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ACCURACY OF THE INDIRECT METHODS OF HYDRAULIC CONDUCTIVITY ESTIMATION IN SELECTED SOILS OF WIELKOPOLSKA PROVINCE

DOKŁADNOŚĆ POŚREDNICH METOD ESTYMACJI WSPÓŁCZYNNIKA FILTRACJI W WYBRANYCH GLEBACH WIELKOPOLSKI

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Abstract: The accuracies of estimation of saturated hydraulic conductivity with the use of selected pedotransfer functions have been analysed for a set of results from 73 soil horizons. The highest accuracy has been obtained for estimations with the power function model $Ks = B(\phi_d)^n$ proposed by Ahuja et al. [1984]. The authors propose new values of B and n parameters of this dependence derived for selected soils of Wielkopolska for which a higher accuracy of Ks estimation has been obtained than those achieved in the earlier published proposals.

Abstrakt: W pracy przeanalizowano dokładność estymacji współczynnika filtracji – Ks przy użyciu wybranych funkcji PTF (*pedotransfer function*). Analizy przeprowadzone na zbiorze oznaczeń z 73 poziomów glebowych wykazały, iż największą dokładność estymacji Ks zapewnia zależność $Ks = B(\phi_d)^n$ [Ahuja i in. 1984]. Dla zależności tej opracowano własne parametry uzyskując wzrost dokładności estymacji Ks w badanych glebach w stosunku do publikowanych rozwiązań.

Key words: saturated hydraulic conductivity, drainage porosity, pedotransfer function (PTF).

Słowa kluczowe: współczynnik filtracji (Ks), porowatość drenażowa, funkcje PTF.

INTRODUCTION

Hydraulic conductivity has usually been calculated by the empirical formulae based on the grain size fraction content [Hazen, Selheim, USBR after Wieczysty 1982]. In some formulae also other physical parameters of the soil have been taken into consideration such as the surface area or porosity coefficient (Kruger equation). Unfortunately, the application of these formulae has been limited and the value of Ks has been estimated with considerable error [Spychalski, Hahnel 2005]. In the last two decades indirect methods of estimation of soil hydraulic properties have been developed, based on the so-called *pedotransfer function* – PTF [Bouma, van Lanen 1987]. In PTF proposals the hydraulic properties of the soil are determined on the basis of routine measurements of soil characteristics. In this paper a comparative analysis of the accuracies of different methods of hydraulic conductivity estimation has been made for the soils from the Wielkopolska region and a new PTF form has been proposed.

MATERIAL AND METHODS

The relationships between the selected soil physical parameters and hydraulic conductivity were studied on a set of 73 determinations. The determinations were made for selected soil horizons of Luvisols, Albeluvisols and Mollic Gleysols formed from glacial tills of the Baltic Glaciation (Würm) and typical of the morainic uplands of Wielkopolska (47 horizons, from the area near Konin, Kleczew, Złotniki, and Turew). The analysis was made taking into consideration the results of measurements for Arenosols and Podzols formed from sandr sand (16 horizons, Potrzebowice and Miały near Krzyż) and hydraulic conductivity measurements of fine valley sand from a bed in Wielowieś near Kalisz (10 density states).

In the monolithic samples collected from particular genetic horizons soil texture was determined by the aerometric method [PKN 1998a], organic carbon content by the method proposed by Walkley-Black [Nelson, Sommers 1982] and particle density (ρ_s) by the pycnometric method [Soil Conservation Service 1992]. The values of hydraulic conductivity were measured in the laboratory [Klute, Dirksen 1986], in samples of undisturbed structure (100 cm^3) in four replications. The pore size distribution was characterised by interpretation of water retention curves (pF). The curves were determined, again in four replications, on the basis of measurements of samples of undisturbed structure (50 cm^3) by the pressure chamber method of Richards [Klute 1986] on 1-bar ceramic plates. For the same samples for which the pF curves were determined, the bulk density (ρ_c) was also measured. A sum of macro- and mesopores known as drainage porosity (ϕ_d), was found as a difference between total porosity ($\phi = 1 - \rho_c/\rho_s$) and moisture content at field water capacity (–10 kPa, eq. 1), corresponding to the total volume of pores of a diameter greater than 30 μm:

