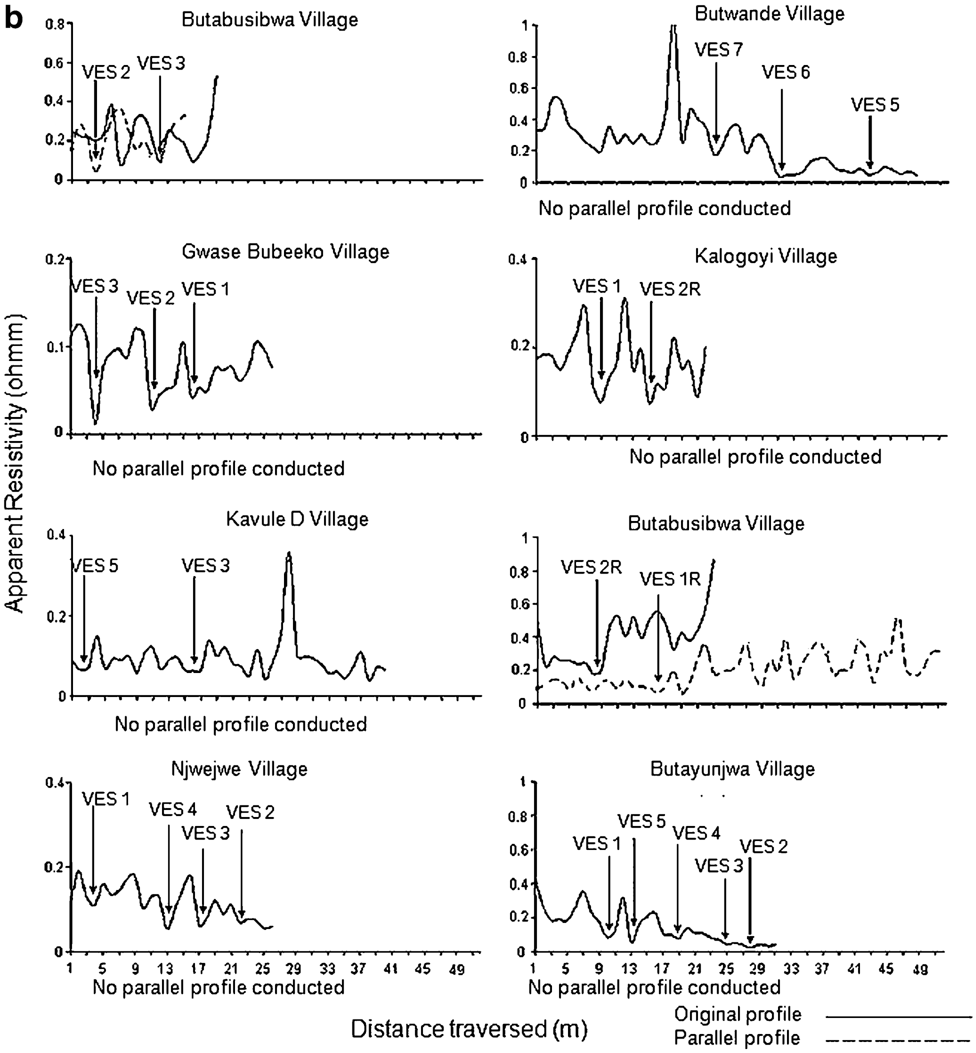

Fig. 5 (continued)

is mostly composed of very highly electrically resistive minerals which impede the flow of current through it such that the current is reflected away the instant it strikes the hard rock surface. A comparison of depth to bedrock gave 45 and 33 m for VES and well logs data, respectively, with a ±36% error. In contrast, the findings of White et al. (1988) were that the depth to bedrock was 33 m from borehole log data, and VES gave a range from 25–41 m with a ±25% error. This demonstrates that VES results have varying margins of error that cannot solely be depended upon to provide definite depths to bedrock. Limitations are inherent in the VES model data that assumes homogeneous and semi-infinite layers, characteristic of sedimentary areas. Using the same models in areas with sometimes extremely variable thicknesses and where the top of the bedrock can be very disturbed should be treated with caution (Zohdy 1978). VES cannot recognize thin layers or lenses which can sometimes contain sufficient water to be suitable for village hand pumps (Kunetz 1966). The interpretation of resistivity data is ambiguous resulting in different combinations of thicknesses and resistivities.

