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ESTIMATION OF HYDRAULIC CONDUCTIVITY USING GEOELECTRICAL DATA FOR ASSESSING OF SCALE EFFECT IN A KARST AQUIFER

UPORABA GEOELEKTRIČNIH PODATKOV ZA OCENO HIDRAVLIČNE PREVODNOSTI IN UČINKA MERILA V KRAŠKEM VODONOSNIKA

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Abstract UDC 551.444:556.34(55)

Alireza Nassimi & Zargham Mohammadi: Estimation of hdraulic conductivity using geoelectrical data for assessing of scale effect in a karst aquifer

The Salman Farsi Dam was constructed on the Ghareh-Aghaj river in the catchment of the Asmari limestone aquifer, Changal Anticline, Zagros region, Iran. In order to estimate the hydraulic conductivity of the aquifer, combination of geoelectrical (i.e., bulk resistivity of the aquifer) and hydrophysical (i.e., electrical conductivity of groundwater) data are used as an alternative approach. Porosity of the aquifer is estimated based on the modified form of Archie's empirical law assuming well-cemented carbonate rocks. Formation resistivity factor and critical pore size of the Asmari limestone aquifer are used for estimating the hydraulic conductivity on the small scale based on the Thompson Equation. The results suggest an average porosity and hydraulic conductivity of 14.4 % and 0.016 m/day, respectively. The estimated value for hydraulic conductivity is smaller than values previously determined for the aquifer, based on tracer, pumping and Lugeon tests. Comparison of the hydraulic conductivity obtained by different methods revealed scale effect of hydraulic conductivity measurements in the Asmari limestone aquifer. As a result, application of the geoelectrical and hydrophysical data can provide a cost-effective and efficient alternative to estimate hydraulic conductivity in karst aquifers on the small scale.

Keywords: hydraulic conductivity, Karst, Scale effect, Vertical electrical sounding, Iran.

Izvleček UDK 551.444:556.34(55)

Alireza Nassimi & Zargham Mohammadi: Uporaba geoelektričnih podatkov za oceno hidravlične prevodnosti in učinka merila v kraškem vodonosnika

Jez Salman Farsi je postavljen na reku Ghareh-Aghaj v območju kraškega vodonosnika Asmari, ki pripada antiklinali Changal v gorovju Zagros, Iran. Hidravlično prevodnost vodonosnika smo ocenili z kombinacijo meritev celokupne električne upornosti vodonosnika in električne prevodnosti podzemne vode. Ocena poroznosti je temeljila na prilagojeni obliki Archiejevega empiričnega zakona, pri čemer smo predpostavili dobro cementirane karbonate. Iz upornosti formacije in kritične velikosti por smo s Thompsonovo enačbo izračunali hidravlično prevodnost v majhnem merilu. Dobljena povprečna poroznost tako znaša 14,4 %, povprečna prevodnost pa 0.016 m/dan. Vrednosti hidravlične prevodnosti so precej manjše of prej dobljenih vrednosti iz sledilnih, črpalnih in Lugeonovih poskusov, kar kaže na pomemben učinek merila v obravnavanem vodonosniku. Raziskava med drugim kaže na primernost geoelektričnih in hidrofizikalnih podatkov za stroškovno ugodno oceno hidravlične prevodnosti v majhnem merilu.

Ključne besede: Hidravlična prevodnost, kras, učinek merila, vertikalno električno sondiranje, Iran.

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INTRODUCTION

Hydraulic conductivity (K) is an important parameter to describe the main characteristics of aquifers especially in heterogeneous karst terrain. Several methods are known for determining of hydraulic conductivity in karst aquifers. Accuracy and applicability of these methods are related to match the real field conditions with the theoretical assumptions of each method. Therefore comparison of the results of different methods is difficult. In order to assess a reliable result it is necessary to know and introduce hydrogeological conditions of the study area.

