Estimation of hydraulic properties of aggregated soils using a two-domain approach

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Wagner, B., Tarnawski, V.R., Wessolek, G. and Plagge, R. 1996. **Estimation of hydraulic properties of aggregated soils using a two-domain approach**. Can. Agric. Eng. **38**:241-247. Hydraulic properties of aggregated field soils estimated from limited data such as grain size distribution and bulk density show large deviations from experimental results. This paper presents an extension of Campbell's model for the estimation of these properties. This was achieved by considering the geometric mean diameter and the average bulk density of the aggregates. It is assumed that these soils are composed of two domains: the pore volume inside the aggregates and the pore volume between the aggregates (intra-and interaggregate pore spaces). Water was assumed to flow primarily from the two domains in sequence. This approach can be especially useful for mathematical modeling of solute movement during soil water drainage. The model was tested for three soil horizons with varying clay and humus contents. The soil water retention curves and the unsaturated hydraulic conductivities of these horizons were determined experimentally together with the dry bulk density and geometric mean diameter of the aggregates. The model shows acceptable agreement with the experimental data. Restrictions have to be made concerning the applicability of the model in wetting cycles, in frozen soils, and in the presence of transpiring vegetation.

Les propriétés hydrauliques des agrégats de sol estimées à partir de données comme la grosseur des particules et la densité apparente sont très différentes des valeurs expérimentales. Cet article présente une extension du modèle de Campbell pour la détermination de ces propriétés. On a examiné la moyenne géométrique des diamètres et la densité apparente moyenne des agrégats. On suppose que ces sols sont composés de deux entités: la porosité à l'intérieur des agrégats et la porosité entre les agrégats (espace poreux intra- et inter-agrégats). On a supposé que l'eau se déplaçait successivement entre les deux entités. Cette approche est particulièrement intéressante pour la modélisation du mouvement de l'eau de drainage du sol. On a testé le modèle sur trois horizons de sol dont les teneurs en argile et en matière organique variaient. Les courbes de rétention d'eau et la conductivité hydraulique non-saturée ont été mesurées pour ces trois horizons de même que la densité apparente (base sèche) et la moyenne géométrique des diamètres des agrégats. Il y a une bonne correspondance entre les valeurs prédites par le modèle et les valeurs mesurées. Cependant, il y a des restrictions quant à l'utilisation du modèle durant le cycle de mouillage des sols, avec des sols gelés et en présence de végétation qui transpire.

INTRODUCTION

The in-situ measurements of hydraulic properties of field soils usually requires laborious and time consuming experiments and ex-situ laboratory measurements often do not reflect field conditions (changes during soil sampling, different boundary conditions, different temperatures, etc.). Therefore, several theoretical and semi-empirical models for predicting the hydraulic properties of soils from more easily available data have been developed (Brooks and Corey 1964; Campbell 1974, 1985; Bloemen 1980; van Genuchten 1980; Arya and Paris 1981). The majority of these models are derived from the earlier work of Childs and Collis-George (1950) and Marshall (1958) by applying the Hagen-Poiseulle law and integrating with respect to pore size radii derived from grain size distribution and bulk density or porosity.

In many applications these models produce satisfactory results and therefore have been frequently used in the computer simulation of water flow or heat and solute transfer in soils. One of the major drawbacks of these models is the inability to handle structured soils and associated effects like preferential flow. These models have a tendency to underestimate the vulnerability of structured soils to the leaching of solutes (Othmer et al. 1991). To accommodate these effects, Durner (1991) developed a bimodal approach for the estimation of unsaturated hydraulic conductivity based on the Mualem-model by applying the van Genuchten model to different sections of the soil-water-characteristic-curves. Gerke and van Genuchten (1993) developed a dynamic model that accounts for water flow in different soil domains. Chen et al. (1993) estimate the hydraulic properties of macroporous soils during drainage.

Nevertheless, there is still a need for a model which will estimate hydraulic properties of structured soils based on field observations and easily available measured data. The objective of this paper is to introduce a semi-empirical method for estimating the hydraulic properties of aggregated field soils. It extends the two-parameter model for predicting soil hydraulic properties (Brooks and Corey 1964; Campbell 1974, 1985) into aggregated field soils.

