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Comparison of Hydrogeological and Electrical Properties of A Consolidated Sandstone Aquifer

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ABSTRACT. The main purpose of this study was to compare hydrogeological and electrical properties of a consolidated sandstone aquifer. Transmissivity and hydraulic conductivity of the aquifer were determined at fourteen sites from controlled pumping and recovery well tests in Gedaref area, Eastern Sudan. Aquifer electrical resistivity, corrected transverse resistance and apparent formation factor were obtained from vertical electrical sounding measurements carried out at the same sites of the aquifer tests. Results of the study show a linear direct correlation between the transmissivity and the corrected transverse resistance. An indirect linear correlation was observed between hydraulic conductivity and apparent formation factor. The methodology adopted for this study can be applied to different areas but not the empirical relationships.

As the need for uncontaminated groundwater grows, method for locating groundwater aquifers increase. Geophysical methods, particularly electrical techniques, have played a considerable role in groundwater exploration. Surface resistivity techniques in many cases have reduced the amount of test-drilling and, therefore, decrease the cost of operations (Kelly 1977). Measurements of aquifer resistivity are useful for estimating aquifer hydraulic conductivity (K) since both electrical and hydraulic conductivities depend on torruosity and porosity (Bear 1971). There are numerous papers and reports on the use of electrical resistivity in hydrogeological investigations, but only few have attempted to relate these measurements to hydraulic properties of aquifers. A summary of papers on the subject can be found in Kelly and Frohlich (1985) and Hussein and Ibrahim (1990).

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Few papers appeared in the literature on the correlation of transverse resistance (T_R) and transmissivity (T_S). Ungemach *et al.* (1969) correlated (T_R) in the Rhine aquifer with (T_S) derived from pumping test. Their results suggested a linear positive trend. Worthington (1977) and Jones and Buford (1951) observed a direct relationship between the two parameters from laboratory measurements. Works such as those of Duprat *et al.* (1970) and Ponzini *et al.* (1984) produced strong relationship between corrected transverse resistance (T_{RC}) obtained from vertical electrical sounding (VES) measurements and hydraulic transmissivity from pumping test.

Correlations were also attempted between apparent formation factor (AFF) and the hydraulic conductivity (K) for unconsolidated aquifers. For the few data obtained, the correlation was satisfactory but this was not the case with laboratory measurements (Kelly and Frohlich 1985 and Croft 1971). The authors are not, however, aware of any previously documented work on the correlation of the above parameters for consolidated sandstone formations.

The study area lies between latitudes 13° 35′ N and 14° 35′ N; and longitudes 35° 15′ E and 35° 55′ E. It covers a surface area of about 2000 km^2 in the Eastern Region of Sudan. Gedaref town is the center for all agricultural and economic activities of the region. More than 50% of the millet in Sudan is produced from Gedaref area. For decades rainfall and river water were the main source of water supply, but since the early seventies drought has heavily affected the region as it did for the whole arid-semi-arid belt of East Africa and together with the increasing demand traditional water sources became insufficient. As a result, efforts have been made to exploit groundwater. A number of deep wells was drilled, and although some gave adequate production rates, other failed. For this reason greater effort is needed to address groundwater exploration and well production. Taking these considerations into account the main purpose of this paper is to compare geophysical and hydrogeological properties of the main water-bearing layer and to compute some empirical relationships between them. Results of this work are expected to contribute towards reduction of expenses on groundwater exploration under similar conditions and to minimize the number of dry wells drilled in the future.

Hydrogeology

The general geologic setting of the area and the main rock units are shown in Fig. 1 and are illustrated on Table (1). The Basement Complex is the oldest rock unit. It outcrops mainly west of longitude 35° 00′ E. In Gedaref area the Basement Complex consists mainly of gneisses, schists, marbles, quartzites and granites. Mafic and ultramafic rocks occur around Qala en Nahl. This unit is impermeable and has negligible storativity and transmissivity (Whiteman 1971).

