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Correlation of Geoelectric Data with Aquifer Parameters to Delineate the Groundwater Potential of Hard rock Terrain in Central Uganda

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Abstract—Knowledge of aquifer parameters is essential for management of groundwater resources. Conventionally, these parameters are estimated through pumping tests carried out on water wells. This paper presents a study that was conducted in three villages (Tumba, Kabazi, and Ndaiga) of Nakasongola District, central Uganda to investigate the hydrogeological characteristics of the basement aquifers. Our objective was to correlate surface resistivity data with aquifer properties in order to reveal the groundwater potential in the district. Existing electrical resistivity and borehole data from 20 villages in Nakasongola District were used to correlate the aquifer apparent resistivity (ρ_e) with its hydraulic conductivity (K_e), and aquifer transverse resistance (TR) with its transmissivity (T_e). K_e was found to be related to ρ_e by; Log $(K_e) = -0.002\rho_e + 2.692$. Similarly, TR was found to be related to T by; $\mathrm{TR} = -0.07T_e + 2260$. Using these expressions, aquifer parameters (T_c and K_c) were extrapolated from measurements obtained from surface resistivity surveys. Our results show very low resistivities for the presumed water-bearing aquifer zones, possibly because of deteriorating quality of the groundwater and their packing and grain size. Drilling at the preferred VES spots was conducted before the pumping tests to reveal the aquifer characteristics. Aquifer parameters (T_o and K_o) as obtained from pumping tests gave values (29,424.7 m^2/day, 374.3 m/day), (9,801.1 m^2/day, 437.0 m/day), (31,852.4 m^2/day, 392.9 m/day). The estimated aquifer parameter (T_c and K_c) when extrapolated from surface geoelectrical data gave (7,142.9 m^2/day, 381.9 m/day), (28,200.0 m^2/day, 463.4 m/day), (19,428.6 m^2/day, 459.2 m/day) for Tumba, Kabazi, and Ndaiga villages, respectively. Interestingly, the similarity between the K_c and K_o pairs was not significantly different. We observed no significant relationships between the T_c and T_o pairs. The root mean square errors were estimated to be 18,159 m^2/day and 41.4 m/day.

Key words: Basement complex, transverse resistance, hydraulic conductivity, groundwater, electrical resistivity methods, Uganda.

1. *Introduction*

Relationships between aquifer characteristics and electrical parameters of the geoelectrical layers have been studied and reviewed by many authors (Kelly, 1977; Niwas and Singhal, 1981; Onuoha and Mbazi, 1988; Mazac *et al.*, 1985; Mbonu *et al.*, 1991; Huntley, 1986). The hydraulic characteristics of subsurface aquifers are important properties for groundwater evaluation, contaminated land assessment, and safe construction of civil engineering structures. The most common in-situ tests for calculation of real water supply and the indirect estimation of hydraulic conductivity in a borehole are the pumping tests performed on wells which involve measurement of the rise and fall of water level with respect to time. The water-level fluctuations with time are then interpreted to arrive at aquifer parameters. Geophysicists have realized that the integration of aquifer parameters derived from existing borehole data and surface resistivity parameters extracted from surface resistivity measurements can be highly effective, because a correlation between hydraulic and electrical aquifer properties can be possible, as both properties are related to the pore space structure and heterogeneity (Kelly, 1977; Mazac *et al.*, 1985; Huntley, 1986; Mazac et al., 1988; Boerner et al., 1996; Christensen and Sorensen, 1998; Rubin and Hubbard, 2005; De Lima *et al.*, 2005; Niwas *et al.*, 2006). Fluid transmissivity (T), transverse resistance (TR), hydraulic conductivity (K), and aquifer depth are fundamental properties describing subsurface hydrology. These parameters are all commonly applied hydraulic parameters in groundwater flow modeling (Freeze and Cherry, 1979; Fitts, 2002).