$$\phi_d = \phi - \Theta_{10\ kPa} \tag{1}$$

Taking into account the logarithmic distribution of hydraulic conductivity, the logarithmic transformation of the data was applied. The accuracy of the hydraulic conductivity estimation was assessed by statistical analysis. The geometric mean of the error ratio GMER and its standard deviation GSDER were calculated after Tietje and Hennings [1996]:

$$Log(GMER) = \frac{1}{N}\sum_{i=1}^{N} Log\varepsilon_i \tag{2}$$

$$\varepsilon_i = \frac{P_i}{O_i} \tag{3}$$

$$Log(GSDER) = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(Log\varepsilon_i - LogG\right.} \tag{4}$$

where: O_i – the measured value, P_i – the predicted value, and N – the number of data

GMER > 1 indicates a tendency to overestimate the parameter and GMER <1 indicates a tendency to underestimate it. The values of GSDER are a measure of deviation from the mean GMER value, and the estimation is accurate for GSDER = 1 [Tietje, Hennings 1996].

The accuracy of estimation was assessed on the basis of the mean square residual (MSR) of the differences between the estimated and measured values and the root mean square residuals (RMSR) [Minasny, McBratney 2000]:

$$MSR = \frac{1}{N}\sum_{i=1}^{N}\left(LogP_i - LogO_i\right)^2 \tag{5}$$

$$RMSR = \sqrt{MSR} \tag{6}$$

RMSR is a dimensionless parameter describing the standard error of PTF (after the logarithmic transformation) and cannot be treated as a logarithm of the standard error. The smallest values of MSR and RMSR correspond to the highest accuracy of the estimation.

To obtain more comprehensive data on the PTF accuracy we applied the Akaike's Information Criterion (AIC) in the modification of Webster and McBratney [1989]. AIC takes only positive values and the smallest value corresponds to the most accurate solution.

$$AIC = N \times Log\left(\sum_{i=1}^{N}\left(P_i - O_i\right)^2\right) + 2np \tag{7}$$

where: np – the number of parameters in PTF, other symbols as in eqs 2 and 3

A comparative analysis was performed for a few selected PTFs (Table 1) whose high accuracy had been established earlier [Tietje, Hennings 1996; Minasny, McBratney

TABLE 1. List of the pedotransfer functions analysed
TABELA 1. Zestawienie analizowanych funkcji PTF

Kod Code	Metoda obliczeń Pedotransfer function	Ilość danych Size of data set	Postać zależności dla Ks w $\mu m \cdot s^{-1}$ Equations forms for Ks in $\mu m \cdot s^{-1}$	Nr równ. Equ. No.
A	Brakensiek et al. [1984]	230	$Ks = 2.78 \cdot \exp(19.52348 \cdot \phi - 8.96847 - 0.028212 \cdot c + 0.00018107 \cdot s^2 - 0.0094125 \cdot c^2 - 8.395215 \cdot \phi^2 + 0.077718 \cdot s \cdot \phi - 0.00298 \cdot s^2 \cdot \phi^2 - 0.019492 \cdot c^2 \cdot \phi^2 + 0.0000173 \cdot s^2 \cdot c + 0.02733 \cdot c^2 \cdot \phi + 0.001434 \cdot s^2 \cdot \phi - 0.0000035 \cdot c^2 \cdot s)$	8
B	Cosby et al. [1984]	1448	$Ks = 7.056 \cdot 10^{(-0.6 + 0.012 \cdot s - 0.064 \cdot c)}$	9
C	Saxton et al. [1986]	230	$Ks = 2.78 \cdot \exp[12.012 - 0.0755 \cdot s + (-3.895 + 0.03671 \cdot s - 0.1103 \cdot c + 0.00087546 \cdot c^2)/\theta_s]$ $\theta_s = 0.332 - 0.0000725 \cdot s + 0.1276 \cdot \log c$	10 11
D	Jabro [1992]	350	$Ks = 2.78 \cdot 10^{[9.6-(0.81 \cdot \log si - 1.09 \cdot \log c - 4.64 \cdot \rho_c)]}$	12
E	Dane and Puckett [1994]	577	$Ks = 84.4 \cdot \exp(-0.144 \cdot c)$	13
F	Minasny, McBratney [2000]	462	$\mathbf{Ks = B(\phi_d)^n}$ B = 6441.819; n = 3.66	14
G	Comegna et al. [2000]	75	$Ks = B(\phi_d)^n$ B = 439.03; n = 2.5371	15
H	Schaap et al. [2001]	1306	ANN Rosetta 1.2/2 – input data: s, si, c, ρ_c	–
I1	Minasny and McBratney [2002]	862	ANN Neuro-θ 5 input data: cs, fs, si, ρ_c Calibr. on Australian training data set	–
I2	Minasny and McBratney [2002]	862	ANN Neuro-θ 6 input data: cs, fs, si, c, ρ_c θ_{10kPa} Calibr. on Australian training data set	–
J	Niedźwiecki et al. [2003]	–	$Ks = 10^6 \cdot 10^{(-0.34 + 0.0566 \cdot c - 3.08 \cdot \rho_c)}$	16
K	Proposed by authors	73	$Ks = B(\phi_d)^n$ B = 2819.95; n = 3.306	17