CAMPBELL'S MODEL

According to Campbell (1974), the relationship between the soil matric head and volumetric water content can be described by the power function:

$$\psi = \psi_e \left(\frac{\theta}{\theta_s} \right)^{-b} \tag{1}$$

where:

ψ = soil matric potential (kPa),

ψ_e = air entry potential (kPa),

θ_s = saturated volumetric water content (m^3/m^3),
θ = unsaturated volumetric water content (m^3/m^3), and
b = a parameter.

The parameter b was found by Campbell (1985) for two data sets of British soils to be given by:

$$b = d_g^{-0.5} + 0.2\,\sigma_g \tag{2}$$

where:
d_g = geometric mean diameter of particles (mm), and
σ_g = geometric standard deviation of geometric mean diameter (Gardner 1956).

The effect of soil bulk density on the moisture retention curve for the same British soils was given by the empirical correction (Campbell 1985):

$$\psi_e = \psi_{es}\left(\frac{\rho_b}{1.3}\right)^{0.67b} \tag{3}$$

where:
ρ_b = dry bulk density of soil (Mg/m^3), and
ψ_{es} = air entry potential at the bulk density of 1.3 Mg/m^3 (kPa), given by:

$$\psi_{es} = -\,0.49 d_g^{-0.5} \tag{4}$$

The geometric mean particle diameter d_g and the geometric standard deviation σ_g are obtained from the relations provided by Shirazi and Boersma (1984) for soils having a log-normal function of particle size distribution:

$$d_g = \exp\left(\sum_1^3 m_i \ln d_i\right) \tag{5}$$

$$\sigma_g = \exp\left[\sum_1^3 m_i (\ln d_i)^2 - \left(\sum_1^3 m_i \ln d_i\right)^2\right]^{0.5} \tag{6}$$

where:
m_1, m_2, m_3 = mass fractions of clay, silt, and sand, respectively,
d_1, d_2, d_3 = geometric mean particle diameters of clay, silt, and sand (d_1 = 0.001 mm, d_2 = 0.026 mm, d_3 = 1.025 mm).

The hydraulic conductivity of an unsaturated soil, K_u (m/d), can be obtained from the relation provided by Campbell (1974):

$$K_u = K_s\left(\frac{\theta}{\theta_s}\right)^{2b+3} \tag{7}$$

where K_s (m/d) = hydraulic conductivity of the water-saturated soil.

EXTENSION OF CAMPBELL'S MODEL FOR AGGREGATED FIELD SOILS

Aggregated soils contain at least two different pore domains: the pore spaces between the aggregates (interaggregate domain) and the pore spaces inside the aggregates (intraaggregate domain). Therefore, a two-domain concept for water movement within non-layered, aggregated soils, free of transpiring vegetation, is applied to the Campbell's model (Fig. 1). For the most part, water is assumed to move into and out of the intraaggregated pores via the interaggregate domain. The mathematical approach is based on the assumptions:

a) The intraaggregate domain is made up of capillaries with smaller diameters than pore spaces between aggregates and conducts soil water slower than the interaggregate domain.
b) During drainage, the interaggregate domain empties first followed by the intraaggregate pore space; the opposite order is assumed to occur when wetting takes place; i.e., the intraaggregate pore space accumulates and stores water first. Certainly, some restrictions have to be made concerning this assumption; temporary storage and bypass flows have to be expected when infiltrated water enters the interaggregate system faster than the aggregates can take up water. This effect is neglected in the model presented here.
c) After saturation of the aggregates, total flow out of the system consists of water contributed from both the interaggregate and the intraaggregate domains; i.e., flow contributions are additive (Chen et al. 1993).

