MODELLING OF SOIL WATER RETENTION PROPERTIES FOR SOIL PHYSICAL QUALITY ASSESSMENT

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Abstract: *Because the soil water retention curve assessment requires (in terms of standardized European methodology) long time for measuring all levels of the soil water suction applied, we have used an indirect estimation methodology (deterministic) in order to have an overview of the soil capacity to retain water at different levels, which correspond to the main soil hidrophysical indicators, particularly important in assessing soil fertility status, as characterized by the ability of soil to maintain water in soil, and release the water when there are needs and / or requirements for crop plants. In this paper we present the model of Arya - Paris, which assess the water retention curve using soil texture and bulk density data. This model is based on the analogy between the soil water retention curve and the cumulative distribution curve by soil particles size. Parameter α introduced by Arya and Paris is an effective way to assess the length of capillaries in natural soils using as a measure spherical particles associated with the class in which was divided the solid fraction of soil. Arya-Paris model with α values calculated was applied to evaluate pairs of θ (soil water content) - ψ (matric potential). The van Genuchten equation was then used to estimate the water retention curve in the analyzed soils. We used in the paper three soil types (Calcic Chernozem, Rendzic Leptosol and Calcaro-calcic Kastanozem) located in the Dobrogea area from SE of Romania. Parameters of the van Genuchten equation, θr, θs, α, n were evaluated using the pairs of values θ - ψ calculated by Arya-Paris model using the Solver tool from Microsoft Excel software package. Van Genuchten equation was then used to assess some parameters that have agronomical significance. Optimum soil water content and soil matric potential for soil workability correspond to the inflection point of the soil water retention curve and were calculated using the van Genuchten parameters. Depending on the characteristics of the soil water retention curve at the inflection point the soil physical quality index, S, was calculated.*

Key words: *soil water retention curve, Arya-Paris model, van Genuchten equation, optimum soil water content, S index*

INTRODUCTION

Plants need water for their growth and they take their water from the soil, which typically is a porous medium. The storage of water in the soil is therefore of crucial importance to plants.

The soil hydraulic properties that are needed in soil water balance calculations are the water retention characteristics, $\theta(h)$, which describes the relationship between the volumetric water content of the soil θ and the water pressure head h and the hydraulic conductivity functions, $K(\theta)$ or $K(h)$, which define the relationships between volumetric water content and hydraulic conductivity or pressure head and hydraulic conductivity respectively.

The soil water retention curve expresses the capacity of soils to store water for plant growth, which is a very important soil property for irrigation and modeling of hydrological properties. Several laboratory methods are employed for the determination of the soil water retention curves, which are grouped in suction-type (porous plate funnel, tension table) and pressure-type cell apparatus (Richard chamber) using both undisturbed and disturbed soil core samples. However, these methods are expensive and difficult to implement. Therefore attention has been paid to the development of indirect methods, which predict the hydraulic properties from more easily measured data, including water retention data and pore- or particle size distributions (e.g. VAN GENUCHTEN et al. 1999, ARYA et al., 1999, PACHEPSKY AND RAWLS, 1999). Indirect methods generally are more convenient, far less costly to implement and generally give hydraulic estimates accurate enough for most applications.

The shape similarity of the particle size distribution curve (PSDC) and the water retention curve (WRC) is the presupposition for the two semi-physical models found in the literature (e.g. ARYA AND PARIS 1981 and HAVERKAMP AND PARLANGE 1986). Using the Arya and Paris model, the cumulative PSDC is divided into a number of fractions, giving a pore volume and a volumetric water content to each fraction and then counting a representative mean pore radius (R_i) and a corresponding water pressure head (h_i) value (HAVERKAMP et al. 1999). Arya and Paris derived a formulation showing the relationship between pore and particle radii for an assemblage of uniformly-sized spherical particles in a cubic packing. This relationship was extended to natural soil materials by means of an empirical parameter, α.