The scale effect for karst terrains was first reported by Király (1975). Karstification is related to the enlargement of fractures and bedding planes and resulting in high variation of estimated hydraulic conductivity which is typically between 10^{-10} to 10^{-1} m/s (Király 1975; Sauter 1991; Quinlan *et al.* 1992; Rovey 1994; Kovács 2003; Geyer 2008). This causes difficulties in karst aquifers (White 2007). With increasing scale (i.e., distance or volume) of hydraulic conductivity measurements, role of macrofractures and dissolution openings are increased in karst terrain, so it is expected that the estimated hydraulic conductivity increases. Some work pointed larger possible ranges in hydraulic conductivity than other media for karst aquifers (White 1988; Ford & Williams 1989; Smart *et al.* 1991).

Geoelectrical methods are the well-known geophysical methods for determining geological structures and overburden thickness (Drew & Goldscheider 2007). Geoelectrical methods employ artificial electrical fields. Results are usually provided as resistivity (Bechtel *et al.* 2007). These methods are suitable for locating major conduits, macrofractures and other preferential flow paths based on electrical resistivity. In these methods, information on the structure and properties of the underground are achieved without drilling, i.e. at relatively low cost (Drew & Goldscheider 2007). Results of geoelectrical methods may be difficult to interpret without ambiguity (non-uniqueness). Resolution is generally reduced with depth of investigation (i.e., the greater the depth, the lower the resolution) (Drew & Goldscheider 2007).

Vertical Electrical Sounding (VES) is the most used method for geoelectric surveying, although nowadays 2D or even 3D geoelectric measurements are state-of-the art, but using VES in this case is appropriate. VES measures the resistivity of a formation. This method has been used successfully in various environments such as limestone or alluvium (Sahu & Sahoo 2006; Dawoud & Raouf 2009; Sikandar *et al.* 2010).

Hydrochemical methods gain hydrochemical characterization (such as electrical conductivity) of groundwater bodies and information on water quality and contamination problems. Hydrochemical methods also may be used as natural tracers for the origin and movement of the water (Drew & Goldscheider 2007).

Combination of geoelectrical and hydrochemical surveys represents indirect methods of studying the porosity and hydraulic conductivity in a limestone aquifer. Geoelectrical (i.e., bulk resistivity of aquifer) and hydrochemical (i.e., electrical conductivity of groundwater) data have been used to obtain porosity in limestone or alluvial aquifers (Keller 1988; Pengra & Wong 1999; Slater 2007; Asfahani 2012; Sikandar & Christen 2012; Khalil & Monteiro Santos 2013) based on Archie's empirical law (Archie 1942). According to Archie's law, electrical resistivity increases with decreasing porosity. In the following, porosity has been used to identify hydraulic conductivity in alluvial aquifers (Slater 2007; Asfahani 2012; Sikandar & Christen 2012; Khalil & Monteiro Santos 2013) based on the Kozeny-Carman equation (Kozeny 1927; Carman 1937; Bear 1972; Domenico & Schwartz 1990). Preliminary applications of the Kozeny-Carman equation have been limited to the alluvial aquifers due to assumptions of this equation. Garing et al. (2014) proposed that the Kozeny-Carman equation is replaced by the Thompson equation (Thompson *et al.* 1987) for limestone aquifers.

The objectives of this research are: (1) estimation of the porosity and hydraulic conductivity in the Asmari limestone aquifer via combination of geoelectrical and hydrochemical data; (2) comparison of the estimated hydraulic conductivity with results of previously applied methods such as Lugeon, pumping and tracer tests.