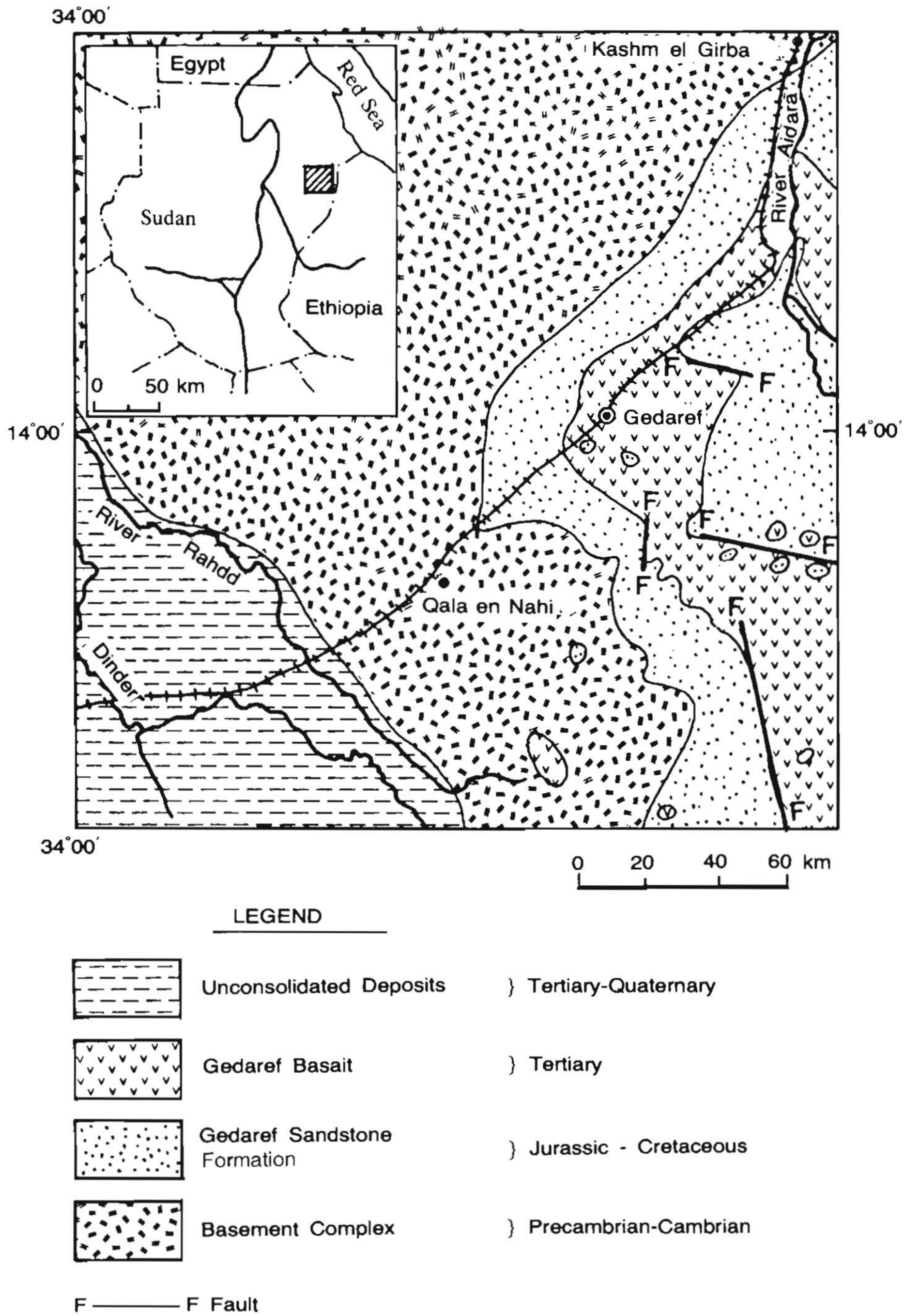

Fig. 1. A generlized geologic map of Gedaref area.

Table 1. Geologic sequence in Gedaref area, Eastern Sudan

Age	Formation	Thickness (m)	Generalized Lithologic Description
Quaternary to Recent	Surficial Deposits	< 40	Unconsolidated heterogeneous assemblage of sand, gravels and silts.
Tertiary to Quaternary	Al Atshan Formation, Cotton Soil	< 335 – 12	mainly unconsolidated deposits: Al Atshan Formation is characterized with pebbles of agate, ironstone nodules and kanker. The cotton soil consists mainly of dark cracking clays.
Oligocene	Gedaref Basalts	35 - 600	fine to very fine grained crinanites and basalts with intrusive trachyte necks and dykes.
Jurassic to Cretaceous	Gedaref Formation	60 - 2000	sandstones, siltstones, claystones and conglomerates.
Precambrian to Cambrian	Basement Complex		gneisses,. schists, granites, basic and ultrabasic rocks.

Mesozoic sandstones of the Gedaref Formation lie unconformably on the Basement Complex. This Formation consists mainly of sandstones, siltstones, claystones and conglomerates and it has been affected by Oligocene tectonic movements resulting in the appearance of normal faults within the area (Whiteman 1971 and Omer 1978). This faulting is related to major tectonic movements in Ethiopia which led to the formation of a series of horsts and grabens within the area (Mula and Omer 1983). Groundwater occurs within the Gedaref Formation at depths ranging from 50-200 m under unconfined and leaky conditions. Two major flow directions exist mainly due east and due west indicating the existence of a groundwater divided between them (Adam 1987). The hydraulic gradient varies from 1/300 to 1/125 with an average of 1/160. The main recharge of the Gedaref Formation comes from River Atbara and River Setit. Direct recharge from rainfall is restricted to outcrop areas. Groundwater obtained from the aquifer has an average total dissolved solids (TDS) of about 400 mg/1 and it is generally suitable for human, livestock and general household purposes (Adam 1987).