In the following presentation, variables referring to properties of the intraaggregate domain are denoted by the subscript "*ag*"; those referring to the interaggregate domain are denoted by "*ig*" (Fig. 2). The porosity of the aggregates is given by:

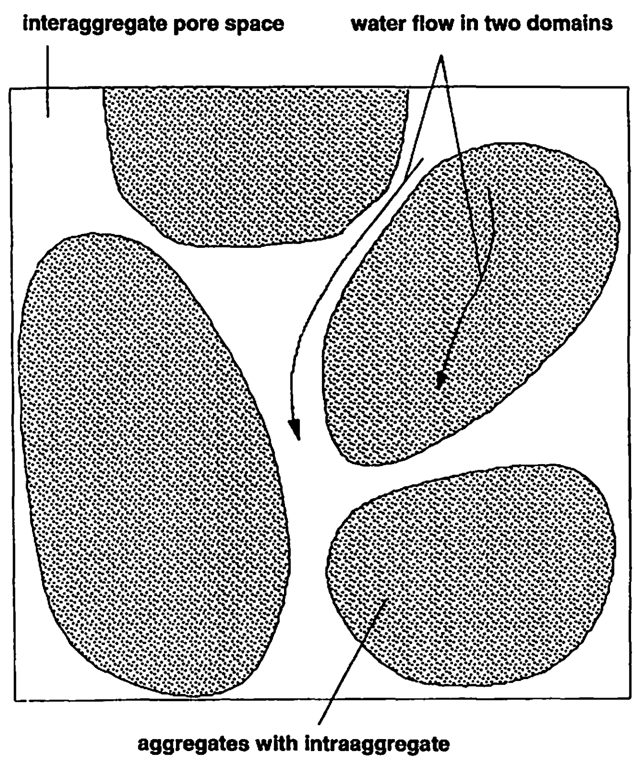

Fig. 1. Schematic representation of the aggregated soil model.

$$\theta_{ag} = 1 - \frac{\rho_{ag}}{\rho_s} \tag{8}$$

where
ρ_{ag} = aggregate density (Mg/m^3),
ρ_s = soil particle density (Mg/m^3), and
σ_{ag} = intraaggregate pore space (m^3/m^3).

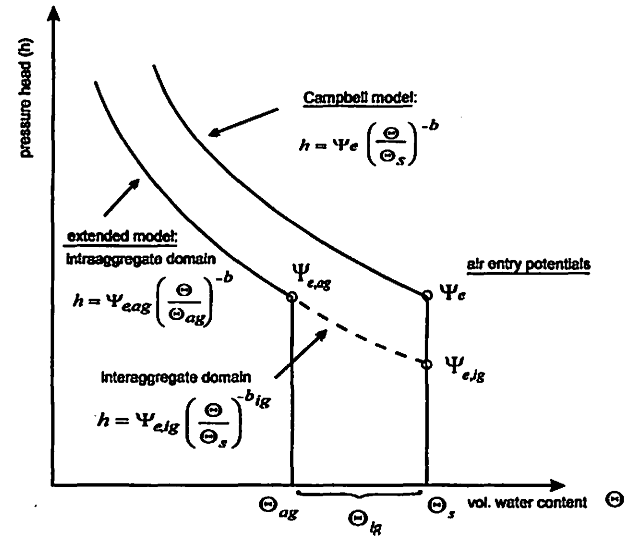

Fig. 2. Denotations of variables for an aggregated soil system on a schematic soil water retention curve.

The interaggregate pore space, θ_{ig}, may then be calculated from total porosity:

$$\theta_{ig} = \theta_s - \theta_{ag} \tag{9}$$

where θ_s = saturated water content (m^3/m^3).

The hydraulic properties of the intraaggregate pore system are calculated according to Eqs. 1 - 7 following the unchanged d_g, σ_g, b, and ψ_{es} of the Campbell model, where:

$$\psi = \psi_{e,ag}\left(\frac{\theta}{\theta_{ag}}\right)^{-b} \quad ; \quad \theta = [0 \cdot\cdot \theta_{ag}] \tag{10}$$

$$\psi_{e,ag} = \psi_{es}\left(\frac{\rho_{ag}}{1.3}\right)^{0.67b} \tag{11}$$

Unsaturated hydraulic conductivity of the aggregates in the range from dryness to θ_{ag} is calculated from:

$$K_{u,ag} = K_{s,ag}\left(\frac{\theta}{\theta_{ag}}\right)^{2b+3} \quad ; \quad \theta = [0 \cdot\cdot \theta_{ag}] \tag{12}$$

At moisture contents above θ_{ag}, $K_{u,ag} = K_{s,ag}$. The saturated hydraulic conductivity $K_{s,ag}$ (m/d) is calculated from the clay (cl) and silt (si) contents corrected for bulk density as described by Campbell (1985):

$$K_{s,ag} = 3.39\left(\frac{\rho_{ag}}{1.3}\right)^{1.3b} \exp\left(-6.88 m_{cl} - 3.63 m_{si} - 0.025\right) \tag{13}$$

