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A Hydrogeophysical Study to Estimate Ater Seepage from Northwestern Lake Nasser, Egypt

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Abstract: Estimating the water seepage from Lake Nasser, southern Egypt, into the adjacent Nubian sandstone aquifer is one of the main factors influencing the water balance of the lake. Up till now, there has been no information about seepage values, particularly in the northwestern part of the lake, due to a complete absence of boreholes. The present study is an approach using the time domain electromagnetic (TDEM) technique to estimate the hydraulic parameters of the shallow Nubian sandstone aquifer which are essential in water seepage calculations. The average porosity of the Nubian sandstone aquifer is calculated using bulk resistivities deduced from a TDEM model by applying the Archie formula. As calculated porosity values are consistent with laboratory measurements, accordingly the void ratio is estimated from the calculated porosity. The calculated void ratio in combination with the grain size diameter of the shallow part of the Nubian sandstone is used to estimate hydraulic conductivity. Then Darcy's low is applied to calculate the seepage value of the lake water in the adjacent Nubian sandstone aquifer. The main result of the current study shows that the anticipated water seepage value is 2.6 × 106 m^3 yr^{-1}. This value seems reasonable in comparison with the total seepage value inferred from isotope studies around Lake Nasser.

Key words: Hydrogeophysics · Time domain electromagnetic water seepage · Lake Nasser · Egypt

INTRODUCTION

Lake Nasser or High Dam lake is one of the largest manmade lakes in the world. It has been the most important and critical element in the social and economic development of Egypt since it was created after the construction of the Aswan High Dam in the 1960s. Lake Nasser extends to about 500 km in length, of which 150 km belongs to Sudan and over a width ranging from 10 to 30 km (Figure 1) and contains around155 milliard cubic metres of fresh water over a surface area of about 6000 km^2 [1, 2]. The most important advantages of the High Dam and Lake Nasser are in hydroelectricity production, flood control, increasing agricultural land, fishing and improving navigation and development in Upper Egypt. However, there is a huge amount of Lake Nasser fresh water seepage in the adjacent Nubian aquifers [3]. Estimating the amount of fresh water infiltration in the subsurface requires monitoring boreholes for hydraulic measurements. However , in areas where no boreholes are available, estimation of the amount of infiltration is a problematic issue. Recently , several attempts have been made to quantitatively evaluate the hydraulic parameters using geophysical techniques [4, 5]. The most extensive efforts were dedicated to studying the relationship between porosity and groundwater salinity on one side and electrical resistivity on the other. Among the different geophysical techniques, the transient electromagnetic method has been extensively developed and adapted over the last three decades to measure electrical resistivity. The method is characterized by its high sensitivity to electrically conductive targets, best vertical and lateral resolutions and highest depth to array size employed during acquisition [6, 7].

Time domain electromagnetic (TDEM) survey involves the transmission of a current through a rectangular loop, commonly laid on the ground. The primary magnetic field spreads into the ground. By rapidly reducing the transmitter current to zero, the changing primary magnetic field will induce eddy currents in the subsurface which are dependent on the subsurface resistivity distributions. The eddy currents will generate a changing magnetic field that can be detected by a receiver coil at the surface. The voltage generated in the receiver coil, which is proportional to the change of the secondary magnetic field created by the eddy currents,