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Field estimations of these hydraulic parameters are not always available. As a result, many investigation techniques are commonly employed with the objective of the estimation of the spatial distribution of these hydraulic parameters. Hydraulic conductivity seems to be the most problematic to obtain because of either the great range of observed values or the unsatisfactory laboratory measurements (ZECHARIAS and BRUTSAERT, 1988; MENDOSA *et al.*, 2003). The application of field hydrogeological methods of assessment is a standard technique for evaluating aquifer properties. Estimation of K and T values from field pumping tests and down-hole well-log data can, however, be very expensive and time-consuming. In this context, surface geophysical methods may provide rapid and effective techniques for groundwater exploration and aquifer evaluation. Studies conducted by various researchers reveal that hydraulic parameter estimates can be obtained from resistivity measurements (BRACE, 1977; BIELLA *et al.*, 1983; BUSSIAN, 1983). The application of geophysical methods has generally proved to be very effective for water content estimation, water quality assessment, and mapping of the depth to water table and bedrock (HUBBARD and RUBIN, 2002). Geophysical studies (FLATHE, 1954; MEIDAV, 1960; VAN DAM and MEULENKAMP, 1967; VINCENZ, 1968; ZOHDY 1969; SERRES, 1969; VAN OVERMEEREN, 1981; STEWART *et al.*, 1983; ARAFIN and LEE, 1987; ARAFIN, 1988; VAN OVERMEEREN, 1989; VAN KUIJK *et al.*, 1985) show ample evidence of the successful use of the resistivity method in groundwater prospecting in alluvial deposits. Success has also been achieved using the resistivity method for siting wells in areas underlain by hard rock terrains (BALLUKRAYA, 2001; GUPTA *et al.*, 2000; PATANGAY *et al.*, 1977; SATPATHY and KANUNGO, 1976). MAZAC *et al.*, (1985) analyzed the correlation between aquifer and geoelectrical parameters in both the saturated and unsaturated zones of the aquifers. The use of Schlumberger electrical resistivity techniques, that is; 1D inversion of geoelectrical sounding (VES) and horizontal resistivity profiling (HRP) have become very common in groundwater exploration and contamination studies whereby there exist standard published direct and indirect interpretation techniques specifically for VES data (cf. JUPP and VOZO, 1975). VES surveys are usually designed to measure the electrical resistivity of subsurface materials and to discriminate between anomalies which are indicative of subsurface electrical resistivity contents associated with lithologic and/or hydrologic characteristics (DENAHAN and SMITH, 1984; SENOSY, 1997) by making measurements at the earth's surface. Its inherent capability is to detect changes in electrical conductivity of subsurface layers that reflect the fluid content of such layers (JAKOSKY, 1950; WEAVER, 1929). VES is suitable for determination of the depth, thickness, and boundary of an aquifer (ZOHDY, 1969; YOUNG *et al.*, 1998), the water content of the aquifer (KESSELS *et al.*, 1985), and K of the aquifer (YADAV and ABOLFAZLI, 1998; TROISI *et al.*, 2000), T of the aquifer (KOSSINSKI and KELLY, 1981), and specific yield of the aquifer (FROHLICH and KELLY, 1987). However, the method has its own limitations, especially if ground inhomogeneties and anisotropy are present (MATIAS, 2002).

This study attempts to reveal the aquifer properties using surface electrical resistivity data of the hard rock terrain in Nakasongola District, central Uganda (Fig. 1). The investigation was conducted in three villages of the district (Tumba, Kabazi, and Ndaiga). Much of the Nakasongola terrain is relatively flat with an altitude ranging between 1000 and 1100 m.a.s.l. It has gentle rises which are separated by swamps, valleys, and seasonal rivers that contain water, or even flow, during the rainy seasons but progressively dry out during the dry season of the year. The district is found in a poorly mapped area of Uganda where it overlies an assemblage of rocks: schists, gneisses, granites, granite gneisses, basic intrusives (basalt), amphibolites, and meta-calcareous assimilated to the Basement Complex of northern Uganda (FELS Consultants Ltd, 2003). Also found in Tumba Village are unconsolidated superficial deposits, especially near Lake Kyoga which include Pleistocene beach deposits and river alluvium derived from the weathering of the Basement Complex. The surface water sources are usually ephemeral/seasonal and prone to contamination by human beings and animals. The consequences of these pathetic situations on the water-supply systems of the people of Nakasongola are the prevalence of such water-borne diseases as guinea worm, cholera, and typhoid fever. As a contribution to improvement and development of water resources in this region, our investigation is necessary to gain valuable information about the groundwater potential in the rocks of the crystalline basement.

2. Methods and Materials

In our study, we investigated the relationship between existing surface and down hole data from 20 different locations in Nakasongola District (Fig. 1). Information on aquifer thickness (h) was extracted from borehole logs. To clarify on our interpretation, we assumed a horizontal one-layer aquifer system of uniform h. Thereafter, we correlated aquifer parameters (K_e and T_e) of existing borehole data with corresponding surface electrical resistivity data (ρ_e and h_e).

