Article

Estimation of hydraulic parameters using VES sounding and fuzzy techniques in semi arid Khanasser Region, Syria

J. Asfahani[1], **Z. Ahmad**[2]
[1]Geology Department, Atomic Energy Commission of Syria, P. O. Box 6091, Syria
[2]Scientific Services Department, Atomic Energy Commission of Syria, P. O. Box 6091, Syria
E-mail: cscientific@aec.org.sy

Received 23 February 2022; *Accepted 12 March 2022*; *Published 1 June 2022*

Abstract
An alternative approach was developed for evaluating the hydraulic conductivity (*K*) and the transmissivity (*T*) of an aquifer. The vertical electrical sounding (VES) measurements and fuzzy techniques (Takagi-Sugeno fuzzy model) are the base of this approach. This approach requires the VES measurements in some points, where available water samples exist to tune fuzzy system with fitting capability, to evaluate the hydraulic parameters. The tuned fuzzy system was used thereafter to extrapolate those parameters, even in VES points where no water samples are available. The Khanasser valley, Northern Syria was taken as a case study to apply the proposed approach. The comparison between the hydraulic parameters values obtained by the proposed approach and those of real pumping test shows an acceptable agreement between them, that attests to the viability of the new proposed technique for characterizing the hydraulic parameters of the aquifers in similar arid and semi arid regions.

Keywords hydraulic conductivity; transmissivity; VES sounding; Khanasser valley; Syria.

Computational Ecology and Software
ISSN 2220-721X
URL: http://www.iaees.org/publications/journals/ces/online-version.asp
RSS: http://www.iaees.org/publications/journals/ces/rss.xml
E-mail: ces@iaees.org
Editor-in-Chief: WenJun Zhang
Publisher: International Academy of Ecology and Environmental Sciences

1 Introduction

The hydraulic conductivity parameter, considered as the most important in hydrogeology is practiced as a groundwater modeling tool for studying and predicting the aquifer behavior during the different stages of water extraction. The hydraulic conductivity parameter is traditionally evaluated through the pumping tests technique.

The pumping tests, however suffer of being expensive, and provide with low spare resolution maps (Shevnin et al., 2006; Soupios et al., 2007). Alternative geophysical approaches are consequently invented to overcome the limitations posed by the pumping tests.

Geophysical techniques are widely practiced to invent new alternative approaches for estimating the hydraulic parameter, where specific relationships between geophysical and hydro-geological parameters are established (Heigold et al., 1979; Frohlich, 1994; Frohlich et al., 1996; Yadav and Abolfazli, 1998; Salem, 1999; De Lima and Niwas, 2000; Niwas and De Lima, 2003; Dhakate and Singh, 2005; Lesmes and Friedman, 2005; Asfahani, 2007a, b, c, 2010a, b; Aretouyap et al., 2015; Aretouyap et al., 2018; Aretouyap et al., 2019).

The geophysical works, particularly the measurements of vertical electrical sounding (VES) technique presented in this paper are a part of an international research program in the Khanasser valley, Northern Syria, in which three scientific organizations; Bonne University, Germany, International Center for Agriculture Research in the Dry Areas (ICARDA), and Syrian Atomic Energy Commission (AEC) have been collaborated. The specific marginal dry-land environments problems were solved by this research program (Schweers et al., 2002).

The use of (VES) technique provides several advantages and has its superiority when is compared with the traditional pumping tests technique. The use of dense VES sounding points allows for obtaining faster information regarding the hydraulic conductivity distribution with high resolution maps.

The new in this research is to evaluate the transmissivity and hydraulic conductivity parameters of the Quaternary aquifer in the semi arid Khanasser valley region, Northern Syria (Fig. 1) through developing and proposing the fuzzy approach, that takes into account only the groundwater salinity.

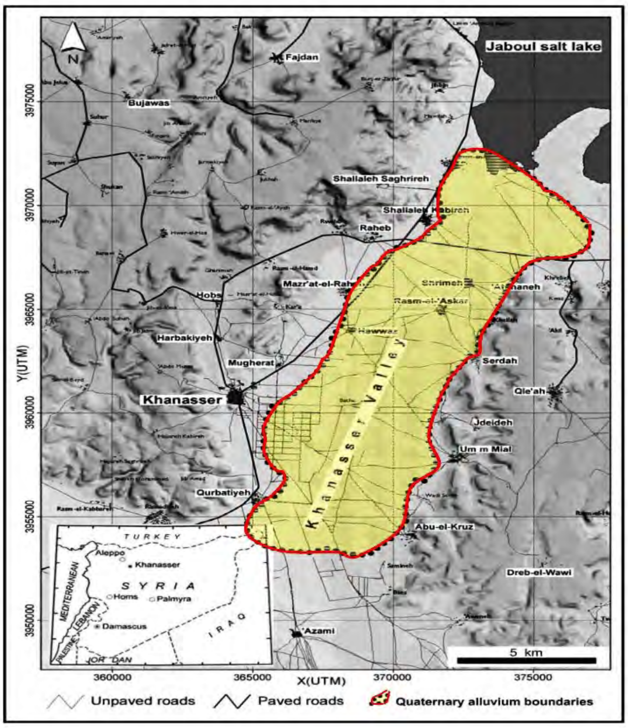

Fig. 1 Location of the Khanasser valley, Northern Syria.

A data-driven approximation of the relation between the parameters of hydraulic conductivity, transmissivity, the saturated aquifer resistivity, and the Quaternary aquifer saturated thickness is provided through the ability of fuzzy system used as function approximator. Similar neural network technique has been already proposed to characterize the Quaternary aquifer of the Khanasser valley region (Asfahani and Ahmad, 2020).

The only four available pumping tests in this work (Asfahani, 2016) are not sufficient to tune fuzzy system. The transmissivity and the hydraulic conductivity values of those pumping tests with those values obtained by using the VES technique (Asfahani, 2016) are conjointly therefore used to tune the fuzzy system.

The main objectives of this paper are therefore the following:

1- To propose and develop a new technique based on the application of vertical electrical sounding (VES) and fuzzy techniques;

2- To evaluate the parameters of aquifer hydraulic conductivity and transmissivity.

2 Hydrogeology of the Khanasser Valley

Khanasser valley study area, located approximately 70 km southeast of Aleppo City lies between two hills; the Jabal Al Hoss in the west and the Jabal Shbeith in the east.

