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Estimation of Aquifer Hydraulic Parameters Using a Surface Electrical Resistivity Measurements

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Abstract: Measuring the aquifers hydraulic parameters is an essential process for groundwater management and sustainable developments. These parameters are typically measured from the expensive and longtime pumping test experiments that require the presence of a number of water wells. Surface electrical resistivity measurements are recently used as less expensive alternative to estimate aquifers hydraulic parameters. A number of 20 vertical electrical resistivity sounding (VES) were acquired at Khuff aquifer in the central part of Saudi Arabia to estimate the characteristic hydraulic parameters of Khuff limestone aquifer. Based on the electrical resistivity measurements, the Khuff aquifer can be divided into a shallow highly fractured zone underlined by a deeper zone with moderate fractures density. The formation factor, porosity, hydraulic conductivity and transmissivity were estimated from the electrical resistivity measurements. These estimated parameters were compared to the parameters obtained from the previous pumping test experiments. The transmissivity values showed a reasonable comparison with the values measured from a previous pumping test experiments. According to the current results surface electrical resistivity proved to be a successful tool in characterizing the Khuff aquifer and estimating most of the aquifer's hydraulic parameters.

Key words: Hydrogeophysics · Khuff Formation · Hydrological parameters · Saudi Arabia

INTRODUCTION

Sustainable groundwater development implies the use of this valuable resource on a long term basis, in an efficient and equitable manner sustaining its quality and environmental diversity. Determination of groundwater hydrological parameters that controls the movement and storage of the water in sediment pore spaces are greatly important to facilitate the management of water resources. Evaluation of the groundwater resources for the purposes of sustainable development requires a clear understating of some aquifer parameters such as; porosity, hydraulic conductivity, transmissivity, aquifer thickness and type of sediments forming the aquifer [1]; [2]. The classical methods used in defining such aquifer parameters rely on hydrological measurements from borehole, surface samples and pumping test experiments. However, such methods are costly, time consuming and only provide subsurface information at the measured location. Therefore, there was a strong motivation to find fast, cost effective and reliable alternative acceptable techniques to estimate such essential hydrological parameters. Geoelectrical resistivity method is one of the most used geophysical technique in the hydrological applications [3]; [4]; [5]. During the last decade, many attempts had been made to estimate aquifer transmissivity and hydraulic conductivity from surface resistivity data [6]; [7]. Such attempts are based on the empirical relationships

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between the electrical resistivity (ρ) and hydraulic conductivity (k). Because the hydraulic parameters of the aquifer depend on the porosity and the specific geometry of the pore spaces. These factors also control the resistivity values of the water saturated sediments [8]; [9]. Generally, the electrical current paths in the subsurface sediments are similar to the hydraulic paths in the sediment pore spaces. Such relationships between these two parameters are controlled by Darcy's law, which specifies the discharge is proportional to hydraulic gradient between two points. This is similar to Ohm's low that describes the current flow in specific formation.

In this work, we are attempting to use the electrical resistivity measurements for estimating the hydrological parameters (porosity, hydraulic conductivity and trasmissivity) of Khuff aquifer at Al Quwy'yia area and compare the results with those obtained from a previous pumping test experiments conducted for some wells in the area. After validating the hydrological parameters estimated from the electrical resistivity measurements, the parameters can be used to enhance the hydrological information that is required for constructing and validating the hydrological model of the multi-layered aquifer system in that area.

Study Area: Al Quwy'yia area is part of a large plain extending northwest - southeast over several hundred kilometers, east to the basement complex rocks exposure of the Arabian Shield (Fig. 1). Al Quway'yia is located about 160 km to the west of Riyadh city along the high way between Riyadh and Taif. Urban. Industry developments are growing rapidly in this area during the past few years that significantly increased the demand on the limited groundwater resources. Topographically the study area is almost flat and covered with limestone soil on the weathered plain that shows a gentle slope from west to east. The area is also dissected by many ephemeral wadis that start from the basement complex in the west and run through the plain to the east. Most of Al Quwy'yia area is covered with alluvium and sand dunes Quaternary deposits. The thickness of this Quaternary deposits ranges from few meters to tens of meters. The Quaternary deposits are underlined by the limestone units of the Khuff Formation (Permian), which is exposed, as a hilly belt 20 km wide, at the eastern side of the basement outcrop (Fig. 2). The Khuff Formation overlies the basement complex as recorded in wells Qap2-1 and Qap1-1 at the western and southern parts of Al Quway'yia area. The Khuff Formation itself consists of a sequence of layered limestone, dolomite, shales, siltstone, sandstone and marl [10].

