INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
I.C.T.P., P.O. BOX 586, 34100 TRIESTE, ITALY, CABLE CENTRATOM TRIESTE

SMR/402 - 25

COLLEGE ON SOIL PHYSICS
9 - 27 October 1989

"Stochastic Approach of Soil Water Flow through the Use of Scaling Factors: Measurements and Simulation "

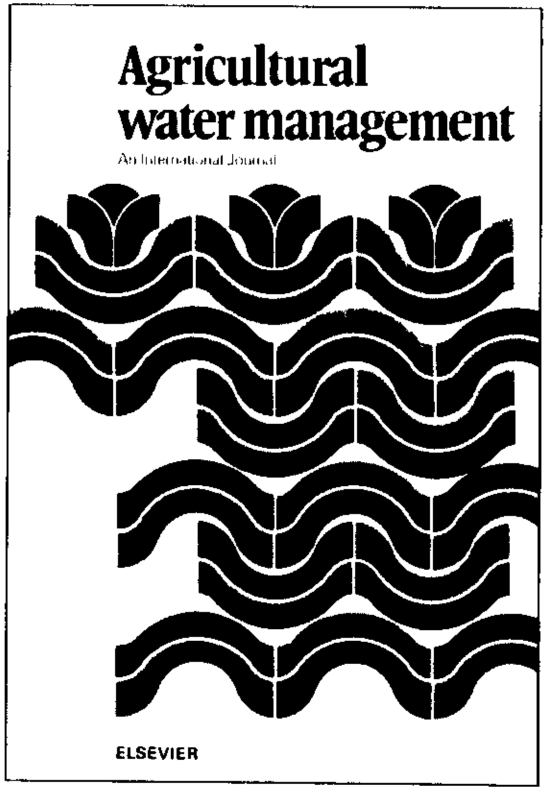
M. VAUCLIN
Institut de Mécanique de Grenoble
C.N.R.S.
Saint Martin d'Hères
France

Stochastic Approach of Soil Water Flow through the Use of Scaling Factors: Measurement and Simulation

GEORGES VACHAUD, MICHEL VAUCLIN and PANOS BALABANIS

Institut de Mécanique de Grenoble, B.P. 68, 38402 St. Martin D'Hères Cédex (France)

REPRINTED FROM:



ELSEVIER SCIENCE PUBLISHERS, AMSTERDAM

Agricultural water management

An International Journal

Editor-in-Chief:

J. Wesseling, Oude Diedenweg 5, 6704 AA Wageningen, The Netherlands

Aims and Scope

Agricultural Water Management is concerned with the publication of scientific papers of international significance to the management of agricultural water. The scope includes such diverse aspects as irrigation and drainage of cultivated areas, collection and storage of precipitation water in relation to soil properties and vegetation cover, the role of ground and surface water in nutrient cycling, water balance problems, exploitation and protection of water resources, control of flooding, erosion and desert creep, water quality and pollution both by, and of, agricultural water, effects of land uses on water resources, water for recreation in rural areas, and economic and legal aspects of water use. Basic soil-water-plant relationships will be considered only as far as is relevant to agricultural water management.

Submission of articles

Manuscripts should be submitted in triplicate to the Editorial Secretariat, Agricultural Water Management, Elsevier Science Publishers B.V., P.O. Box 330, 1000 AH Amsterdam, The Netherlands.

AGRICULTURAL WATER MANAGEMENT HAS NO PAGE CHARGES
A DETAILED GUIDE TO AUTHORS AND A FREE SAMPLE COPY OF THE JOURNAL ARE AVAILABLE ON REQUEST

Agricultural Water Management, 13 (1988) 249–261
Elsevier Science Publishers B.V., Amsterdam — Printed in The Netherlands

Stochastic Approach of Soil Water Flow through the Use of Scaling Factors: Measurement and Simulation

GEORGES VACHAUD, MICHEL VAUCLIN and PANOS BALABANIS

Institut de Mécanique de Grenoble, B.P. 68, 38402 St. Martin D'Hères Cédex (France)

ABSTRACT

Vachaud, G., Vauclin, M. and Balabanis, P., 1988. Stochastic approach of soil water flow through the use of scaling factors: measurement and simulation. *Agric. Water Manage.*, 13: 249–261.

The method of scaling, which is extensively used in hydraulics and fluid mechanics, has not been widely developed in soil physics, most probably due to the fact that vigorous assumptions are rarely met in nature. It will, however, be shown that heterogeneity from location to location within a field or at the scale of a watershed may be approximated with the use of a scaling coefficient for each site.