GEOLOGY AND METHODS

STUDY AREA

The Salman Farsi Dam Site (SFDS) is located at the entrance of the Karzin Gorge on the Ghareh-Aghaj River (Fig. 1). The gorge is nearly V-shaped and symmetrical at the dam site. Slope dip of the right bank is about 25° in the lower sections, increasing to 55° from elevation 850 m above mean sea level (a.m.s.l.). Dip slope of the left bank is low on the alluvial plain, then increasing to 25° to

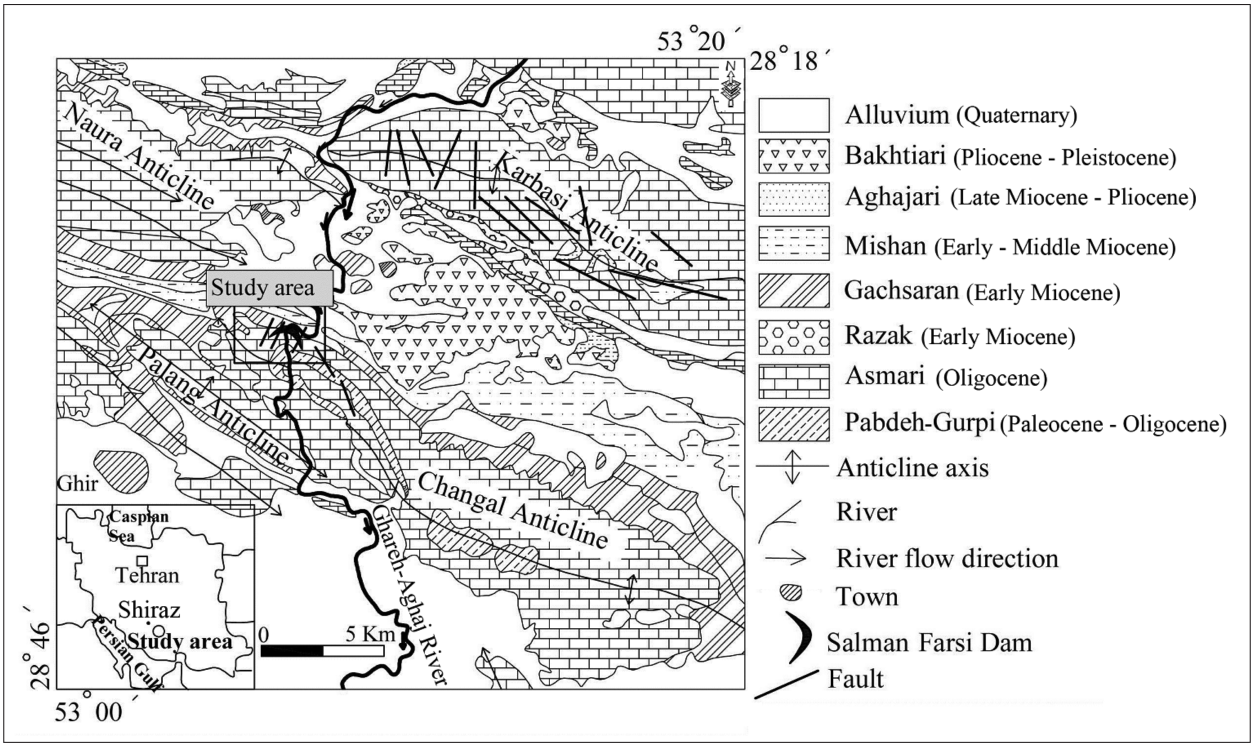

Fig. 1: General geological map of the study area (modified from Mohammadi et al. 2010).

50° upwards from elevation 880 m a.m.s.l.. The river bed is about 833 m a.m.s.l. and 20 m wide. The river channel is filled by alluvial deposits on the left bank, whereas bedrock outcrops on the right side (Fars Regional Water Authority 1994). A simplified stratigraphic sequence of the study area is shown in Tab. 1.

It is possible to group the units of the Asmari Formation in three principal sub-units and to correlate them with the stratigraphy. The upper unit of the Asmari Formation is made out of a very heterogeneous sequence of thinly bedded limestone with marls and siltstones. The central unit is more homogeneous and thickly bedded.

