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Unsaturated hydraulic conductivity of disturbed and undisturbed loam soil

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Abstract

The soil water content-pressure head curve [θ(h)], described by van Genuchten, was used to predict some hydraulic characteristics of a Xeric torriorthent soil. Experimental data of volumetric soil water content (θ) and pressure head (h) were adjusted to the model, obtaining the three independent parameters used to calculate the unsaturated soil hydraulic conductivity (K) and soil water diffusivity (D). The K(θ) functions for disturbed and undisturbed soil samples were statistically different pointing to the effect of soil structure on soil water flow. For soil moisture values close to saturation, K values were ≥ 0.392 and ≥ 0.019 cm h^{-1}, for undisturbed and disturbed soils, respectively. These low values would reflect the loam texture of the soil studied. In absence of roots capable of absorbing water, a supply of more than 4 L m^{-2} h^{-1} will lead to water-logging and losses through evaporation and runoff.

Additional key words: Mualem model, soil water diffusivity, soil water retention curve, van Genuchten model.

Resumen

Conductividad hidráulica insaturada de un suelo franco alterado e inalterado

Se ha empleado la curva carga de presión-humedad del suelo [θ(h)], descrita por van Genuchten, para predecir algunas características de un suelo Xeric torriorthent. Los datos experimentales se ajustaron al modelo, obteniéndose los parámetros que se han usado para calcular la conductividad hidráulica insaturada (K) y la difusividad del agua en el suelo (D). La existencia de diferencias estadísticamente significativas entre las funciones K(θ) para muestras de suelo alteradas y no alteradas, muestra el efecto de la estructura del suelo sobre el flujo de agua. Para valores de humedad del suelo próximos a la saturación, se han obtenido valores de K ≥ 0,392 y ≥ 0,019 cm h^{-1}, para muestras de suelo no alterado y alterado respectivamente. Por tanto, en ausencia de raíces capaces de absorber agua, un aporte hídrico superior a 4 L m^{-2} h^{-1}, producirá encharcamiento, pérdidas por evaporación y escorrentía.

Palabras clave adicionales: curva de retención de agua en el suelo, difusividad del agua en el suelo, modelo de Mualem, modelo de van Genutchen

Introduction

The relation between pressure head and volumetric water content in a soil is termed the soil water retention curve or soil moisture characteristic curve because each curve is characteristic of a given soil. The differences between soil water retention curves are attributed primarily to the differences in pore size distribution among soils. These curves are sensitive to changes in bulk densities and the disturbance of soil structures. The curves generally show hysteresis according to the wetting or drying of soils. Therefore it is recommended that these conditions be added to each curve, as required (Miyazaki, 1993).

There is a wide body of literature in which the hydrodynamic characteristics of soils are described based on its water retention curve. Using constant-head Guelph permeameters and a volumetric pressure plate

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extractor, Giakoumakis and Tsarikis (1999) carried out laboratory experiments to determine hydraulic conductivity during infiltration in an unsaturated sandy loam soil. Ahuja *et al.* (1998) described changes in the soil water retention curve as a consequence of tillage practices and its subsequent natural reconsolidation. Assouline *et al.* (1998) studied a conceptual model based on the assumption that soil structure evolves from a uniform random fragmentation process to define the water retention function. Nimmo (1997) quantified the influence of soil structure on the water retention curve. Bird *et al.* (1996), Perfect *et al.* (1996), Guerrini and Swartzendruber (1997), and Pachepsky and Timlin (1998) applied fractal theory to the study of soil water retention and soil water diffusivity curves. Using the representation of Brooks-Corey for the soil water retention curve, Chu (1995) determined the effect of the initial water content on the parameters of the Green-Ampt equation. Tamari *et al.* (1993) described a straightforward laboratory procedure for determining the soil hydraulic properties. Both soil water retention curve and unsaturated hydraulic conductivity data are often necessary for solving unsaturated flow problems. Parlange and Hogarth (1997) made a wider ranging commentary on Shao and Horton theory concerning the determination of soil water diffusivity. Parlange *et al.* (1997) presented a general approximation for the solution to the one-dimensional Richards equation. The results were very accurate when the diffusivity is constant, suggesting that the present general formulation is reliable.

