Modelling the saturated hydraulic conductivity of soils amended with different biochars

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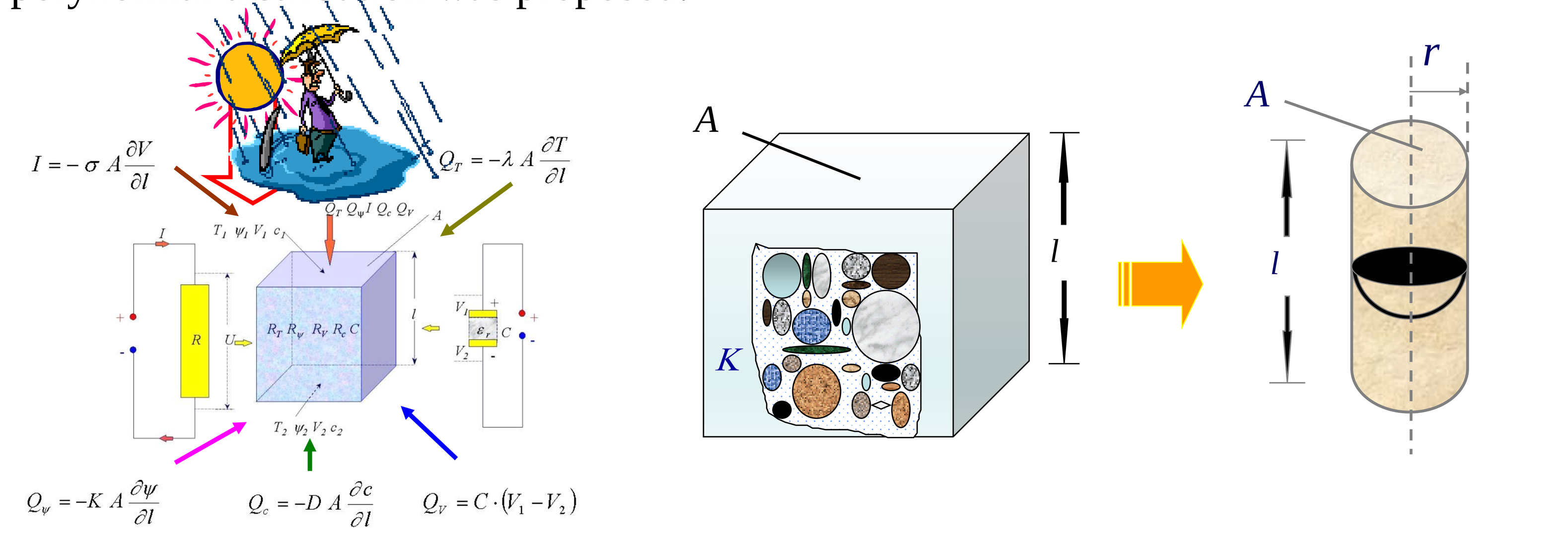
Soil organic carbon accumulation is central to the improvement of many soil properties and functions. Biochar use and management could be particularly beneficial for soils with low organic carbon content. It's known that many of soils in the world intrinsically exhibit little ability to retain water and nutrients due to their texture and mineralogy. Also, acquiring biomass for other than agricultural purposes can reduce the organic carbon accumulation and worsens the soil quality. Adding biochar to the soil can affect saturated hydraulic conductivity, water holding capacity and reduce soil erosion and mineral fertilization. It has been shown that saturated hydraulic conductivity depends on type of feedstock and pyrolysis temperatures used for biochar production and application dose but the results are inconsistent. Therefore, in order to explain the different biochar impacts, we propose in this study the use the physical-statistical model of B. Usowicz [1] for predicting the saturated hydraulic conductivity using literature data for various soils amended with biochars (from woodchip, rice straw and dairy manure), pyrolyzed at 300, 500 and 700 °C [2,3]. The method of estimating hydraulic conductivity of porous media based on physical-statistical model proposed by B. Usowicz is presented Fig 1.

In respect to soil medium the physical-statistical model based on terms of hydraulic resistance, capacitors (Ohm's law and Darcy's law), two laws of Kirchhoff and polynomial distribution was proposed.