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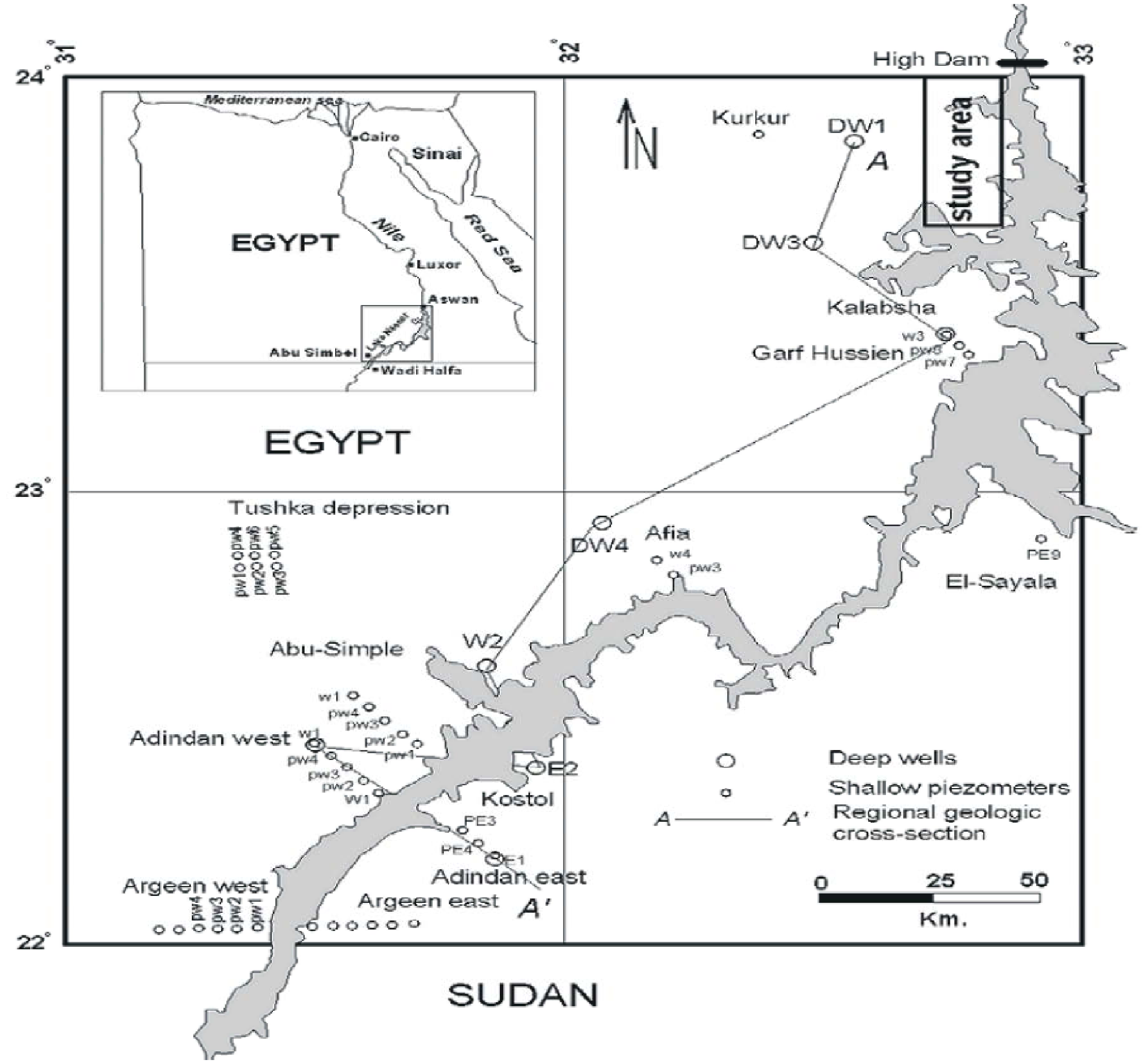

Fig. 1: Location map of the Lake Nasser study area and the distribution of the available boreholes

is measured versus the time [7]. Secondary magnetic fields decay quickly in poor conductor sand slowly in good conductors. By measuring the decay of the magnetic field, an estimate of subsurface resistivities can be achieved. The measured voltages can be transformed into apparent resistivity values to represent the properties of the subsurface [8]. Interpretation of transient data is accomplished by curve matching [6, 9]. The inversion methods will give a better fit to data than curve matching, thereby limiting the uncertainty in the fit to noisy measurement [8, 10]. Although the final output is similar to that from conventional dc electrical resistivity techniques, several advantages with the electromagnetic techniques are significant and result in improved speed of operation: there are no problems with injecting current into a resistive surface layer, the exploration depth ranges from a couple of meters to several kilometers down and it is less affected by conductive overburden than most other dc electrical resistivity methods [11, 12]. The main aim of the present study is to estimate the amount of fresh water recharge, from Lake Nasser, to the existing Nubian sandstone aquifer along the shoreline of about 47.5 km of the northeastern lake using surface TDEM measurements. Determining the amount of leach water is an important issue in understanding the water budget of Lake Nasser. However, the seepage of surface water in the subsurface aquifer is mainly estimated from monitoring boreholes. So special attention is paid to the studied area where there are no boreholes for measuring the hydraulic parameters by traditional hydrological methods.