s – sand/piasek (%; cs – coarse/gruby, fs – fine/drobny); si – silt/pył (%); c – clay/ił (%); ρ_c – bulk density/gęstość obj. gleby suchej ($Mg \cdot m^{-3}$); ϕ – porosity/porowatość ($m^3 \cdot m^{-3}$); ϕ_d – drainage porosity/porowatość drenażowa ($m^3 \cdot m^{-3}$); θ_s – saturated vol. water content/ wilgotność obj. gleby nasyconej wodą ($m^3 \cdot m^{-3}$)

2000; Schaap et al. 2001]; additionally, the expressions proposed by Jabro [1992] and Niedźwiecki et al. [2003] where also evaluated.

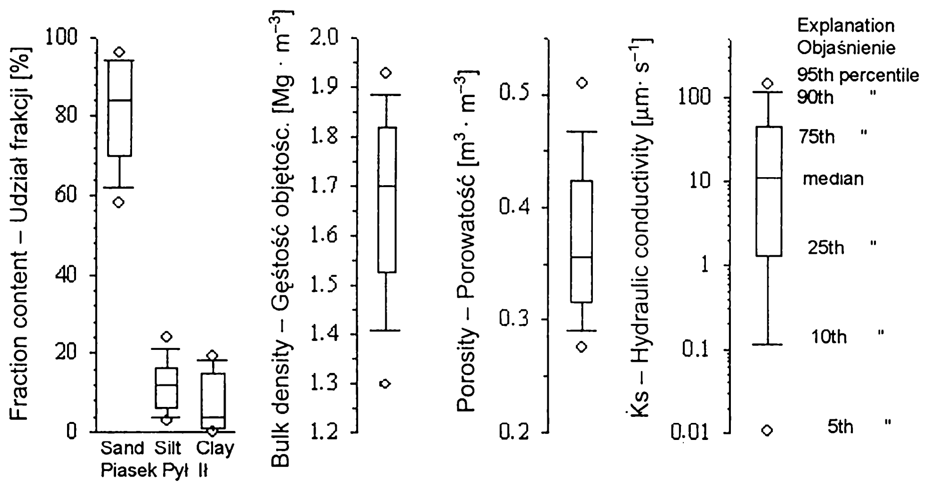

FIGURE 1. Boxplots of textural composition and physical properties of the soils used in the analysis
RYSUNEK 1. Wykresy skrzynkowe uziarnienia i wybranych właściwości fizycznych gleb uwzględnionych w analizie

RESULTS

The set of soil samples studied comprises mainly sandy soils [PKN 1998b]: 29 samples have been classified as sands, 8 as light loamy sands and 6 as loamy sands – the majority are medium grained material. Moreover, the set includes the data for 21 sandy loam soil horizons, 7 light loams, 1 loam and 1 medium-heavy loam. General characteristics of the content of sand, silt and clay fractions and the scale of variation in the physical properties of the soils studied are presented in Figure 1. The soils studied are characterised by a relatively high mean bulk density and a very wide range of variation in the hydraulic conductivity (Fig. 1).