Soil with biochar and pores between them can be represented by a pattern (net) of more or less cylindrically interconnected channels with different capillary radius (Fig. 1). When we view a porous medium as a net of interconnected capillaries, we can apply a statistical approach for the description of the liquid or gas flow. The soil and biochar phases and their configuration is decisive for pore distribution and the course of the water retention curve in this medium. The physical-statistical model considers the pore space as the capillary net that is represented by parallel and serial connections of hydraulic resistors in the layer and between the layers, respectively. The polynomial distribution was used in this model to determine probability of the occurrence of a given capillary configuration (Fig. 2). Capillary size radii and the probability of occurrence of a given capillary configuration were calculated based on the measured water retention curve and saturated water content (Fig. 3).

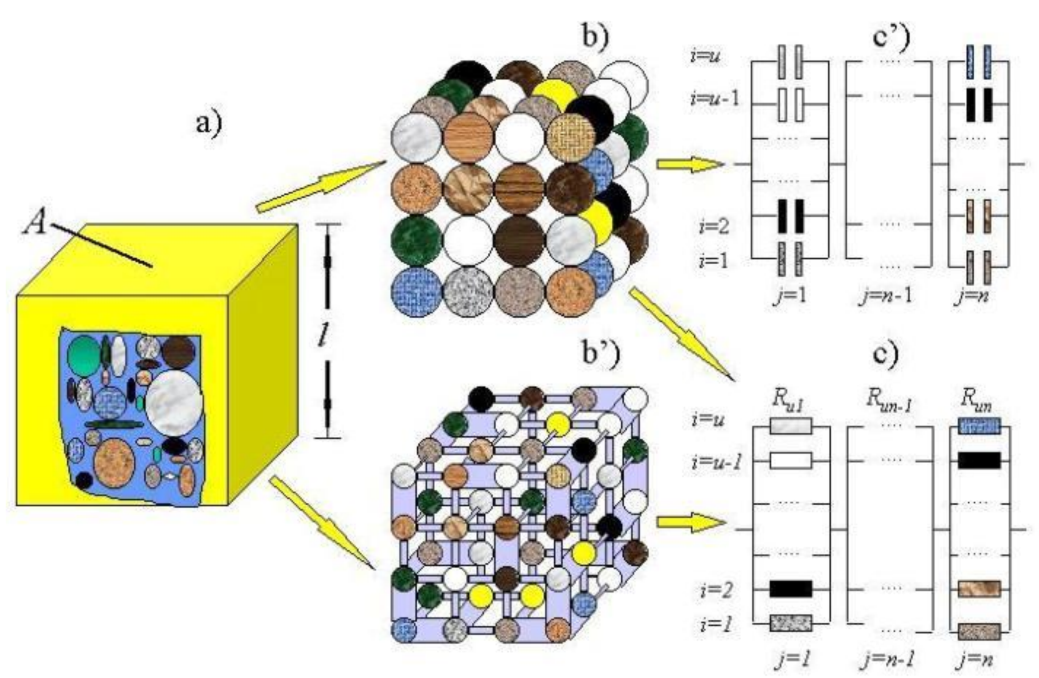


Fig. 1. A schematic diagram of the statistical model construction, a) soil unit volume, b) a system of spheres forming overlapping layers, b') a system of capillaries forming overlapping layers, c) parallel connection of resistors in the layers and series between layers, c') parallel connection of capacitors in the layers and series between layers.

The hydraulic conductivity of a porous medium expressed by the mean hydrodynamic radius of Hagena-Poiseuille's equation, K, like the hydraulic conductivity of an elemental capillary in the net K_{ij}:

$$Q_\psi = \frac{\rho g r^2 A}{8\eta}\frac{\Delta\psi}{l} = \frac{KA}{l}\Delta\psi = \frac{1}{R}\Delta\psi \qquad K = \frac{\rho g}{8\eta} r^2 \qquad K_{ij} = \frac{\rho g}{8\eta} r_{ij}^2$$

where: r denotes a capillary radius, ρ – liquid density, g – acceleration of gravity, η is liquid viscosity. Inserting K and K_{ij}, into the equation for the total resistance of a parallel and serial configuration of resistors and assuming that A corresponds to u mean surface areas πr^2, and A_{ij} equals, πr_{ij}^2, and there are n unit serial connections in the length l, after substituting, we arrive at an equation for the calculation of a mean hydrodynamic squared radius. Putting r^2 again into the equation for K calculation with a mean hydrodynamic radius and following the method applied earlier for the model of electric conductivity, we can set down a general equation for hydraulic conductivity:

$$\frac{l}{AK} = \sum_{j=1}^{n} \frac{1}{\sum_{i=1}^{u} \frac{1}{\frac{l_{ij}}{A_{ij}K_{ij}}}} \qquad r^2 = \sqrt{\frac{1}{\frac{u}{n}\sum_{j=1}^{n}\frac{1}{\sum_{i=1}^{u}\frac{r_{ij}^4}{l_{ij}}}}} \qquad K = \frac{\rho g}{8\eta}\sqrt{\frac{1}{u\sum_{j=1}^{L}\frac{P(x_{1j},\dots,x_{kj})}{x_{1j}\frac{r_1^4}{l_1}+\dots+x_{kj}\frac{r_k^4}{l_k}}}}$$

In the universal, the model probability $P(x_{ij})$ of the occurrence of a given configuration, the constituent elements of a porous medium, should also be determined (Fig. 2). This was determined from the polynomial distribution $P(x_{ij})$:

$P(x_{ij})$ - probability of occurrence of a given soil particle configuration

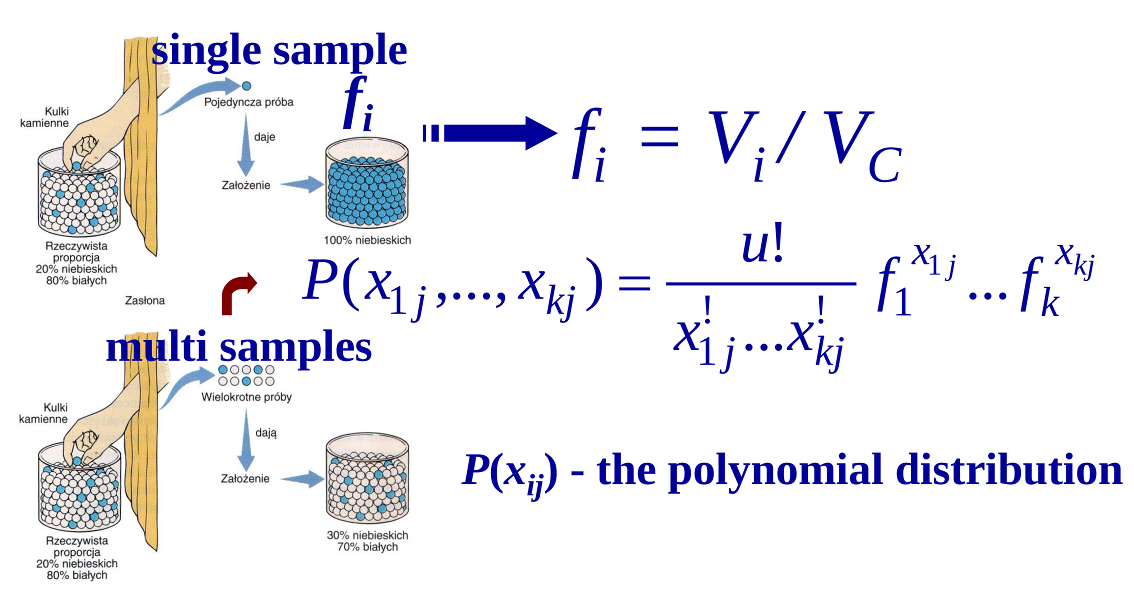


Fig. 2. $P(x_{ij})$ – describes the probability of the event that in u, independent trials exactly x_{ij} results of the j type were obtained, if the probability of the i result in a single trial is f_i, $i = 1, 2, \dots, k$..

