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Comparison of pedotransfer functions for the determination of saturated hydraulic conductivity coefficient

Porównanie funkcji pedotransferowych do wyznaczania współczynnika przewodnictwa hydraulicznego w strefie nasyconej

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Abstract

On one hand, direct methods of measurement of saturated hydraulic conductivity coefficient are time consuming, and on the other hand, laboratory methods are cost consuming. That is why the popularity of empirical methods has increased. Their main advantages are speed of calculations and low costs. Comparison of various empirical methods (pedotransfer functions) for the determination of saturated hydraulic conductivity coefficient was the purpose of this work. The methods used were Shepard's, Hazen's, USBR (United States Bureau of Reclamation), Saxton et al.'s, Kozeny–Carman's, Krüger's, Terzaghi's, Chapuis's, Sheelheim's, Chapuis', and NAVFAC (Naval Facilities Engineering Command) methods. Calculations were carried out for the soil samples of differential texture. The obtained results shows the methods used for the determination of permeability coefficient differ considerably. Mean values obtained by analysed methods fluctuated between 0.0006 and 12.0 m•day^{-1}. The results of calculations by the chosen methods were compared with the results of the laboratory method. The best compatibility with laboratory method was obtained by using the Terzaghi method.

Streszczenie

Bezpośrednie pomiary przewodnictwa hydraulicznego w strefie nasyconej są czasochłonne, a z drugiej strony metody laboratoryjne są kosztochłonne. Dlatego wzrasta popularność metod empirycznych. Ich główną zaletą jest szybkość wyznaczania i niskie koszty. Celem niniejszej pracy było porównanie różnych metod empirycznych (funkcje pedotransferowe) do wyznaczania współczynnika przewodnictwa hydraulicznego w strefie nasyconej. Badanymi metodami były: Sheparda, Hazena, USBR, Saxtona i in., Kozeny-Carmana, Krügera, Terzaghiego, Chapuisa, Sheelheima i NAVFAC. Obliczenia zostały przeprowadzone dla gleb o różnym składzie granulometrycznym. Otrzymane rezultaty pokazują, że badane metody dają zróżnicowane rezultaty. Średnie wartości otrzymane analizowanymi metodami wahały się między 0,0006 i 12,0 m•d^{-1}. Rezultaty oznaczeń metodami empirycznymi zostały porównane z metodą laboratoryjną. Najlepszą zgodność z badaniem laboratoryjnym dała metoda Terzaghiego.

1. INTRODUCTION

Determination of water properties of ground has a great significance both in water engineering and in natural environment investigations. One of the basic properties connected with water flow in ground is saturated hydraulic conductivity, known as filtration coefficient. The methods for the determination of saturated hydraulic conductivity are very differential. Generally, there are three methods: laboratory, field and empirical methods [Jabro 1992]. The field method is commonly regarded as the most accurate one. Direct measurement in a field excludes errors but is very time and cost consuming. On the other hand, the laboratory method is usually rapid but requires complicated devices. The most popular methods are recently the empirical ones. Their main advantage is quick result and easier methods for proper data obtaining, usually texture and porosity. At present, in literature, these methods are commonly called the pedotransfer functions. In literature, empirical functions that can be grouped in three categories were presented. The first one is based only on grains characteristics diameters. The second one, apart from grains characteristic diameters, regards some physical properties of soil, most often porosity. The third one is based additionally on physical properties of water [Twardowski i Drożdżak 2006]. In this paper, comparable analysis of chosen methods for the determination of saturated hydraulic conductivity for grounds of various grain size distribution was carried out. Results were then compared with the laboratory method.

2. MATERIAL AND METHODS

Samples of ground were taken from various places located in southern Poland, from 0- to 25-cm soil layer. The number of samples was 43, and they had differentiated texture. There are many empirical methods for the determination of saturated hydraulic conductivity (K_s). In this work, 10 methods were used:

- Shepard's method [Twardowski and Drożdżak 2006]:

$$K_s = a \cdot d_{10}^{b} \text{ [m·day}^{-1}\text{]}$$

where:
d_{10} is the effective grain size, soil particle diameter [mm] such that 10% of all particles are finer by weight, *a* and *b* are the empirical coefficients.

