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Key words: *empirical formulas, sand sediments; saturated hydraulic conductivity K_{sa}*
doi:10.5937/jaes0-34334

Cite article:

Dulovičová R., Ovcharovichova J., Velísková Y. (2022) STATISTICAL METHOD FOR A HYDRAULIC CONDUCTIVITY ESTIMATE USING EMPIRICAL FORMULAS, *Journal of Applied Engineering Science*, 20(2), 455 - 463, DOI:10.5937/ jaes0-34334

Online aceess *of full paper is available at: www.engineeringscience.rs/browse-issues* doi:10.5937/jaes0-34334

Paper number: 20(2022)2, 952, 455-463

STATISTICAL METHOD FOR A HYDRAULIC CONDUCTIVITY ESTIMATE USING EMPIRICAL FORMULAS

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Sediment's hydraulic conductivity is one of the key inputs for estimating solute and water movement in a vadose zone. Laboratory and field measurements are time consuming and subject to substantial inaccuracies. Thus numerous empirical formulas have been adopted to predict hydraulic conductivity from measurable soil properties such as grain size distribution, soil temperature or bulk density. The objective of this study was twofold: (1) assess the hydraulic conductivities calculated from empirical formulas and (2) develop a simple method to estimate hydraulic conductivities for clayey sand sediments. Using sediment samples extracted from irrigation canals in Zitny Ostrov, Southern Slovakia, we evaluated fourteen empirical formulas. Three sets of parameters were assessed using common statistical methods. The sets included computed hydraulic conductivities, logarithmically transformed hydraulic conductivities, and measured values of hydraulic conductivities. Field measurements and laboratory investigations of hydraulic conductivities were performed to supplement our empirical calculations. The three sets of parameters were compared and formed the foundation for developing an original regression equation: $K_{sat\ me} = 0.019\ (LTK_{sat})^2 + 0.183\ (LTK_{sat}) + 4.863$– an equation that captures the variables with reasonable agreement. The logarithmically transformed and measured values correlated, yielding $R^2 = 0.945$. Thus, the measured values validated our regression equation.

Key words: empirical formulas, sand sediments; saturated hydraulic conductivity K_{sat}

INTRODUCTION

Engineering practice often requires the investigation of ground water movement, volumes in storage and computation of the amount of infiltrated or exfiltrated water into and from the aquifer. Hydrological and hydro geological input among other variables includes saturated hydraulic conductivity, abbreviated K_{sat}. Although many models have been developed to quantify K_{sat} its estimation is commonly done using simplified methods, usually empirical formulas, to avoid the high cost of complex field investigations. A number of empirical formulas for determining K_{sat} are being used in engineering practice. Most of the ground water textbooks reference formulas are from institutions and scholars such as Hazen, Beyer, Sauerbrei, Kozeny, USBR, Pavchich, Schlichter, Terzaghi, Kruger, Zunker, Zamarin, Boonstra and de Ridder, Špaček, Palagin, Schweiger, Carman-Kozeny, Seelheim, Orechová, Zieschang and others [1]. Most of the empirical formulas are based on laboratory or field experiments. The structure of these formulas ranges from a simple function of grain size d_{10}, d_{50} or d_{60} to the most complex exponential equations with a number of other input data and parameters, which need to be computed through additional equations. However, many textbooks do not describe the conditions under which a formula was derived, nor the range of its application. Unfortunately, the values of K_{sat} documented in the literature do not always include the sizes of databases. Computed values exhibit a wide range of results which differ by factors of ten, hundred, thousands or more. Decisions about which formula can justify a result are often subjective. Thus, results might not always be in agreement with the values computed from formulas or values reported in the literature. Soil hydraulic properties can be measured in the field, however doing this is both costly and time-consuming. Sometimes the results that are obtained are unreliable, based on soil heterogeneity and experimental errors. When large areas are studied, it is virtually impossible to gather enough measurements to be meaningful. It is critical to have an inexpensive and rapid way to evaluate soil hydraulic properties. In the current literature, research papers usually focus on a wide variety of K_{sat} related topics. Below is a brief overview of selected articles addressing hydraulic conductivity published internationally. Habtamu et al. [2] evaluated saturated hydraulic conductivity with different landuses of disturbed and undisturbed soil. They developed an equation which replaces in-situ saturated hydraulic conductivity measurement. Duong et al. [3] clarify the effects of soil hydraulic conductivity and rainfall intensity on riverbank stability using a GeoSlope analysis. Wang et al.[4] present an alternative model to predict soil hydraulic conductivities. In Wang's study model testing with 24 soil data sets was successful in predicting conductivities over a range of moistures. Ren and Santamarina [5] present an analysis of hydraulic conductivity of sediments as a function of void ratio. Hwang et al. [6] compared saturated hydraulic conductivities of sandy soils to characterize properties of water retention. Ghanbarian et al. [7] proposed scale dependent pedotransfer functions