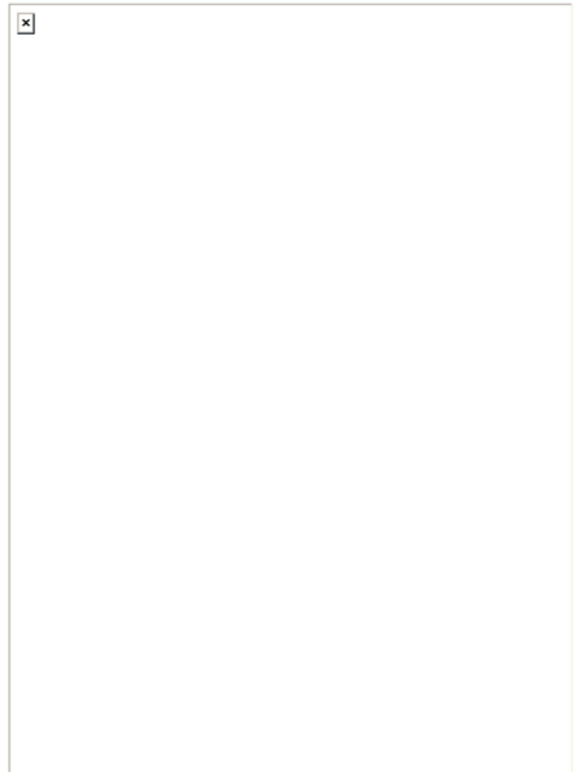

Fig. 1: Geological map of Al Quwy'yia area and its surroundings showing the locations of the VES stations. (Modified after [10]

Khuff limestone formation at Al Quwy'yia area is not a principal groundwater aquifer, however it is the only source of drinking water in the area [11]. The aquifer in this area composed mainly of limestone of low hydraulic parameters, however, the fracture system in the aquifer assists the water flow downstream to the east and southeast.

Geoelectrical Resistivity Measurements and Results: Using the Syscal R2 acquisition system and utilizing the Schlumberger electrode configuration, 16 Vertical Electrical Resistivity Sounding (VES) data sets were recorded along three profiles passing through Al Quwy'yia area (Fig. 1). For each VES, the current electrodes (AB/2) were varied from 3 to 1000 m and the potential electrodes (MN) were extended from 0.5 to 200 m in successive steps. Two VES (B2 and B3) have been carried out close to two boreholes (Qap2-1 and Qap 1-1), respectively. The geological data obtained from the wells were used in calibrating the geoelectrical models, minimize the uncertainties of the 1D inverted models and constraining the interpretation (Fig. 3).

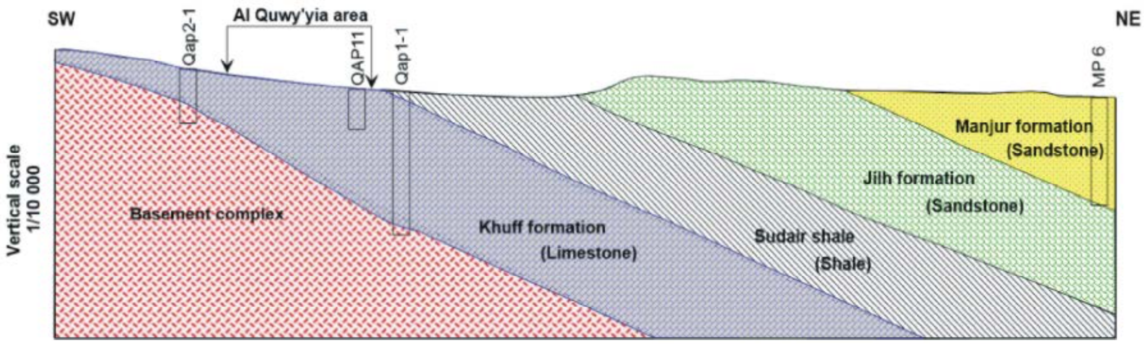

Fig. 2: Geological cross section (W-E) along Al Quwy'yia area showing different geological formations (modified after [11]