- Hazen's method [Nieć and Spychała 2014, Salarashayeri and Siosemarde 2012]:

$$K_s = c \cdot d_{10}^{2} \text{ [m·day}^{-1}\text{]}$$

where:
d_{10} is the effective grain size,
c- is a constant that varies from 1.0 to 1.5 if K_s is expressed in cm·s^{-1} in original method proposed by Hazen; in the work, it was taken according to Lange [Nieć and Spychała 2014] as $c = [400 + 40 \cdot (n - 26)]$, where *n* is the total porosity [%].

- USBR method [Parylak et al. 2013, Vukovic and Soro 1992]:

$$K_s = 311{,}04 \cdot d_{20}^{2.3} \text{ [m·day}^{-1}\text{]}$$

where:
d_{20} is the effective grain size, soil particle diameter [mm] such that 20% of all particles are finer by weight.

- Saxton et al.'s method [Sobieraj et al. 2001]:

$$K_s = e^{12.012 - 0.0755\cdot(S) + (-3.895 + 0.0367\cdot(S) - 0.1103\cdot(C) + \frac{0.00087546\cdot(C)^2}{\theta_s}} \text{[m·day}^{-1}\text{]}$$

where:
C - is the clay fraction content (<0.002 mm) [%],
S - is the sand fraction content (2–0.05 mm) [%],
θ_s- is the saturated soil moisture [m^3·m^{-3}], which is calculated as θ_s=0.332-0.0007251·S+0.1276·log(*C*)·

- The Kozeny–Carman method [Carrier 2003]:

$$K_s = \left(\frac{\gamma}{\mu}\right) \cdot \left(\frac{1}{C_{KC} - S_0^2}\right) \cdot \left(\frac{e^3}{1+e}\right) \text{ [m·day}^{-1}\text{]}$$

where:
γ- is the specific density of water [kg·m^{-3}],
μ - is the dynamic liquid viscosity coefficient [m·s^{-2}],
e - is the void ratio [–],
S_0- is the specific area [cm^{-1}],
C_{KC}- is the Kozeny–Carman constant, which is taken most often as 5.

- Krüger's method [Twardowski and Drożdżak 2006, Wieczysty 1982]:

$$K = 322 \cdot \frac{n}{(1-n)^2} \cdot d_e^2 \text{ [m·day}^{-1}\text{]}$$

where:
n - is the total porosity [–]
d_e- is the effective diameter [mm], which is calculated as $d_e = \frac{100}{\sum_1^N \frac{a_i}{d_i}}$,
where *N* - is the number of fraction
a_i- is the percentage of the following fractions in texture
d_i- is the grain diameter within following fractions from 1 to N [mm], which is calculated as: $d_i = \frac{d_y + d_x}{2}$, where d_y and d_x - are the lower and upper diameter of the following fractions from 1 to N

- Terzaghi's method [Odong 2007]:

$$K_s = 0.0084 \cdot \frac{g}{v} \cdot \left(\frac{n - 0.13}{\sqrt[3]{1-n}}\right)^2 \cdot d_{10}^2 \text{ [m·day}^{-1}\text{]}$$

where
g - is the acceleration due to gravity [m·s^{-2}],
v - is the kinematic viscosity [Pa·s],
n - is the total porosity [–],
d_{10}- is the effective diameter [cm].

- Chapuis' method [Chapuis 2008]:

$$K_s = a \cdot 2.4622 \cdot d_{10}^2 \cdot \left(\frac{e^3}{1+e}\right)^{0.7825} \text{ [m·day}^{-1}\text{]}$$

where:
e - is the void ratio [–],
d_{10} - is the effective diameter [mm],
a - is the coefficient changing units from originally cm·s^{-1} to m·day^{-1}, which is equal to 864.

- Seelheim's method [Kozerski 1977]:

$$K_s = a \cdot 0.357 \cdot d_{50}^2 \text{ [m·day}^{-1}\text{]}$$

where:
d_{50} - is the effective diameter [mm],
a - is the coefficient changing units from originally cm·s^{-1} to m·day^{-1}, which is equal to 864.