A comparison of the statistical measures describing the quality of estimation of Ks for selected PTFs (Table 2) has shown that the most accurate estimations of the hydraulic conductivity of the soils studied in Wielkopolska are provided by the equation of Minasny and McBratney [2000] (entry F in Table 1). This equation is a modification of the power function model of Ahuja et al. [1984] derived from the Kozeny-Carman model. In the solution of Minasny and McBratney [2000] Ks is estimated on the basis of drainage porosity corresponding to the partial pore volume of pores of diameters larger than 30 μm. The greater estimation error for the other PTFs indicates that the estimators taken into consideration in them are only indirectly related to the estimated Ks value. The highest accuracy of the PTFs based on the concept of drainage porosity has prompted the present authors to propose local parameters of this equation (entry K in Table 1). By taking into account the parameters proposed here it was possible to improve the accuracy of estimation of hydraulic conductivity as confirmed by the values of all statistical measures considered (Table 2, Fig. 2).

TABLE 2. Goodness-of-fit criteria of PTFs on the prediction of Ks
TABELA 2. Miary dokładności estymacji Ks dla analizowanych PTF

Kod Co-de	Metoda obliczeń Pedotransfer function	GMER [-]	GSDER [-]	MSR [-]	RMSR log(μm/s)	np [-]	AIC [-]
A	Brakensiek et al. [1984]	1.969	± 3.984	0.422	0.665	3	116.14
B	Cosby et al. [1984]	2.693	± 14.014	1.482	1.217	2	152.49
C	Saxton et al. [1986]	1.167	± 3.701	0.323	0.568	3	106.21
D	Jabro [1992]	1.797	± 7.897	0.859	0.927	3	137.21
E	Dane and Puckett [1994]	5.234	± 9.841	1.489	1.220	1	150.65
F	Minasny and McBratney [2000]	1.084	± 2.648	0.178	0.422	1	83.24
G	Comegna et al. [2000]	0.632	± 3.186	0.289	0.538	1	98.72
H	Schaap et al. [2001]	1.612	± 4.865	0.509	0.713	37	188.59
I1	Minasny and McBratney [2002]	0.549	± 12.663	1.267	1.125	36	215.52
I2	Minasny and McBratney [2002]	3.279	± 7.444	1.016	1.008	50	236.51
J	Niedźwiecki et al. [2003]	1.619	± 18.307	1.616	1.271	2	155.24
K	Proposed by authors	0.934	± 2.539	0.162	0.403	1	80.40

The assessment of the accuracy of hydraulic conductivity made separately for the sandy and loamy soil horizons has revealed different effectiveness of the PTFs analysed depending on the soil texture. Figure 2 presents the scale of changes in GMER for the PTFs analysed illustrating the tendency of the model to give underestimated (GMER < 1) or overestimated values (GMER > 1). The PTFs for which the GMER values were close to 1 in sands evidently overestimate Ks values in loams (A – Brakensiek et al. [1984], H – Schaap et al. [2001], I2 – Minasny and McBratney [2002b]), whereas the PTFs of GMER close to 1 in loams underestimate the Ks values in sands (G – Comegna et al. [2000]). The modification of the power function model of Ahuja et al. [1984] proposed by Minasny and McBratney [2000] (F) also yields divergent results for the two textural classes (Fig. 2), the Ks values are somewhat overestimated in sands and underestimated in loams.

The introduction of the parameters of the model of Ahuja et al. ([1984], Table 1, eq. 10) proposed here has brought about the levelling of GMER for the two textural classes (0.983 for sands and 0.867 for loams). Figure 3 presents the differences in the root mean square residuals (RMSR) for the PTFs studied between the two textural classes. The results illustrate that out of the PTFs proposed, those showing the smallest RMSR