Without a priori knowledge of the exact number of layers constituting the geoelectric section, it is customary to assume a number of layers ranging between three and six at the most. This commonly results in a geoelectric section that groups together several individual layers (Mohamed 1975). Flathe (1963) showed that in layered formations, lower layers are detectable only if the near surface layers are resistant and the conductance of the intermediate clay lenses were very high. Despite the drawbacks, the resistivity method does provide a unique measure of the longitudinal conductance of the subsurface. These views are consistent with the findings of earlier studies (Koefoed 1979) that if the various limitations are taken into account, analysis of data collected during the siting of boreholes shows that geophysical techniques can be used fairly reliably to determine regolith

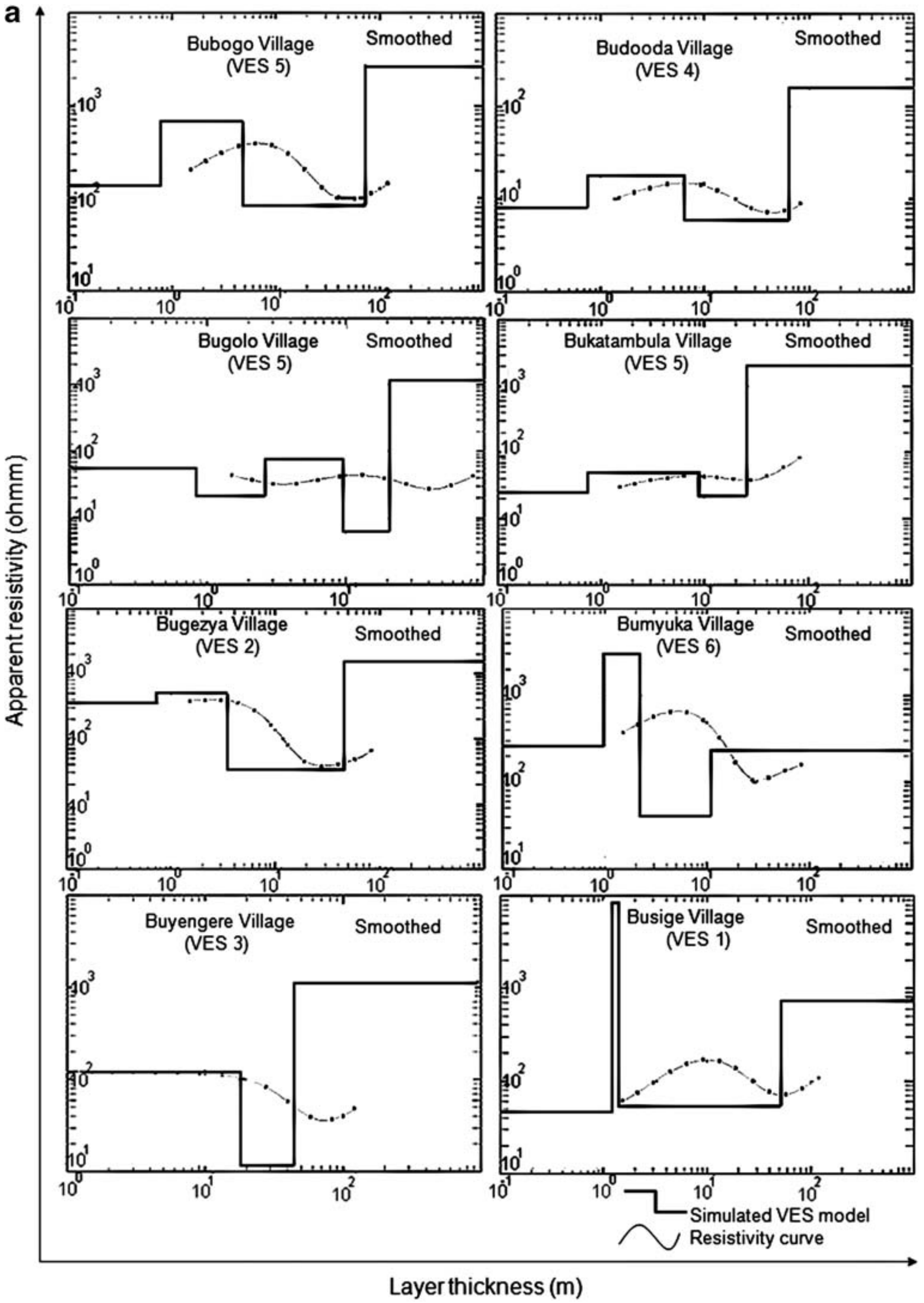

Fig. 6 **a** VES with plots of apparent resistivity against layer thickness performed in different villages at resistivity anomalies. **b** VES with plots of apparent resistivity against layer thickness performed in different villages at resistivity anomalies

thickness and provide an indication of regolith lithology. In general, resistivity can be used to identify formations with high water yielding potential.

Relationship between specific yield, hydraulic conductivity and electrical resistivity

No significant statistical correlations could be drawn between the aquifer's specific capacity, hydraulic conductivity and electrical resistivity because of the limited number of data (Fig. 8). However, both hydraulic conductivity of the aquifer and specific capacity vary inversely with electrical resistivity. McDowell (1979) reported that in the weathered basement crystalline rocks of Botswana, low yielding boreholes were characterized by generally higher resistivity levels for the intermediate layer (i.e., weathered basement/saprolite). However, the presence of clay also has an implication for borehole siting since it tends to mask any relationship between electrical resistivity and specific capacity (White et al.