Tab. 1: Summarized stratigraphy of the study area (Fars Regional Water Authority 1994).

Age	*Formation*	*Abbreviation*	*Lithology in the study area*	*Exposition in the study area*
Quaternary	-	Q	river alluvium, co-alluvial deposits	Reservoir
Late Pliocene to Pleistocene	Bakhtiari	Bk	unconformable deposited massive conglomerate and sandstone	Reservoir
Late Miocene to Pliocene	Aghajari	Aj	calcareous sandstone, red marls and siltstone	Discontinuously outcropping in the Reservoir
Early to Middle Miocene	Mishan	Mn	grey marl and shelly limestone	Reservoir
Early Miocene	Razak or Gachsaran	Rz or Gs	"red" shale and siltstone with marls and gypsum	Reservoir
Oligocene to Early Miocene	Asmari	As	cream to brown weathered, nummolitic limestone with marly and shelly intercalations	Dam foundation area Rim of the reservoir
Late Paleocene to Oligocene	Pabdeh	Pd	cherty, fossiliferous and conglomeratic limestone (bottom) passing into shale interbedded with thinly bedded marly limestone	Core of the Changal Anticline (downstream of the dam site)
Up. Cretaceous – Paleocene	Gurpi	Gu	bluish-grey marl and shale	Core of the Changal Anticline
Up. Cretaceous	Sarvak	Sr	well bedded brown massive limestone with abundant siliceous nodules and ferruginous brecciated limestone at the top	Core of the Changal Anticline

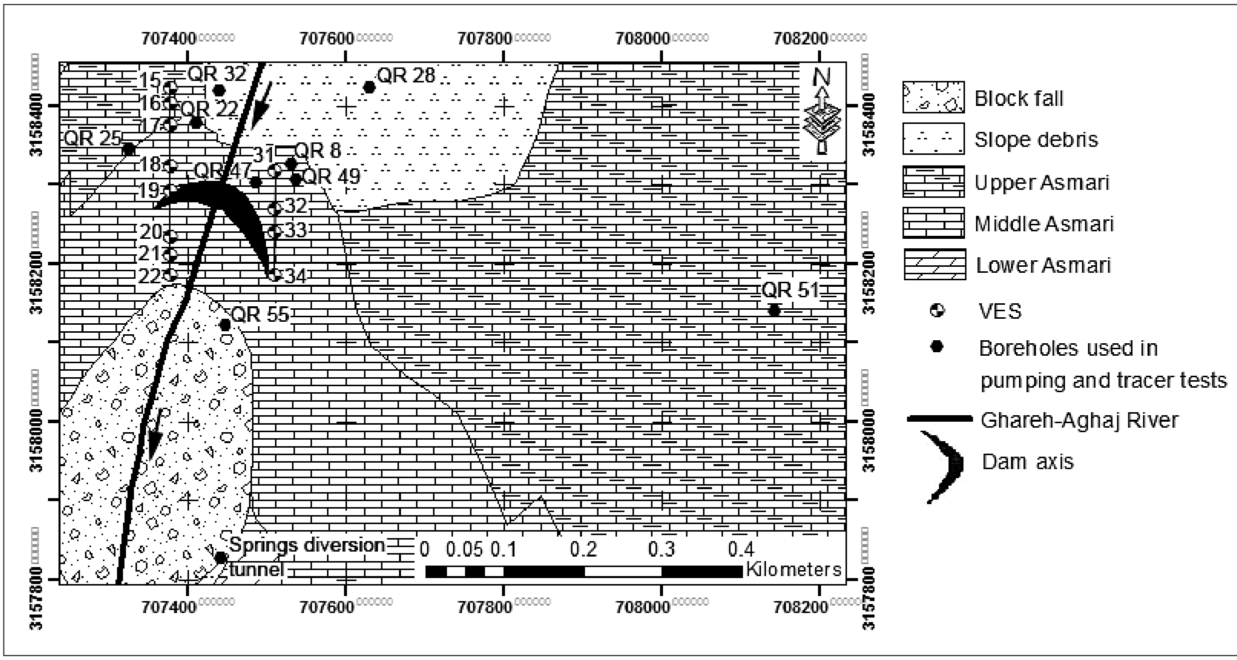

Fig. 2: Location of the geoelectrical profiles in the geological map of the SFDS.