In the present work, the unsaturated hydraulic conductivity and diffusivity of disturbed soil samples were calculated before fitting to the van Genuchten soil water retention curve model (van Genuchten, 1980). It was used the Mualem (1976) model rather than that of Burdine (1953) since it better fitted our experimental data. A comparative study of the hydraulic conductivity as function of volumetric water content [K(θ)] for disturbed and undisturbed soil samples was carried out.

Material and Methods

Experiments were conducted at a commercial mature apricot tree orchard under drip irrigation conditions (Abrisqueta *et al.,* 2001; Plana *et al.,* 2002). The soil was a Xeric torriorthent (Soil Taxonomy) with a loam texture (4% coarse sand, 28% fine sand, 44% silt and 24% clay) according to the USDA (1979).

Four air-dried samples of disturbed soil were taken from the top 25 cm of representative sites of the orchard. The water content of the saturated samples was measured at nineteen potentials (hydraulic heads). Tempe pressure cells were used for water potentials between –2 and –30 kPa, and a conventional pressure plate in the range –100 to –1500 kPa (Startsev and McNabb, 2001).

The soil water content (θ) and pressure head (h) data were fitted to the van Genuchten model [Eq. 1]:

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha \cdot h)^n]^m} \qquad [1]$$

where θ_s and θ_r are the saturated and residual volumetric water content of the soil, respectively. Values of α, m and n were obtained empirically during the fitting procedure. To simplify notation, h in Eq. [1] was assumed to be positive. Equation [1] with $m = 1$ has been successfully used in many studies to describe soil-water retention data (Ahuja and Swartzendruber, 1972; Endelman *et al.,* 1974; Haverkamp *et al.,* 1977).

The saturated and residual soil water content, as well as saturated hydraulic conductivity (K_s), were calculated using the methods of Trout *et al.* (1982) and van Genuchten (1980) (Table 1).

Table 1. Physical properties of experimental soil

θ_s (cm³ cm⁻³)	θ_r (cm³ cm⁻³)	K_s (cm h⁻¹)	Reference
0.32		0.132	Trout *et al.* (1982)
	0.11		Van Genuchten (1980)

The Mualem model established an equation for predicting the relative hydraulic conductivity (K_r) and soil water diffusivity (D) from knowledge of the soil water retention curve (Mualem, 1976). The mathematical expressions are the following:

$$K_r = \frac{\{1-(\alpha \cdot h)^{n-1} \cdot [1+(\alpha \cdot h)^n]^{-m}\}^2}{[1+(\alpha \cdot h)^n]^{\frac{m}{2}}} \quad \left(m = 1 - \frac{1}{n}\right) \quad [2]$$

$$D = \frac{(1-m)\cdot K_S}{\alpha \cdot m \cdot (\theta_S - \theta_r)} \cdot \theta^{\left(\frac{1}{2}-\frac{1}{m}\right)} \cdot \left[\left(1-\theta^{\frac{1}{m}}\right)^{-m} + \left(1-\theta^{\frac{1}{m}}\right)^{m} - 2\right] \quad [3]$$

The relative hydraulic conductivity (K_r) is defined as:

$$K_r = \frac{K}{K_s} \quad [4]$$

where K is the unsaturated hydraulic conductivity, and θ is the dimensionless soil water content, which is defined as:

$$\theta = \frac{\theta - \theta_r}{\theta_s - \theta_r} \quad [5]$$

Results and Discussion

Soil water retention curve

Fitting the experimental data of volumetric soil water content (θ) and pressure head (h) to the model described by van Genuchten (1980) gives the regression curve (water retention curve) which is illustrated in Fig. 1. All the parameters that intervene in the analysis (α, m and n) were statistically significant (Table 2).