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to estimate saturated hydraulic conductivity more accurately than seven other frequently used models. Gadi et al. [8] studied spatial and temporal variation of hydraulic conductivity and vegetation growth in green infrastructures, using an infiltrometer and a visual technique. Yusuf et al. [9] studied hydraulic conductivity of compacted laterite, treated with iron ore tailings. Hussain and Nabi [10] used seven empirical formulas to calculate hydraulic conductivity, based on grain size distribution of unconsolidated aquifer materials. The current research was conducted in Zitny Ostrov (ZO) Slovakia. The computations of K_{sat} performed by Slovak scientists and scholars are included as well. Dulovičová et al. [11] investigated the infiltration capability of the silt deposited at the bottom of the irrigation canals in ZO. Empirical formulas by Beyer-Schweiger and Spacek [12] were used to estimate saturated hydraulic conductivity. Jánošík et al. [13] tested the soils in Southern Slovakia. These researchers used field measurements of the grain size distribution, followed by a laboratory test of hydraulic conductivity. Dulovičová and Velisková [1] analyzed the grain size distribution of irrigation canals sediments and its effect on K_{sat}, as computed via empirical formulas by Spacek [12]. Kosorin et al. [14] simulated hydraulic connection and the dynamics of water exchange between the Danube River and the aquifer. The relationships between the bed morphology, hydraulic conductivity and infiltration were investigated.Hydraulic engineers, hydrologists, and hydrogeologists have been studying this topic for decades with a variety of conclusions. Focus was on developing a simple and useful method for quantifying hydraulic conductivity. Our approach encompasses the assessment of results obtained from selected empirical formulas.

LOCATION AND SITE DESCRIPTION

This study of K_{sat} was conducted in the environment of the irrigation canals network of ZO in Southern Slovakia. In Slovakia, ZO is the area between two branches of the Danube River which are the main sources of water for the irrigation canal network, (Fig. 1). Enlarged plan view of ZO with five sampling locations Baka, Narad, Aszod, Okolicne and Golyas is shown in Fig. 2. The soils of ZO have been accumulating as a result of flooding by the Danube River and sedimentation. Sediments in the irrigation canals have been depositing since the end of the 19th century and the process still continues [15], [16]. The layers of silt reach 0.1 meter to over 1.5 meters in thickness.