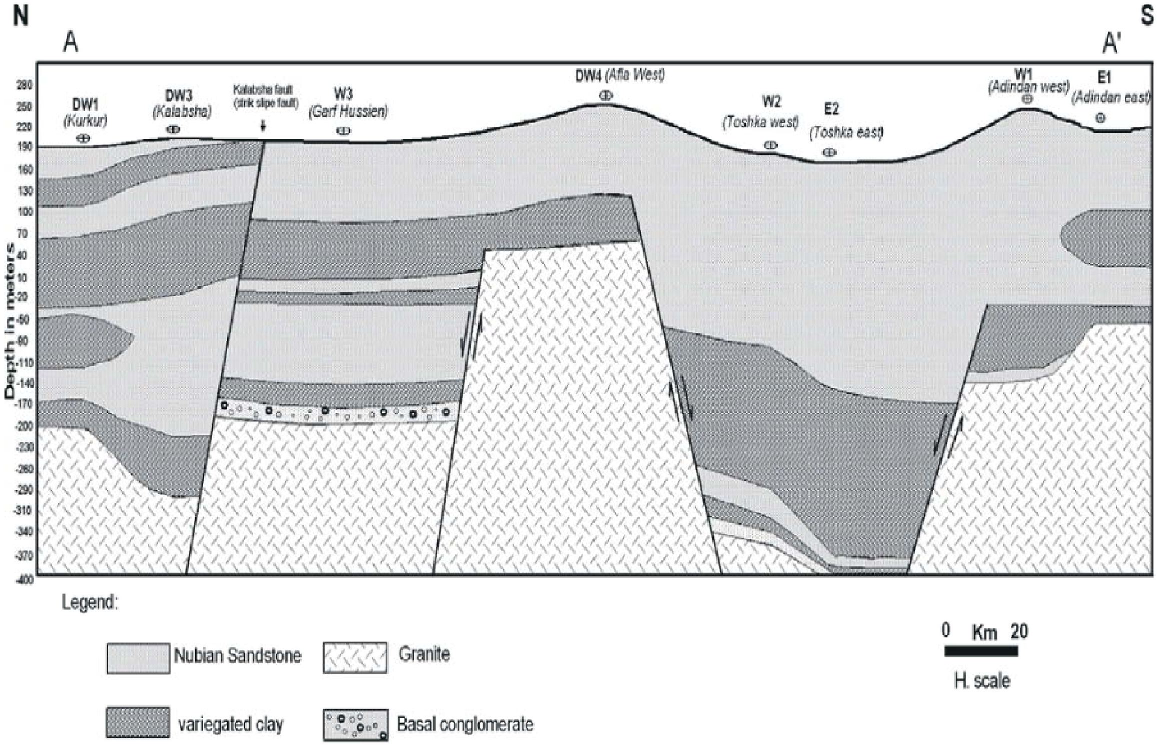

Fig. 2: Regional geologic cross section A–A_.