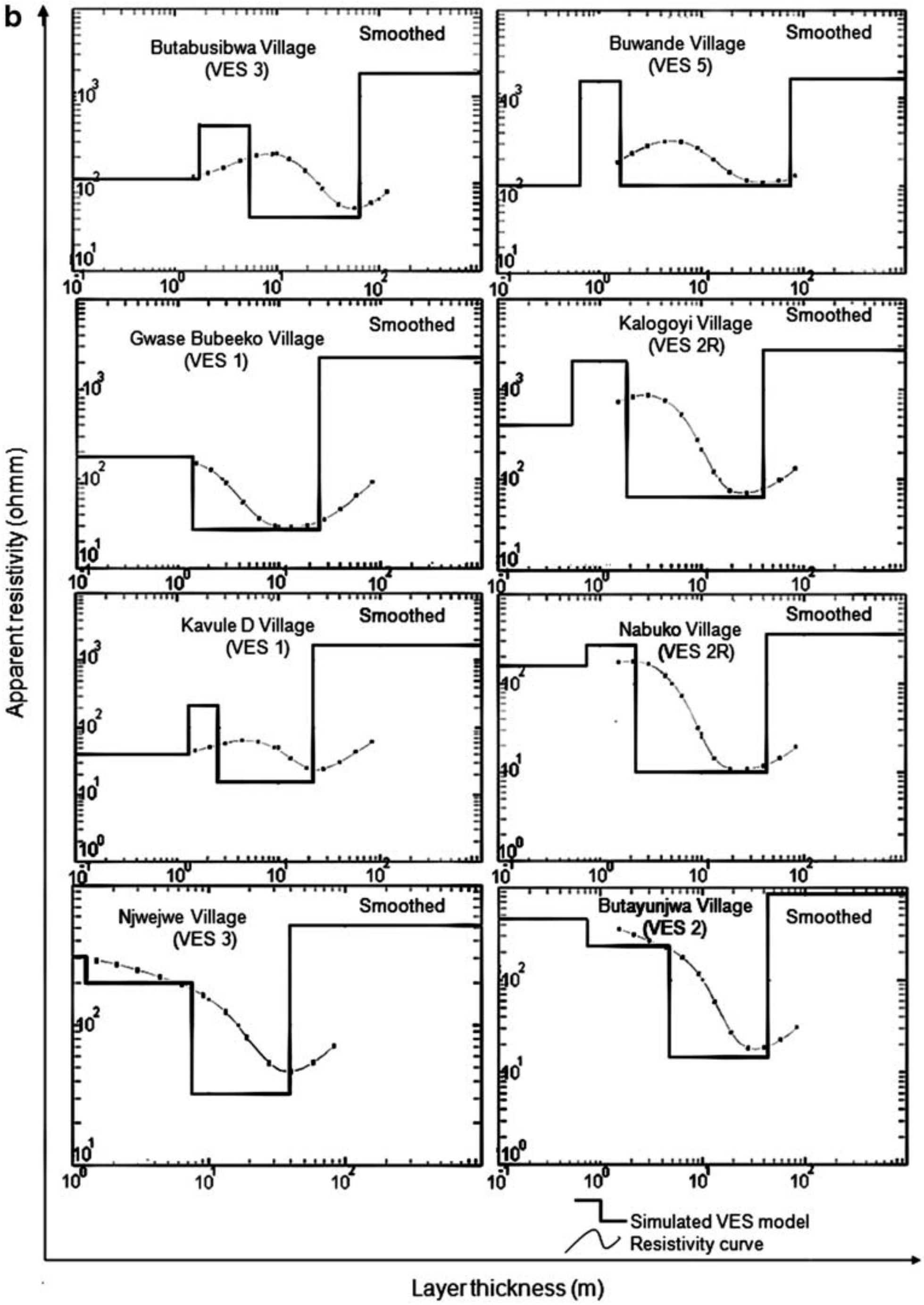

Fig. 6 (continued)

1988). The hydraulic conductivity in fractured rocks however, largely depends on the density of fracturing and the width of their aperture. Fractures can increase the hydraulic conductivity of solid rock by several orders of magnitude (Kruseman and de Ridder 1990). Ideally, the presence of water and its chemical character are the principle controls on the flow of electrical current because most rock particles offer resistance to electrical flow. Resistivity thus constrains the mostly likely places to carry out subsequent comprehensive surveys so as to improve the likelihood of striking sustainable groundwater sources.

Conclusions

It is now generally accepted that abundant groundwater reserves exist in areas underlain by crystalline basement complex rocks, common to many parts of Sub-Saharan