For the interaggregate pore system, the air entry potential $\psi_{e,ig}$ is calculated from Eq. 4 with d_{ga} (mm) as the average geometric mean diameter of aggregate size (Gardner 1956):

$$\psi_{es,ig} = -0.49 d_{ga}^{-0.5} \tag{14}$$

Assuming ρ_b =1.3 Mg/m^3, $\psi_{e,ig} = \psi_{es,ig}$. The retention curve is assumed to be represented by a linear relation between $\psi_{e,ag}$ and $\psi_{e,ig}$ on a logarithmic scale. To obtain this, b_{ig} has to be calculated as:

$$b_{ig} = \frac{\ln(\psi_{e,ag}) - \ln(\psi_{e,ig})}{\ln(\theta_s) - \ln(\theta_{ag})} \tag{15}$$

Interaggregate hydraulic properties in the range from θ_{ag} to θ_s can then be obtained from:

$$\psi = \psi_{e,ig}\left(\frac{\theta}{\theta_s}\right)^{-b_{ig}} \quad ; \quad \theta = [\theta_{ag} \cdot\cdot \theta_s] \tag{16}$$

$$K_{u,ig} = K_{s,ig}\left(\frac{\theta}{\theta_s}\right)^{2b_{ig}+3} \quad ; \quad \theta = [\theta_{ag} \cdot\cdot \theta_s] \tag{17}$$

where $K_{s,ig}$ is the saturated hydraulic conductivity of the interaggregate pore domain and must be measured. Equation 17 is basically identical to Eq. 7 and applies as long as the relative water content of the soil (θ) is less than θ_{ag} and the bulk of the soil water originates from, or enters, the intraaggregate pores. At water contents where θ is greater than θ_{ag}, water flows in either domain at rates controlled by the interaggregate system. Flow between the two domains can occur at any time, but flux into or out of the soil usually occurs via the interaggregate domain. These concepts give rise to the assumption of additive flows:

$$Q_{tot} = Q_{ag} + Q_{ig} \tag{18}$$

where:
Q_{tot} = total water flow (m^3/d), and
Q_{ag},Q_{ig} = flows contributed from the intra- and interaggregate pore domains (m^3/d), respectively.

Water flows in the interaggregate pores are simulated taking place through an area, A, of the system, such that:

$$Q_{ig} = K_{u,ig} A \, i_{ig} \tag{19}$$

while flows in the intraaggregate domain only take place through the area A_{ag} filled by the aggregates:

$$Q_{ag} = K_{u,ag} A_{ag} \, i_{ag} \tag{20}$$

where i_{ig},i_{ag} = hydraulic gradients in the inter- and intraaggregate pore domains, respectively.

Assuming that there are no differences in the hydraulic gradients of the different pore systems, the total hydraulic conductivity $K_{u,tot}$ of the aggregated soil follows from Eqs. 18 - 20:

$$K_{u,tot} = K_{u,ig} + K_{u,ag}(1 - \theta_{ig}) \tag{21}$$

The accuracy of the extended model outlined above was tested by comparison with experimental data obtained from three different soil horizons.

MATERIALS AND METHODS

Two field sites in Germany provided soil samples with varying clay and humus contents for model testing (nomenclature according to U.S. soil classification system): a clayey loam (vertic Cambisol) from Hordorf near Braunschweig and a loess soil (haplic Luvisol) from Ohlendorf near Hannover (Table I). A visual analysis of both soil profiles showed great differences in structure and aggregation (Table II). Three soil horizons were sampled. The Ap horizon of the loess is homogeneous and has a fine structure with a weak tendency to form small crumbs. In contrast, the vertic Cambisol with a clay content between 30 and > 60% shows polyhedronic aggregates in the Ap horizon and prismatic lumps in the Sw horizon. In the wet and dry ranges, swelling and shrinkage occur. The pH and cation exchange capacity (CEC) of the three horizons are high (Table I).