INTRODUCTION

One of the major problems met by hydrologists and soil physicists is related to the spatial variability of soil hydraulic properties. They must be used to describe water flow in the vadose zone, but they can exhibit a very large degree of spatial variations, as shown by many authors.

The scaling technique appears to be a promising simplified method for describing spatial variability of these properties (Warrick et al., 1977; Simmons et al., 1979; Russo and Bresler, 1981) and for modeling unsaturated-flow processes on a large scale (Peck et al., 1977; Sharma and Luxmoore, 1979; Warrick and Amoozegar-Fard, 1979; Clapp et al., 1983; Ahuja et al., 1984).

The purpose of this paper is to elaborate on this interesting technique.

THEORY

Scale factors derived from similitude analysis were introduced in soil science by Miller and Miller (1956), for soil water properties such as hydraulic conductivity $K(\theta)$, soil water pressure head $h(\theta)$, and diffusivity $D(\theta)$, on the

0378-3774/88/$03.50

assumption that water flows are governed by hydrodynamic laws of surface tension (σ) and viscosity (μ).

With the concept of similar media associated with the invariance of σ and μ, it can be shown from dimensional analysis that:

$$h_i\lambda_i = C_1, \qquad K_i/\lambda_i^2 = C_2, \qquad D_i/\lambda_i = C_3 \tag{1}$$

where λ_i characterizes the pore scale of the element i, and C_1, C_2 and C_3 are three constants for isothermal conditions.

For similar media, the internal geometry differs only by λ_i. Such materials would have identical porosity and the same relative particle- and pore-size distributions. The consequences are that, for a given volumetric water content, $h_i(\theta)$, $K_i(\theta)$, $D_i(\theta)$ are related to reference values $h^*(\theta)$, $K^*(\theta)$ and $D^*(\theta)$ by:

$$h_i(\theta) = 1/\alpha_i\ h^*(\theta)\ ;\ K_i(\theta) = \alpha_i^2\ K^*(\theta)\ ;\ D_i(\theta) = \alpha_i\ D^*(\theta) \tag{2}$$

where $\alpha_i = \lambda_i/\lambda_m$ is the scale factor, λ_m being the characteristic length of the reference medium.

From dimensional argument, it is possible to develop a generic expression:

$$W_i = \alpha_i^p\ W^* \tag{3}$$

with $p=2$ for hydraulic conductivity or flux, $p=-1$ for water pressure head, $p=1$ for capillary diffusivity, and $p=1/2$ for capillary sorptivity.

In fact, soils do not generally have identical values of porosity, therefore the theoretical concept of similar media does not hold. It is the reason why several authors use the degree of saturation $S=\theta/\theta_S$, where θ_S is the saturated water content. Furthermore, one can always scale soil hydraulic properties through the functional normalization method (Tillotson and Nielsen, 1984), assuming that equation (3) takes the form:

$$W_i = \alpha_{W,i}^p\ W^* \tag{4}$$

where $\alpha_{W,i}$ is a scale factor associated with the location i and the property W. Considering that the physical model function W_i for each location is similar to the reference function W^* the model functions must have the form:

$$W_i = a_i\ f(S, \text{parameters}) \qquad \text{and} \qquad W^* = a^*\ f(S, \text{parameters}) \tag{5}$$

where the curve shape function $f(S$, parameters) is independent of i.

From equations (4) and (5):

$$a_i = \alpha_{W,i}^p a^* \tag{6}$$

or, with the use of complementary constraint such as:

$$\frac{1}{N}\sum_{i=1}^{N} \alpha_{W,i} = 1 \tag{7}$$

$$a^{*\,1/p} = \frac{1}{N}\sum_{i=1}^{N} a_i^{1/p} \tag{8}$$

where N is the number of measurement sites.

A proper choice for the function $f(S$, parameters) depends on the soil-water properties of interest. This function constitutes a physical model if it describes the measured data within limits of statistical error at each location.

Any soil-water property can be scaled with respect to a given physical model (5) if and only if a common set of parameters can be estimated so that the function fits the measured data at each location. More generally, we will say that scaling applies to a soil if different soil water properties W_i can be scaled independently according to (4), and if the scale factors $\alpha_{W,i}$ defined by (6) and (8) for each property are *identical* for each location.

It should be pointed out that the scaling factors thus calculated depend on both the choice of the functional model and the normalizing constraint (equation 8).

They have to be viewed as conversion factors which empirically relate properties of two or more soils or locations.

On the other hand, scale factors obtained from dimensional or inspectional analysis have physical meaning in terms of the system being studied.