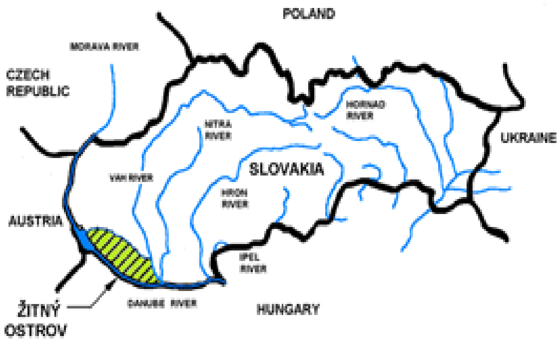

Figure 1: Location of Zitny Ostrov in Slovakia

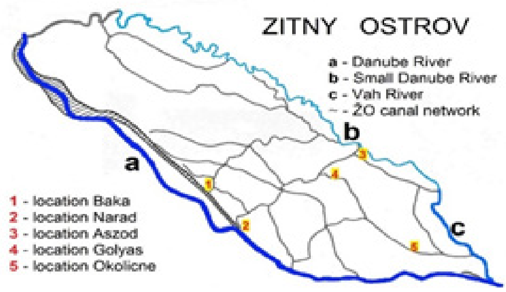

Figure 2: Zitny Ostrov with five research locations

Sediments from the irrigation canals were extracted several times from year 2004. Additional sampling was performed between 2014 and 2019. Sediment sampling was conducted using the 04.23 Sediment Core Sampler, a rod operated type Beeker. This instrument collects one meter long core samples of sediments in an acrylic tube as shown in Fig.3. The sediments have been identified as clayey sands.

Figure 3: View at the irrigation canal and Beeker sampler filled with sediments

METHODOLOGY

Our methodology involves assessment of hydraulic conductivities K_{sat} of sediments extracted from the five primary locations and their sub-locations on irrigation canals described above, computed from fourteen empirical formulas (Dulovičová, Velisková, 2005). Additional sampling was performed at three different sub-locations within 15 to 20 meters downstream or upstream of each of the primary locations. The sampling was performed from a boat. The formulas include the following authors: Sauerbrei, Kozeny I, Kozeny II, Zamarin I, Zamarin II, Schlichter I, Schlichter II, Schlichter III, Krueger, Carman-Kozeny, USBR formula, Palagin, Orechova and Seelheim. The formulas, including conditions of the validity, are listed in the Appendix of the paper. Sediment samples were extracted from the bottom of the canals at five primary locations, Aszod, Baka, Golyas, Okolicne and Narad, as shown in Fig. 2. Extraction started approximately at a distance of one meter from the edge of canal and continued at one meter distances across the section. As a result we obtained at each cross section ten core samples up to 1.0 meter long. We obtained 50 core samples from the primary locations and additional 150 core samples from the 15 sub-locations, all together 200 core samples. As a first step, hydraulic conductivity K_{sat} was computed from empirical formulas. The results are shown in Table 1. As it is evident, some values of K_{sat} in Table 1 are missing. Further discussion in section Results and Discussion will cover this issue. A basic statistical procedure was used to assess the data [17]. Separate column charts of K_{sat} were constructed for each sampling location. Major statistical indexes such as arithmetic mean, harmonic mean, geometric mean, standard deviation, median and coefficients of determination (R^2) were computed. Logarithmic trend lines were also plotted in the column charts. Note that the geometric mean is sometimes referred to as the logarithmic average [17], because it can also be expressed as an exponential of the arithmetic mean of logarithms. The paper works with the natural logarithm ln (base e = 2.718). In the current research, we did not analyze the performance of individual formulas. Instead, we worked with averages. The geometric mean was primarily considered and the other statistical indexes are not listed in this paper. The second statistical procedure involved the transformation of K_{sat} into a logarithmic scale. Ln of K_{sat} amounts were presented with logarithmic-normal frequency distribution. The previous procedure was replicated. Separate column charts of ln of K_{sat} were constructed for each sampling location. Major statistical indexes were computed with the focus on geometric means and coefficients of determination R^2. Logarithmic trend lines were plotted on the column charts. Geometric means of ln of K_{sat} amounts were then returned through the antilog into their original non logarithmic scale values. A new terminology, logarithmically transformed hydraulic conductivities LTK_{sat}, was introduced. The relationship between the geometric means of K_{sat} and logarithmically transformed hydraulic conductivity LTK_{sat} was then described with a regression equation. The third statistical procedure involved analyzing the measured values of hydraulic conductivity $K_{sat\ me}$. The relationship between the measured $K_{sat\ me}$ and the logarithmically transformed LTK_{sat} was investigated. The graphical representation of these two variables yielded a polynomial regression equation, which was derived and is proposed to be used for estimations of K_{sat} in lieu of field measurements.