The soil water retention curves and the saturated hydraulic conductivity were determined for the three horizons using laboratory-based, ceramic plates and a permeameter similar to that described by Hartge and Horn (1995). In addition, hydraulic conductivity near saturation (2-10 kPa) was determined by a modified instantaneous profile approach (Plagge 1991).

Measurements giving the density and geometric mean diameter of the aggregates were performed for all soils. Bulk density was measured by dividing the aggregates of different aggregate size fractions in water and weighing. Geometric mean diameter was determined from two samples for each soil by drying and disintegrating the soil into the single aggregates manually; aggregates were then sieved and weighed (sieve sizes: 1, 2, 4, 10, 20 and 70 mm).

Table I: Physical properties of soil horizons

Soil horizon	Texture (kg/kg)			Bulk density (Mg/m^3)	Saturated volumetric water content
	Clay	Silt	Sand		
Hordorf Sw	0.616	0.379	0.005	1.44	0.42
Hordorf Ap	0.348	0.430	0.222	1.50	0.43
Ohlendorf Ap	0.092	0.872	0.036	1.42	0.48

Soil horizon	Texture	Organic matter (kg/kg)	CEC ($cmol_c$ /kg)	pH ($CaCl_2$)	K_s (m/d)
Hordorf Sw	Silty clay	0.006	24.7	7.5	0.002
Hordorf Ap	Clay loam	0.041	29.8	6.9	0.168
Ohlendorf Ap	Silt	0.014	11.2	6.3	0.350

RESULTS AND DISCUSSIONS

Geometric mean diameters of aggregates and average aggregate densities are listed in Table III. The measured geometric mean diameter of aggregates varied between 3.1 and 19.3 mm. No significant differences in bulk density could be found for the different aggregate size fractions.

Figure 3 gives the measured and calculated water retention and unsaturated hydraulic conductivity for the Hordorf Sw horizon. Using measured aggregate parameters in the extended Campbell prediction model, gives a good fit between calculated and measured retention data. Measured unsaturated hydraulic conductivity is not fully matched, but the decline of hydraulic conductivity at lower suctions shows that the predictions are closer to the measurements than the Campbell model. To test the sensitivity of the extended model, geometric mean diameter and aggregate bulk density of the Hordorf Sw horizon were varied within a broad range of aggregate properties with densities (1.6 - 2.0 Mg/m^3) and geometric mean diameters (0.2 - 40 mm)(Fig. 3, Table III). Aggregation of the soil should lead to lower water contents at the same suctions depending on dry bulk density of the aggregates, while the air entry point is determined by the aggregate sizes. Unsaturated hydraulic conductivity declines at lower suctions, depending on aggregate sizes, while at high suctions (above 1000 kPa) predicted values are nearly independent of aggregate dry bulk density.

Results of water retention functions produced by the Campbell model show significant deviation from experimental data. This is due to the fact that Campbell's model was originally developed for a homogeneous distribution of soil particles and does not account for aggregated soil structure.

Figure 4 gives measured and calculated hydraulic proper-

Table II: Aggregation of investigated soil horizons

Soil horizon	Aggregation (visual analysis)
Hordorf Sw	prismatic lumps, slickensides, elastic deformation
Hordorf Ap	polyhedronic aggregates, coarse grained, swelling/shrinkage
Ohlendorf Ap	fine texture, uniform small crumbs

Table III. Model parameters of investigated soil horizons

Soil horizon	Density of aggregates (Mg/m^3)	b	ψ_e (kPa)	d_{ga} (mm)	$\psi_{e,ag}$ (kPa)	b_{ig}	$\psi_{e,ig}$ (kPa)
Hordorf Sw 1 (measured data)	1.8	17.5	48	19.3	307	29.2	0.12
Hordorf Sw 2 (sensitivity analysis, lower range)	1.6	17.5	48	0.2	77	72.3	1.14
Hordorf Sw 3 (sensitivity analysis, upper range)	2.0	17.5	48	40.0	1060	17.6	0.08
Hordorf Ap	1.8	9.9	8.8	4.3	28.2	16.2	0.25
Ohlendorf Ap	1.52	7.4	5.5	3.1	8.8	26.8	0.29

b = parameter from Campbell's model, ψ_e = air-entry potential in Campbell's model, d_{ga} = geometric mean diameter of aggregates, $\psi_{e,ag}$ = air-entry potential of aggregates in aggregated soil, b_{ig} = parameter in the extended model, $\psi_{e,ig}$ = air-entry potential aggregated soil