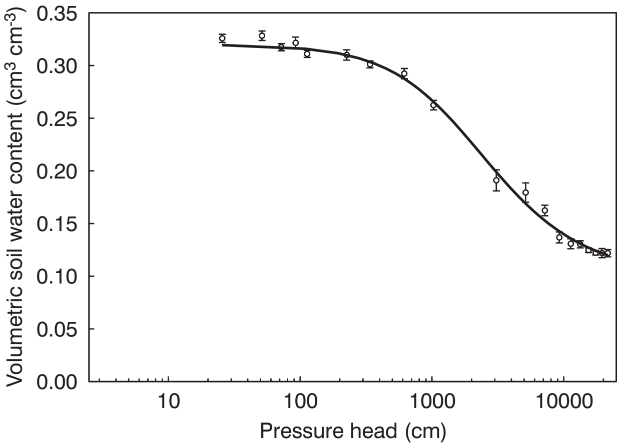

Figure 1. Water retention curve of experimental soil (van Genuchten's model). Bars on data points are ±SE of the mean (n=4).

The agreement with the model was very good as indicated the determination coefficient (R^2 = 0.99) (Table 2). The limits of this function when $h \rightarrow \infty$ and when $h \rightarrow 0$, corresponds to the residual and saturated moisture, respectively (Fig. 1). This equation has been successfully used in many studies to describe soil water retention data (Tamari *et al.,* 1993; Wu *et al.,* 1993; Zavattaro *et al.,* 1999; Startsev and McNabb, 2001).

Relative hydraulic conductivity *versus* pressure head curve

Substitution of parameters α, n and m (= 1–1/n) (Table 2) into Eq. [2] and plotting relative hydraulic

Table 2. Parameters of the regression analysis: pressure head *vs* soil water content of experimental soil (Van Genuchten's model)

α	m	n	R^2 (1)	SE(2)
$5.347 \cdot 10^{-4}$ (P(3) = 0.009)	0.750 (P = 0.003)	1.294 (P < 0.0001)	0.9964 (P < 0.0001)	0.005

(1) Determination coefficient. (2) Standard error. (3) Statistic probability level.

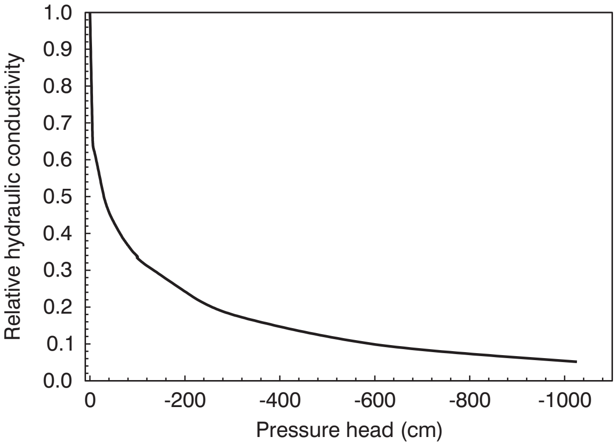

Figure 2. Relative hydraulic conductivity *vs.* pressure head curve [Eq. 2] of experimental soil.

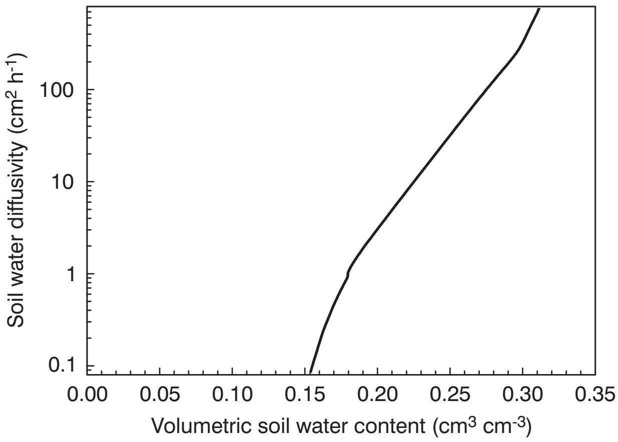

Figure 3. Soil water diffusivity *vs.* volumetric soil water content curve [Eq. 3] of experimental soil.

conductivity *versus* pressure head gives the graphic representation of Mualem's model (1976) (Fig. 2).

It is clear that for pressure head values near zero, the value of K_r is equal to unity (Fig. 2), i.e., $K = K_s$ [Eq. 4]. As the pressure head increases, the value of K_r decreases asymptotically to reach a minimum value corresponding to the residual volumetric water content in the soil. Substituting the values of K_r into Eq. [4], the hydraulic conductivity of the unsaturated soil can be calculated.