The relation between soil water retention and other more easily measured soil properties has been extensively researched and numerous empirical models and methods have been developed (e.g. CONNOLLY, 1998). An example of such methods based on the soil water retention characteristic is that presented by DEXTER AND BIRD (2001). They developed a method for predicting the lower (dry) limit, the optimum water content, and the upper (wet) limit for tillage based on the water retention curve. The optimum water content for tillage estimated by using this method was identified as the water content at the "inflection point" on the water retention curve and can be defined as 'the water content at which tillage operations can result in production of greatest proportion of small aggregates' (DEXTER AND BIRD, 2001).

The objectives of the work presented in this paper were modelling of the soil water retention properties by using the Arya-Paris model for calculation of the parameters of van Genuchten equation and then use of these parameters for estimation of other physical indices, such as: soil physical quality index (S), optimum water content (θ_{opt}) and optimum water pressure (ψ_{opt}) for workability of arable soils. The estimations of the physical indices were done on three soil types from SE of Constanța county.

MATHERIALS AND METHODS

Particle size distribution, bulk density and organic matter content data used in the present study were obtained by authors from the RISSA soil database. The selected soils for this study are located in SE of Constanta county, namely: profile P1 in Basarabi location, profile P2 in Basarabi location and profile P3 in Valu lui Traian location. According to the SRTS (2003) soil classification, the soils used in this paper are: P1 – Calcic Chernozem, P2 – Rendzic Leptosol and P3 – Calcaro-calcic Kastanozem. The basic physical characteristics of the soil profiles investigated are presented in ***Table 1***.

Arya-Paris model

Given that the soil water retention curve assessment requires long time, in terms of methodology, standardized at European level, for completing all levels in the soil water retention, we propose an indirect estimation methodology (deterministic) in order to have an overview of the capacity of soil to retain water at different levels of suction, which correspond to the main soil hydrophysical indices, particularly important in assessing soil fertility status, as characterized by the ability to maintain water in soil, at times when the needs and / or requirements of crop plants have to be fulfilled.

In this respect, we present the Arya-Paris model which assesses the soil water retention curve using soil texture and bulk density data.

Table 1

Physical characterization of the investigated soils

Location	Soil type	Horizon / Depth (cm)	sand (>20μm) ($g\ g^{-1}$)	silt (20-2μm) ($g\ g^{-1}$)	clay (<2μm) ($g\ g^{-1}$)	Soil texture class	Organic matter (%)	Bulk density ($g\ cm^{-3}$)
Basarabi (P1)	**CHca**	Ap 0-16	39.5	31.3	29.2	LL	4.0	1.29
		Am 16-41	34.4	34.4	31.2	LP	3.8	1.24
		AC 41-62	36.0	31.4	32.6	LL	3.0	1.26
		AC 62-86	41.4	28.3	30.3	LL	2.9	1.29
		Cc 86-115	40.9	29.4	29.7	LL	1.4	1.33
		Cc 115-250	42.0	30.0	28.0	LL	0.7	1.30
Basarabi (P2)	**LPrz**	Am 0-14	25.0	18.1	56.9	AL	3.4	1.40
		Am 14-35	26.1	14.8	59.1	AL	3.1	1.32
		AR 35-50	25.4	16.2	58.4	AL	2.3	1.38
		Rn 50-110	75.0	15.0	10.0	UG	1.4	1.30
Valu lui Traian (P3)	**KCcc-ca**	Ap 0-22	37.8	29.0	33.2	TT	3.0	1.11
		Am 22-42	34.1	31.1	34.8	TT	3.0	1.20
		AC 42-60	31.0	36.4	32.6	TT	1.8	1.15
		Cc 60-95	30.2	38.4	31.4	LP	1.5	1.16
		Cc 95-125	34.3	35.4	30.3	LP	1.3	1.30
		Cc 125-150	34.0	34.7	31.3	LP	0.7	1.32

This model is based on the analogy between the soil water retention curve and the cumulative curve of distribution by size of soil particles.