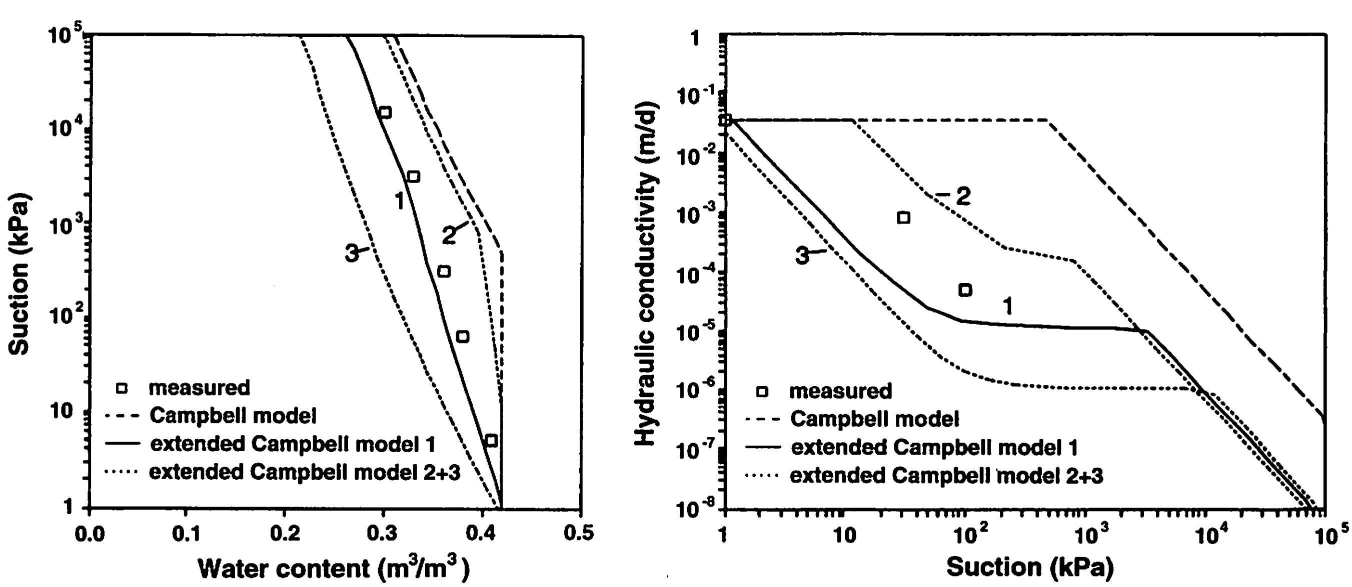

Fig. 3. Measured and predicted (Campbell model and extended model) soil water characteristic curves of the Hordorf Sw. Results of the extended model are shown for measured aggregate parameters (model 1) and the expected low and high range of aggregate parameters (models 2 and 3) as given in Table III.

ties of the Hordorf Ap horizon. Water retention is well represented by the extended model, but unsaturated hydraulic conductivity is overestimated. On the other hand, the estimation of the extended model clearly gives a better fit to the measurements than the original Campbell model. This applies especially at suctions below 2 kPa.

Figure 5 shows results of measurements and calculations for the Ohlendorf Ap horizon. The lower air entry point is well met by the extended model, but at higher suctions water contents are overestimated. Again, the model gives a better fit to measured data than the original Campbell model and the improvement is best at low suctions.

A possible reason for the deviations between the extended model and measurements could be the influence of high humus content on soil hydraulic properties, especially in the Hordorf Ap horizon. One common characteristic seen in all figures is that calculated hydraulic conductivity data are approximated by two linear functions on the log-log scale connected by a non-linear one. This is explained by the fact that in the model the two different curves for unsaturated hydraulic conductivity in the two domains of the aggregate flow model are overlain. After drainage of the interaggregate pore space, the air entry point of the aggregates has not yet been reached, so that unsaturated hydraulic conductivity remains relatively constant until drying of aggregates starts. This stepwise function is not reflected in the measurements and likely due to the fact that sharp distinctions of drainage between intraaggregate and interaggregate pore space do not occur. The transition tends to follow smoothly. Nevertheless, Figs. 3, 4, and 5 show that the extended model allows a much better prediction of unsaturated hydraulic conductivity than the Campbell model, especially at lower suctions.