The objective of these correlations was to obtain empirical relations with which we would be in a

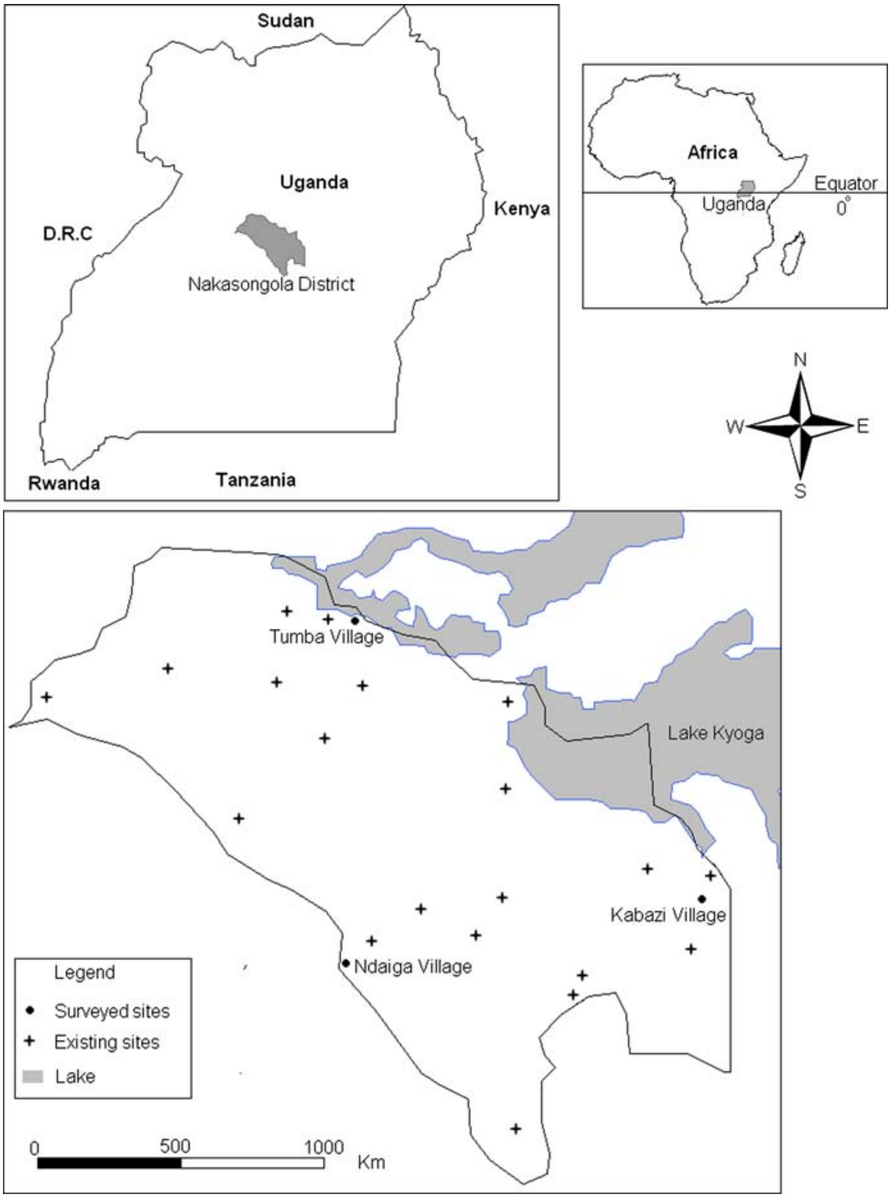

Figure 1
Geographic location of our study areas

position to extrapolate aquifer parameters using surface resistivity measurements. We proceeded to conduct surface resistivity measurements in the three proposed villages. Prior to the resistivity surveys, we conducted preliminary investigations. These involved detailed study of existing groundwater reports and geological maps about the areas. Because the occurrence and yield potential of groundwater sanctuary are basically controlled by the geology, geomorphology, and structural setup of an area, it is important to target the groundwater potential zone before any planning for groundwater development. The aerial photographic technique has proven an indispensable tool for groundwater targeting in hard rock areas, because the topographic expression and terrain characteristics have a direct relationship to the geological characteristics of rocks and their structural setup. We therefore traced fractures on aerial photographs (1:40,000) to locate the presence of deep faults in the hard rock which are representative of groundwater reservoirs. We suspect the groundwater in the district to be structurally controlled. One of the greatest advantages of using the aerial photographic technique for hydro–geological investigation and monitoring is its ability to generate information in the spatial and temporal domains, which is very crucial for successful analysis, prediction, and validation (Saraf, 1999). Information about the orientation and location of fractures in the study area are made available for detailed groundwater resistivity mapping. Although various geophysical techniques are currently being used to explore and assess water resources (e.g. the gravity method (Ali and Whiteley, 1981), the seismic method (Geissler, 1989), the electromagnetic ground conductivity method (Palacky *et al.*, 1981; Van Lissa *et al.*, 1987), the geoelectrical section method (Stewart *et al.*, 1983), resistivity imaging methods (Ioannis *et al.*, 2002), conventional VLF and VLF resistivity methods (Poddar and Rathor, 1983); electrical and magnetotelluric surveys (Quarto and Schiavone, 1994), and electrical resistivity tomography (Ritz *et al.*, 1999)), the electrical resistivity method still proves the most powerful. We selected this method for our research because the instrumentation is portable, inexpensive in terms of logistics, straightforward, analysis of the data is less tedious and is economical (Zohdy *et al.*, 1974; Ekine and Osobonye, 1996; Ako and Olorunfemi, 1989; Batte *et al.