The Tertiary Basalts occur in the study area in the form of flows, silts and dykes. In the vicinity of Gedaref enormous flows and dykes cut through the sandstones. When weathered or highly fractured, the Basalts act as water-bearing horizons producing low quality water of total dissolved solids in the range of 1000-3000 mg/l, otherwise the Basalt flows act as confining beds for the Gedaref Sandstone Aquifer (Adam 1987).

The Unconsolidated Deposits in the Eastern Sudan included Al-Atshan Formation, Cotton Soils and Superficial Deposits. Al Atshan Formation is a continental deposit with pebbles of agate and ironstone nodules. A maximum thickness of 335 m has been recorded for these deposits (Whiteman 1971). In Butana area a clay plain is developed on the Basement Complex rocks. In the vicinity of Khasm el Girba these clays reach a maximum thickness of some 12 m. Superficial Deposits are heterogeneous assemblage of river deposits, weathering aureoles around outcrops and wind deposits. Due to their nature almost all Unconsolidated Deposits can be considered aquicludes as far as groundwater is concerned; exceptions are the river deposits. Generally the Unconsolidated Deposits are characterized with high porosities but low permeabilities.

Aquifer hydraulic properties such as storativity and transmissivity can be determined by the aid of controlled field experiment or aquifer pumping test. The testing procedures generally consisted of a constant-rate pumping test and the observation of groundwater level changes with time due to pumping. The response of the aquifer is completed by analytical methods or solutions estimating the transmissivity and storativity. Aquifer pumping tests were run over 14 boreholes tapping the Mesozoic Sandstones Fig. 2. Most of the boreholes were 13.5 cm and 18 cm in diameter and were drilled by rotary rigs. Submersible pumps were used for testing. The discharge pipes were equipped with standard water meters. Water levels in the pumped wells were measured with an electric sounder. Pretest water-levels were measured one or two hours prior to the start of the test. Pumping tests were run for about 36 to 48 hours. Recovery tests were conducted until total recovery is attained. Time-drawdown data were analyzed using the Theis non-equilibrium method (Theis 1935), the Cooper and Jacob (1946) modification of the Theis formula and Logan's approximation method (Logan 1964). Recovery data were analyzed using Theis recovery formula. Observation wells were not available for most of the wells tested and hence only values of aquifer transmissivity were determined. Hydraulic conductivity values were obtained by dividing the transmissivity of the exploited zone by its saturated thickness. Table (2) summarizes the results of the aquifer pumping tests conducted in the study area. The average thickness of the exploited aquifer as deduced from well logs is about 35 m and the average transmissivity of this thickness ranges from 15 m^2/day to 75m^2/day. Specific capacity values vary from 0.34 m^2/h to 18.76 m^2/h. Hydraulic conductivity of the aquifer is in the order of 0.57 m/day to 2.81 m/day.

Geoelectric Measurements and Interpretations

Measurements

The Schlumberger four electrode in-line configuration was used throughout the study area, employing the Vertical Electrical Sounding (VES) technique. The procedure is suitable for the determination of the resistivity profile with depth. The basis for making soundings is that the farther away from the current source the measurement is made, the deeper the penetration will be. The apparent resistivity (ρ_a) values are then plotted as a function of half current electrode separation on bi-logarithmic paper to obtain a sounding curve (Keller and Frischknecht 1966).

A portable ABEM-SAS 300 resistivity unit was used for all measurements. The system consists of three main units, all housed in a single casing; the transmitter, the receiver and the microprocessor. The transmitter is capable of supplying a well-defined and regulated signal currents. The current ranges between 0.2 and 20 mA and a maximum voltage of 160 DC volts. The receiver has a range from one ohm to one mega-ohm resistance, with an accuracy of $\pm$ 0.5 milliohms at the one ohm range. Steel rods were used as current and potential electrodes and frequently watered to reduce the contact resistance between the electrodes and the top soil layer.