Arya-Paris model divides the cumulative distribution curve by size of soil particles in n fractions as defined by the average particle radius. Capillaries volume and their associated radius is calculated for each fraction using the equation:

$$V_i = (W_i / \rho_p) \cdot e \quad i = 1 \ldots n \tag{1}$$

where Vi is the volume of capillaries (per unit mass of sample) associated to the particles from class i, Wi is the mass of particles from class i relative to the total mass of the sample, ρ_p the particle density and e is the pore index.

Volumetric water content is obtained by progressive accumulation of the volume of capillaries and their division to soil bulk density (assumed equal for all fractions):

$$\theta_i = \sum_{j=1}^{j=i} \frac{V_j}{V_b} \tag{2}$$

$i = 1, 2, \ldots , n$

where θ_i is the water content (as volume base) represented by the volume of capillaries for which the upper limit of capillary radius corresponds to the upper limit associated to the i class of pores, V_b is the volume of soil sample ($=1/\rho b$, where ρb is the bulk density of the undisturbed soil sample).

Assuming that the solid mass of soil from domain of i particles is composed from spherical particles of the same size, the relationship between the radius of capillaries associated with this class of particles and the particle size is:

$$r_i = R_i \sqrt{\frac{4en_i^{1-\alpha}}{6}} \qquad (3)$$

where r_i is the radius of capillaries, and R_i is the mean size of particles.

The radius of capillaries is converted to matric potential by using the Jurin law:

$$\psi_i = \frac{2\sigma}{\rho_w g r_i} \qquad (4)$$

where ψ_i is the capillary water pressure, σ is the superficial tension, ρ_w is the water density and g is gravitational acceleration.

The α parameter introduced by Arya and Paris is an effective way to assess the length of capillaries in natural soils using as a measure spherical particles associated with the class in which was divided the solid fraction of soil. In the original version of the model the α parameter value was 1.38 for all soils tested.

In a further approach, TYLER AND WHEATCRAFT (1989, 1990, 1992) associated the α parameter with the fractal dimension of pore space, based on observation that the capillary length increases with decreasing of the size of associated solid soil particles. It was considered that the α parameter is influenced by fractal like mechanisms associated to the water retention in soil at low levels of water content.

In this way it can be considered as the value of fractal dimension of soil the α parameter value calculated by equalizing the water content determined by the Arya-Paris model corresponding to 15 bar matric potential with the experimentally measured value (Mitscherlich hygroscopicity coefficient).

Arya-Paris model with the α values calculated by the previous method was applied to evaluate pairs of θ (soil water content) – ψ (matric potential).

It was then used the van Genuchten equation for estimation of the soil water retention curve in the analyzed soils:

$$\theta = \theta_r + (\theta_s - \theta_r) \cdot \left[\frac{1}{1+(\alpha \cdot \psi)^n}\right]^{\left(1-\frac{1}{n}\right)} \qquad (5)$$

where: θ water content at the suction h (kg kg-1);
θ_{sat} water content at saturation (kg kg-1);
θ_{res} residual water content (kg kg-1);
α adjustable scaling factor (hPa-1);
h water suction (equal to the modulus of the matric potential (hPa));
m, n adjustable shape factors.

Parameters of the van Genuchten equation, θ_r, θ_s, α, n were evaluated using the $\theta - \psi$ values pairs calculated with Arya-Paris model by using the Solver tool from Microsoft Excel software package.

The van Genuchten equation was used to assess some parameters with agronomic significance. Optimum soil water content and matric potential for workability correspond to the inflection point of the soil water retention curve.