*, 2008). We proceeded to conduct resistivity surveys in our study area using the 1D Schlumberger array. Resistivity values were obtained by two different surface exploration methods, during which we assumed that for an aquifer in our study area to be water bearing it should reflect a high electrical conductivity and, hence, low aquifer resistivity ($10 \geq \rho \leq 200$ Ωm). The first resistivity exploration technique we employed, horizontal electrical resistivity profiling (HRP), involved the use of a geophysical resistivity meter (ABEM Terrameter; SAS 300), as augmented by the precise locate the resistivity anomaly. This was done to produce a numerical picture of the subsurface material at the chosen depth across a horizontal plane and involved measurement of the resistivities of soils and rock as a function of depth and/or position. In HRP, the electrode spacing (AB and MN for current and potential electrode spacing, respectively), and thus the depth penetration of the current, remained approximately constant. The whole array was displaced in a straight line profile with measurements every 10 or 20 m. In the study, MN and AB were kept constant at 20 and 200 m, respectively, an array that allowed detection of bedrock anomalies (faults, joints) in the upper 30–60 m. Correlations of ρ against distance traversed were made. To complement the HRP resistivity exploration technique we used the VES on a series of electrical resistivity anomalies identified on the HRP. These VESs were later transferred to a vertical cross-section. By evaluating the resistivity values, an understanding of subsurface materials can be developed. This exploration method is especially useful for estimating the depth of sand, gravel, bedrock, or water-bearing strata, or for estimating the thickness of selected formations. In VES, electrodes' spacing was progressively increased, which resulted in progressively deeper penetration. The VES required that the center point of the electrode array remained fixed at the selected anomaly, but the spacing between the electrodes was increased. The h_c and ρ_c of the aquifer at various observation points were obtained by inversion of the VES data. We recommended suitable sites for drilling. The rotary down-the-hole hammer air-flush method of drilling was used, during which lithological samples at intervals of 1 m were collected. Borehole yield estimates were determined for all the measurable water strikes each time a new strike of water was encountered. Pumping tests were conducted on the yielding boreholes to reveal aquifer characteristics using an electrical submersible pump (Grundfos 15SQ15-290). The pumped boreholes were similarly used as observation boreholes. Each borehole was pumped at a rate of 1 m^3/h for 5 h followed by monitoring of the water level recovery for 1.5 h. Standard plots of water-level recovery against log time were made. The aquifer's T at each drilled borehole was estimated from recovery data. Use of recovery data is viable because recovery smoothes out any small changes in pumping rate and the errors due to well losses are minimal. Following these procedures, we extrapolated aquifer parameters (T_c and K_c) using corresponding surface resistivity data (ρ_c and h_c) derived from the three villages. Data from pumping tests (T_o and K_o) obtained after the drilling at locations in the three villages were compared with the extrapolated aquifer parameters T_c and K_c.