RESULTS AND DISCUSSION

Table 1 summarizes the computed hydraulic conductivities K_{sat} from empirical formulas at five sampling locations, Aszod, Baka, Golyas, Okolicne and Narad. Not every location was a candidate for a complete set of computations using all 14 formulas. At locations, where any of the input data, such as d_1, d_{20}, d_{50}, etc., was outside of range required for the formula applicability, there are less than 14 results. The symbol (-) is used in the table for such cases. It is evident from the table that empirically computed K_{sat} values exhibited a very wide range of results. For illustration Fig.4, 5, 6 exhibit column charts of K_{sat} for three selected sampling locations, Aszod, Baka and Narad. The names of the formulas are presented along the horizontal axes.

Table 1L: Hydraulic conductivities Ksat computed from empirical formulas sorted by locations Aszod, Baka, Golyas, Okolicne and Narad

No.	Formula	Aszod	Baka	Golyas	Okolicne	Narad
		[m year^{-1}]	[m year^{-1}]	[m year^{-1}]	[m year^{-1}]	[m year^{-1}]
1	Sauerbrei	1.44	35.00	0.45	3.41	1.33
2	Kozeny I	12.20	35.60	8.45	19.36	13.81
3	Kozeny II	181.02	217.90	93.03	134.66	156.73
4	Zamarin I	3.82	(-)	2.25	(-)	0.31
5	Zamarin II	0.37	(-)	0.02	(-)	0.03
6	Schlichter I	10.53	22.42	(-)	(-)	9.30
7	Schlichter II	5.48	16.27	(-)	(-)	6.28
8	Schlichter III	(-)	3.31	(-)	(-)	(-)
9	Krueger	20.94	51.72	(-)	(-)	20.12
10	Carman-Kozeny	5.08	16.99	3.69	7.82	4.16
11	USBR	(-)	196.46	(-)	19.96	3.44
12	Palagin	4.67	10.59	2.46	5.80	4.07
13	Orechova	(-)	633.87	(-)	72.85	(-)
14	Seelheim	(-)	2292.66	(-)	3109.40	(-)