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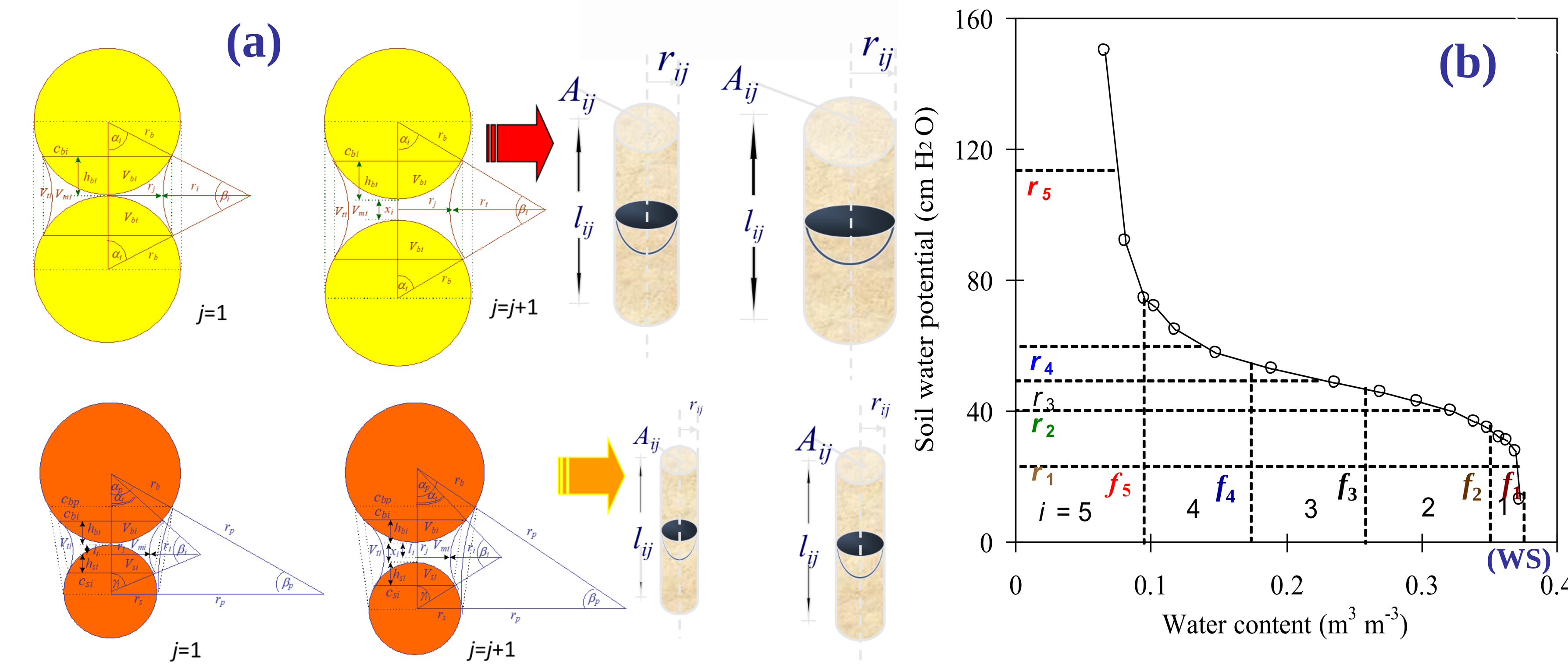


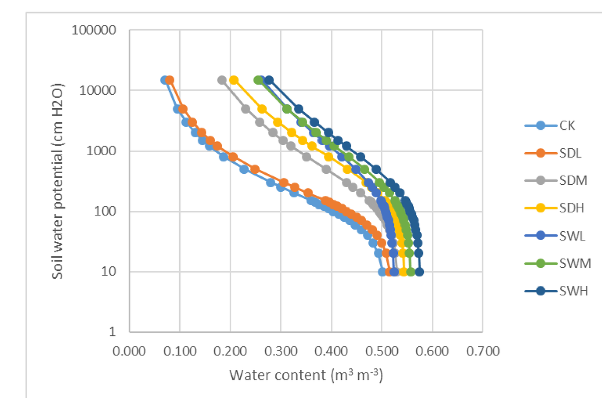
Fig. 3. General systems of capillary bridges between spherical particles with marked capillary radii and configuration (a) and measured water retention curve with marked saturated water content (WS) (b)

Results

Verification of the physical-statistical model has been done by comparing the compatibility of calculation results from the model with the data measured.

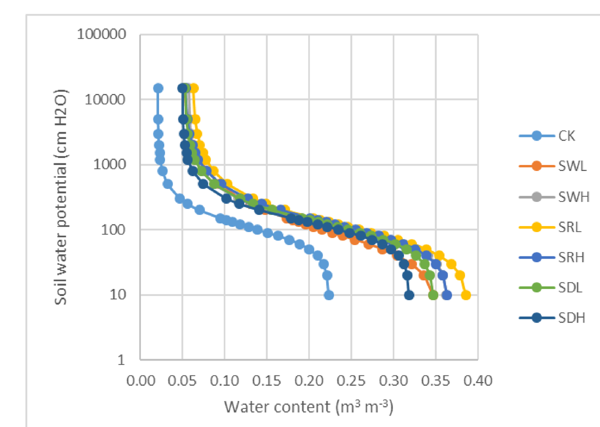
Table 1. Model parameters.