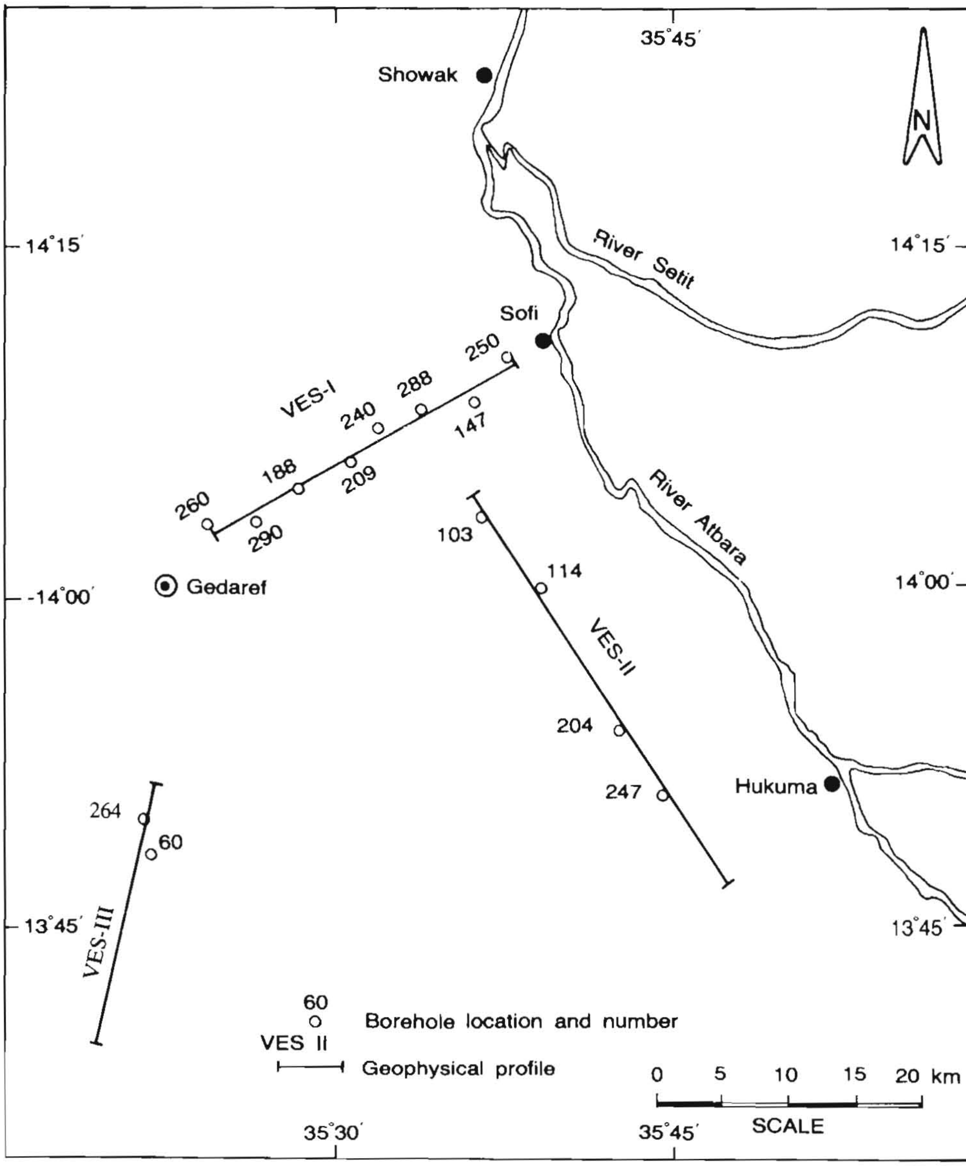

Fig. 2. Location of geophysical profiles and aquifer pumping tests boreholes.

Table 2. Results of aquifer- pumping tests, Gedaref Formation

Borehole No.	Discharge Q (m^3/h)	Screened thickness (m)	Transmissivity of screened-thick. T (m^2/day)	Hydraulic Conductivity K (m/day)
260	8.7	35	45	1.29
290	9.8	38	52	1.37
188	13.1	30	55	1.83
209	12.3	25	50	2.00
240	21.8	40	63	1.58
288	21.7	42	65	1.55
147	10.8	31	60	1.94
250	10.6	25	60	2.40
247	9.1	30	52	1.73
204	48.8	60	75	1.25
114	10.9	16	45	2.81
103	4.3	50	45	0.90
264	12.4	35	20	0.57
60	16.9	25	15	0.60

Interpretations

The VES soundings were initially interpreted by curve matching using available two-and-three layer master curves (Campagnie Generale de Geophysique 1955). In general, field curves indicated four-layer sections. The top two layers are usually clay and basalt (fractured and hard) representing unsaturated strata above the water table. The third layer (sandstone) representing the saturated aquifer, which is underlain by silicified sandstone. The interpretations, however, were not unique and might not correlate with geology. This is because of equivalence and suppression problems which can not be resolved without independent geologic control (Keller and Frischknecht. 1966) or test-drilling.

Transmissivity values used in this investigation are obtained on the assumption of horizontal radial flow, parallel to the aquifer layer (Walton 1970). Also electrical flow is considered to be principally horizontal at the aquifer scale (Kosinski and Kelly 1981).

In the final phase of interpretation boring lithological logs were used for geologic control. The interpretations have been mathematically tested by the of a computer program to calculate the theoretical curves ρ_a = f (AB/2). The geoelectrical sections derived from the VES interpretations near some test sites and the lithological logs of these wells were consistent.

Results and Discussions

A total of 36 soundings were performed during this study with a maximum current electrode separation of 2000 m, which is sufficient to ensure a penetration depth of up 300 m. The data were collected along three profiles with different orientations (Fig. 2). The total length of these profiles is approximately 97 km. Of the 36 soundings, measured only those at the 14 pumping test sites, were interpreted and will be discussed. Fig. 3 shows VES 3 of profile II near borehole 147. Inspection of this sounding indicates a probable five-layer case. Fig. 4 represents resistivity cross-sections of profiles I and II as derived from resistivity interpretations. A summary of lithological characteristics and resistivities for the study area is given in Table (3). The Basalts thickness in the area is believed to be structurally controlled by preexisting fault system or by a later phase of faulting (Adam 1987). The total thickness of these basalts as inferred from resistivity interpretations is conformable with the values obtained from borehole data.