APPLICATIONS

Four illustrative examples of the scaling theory are given: scaling of water retention and conductivity soil properties; prediction of hydraulic conductivity curves from knowledge of retention curves; scaling of an infiltration law obtained by double-ring infiltrometer tests; and stochastic modeling of infiltration and drainage.

Scaling of $h(\theta)$ and $K(\theta)$ curves

Soil-water properties were determined on 1 ha of bare sandy soil (Imbernon, 1981). The experimental procedure is described in detail by Vauclin et al. (1983). Briefly, two sets of data are available for our analysis: (a) $h(\theta)$ and $K(\theta)$ curves obtained during internal drainage experiments, with use of neutron probe and tensiometers on four sites, at ten depths; (b) $h(\theta)$ curves obtained during redistribution following infiltration at 19 sites, at three depths, with the use of neutron probes and tensiometers.

The experimental data are given in Figs. 1a and 2a. All the data were scaled by using the regression technique proposed by Simmons et al. (1979) and through application of the Brooks and Corey (1964) functions. The corresponding mean scale functions were found to be:

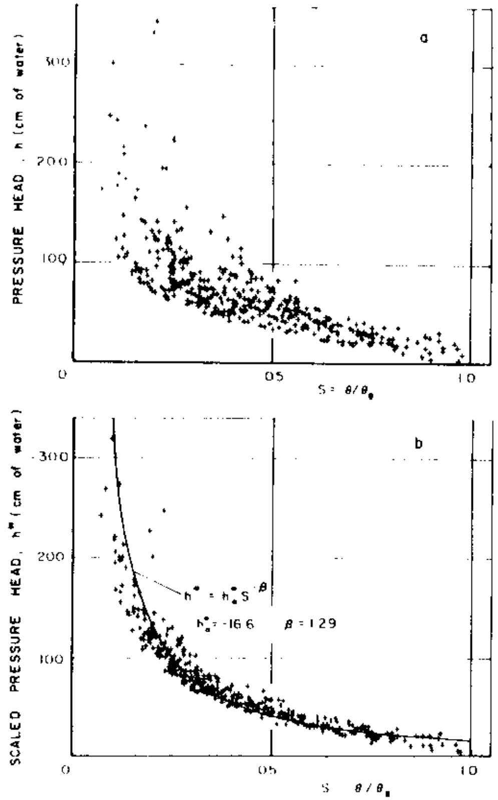


Fig. 1. Bambey, Senegal: Comparison between measured (a) and scaled (b) soil water retention curve $h(S)$.

$$K^*(S) = K_0^* S^b \quad \text{with} \quad K_0^* = 6.75\times10^{-5}\ \text{m/s},\ b = 6.87 \tag{9}$$

$$h^*(S) = h_0^* S^\beta \quad \text{with} \quad h_0^* = -0.166\ \text{m of water},\ \beta = -1.294 \tag{10}$$

The scaled values are reported Figs. 1b and 2b as well as the curves given by (9) and (10).

The scaling factors of the water pressure head α_h, calculated at 23 locations, were found to be log-normally distributed (e.g. the probability function of $X = \ln \alpha_h$ is normal with mean value $m_X = -0.1229$ and standard deviation $\sigma_X = 0.5247$).

Furthermore, the good linear correlation between α_h and α_K ($\alpha_K = 0.97\alpha_h$ with a coefficient of determination $r^2 = 0.85$) tends to show that the concept

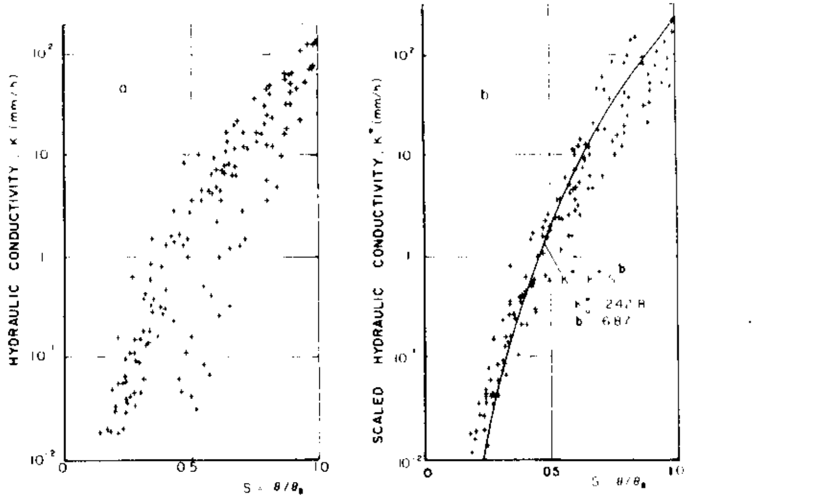


Fig. 2. Bambey, Senegal: Comparison between measured (a) and scaled (b) hydraulic conductivity curve $K(S)$.

of similar porous media can be adequately accepted. Figures 1 and 2 show clearly that the result of the scaling procedure is to coalesce the original data into a narrow band around the scale mean curves.