The drainage of the northern part of the study valley is directed towards the Jaboulsalt lake, while the drainage of the southern part is directed towards the Adami depression in the south (Fig. 1). Fig. 2 shows the geological map of the study region (Ponikarov, 1964), with the VES locations, while Fig. 3 shows a geological cross-section along the AB profile.

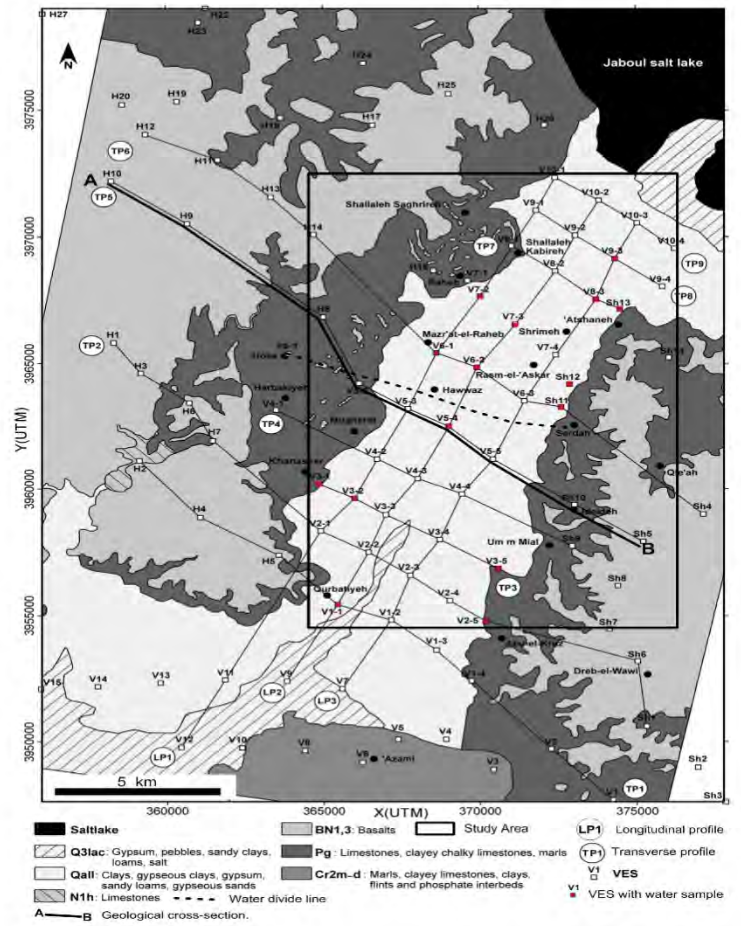

Fig. 2 Geological map of the Khanasser valley region, Northern Syria, and its surroundings (After Ponikarov, 1964), with the VES sounding locations (Asfahani, 2016).

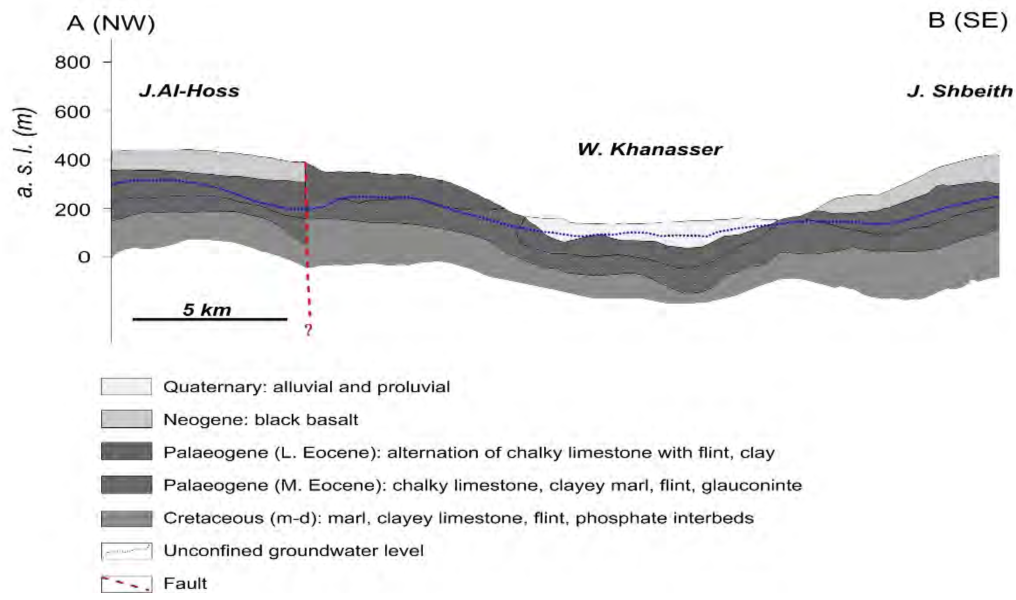

Fig. 3 Geological cross-section along the AB profile (Asfahani, 2013).

Three aquifers exist in the Khanasser valley for the groundwater extraction. The deepest one at 400 m below ground level is related to upper Cretaceous. The second one has a low productivity and is related to the Paleocene-Lower Eocene limestone aquifer (ACSAD, 1984). The average hydraulic conductivity (*k*) of 0.0054 m/day for this aquifer is referred from the pumping test (Schweers et al., 2002). The Paleogene formation has an hydraulic conductivity ranging between 0.008 m/day and 0.5 m/day as revealed by Lengiprovodkhoz (1987).

The paleogene strata in the central part of Khanasser valley above the Maestrichtian are relatively not very thick; about 50 m of lower Eocene and Paleocene.

The Quaternary water bearing formations is the most transmissive third aquifer in the study region. It is situated near the surface, and covered by some of 10 m of alluvial and proluvial soil. The direct recharge from rainwater as well as infiltrating runoff and the subsurface flow from the slopes of Jabal Shbeith and Jabal Al Hoss are the main sources for this aquifer.

The rapid development of motorized irrigation wells is responsible of the substantial increase observed during the last two decades in groundwater withdrawal from the upper, unconfined aquifer system.

The salt water intrusion originated from the Jaboulsalt lake affects Khanasser valley as indicated by the groundwater monitoring analysis, where considerable changes are clearly observed since 1998 in the quality and water level (Hoogeveen and Zobisch, 1999).