Soil water diffusivity *versus* water content curve

Substitution of the same parameters α, n and m (= $1–1/n$) (Table 2) into Eq. [3] gives a graphical representation of Mualem's model of the soil water diffusivity *versus* volumetric water content (Fig. 3).

Note that $D(\theta)$ becomes infinite when θ equals θ_s. Only at intermediate values of θ (between 0.18 and 0.30 in Fig. 3) does the diffusivity acquire an exponential dependency on the soil water content. Similar features of the soil water diffusivity were also obtained by Ahuja and Swartzendruber (1972) and by Murali *et al.* (1979).

The diffusivity, $D(\theta)$, was used because water content gradients are sometimes easier to measure, and also because some water flow equations are more easily solved with diffusivity than with hydraulic conductivity. The term diffusivity does not indicate moisture transfer by diffusion (Yong and Warkentin, 1975).

Unsaturated hydraulic conductivity *versus* soil water content curve

Although several $K(\theta)$ parametric relationships have been proposed and successfully used in the literature (Kutílek and Nielsen, 1994), an exponential model [Eq. 6] was selected for its simplicity and the good fitting obtained:

$$K = a + b \cdot e^{c \cdot \theta} \qquad [6]$$

The relationship between the volumetric soil water content experimental values and the unsaturated hydraulic conductivity values obtained by Eq. [4] were adjusted to the proposed model [Eq. 6], as can be seen from Fig. 4.

The fitting of the data to the proposed model [Eq. 6] was statistically significant (Table 3). The regression coefficients a and b were not significant (Table 3), which denote that the model can be simplified. If data of volumetric soil water content lower than 0.18 and higher than 0.30 were omitted, a simpler and statistically significant ($P < 0.001$) equation was obtained [Eq. 7]:

$$K = 3.145 \cdot 10^{-7} \cdot e^{0.368 \cdot \theta} \qquad R^2 = 0.9814 \qquad [7]$$

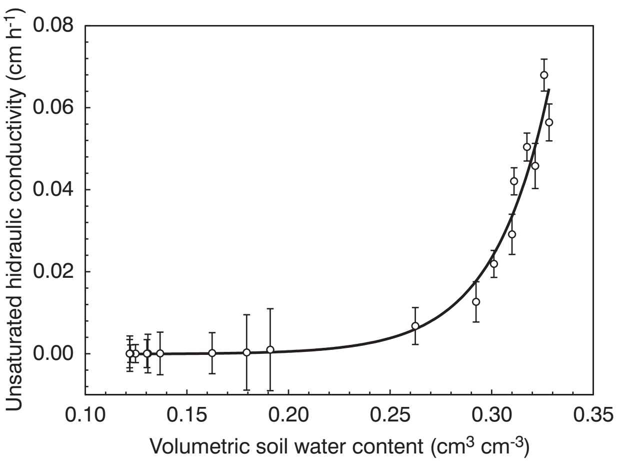

Figure 4. Unsaturated hydraulic conductivity *vs.* volumetric soil water content curve [Eq. 6] of experimental soil. Bars on data points are ± SE of the mean (n = 4).

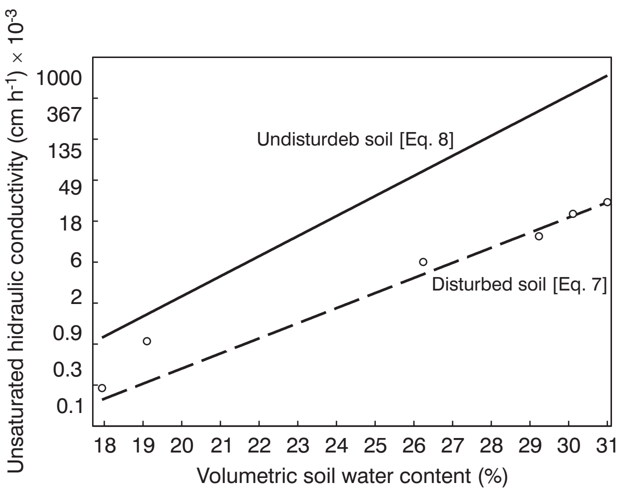

Figure 5. Comparison of K(θ) functions for disturbed (o, ---) and undisturbed (—) soil samples. Natural logarithmic scaling is in the ordinate axis.