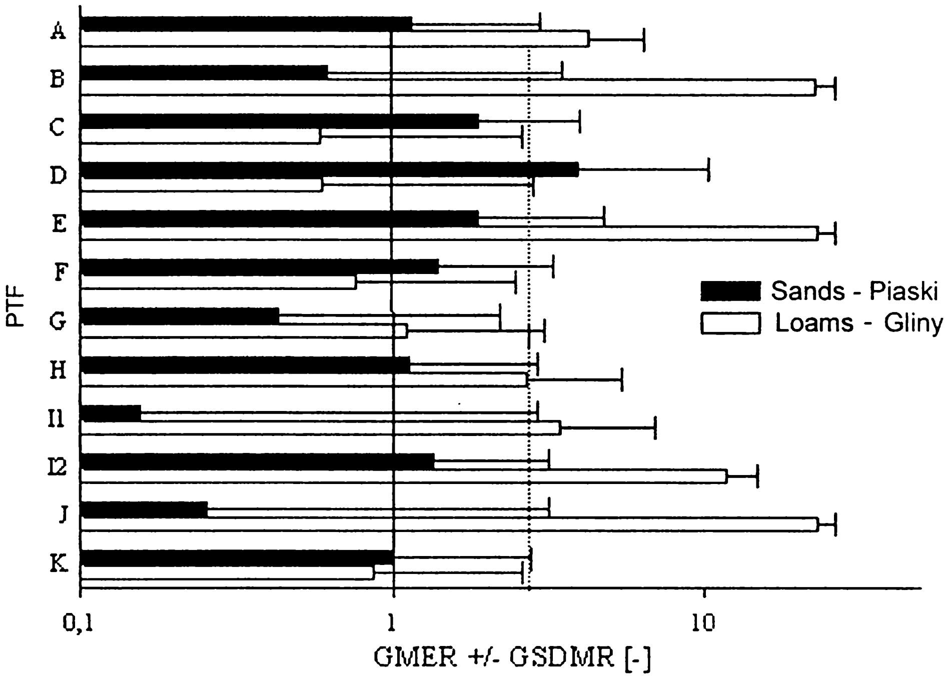

FIGURE 2. The geometric mean of error ratio on the Ks prediction of PTFs
RYSUNEK 2 . Średni geometryczny wskaźnik błędu estymacji Ks dla analizowanych PTF

value in sands give unsatisfactory results in loams (A – Brakensick et al. [1984], H – Schaap et al. [2001], I2 – Minasny and McBratney [2002]). Moreover, in general the errors of Ks value estimation are greater for loamy soil horizons. It is only for the equation proposed by Jabro [1992] that RMSR for loams (0.824) is lower than that for sands (0.992), however, the RMSR values are higher than for the other PTF, which puts in doubt the applicability of this formula for both textural classes (Fig. 3). Out of the PTFs proposed hitherto, the smallest differences in the RMSR of Ks value estimation have been found for the model of Ahuja et al. [1984]. For sandy soils, the more accurate is the equation with the parameters proposed by Minasny and McBratney [2000], while for loamy soils – the one with the parameters proposed by Comegna et al. [2000]. However, the dependence with the parameters proposed in this work, applied to the soil studied (K, Table 1), permits an even more accurate estimation of the Ks value both for sands and loams (RMSRs of 0.235 and 0.573, respectively, Figs. 2 and 3).

DISCUSSION

As follows from the analysis of the data, both types of pedotransfer functions: those based on artificial neural networks [Schaap et al. 2001; Minasny and McBratney 2002] and those based on multi-factor equations taking into account texture, bulk density