3 VES Measurements and Interpretation

Ninety-six VES were measured during this research work by using the Schlumberger configuration. Fig. 2 shows the locations of those VES points (Asfahani, 2010a, 2007a).

The distance current electrode spacing (AB/2) was between 3 m and 500 m for all those VES soundings. the two electrodes A and B are symmetrically expanded about the center of the array, while the other two M and N potential electrodes remain fixed.

For a given position of the four current and potential electrodes, the apparent resistivity (ρa) is expressed by the following equation:

$$\rho a = \frac{2\pi}{\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}} \frac{\Delta V}{I}$$

In which I is the current injected into the earth, ΔV is the measured potential difference between the two potential electrodes, and *AM*, *BN*, *AN* and *BN* are inter-distance spacing.

The field resistivity curves were interpreted by using the curve matching technique and the master curves (Orellana and Mooney, 1966) to get an initial approximate model of thicknesses and resistivities of the corresponding layers.

The initial model parameters are thereafter taken into consideration by an inverse technique Resist program (Velpen, 2004) to correctly interpret them until an acceptable fit is obtained between the resistivity field curve and the theoretical computed regenerated one (Zohdy, 1989; Zohdy and Bisdorf, 1989). The one-dimensional model (1D) is assumed while interpreting the VES points realized in the study area of Khanasser valley region. Fig. 4 shows an example of field VES sounding at the point V2-3, with its 1D interpretation and the description of the lithology of the well No.1, located as closely to this measured VES point.

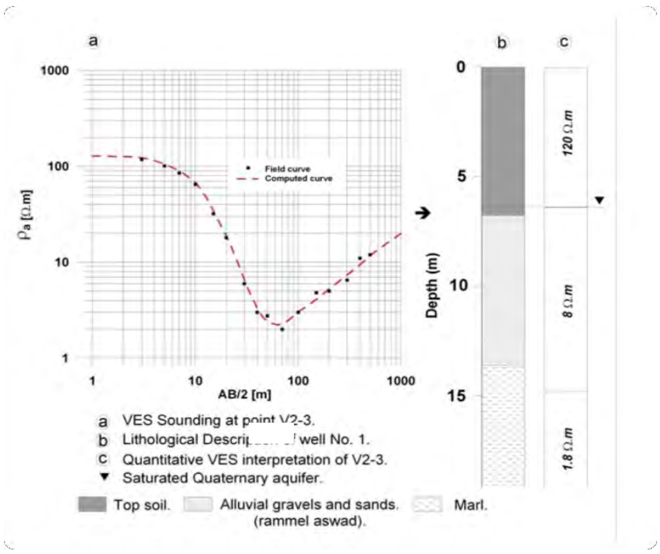

Fig. 4 Field VES example at V2-3 and its 1D interpretation, with lithological description of well No.1 for comparison.

The quantitative interpretations of the ninety six VES points, distributed on three longitudinal profiles and nine transverse profiles (Fig. 2), with the adaption of one dimensional model (1D) enabled (Asfahani, 2007a) to identify the geoelectrical characteristics of Quaternary, Paleogene and Maistrechtian deposits and the geometry of the study Khanasser valley area.

The quantitative (1D) interpretation of the VES points, distributed along the TP5 transverse profile (TP5 corresponds to the AB geological cross-section shown in Figs. 2 and 3) allows to get the subsurface geoelectrical model under TP5 as shown in Fig. 5.

The resistivity and thickness values of the Quaternary and Paleogene aquifers are well identified (Fig. 5).

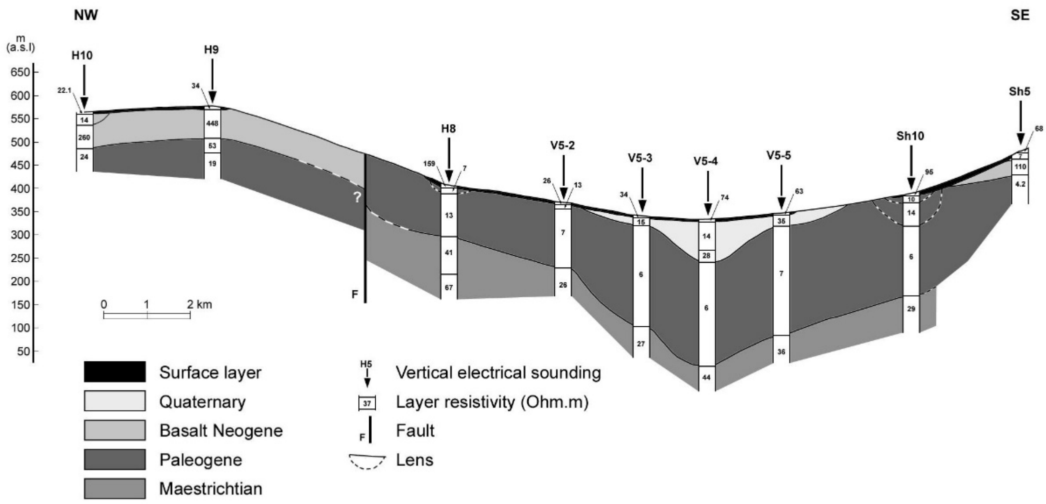

Fig. 5 subsurface geoelectrical model under TP5 profile (Asfahani, 2013).

Two geological structures revealing a clear deep tectonic effect are in presence in the study region of Khanasser valley, one in the south and the other in of the line joining the Hobs and Sirdah towns (Fig. 2), as previously indicated by Asfahani (2007a).

4 Fuzzy Function Approximation

Fuzzy Logic is one of the three roots of soft-computing; it has been successfully practiced in several applications in scientific and engineering sectors, due to its broad number of benefits. The easy understandability and the simplicity of the model while encapsulating complex relations among variables are ones of the keys of the paradigm. The other main characteristic of the fuzzy logic technique is its capability to bring meaning to the variables involved in the studied problem and to interpret the model through the use of linguistic values.

Many authors have in general obtained good enough results through dealing with fuzzy systems and fuzzy logic for function approximation from an input/output data set, using grid as well as clustering techniques . Specifically, the TSK model (Takagi and Sugeno, 1985) fits better to different and several problems due to its computational capability.

The fuzzy inference method proposed by Takagi, Sugeno and Kang, which is known as the TSK model in fuzzy systems field, has been one of the major issues in both theoretical and practical research for fuzzy modeling (Yen and Wang, 1998). The basic idea is the subdivision of the input space into fuzzy regions and to approximate the system in each subdivision by a simple model.