- NAVFAC method [Chapuis 2008]:

$$K_s = \mathrm{a} \cdot 10^{1.291 \cdot e - 0.6435} \cdot d_{10}^{10^{0.5504 - 0.2937 \cdot e}} \text{ [m·day}-^{1}\text{]}$$

where
e - is the void ratio [–],
d_{10} - is the effective diameter [mm],
a - is the coefficient changing units from originally cm·s$-^{1}$ to m·day^{-1}, which is equal to 864.

Texture was determined by using Casagrande's method of sieve (for sand) and sedimentation (for other fractions). Classification of fractions and granular groups was carried out according to the USDA (United States Department of Agriculture). Total porosity was determined based on bulk density (ρ_0) and specific density (ρ_s):

$$n = 1 - \frac{\rho_0}{\rho_s},$$

where bulk density was determined using ring method and specific density by pycnometric method. Saturated hydraulic conductivity was determined in laboratory by means of apparatus based on Darcy's law with constant water head in not disturbed samples of 100 cm^3 volume [Lipka et al. 2006]. Analysis of adjustment of empirical models to experimental data was carried out by means of the following measures [Rahnama and Barani 2005]:
- mean error of prognosis (MEP)

$$\mathrm{MEP} = \frac{1}{n} \cdot \sum_{i=1}^{n} \left(C_i^m - C_i^p\right)$$

- root-mean-square error (RMSE)

$$\mathrm{RMSE} = \sqrt{\frac{1}{n} \cdot \sum_{i=1}^{n} \left(C_i^m - C_i^p\right)^2}$$

- mean percentage error (MPE)

$$\mathrm{MPE} = \frac{1}{n} \cdot \sum_{i=1}^{n} \frac{C_i^m - C_i^p}{C_i^m} \cdot 100\ [\%]$$

- model efficiency (ME) [Nash and Sutclife 1970, Tiwari et al. 2000]

$$\mathrm{ME} = 1 - \frac{\sum_{i=1}^{n} \left(C_i^m - C_i^p\right)^2}{\sum_{i=1}^{n} \left(C_i^m - \bar{C}\right)^2}$$

where:
C_i^m - is the measured values,
C_i^p – is the simulated values,
n – is the number of data.

Table 1. Texture, total porosity and effective diameters.