The water content and matric potential optimum for soil workability are calculated by using the following formulas:

$$\theta_{opt} = (\theta_s - \theta_r) \cdot \left[1 + \frac{1}{m}\right]^{-m} + \theta_r \qquad (6)$$

$$\psi_{opt} = \frac{1}{\alpha} \cdot \left[\left(\frac{\theta_{opt} - \theta_r}{\theta_s - \theta_r} \right)^{-\frac{1}{m}} - 1 \right]^{\frac{1}{m}} \quad (7)$$

Depending on the characteristics of the soil water retention curve near the inflection point, the index *S* was calculated to assess the soil hidrophysical quality:

$$S = -n \cdot (\theta_s - \theta_r) \cdot \left[1 + \frac{1}{m} \right]^{-(1+m)} \quad (8)$$

The *S* index has different areas of variation, depending on which the soil presents or not agrophysical degradation status. This way of addressing issues related to soil agrophysical degradation is new, easier to measure, the *S* index encompassing more indicators to estimate the level of soil degradation.

RESULTS AND DISCUSSIONS

The mean values of the parameters of van Genuchten equation (Eq. 5) together with the calculated values of *S* index and the optimum water contents (θ_{opt}) and optimum matric potential (ψ_{opt}) for soil workability are presented in *Table 2* for all the three soil profiles. In general, the values of *S* index (0.039 – 0.072) were in the range of the *S* values defining a good soil physical quality according to DEXTER (2004a,b,c). Therefore, a good soil physical quality in terms of *S* results was associated with low bulk density values and relatively high organic matter values, and also is due to equilibrated medium – fine texture of the investigated soils (see also *Table 1*).

Table 2

Values of the parameters of van Genuchten equation obtained using Arya-Paris model and of the *S* index, optimum soil water content (θ_{opt}), optimum matric potential (ψ_{opt}) and pF

Location	Soil type	Horizon	Depth (cm)	θ_s (kg kg^{-1})	θ_r (kg kg^{-1})	α (h Pa^{-1})	n (-)	S (-)	θ_{opt} (kg kg^{-1})	ψ_{opt} (hPa)	pF
Basarabi (P1)	CHca	Ap	0-16	0.3588	0.0495	0.0255	1.4796	**0.071**	**0.2455**	**83.97**	**1.92**
		Am	16-41	0.3893	0.0027	0.0244	1.2001	**0.048**	**0.2822**	**181.94**	**2.26**
		AC	41-62	0.4529	0.0013	0.0248	1.1989	**0.054**	**0.3314**	**180.15**	**2.26**
		AC	62-86	0.3729	0.0485	0.026	1.4011	**0.066**	**0.2595**	**93.91**	**1.97**
		Cc	86-115	0.4567	0.0131	0.0253	1.1989	**0.055**	**0.3341**	**176.69**	**2.25**
		Cc	115-250	0.4563	0.0121	0.02577	1.1967	**0.054**	**0.3341**	**175.42**	**2.24**
Basarabi (P2)	LPrz	Am	0-14	0.4177	0.0165	0.0287	1.2426	**0.057**	**0.2982**	**129.77**	**2.11**
		Am	14-35	0.4304	0.0226	0.0287	1.2104	**0.052**	**0.3161**	**147.90**	**2.17**
		AR	35-50	0.4357	0.0000	0.0287	1.1836	**0.051**	**0.3191**	**168.28**	**2.23**
		Rn	50-110	0.4152	0.0129	0.0195	1.2026	**0.058**	**0.3534**	**155.87**	**2.19**
Valu lui Traian (P3)	KCcc -ca	Ap	0-22	0.4216	0.0329	0.0258	1.2033	**0.049**	**0.3133**	**169.91**	**2.23**
		Am	22-42	0.4432	0.0131	0.0244	1.3022	**0.072**	**0.3050**	**125.99**	**2.10**
		AC	42-60	0.4062	0.0000	0.0237	1.1624	**0.043**	**0.3030**	**229.52**	**2.36**
		Cc	60-95	0.4307	0.0088	0.0233	1.1926	**0.051**	**0.3156**	**197.64**	**2.29**
		Cc	95-125	0.3808	0.0000	0.0221	1.1551	**0.039**	**0.2859**	**257.50**	**2.41**
		Cc	125-150	0.4379	0.0124	0.0228	1.1993	**0.053**	**0.3202**	**195.72**	**2.29**