The Takagi-Sugeno fuzzy models are suitable to approximate a large class of nonlinear functions. Takagi-Sugeno fuzzy model includes if-then rules with mathematical functions and fuzzy antecedents in the consequent part (Takagi andSugeno, 1985). The antecedent fuzzy sets divide the input space into a number of fuzzy regions, while the consequent functions describe the system’s behavior in these regions. The unknown nonlinear function *f* can be throughout this contribution approximated by Takagi-Sugeno type fuzzy rules (Takagi and Sugeno, 1985). The rule base comprises a collection of *N* rules of the form:

$$R^{(r)}: if\ x_1\ is\ X_1^{(r)}\ and\ x_2\ is\ X_2^{(r)} \cdots x_p\ is\ X_p^{(r)}\ then\ f^{(r)}(x) = a_r^T x \tag{1}$$

where the upper index represents the rule number, $X_i^{(r)}$ is an activated fuzzy set defined in the universe of discourse of the i^{th} input x_i . The input vector defines the subsets of elements in the rule premise part and in the rule consequent part, x_1, x_2, …,x_p are the current values of the fuzzy model input variables. a_r is a parameter vector. Such a very simplified fuzzy model can be regarded as a collection of many linear models applied locally in the fuzzy regions defined by the rule premises. The structure of the fuzzy model includes two blocks a fuzzifier and an inference engine. The fuzzifier performs the function of fuzzification and converts input data from an observed input space into proper linguistic values of fuzzy sets through predefined input membership functions. The fuzzy inference engine should match the output of the fuzzifier with the fuzzy logic rules, performing fuzzy implication and approximation reasoning to decide the value of the modeled output variable. Fuzzy implication in the i^{th} rule (1) can be realized by means of a product composition:

$$\mu^{(r)}(x) = \prod_{j=1}^{p} \mu_{X_j^{(r)}}(x_j) \tag{2}$$

where $\mu_{X_j^{(r)}}$ is the membership function defined on the fuzzy set $X_j^{(r)}$ and $\mu_{X_j^{(r)}}(x_j)$ specify the membership fulfillment degrees upon the j^{th} fuzzy set of the corresponded j^{th} input signal and they are calculated according to the chosen B-spline membership function.

$$\mu_{X_j^{(r)}}(x_j) = B_{r,k_j}(x_j) \tag{3}$$

Using the centre of gravity method to defuzzify the fuzzy set, the real output of the system is given by the following inference formula (Takagi and Sugeno, 1985).

$$f(x) = \frac{\sum_{r=1}^{N} f^{(r)}(x)\mu^{(r)}(x)}{\sum_{r=1}^{N} \mu^{(r)}(x)} \tag{4}$$

given a set D of input/output data, and a configuration of membership functions for the input variables, how to adapt the consequents of the rules so that the TSK model output optimally fits the data set D. The Least Square Error (LSE) algorithm will be used for that purpose. LSE tries to minimize the error function:

$$J = \sum_{m \in D} \left(y_m - f(x_m)\right) \tag{5}$$

where f is the output of the TSK fuzzy system as in (4).

5 Application to Hydraulic Parameters Estimation

Fuzzy system illustrated in Fig. 6 is used in this paper to provide a data-driven approximation of the relation between hydraulic conductivity (K), the saturated thickness of the Quaternary aquifer (h) and the saturated aquifer resistivity (ρ_{rock}), and between transmissivity T, ρ_{rock} and h.

Four pumping tests are only available in this work (Asfahani, 2016), which are not sufficient to tune fuzzy system. The computed values of the transmissivity and the hydraulic conductivity based on the VES measurements, recently obtained by Asfahani (2016) and those additional four available pumping test measured values are therefore used.

The proposed methodology based on the fuzzy system is established as follows:

1. Carry out firstly the field VES measurements in the locations, where water samples are available for the Quaternary aquifer to estimate their water resistivities (ρ_w). Fifteen VES points close to the water sample locations have been located and measured. Their quantitative interpretative results of the thickness and the resistivity of the saturated Quaternary aquifer (ρ_{rock} and h) are shown in Table 1 (Asfahani, 2016).
2. Determine the formation factor (F), that we need when applying Archie's law 1942 (Archie, 1942).
3. Apply Salem's formula 2001 to compute the corresponding hydraulic conductivity (K) (Salem, 2001; Asfahani, 2016).
4.

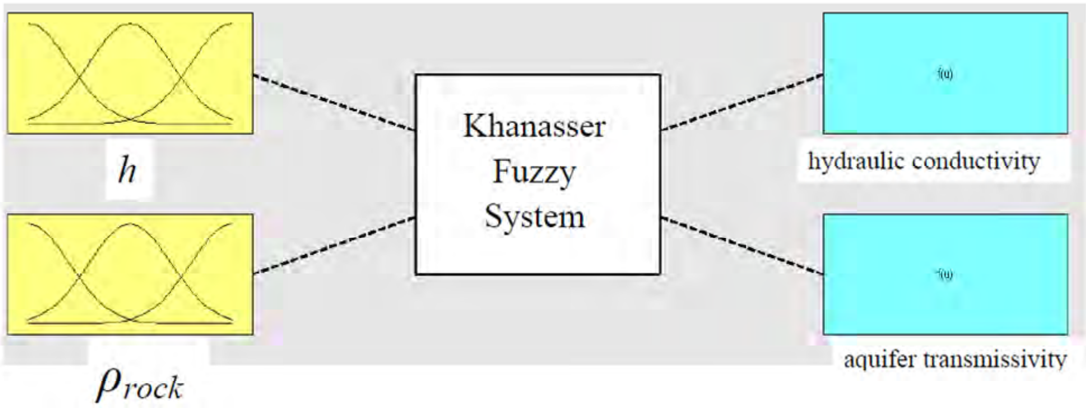

Fig. 6 Khanasser fuzzy system in Matlab.

5. Compute the aquifer transmissivity (T) through knowing the average of the hydraulic conductivity ($\bar{K}$) of those 15 VES points and their saturated thickness (h).
6. Tune fuzzy system with fitting capability using the data computed in step 2, 3, and 4 shown in Table 1.
7. Carry out the VES measurements secondly in the locations having no water samples.
8. Use the fuzzy system tuned in step 5 to extrapolate the hydraulic conductivity (K) and the transmissivity (T) in the VES points, even where no water samples are available.