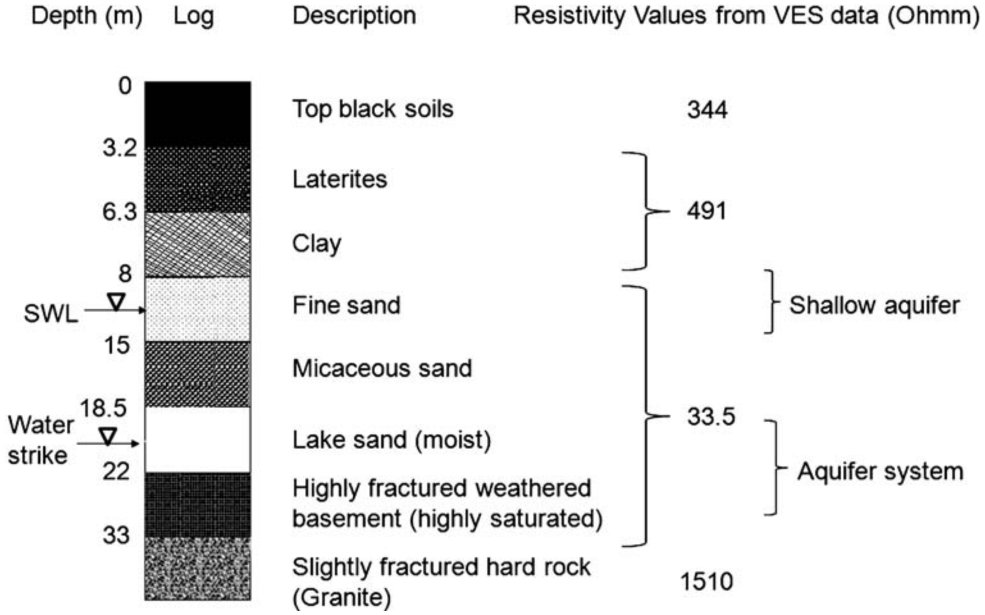

Fig. 7 An average borehole log and its corresponding apparent resistivity values

Africa. The occurrence of groundwater is highly localized and unpredictable and therefore, requires a comprehensive scientific approach in siting boreholes. Currently, there is a clear drive for the use of a combination of complimentary geophysical techniques together with other groundwater processes in order to locate sustainable groundwater sources. Despite its pitfalls, electrical resistivity methods have proved to be an extremely cost effective option in the location and delineation of zones of weathering in the crystalline basement. The analysis of data from boreholes drilled in Kamuli District has shown that a priori knowledge is still vital in determining the relationship between hydrogeological regimes and electrical geophysical parameters. Resistivity techniques in particular have been shown to be rapid and relatively accurate in the location of the deeper and narrower zones which are especially important for abstraction of groundwater in the basement complex. Attempts to locate bedrock were successful where there was a clearly measurable difference in resistivity between bedrock and overburden formations. Narrow buried valleys of coarse sand and gravel that might be the only source of groundwater in some areas were not that easy to map. In summary, resistivity alone cannot provide definite information about the underlying formations in the study area; however, it has been shown to be a significant influence on constraining the location of likely groundwater sources, especially where it was not possible to carry out comprehensive hydrogeological surveys.

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Table 1 Approximate resistivity ranges for various rock and water types in the basement complex area (after Telford et al. 1976)

Rock type	Resistivity (Ohmm)
Clay and marl	1–67
Top soil	67–100
Clayey soil	100–133
Sandy soil	670–1,330
Limestone	67–1,000
Sandstone	33–6,700
Sand and gravel	100–180
Schist	10–1,000
Granite	25–1,500
Surface water (in igneous rock)	30–500
Groundwater (in igneous rock)	30–150
Weathered latelite	200–500
Fresh latelite	500–600
Weathered/fractured basement rock	100–500
Fresh basement rock	>1,000

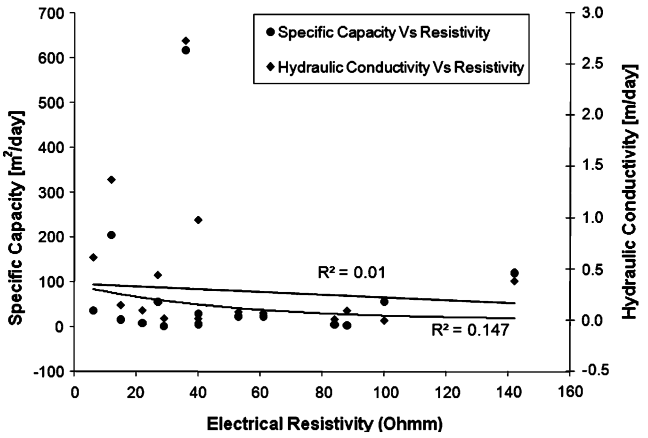

Fig. 8 A plot of specific capacity and hydraulic conductivity versus electrical resistivity

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