The slope, *S*, of the soil water retention curve indicates the extent to which the soil porosity is concentrated into a narrow range of pore sizes, a larger value of *S* means the presence of a better-defined micro-structure, and consequently a good physical quality of the soil (see also ***Figures** 1, 2* and *3*). In turn, soil physical degradation, such as compaction, can change the pore size distribution and consequently the shape of the water retention curve. Compaction reduces both the water content at saturation, θ_{sat}, and the slope of the retention curve at the inflection point. As a result, a small value of *S* represents a soil that is structureless (homogeneous), whereas a greater value of the slope *S* corresponds to a soil that has a well-developed micro-structure.

In *Figures 1, 2* and *3* the model-predicted soil water retention curves based on the best-fit values of α for the investigated soils are presented. A value of 1.38 was considered as the best estimate of α. Using this value of α, the model was used on three soils from SE of Constanța county in order to predict the soil water retention characteristics. The Arya-Paris model is based on the idea that the size of particles and the packing density are the primary determinants of the pore size. However, aggregation of primary particles into secondary and tertiary particles, root channels and microcracks would account for a fraction of the pore volume with radii not determined by the distribution of primary particles (ARYA AND PARIS, 1981).

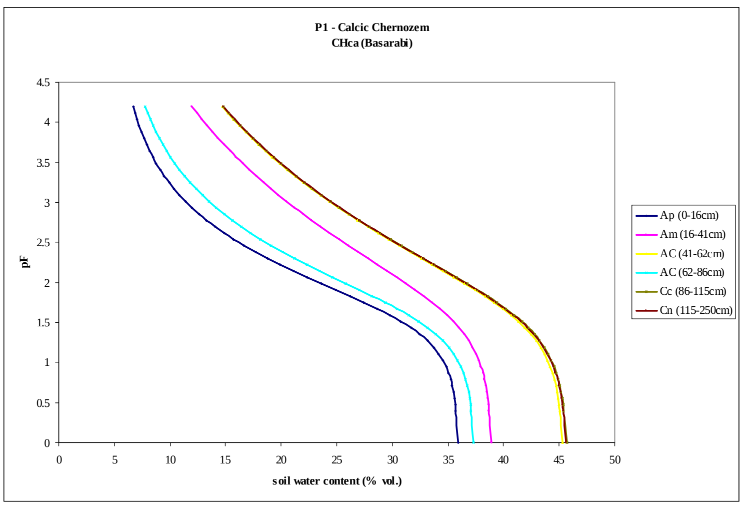

Figure 1. Soil water retention curves of the Calcic Chernozem from Basarabi

The most limiting factor for tillage is the soil water content. If tillage is performed in wet soil, it will result in soil compaction and structural damage and if tillage is performed in dry soil, large clods are produced and energy consumption is increased too. Soil tillage operation has two aspects: i) workability: effect of engaged tools with soil on structure, compaction and fracture of soil, and ii) trafficability: possibility of tractors and agricultural machinery passing on the soil surface. The workability of soil indicates the condition when tillage operations can be performed for making the desired structure and shape of its surface (HOOGMOED *ET AL.*, 2003). ROUNSEVELL AND JONES (1993) defined workability as a condition in which soil tillage operations (e.g. ploughing and seedbed preparation) can be performed. They defined trafficability as the capacity of soil to support and withstand traffic with negligible soil structural damage and no adverse effects on crop yield. DROOGERS ET AL.

(1996) illustrated that soil trafficability is the condition that 'soil traffic is possible without causing unfavorable compaction'. It seems that minimizing soil compaction is the main criterion. A workable soil is trafficable too, although the reverse is not necessarily true. As a result, estimation of workability can represent trafficability too.