Table 3. Regression analysis: unsaturated hydraulic conductivity *vs.* soil volumetric water content of experimental soil

a	b	c	$R^{2(1)}$	SE(2)
$-1.04 \cdot 10^{-4}$ (P(3) = 0.942)	$4.94 \cdot 10^{-7}$ (P = 0.487)	35.89 (P < 0.0001)	0.9648 (P < 0.0001)	0.004

(1) Adjusted determination coefficient. (2) Standard error. (3) Statistic probability level.

Comparison with undisturbed soil samples

Working with undisturbed samples of the same soil under the same edaphoclimatic conditions, Ruiz-Canales (2000) obtained the following statistically significant (P < 0.001) equation [Eq. 8] for unsaturated hydraulic conductivity *vs.* volumetric water content relation:

$$K = 1.62 \cdot 10^{-7} \cdot e^{0.49 \cdot \theta} \qquad R^2 = 0.9961 \qquad [8]$$

Equations [7] and [8] are shown graphically in Fig. 5. The differences between disturbed [7] and undisturbed [8] soil samples were evaluated by covariance analysis, which indicated that both the ordinate and the slope of the curves were statistically significant different (data not shown). For soil moisture values close to saturation ($\theta \geq 30\%$), hydraulic conductivity was ≥ 0.392 cm h^{-1} for undisturbed soil, whereas it was lower (≥ 0.019 cm h^{-1}) in disturbed soil. These low values (according to Trout *et al.,* 1980) would reflect the loam texture of the soil under study.

Under drip irrigation conditions, the soil water content near the emitters is maintained close to saturation, so that the supply of water in excess of 3.92 L m^{-2} h^{-1} will result in water-logging and losses through evaporation, as natural process, and runoff if no plant roots are present to absorb water.

As conclusions, the Van Genuchten (1980) equation provides a useful method of assessing differences in macroscopic soil conditions, and Mualem's model permits the straightforward calculation of unsaturated hydraulic conductivity and the soil water diffusivity, two parameters which are much used in unsaturated flow studies.

There were clear differences between the $K(\theta)$ functions for disturbed and undisturbed soil samples, pointing to the importance of soil structure in the unsaturated flow of water. For soils close to saturation, significantly different K values were obtained, and for both disturbed and undisturbed soils flows can be considered very low.

In the absence of roots capable of absorbing water, a supply of water in excess of 4 L m^{-2} h^{-1} will lead to water-logging and losses through evaporation and runoff.

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References

ABRISQUETA J.M., RUIZ-CANALES A., FRANCO J.A., 2001. Water balance of apricot trees (*Prunus armeniaca* L. cv Búlida) under drip irrigation. Agric Water Manage 50, 211-227.

AHUJA L.R., SWARTZENDRUBER D., 1972. An improved form of soil-water diffusivity function. Soil Sci Soc Am J 36, 9-14.

AHUJA L.R., FIEDLER F., DUNN G.H., BENJAMIN J.G., GARRISON A., 1998. Changes in soil water retention curves due to tillage and natural reconsolidation. Soil Sci Soc Am J 62, 1228-1233.

ASSOULINE S., TESSIER D., BRUAND A., 1998. A conceptual model of the soil water retention curve. Water Resour Res 34, 223-231.

BIRD N.R.A., BARTOLI F., DEXTER A.R., 1996. Water retention models for fractal soil structures. Eur J Soil Sci 47, 1-6.

BURDINE N.T., 1953. Relative permeability calculations from pore-size distribution data. Petr Trans Am Inst Minning Metall Eng 198, 71-77.

CHU S.T., 1995. Effects of initial water content on Green-Ampt parameters. T ASAE 38, 839-841.