Archie's law in its general form is practiced to evaluate the formation factor (F) as follows:

$$F=\rho_{rock}/\rho_w \qquad (6)$$

In which, the saturated aquifer resistivity (ρ_{rock}) is estimated from the quantitative interpretation of the measured VES points, and the pore fluid resistivity (ρ_w) is obtained through converting water conductivity.

Salem's formula (2001) relates the hydraulic conductivity (K) in a given VES point with the formation factor (F) obtained by using the VES method. It is used to get the hydraulic conductivity (K) as follows:

$$K= 0.66528*F^{2.09} \qquad (7)$$

The transmissivity (T) is thereafter computed for the interpreted fifteen VES points as follows:

$$T = \bar{K} * h \qquad (8)$$

In which, $\bar{K}$ is the average of the hydraulic conductivity of the available fifteen water samples indicated in Table 1, h is the saturated Quaternary aquifer thickness at a given VES point.

6 Results and Discussion

A tune fuzzy system with fitting capability was created by the application of MATLAB fuzzy Toolbox to evaluate the transmissivity and the hydraulic conductivity of the Quaternary aquifer in Khanasser valley region (MATLAB, 2009). The measured input and the measured outputs data are required in such a tunings procedure. The resulting thickness and resistivity of the saturated Quaternary aquifer (ρ_{rock} and h) shown in Table 1 are the measured inputs in this paper. The computed values of (K) and (T) in the fifteen VES locations, for which water samples of the Quaternary aquifer exist are the computed outputs.

The four available measured values of (K) derived by the pumping tests in the study Khanasser valley region were used instead of the calculated (K) related to the VES points, realized as nearest to those pumping tests locations, at VES locations of V1-1 (at the locations of Qurbatieh), V3-1 (Khanasser), V5-4 (Batha), and V6-2 (Rasm Askar). The hydraulic conductivity values obtained by pumping tests at those mentioned points were 1.55 m/day, 4.4 m/day, 6.56 m/day, and 54.4 m/day, respectively (Schweers et al., 2002).

The results presented in Table 1 are directly used at the first stage for applying the developed fuzzy approach. The average aquifer water resistivity of the fifteen water samplings of 3.35 Ω.m was used instead of (ρ_w) to estimate the formation factor (F) as explained above in equation (6).

The spatial variations of both resistivity (ρ) and saturated thickness (h) of the Quaternary aquifer for the thirty four VES locations (15 VES with water samples and 19 VES without water samples) in the study Khanasser valley are shown in Fig. 7a and b.

The hydraulic conductivity estimated based on Salem formula (equation (7)) for those 15 VES points varies between 2.65 m/day at VES (V1-1) point and 37 m/day at VES (V6-2) point, with an average ($\bar{K}$) of 13.8 m/day and a standard deviation of 9.4 m/day.

The use of an average ($\bar{K}$) of 13.8 m/day allows to compute the transmissivity (T) as explained by equation (8). T varies between 79 m^2/day at the VES (V7-3) point and 814 m^2/day at the VES (V5-4) point with 277 m^2/day as an average.

Table 1 Data used to tune fuzzy system.

Location	ρ_w (Ω.m)	ρ_{rock} (Ω.m)	***h*** **(m)**	***K*** **(m/day)**	***K**** **(m/day)**	***T*** **(m^2/day)**
V6-1	3.03	8.5	12	4.65		165.6
V9-3	1.3	11	22.5	7.98		310.5
V2-5	2.16	9.6	23.8	6		328.44
V1-1	1.79	6.5	31.4	2.65	1.55	433.32
Sh11	2.506	30	31.9			440.22
Sh12	7.44	15.5	25	16.3		345
Sh13	4.52	9	10	5.25		138
V8-3	3.47	17	11.5	19.82		158.7

V3-1	6.85	10	7.7	6.54	4.4	106.26
V3-2	6.02	15	25	15		345
V7-2	4.33	16	6	17.5		82.8
V7-3	3.03	16	5.7	17.5		78.66
V3-5	1.67	19	12.9	25		178.02
V5-4	1.2	14	59	13	6.56	814.2
V6-2	1	23	17.2	37	54.4	237.36

K* is the pumping test value.

The resulting tuned fuzzy system and its application allow getting the values of (*K*) and (*T*) in the other nineteen VES points, where no water samples are available. Such a turned fuzzy procedure is to characterize as a first approximation the Quaternary aquifer in the study Khanasser valley (Table 2). The tuned fuzzy system allows to directly get the transmissivity and the hydraulic conductivity values as shown in Table 2.

The hydraulic conductivity values *K* for the 19 VES points vary between 4.88 m/day at VES (V9-2) point, and 40.67 m/day at VES (V4-3) point, with an average of 14.43 m/day and a standard deviation of 8.96 m/day.

The transmissivity values for the nineteen VES vary between 167.21 m^2/day at VES (V2-3) point, and 456.28 m^2/day at VES (V2-1), with an average of 274.53 m^2/day and a standard deviation of 101.22 m^2/day.

Table 3 shows the statistical results of (*K*) and (*T*) for the nineteen VES points obtained by using fuzzy technique.

E_K and E_T in the Table 2 are the absolute difference between (*K*) and (*T*) values computed using fuzzy system and those computed using the approach proposed in (Asfahani, 2016). E_K varies between 0.02, and 1.61 m/day, with an average of 0.72 m/day and a standard deviation of 0.39 m/day. E_T varies between 0.82 m^2/day and 29.71 m^2/day, with an average of 11.42 m^2/day and a standard deviation of 7.49 m^2/day.

Table 2 Hydraulic conductivity (*K*) and transmissivity (*T*) *by* using fuzzy system in nineteen VES points, where no water samples are available.