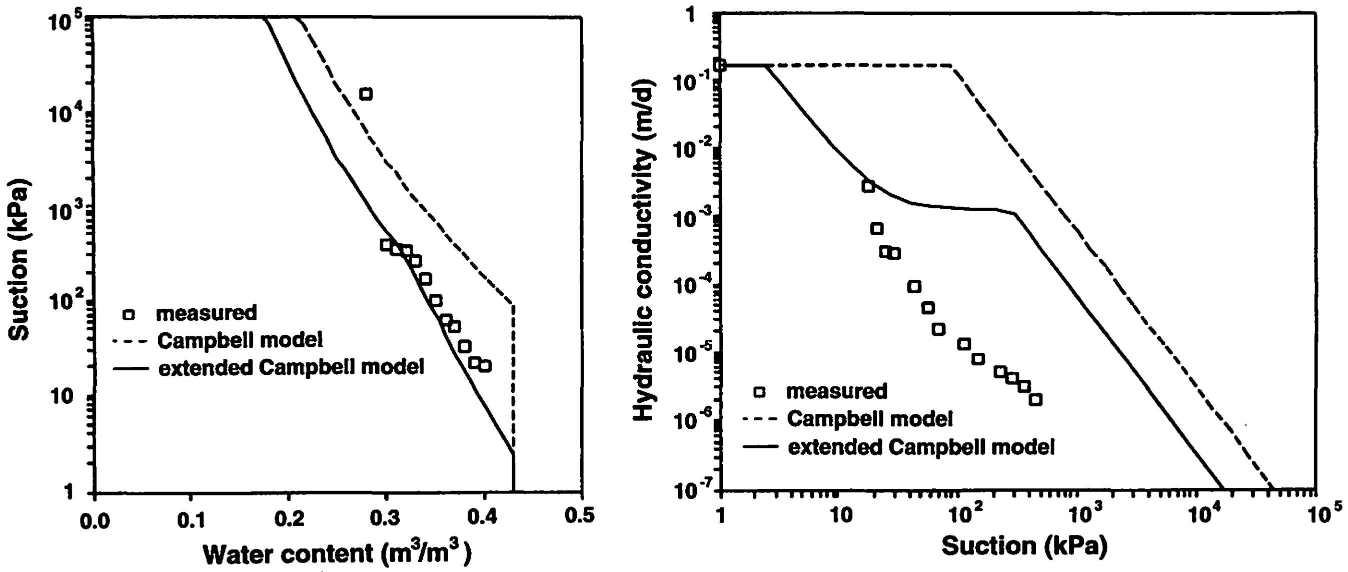

Fig. 4. Measured and predicted (Campbell model and extended model) soil water characteristic curves of the Hordorf Ap.