No.	Percentage of fraction [%]			Granular group*	Total porosity n [–]	Effective diameter [mm]			K_{s10}** [m·day^{-1}]
	Sand 2–0.05 mm	Silt 0.05–0.002 mm	Clay <0.002 mm			d_{10}	d_{20}	d_{50}	
1	42	33	25	L	0.413	0.0005	0.0018	0.028	$1.59 \cdot 10^{-3}$
2	76	8	16	LS	0.370	0.0011	0.018	0.375	$3.68 \cdot 10^{-1}$
3	59	35	6	SL	0.415	0.004	0.016	0.12	$5.53 \cdot 10^{-3}$
4	61	35	4	SL	0.408	0.005	0.015	0.14	$2.45 \cdot 10^{-3}$
5	24	59	17	SiL	0.475	0.0005	0.003	0.027	$8.10 \cdot 10^{-4}$
6	27	52	21	SiL	0.495	0.0004	0.002	0.03	$2.45 \cdot 10^{-3}$
7	22	63	15	SiL	0.504	0.0014	0.004	0.029	$2.50 \cdot 10^{-3}$
8	49	46	5	SL	0.477	0.0035	0.008	0.05	$5.35 \cdot 10^{-3}$
9	19	63	18	SiL	0.471	0.0011	0.0028	0.022	$7.07 \cdot 10^{-4}$
10	14	83	3	Si	0.511	0.003	0.006	0.027	$2.36 \cdot 10^{-3}$
11	60	34	6	SL	0.469	0.0032	0.01	0.08	$5.45 \cdot 10^{-3}$
12	34	52	14	SiL	0.505	0.0015	0.0035	0.08	$7.46 \cdot 10^{-4}$
13	25	57	18	SiL	0.497	0.0011	0.0027	0.027	$7.53 \cdot 10^{-4}$
14	23	45	32	CL	0.516	0.0004	0.0007	0.0019	$8.06 \cdot 10^{-4}$
15	36	32	32	CL	0.512	0.0007	0.0012	0.018	$3.94 \cdot 10^{-3}$
16	42	40	18	L	0.417	0.0007	0.0035	0.035	$3.44 \cdot 10^{-3}$
17	32	55	13	SiL	0.438	0.0013	0.005	0.035	$7.25 \cdot 10^{-3}$
18	48	42	10	L	0.413	0.002	0.013	0.045	$2.05 \cdot 10^{-3}$
19	59	17	24	SCL	0.428	0.0005	0.012	0.12	$6.45 \cdot 10^{-3}$
20	58	32	10	SL	0.413	0.002	0.008	0.16	$4.34 \cdot 10^{-2}$
21	46	38	16	L	0.428	0.009	0.004	0.04	$3.00 \cdot 10^{-2}$
22	60	37	3	SL	0.404	0.006	0.02	0.09	$9.54 \cdot 10^{-2}$
23	76	8	16	LS	0.370	0.001	0.03	0.31	$2.47 \cdot 10^{-1}$
24	82	10	8	LS	0.368	0.008	0.06	0.25	$3.08 \cdot 10^{-1}$
25	55	40	5	SL	0.397	0.004	0.009	0.06	$6.80 \cdot 10^{-2}$
26	60	26	14	SL	0.411	0.001	0.012	0.1	$1.82 \cdot 10^{-1}$
27	80	10	10	LS	0.371	0.002	0.05	0.18	$1.75 \cdot 10^{-1}$
28	85	11	4	LS	0.374	0.015	0.07	0.28	$3.22 \cdot 10^{-1}$
29	81	8	11	LS	0.386	0.0014	0.055	0.18	$2.50 \cdot 10^{-1}$
30	76	18	6	LS	0.370	0.004	0.03	0.16	$5.30 \cdot 10^{-1}$
31	70	21	9	SL	0.397	0.006	0.028	0.18	$7.85 \cdot 10^{-2}$
32	92	6	2	S	0.360	0.055	0.09	0.43	$9.23 \cdot 10^{0}$
33	74	23	3	LS	0.375	0.022	0.038	0.12	$1.19 \cdot 10^{0}$
34	87	9	4	S	0.348	0.02	0.15	0.6	$4.62 \cdot 10^{0}$
35	40	38	22	L	0.388	0.0003	0.0018	0.03	$2.68 \cdot 10^{-2}$
36	82	7	11	LS	0.426	0.0018	0.06	0.33	$2.40 \cdot 10^{-1}$
37	27	64	9	SiL	0.467	0.0022	0.004	0.02	$2.40 \cdot 10^{-1}$
38	20	57	23	SiL	0.493	0.0004	0.0015	0.025	$8.75 \cdot 10^{-3}$
39	57	12	31	SCL	0.431	0.0002	0.0006	0.1	$7.05 \cdot 10^{-4}$
40	61	36	3	SL	0.347	0.008	0.027	0.18	$2.74 \cdot 10^{-2}$
41	26	60	14	SiL	0.492	0.001	0.0032	0.024	$2.50 \cdot 10^{-1}$
42	61	32	7	SL	0.372	0.012	0.025	0.14	$7.04 \cdot 10^{-4}$
43	18	57	25	SiL	0.477	0.0005	0.0018	0.014	$3.76 \cdot 10^{-1}$

*L, loam; LS, loamy sand; SL, sandy loam; SiL, silt loam; C, clay; CL, clay loam; SCL, sandy clay loam.
** Saturated hydraulic conductivity for 10 °C determined by laboratory method.

Statistical significance of differences between pedotransfer functions was checked by means of LSD_{Tukey} (least significant differences by Tukey's test).