Lithologically, this unit is characterized by the vuggy, porous limestone, and the nummulitic limestone, so called "calcarenite". Finally the lower unit of the Asmari Formation is characterized by a very regularly bedded, finely grained brown limestone at the top, very thickly bedded cherty limestone in the center and an extremely regularly sequence of thinly bedded limestone with thin marly beds at the base (Fars Regional Water Authority 1994).

There are a few joint sets in the dam site area. The major joints are predominant and play a basic role in underground karst features. However minor joints (much shorter in length) have also been important in some parts of the investigated area. According to the statistical orientation, two main systems of joints (small-scale faults) are presented: J1 (135/80°) and J2 (275/80°) (Vucković & Milanović 2001).

The main discontinuities (J1 and J2) were developed by the stress field of the folding phase. Both systems are very steeply dipping, subvertical to vertical (Vucković & Milanović 2001).

System J1 was frequently slickensided and striated due to shearing. In the geological past, movements have occurred either in the form of transcurrent or normal reverse faults. Rock wall contacts vary between rough and undulating. Some of them have aperture 0.5–2 m, filled with mylonitic material (clay and sandy clay with crushed limestone blocks) (Vucković & Milanović 2001).

System J2 is quite uniformly orientated and mostly found on the left dam bank. Displacements range between a few decimeters and up to several meters (Vucković & Milanović 2001).

A few flat lying discontinuities (18/32, 161/22 and 133/25) were measured on the right abutment (Vucković & Milanović 2001). At this area, high karstification is generally located around the intersection of faults or discontinuities (Fazeli 2007).

METHOD OF STUDY

Porosity was calculated via the modified form of Archie's empirical law for well-cemented sedimentary rocks (Keller 1988):

$$\frac{1}{\rho_e} = \frac{1}{a} \emptyset^m S^n \sigma_w \quad (1)$$

where ρ_e is the bulk resistivity of aquifer, σ_w is the electrical conductivity of groundwater, and Ø is the porosity. Then S, the water saturation, is in this case S=1, and from two measurements (ρ_e and σ_w) could be determined the porosity, if both α (the tortuosity factor) and m (the cementation exponent) are known. The parameters α and m are used to force the function to fit the data from a given rock. Parameters α and m for well-cemented sedimentary rocks are in the order 0.62 and 1.95, respectively (Keller 1988).

Garing *et al.* (2014) who showed the results of Thompson equation fit remarkably well with heterogeneous carbonate rocks situation. Hydraulic conductivity (m/s) was computed by using the Thompson equation (Thompson *et al.* 1987):

$$K = \left(\frac{1}{226}\right) \times \left(\frac{d_c^2}{F}\right) \times \left(\frac{\rho g}{\mu}\right) \quad (2)$$

Where d_c is the critical pore size (pore size below which mineral precipitation no longer occurs, 10 μm in the Asmari limestone aquifer), F is the formation resistivity factor $F = \rho_e \cdot \sigma_w$), ρ is density of the fluid (996.636 kg/m^3 at 25°C), μ is the dynamic viscosity of the fluid (0.00089 kg/(m*s) at 25°C), and g is the gravity (9.81 m/s^2).

The geoelectrical method, VES, was performed in the SFDS by the Tehran University Geophysics Institute. The electrical resistivity (ρ_e) was measured on two profiles, which were located around the Ghareh-Aghaj River (Fig. 2). VES's were conducted in the 12 points of the Asmari limestone aquifer at the SFDS by employing a Schlumberger electrode configuration. The electrode spacing (AB/2) used for all the soundings was maximum up to 1000 m (Riahi *et al.* 1997). Electrical conductivity of groundwater (σ_w) was extracted from Fars Regional Water Authority (1997).