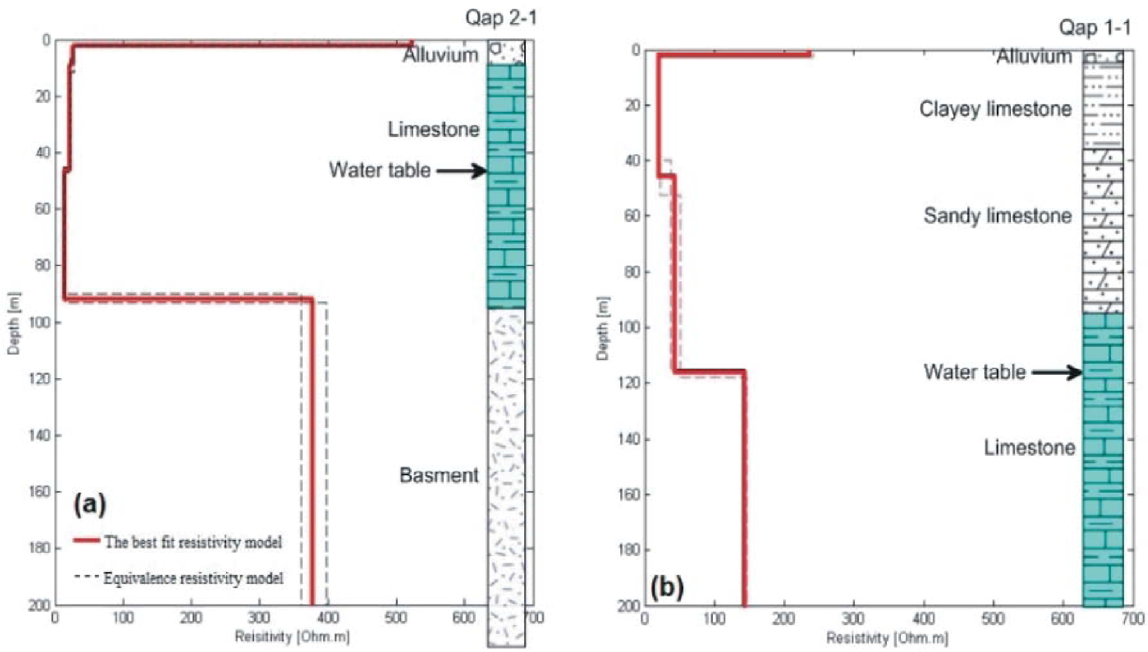

Fig. 3: The layered resistivity model compared to the geological controls from two wells along profile B; (a) VES (B2) and well (Qap2-1); (b) VES (B3) and well (Qap1-1); (after [12]

Since most of the VES data points were recorded along quasi-linear profiles, it is possible to process the acquired data in the form of continuous 2D subsurface models [13]. Applying the Uchida's (1991) algorithm, 2D resistivity models were derived for the available VES profiles. The algorithm is based on the ABIC (Akaike Bayesian Information Criterion) and utilizes finite element calculation mesh [15]; [16].

Based on the resultant 2D inversion of VES data, the electrical resistivity data are set of multi-layered models; each of them fits the observed field curve and describes the electrical properties of the subsurface medium. Linear color scale has been used to visualize the limited resistivity range (1–700 Ohm.m). Generally, there are many features that can be interpreted from the resistivity cross sections. First, underneath the most topographically elevated area in the south western side, the resistivity values are relatively high (> 500 Ohm.m) and mainly due to the occurrence of the basement rocks (Fig. 3). This fact has been confirmed by the correlation between the well (Qap2-1) and the nearby VES (B2) (Fig. 3a). The sedimentary cover overlying the basement rocks, shows resistivity values much lower than the basement (<70 Ohm.m). It is noticeable that the basement surface can easily be identified along both resistivity sections (A and B) and at the southern west of profile (C). The high resistivity values (450-500 Ohm.m) underneath VES (C2) along profile (C) are referring to the basement

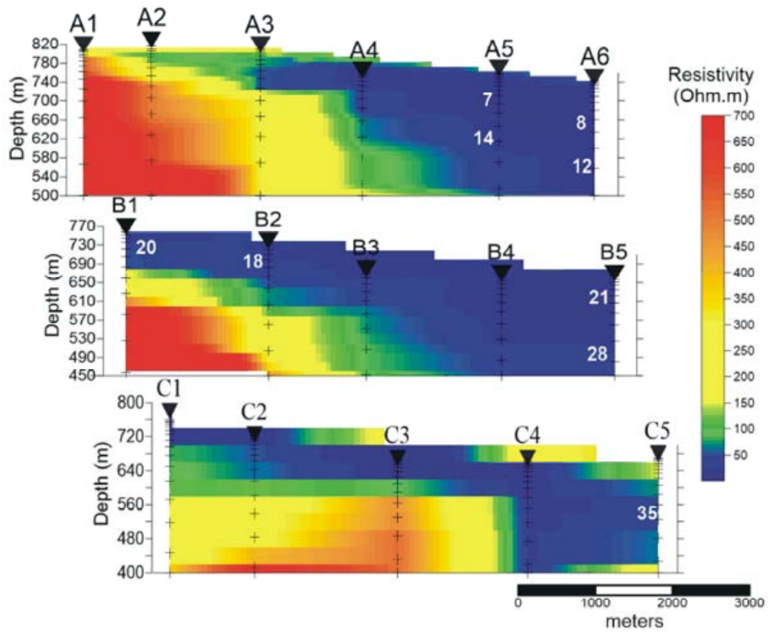

Fig. 4: 2D Geoelectrical cross sections generated from a 2D inversion of a number of 1D VESs. (modified after [10]

surface, while the relatively high values (400-450 Ohm.m) underneath VES (C3) is due to the massive limestone (dolomitized limestone). The eastern side of the area which is topographically flat shows relatively low resistivity values. This low resistivity body represents the Khuff limestone aquifer (Fig. 4).