Hydrostratigraphic Situation: Many researchers have studied the Nubian section in the Aswan area, which lies just north of the basement trough. [13, 14, 15] divided the Nubian formation into three members from bottom to top into the Tarf member, Qusier member and Shab member. The Tarf member overlies the Precambrian basement consisting of yellowish and white coloured sandstone, shale and pebbly sandstone. The sandstone is well cemented and has a grain size ranging from fine to coarse. This is overlain unconformably by the Qusier member, which consists of buff, white to yellowish sandstone and shale ranging from fine to very fine grained and is well cemented and sometimes friable. The Shab member overlies the Qusier member conformably and it consists of fine-grained sandstone with some shale and siltstone. The sandstone is generally friable in this member and in some places it is well sorted with colours ranging from yellowish to grey–white, brown or grey–red, from which the monuments in the Abu Simbel area were sculpted. The shale in the Shab member is varicoloured and laminated in some places. The siltstone has a grey colour and is interbedded with the sandstone. From the hydrogeological point of view, the Nubian formation in the area consists of three horizontal units of total maximum thickness of 400 m. The lowermost unit, overlying the granitic basement, is an aquifer of fluvial sandstones and has a large-scale (several kilometers) horizontal permeability of 0.32-0.43µm2. The middle unit is an aquiclude that extends unbroken under the lake and leaks at periods longer than several years. This lower aquifer is confined up to periods of several years. The uppermost unit is the water table aquifer, which is composed of 25-30% porosity sandstones with interspersed claystone lenses and has a large-scale. permeability of 1.0-1.5 µm^2 [3, 16]. The vertical and horizontal distributions of the three facies are shown in the regional geologic cross section (A–A) (Figure 2), which is extending nearly parallel to Lake Nasser (Figure 1).

Time domainelectromagnetic (TDEM) Dat a Acquision: A simple coincident loop configuration, in which the same loop transmits and receives signals [17], is employed. The loop side length is varied from 25 to 100 m according to the local recording conditions. Using the SIROTEM III acquisition system, a suite of 12 TDEM measurements are carried out very close to the Lake Nasser shoreline (Figure 3). At some sites, the field procedures are repeated two to three times with varying acquisition arameters using the loop shift method with a maximum distance of

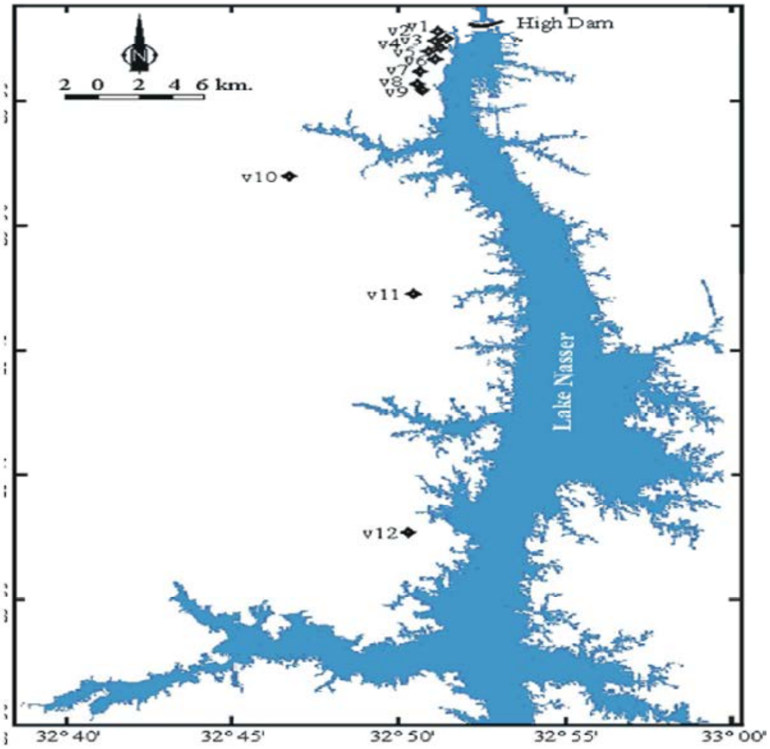

Fig. 3: Location map for the conducted TDEM station along the northwestern part of Lake Nasser

25 to 50 m. This acquisition scheme provides a multiple of measured data sets at each station. The best signal-to-noise data sets are chosen for further processing and interpretation.