RESULTS AND DISCUSSION

The results of the estimated porosity and hydraulic conductivity are presented in Tab. 2. The average porosity was estimated 14.4 %, based on combination of the geoelectrical and hydrochemical data (Tab. 2). Additionally, the average porosity was estimated 12.2 % from 46 rock samples of the study area in the laboratory (Fars Regional Water Authority 1995). The difference is due to the difference in location of the sampling points.

In order to calculate of the hydraulic conductivity in the small scale, formation resistivity factor (F) is the main parameter. Fig. 3 shows variation of the hydraulic conductivity versus formation resistivity factor (F) at the SFDS. Increasing the formation resistivity factor (F) is accompanied by decreasing of the hydraulic conductivity (Eq. 2 and Fig. 3).

The average hydraulic conductivity was estimated 0.016 m/day on the small scale at the SFDS (Tab. 2). Hydraulic conductivity has also been calculated for different scales and methods at the SFDS (Tab. 3) by Nassimi and Mohammadi (2016). Tab. 3 nicely shows that the borehole QR 22 at depth 18 to 23 m hit a larger conduit.

Tab. 2: Estimation of the porosity and hydraulic conductivity via combination of geoelectrical and hydrochemical data at the SFDS.

VES Number	ρ_e (Ω.m)	σ_w (S/m)	Ø (%)	K (m/day)
15	175	0.1989	12.7	0.012
16	185	0.1875	12.7	0.012
17	190	0.1714	13.1	0.013
18	320	0.1417	11.1	0.009
19	225	0.1246	14.2	0.015
20	420	0.0903	12.1	0.011
21	230	0.0777	17.8	0.024
22	420	0.0628	14.6	0.016
31	160	0.1291	16.6	0.020
32	145	0.1411	16.6	0.021
33	145	0.1486	16.2	0.019
34	155	0.1622	15.0	0.017
Average	-	-	14.4	0.016

Fig. 4 shows the hydraulic conductivity versus distance (i.e., scale) at the SFDS. Figure 5 also shows scale effect

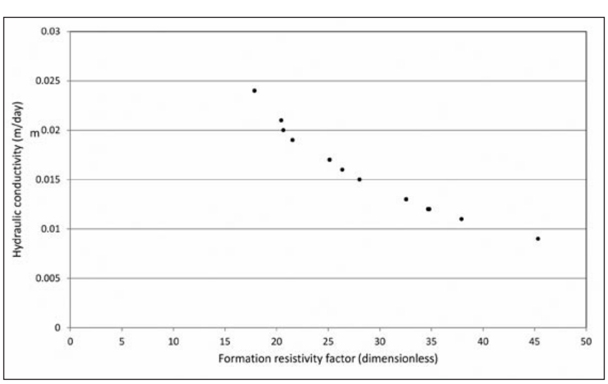

Fig. 3: The hydraulic conductivity versus formation resistivity factor (F) at the SFDS.

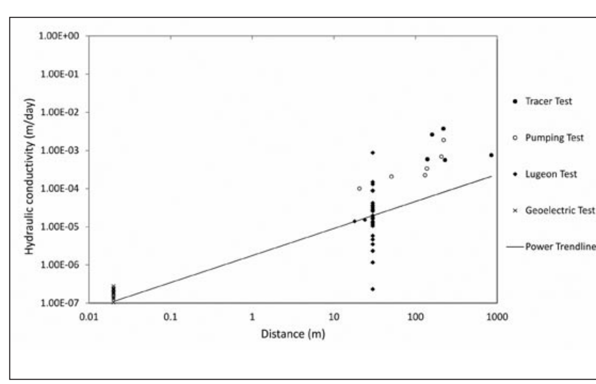

Fig. 4: The hydraulic conductivity versus distance (i.e., scale of measuring approach) at the SFDS.