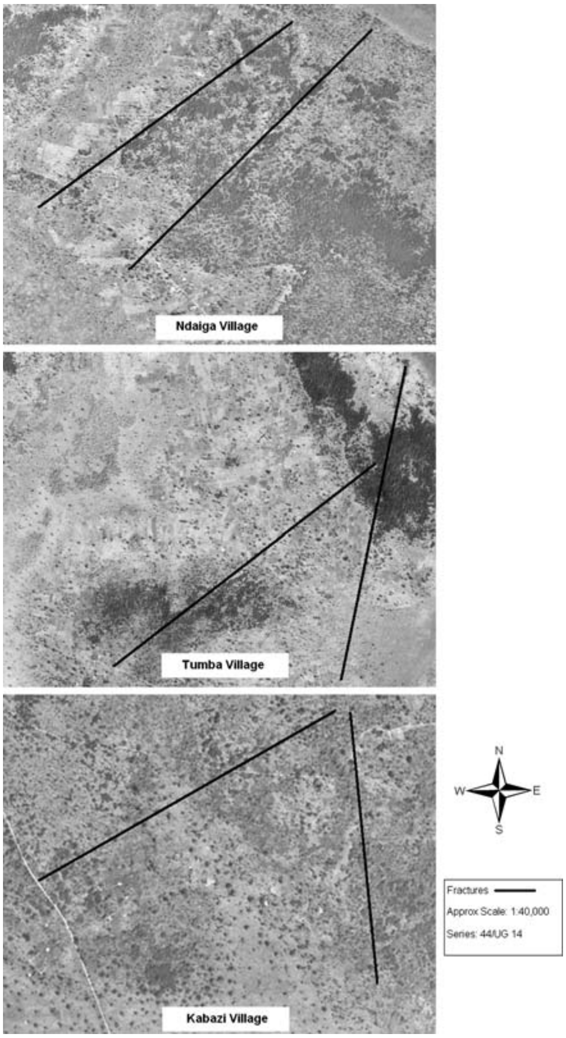

Figure 2
Fracture traces on aerial photographs that were captured over the each of the 3 villages

3. *Results and Discussion*

The key to the success of any geophysical survey is calibration of the geophysical data with hydrogeological and geological ground truth information. Fracture trace analysis of aerial photographs of our study area is given in Fig. 2. The general trend of the major fractures in the surveyed areas is in the direction NNE-SSW (20°–25°), almost perpendicular to the Achwa shear zone, a structure following a northwesterly trend for over 300 km through northern Uganda and into southern Sudan (Schlüter, 2006). These fractures probably attest to the secondary shearing episode after the major tectonic event that caused the formation of the Achwa shear zone. Charukalas and Tamblyn (1987) concluded that by using aerial photography techniques it is possible to identify geomorphologic features such as paleochannels in which the shallow aquifer is often found. Using the fracture traces on aerial photographs, detailed resistivity surveys were conducted in selected areas. This technique, in combination with ground-based resistivity measurements using Schlumberger HRP and VES methods based on the assumption of existence of horizontally layered strata, were used to obtain surface resistivity measurements of the surveyed area. HRP are presented as standard plots of ρ against distance traversed for the different sites (Fig. 3). Similarly, VES are presented as log–log plots of ρ against 0.5 AB (Fig. 4) using the Schlumberger configuration model of the prospected layers with Gosh's linear filters; this resulted in characteristic VES curves. These curves can be calculated and interpreted in terms of soil/rock layers with their different ρ and h in a particular location.