TDEM Data Processing and Interpretation: The individual TDEM data sets are first iteratively inverted [18] using the general geological model (Figure 2) as the starting model. The start 1D models consist of three to five layers with varying thickness and alternating low and high resistivity. The choice of an propriate start model for each measured data set is controlled by the fitting degree between the measured and synthetic data calculated during the forward calculations. After inverting the suit of TDEM data, it is found that the misfits between the observed and calculated data are fairly good, ranging from 1.7 to 8. Figures 4(*a*) and (*c*) show examples of fitting degrees between the measured (open squares) and the calculated (solid line) TDEM data measured at stations v6 and v10 (Figure 3). The resultant layered resistivity models (solid line) and the set of related equivalences, which provide an RMS difference of 1.7 and 7, are displayed in figures 4(*b*) and (*d*). The most ignificant problem that affects the feasibility of the TDEM technique in estimating the porosity and hence the hydraulic parameters as important steps in estimating the water seepage, is the so-called equivalence range [5]. The equivalence analysis of TDEM easurements exhibits a wide range of resistivities and thicknesses for each specific layer. Therefore in following TDEM processing the average resistivity of each layer is considered and used in the porosity calculations. Figure 4(*b*) is an interpreted example of the resistivity model relative to the geological model. The first resistivity layer has an average resistivity of 195 m and extends to a depth of about 24 m. This layer represents the surface sand layer. The resistivity sharply decreases to 1 m and extends to a depth of 38 m, which represents the first clay intercalation. The resistivity increases again to 143 m and reaches a depth of 56 m. This layer represents the shallow Nubian sandstone aquifer. The resistivity decreases to about 2 m as a response to the occurrence of the second clay intercalation with a thickness reaching to 24 m. At the bottom of the layered model, the resistivity increases to about 124_m indicating the presence of the second Nubian sandstone aquifer that extends to the maximum depth of investigation. Based on the above considerations and the inversion results of TDEM stations, a geoelectrical cross section is constructed along the western bank of Lake Nasser, as shown in Figure 5.

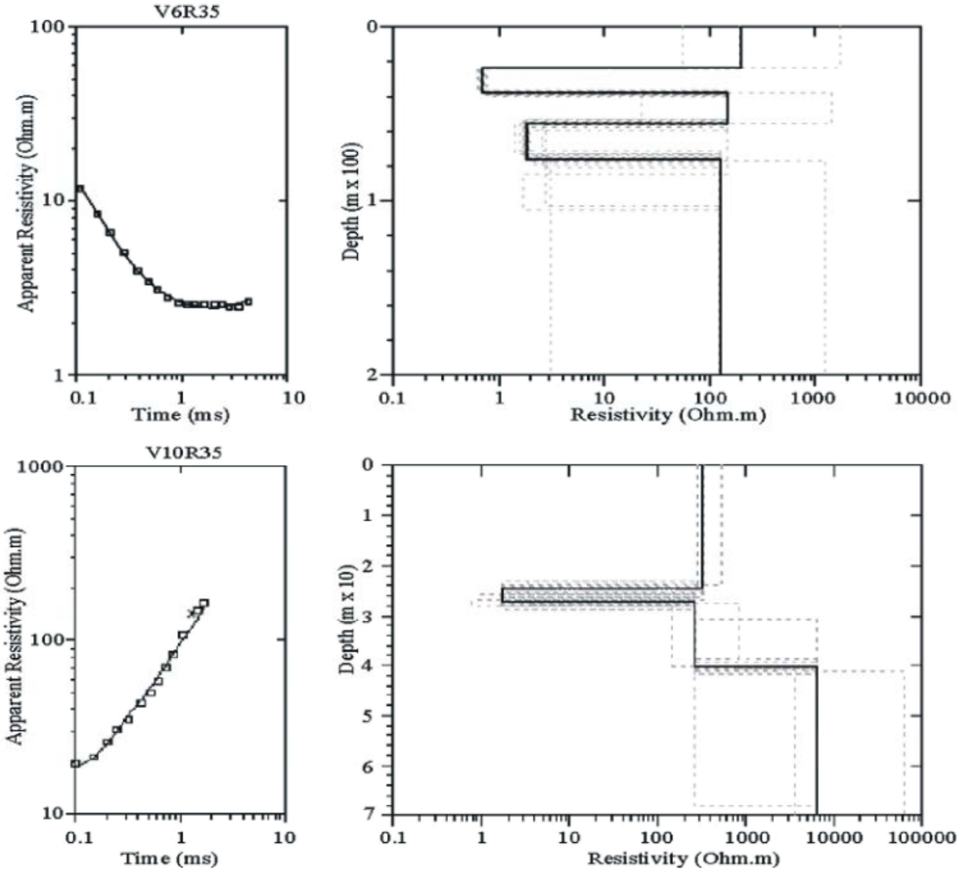

Fig. 4: TDEM data at stations V6 and V10 (for location see figure 3) with the resulting resistivity models: (*a*) and (*c*) are the measured (squares) and calculated (solid line) data and (*b*) and (*d*) the set of equivalence solutions by layered model inversion. Note that *V* is the station number and *R* is the run number.