The static water table is consistent with the gradient of the limestone strata, giving an indication that the aquifer depth and thickness are increasing eastward. However, there is a small groundwater potentiality below the elevated VES stations in the south western side due to the small thickness of the limestone unit and also due to fast movement of groundwater eastward due to the dipping of the underlying basement rock towards the eastern direction.

Estimating Aquifer Hydraulic Parameters: Archie (1942 and 1950) introduced a formula that established a relationship between the formation factor (*F*), resistivity of sediments and its brine filled sediments in clay free sediments.

$$F = \rho_a / \rho_w \quad (1)$$

where (ρ_a) is the bulk resistivity and (ρ_w) is the fluid (pore water) resistivity.

However, the relation between the formation factor (F) and the porosity of the sedimentary unit can be calculated as follow;

Table 1: Values of formation constants (a) and (m) for carbonate rocks.

Lithology	*a*	*M*	Authors
Carbonates	0.73-2.3	1.64-2.1	[25]
	0.45-1.25	1.78-2.38	[24]
	0.33-78.0	0.39-2.63	[23]
	0.35-0.8	1.7-2.3	[22]
	1	2.2	Used in the current work

$$F = a / \varnothing^m \quad (2)$$

where (Ø) is the porosity of the medium, *a* and *m* are the cementation factors. The quantities (*a*) and (*m*) have been reported to vary widely for different formations. Some of the reported ranges for carbonate rocks in the literatures are listed (Table 1) as well as the average values that have been used in the current study based on the classification of the carbonate rocks of Khuff formation [11].

The second Archie's law expresses the relation between the formation factor, porosity, bulk resistivity and fluid resistivity including the two variable (*a* and m) as follow.

$$F = \frac{\rho_a}{\rho_w} = a\varnothing^{-m} S_w^{-n} \quad (3)$$

where ρ_a is the formation resistivity, ρ_w is the pore water resistivity, Ø is the porosity, S_w is the water saturation.

From equations (2 and 3) and measured bulk resistivity from the surface electrical resistivity measurements and using the standred values for fluild

Table 2: The estimated hydraulic parameters for Khuff Formation

Electrical resistivity station No.	Aquifer Resistivity (Ohm.m)	Pore water resistivity (Ohm.m) (BRGM, 1992)	Aquifer thickness (m)	Formation factor	Porosity (estimated)	Hydraulic conductivity (m/day) (estimated)	Transmissivity (m^2/day) Estimated	Transmissivity (m^2/day) Pumping test
a5 _upper	7	0.0525	100	133.3333	0.11	0.155	15.47	Na
a5_lower	12		125	266.6667	0.08	0.056	7.05	9.17
a6_ upper	8		125	152.3810	0.10	0.127	15.89	Na
a6_lower	12		120	228.5714	0.08	0.070	8.45	7.30
b5_ upper	21		120	76.1905	0.07	0.032	3.78	0.90
b5_lower	28		120	495.2381	0.06	0.021	2.51	Na
c5	35		80	666.666	0.05	0.015	1.22	Na

resistivity for the water samples from the wells in Al Quwy'yia area (water conductivity at 25° is 8.25 mmhos/cm). It can estimate the formation factor at the measured stations. The porosity values can be calculated as well at each values for bulk resistivity. Table (2) shows the estimated and calculated values for the standred and calculated formation and hydraulic parameters for Khuff limestone aquifer.

Average hydraulic conductivity can be calculated using the Kozeny-Carman-Bear equation (4) [26] for the seven possible locations wheras the resistivity values domenstrate the locations of the saturated limestone unites (Fig. 4):

$$K = \left(\frac{\delta_w g}{\mu}\right) \cdot \left(\frac{d^2}{180}\right) \cdot \left[\frac{\varnothing^3}{(1-\varnothing)^2}\right] \quad (4)$$

where:

δ_w: is the fluid density (supposed to be 1000 kg/m^3).

μ: is the dynamic viscosity (0.0014 kg/ms, [19].

d: is the grain size (0.001mm) for nonclastic limestone of the Khuff Formation.