Location	***h*** **(m)**	ρ_{rock} **(Ω.m)**	K_{fuzzy} **(m/day)**	T_{fuzzy} **(m^2/day)**	E_K	E_T
V10-4	53	12	8.43	447.42	0.16	8.88
V10-3	18	7	11.41	205.64	0.71	12.95
V10-1	34	10	9.42	320.64	0.72	24.79
V10-2	40	15	10.54	422.00	0.02	0.82
V9-1	21	15	14.43	303.13	0.92	19.33
V9-2	50	4.3	4.88	244.53	0.17	8.94
V9-4	21	9	11.50	241.61	0.88	18.55
V8-2	16.7	11	13.86	231.58	0.66	11.08
V6-3	35	17	12.80	448.48	0.84	29.71
V5-3	15	15	16.70	250.72	0.68	10.31
V5-5	14	36	27.58	386.33	0.81	11.42
V4-3	4.5	22	40.67	183.07	0.75	3.40
V3-3	19	15	14.44	274.53	0.27	5.20

V3-4	11.8	26	25.32	298.93	1.61	19.09
V2-1	15	43	30.41	456.28	0.89	13.40
V2-2	9	6.6	18.80	169.27	0.96	8.69
V2-3	8.5	8	19.67	167.21	0.29	2.48
V2-4	14	11.5	16.00	224.18	1.04	14.62
V1-2	58	10	7.35	427.11	0.26	15.57

Table 3 Statistical parameters using nineteen VES points with no water samples.

	h **(m)**	ρ_{rock} **(Ω.m)**	***K*** **(m/day)**	***T*** **(m^2/day)**	E_K	E_T
Min	4.5	4.3	4.88	167.21	0.02	0.82
Max	59	43	40.67	456.28	1.61	29.71
Average	22	14.8	14.43	274.53	0.72	11.42
SD	15	8.5	8.96	101.22	0.39	7.49

The hydraulic conductivity values (*K*) for the total of thirty four VES points (fifteen VES with available water samples, and nineteen VES with no water samples) vary between 2.74 m/day at the VES (V1-1) point, and 40.67 m/day at the VES (V6-2) point, with an average of 14.43 m/day and a standard deviation of 9.19 m/day as shown in Fig. 7c.

The transmissivity values (*T*) for the total of thirty four VES points (fifteen VES with available water samples, and nineteen VES with no water samples) vary between 81.3 m^2/day at the VES (V7-3) point, and 837.48 m^2/day at the VES (V5-4) point, with an average of 262.63 m^2/day and a standard deviation of 148.74 m^2/day as indicated in Fig. 7d.

A clear distinct transmissive structure is observed at the south of Hobs-Sirdah joining line determined by Asfahani (2007a) as indicated on the transmissivity map (Fig.7d).

This transmissivity is low at the north of the joining line and increases towards the Sabkha.

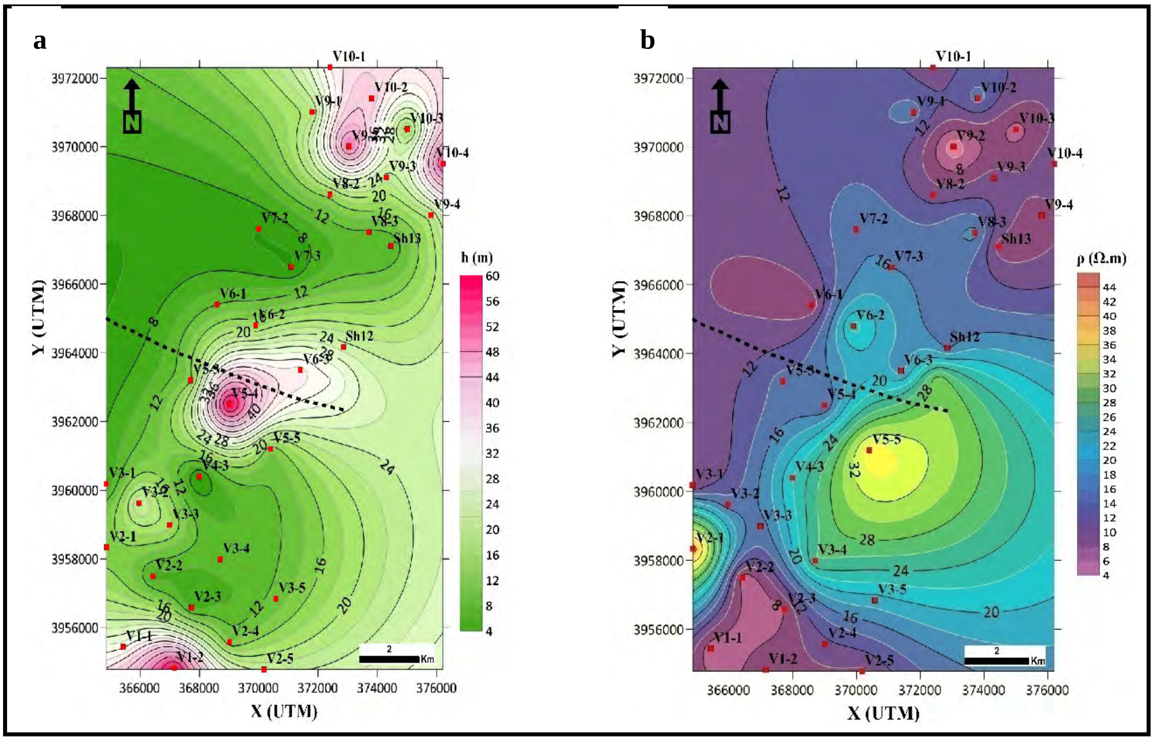

Fig. 7a: Thickness of Quaternary aquifer (*h*) in thirty four VES points in the research area, **b**: Resistivity (*ρ*) of the Quaternary aquifer in thirty four VES points in the research area.