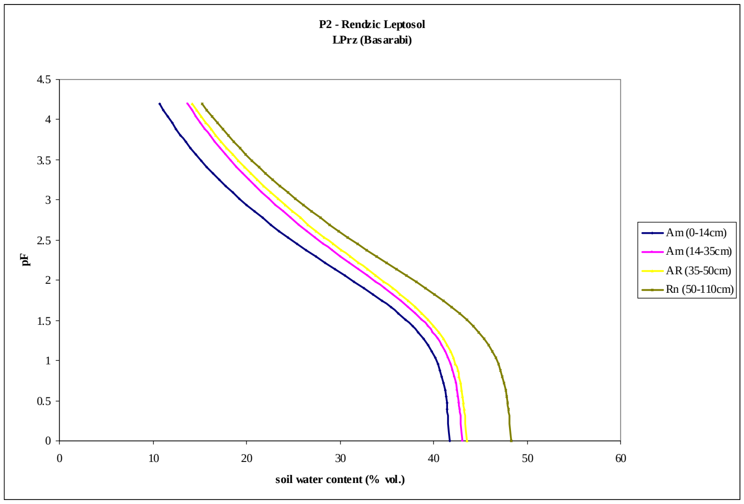

Figure 2. Soil water retention curves of the Rendzic Leptosol from Basarabi

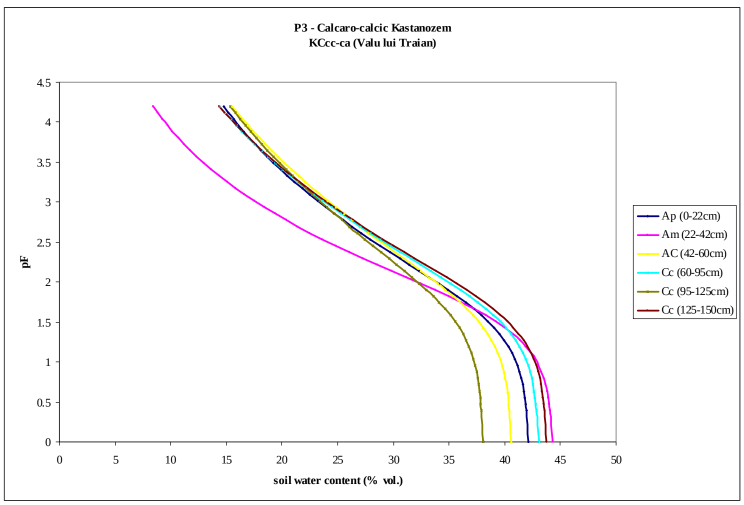

Figure 3. Soil water retention curves of the Calcaro-calcic Kastanozem from Valu lui Traian

Therefore, in this paper we estimated the optimum soil water content and optimum soil matric potential for workability. The values presented in ***Table 2*** shows that in the case of all three soils studied and all the genetic horizons the optimum soil water content for workability was recorded at pF values corresponding to field capacity.

The soil workability status for each soil and tillage operation is very related with the produced surface roughness and other soil physical properties. The ***soil workability status*** is considered as the optimum soil water content where the tillage operation has the desired effect producing the greatest proportion of small aggregates (DEXTER AND BIRD, 2001). Out of this interval the soil is too wet or too dry, and therefore the tillage operation alters in an adverse way the soil physical properties and facilitates the soil erosion. Taking into account the water workability limits for each soil and tillage operation is possible to reduce the soil erosion effects. Soil workability and its influence in soil tillage are widely analyzed by DEXTER (2004 a, b, c) as an important aspect of his interesting *S*-theory on soil physical quality.

CONCLUSIONS

The Arya-Paris model used in these investigations was able to describe the soil water retention properties. As a further research the verification of the model with measured data is needed so that the model can be used in practice.

The estimated *S* index that describes the physical quality of all the investigated soils had high values due to low bulk density values, relatively high organic matter values and equilibrated medium – fine soil texture.

It was demonstrated also that the optimum soil water content and optimum matric potential for soil workability is recorded at pF values which correspond to the field capacity.

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