3. RESULTS AND DISCUSSION

In the analysed samples, loam prevailed in 20 samples (in which loam – 5, sandy loam – 11, clay loam – 2 and sandy clay loam – 2). Sand was represented in 12 samples (loamy sand – 10 and sand – 2) and silt in 11 samples (silt loam) (Table 1).

Values of total porosity were between 0.347 and 0.516. Effective diameter d_{10} varied from 0.0002 to 0.055 mm, d_{20} between 0.0007 and 0.15 mm, whilst d_{50} between 0.0019 and 0.375 mm. Values of saturated hydraulic conductivity, K_s, for analysed samples were between $6.12 \cdot 10^{-4}$ and 12.0 $m \cdot day^{-1}$. Values obtained for the chosen pedotransfer functions were presented in Table 2.

The highest values were obtained for the Saxton function, whilst the lowest ones for the Krüger function. Figure 1 presents the comparison of the values for K_s obtained by means of the following pedotransfer functions with the ones obtained in experimental laboratory investigations.

For the purpose of choosing the best universal function simulating saturated hydraulic conductivity for the soils of differentiated texture, the various model efficiency measures were used (Table 3). Values of correlation coefficient r for pedotransfer functions fluctuated between 0.654 and 0.946. All were essential for confidence level of 0.05. The best accordance with the laboratory method regarding correlation coefficient had the Shepard's function, whilst the most abandoning one was the USBR function. Results obtained for MEP showed that maximum underestimation attained 9.29, whilst little overestimation took place in four examples, for the Hazen's, Krüger's, Chapuis's and USBR functions. MPE shows good results of estimation for the Shepard's function. Its value was 0.04% and approximated to the Kozeny–Carman's function (−0.69%). The Seelheim's (−49.57%) and Saxton's (−60.55%) methods had extreme bad adjustment. RMSE attained high overestimation for the Seelheim's ($6.09 \cdot 10^{1} \cdot m \cdot day^{-1}$) and Saxton's methods ($7.44 \cdot 10^{1} \cdot m \cdot day^{-1}$). Terzaghi's function attained the best results, the mean values was higher than that for the laboratory method of 0.75 $m \cdot day^{-1}$. Terzaghi's one turned out to be the best adjusted model , regarding the shape of particles, porosity, texture and water parameters. To the models regarding effective surface of particles belong the Kozeny–Carman's and Krüger's functions, but the results are less comparable with experimental results. To the functions giving the greatest differences in comparison to experimental data were the Saxton's and Seelheim's ones. In both the cases, great underestimation took place and the results were several times lower. Analysis of homogeneity of mean values (Table 4) using the LSD_{Tukey} showed that the Saxton's, Seelheim's and USBR methods differed statistically between themselves and from the others methods. In turn, the remaining methods did not differ statistically.

Table 2. Minimum, maximum and mean values of saturated hydraulic conductivity obtained for the chosen pedotransfer functions.

No.	Pedotransfer function	Saturated hydraulic conductivity [m·day⁻¹]		
		Minimum	Maximum	Mean
1	Shepard	$1.06 \cdot 10^{-3}$	2.92	1.21
2	Hazen	$4.01 \cdot 10^{-5}$	3.03	0.11
3	USBR	$1.21 \cdot 10^{-5}$	3.96	0.27
4	Saxton	1.80	51.60	11.78
5	Kozeny–Carman	$4.13 \cdot 10^{-4}$	14.40	0.59
6	Krüger	$2.42 \cdot 10^{-3}$	$4.07 \cdot 10^{-1}$	$0.49 \cdot 10^{-1}$
7	Terzaghi	$4.80 \cdot 10^{-4}$	12.20	0.51
8	Chapuis	$1.16 \cdot 10^{-3}$	4.16	0.22
9	Seelheim	$1.11 \cdot 10^{-3}$	$1.11 \cdot 10^{2}$	9.72
10	NAVFAC	$9.02 \cdot 10^{-4}$	92.00	4.10