The transmissivity (T in m^2/s or m^2/day) is estimated for the aquifer saturated layer of thickness (h) for the cross sections interpreted from electrical resistivity measurements from the equation (5) below;

$$T = K.h \quad (5)$$

Inspection of the geological cross section (Fig. 2) and the interpreted geoelectrical sections (Fig. 4) reveals that the Khuff limestone aquifer is dominant towards the eastern direction, whereas the limestone layer can be characterized into two parts based on the porosity percent and the fracture density. The upper part has lower resistivity values (7, 8 and 21 Ohm.m) due to increase of the water contents in the fractures and pores of the limestone unit. The lower part is massive and unweathered limestone, possessing relatively higher resistivity values (12, 12, 28 and 35) due to the lower fracture density and, hence, less water saturation.

The transverse resistivity values, which are the product of formation resistivity and layer thickness (ρ_a*T) have been calculated for the measured stations and plotted against the transmissivity values (Fig. 5a). The regression line fitted to these data (R^2 = 0.8775) indicate that the higher transmissivity values are related to the low resistivity (Fig. 5b and Table 2). The locations with high transmissivity are considered the locations of favorable target for groundwater exploration.

After calculating the hydraulic parameters for the Khuff limestone aquifer at Al Quwy'yia area, it was essential to compare the results particularly the tranmissivity with that measured by a previous pumping test in the area conducted by BRGM (1982). Long duration pumping test was conducted formerly for 24 hours [11] and new interpretation method was carried out using Aquifer Test (2014.1) software [20]. The unconfined, infinite extension, an isotropic constant discharge and partial penetration assumptions were considered using Neuman (1974) method. Figures (6 and 7) show two straight segments, the first one has a constant slope and the other segment slope is doubled the first segments. This is may be due to the drawdown cone had reached the boundary of the aquifer. The calculated transmissivity values (T) for wells QPB1-1 and QBT-3 close to VES's A5 and A6 are 9.17 and 8.19 m^2/d, the specific yield values (Sy) are $3.56*10^{-3}$ and $5.68*10^{-6}$ and the ratio of vertical to horizontal hydraulic conductivity values (Kv/kh) are $1.26*10^{-3}$ and $4.55*10^{-2}$. The calibrated constructed hydrological model covering the VES's locations B1 and B2 were used to estimate the transmissivity [12].

From such measurements and taking in consideration the thickness of the limestone formation from the lithological data, it was possible to calculate the hydraulic conductivity and transmissivity. However, such procedures are limited to the pumping test locations. It was observed that the calculated values from the pumping test and those estimated using the surface resistivity data are in acceptable match (Table 2 and Fig. 8).

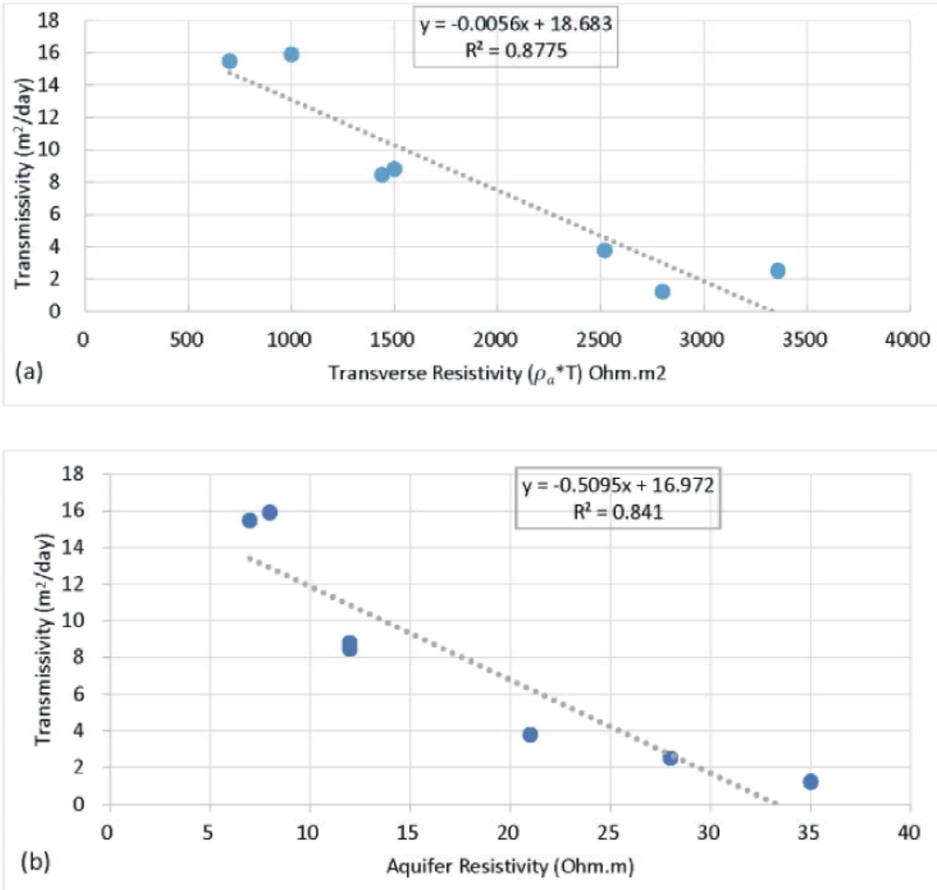

Fig. 5: (a) Relation between estimated Transmissivity and transverse resistivity for Khuff formation (b). Relation between estimated Transmissivity and Formation resistivity for Khuff formation deduced from the measured VES stations