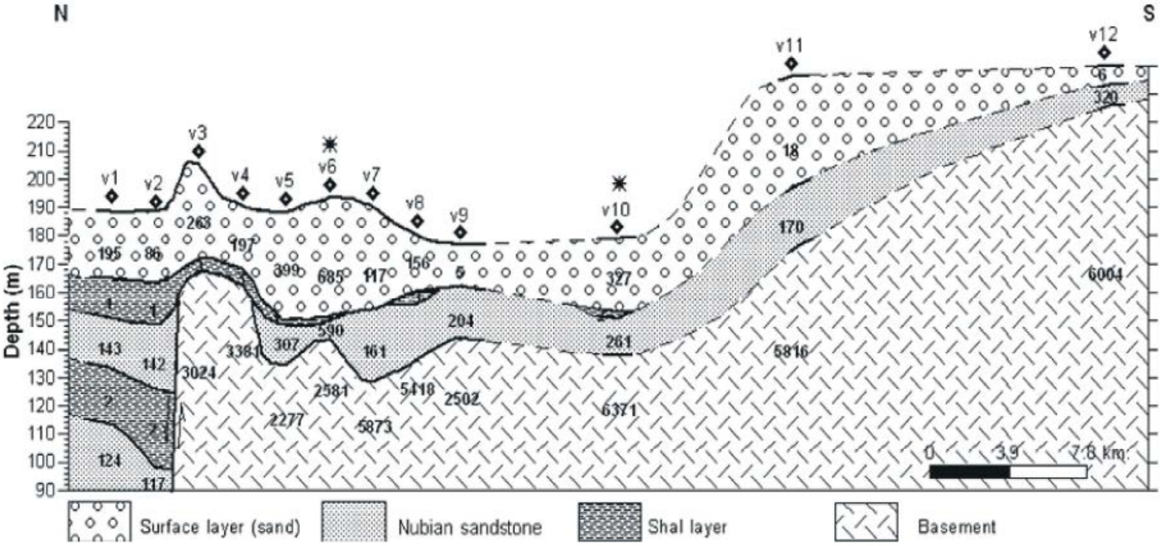

Fig. 5: Resistivity cross section along the northwestern side of Lake Nasser based on the inversion of the measured TDEM stations, Figure 3. Stars identify the two stations presented in Figure 4. Dashed lines suggest the interpolation between the stations is uncertain

Theory of the Utilized Approach: In most rocks there is an empirical relationship between the ratio of bulk rock resistivity to pore fluid resistivity and volume fraction porosity [19]. The relationship is called

Archie's law:

$$\rho w/\rho = a\varphi m, \qquad (1)$$

where ρw is the resistivity of water within the pore space, ρ is the bulk resistivity of the rock, φ is the porosity of the rock (approximately representing the volume of water filling the pore space), a and m are certain empirical factors depending on the type of material, forcing the equation to fit the behavior of the specified rock. The value of a is a level of saturation with water, whereas the value of m (cementation index) increases with the degree of cementation. [19] introduced the concept of formation factor in his work on the petrophysics of brine-filled rocks. The formation factor, F, is given by;

$$F = Ro/ Rw \qquad (2)$$

where Ro is the resistivity of the brine-saturated rock, Rw is the resistivity of the brine and F is the resistivity formation factor.

According to Archie, the formation factor is related to porosity (φ) by;

$$F = a\ \varphi\text{-}m \qquad (3)$$

where a and m are constants related to the rock type.