Prediction of unsaturated hydraulic conductivity curve

An experiment was conducted in Tunisia (Vachaud et al., 1985) in order to determine, at the field scale, soil water-balance for different surface covers: 1 ha of rainfed wheat; 0.4 ha of irrigated grass; and 0.4 ha of bare soil. Nine sites of measurements were selected. At each site, textural components and bulk density (by gamma-densitomer) profile were determined. Time evolution of water content (by a neutron probe) and of water pressure-head (by tensiometers) profiles were routinely measured. In addition, classical internal drainage experiments were performed at two sites, in order to determine both $K(\theta)$ — and $h(\theta)$ — curves at several depths.

All the raw data $K_i(\theta)$ and $h_i(\theta)$ were analyzed through the functional normalization procedure previously described. The resulting mean scale functions are:

$$h^*(S) = -0.0613 S^{-4.42}\ \text{(m of water)} \tag{11}$$

$$K^*(S) = 2.46\times10^{-6}\ S^{10.47}\ \text{(m/s)}$$

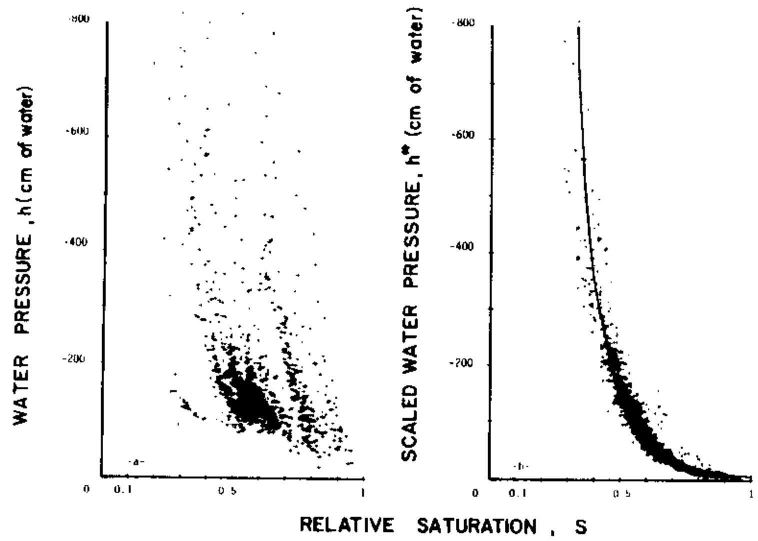


Fig. 3. Mornag, Tunisia: Comparison between measured (a) and scaled (b) soil water retention curve $h(S)$.

An example is given in Fig. 3 for the water-retention soil property. The scaling factors α_h and α_K were found to be log-normally distributed and linearly correlated ($\alpha_h = 0.98\ \alpha_K$; $r^2 = 0.89$). In addition, a multiple regression between α_h, the silt+clay contents [Si+C] and the dry bulk density (ρ_d) led to:

$$\ln \alpha_h = -2.09 \ln [\mathrm{Si+C}] - 4.22\rho_d + 13.53 \tag{12}$$

(with $r^2 = 0.69$ for 29 points).

This regression was used predict the $K(\theta)$ relation at a site where ρ_d and [Si+C] are known, using the relation:

$$K_r(S) = \alpha_r^2\ K^*(S) \tag{13}$$

In order to obtain an evaluation of this prediction, the site was chosen at a location where $K(\theta)$ was known, but not used in the original scaling treatment. For this site, [Si+C] = 8%, $\rho_d = 1.62$ g/cm^3 and, from equation (12), $\alpha_r = 10.2$.

The corresponding hydraulic conductivity curve calculated by equation (13) with $\theta_S = 0.354$ cm^3/cm^3 (estimated by 90% of the porosity) is reported in Fig. 4, and fairly agrees with measured values. It should be noted that errors associated with the experimental and calculated values can be estimated (Balabanis, 1983).

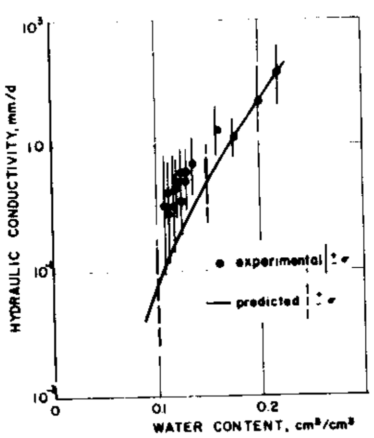


Fig. 4. Mornag, Tunisia: Prediction of $K(S)$ from scaling factors of Fig. 3 and comparison with measured values.