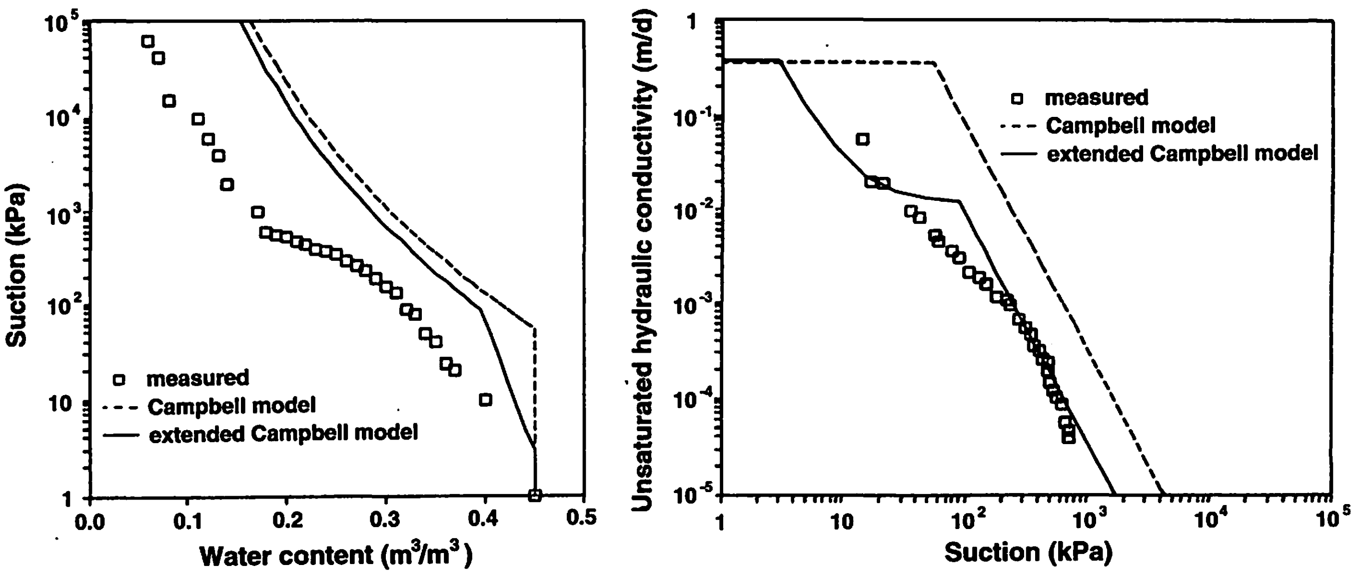

Fig. 5. Measured and predicted (Campbell model and extended model) soil water characteristic curves of the Ohlendorf

CONCLUSIONS AND RECOMMENDATIONS

A semi-empirical approach to the estimation of hydraulic properties of aggregated field soils from grain size distribution, porosity, and bulk density data has been developed. The model extends the Campbell model by introducing two parameters: density and geometric mean diameter of the aggregates. Measured values of these parameters gave improved predictions of the hydraulic parameters of the investigated soil horizons.

The following conclusions can be drawn about the new model:

1) it allows the adaption of the Campbell model to simulate water movement, especially for drainage, through aggregated soils by a parameter fitting procedure;
2) an adaption of the model to measured soil water characteristics will improve predictions of unsaturated hydraulic conductivity;
3) a better prediction of hydraulic properties based on grain size distribution may be achieved by integrating field observations of aggregation into the model.

It is anticipated that the concepts outlined above in the extended Campbell model will greatly improve predictions of water and solute transport in aggregated soils limited by input data (e.g., only grain size analysis and bulk densities are necessary). This approach can be particularly useful for modelling leaching phenomena in aggregated soils induced by macroporous flows. Water moving through the interaggregate domain following high infiltration rates (e.g., after heavy rains), and bypassing the aggregates, is not accounted for in the model. Nor is the model applicable to soils with frozen layers, nor those soils where vegetation is actively transpiring.

Recommendations for further study include development and testing of the extended model with a larger data set of aggregate densities and geometric mean diameters.

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NOTATION

A	area, (m^2)
b	constant in Campbell's equation
b_{ig}	constant in extended aggregate model
d	24 hrs period of time
d_g	geometric mean particle diameter (mm)
d_{ga}	geometric mean diameter of aggregates (mm)
d_i	geometric mean diameter of soil separates (mm)
i	hydraulic gradient (m/m)
m_i	mass fractions of soil separates
Q	flux of water (m^3/d)
K_s	saturated hydraulic conductivity (m/d)
K_u	unsaturated hydraulic conductivity (m/d)
$K_{u,tot}$	total unsaturated hydraulic conductivity (m/d)
ψ	soil matric potential (kPa)
ψ_{es}	air entry potential (kPa)
ψ_e	air entry potential (corrected for bulk density) (kP_a)
$\psi_{e,ig}$	air entry potential of interaggregate pores (kPa)
$\psi_{e,ag}$	air entry potential of aggregates (kPa)
σ_g	standard deviation of geometric mean particle diameter
θ	volumetric moisture content
θ_s	saturated moisture content
θ_{ag}	porosity of aggregate domain
θ_{ig}	porosity of inter-aggregate domain
A_s	density of solid particles (Mg/m^3)
A_b	bulk density of dry soil (Mg/m^3)
A_{ag}	bulk density of aggregates (Mg/m^3)

Subscripts

ag	intraaggregate domain
ig	interaggregate domain