Table (4) summarizes the results of the resistivity interpretations of the sounding curves selected for analysis, while Table (5) gives a summary of electric and hydraulic results.

Table 3. Summary of lithological characteristics and resistivities

Lithology	Average Thickness (m)	Average Resistivity (Ωm)
Clay	5	8
mudstone	47	35
hard basalt	75	214
fractured basalt	38	43
sandstone aquifer	120	79
silicified sandstone	—	⩾ 500

Corrected Transverse Resistance vs Hydraulic Transmissivity

Transverse resistance T_R of an aquifer is defined as the product of its thickness and average resistivity when the electrical currents flow in a direction perpendicular to the groundwater flow in the aquifer. It is customary to correct the transverse resistance for the effect of the aquifer true resistivity, This is usually done by dividing it by water resistivity ρ_w. Porewater resistivities were corrected to field temperature (25°C for this study) by multiplying the field water resistivities by a factor of 1.5 (Keller and Frischknecht 1966). A constant

Table 4. Summary of geoelectrical sounding results

Location			Layer 1		Layer 2		Layer 3		Layer 4		Trans. Resis.
Profile	VES	B.H.	Resis. ohm-m	Thick. m	Resis. ohm-m	Thick. m	Resis. ohm-m	Thick. m	Resis. ohm-m	Thick. m	T_R ohm-m^2
I	1	260	10	4	90	24	110	130	80	170	13600
	2	290	15	5	195	45	180	80	85	120	10200
	3	188	10	4.5	90	40	165	100	-	-	16500
	4	209	3	3.4	170	40	55	60	-	-	330
	5	240	5.5	3.6	33	50	150	80	130	200	26000
	6	288	8.5	3.0	130	32	80	215	-	-	17200
	8	147	15	6.5	280	44	90	150	-	-	13500
	10	250	5	9	90	55	40	53	-	-	2120
II	3	247	9.5	1.5	3	3	27	75	30	-	2550
	5	204	9	4.6	75	80	70	185	-	-	12950
	9	114	10	1.2	24	29	60	140	-	-	8400
	13	103	8.5	1.1	3.2	5.5	36	42	200	200	40000
III	2	264	8	2.0	15	12	250	90	80	100	-
	3	60	4	3.4	10	10.5	50	50	-	-	-

value of 25 ohm-m was assigned for porewater resistivity in the entire study area. In Fig. (5) the hydraulic transmissivity, T_s computed from pumping test data are plotted as abscissa versus the corresponding corrected transverse resistance, T_{RC} computed from VES interpretations and corrected for porewater resistivities (Ponzini *et al.* 1984).

The least square regression line fitting of the data indicated a linear relationship between the two parameters of the type:

$$T_{RC} = a\,T_s^b \qquad (1)$$

where $a = 6.52{*}10^{-2}$ (m) and $b = 1.343$ (d/m). T_s is the transmissivity in(m^2 /d) and T_{RC} is the corrected transverse resistance in (m). Linearization is achieved through logarithmic transformation. Because the number of measurements is relatively small,a higher significant level of 95% was used to fit the data. The correlation coefficient of 0.58 was computed. No significant improvement was achieved in the fit when a significant level of 99% was used. The above equation is physically reliable for the range of transmissivities indicated on the graph.

Table 5. Summary of electric and hydrogeological properties of Gedaref Formation

Profile	Location VES,B.H.	Thickness of Saturated Layer (m)	Resistivity ρ_a (ohm-m)	Hydraulic Conductivity K (m/day)	Transmissivity of Saturated Layer T_s (m^2/day)	Corrected Transverse Resistance T_{RC} (ohm-m	Apparent Formation Factor AFF
I	1 260	170	80	1.29	219	544	3.2
	2 290	120	85	1.37	164	408	3.4
	3 188	100	165	1.83	183	660	6.6
	4 209	60	55	2.00	120	132	2.2
	5 240	200	130	1.58	316	1040	5.1
	6 288	215	80	1.55	333	688	3.2
	8 147	150	90	1.94	291	540	3.6
	10 250	53	40	2.40	127	85	1.6
II	3 247	65	30	1.73	147	102	1.2
	5 204	185	70	1.25	231	518	2.8
	9 114	140	60	2.81	393	336	2.4
	13 103	200	200	0.9	180	1600	8.0
III	2 264	-	80	0.57	-	-	3.2
	3 60	-	50	0.60	-	-	2.0