Tab. 3: Estimation of hydraulic conductivity via tracer, pumping and Lugeon tests at the SFDS (extracted from Nassimi & Mohammadi 2016). QR means borehole.

Test	*Place*	*Distance or test size (m)*	*K (m/day)*
Tracer test	QR 51- Springs diversion tunnel	850	64.7
	QR 32- QR 28	220	319.0
	QR 32- The river at the location of the dam	160	223.4
	QR 28- QR 8	140	50.3
	QR 28- QR 55	230	48.3
Pumping test	QR 8- QR 49	20.6	8.6
	QR 8- QR 47	51.0	17.7
	QR 8- QR 22	131.1	19.3
	QR 8- QR 28	138.4	28.9
	QR 8- QR 25	207.5	59.2
	QR 8- QR 55	221.4	160.6
Lugeon test	QR 22 depth 13 to 18 m	30	3.2
	QR 22 depth 18 to 23 m	30	74.8
	QR 22 depth 23 to 28 m	30	0.4
	QR 22 depth 28 to 33 m	30	0.2
	QR 22 depth 33 to 38 m	30	0.1
	QR 22 depth 38 to 43 m	30	0.1
	QR 22 depth 43 to 48 m	30	0.2
	QR 22 depth 48 to 53 m	30	1.7
	QR 22 depth 53 to 58 m	30	0.1
	QR 22 depth 58 to 63 m	30	2.3
	QR 22 depth 63 to 68 m	30	0.1
	QR 22 depth 68 to 73 m	30	0.5
	QR 22 depth 73 to 78 m	30	1.1
	QR 22 depth 78 to 83 m	30	1.5
	QR 22 depth 83 to 88 m	30	3.1
	QR 22 depth 88 to 93 m	30	3.6
	QR 22 depth 93 to 98 m	30	1.2
	QR 22 depth 98 to 103 m	30	0.2
	QR 22 depth 103 to 108 m	30	1.1
	QR 22 depth 108 to 113 m	30	0.9
	QR 22 depth 113 to 118 m	30	1.4
	QR 22 depth 118 to 123 m	30	0.2
	QR 22 depth 123 to 128 m	30	0.2
	QR 22 depth 128 to 133 m	30	0.1
	QR 22 depth 133 to 138 m	30	0.2
	QR 22 depth 138 to 143 m	30	2.5
	QR 22 depth 143 to 148 m	30	0.1
	QR 22 depth 148 to 153 m	30	0.1
	QR 28 depth 33 to 37 m	24	1.3
	QR 28 depth 37 to 40 m	18	1.2
	QR 28 depth 40 to 45 m	30	0.02
	QR 28 depth 45 to 50 m	30	1.0
	QR 28 depth 50 to 55 m	30	1.4
	QR 28 depth 55 to 60 m	30	2.2
	QR 28 depth 60 to 65 m	30	7.7
	QR 28 depth 65 to 70 m	30	0.2
	QR 28 depth 75 to 80 m	30	0.3
	QR 32 depth 5.7 to 10.7 m	30	11.2
	QR 32 depth 10.7 to 15.7 m	30	2.8
	QR 32 depth 15.7 to 20.7 m	30	12.8
	QR 32 depth 20.7 to 25.7 m	30	7.5
	QR 32 depth 25.7 to 30.7 m	30	7.6

on the hydraulic conductivity in karstified limestone aquifers. These two figures revealed scale effect at the SFDS.