(a)



		CK	SDL	SDM	SDH	SWL	SWM	SWH
r_i	r_i, µm	f_i, m³ m⁻³						
1	360.39	0.035	0.028	0.013	0.008	0.006	0.007	0.007
2	23.34	0.067	0.060	0.025	0.017	0.011	0.014	0.013
3	11.49	0.078	0.076	0.036	0.027	0.018	0.022	0.021
4	3.64	0.181	0.194	0.154	0.149	0.107	0.125	0.122
5	0.53	0.145	0.160	0.304	0.344	0.382	0.390	0.414
6	0.24	0.506	0.519	0.532	0.545	0.525	0.558	0.576
	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$
	l (m)	3.2	2.3	13	20	72	36	45
Bulk density [2]	(Mg m⁻³)	1.190	1.071	1.052	1.062	1.010	1.049	1.051
SSA [2]	(m² g⁻¹)	11.5	14.3	44.1	83.4	24.04	67.3	124
Measured Ksat [2]	(m s⁻¹)	6.898E-06	7.037E-06	7.153E-06	6.968E-06	9.005E-06	9.838E-06	1.028E-05
Calculated Ksat	(m s⁻¹)	6.868E-06	7.011E-06	7.154E-06	6.989E-06	9.057E-06	9.837E-06	1.033E-05

(b)



		CK	SWL	SWH	SRL	SRH	SDL	SDH
r_i	r_i, µm	f_i, m³ m⁻³						
1	360.39	0.014	0.046	0.023	0.033	0.026	0.021	0.013
2	23.34	0.071	0.089	0.091	0.095	0.084	0.081	0.071
3	11.49	0.069	0.068	0.095	0.088	0.088	0.090	0.094
4	3.64	0.047	0.081	0.091	0.097	0.102	0.095	0.087
5	0.53	0.023	0.066	0.064	0.074	0.065	0.062	0.055
6	0.24	0.224	0.351	0.364	0.388	0.365	0.348	0.319
		$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$	$u = 7$
	l (m)	1.13	1.12	0.597	1.17	0.64	0.43	0.42
Bulk density [3]	(Mg m⁻³)	1.53	1.17	1.24	1.2	1.25	1.23	1.27
SSA [3]	(m² g⁻¹)	3.36	1.4	392	2.11	187	3.59	168
Measured Ksat [3]	(m s⁻¹)	6.135E-05	5.215E-05	5.522E-05	3.823E-05	3.540E-05	4.602E-05	4.554E-05
Calculated Ksat	(m s-1)	6.138E-05	5.216E-05	5.222E-05	3.824E-05	3.536E-05	4.618E-05	4.567E-05

Fig. 4 and Table 1. Soil water potential as a function of water content. Model parameters. Bulk density of soil and soil with biochar. SSA represents the specific surface area of soil and biochar. Measured and calculated hydraulic conductivity as a function of saturated water content. Saturated hydraulic conductivities of a the control (CK: pure soil) and treatments with dairy manure biochars (SDL: soil+dairy manure pyrolysized at 300°C; SDM: soil+dairy manure pyrolysized at 500°C; SDH: soil+dairy manure pyrolysized at 700 °C), and b the control (CK: pure soil) and treatments with woodchip biochars (SWL: soil+woodchip pyrolysized at 300 °C; SWM: soil+woodchip pyrolysized at 500 °C; SWH: soil+woodchip pyrolysized at 700 °C). SRL and SRH represent treatments of soil + rice straw biochar pyrolyzed at 300 and 700 °C. The soils were: a loamy soil with 40 % sand, 35 % silt, and 25 % clay (a) and sandy soil with 97.8% sand and 2.2% silty (b). Empirical data (o) were from the references [2, 3].

Conclusions

The physical-statistical model was used for predicting saturated hydraulic conductivity of soils amended with different doses of biochar using measured water retention curve and saturated water content (Figs. 3 and 4a,b). It was found a good agreement between measured and the model-predicted hydraulic conductivity data for the biochar amended soils (Table 1a,b). This indicates that the used variables and model parameters to predict the saturated hydraulic conductivities of the soils were chosen correctly. The different types and pyrolysis temperatures of biochars affected the soil water retention and the equivalent length of the capillaries that characterize the pore tortuosity in the soil (Table 1a,b).