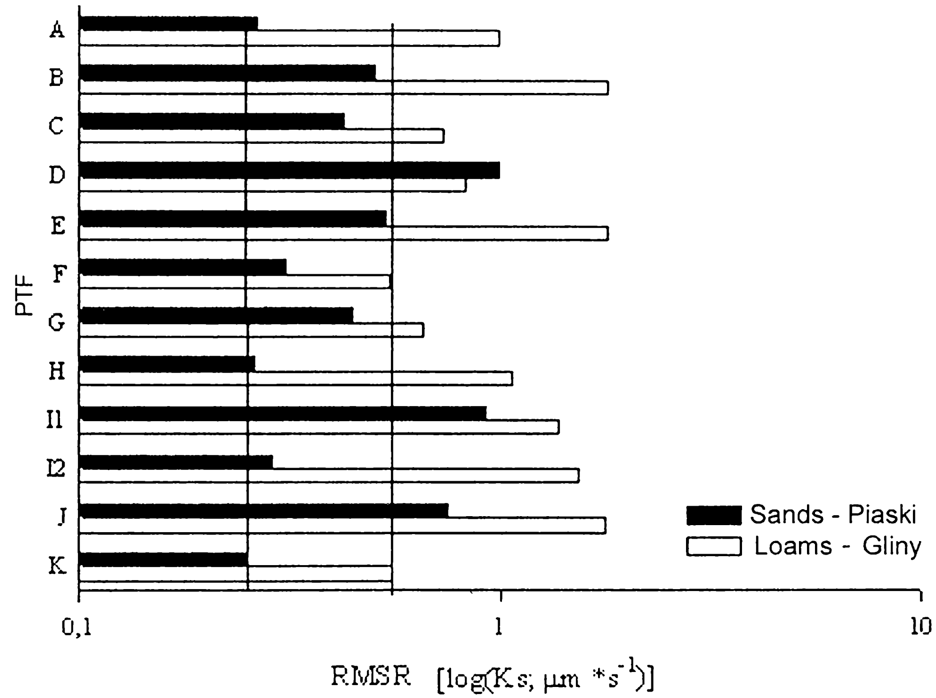

FIGURE 3. The root mean squared residual (RMSR) on Ks prediction of PTFs for sands and loams
RYSUNEK 3. Średni błąd kwadratowy (RMSR) estymacji Ks w utworach piaszczystych i gliniastych dla analizowanych PTF

and total porosity [Brakensiek et al. 1984; Cosby et al. 1984; Saxton et al. 1986; Jabro 1992; Dane, Puckett 1994; Niedźwiecki et al. 2003] (Table 1), do not ensure adequate accuracy for the analysed soils. Also Tietje and Hennings [1996] have proved insufficient accuracy of the PTFs based on multi-factor equations for the soils of Lower Saxony for indirect determination of Ks value. It seems that in the above PTFs, the factors indirectly related to hydraulic conductivity have been taken into account, despite the use of large data sets (230–1448, Table 1). In spite of the above reservations, the equation of Brakensiek et al. [1984] or the Rosetta model [Schaap et al. 2001] provide acceptable accuracy of Ks value estimation when no data on drainage porosity are available, while the equation of Saxton et al. [1986] can be applied for loamy soils.

Out of the hitherto published PTFs, the highest accuracy of Ks value estimation in sand is provided by the power function model of Ahuja et al. [1984] with the parameters proposed by Minasny and McBratney [2000] (eq. 14 in Table 1), while with the parameters of Comegna et al. [2000] (eq. 15 in Table 1) in loams. The high accuracy of the equation proposed by Minasny and McBratney [2000] was proved by these authors on an independent UNSODA data set for which this equation was the most accurate of the many PTFs considered (GMER = 0.682; RMSR [ln(mm/h] = 2.09).

The parameters B and n in the model of Ahuja et al. [1984], optimised for the soils from the Wielkopolska region, permitted the most accurate estimation of the Ks value, confirmed by the results of statistical analysis with all statistical measures of the estimation quality considered (Table 2, Figs. 2 and 3).

The highest accuracy of the power function model of Ahuja et al. [1984] indicates that drainage porosity has a determining effect on the hydraulic conductivity value. This thesis is in agreement with the results of the earlier studies by Baver [1938], Jarvis et al. [1991], Lebron et al. [1999] and Lin et al. [1999] proving that the pore size distribution in the soil, and in particular the content of macro- and mesopores has the greatest effect on hydraulic conductivity. Although drainage porosity is related to the soil texture and total porosity, the latter two features are only indirectly related to hydraulic conductivity.

The different values of the parameters B and n reported by Minasny and McBratney [2000], Comegna et al. [2000] and in this paper (Table 1) confirm the regional character of these parameters, earlier suggested by Rawls et al. [1998]. Therefore, prior to applying the PTF based on the concept of Ahuja et al. [1984], the values of parameters B and n to be used should be verified or determined for the local conditions.

It has been reported that the error of Ks value estimation is in general twice as high for loams as for sands (Figs. 2 and 3). A possible explanation is that it is a consequence of a greater diversity of soil structures in loamy soils and hence, a greater diversity of types of pore distributions in loams than in sands.

CONCLUSIONS

1. For the selected soils from the Wielkopolska region, the most accurate estimation of the hydraulic conductivity value has been obtained using the power function model of Ahuja et al. [1984]. The application of the proposed values of parameters of this model has increased the accuracy of Ks value estimation with respect to the hitherto published solutions. The results have confirmed the thesis of a regional character of the parameters B and n and suggest the need for determination of their local values.
2. The analysis has confirmed the determining effect of pores of a diameter greater than 30 μm (drainage porosity) on soil hydraulic conductivity. The other physical parameters of the soil considered, such as the content of the particular grain size fractions, bulk density and total porosity, are only indirectly correlated with the Ks value, so the PTFs based on these estimators do not have a universal character.

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