ENDELMAN F.J., BOX G.E.P., BOYLE J.R., HUGHES R.R., KEENEY D.R., NORTHRUP M.L., SAFFIGNA P.G., 1974. The mathematical modelling of soil-water nitrogen phenomena. Oak Ridge National Laboratory, Oak Ridge, Tenn. USA.

GIAKOUMAKIS S.G., TSAKIRIS G.P., 1999. Quick estimation of hydraulic conductivity in unsaturated sandy loam soil. Irrig Drain Syst 13, 349-359.

GUERRINI I.A., SWARTZENDRUBER D., 1997. Fractal concepts in relation to soil water diffusivity. Soil Sci 162, 767-770.

HAVERKAMP R., VAUCLIN M., TOUMA J., WIERENGA P.J., VACHAUD G., 1977. A comparison of numerical simulation models for one-dimensional infiltration. Soil Sci Soc Am J 41, 285-294.

KUTÍLEK M., NIELSEN D.R., 1994. Soil Hydrology. Catena Verlag. Cremlingen, Germany.

MIYAZAKI T., 1993. Water flow in soils. Ed. Marcel Dekker, Inc. New York. 295 pp.

MUALEM Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour Res 12, 513-522.

MURALI V., KRISHNA MURTI G.S.R., SINHA A.K., 1979. Note on the three-parameter functions for soil water diffusivity-water content relationships. Aust J Soil Res 17, 361-366.

NIMMO J.R., 1997. Modelling structural influences on soil water retention. Soil Sci Soc Am J 61, 712-719.

PACHEPSKY Y., TIMLIN D., 1998. Water transport in soils as in fractal media. J Hydrol 204, 98-107.

PARLANGE J.Y., HOGARTH W.L., 1997. Soil water diffusivity determination by general theory. Comments. Soil Sci 162, 767-770.

PARLANGE J.Y., BARRY D.A., PARLANGE M.B., HOGARTH W.L., HAVERKAMP R., ROSS P.J., LING L., STEENHUIS T.S., 1997. New approximate analytical technique to solve Richards equation for arbitrary surface boundary conditions. Water Resour Res 33, 903-906.

PERFECT E., McCLAUGHLIN N.B., KAY B.D., TOPP G.C., 1996. An improved fractal equation for the soil water retention curve. Water Resour Res 32, 281-287.

PLANA V., RUIZ-CANALES A., RUIZ-SÁNCHEZ M.C. FRANCO J.A., ABRISQUETA J.M., 2002. Spatial representativity of the possible sites for measuring the water balance of apricot trees. Agric Water Manage 57, 145-153.

RUIZ-CANALES A., 2000. Balance hídrico y respuesta del albaricoquero (*Prunus armeniaca* L. cv. Búlida) a dos dosis de riego por goteo. Doctoral thesis Univ Politécnica de Cartagena, Murcia, Spain. 313 pp.

STARTSEV A.D., MCNABB D.H., 2001. Skidder traffic effects on water retention pore size distribution and van Genuchten parameters of boreal forest soils. Soil Sci Soc Am J 65, 224-231.

TAMARI S., BRUCKLER L., HALBERTSMA J., CHADOEUF J., 1993. A simple method for determining soil hydraulic properties in the laboratory. Soil Sci Soc Am J 57, 642-651.

TROUT J.T., GARCÍA-CASTILLAS I.G., HART W.E., 1982. Soil water engineering. Field and laboratory manual No. 1. Dpto Agric Chem Eng, Colorado State Univ, USA, 193 pp.

USDA, 1979. Soil Conservation Service. Engineering Field Manual USDA, SCS.

VAN GENUCHTEN M.T.H., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci Soc Am J 44, 892-989.

WU L., SWAN J.B., NIEBER J.L., ALLMARAS R.R., 1993. Soil-macropore and layer influences on saturated hydraulic conductivity measured with borehole permeameters. Soil Sci Soc Am J 57, 917-923.

YONG R.N., WARKENTIN B.P., 1975. Soil properties and behaviour. Elsevier Scientific Publishing Company, Amsterdam. NL. 450 pp.

ZAVATTARO L., JARVIS N., PERSSON L., 1999. Use of similar media scaling to characterize spatial dependence of near-saturated hydraulic conductivity. Soil Sci Soc Am J 63, 486-492.