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where a and m are constants related to the rock type. [20] extended the use of this equation, relating the formation factor and porosity to the fresh-water saturated granular aquifer, which is the case in the present study. heoretically, all surface geophysical measurements whose parameters depend on Ro may be used for the determination of porosity (4). Hydraulic conductivity (permeability) increases with porosity. This increase is largely due to an increase in individual pore size and to a smaller extent to an increase in the flow area [21]. The relationship between the permeability (k) of fine or medium sand at any void ratio (e) and the permeability of the same sand at a void ratio of 0.85 was studied against the void ratio by [22] (Figure 6). The ratio of the volume of voids to the volume of solids (void ratio) is given by the equation

$$e = \varphi/1 - \varphi\ [21], \qquad (4)$$

where e is the void ratio (dimensionless) and φ is the porosity. On the other hand, the finer particles in soils govern the size of the percolation channels and, according to the Allen–Hazen equation [23], the size of the soil particles such that 10% are finer by weight, represented by $d10$, governs the permeability. For fairly uniform sands in loose state, $K0.85$ is determined by the following equation:

$$K = cd^2 10\ [21] \qquad (5)$$

where $d10$ is the grain size in mm, such that 10% is finer. K is the hydraulic conductivity in m day-1 and C is a constant (the average value is 850).

As $K0.85$ can be calculated from the grain size diameter (0.1–1 mm for Nubian sandstone) and the void ratio (e) is calculated from porosity (φ), then hydraulic conductivity (K) can be simply calculated. From Darcy's law,

$$Q = KIA, \qquad (6)$$

where Q is the discharge in m3 day-1, K is the hydraulic conductivity in m day-1, A is the area of discharge in m^2 and I is the hydraulic gradient ($\_h/L$) (unitless). The discharge or the seepage from Lake Nasser to the adjacent Nubian sandstone aquifer can be estimated.

Field Study: It is well known that geophysical logging is the most favourable method to determine the porosity and fracturing within subsurface layers, whereas surface geophysical measurements can only be used under exceptionally favourable conditions. [4]. Our attempt in the present study aims to presume porosity from time domain electromagnetic (TDEM) surface measurements. Consequently, the estimation of the seepage via integrated hydrogeophysical study is achieved. As the value of total dissolved solids (TDS) of surface water that infiltrates the aquifer is 162 ppm (High Dam Authority 2000, internal report, personal communication), then the water resistivity (Rw) is calculated using the salinity/ resistivity nomogram [24] as 40 _ m. The aquifer resistivities that have been deduced from TDEM measurements are found to range from 142 _ m at station no 2 to 658 _ m at station no 6 (Table 1). The formation factor for very station is estimated from equation (1)

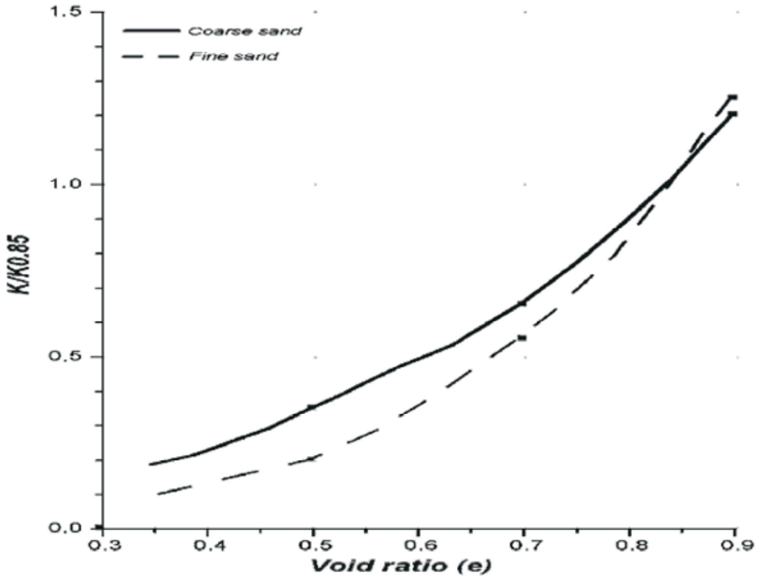

Fig. 6: Relationship between the permeability and void ratio of sand (after 22)

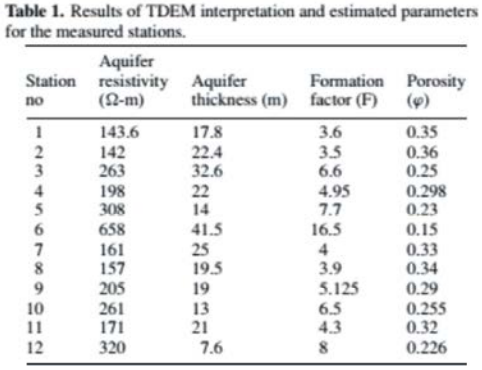

Table 1. Results of TDEM interpretation and estimated parameters for the measured stations.

