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A simplified approach to estimate water retention for Sicilian soils by the Arya–Paris model

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ABSTRACT

Application of the Arya and Paris (AP) model to estimate the soil water retention curve requires a detailed description of the particle-size distribution (PSD) because the scale factor α, relating the pore length of an ideal soil to that of the natural one, depends on the particle-size distribution parameters. For a dataset of 140 Sicilian soils that were grouped in five texture groups, the logistic and linear models were applied to evaluate α, and the water retention values predicted by the AP model were compared with the measured ones. Using the parameters proposed by Arya et al. (1999), the two models yielded similar unsystematic root mean error of estimate ($RMSE_u$). Therefore, their potential accuracy was considered comparable. However, the water retention data predicted by the logistic model were more biased (higher systematic root mean error of estimate, $RMSE_s$) than those predicted by the linear model. A calibration was conducted for the logistic model to obtain five sets of parameters specifically developed for Sicilian soils. The calibrated logistic model only minimally improved the prediction accuracy of the AP model. This result also supported Arya et al.'s (1999) procedure for soils that were not included in their original calibration dataset. With the aim to simplify AP model application, an alternative procedure was developed by optimizing a soil-specific α value in the range of measured water content values. For Sicilian soils, the optimized values of the scale parameter (α_{OPT}) were significantly correlated with clay content and bulk density. The empirical relationship that was obtained for the calibration dataset allowed estimation of the water retention data of the validation dataset ($N = 70$) with an estimation error ($RMSE = 0.042$ cm^3 cm^{-3}) lower than that of the traditional approach based on the logistic model. Therefore, it can be considered as a reasonable alternative to the more complex logistic model for estimating the water retention curve of Sicilian soils.

1. Introduction

The soil water retention curve, i.e. the relationship between soil water pressure head, h, and water content, θ, expresses the capacity of soils to store water. It is an important soil property for modeling water and chemical transport in unsaturated soils. Since laboratory procedures for the determination of $h(\theta)$ are time-consuming, there is great interest in models estimating the soil water retention curve from routinely measured soil properties such as texture, organic carbon content, and bulk density.

Empirically derived pedotransfer functions (PTF) have often been used to predict the soil water retention characteristics (e.g., Tietje and Tapkenhinrichs, 1993). However, their applicability may be limited to the data used to define them and their use for other soils may yield unreliable predictions (Wösten et al., 2001). Therefore, testing several PTFs with measured water retention curve is important in deciding whether or not a particular PTF is suitable for a particular region (Antinoro et al., 2008). The PTF-based relationships are mostly correlational, and they do not provide physical basis for relationships between related properties.

Arya and Paris (1981) and Haverkamp and Parlange (1986) have presented physically-based approaches that rely on the similarity between the shape of the particle-size distribution (PSD) and the water retention curve. In the model by Arya and Paris (AP), the pore size that is associated with a pore volume is determined by scaling the pore length of an ideal soil to that of a natural soil. The scale factor, α, is calculated from the number of spherical particles in cubic close-packed assemblages and those required to trace the pore length in counterpart naturally-packed assemblages. Originally, the AP model proved to work relatively well for sandy soils with a constant α value of 1.38 (Arya and Paris, 1981). Later investigations by Arya et al. (1982) showed that the mean α value varied among textural classes ranging from 1.1 for fine-textured soils to 2.5 for coarse-textured ones. Tyler and Wheatcraft (1989) obtained single values of α for differently textured materials and argued that it had a physical significance. Several researchers (e.g., Basile and D'Urso, 1997; Schuh et al., 1988) showed that the assumption of a constant value for α over the entire range of water potential is questionable, and the predictions of the water retention curve would improve using α values which vary over the range of

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particle sizes. Arya et al. (1999) proposed two formulations to express the scale factor α as a function of particle-size distribution parameters, namely a logistic growth model and a linear model, that were tested against 24 soils gathered from five texture classes of the UNSODA hydraulic property database (Leij et al., 1996). Vaz et al. (2005) proposed an expression to calculate the α value for a set of 104 Brazilian soils as a function of the soil water content. Compared to the α as a function of soil water pressure originally proposed by Basile and D'Urso (1997), the relationship proposed by Vaz et al. (2005) appeared to be easier to apply in the model, given that it did not require an iterative procedure. To the best of our knowledge, a wide validation of the formulations for the scale factor α proposed by Arya et al. (1999) has not been conducted for soils differing from those included in the UNSODA database.

A possible reason for the very limited application of the AP model at a regional scale could be due to the difficulty in obtaining detailed PSD data. At least twenty fractions are necessary to reasonably apply the AP model whereas soil survey information generally comprises only soil texture data or a limited number of PSD data points. Fitting a continuous model to experimental PSD data is therefore the only viable technique for applying the AP model when the PSD data points are limited. Skaggs et al. (2001) used a generalized logistic model to estimate the PSD from only the clay, silt and fine plus very fine sand mass fractions. They concluded that, when a complete PSD measurement is not available, the minimal texture knowledge could be beneficially integrated by at least one sand fraction. Bagarello et al. (2009) and Bagarello and Iovino (2012) showed that the PSD model by Fredlund et al. (2000) (FR) allows an accurate description of PSD for most soil texture classes, provided that at least 12–14 experimental PSD points are available. In any case, the time and cost required by a more detailed determination of the PSD is generally low as compared with a complete $h(\theta)$ measurement. For the Sicilian soils, the FR model estimated the cumulative particle fraction with a mean value of the relative error, E_r, equal to 0.036. In particular, for a clay content higher than 26.6%, the fitting of FR model was always satisfactory according to the criterion proposed by Lassabatère et al. (2006), given that $E_r < 0.05$ was found. According to Hwang and Powers (2003), the FR model should show the best estimates for the soil hydraulic properties. The FR model was also used by Antinoro et al. (2012) to thicken the PSD data obtained with the conventional sieve-hydrometer method and to compare the results with the laser diffraction technique. Provided that application of the FR model minimally influences description of soil PSD, it could be used for deriving the parameters of the logistic and linear models proposed to express the scale factor α.