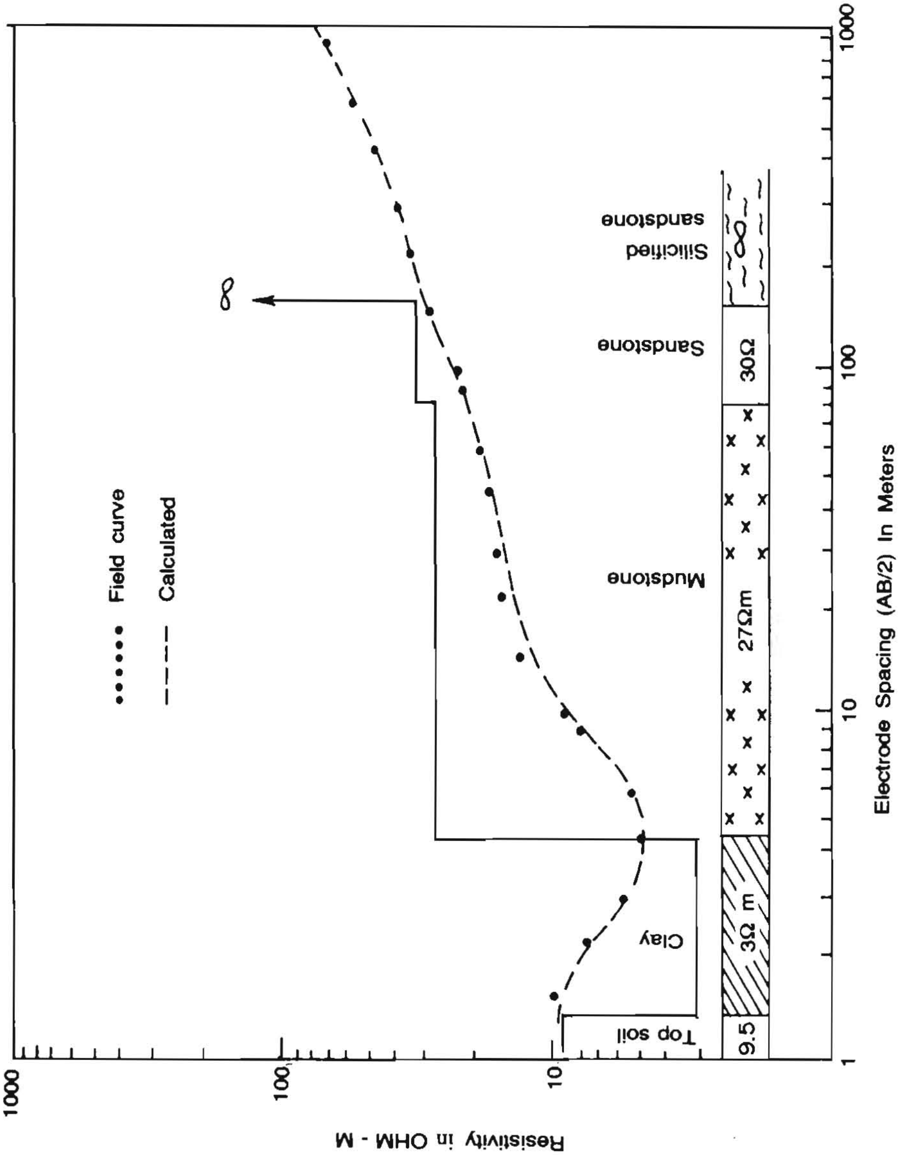

Fig 3. A typical vertical electrical sounding curve in the Gedaref area.