Station no	Aquifer resistivity (Ω-m)	Aquifer thickness (m)	Formation factor (F)	Porosity (φ)
1	143.6	17.8	3.6	0.35
2	142	22.4	3.5	0.36
3	263	32.6	6.6	0.25
4	198	22	4.95	0.298
5	308	14	7.7	0.23
6	658	41.5	16.5	0.15
7	161	25	4	0.33
8	157	19.5	3.9	0.34
9	205	19	5.125	0.29
10	261	13	6.5	0.255
11	171	21	4.3	0.32
12	320	7.6	8	0.226

and is found to range from 3.5 to 16.5. The total porosity is estimated from equation (2) where *a* and *m* are equal to 0.62 and 1.72, respectively, as the study area contains moderately well cemented sands [25]. The estimated porosity ranges from 0.15 to 0.36 with an average value of 0.28.

It is worthwhile mentioning that the estimated porosity value is in agreement with the previous approach [26]. They measured the porosity in core samples to be 17.1% for friable sand and 28.4% for fine-grained sandstone. Other values of porosity for the upper.

Nubian sandstone aquifer, the zone under discussion, range from 25% to 30% (3) As the porosity is estimated, the void ratio (*e*) can be calculated from equation (4). Using the average porosity value (28%), the void ratio equals 0.4. The grain size diameter of the Nubian sandstone in the study zone ranges from 0.1 mm to 1mm [27]. Applying the average grain size diameter of 0.5 mm to equation (5) produces a value of 21.25 for *K*0.85.

From [2], (Figure 6), the ratio (*K/K*0.85) that corresponds to a void ratio of 0.4 for medium to course sands is 0.2, so the hydraulic conductivity equals 4.25 m day^{-1}.

Estimation of the Water Seepage: The area of infiltration is calculated from the TDEM layered model, where the thickness of the shallow aquifer ranges from 13 m to 41.5 m with an average value of 20.7 m along a horizontal distance of 47.5 km, (Figure 5). This gives an area of 983 250 m^2 in the Nubian sandstone layer. From the different values from different places around Lake Nasser given by [28] the average hydraulic gradient is estimated to be 1.74×10-3. Considering an estimated ydraulic conductivity of 4.25 m day^{-1} and applying Darcy's law, the resultant discharge value is calculated to be 2.588 523 m3 yr^{-1}. The estimated water seepage value seems to be reasonable compared with the corresponding distance (47.5 km). The total seepage around the lake is found, using the environmental isotope study of [29], to be 12 126 100 m3 yr^{-1} for a distance of 540 km around the lake.

CONCLUSION

Surface geophysical techniques, especially TDEM resistivity measurements, provide a fast and accurate estimation for the geometry and bulk resistivity of the target formations that are located close to the shoreline of Lake Nasser. Porosity values of the Nubian sandstone aquifer are accurately determined and have a value of the order of 0.28. This is followed by calculation of the hydraulic conductivity, which equals 4.25 m day^{-1}.

The area of infiltration is calculated from the TDEM layered model, where the thickness of the shallow aquifer has an average of 20.7 m along a horizontal distance of 47.5 km giving an area of 983 250 m^2. The average hydraulic gradient is estimated to be 1.74×10^{-3} around Lake Nasser. Considering the estimated hydraulic conductivity of 4.25 m day–1 and applying Darcy's law, the resultant discharge value is estimated to be 2.588 523 $m^3 yr^{-1}$. The calculated water seepage value seems to be reasonable compared with the earlier isotope studies carried out around Lake Nasser.

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