Scaling of infiltration laws

An experiment was conducted in the People's Republic of China (Henan Province), on a scale of 3000 m^2. Apart from the spatial analysis of various observations, such as grain size, bulk density, hydraulic conductivity, etc. (Lei Zhi Dong et al., 1987), a series of 10 double-ring, constant-head infiltration tests was also done on the site. The cumulative infiltration measurements were analyzed in light of the vertical heterogeneity of the soil profile and of the horizontal spatial variability of the field.

Infiltration parameters were identified from equation:

$$I = st^{1/2} + At \tag{14}$$

(Philip, 1957). A special procedure developed by Lei Zhi Dong et al., (1987) was used to test the validity of the parameters S and A, whose values are given in Table 1.

The probability distribution function of both A and S corresponds to log-normal distributions. In order to cope with the large variability of these two parameters, and to obtain easily an estimation of the infiltration of water, under the same conditions as during the experiment, at any time, and in any point of the field, we have used the method of scaling published by Sharma et al. (1980).

By application of (3), we can define scaled infiltration I^* and scaled time t^* such that:

$$I_i = \alpha_i^{-1} I^* \quad \text{and} \quad t_i = \alpha_i^{-3} t^* \tag{15}$$

TABLE 1

Shanqiu, Henan Province, People's Republic of China: Values of parameter S and A determined for every infiltration test, and corresponding scaling factors

Site	A_i	$\alpha_{A_i}=\left(\frac{A_i}{\bar{A}}\right)^{1/2}$	s_i	$\alpha_{s_i}=\left(\frac{s_i}{\bar{s}}\right)^2$	$\alpha_{H,A,s}$
F0	0.4	1.31	1.75	0.73	0.94
F1	0.15	0.80	4.4	4.7	1.37
F2	0.18	0.88	0.9	0.2	0.325
F3	0.5	1.46	0.9	0.2	0.35
F4	0.06	0.51	3.1	2.3	0.82
F5	0.08	0.58	2.8	1.87	0.81
F6	0.15	0.80	1.8	0.77	0.79
F7	0.10	0.65	2.5	1.5	0.91
F8	0.36	1.24	2.2	1.15	1.19
F9	0.34	1.21	0.1	0.02	4.10
	$\bar{A}=0.232$		$\bar{s}=2.04$		$\alpha_{H,A,s}=\frac{2\alpha_A\alpha_s}{\alpha_s+\alpha_A}$
	$\bar{A}=\frac{1}{n}\sum_{i=1}^{n}A_i$		$\bar{s}=\frac{1}{n}\sum_{i=1}^{n}s_i$		

If the theory of similar media applies, α_i, at a given site, can be computed from measurement of s_i or A_i at every site. On Table 1 are also given the values of α_{A_i} and α_{s_i}, relative respectively to those two parameters, and given by:

$$\alpha_{A_i}=\left(\frac{A_i}{\bar{A}}\right)^{1/2} \quad \text{and} \quad \alpha_{s_i}=\left(\frac{s_i}{\bar{s}}\right)^2 \tag{16}$$

where $\bar{A}$ and $\bar{s}$ are the arithmetic means of measured values. Obviously, no correlation can be obtained between the two sets (Sharma et al., 1980; Tillotson-Nielsen, 1984). This discrepancy with the theory will be discussed later.

Following the suggestion of Sharma, the harmonic mean:

$$\alpha_{H,A_i,s_i}=\frac{2\alpha_{A_i}\alpha_{s_i}}{\alpha_{A_i}+\alpha_{s_i}} \tag{17}$$

was finally used to determined the scaled infiltration I^* and the scaled time t^* from (15). This combination accounts for some weighting between the initial stage of infiltration (s) and the late-stage period (A). Example of results obtained with this parameter is given in Fig. 5. All the measured values, after scaling, coalesce around a unique scaled infiltration curve which is given by:

$$I^*=\bar{s}t^{*1/2}+\bar{A}t^* \tag{18}$$

In the present experiment, the fact that factors of similitude obtained for A and $\bar{s}$ are quite different would tend to reject the assumption of similar media, contrary to what has been obtained previously. A careful analysis of the experimental techniques which are involved here should, however, have been done before generalizing this conclusion. The identification of s (sorptivity) is indeed extremely sensitive to measurements of cumulative infiltration taken within a short time-scale, a domain where in practice very few data are available. To the contrary, A is affected by measurements taken within a long time-scale, where experimental values should be taken cautionly due to probable inference of lateral flow.