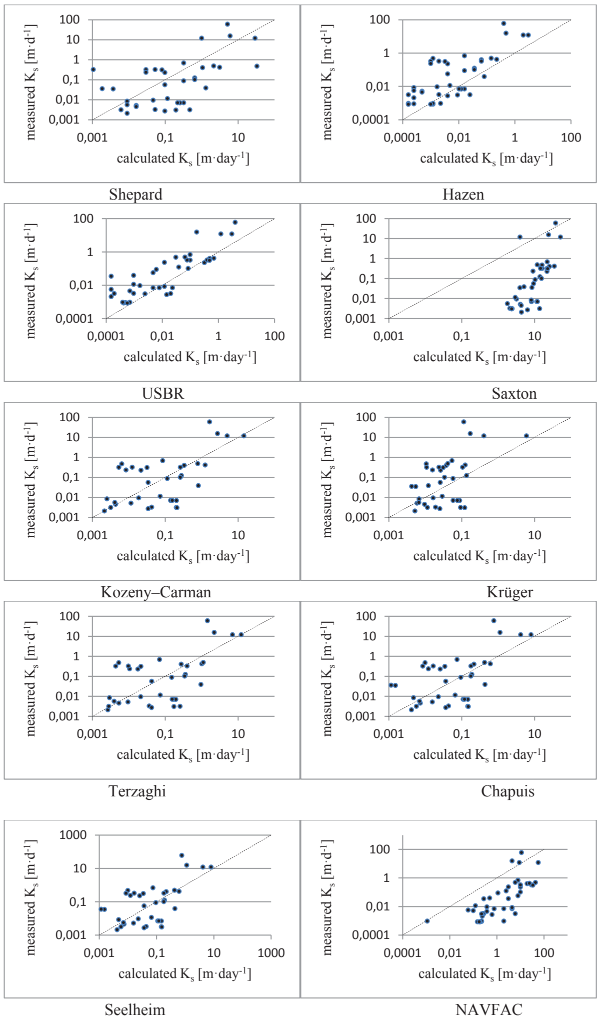

Figure 2. Relationship between saturated hydraulic conductivity determined using laboratory methods and one determined using chosen pedotransfer functions.

Table 3. Model efficiency measures.

Pedotransfer function	Efficiency measures				
	MEP [m·day^{-1}]	MPE [%]	RMSE [m·day^{-1}]	ME [−]	r [−]
Shepard	$-8.05\cdot10^{-1}$	−0.04	2.77	−0.93	0.946
Hazen	$3.26\cdot10^{-1}$	1.74	1.63	0.33	0.939
USBR	$2.42\cdot10^{-1}$	1.29	1.69	0.28	0.654
Saxton	$-1.13\cdot10$	−60.55	$1.47\cdot10$	$-5.35\cdot10$	0.738
Kozeny – Carman	$-1.30\cdot10^{-1}$	−0.69	0.82	0.83	0.928
Krüger	$3.87\cdot10^{-1}$	2.06	2.00	$-1.16\cdot10^{-2}$	0.817
Terzaghi	$-7.35\cdot10^{-2}$	−0.39	0.75	0.86	0.927
Chapuis	$2.11\cdot10^{-1}$	1.13	1.45	0.47	0.930
Seelheim	−9.29	−49.57	$2.07\cdot10$	$-1.07\cdot10^{2}$	0.704
NAVFAC	−3.67	−19.57	$1.28\cdot10$	0.10	0.889

Table 4. Determination of homogeneity of mean values of saturated hydraulic conductivity calculated using the chosen pedotransfer functions.

No.	Method	Mean [m·day^{-1}]	LSD_{Tukey}	Homogeneous groups
1	Saxton	11.782	4.104	a
2	Seelheim	9.726		b
3	Chapuis	4.104		c
4	Shepard	1.241		d
5	Kozeny–Carman	0.565		d
6	Terzaghi	0.509		d
7	NAVFAC	0.224		d
8	USBR	0.193		d
9	Hazen	0.110		d
10	Krüger	0.049		d

4. CONCLUSIONS

1. According to the results of the calculations for the investigated samples – covering sand, loam and silt – concerning assumed purposes, the method generating saturated hydraulic conductivity the best approximated to the laboratory investigations and most universal one is Terzaghi's function.
2. Saxton's, Seelheim's and USBR methods differed statistically between themselves and from the others methods. In turn, the remaining methods did not differ statistically.
3. The analysed pedotransfer functions cannot be used as universal method for all granular groups in engineering works regarding their divergence, what testify their inaccuracy. Most of the methods have limited use to grounds of a given texture. Further investigations are necessary.
4. Terzaghi's method seems to be the most universal one for investigating granular groups: sand, loam and silt.