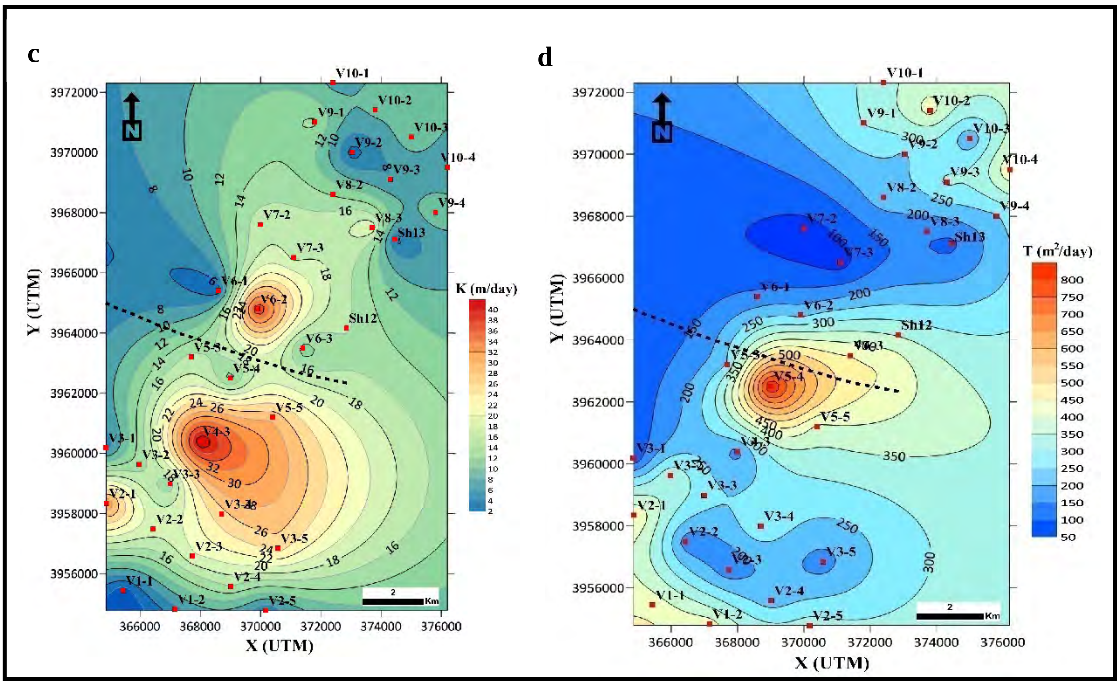

Fig. 7c: Hydraulic conductivity (*K*) of the Quaternary aquifer in thirty four VES points in the research area, **d**: Transmissivity (*T*) of the Quaternary aquifer in thirty four VES points in the research area.

Table 4 summarizes the main statistical hydrogeological and geophysical parameters obtained for the Quaternary aquifer at the totality of thirty four VES points in the Khanasser valley region.

Table 4 Statistical geophysical and hydrological parameters at the thirty four VES points for Quaternary aquifer in the study Khanasser valley, Syria.

	ρ_{rock} (Ω.m)	***h*** (m)	***K*** (m/day)	***T*** (m^2/day)
Min	4.3	4.5	2.74	81.3
Max	43	59	40.67	837.48
Average	14.8	22	14.43	262.63
SD	8.5	15	9.19	148.74

The results shown in Table 4 are quite similar to those obtained recently while characterizing the Quaternary aquifer of the study Khanasser valley by using the neural network technique (Asfahani and Ahmad, 2020).

The high thicknesses of the alluvial gravels and sands, labeled locally as rammelaswad of the Quaternary aquifer in the Khanasser valley observed in some studied VES points are the main responsible of the high transmissivity and yields in those VES points. The sharpen lateral and vertical variations of the rammelaswad from place to another even in very short distances explains the drastic change in the productivity of wells and the large differences in their yields.

The geoelectrical transmissivity distribution results of the fuzzy approach technique applied in this research to characterize the Quaternary aquifer in the study Khanasser valley are in a good agreement with the hydrogeological field observations. This attests the efficacy of the proposed approach for characterizing the aquifer systems in the semi arid regions worldwide.

7 Conclusion

The vertical electrical sounding (VES) and fuzzy system techniques are proposed to be used together as a new alternative technique to evaluate the hydraulic conductivity (*K*) and the transmissivity (*T*) of an aquifer.

The transmissivity and the hydraulic conductivity are estimated through tuning a fuzzy system in the VES points, where available water samples exist.

The application of tuned fuzzy system allows to extrapolate the transmissivity and the hydraulic conductivity and in the VES points, where no available water samples.

The distributions of hydraulic conductivity and the transmissivity parameters of the Quaternary aquifer in the study Khanasser valley, Northern Syria are easily characterized according to this fuzzy approach.

An acceptable agreement is clearly noticed between the hydraulic conductivity values obtained by the fuzzy approach and the real hydrological situation, indicated by the pumping tests.

The application of the fuzzy technique gives quite similar results to those obtained by using the neural approach. The main advantage of the fuzzy approach is the possibility to integrate the results of both the (VES) measurements and the pumping tests, and no intermediate empirical relations are needed. Fuzzy approach can integrate human expert knowledge expressed in if then rule to approximate the unknown relation. This makes fuzzy technique human interpretable, while the neural technique is not. The fuzzy technique requires less data than the computationally expensive neural technique.

The proposed Fuzzy approach provides a greater accuracy in predicting (*K*) and (*T*) if more pumping tests are available, and can be easily extended to be used with additional input parameters as soil porosity and density to further potentially increase its performance. The easy fuzzy approach is recommended for treating other hydrogeological problems related to semi arid regions worldwide.

Acknowledgment

Authors would like to thank Dr. I. Othman, General Director of Syrian Atomic Energy Commission for his approval to publish this research work.

Author contribution statement

J. Asfahani: Conceptualization, Methodology, Measuring and interpreting VES data, Writing-original draft preparation, Writing-review & editing. Z. Ahmad: Data VES interpretation by using fuzzy technique.

References

ACSAD, 1984. Water Resources Map of the Arab Countries. The Arab Center for the Studies of Arid Zones and Dry Lands, Damascus, Syria

Archie E. 1942. The electrical resistivity log as an aid in determining some reservoir characterestics. Technical Publication 1422, Petroleum Technology. American Institute of Mining and Metallurgical Engineer, New York, USA

Aretouyap Zakari, Nouayou Robert, Njandjock Nouck Philippe, Asfahani Jamal. 2015. Aquifers productivity in the Pan-African context. Journal of Earth System Science, 124(3): 527-539

Aretouyap Zakari, Bisso D, Njandjock Nouck P, et al. 2018. Hydrogeophysical Characteristics of Pan-African Aquifer Specified Through an Alternative Approach Based on the Interpretation of Vertical Electrical Sounding Data in the Adamawa Region, Central Africa. Natural Resources Research. https://doi.org/10.1007/s11053-018-9373-8

Aretouyap Zakari, Dieudonné Bisso, Jorelle Larissa Méli'i, et al. 2019. Hydraulic parameters evaluation of the Pan-African aquifer by applying an alternative geoelectrical approach based on vertical electrical soundings. Geofísica Internacional, 58(2): 113-126