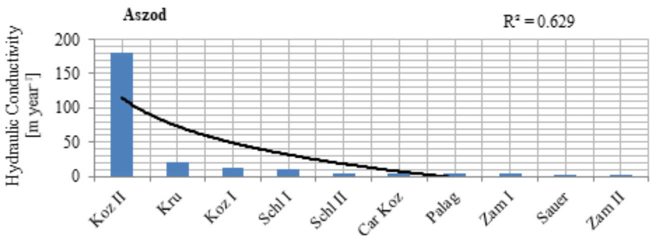

Figure 4: Hydraulic conductivity K_{sat}, Aszod

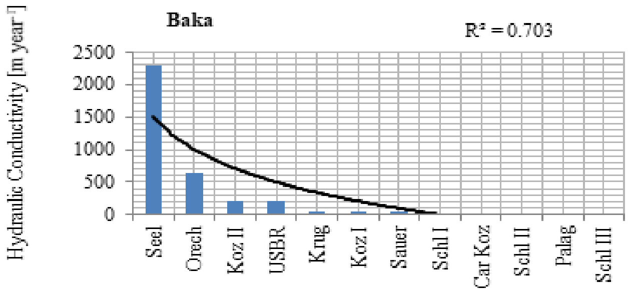

Figure 5: Hydraulic conductivity K_{sat}, Baka

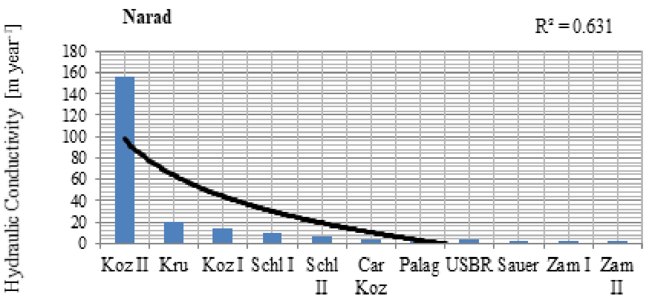

Figure 6: Hydraulic conductivity K_{sat}, Narad

The coefficients of correlation are R^2: Aszod R^2= 0.629, Baka R^2 = 0.703, Golyas R^2 = 0.693, Okolicne R^2 = 0.617 and Narad R^2 = 0.631. These numbers indicate a wide spread of K_{sat} values, varying from formula to formula. Similar column charts were constructed for the sub-locations. Higher coefficients of determination occurred by replacing K_{sat} with corresponding logarithms, ln of K_{sat} illustrated in graphs for selected locations Aszod, Baka and Narad, Fig. 7, 8, 9.

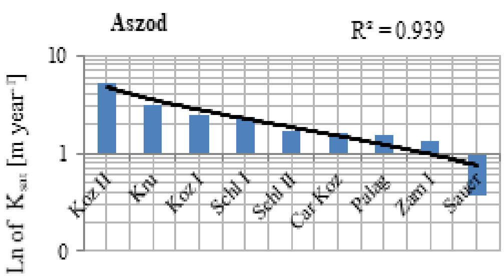

Figure 7: Ln of K_{sat}, Aszod

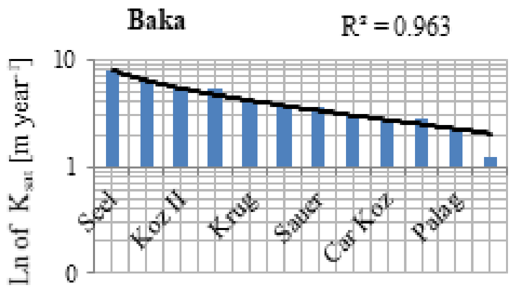

Figure 8: Ln of K_{sat}, Baka

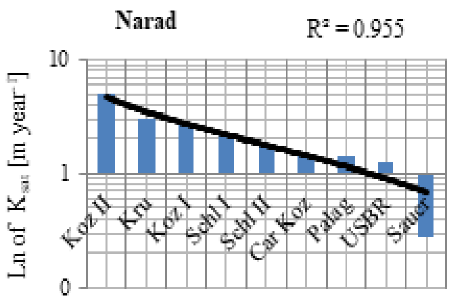

Figure 9: Ln of K_{sat}, Narad

The coefficients of determination for logarithms of K_{sat} indicate substantially higher correlations: Aszod R^2= 0.939, Baka R^2 = 0.963, Golyas R^2 = 0.969, Okolicne R^2 = 0.977and Narad R^2 = 0.955. After K_{sat} values were transformed into logarithms, ln of K_{sat}, a new set of geometric means was computed for each location and sub-location. These numbers were turned back to their nonlogarithmic format trough antilog, producing the logarithmically transformed hydraulic conductivities LTK_{sat}. As shown in Table 2, these new values are significantly to moderately lower than K_{sat} values. Fig. 10 shows a graphical plot of geometric means of K_{sat} on the horizontal axis and logarithmically transformed LTK_{sat} values on the vertical axis.

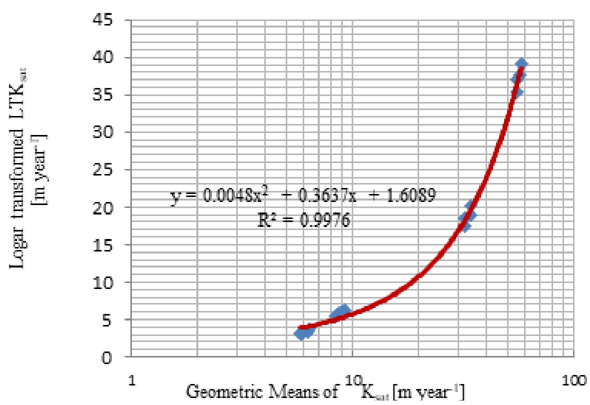

Figure 10: Logarithmically transformed hydraulic conductivity LTK_{sat} [m year^{-1}].