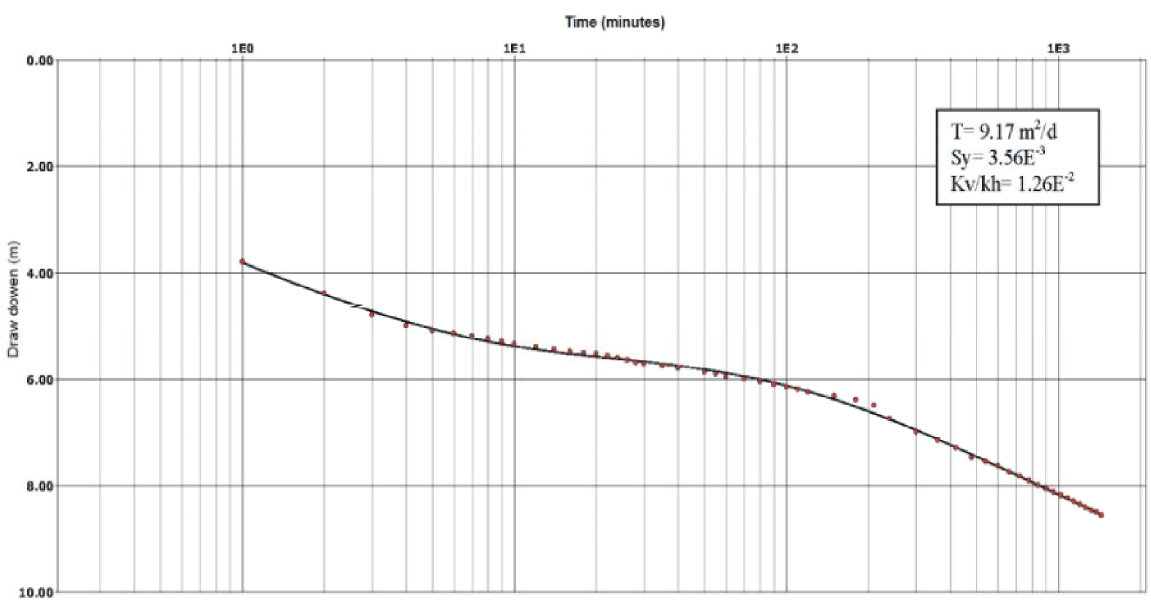

Fig. 6: Long duration pumping test of the well QPB 1-1

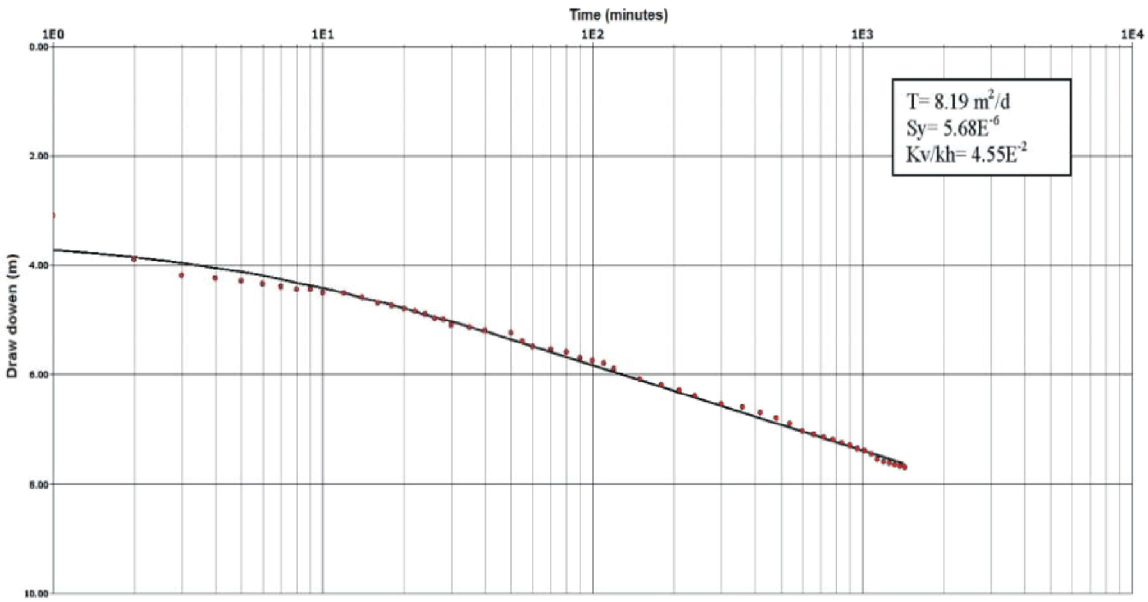

Fig. 7: Long duration pumping test of the well QBT-3

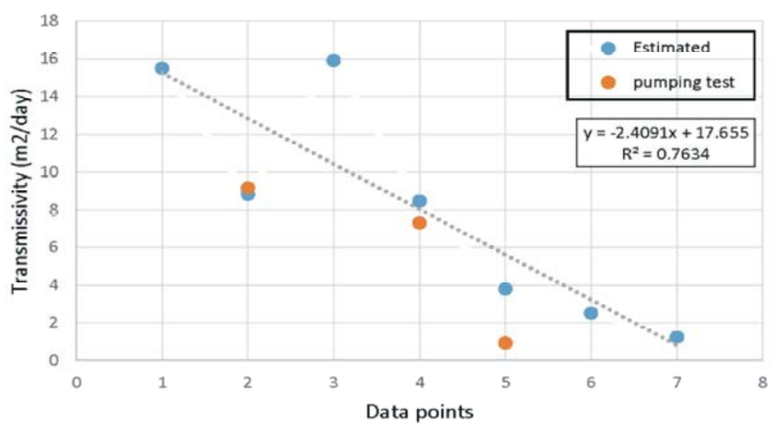

Fig. 8: Correlation between the calculated and measured transmissivity values

The transmissivity values are estimated from the resistivity measurements at each VES location and compared to transmissivity values measured from a previous pumping test at the corresponding locations (Figs. 6 and 7). The transmissivity values measured from the two methods seem to be well correlating with regression fitting ($R^2 = 0.763$), proofing that the electrical resistivity method can be, efficiently, used for estimating the aquifer hydraulic parameters, whereas, there is no available boreholes or even there is no pumping test measurements along the whole site. Such type of research properly emphasis the importance to apply more than one technique for estimating Dar-Zarrouk parameters for any aquifer and hence calculating the hydraulic properties in more accurate manner.

CONCLUSION

The water resources in the central part of Saudi Arabia are rather limited due to the arid conditions, lower thickness of sediments cover and the carbonate nature of this sedimentary cover (Khuff limestone). The sustainable development projects in the area require a better understanding of the hydrological aspects of the aquifer using subsurface measurements such as pumping test, core sample analysis and well logging. However, those measurements are very costly, time consuming and need a lot of processing steps. Therefore attempt has been carried out for estimating the essential hydraulic parameters from the surface electrical resistivity measurements. The data have been processed in terms of