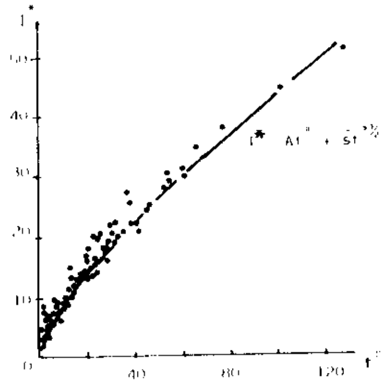


Fig. 5. Shaniqiu, Hean Province, People's Republic of China. Scaled cumulative infiltration curve using from α, the harmonic mean between α_A and α_s (Table 1).

We sould therefore tend to say that in this last case the scaling procedure should be viewed more as a technique of similitude applied to a given experimentation (Tillotson-Nielsen, 1984) than as a method of scaling soil properties in the sense of Miller and Miller (1956).

Stochastic modeling of water flows

Let us now look at the consequences of the variability of soil water properties for water-flow modeling. Isothermal soil water movement such as infiltration or drainage is classically described at the macroscopic level by Richards' equation which, in one spatial vertical dimension, has one of the two following forms:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[D(\theta)\frac{\partial\theta}{\partial z}\right]-\frac{\partial K(\theta)}{\partial z} \tag{19}$$

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}-1\right)\right] \tag{20}$$

For homogeneous soils characterized by $K(\theta)$, $h(\theta)$ and $D(\theta)=K(\theta)\ \mathrm{d}h/\mathrm{d}\theta$

curves, the solution of (19) and (20) for relevant initial and boundary conditions provides time and space evolutions of soil water content (Haverkamp et al., 1981). In non-homogeneous soils we can consider a field on its horizontal extension as a collection of vertical columns, each of them being described by its proper $K_i(\theta)$, $h_i(\theta)$ and $D_i(\theta)$ curves. If all the soils columns can be approximated as similar media, we can easily show that the following set of transformations:

$$S=\theta/\theta_S, \quad t^*=(\alpha^3/\theta_S)t, \quad z^*=\alpha z \tag{21}$$

applied at (17) or (18) leads to:

$$\frac{\partial S}{\partial t^*}=\frac{\partial}{\partial z^*}\left[D^*(S)\frac{\partial S}{\partial z^*}\right]-\frac{\partial K^*(S)}{\partial z^*} \tag{22}$$

$$\frac{\partial S}{\partial t^*}=\frac{\partial}{\partial z^*}\left[K^*(S)\left(\frac{\partial h^*}{\partial z^*}-1\right)\right] \tag{23}$$

The solutions of (22) or (23) are space-invariant and unique for a fictitious soil characterized by the 'mean' hydrodynamic soil properties: $K^*(S)$, $h^*(S)$ and $D^*(S)$. Applying the inverse transformations (21) we obtain stochastic solutions of (19) or (20) since α_i can be viewed as a random variable defined by its probability density function.

Two short examples of application can be given on the measurements done by Imberdon in Senegal:

Infiltration using Philip's quasi-analytical solution. With the proper conditions (Philip, 1957), equation (20) has the following solution:

$$z^*(S,t^*)=\sum_{q=1}^{n} f_q^*(S)\; t^{*q/2} \tag{24}$$

for the water content profiles, and:

$$I^*(t^*)=\sum_{q=1}^{n} A_q^*(S)\; t^{*q/2} \tag{25}$$

for the cumulative infiltration. f_q^* are solutions of ordinary differential equations and A^*_q are estimated by:

$$\int_{S_0}^{1} f_q^*(S)\,\mathrm{d}S$$

The distribution of water infiltration at the field scale can be described by the 'inverse' stochastic solutions:

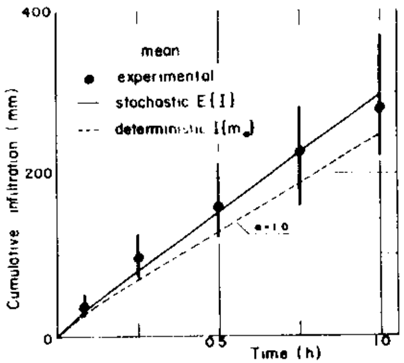


Fig. 6. Bambey, Senegal: Comparison between measured and stochastically simulated values of cumulative infiltration for 19 sites.

$$z(S,t^*,\alpha)=\frac{1}{\alpha}z^*(S,t^*) \tag{26}$$

$$I(t^*,\alpha)=\frac{\theta_S}{\alpha}I^*(t^*) \tag{27}$$

where t^* stands for $(\alpha^3/\theta_S)t$.