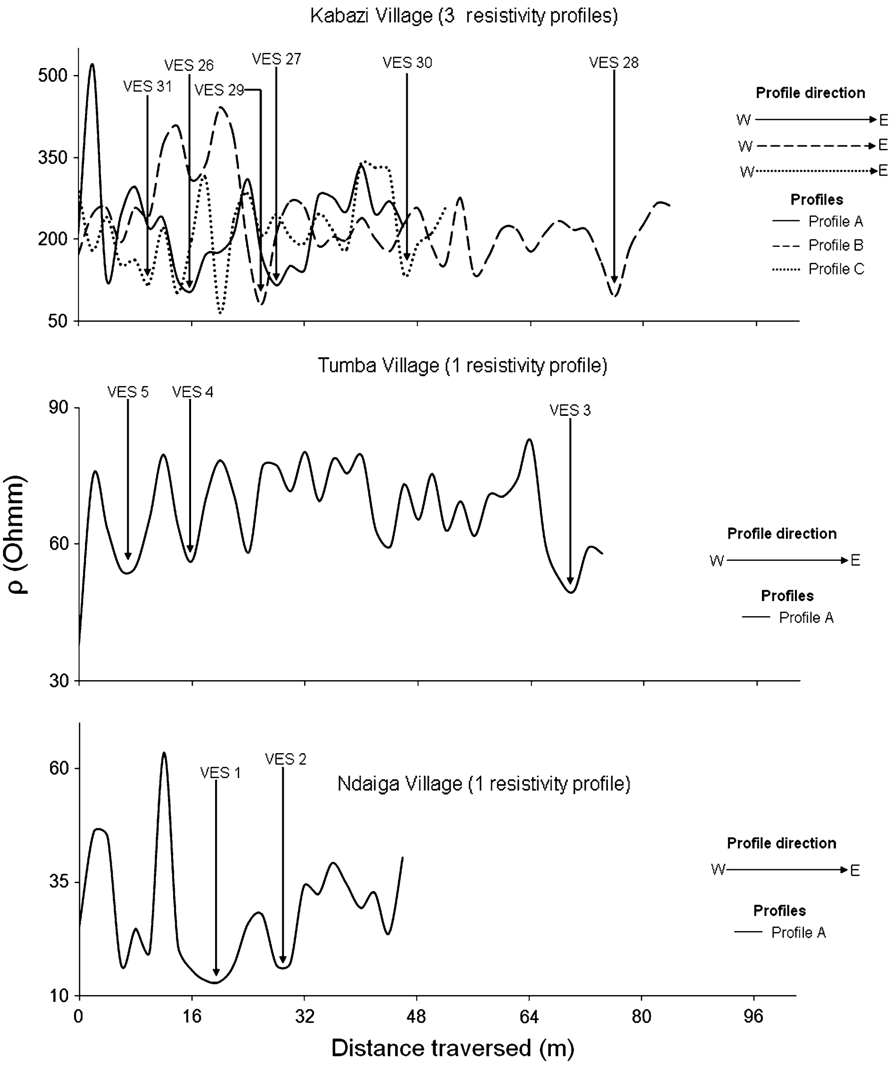

Figure 3
Resistivity plots of HRP conducted in each of the 3 villages

Roy and Elliot, (1981) concluded that the depth of investigation in a Schlumberger VES configuration typically varies between 0.25 AB and 0.5 AB. The advantages of using a log–log plot is 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 (Batte *et al.*, 2008). Our results show very low resistivity values at HRP anomalies and selected VESs. We suspect the possibility of deteriorating quality of groundwater in the aquifers besides their packing and grain size.

3.1. Correlation of Observed and Estimated Hydraulic Parameters

In porous media and alluvial aquifers, *T*, formation factors and *K* can be estimated using empirical/semi-empirical correlations, often using simple linear relations (Kelly, 1977, 1979; Heigold *et al.*, 1979; Urish, 1981; Chen and Hubbard, 2001). Plots were

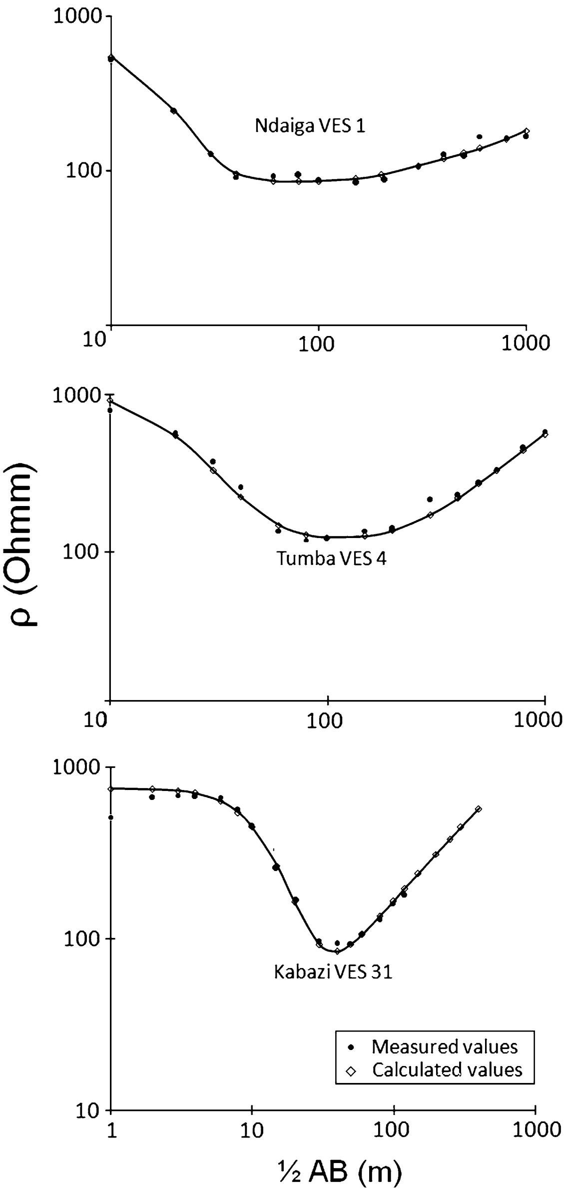

Figure 4
Resistivity plots of VES conducted at selected spots in each village

made to correlate K_e and T_e with ρ_e (Figs. 5, 6) from which empirical relations were derived. We observed an inverse correlation in both relationships. Surprisingly, in both cases K_e and T_e proved best correlated with ρ_e when linear trends were fitted. For a standard plot of log (K_e) versus ρ_e, K_e decreases with increasing ρ_e (Fig. 5; Eq. 1).