Table 2: Logarithmically transformed saturated hydraulic conductivity LTKsat for primary locations Aszod, Baka, Golyas, Okolicne and Narad, and sub-locations

Location and sub-locations	Geometric Means of K_{sat}	R^2	Geometric Means of Ln of K_{sat}	R^2	LTK_{sat}
	[m year^{-1}]	[%]		[%]	[m year^{-1}]
Aszod	8.89	62.90	1.80	93.90	6.02
Aszod - 1	8.73	63.20	1.76	94.50	5.83
Aszod - 2	8.52	63.50	1.74	95.10	5.68
Aszod - 3	8.38	64.20	1.71	95.50	5.52
Baka	55.60	70.30	3.61	96.30	37.06
Baka - 1	55.20	70.10	3.57	96.30	35.44
Baka - 2	57.79	72.60	3.66	96.10	39.02
Baka - 3	57.07	71.80	3.63	96.10	37.63
Golyas	9.19	69.30	1.84	96.90	6.28
Golyas - 1	6.40	68.30	1.20	96.60	3.31
Golyas - 2	4.78	68.20	0.62	96.50	1.86
Golyas - 3	6.27	68.20	1.30	96.20	3.66
Okolicne	34.09	61.70	3.00	97.70	20.19
Okolic - 1	34.21	61.40	2.94	97.50	18.92
Okolic - 2	32.20	61.40	2.86	97.60	17.41
Okolic - 3	32.40	61.70	2.92	97.80	18.51
Narad	8.34	63.10	1.69	95.50	5.43
Narad - 1	6.04	63.40	1.17	97.90	3.24
Narad - 2	5.88	62.20	1.17	97.30	3.23
Narad - 3	5.81	62.40	1.13	97.50	3.10

The curve is best described by a polynomial trend line with the equation:

$$LTK_{sat}= 0.0048(K_{sat})^2 + 0.3637(K_{sat}) + 1.6089 \quad (1)$$
$$R^2 = 0.9976$$

where y is LTK_{sat} (m year^{-1}) and x is K_{sat} (m year^{-1}).This equation describes the relationship between geometric means of hydraulic conductivities K_{sat} and logarithmically transformed hydraulic conductivities, LTK_{sat}, both computed from empirical formulas. The correlation between these two variables produced $R^2 = 0.9976$.From 2014 the additional field and laboratory measurements were conducted. Measured hydraulic conductivities $K_{sat\ me}$ were determined by a falling head method. Table 3 shows the results for the primary locations. Just like empirically computed K_{sat}, the measured values show a fluctuation. However, the fluctuations are not as extreme as the empirically computed values in Table 3. The plot of LTK_{sat} with the measured Ksat me is presented in Fig. 11.

Table 3: Laboratory measured saturated hydraulic conductivity K_{sat} at locations Aszod, Baka, Golyas, Okolicne and Narad.

Location	Location	Location	Location	Location
Aszod	Baka	Golyas	Okolicne	Narad
[m year-1]	[m year-1]	[m year-1]	[m year-1]	[m year-1]
6.87	47.15	8.42	22.56	5.05
6.42	38.95	4.66	17.38	3.49
5.96	30.76	4.27	12.21	3.10
5.49	35.44	3.88	9.27	2.69