Asfahani J. 2007a. Geoelectrical Investigation for characterizing the hydrogeological conditions in semi-arid region in Khanasser Valley, Syria. Journal of Arid Environments, 68: 31-52

Asfahani J. 2007b. Neogeneaquifer properties specified through the interpretation of electrical sounding data, Sallamiyeh region, central Syria. Hydrological Processes, 21: 2934-2943

Asfahani J. 2007c. Electrical Earth Resistivity surveying for delineating the characteristics of groundwater in semiarid region in Khanaser Valley, Northern Syria. Hydrological Processes, 21: 1085-1097

Asfahani J. 2010a. Application of surfacial geoelectrical resistivity technique in hydrogeology domain for characterizing saline groundwater in semi arid regions. In: Horizons in Earth Science Research Series (Volume 1) (Benjamin Veress, Jozsi Szigethy, eds). 351-381, NOVA Science Publishers, USA

Asfahani J. 2010b. Electricalresistivityinvestigationsforguiding and controlingfreshwaterwelldrilling in semi aridregion in Khanasservalley, Northern Syria. Acta Geophysica, DOI: 10.2478/s11600-010-0031-8

Asfahani J. 2013. Groundwater potential estimation using vertical electrical sounding measurements in the semi-arid Khanasser Valley region, Syria. Hydrological Sciences Journal – Journal des Sciences Hydrologiques. http://dx.doi.org/10.1080/02626667.2012.751109

Asfahani J. 2016. Hydraulic parameters estimation by using an approach based onvertical electrical soundings (VES) in the semi-arid Khanasser valley region, Syria. Journal of African Earth Sciences, 117(2016): 196-

206
Asfahani J, Ahmad Z. 2020. Estimation of hydraulic parameters by using VES sounding and neural network techniques in the semi-arid Khanasser valley region, Syria. Contributions to Geophysics and Geodesy, 50(1): 113-133
Dhakate R, Singh VS. 2005.Estimation of hydraulic parameters from surface geophysical methods, Kaliapani Ultramafic Complex, Orissa, India. Journal of Environmental Hydrology, 13
De Lima OAL, Niwas S. 2000. Estimation of hydraulic parameters of shaly sandstone aquifers from geological measurements. Journal of Hydrology, 235: 12-26
Frohlich RK. 1994. The electric-hydraulic relationship. A geophysical model. Trends in Hydrogeology, 1: 347-358
Frohlich RK, Fisher J, Summerly E. 1996**.** Electric-hydraulic conductivity correlation in fractured crystaline bedrock: Central Landfill, Islande, USA. Journal of Applied Geophysics, 35: 249-259
Heigold PC, Gilkeson RH, Cartwright K, Reed PC. 1979.Aquifer transmissivity from surfacial electrical methods. Ground Water, 17(4): 338-345
Hoogeveen RJA, Zobisch M. 1999. Decline of groundwater quality in Khanasservalley (Syria) due to salt-water intrusion. In: Paper Presented at International Dryland Conference. Cairo, Egypt
Lengiprovodkhoz. 1987. Water resources in the Syrian desert, Syrian Arab Republic for pasture water supply. Vol.1 Natural conditions- book 2 Hydrogeology, Moscow. USRR Ministry of land reclamation and water management, Russia
Lesmes D, Friedman SP. 2005. Relationships between the electrical and hydrogeological properties of rocks and soils. In: Hydrogeophysics, Water Science and Technology Library (Rubin Y, Hubbard S, eds). 87-128, Springer
MATLAB. 2009. Neural Network Toolbox6 Users Guide. USA
Niwas S, De Lima OA. 2003. Aquifer parameter estimation from surface resistivity data. Groundwater, 41(1): 94-99
Orellana E, Mooney HM. 1966. Master Tables and Curves For Vertical Electrical Sounding Over Layered Structures. Interciencia, Madrid, Spain
Ponikarov. 1964. The Geological Map of Syria, 1:200.000 and Explanatory Notes. Ministry of Industry, Department of Geological and Mineral Research, Damascus, Syria
Salem HS. 1999. Determination of fluid transmissivity and electric transverse resistance for shallow aquifers and deep reservoirs from surface and well-log electric measurments. Hydrology and Earth System Sciences, 3(3): 421-427
Salem HS. 2001. Modeling of lithology and hydraulic conductivity of shallow sediments from resistivity measurements using Schlumberger vertical electrical soundings. Energy Sources, 23(7): 599-618
Schweers W, Rieser A, Bruggeman A, Abu-Zakhem B, et al. 2002. Assessment of groundwater resources for sustainable management in the Khanasser valley, northwest Syria. Paper presented at ACSAD/BGR Workshop on Soil and Groundwater Quality: Monitoring Management and Protection, Amman
Shevnin V, Delgado-Rodriguez O, Mousatov A, Ryjov A. 2006. Estimation of hydraulic conductivity on clay content in soil determined from resistivity data. Geofisica Internacional, 45(3): 195-207
Soupios PM, Kouli M, Vallianatos F, Vafidis A, Stavroulakis G. 2007. Estimation of aquifer hydraulic parameters from surfacial geophysical methods: A case study of Keritis basin in Chania (Crete-Greece). Journal of Hydrology, 338: 122-131
Takagi T, Sugeno M. 1985. Fuzzy identification of systems and its applications to modelling and control. IEEE Transactions on Systems, Man, and Cybernetics, 15: 116-132

Velpen BA. 2004. Win RESIST Version 1.0. MSc Research Project. ITC, Deft, Netherlands

Yadav GS, Abolfazli H. 1998. Geoelectrical soundings and their relationship to hydraulic parameters in semi arid regions of Jalore, Northwestern India. Journal of Applied Geophysics, 39: 35-51

Yadav GS, Singh SK. 2007. Integrated resistivity surveys for delineation of fractures for ground water exploration in hard rock area. Journal of Applied Geophysics, 62(3): 301-312

Yen J, Wang L, Gillespie CW. 1998. Improving the interpretability of TSK fuzzy models by combining global learning and local learning. IEEE Transactions on Fuzzy Systems, 6(4): 530-537

Zohdy AAR. 1989. A new method for the automatic interpretation of Schlumberger and Wenner sounding curves. Geophysics, 54: 245e253

Zohdy AAR, Bisdorf RJ. 1989. Schlumberger Sounding Data Processing and Interpretation Program. USA Geological Survey, Denver, USA