$$\mathrm{Log}(K_e) = -0.002\rho_e + 2.692 \qquad (1)$$

This expression agrees with the discussion of Singh, (2005) who suggested that the presence of hard rock lithologies may cause the negative correlation of the variation in permeability with resistivity. We proceeded to study the relationship between TR and T_e using data obtained from 20 existing villages of Nakasongola. The TR is expressed as the product of aquifer ρ_e and h_e. Similarly, the use of layer h_e, as derived from the interpretation of VES data, and K_e, calculated on the basis of both hydrogeological and geophysical data, led to the calculation of aquifer T_e. This is one of the most important parameters in electrical prospecting which defines the Dar Zarrouk parameters (Maillet, 1947). This gave a linear relationship (Fig. 6; Eq. 2);

$$\mathrm{TR} = -0.07T_e + 2260 \qquad (2)$$

The knowledge of true resistivity distribution is a fundamental source of information for establishing a hydrogeological model. A similar study was conducted using 11 data points, giving the expression:TR $= 0.19T^{1.28}$ (c.f. Soupios *et al.*, 2007). Our results, as obtained from surface resistivity measurements at the selected VES spots in the three villages, are listed in Table 1. The values in Table 1 were used to extrapolate aquifer parameters (K_c and T_c), in the studied villages using Eqs. 1 and 2, respectively. T_c and K_c values were compared with those of the observed aquifer parameters (T_o and K_o) from pumping test data obtained at the three drilled locations (Table 2). Interestingly, our results show that the K_c, K_o pairs were not significantly different. Using the empirical relationship (Eq. 2), we, however, observed no significant relationship between the T_o and T_c pairs. The aforementioned simultaneous changes are attributed to the effect of the hydraulic and electric anisotropies, variations in the lithology, mineralogy, size of the grains, and to the size and shape of the pores and pore channels. The root-mean-squared errors were calculated (18,159 m^2/day and 41.4 m/day) for T_c and K_c, respectively (Eq. 3);

$$\textit{Root mean square error} = \left\{\frac{1}{n-1}\sum_{i=1}^{n}(x_{ie}-x_{io})^2\right\}^{\frac{1}{2}} \qquad (3)$$