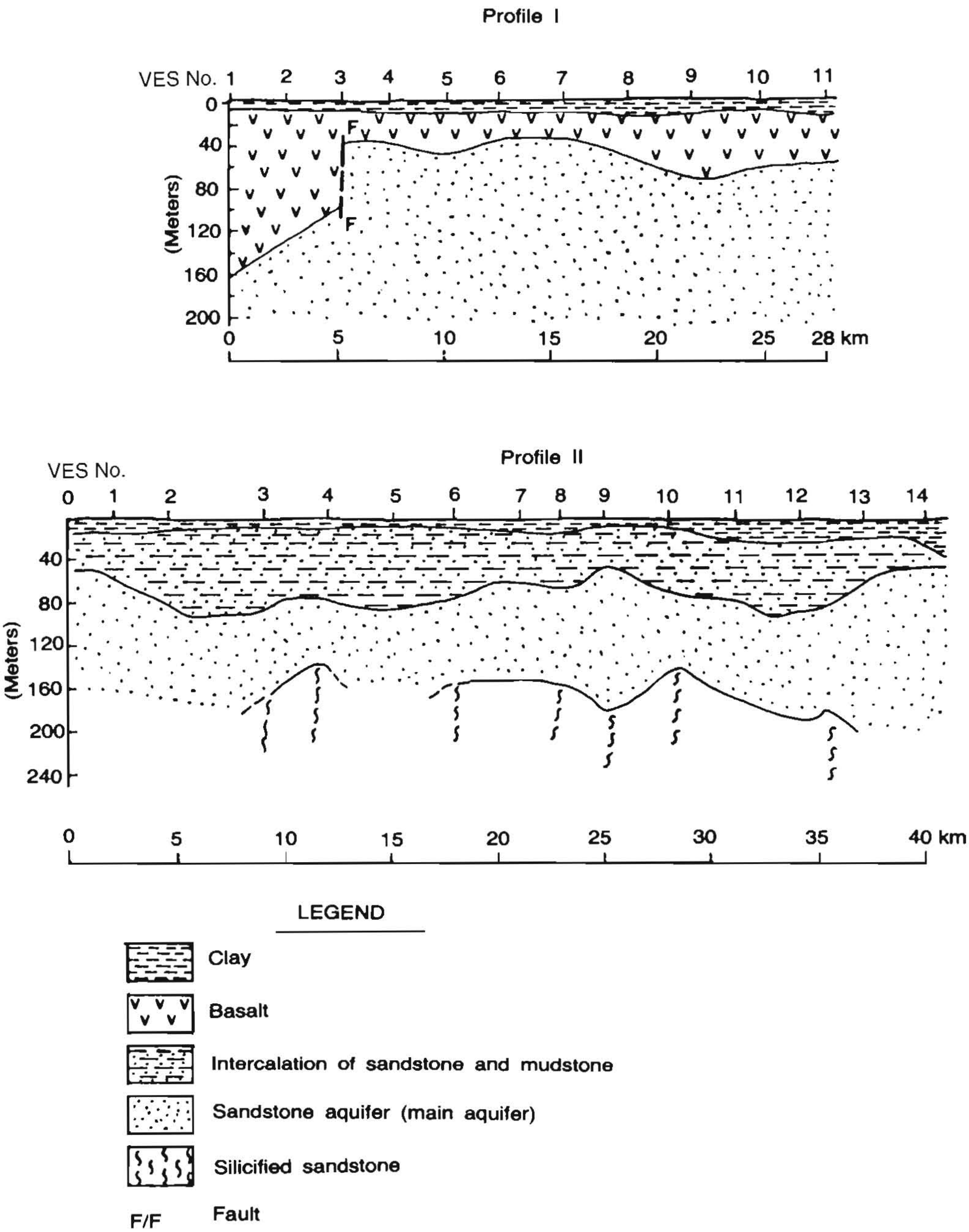

Fig. 4. Electrical resistivity profiles I and II, illustrating the geologic succession in the Gedaref area.

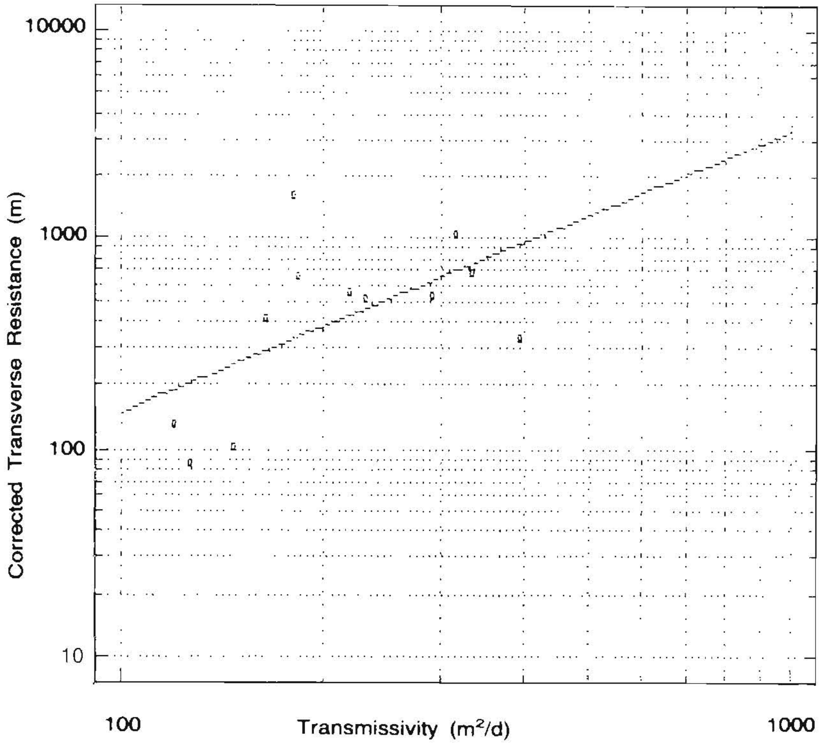

Fig. 5. Plot of Transmissivity versus Transverse Resistance

This linear direct correlation can be attributed to geological factors governing both the flow of groundwater and that of the electric current. Among these factors we mention the variation in grain size, nature and degree of cementation. consolidation and formation of secondary porosity caused by fracturing of Gedaref Formation in response to Oligocene tectonics that had affected the region. Each of these factors should be examined in detail and evaluated.