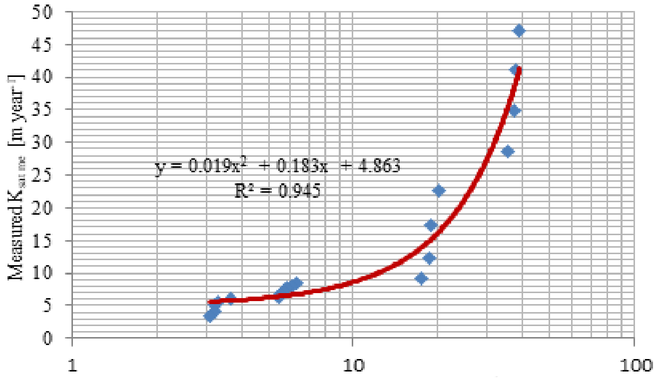

Figure 11: Logarithmically transformed LTK_{sat} versus measured K_{sat}.

The pattern of results in this graph suggests that LTK_{sat} and $K_{sat\ me}$ correlate well. The trend line is represented by a polynomial curve with a very high coefficient of determination, R^2 =0.946, which supports this finding.

$$K_{sat\ me} = 0.019\ (LTK_{sat})^2 + 0.183\ (LTK_{sat}) + 4.863 \qquad (2)$$
$$R^2 = 0.945$$

where y represents measured $K_{sat\ me}$ [m year^{-1}] and x represents LTK_{sat} [m year^{-1}].

The authors propose that this equation could be used for predictions of K_{sat} me for clayey sand sediments in the absence of field measurements of hydraulic conductivity.

CONCLUSIONS

In this study, hydraulic conductivities were computed for clayey sand sediments deposited in the irrigation canals of ZO in Southern Slovakia. Fourteen empirical formulas were utilized. Graphical representation of the computed hydraulic conductivities showed that the data are grouped reasonably close to logarithmic trend lines. A new equation $K_{sat\ me} = 0.019\ (LTK_{sat})^2 + 0.183\ (LTK_{sat}) + 4.863$, $R^2 = 0.945$ was developed that the authors believe to be important contribution to the computation of hydraulic conductivity literature. The variables in this equation indicate procedure which if replicated will assist in hydraulic conductivity estimations. Three main components were involved to determine this equation: hydraulic conductivities (K_{sat}, computed from empirical formulas), logarithmically transformed hydraulic conductivities (LTK_{sat}) and measured hydraulic conductivities ($K_{sat\ me}$). Once the equation for a specific soil is derived, the field measurements could be either significantly reduced or eliminated. Other researchers should derive similar equations based on soil knowledge of the specific sites. The proposed logarithmic method produced hydraulic conductivities of clayey sand sediments that fit well with field measured values. The logarithmically transferred LTK_{sat} reached the values between 3.10 m year^{-1} to 39.02 m year^{-1}, while measured values ranged between $K_{sat\ me}$ 2.69 m year^{-1} to 47.15 m year^{-1}. A comparison of these two sets of results justifies the proposed method. Thus, the authors recommend this method for K_{sat} estimates.

ACKNOWLEDGEMENT

This work was supported by the contract No. VEGA-02/0025/19.

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APPENDIX
Empirical formulas for computation of hydraulic conductivity

Author	Formula	Variable	Conditions of validity
SAUERBREJ	$k = \dfrac{\beta \dfrac{m^3}{(1-m)}(d_{17})^2}{86400}$	β = 2880 - 3010 (recommended value 1150)	($g_{0.063} < 65$)
KOZENY I	$k = \dfrac{5400 \dfrac{m^3}{(1-m)}(d_e)^2}{86400}$	$d_e = \dfrac{100}{\dfrac{3g_1}{2d_1} + \sum \dfrac{g_i}{d_i}}$ $d_i = \dfrac{2}{\dfrac{1}{d_i} + \dfrac{1}{d(i+1)}}$	
KOZENY II	$k = \dfrac{780 \dfrac{m^3}{(1-m^2)} \alpha^2 \dfrac{d_e}{100}}{100}$	α = 1.3875 *m* d_e – according to Kozeny I	