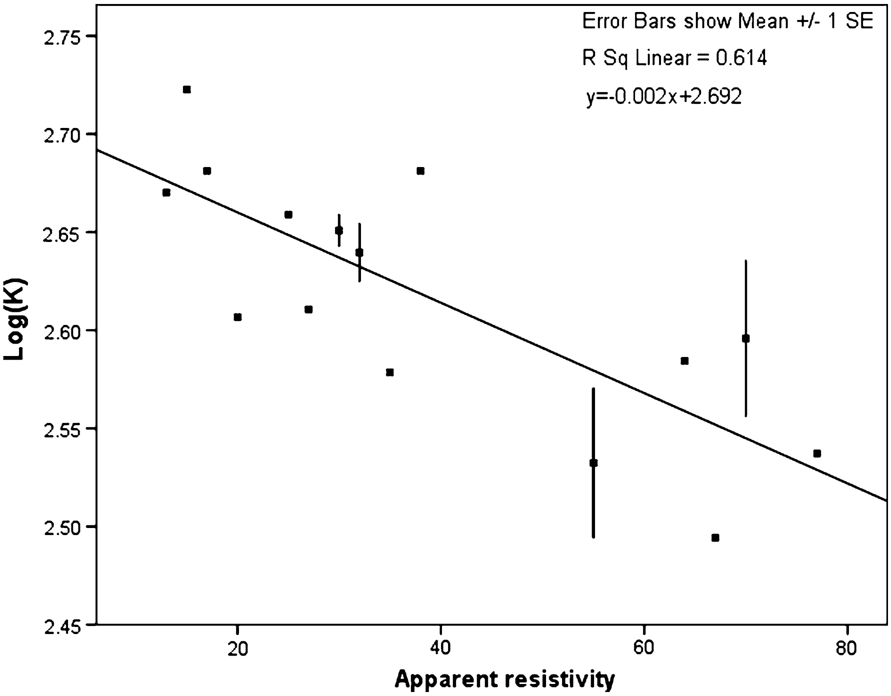

Figure 5
Standard plot of k against ρ

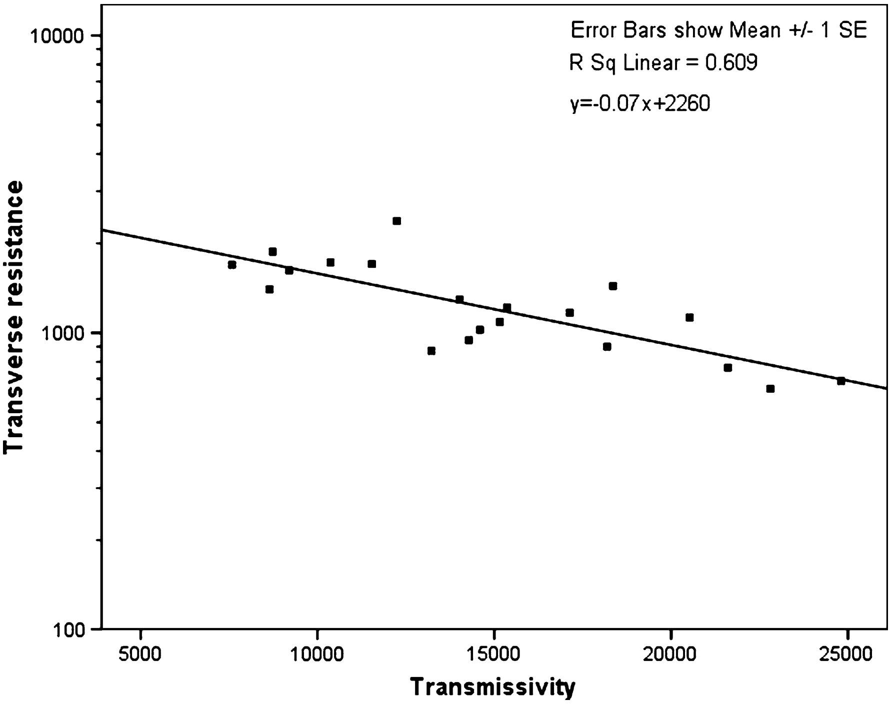

Figure 6
A semi-log plot of TR with T

Table 1

Surface resistivity measurements for the three study sites

Village	ρ_c (Ωm)	h_c (m)	TR (Ωm^2)
Kabazi	55	32	1760
Tumba	13	22	286
Ndaiga	15	60	900

Table 2

Comparison of K_c and T_c values with K_o and T_o derived from the three study sites

Estimates using Eqs. 1 and 2			Pumping test measurements	
Villages	K_c (m/day)	T_c (m^2/day)	K_o (m/day)	T_o (m^2/day)
Tumba	381.9	7142.9	374.3	29424.7
Kabazi	463.4	28200	437.0	9801.1
Ndaiga	459.2	19428.6	392.9	31852.4

where x_{ie} is the estimated value for site i, x_{io} is the observed value for site i, and n the total number of sites.

Therefore, using the empirical linear fits, there is a possibility of identifying generalized equations for the variation of K_e and T_e with ρ_e i.e. $\text{Log}(K_e) = -A\rho_e + B$ and $\text{TR} = -CT_e + D$ where $A < 0$, $B > 0$, $C < 0$, and $D > 0$. Determining T_c from surface resistivity data, especially in the hard rock terrain of Nakasongola District, was achievable with very low accuracy relative to T_o. However, obtaining K from resistivity data is a cost-effective alternative, especially for evaluation of the groundwater potential in the basement complex area of central Uganda.

4. Conclusion

In this paper, we disclose how the aquifer parameters of the Basement Complex of Nakasongola District, central Uganda vary with ρ. The application of surface resistivity exploration techniques permitted the extrapolation of aquifer parameters in the study area. This technique can be used to provide valuable information for flow modeling and recharge of groundwater, and to find suitable sites for groundwater exploration. However, before generalizing this approach, application of resistivity and aerial photographic techniques for groundwater prospecting must be taken into consideration to understand the groundwater potential of the area to be studied in terms of lithologic units and fracture traces. The agreement between K_c and T_c with K_o and T_o, respectively, emphasized the contribution of the geoelectrical methods to determination of the aquifer parameters. The study will help the planners and decision makers to devise sound and feasible groundwater development plans for water resources. The good agreement between aquifer hydraulic conductivities obtained from the resistivity soundings interpretation and those deduced from pumping test analysis emphasizes the potential of the method.

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