1D and 2D modeling schemes for getting the true formation resistivity values and portraying the aquifer geometry.

The basement rocks were identified clearly from the high values of resistivity data, while the limestone aquifer layer has been determined as well. Such results have been confirmed by correlating the resistivity values with corresponding lithological units at two boreholes. The Khuff formation was classified into two zones based on the resistivity values. The shallower zone with low resistivity values has higher fracture density. The deeper zone of the aquifer is less fractured and has relatively higher resistivity values. The two parts of the aquifer are fully saturated eastward. Applying Archie Formula using the resistivity values for the Khuff limestone rocks and pore water sediments, the formation factor was estimated. Then the porosity also was calculated at each values for bulk resistivity along the 2D resistivity sections. The Average hydraulic conductivity was calculated using the Kozeny-Carman-Bear equation. Then the transmissivity was estimated along the saturated thickness of the cross sections interpreted from electrical resistivity measurements. Then, the transverse resistivity values were plotted against transmissivity. The regression line fitted to these data indicates acceptable accuracy of the estimated values of the transmissivity. The estimated values of transmissivity have been compared with those calculated from the pumping tests and calibatred hydrologic model and the results are promissing for getting the transmissivity values for the areas whereas no pumping test exist, or even no borehole exists. Higher transmissivity values correspond to either lower resistivity values or larger aquifer thickness. Such locations with high transmissivity are considered the favorable target of groundwater exploitation.