As an example, Fig. 6 represents the expected value E{I} calculated by (22) (with $n=4$) and (27) as a function of time. Soil hydraulic properties correspond to (10).

As a validation of the method experimental measured cumulative infiltration values are given in Fig. 6 together with their domain of uncertainty.

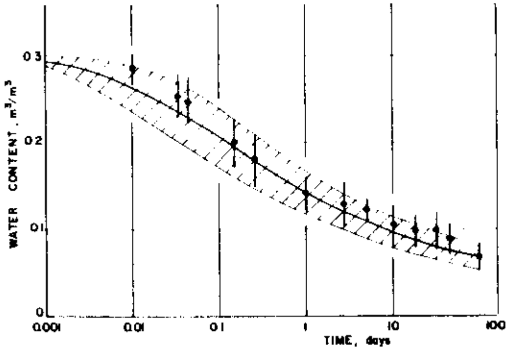


Fig. 7. Bambey, Senegal: Comparison between measured and stochastically simulated values of change of water content a 1.1 m at 19 sites, following infiltration.

Gravity drainage. Similary, one can describe the drainage of soil under gravity with the use of the simplified approach of Libardi et al., 1980, the solution of Richard's equation can be written as:

$$\theta(z,t)=\theta_S\left[1+\alpha^2\frac{b-1}{\theta_S}K_o^*\frac{t}{z}\right]^{1/(1-b)} \quad (28)$$

where b is already introduced in (10).

On Fig. 7 are given the expected value of water content, at depth $z=110$ cm, under gravity drainage on the site of Bambey, together with measurements obtained from 23 sites. Again, a fair agreement is obtained between stochastic predicted values and measurements.

CONCLUSIONS

In light of our experience, the following conclusions can be drawn:

(1) Even if, strictly speaking, the conditions of similarity are not found in natural soils, it is possible to use normalization methods to scale soil water properties and to obtain a strong coalescence of the natural variability.

(2) If the scaling factors are the same for both the hydraulic conductivity and the soil suction relationships, the similar-media theory can be extremely useful: (a) to predict $K(\theta)$, or $h(\theta)$ in sites where measurements are not available; (b) to develop stochastic solution of the equation of water flow in unsaturated soils which gives the expected values of the variables, together with its expected domain of uncertainty over the site.

ACKNOWLEDGMENTS

The experimental values which are used in this study were obtained through joint research with: the Institut Sénégalais de Recherches Agricoles and the joint FAO/IAEA Division at Bambey, Sénégal; the Centre de Recherches du Génie Rural, at Mornag, Tunis (Tunisia); the Office de Recherche Scientifique d'Outre-Mer, Orstom, Paris; and the General Station of Environmental Hydrogeology, Bureau of Geology and Mineral Resources, Zhengzhou, Henan Province, and the Department of Hydraulic Engineering, Tsinghua University of Beijing, People's Republic of China. We thank our colleagues for making the data available.

REFERENCES

Ahuja, L.R., Naney, J.W. and Nielsen, D.R., 1984. Scaling soil water properties and infiltration modeling. Soil Sci. Soc. Am. J., 48: 970-973.

Balabanis, P., 1983. Mise en facteur d'échelle des propriétés hydrauliques d'un sol hétérogène. Rapp. Diplome d'Etudes Approfondies, Université Scientifique et Medicale, Grenoble, 34 pp.

Brooks, R.H. and Corey, A.T., 1964. Hydraulic properties of porous media. Colo. State Univ. Hydrol. Pap. 3.

Clapp, R.B., Hornberger, G.M. and Cosby, B.J., 1983. Estimating spatial variability in soil moisture with a simplified dynamic model. Water Resour. Res., 19: 739-745.

Haverkamp, R. and Vauclin, M., 1981. A comparative study of three forms of the Richard's equation used for predicting one-dimensional infiltration in unsaturated soil. Soil Sci. Soc. Am. J., 45: 13-20.

Imbernon, J., 1981. Variabilité spatiale des caractéristiques hydrodynamiques d'un sol du Sénégal. Doctorat 3ème cycle, Université Scientifique et Medicale, Grenoble, 152 pp.

Lei Zhi Dong, Yang Shi Xiu, Xu Zhi Rong and Vachaud, G., 1987. Spatial variability of infiltration of water at the field scale. In: Yu Si Fok (Editor), Measurements and Stochastic Simulation. Int. Conf. Infiltration Development and Application, 6-8 January 1987, University of Hawaii, Manao, HI.