This study was conducted in Sicily, South Italy, where hydraulic property data are generally scarce but there is the need for improving the knowledge of the soil retention characteristics for managing rainfed agriculture under typical Mediterranean climate. The objectives of the study were: i) to improve the estimates of the scale factor α as a function of particle-size distribution parameters through a specific calibration of the logistic and linear models proposed by Arya et al. (1999); and ii) to propose an alternative procedure to derive α for soils in which the available information is limited to texture and other basic soil survey data.

2. Theory

In the AP model, the PSD curve is divided into k size fractions, and a solid mass in each fraction, w_i (M M^{-1}), is assembled to form a hypothetical, cubic close-packed structure consisting of uniform size spherical particles. Arya and Paris (1981) found $k = 20$ as a reasonable number of fractions, with fraction boundaries at particle diameters of 2000, 1500, 1000, 800, 600, 400, 300, 200, 150, 100, 70, 50, 40, 30, 20, 10, 5, 3, 2 and 1 μm. The pore volume in each mass fraction is calculated from the bulk density and particle density measured on the natural structure soil. Starting with the first fraction, the calculated pore volumes are progressively summed and considered filled with water. The volumetric water content, θ_i (L^{3}L^{-3}), at the upper bounds of successive mass fractions is obtained by dividing the cumulative pore volumes by the bulk volume of the sample under the assumption of rigid soil. An equivalent pore radius, r_i (L), is calculated for each mass fraction and converted to soil water pressure head, h_i (L), using the capillarity equation. Calculated pressure heads are sequentially paired with calculated water contents to obtain the soil water retention curve.

Table 1
Distribution of the soil samples in the five texture groups.

Arya et al. (1999) texture group	USDA texture class	Complete database	Calibration dataset	Validation dataset
Clay	Clay, silty clay	22	15	7
Silt loam	Silt loam, silty clay loam, silt	27	18	9
Loam	Loam, CLAY loam	78	52	26
Sandy loam	Sandy loam, sandy clay loam, sandy clay	72	48	24
Sand	Sand, loamy sand	11	7	4
Total soil samples		210	140	70

To establish a relationship between r_i and the particle radius, R_i (L), Arya and Paris (1981) scaled the pore length in an ideal soil to that of a corresponding natural soil. In an ideal soil, the pore length is equal to the sum of physical lengths of the particle diameters arranged in straight columns. Thus, for an ideal soil, the pore length is estimated by $2n_iR_i$, where n_i is the number of spherical particles for each fraction of the PSD. However, particles in a natural soil may contribute to pore length in more than one dimension. In addition, pressure head also depends on soil structure, organic matter, solutes and electrochemical properties of the solid surfaces (Arya et al., 1999). Therefore, the number of spherical particles, N_i, of radius R_i required to trace the pore length in the natural soil, corresponding with the ideal soil, is given by $N_i = n_i^{\alpha i}$. The resulting relationship between r_i and R_i is:

$$r_i = 0.816R_i\sqrt{en_i^{(1-\alpha i)}} \quad (1)$$

where e is the void ratio, given by:

$$e = (\rho_s - \rho_b)/\rho_b \quad (2)$$

where ρ_s (M L^{-3}) is the particle density (≈2.65 Mg m^{-3}), and ρ_b (M L^{-3}) is the soil bulk density. The number of spherical particles,

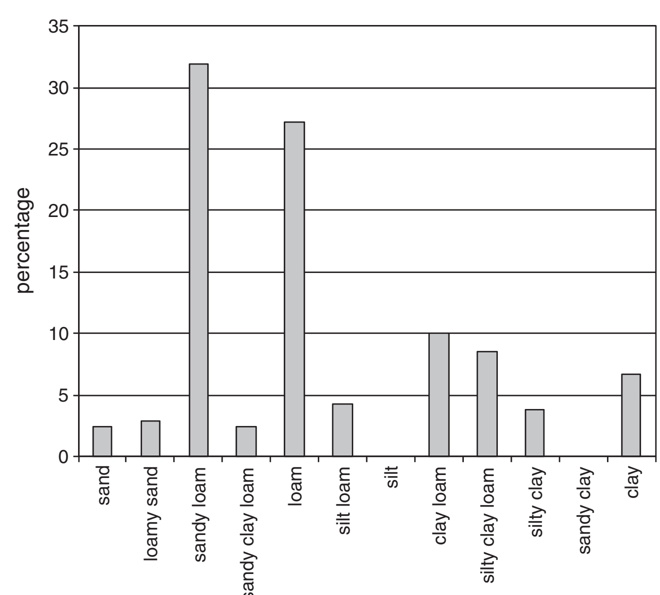

Fig. 1. Texture composition of the dataset of Sicilian soils.