REFERENCES

1. Mendosa, F.G., S.T. Steenhui, M. Todd Walter and J.Y. Parlange, 2003. Estimating basin-wide hydraulic parameters of a semi-arid mountainous watershed by recession-flow analysis. Journal of Hydrology, 279: 57-69.
2. Niwas, S., B. Tezkan and M. Israil, 2011. Aquifer hydraulic conductivity estimation from surface geoelectrical measurements for Krauthausen test site, Germany. Hydrogeology Journal, 19: 307-315.
3. Telford, W.M., L.P. Geldert and R.E. Sheriff, 1991. Applied geophysics. Cambridge Univ, New York.
4. Metwaly, M., M. Khalil, E. El-Sayed and S. Osman, 2006. Hydrogeophysical study to estimate water seepage from the northwestern Lake Nasser, Egypt. Journal of Geophysics and Engineering, 3: 21-27.
5. Utom, A.U., B.I. Odoh, B.C.E. Egboka, N.E. Rgboka and H.C. Okeke, 2013. Estimation of subsurface hydrological parameters around Akwuke, Enugu, Nigeria using surface resistivity measurements, J. Geophys. Eng., 10: 1-8.
6. Tizro, A.T., K.S. Voudouris, M. Salehzade and H. Mashayekhi, 2010. Hydrogeological framework and estimation of aquifer hydraulic parameters using geoelectrical data: a case study from West Iran, Hydrogeology Journal, 18: 917-929.
7. Khalil, M., A. Hafez, M.A. Santos, F.M. Ramalho, E.C. Mesbah H.S. and G.M. El-Qady, 2010. An approach to estimate porosity and groundwater salinity by combined application of GPR and VES: a case study in the Nubian sandstone aquifer. Near Surface Geophysics, 8: 223-233.
8. Attwa, M., A.T. Basokur and I. Akea, 2014. Hydraulic conductivity estimation using direct current (DC) sounding data: a case study in East Nile Delta, Egypt, Hydrogeology Journal, 22(5): 1163-1178.
9. Kazakis, N., G. Vargemezis and K.S. Voudouris, 2016. Estimation of hydraulic parameters in a complex porous aquifer system using geoelectrical methods, Science of the Total Environment, 550: 742-750.
10. Metwaly, M., E. Elawadi, SS.R. Moustafal, F. Al Fouzan, S. Al Mogren and N. Al Arifi, 2012. Groundwater exploration using geoelectrical resistivity technique at Al-Quwy'yia area central Saudi Arabia. Int J. Phys. Sci., 7: 317-326.
11. Bureau de Recherches Geologiques et Minieres Agence D'interventions (BRGM), 1982. Hydrogeological investigations in Al Quwayyah area (Pumping test) internal report submitted to Ministry of Agriculture and Water.
12. Metwaly, M., 2013. Groundwater contamination assessment at Al-Quwiy'yia area, central Saudi Arabia. Final Internal report, NPST, King Saud University. Project No. 09-ENV836-02, pp: 175.
13. Sasaki, Y., 1989. Two-dimensional joint inversion of magnetotelluric and dipole-dipole resistivity data. Geophys, 54: 254-262.
14. Uchida, T., 1991. Two resistivity inversion for Schlumberger sounding, Geophs. Explor. of Japan (ButsuriTansa), 44: 1-17.

15. Tripp, A.C., G.W. Hohmann and C.M. Swift, 1984. Two-dimensional resistivity inversion, Geophys., 49: 1708-1717.
16. Shima, H., 1990. Two dimensional automatic resistivity inversion technique using alpha centres, Geophys., 55: 682-694.
17. Archie, G.E., 1942. The electrical resistivity log as an aid in determining some reservoir characteristics. Trans. Am. Inst. Min. Metall. Eng., 146: 56-62.
18. Archie, G., 1950. Introduction to petrophysics of reservoir rocks. AAPG Bull., 34: 943-961.
19. Fetter, C.W., 1994. Applied Hydrogeology, 3rd ed., pp: 600, Prentice-Hall, Inc., New Jersey.
20. Schlumberger, 2014. Aquifer test tutorial, documentations and Aquifer Test Method Selection Advisor. http://www.swstechnology.com/help/aquifertest/.
21. Neuman, S.P., 1974. Effect of partial penetration on flow in unconfined aquifers considering delayed gravity response, Water Resources Research, 10(2): 303-312.
22. Schon, J., 1983. Petrophysik. Akademie-Verlag, Berlin, pp: 405.
23. Gomez-Rivero, O., 1977. Some considerations about the possible use of the parameters a and m as a formation evaluation tool through well logs. Trans SPWLA 18th Ann Logging Symp J., pp: 1-24.
24. Carothers, J.E., 1968. A statistical study of the formation factor relation. Log Anal., 9(5): 13-20.
25. Hill, H.J. and J.D. Milburn, 1956. Effect of clay and water salinity on electrochemical behaviour of reservoir rocks. Trans AIME, 207: 65-72.
26. Domenico, P.A. and F.W. Schwartz, 1990. Physical and Chemical Hydrogeology (New York; Wiley).