CARMAN-KOZENY	$k=\frac{1}{5}\frac{g.n^3}{\gamma(1-n)^2}\left(\frac{d_n}{\alpha}\right)^2$	$d_1=\frac{d_{10}}{100}41.5$ $d_2=\frac{3}{\frac{1}{d_{10}}+\frac{2}{d_{10}+d_{20}}+\frac{1}{d_{20}}}$ $d_{10}=\frac{3}{\frac{1}{d_{90}}+\frac{2}{d_{90}+d_{100}}+\frac{1}{d_{100}}}$ $\gamma=\frac{1.77810^{-6}}{1+0.0337t+0.000221t^2}$ $n_1=0.4\left[1+10x0.4^3\left(\log\frac{\alpha}{6}\right)^2\right]$ $n=\frac{2}{3}n_1+\frac{1}{3}n_1\exp\left(-\frac{U-1}{2}\right)$ $U=\frac{d_{60}}{d_{10}}$ $A_i=16-2\log(d_i+2)$ $\alpha=\frac{1}{10}\sum_1^{10}A_i$ $d_n=\frac{1}{\sum\frac{100}{d_i}}$	
ZAMARIN I	$k=\frac{5572\frac{m}{(1-m^2)}\alpha^2 d_e^{\,2}}{86400}$	$d_e=\frac{100}{\frac{3g_1}{2d_1}+\sum_2\left[\frac{g_i}{d_i-d(i-1)}\ln\left(\frac{d_i}{d(i-1)}\right)\right]}$ α = 1.3875 *m*	(35< $g_{0.063}$ < 65)
ZAMARIN II	$k=\frac{5572\frac{m^3}{(1-m^2)}\alpha^2 d_e^{\,2}}{86400}$	α = 1.3875 *m* d_e – by Zamarin I	(35 < $g_{0.063}$ < 65)
SCHLICHTER I	$k=\frac{4960x1.011038m^{3.29938}d_e^{\,2}}{86400}$	$d_e=\frac{100}{\sum\frac{g_i}{d_i}}$ $d_i=\frac{d_i+d(i-1)}{2}$	(0.01 < de < 5) ^ (U < 20)
SCHLICHTER II	$k=\frac{4960x1.011038m^{3.29938}d_e^{\,2}}{86400}$	d_e - according to Kozeny I	(0.01 < de < 5) ^ (U < 20)

SCHLICHTER III	$k = \frac{4960x1.011038 m^{3.29938} d_e^{\ 2}}{86400}$	d_e - according to Zamarin I	$(0.01 < d_e < 5)$ ^ (U < 20)
KRUEGER	$k = \frac{322 \frac{m}{(1-m^2)} d_e^{\ 2}}{86400}$	d_e - according to Schlichter I	$(00.06 < d_{10} < 0.6)$ ^ (U < 20)
PALAGIN	if n <= 1.05 => $k = 13.2(d_{50})^2(1.3-0.03t)\frac{m}{n_1}$ if n >1.05 disturbed samples: $k = \frac{d_{50}m}{(0.145+0.2d_{50})n_1}$ undisturbed samples: $k = \frac{d_{50}m}{(0.083+0.0217d_{50})n_1}$	$U = \frac{d_{60}}{d_{10}}$ U <= 3 < n_1 => $0.0243U^{2.18} + 0.26$ U > 3 < n_1 => $0.109U^{1.77} + 0.396$ disturbed samples $n = \frac{d_{50}m}{0.109+0.211d_{50}}$ undisturbed samples: $n = \frac{d_{50}m}{0.069+0.238d_{50}}$	
ORECHOVA	$k = \frac{640(d_{17})^2}{86400}$		$(g_{0.063} < 35)$
USBR	$k = \frac{0.36(d_{20})^{2.3}}{100}$		$(0.01 < d_{20} < 2.0)$
SEELHEIM	$k = \frac{0.357(d_{50})^2}{100}$		$(g_{0.063} < 35)$

Paper submitted: 11.10.2021.
Paper accepted: 21.12.2021.