Apparent Formation Factor vs Hydraulic Conductivity

According to Archie (1942) the formation factor of a saturated material is defined as the total resistivity of the material divided by the resistivity of the saturating fluid. Archie's formula is strictly applied to clean sand with broadly constant porosity and porewater resistivity. Fig. 6 shows the least square regression line relating log permeability, K, to apparent formation factor (AFF). The regression formula is of the type:

$AFF = a\,K^{b}$ .... (2)

where (AFF) is the dimensionless apparent formation factor (normalized resistivity), K is the hydraulic conductivity (m/d); a = 41.68 and b (slope) = 0.944 (d/m).

A significant level of 95% was chosen and a correlation coefficient of -0.533 was computed. The negative slope indicates an indirect relationship between the two parameters which can be explained in terms of reduced grain size and high aquifer resistivity which in effect reduces the surface conduction.

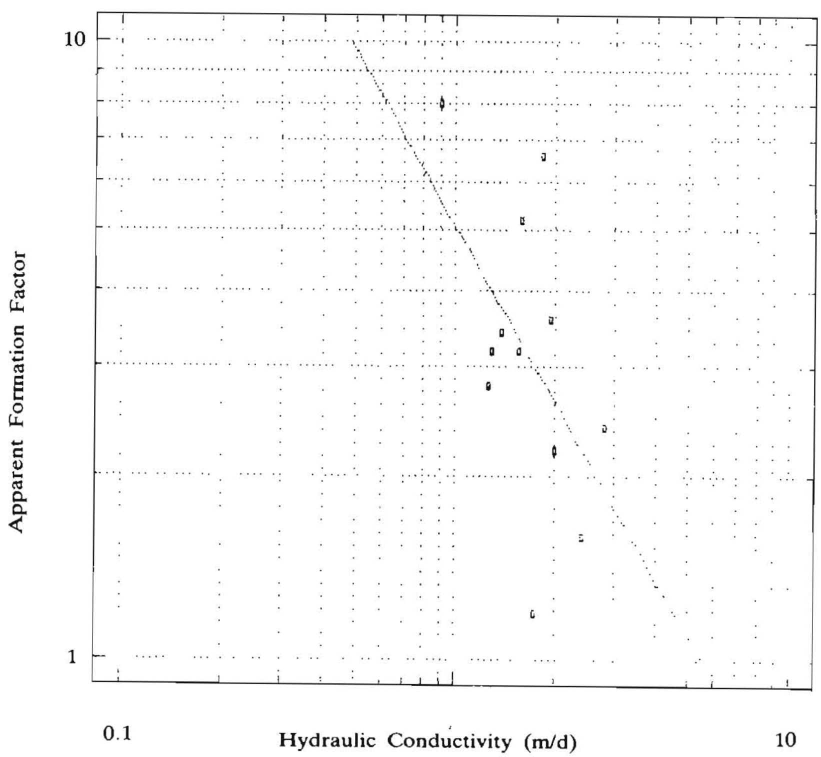

Fig. 6 Plot of Apparent Formation Factor versus Hydraulic Conductivity.

Empirical and laboratory relationships between hydrogeological and geoelectrical parameters for alluvium aquifers are documented in the literature (Worthington 1977, Urich 1981, Ponzini *et al.* 1984 and Kosinski and Kelly 1981). Comparison of the present work with any of the previous ones is not possible due to the different nature of the present aquifer and the existence of both primary and secondary porosities in the sandstones.

Conclusions

The study allowed the comparison of some hydrogeological and electrical properties of sandstone aquifer. A linear relationship between aquifer transmissivity and corrected transverse resistance has been obtained. Plots of apparent formation factor and hydraulic conductivity show a linear indirect weak correlation. The role of factors such as grain size, cementation and secondary porosity in sandstone should be examined more carefully in any future investigations. The empirical relationships thus obtained are not expected to apply to other areas, but the methodology will.

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مقارنة الخصائص الهيدروجيولوجية والكهربية لحجر رملي متصلب حامل للمياه

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الغرض الأساسي لهذه الدراسة هو مقارنة الخصائص الهيدروجيولوجية والكهربية لحجر رملي متصلب حامل للمياه .

تم تحديد الناقلية والايصالية الهيدروليكية للخزان المائي في أربعة عشر موقعا في منطقة القضارف بشرق السودان، بواسطة تجارب الضخ والاستعاضة لآبار تخترق هذا الخزان المائي ، كما وتم الحصول على المقاومة الكهربية لهذا التكوين وكذلك المقاومة المستعرضة المصححة له، ومعامل التكوين الظاهري من قياسات السبر الكهربي في نفس مواقع تجارب الضخ والاستعاضة للخزان المائي .

أوضحت نتائج الدراسة وجود علاقة خطية طردية بين الناقلية والمقاومة المستعرضة المصححة . كما لوحظ من الدراسة وجود علاقة خطية عكسية بين الايصالية الهيدروليكية ومعامل التكوين الظاهري . من الممكن تطبيق المنهجية التي أتبعت في هذا البحث في مناطق دراسية أخرى. أما العلاقات الاختبارية المستخلصة من الدراسة فلا يمكن تعميمها .

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