The average hydraulic conductivity obtained by the combination of geoelectrical and hydrochemical data (Thompson equation) was much less than the Lugeon, pumping and tracer tests results (Fig. 4). Smaller values for the hydraulic conductivity based on the Thompson equation (combination of geoelectrical and hydrochemical data) are due to the scale effect (Fig. 4, Fig. 5); because the distance in the samples studied to obtain the Thompson equation (maximum 0.02 m) is much less than the geometric mean of the distance in the Lugeon (30 m), pumping (97.8 m) and tracer tests (249.3 m). In other words, in the karst terrain, estimated values of K based on larger scale experiments is bigger (Bear 1972; Rovey & Cherkauer 1995; Vacher & Florea 2015) and more reliable (Vandenbohede & Lebbe 2003; Nassimi & Mohammadi 2016) than those based on the smaller scale, due to important role of preferential flow paths in the larger scale. Rovey and Cherkauer (1995) showed hydraulic conductivity increases approximately linearly with distance on log-log plots for a range between 20 and 220 m. Some research also showed scale effect in the karst aquifers (Király 1975; Quinlan et al. 1992; Rovey 1994; Sauter 2005). Scale effect revealed the relative importance of secondary and primary porosity in value of hydraulic conductivity.

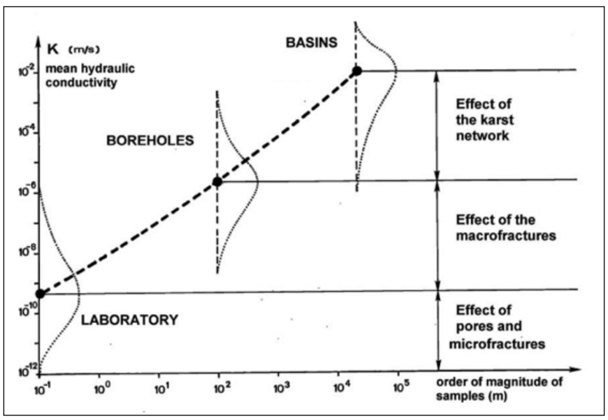

Fig. 5: Scale effect on the hydraulic conductivity in karstified limestone aquifers (modified from Király 2002). The dashed line is from Király (2002), but the solid line above the dashed line are our result: solid circle is geometric mean of the hydraulic conductivities based on tracer tests at the SFDS, hollow circle is geometric mean of the hydraulic conductivities based on pumping test at the SFDS, solid diamond is average of the hydraulic conductivities based on Lugeon tests at the SFDS, and multiplication sign is average of the hydraulic conductivities based on geoelectric tests at the SFDS.

In pumping test with boreholes scale, hydraulic conductivity is affected by both the matrix and fractures (Moench 1984; Nassimi & Mohammadi 2016), but with increasing the scale of the experiments the role of fractures and dissolution routes are increased, and with decreasing the scale the role of matrix are increased. Therefore it is expected that the hydraulic conductivity increases with increasing the scale, and the hydraulic conductivity decreases with decreasing the scale.

In the study area with several conduits and joint systems, the data obtained from the Thompson equation represents the small scale (mainly matrix conditions), therefore combination of geoelectrical and hydrochemical data would cause considerable underestimation of hydraulic conductivity due to the scale effect in the karst aquifer (Fig. 4).

CONCLUSIONS

Hydraulic conductivity (*K*) was estimated about 0.016 m/day based on the Thompson equation (combination of geoelectrical and hydrochemical data) on the small scale in the study area. This value of *K* much less than the K derived from Lugeon, pumping and tracer test. In the karst terrain, estimated value of *K* based on the larger scale is more characteristic for karst structures that those based on the smaller scale, due to dominant role of preferential flow paths in the larger scale. As a result, for areas with preferential flow paths, such as karst aquifers, the hydraulic conductivity obtained from larger scale are greater than the hydraulic conductivity obtained from smaller scale. Pumping test shows a value for hydraulic conductivity at the SFDS that matches with dual-porosity (matrix and fracture) in the scale of borehole, but with increasing the scale the hydraulic conductivity are increased, and with decreasing the scale the hydraulic conductivity are decreased.

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