REFERENCES

CARRIER D. 2003. Goodbye, Hazen; Hello, Kozeny-Carman, Technical notes. Journal of Geotechnical and Geoenvironmental Engineering(129:11), p. 1054-1056.

CHAPUIS R. 2008. Predicting the Saturated Hydraulic Conductivity of Natural Soils. Geotechnical News, 26, 2: 47-50.

JABRO J. 1992. Estimation of saturated conductivity of soils from particle size distribution and bulk density date. Transactions of the American Society of Agricultural Engineers,35: 557-560.

KOZERSKI B. 1977. Zasady obliczeń hydraulicznych ujęć wód podziemnych. Wytyczne określenia współczynnika filtracji metodami pośrednimi i laboratoryjnymi. Wydawnictwo Geologiczne. Warszawa.

LIPKA K., RYCZEK M., ZAJĄC E., STABRYŁA J. 2006. Przepuszczalność wodna gleb torfowo-murszowych na terenach poeksploatacyjnych wybranych torfowisk w Polsce Południowej, p. 141-148. In: Właściwości fizyczne i chemiczne gleb organicznych. Wydawnictwo SGGW, Warszawa.

NASH J.E., SUTCLIFFE J.V. 1970. River flow forecasting through conceptual models. Part I. A discussion of principles. J. Hydrol. 10: 282-290.

NIEĆ J., SPYCHAŁA M. 2014. Hydraulic Conductivity Estimation Test Impact on Long-Term Acceptance Rate and Soil Absorption System Design. Water 6: 2808-2820.

PARYLAK K., ZIĘBA Z., BUŁDYS A. I., WITEK K. 2013. Weryfikacja wyznaczania współczynnika filtracji gruntów niespoistych za pomocą wzorów empirycznych w ujęciu ich mikrostruktury. Acta Scientiarum Polonorum12, 2: 43-51.

ODONG J. 2007. Evaluation of empirical formulae for determination of hydraulic conductivity based on grain size analysis. J. Am. Sci. 3: 54-60.

PAZDRO Z. I., KOZERSKI, B. 1990. Hydrologia ogólna. Wydawnictwo geologiczne. Warszawa.

RAHNAMA M. B., BARANI G. A. 2005. Application of rainfall-runoff models to Zard river catchment. American Journal of Environmental Sciences 1, 1: 86-89.

SALARASHAYERI A.F., SIOSEMARDE M. 2012. Prediction of Soil Hydraulic Conductivity from Particle Size Distribution Analysis. World Academy of Science, Engineering and Technology 6, 1.

SAXTON K.E., RAWLS W.J., ROMBERGER J.S., PEPENDICK R.I. 1986. Estimating generalized soil water characteristics from soil texture. Soil Sci. Soc. Am. J. 55: 1231-1238.

SEZER A., GÖKTEPE A. B. I., ALTUN S. 2009. Estimation of the permeability of granular soils using neuro-fuzzy system. Turkey: Workshops Proceedings Department of Civil Engineering.

SOBIERAJ J. A., ELSENBEER H. I., VERTESSY R. A. 2001. Pedotransfer functions for estimating saturated hydraulic conductivity: implications for modeling storm flow generation. Journal of Hydrology 251: 202-220.

TIWARI A. K., RISSE L. M., NEARING M. A. 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. Transactions of the ASAE 43,5: 1129-1135.

TWARDOWSKI K. I., DROŻDŻAK R. 2006. Pośrednie metody oceny właściwości filtracyjnych gruntów. Wiertnictwo Nafta Gaz 23,1: 477-486.

VUKOVIC M., SORO A. 1992. Determination of Hydraulic Conductivity of Porous Media from Grain Size Composition. Water Resources Publications, USA.