Libardi, P.L., Reichardt, K., Nielsen, D.R. and Biggar, J.W., 1980. Simple field methods for estimating soil hydraulic conductivity. Soil Sci. Soc. Am. J., 44: 3-7.

Miller, E.E. and Miller, R.D., 1956. Physical theory for capillary flow phenomena. J. Appl. Phys., 27: 324-332.

Peck, A.J., Luxmoore, R.J. and Stolzy, J.L., 1977. Effects of spatial variability of soil hydraulic properties in water budget modeling. Water Resour. Res., 13: 348-354.

Philip, J.R., 1957. The theory of infiltration. 4. Sorptivity and algebraic infiltration equation. Soil Sci., 83: 257-264.

Russo, D. and Bresler, E., 1981. Soil hydraulic properties as stochastic process. 1. An analysis of field spatial variability. Soil Sci. Soc. Am. J., 45: 682-687.

Sharma, M.L. and Luxmoore, R.J., 1979. Spatial variability and its consequences on simulated water balance. Water Resour. Res., 15: 1567-1573.

Sharma, M.L., Gander, G.A. and Hunt, C.G., 1980. Spatial variability of infiltration in a watershed. J. Hydrol., 45: 101-122.

Simmons, C.S., Nielsen, D.R. and Biggar, J.W., 1979. Scaling of field-measured soil water properties. Hilgardia, 47: 77-154.

Tillotson, P.M. and Nielsen, D.R., 1984. Scale factors in soil science. Soil Sci. Soc. Am. J., 48: 953-959.

Vachaud, G., Vauclin, M., Riou, C. and Chaabouni, Z., 1985. Evatranpiration en zone semi-aride de deux couverts végétaux obtenue par plusieurs méthodes. II. Méthodes neutroniques et tensiométriques. Agronomie, 5: 267-274.

Vauclin, M., Imbernon, J., Vachaud, G. and Dancette, C., 1983. Description experimentale et modélisation stochastique des transferts par la mise en échelle des propriétés hydrodynamiques des sols. In: Colloq. Int. L'Emploi des Techniques des isotopes et des Rayonnements dans les Études sur la Physique des Sols et l'Irrigation, 19-22 avril 1983, Aix en Provence. International Atomic Energy Agency, Vienna, pp. 533-549.

Warrick, A.W. and Amoozgar-Fard, A., 1979. Infiltration and drainage calculations using spatially scaled hydraulic properties. Water Resour. Res., 15: 1116-1120.

Warrick, A.W., Mullen, G.J. and Nielsen, D.R., 1977. Scaling field-measured soil hydraulic properties using a similar media concept. Water Resour. Res., 13: 355-362.

NOTE TO CONTRIBUTORS

A detailed ***Guide for Authors*** is available upon request and is also printed in the first volume to appear each year. You are kindly asked to consult this guide. Please pay special attention to the following notes:

Types of papers published in the journal

- papers reporting results of original research – review articles – short communications – editorials
- book reviews – news and announcements.

Language

The official language of the journal is English. Authors whose mother tongue is not English are strongly advised to have their manuscripts checked by an English-speaking colleague prior to submission.

Preparation of the text

(a) The manuscript should include at the beginning an abstract of not more than 400 words.
(b) It should be typewritten with double spacing and wide margins. Words to be printed in italics should be underlined. SI units should be used throughout.
(c) The title page should include: the title, the name(s) of the author(s), and their affiliation(s).
(d) Submit the original plus 2 copies of the manuscript (original illustrations or computer print-outs plus 2 photocopies – for photographs, 3 prints should be supplied).

References

(a) References in the text should be cited as the name of the author(s), followed by the year of publication.
(b) The reference list should be in alphabetical order and on sheets separate from the text.

Tables

Tables should be compiled on separate sheets. A title should be provided for each table and all tables should be referred to in the text.

Illustrations

(a) Illustrations should be numbered consecutively and referred to in the text. All illustrations (line drawings, computer printouts and photographs) should be submitted separately, unmounted and not folded.
(b) Drawings should be fully annotated, the size of the lettering being appropriate to that of the drawings, but taking into account the possible need for reduction in size (preferably not more than 50%). The page format of the journal should be considered when designing drawings.
(c) Photographs must be of good quality, printed on glossy paper.
(d) Figure captions should be supplied on a separate sheet.

Reprints and page charges

There is no page charge. Fifty reprints of each article published will be supplied free of charge. Additional reprints can be ordered on a reprint order form which is included with the proofs.

All contributions will be carefully refereed for international relevance and quality.

Submission of an article is understood to imply that the article is original and unpublished and is not being considered for publication elsewhere.