Journal of Hydrology 238 (2000) 78–89

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Modeling flow and transport in a two-dimensional dual-permeability system with spatially variable hydraulic properties

T. Vogel[a,*], H.H. Gerke[b,1], R. Zhang[c,2], M.Th. Van Genuchten[d,3]

[a]Czech Technical University, Faculty of Civil Engineering, Thakurova 7, 16629 Prague, Czech Republic
[b]Department of Soil Landscape Research, Center for Agricultural Landscape and Land Use Research (ZALF), Eberswalder Str. 84, D-15374 Müncheberg, Germany
[c]University of Wyoming, Department of Renewable Resources, Laramie, WY 82071-3354, USA
[d]George E. Brown Jr., Salinity Laboratory, USDA-ARS, 450 West Big Springs Road, Riverside, CA 92507-4617, USA

Received 22 December 1999; revised 6 June 2000; accepted 21 August 2000

Abstract

Most field soils exhibit soil spatial variability as well as soil structure. The challenge is to account adequately for both types of spatial heterogeneity in simulation models. A numerical finite element code was used to compare single- and dual-permeability approaches for modeling variably saturated flow and transport in two-dimensional heterogeneous soil systems. The code was based on the Richards' equation for water flow and the advection-dispersion equation for solute transport. Spatial variability in the soil hydraulic properties was accounted for by randomly generating a hydraulic conductivity field using a one-dimensional first-order Markov process. Soil structural effects were modeled with a two-domain concept in which a first-order kinetic expression is used to describe the transfer of water and solute between the two domains. Numerical experiments were carried out for the case of furrow irrigation, including the breakthrough of a conservative solute to the groundwater table. We compared five different scenarios: a single domain having uniform hydraulic properties (SU), a single domain with a randomly distributed hydraulic conductivity (SR), a dual-permeability system with uniform hydraulic properties (DU), a dual-permeability system with a randomly distributed fracture hydraulic conductivity (DRF), and a dual-permeability system having a randomly distributed matrix hydraulic conductivity (DRM). All scenarios started with pressure heads in equilibrium with a constant groundwater table 150 cm below the soil surface and zero initial solute concentrations. The simulated two-dimensional (2D) vertical concentration profiles showed preferential pathways resulting from both the spatial variability (SR) and soil structure (DRF) scenarios. As expected, drainage of water from the bottom of the profile occurred significantly earlier for dual- than for single-permeability scenarios. The combination of having spatial variability in the hydraulic properties and invoking the dual-permeability approach yielded the quickest and largest leaching of solute. The 2D dual-permeability approach should considerably improve the simulation of water and solute movement in naturally heterogeneous field soils.

Keywords: Dual-permeability media; Preferential flow; Unsaturated flow; Solute transport; Spatial variability; Soil structure

* Corresponding author. Fax: +420-2-2431-0782.
E-mail addresses: vogel@fsv.cvut.cz (T. Vogel), hgerke@zalf.de (H.H. Gerke), renduo@uwyo.edu (R. Zhang).
[1] Fax: +49-33432-82280.
[2] Fax: +307-766-6403.
[3] Fax: +909-342-4964.

PII: S0022-1694(00)00327-9

1. Introduction

One-dimensional (1D) models assuming homogeneous soil properties often fail to accurately predict solute movement at the field scale. Realistic models must consider the horizontal and vertical variability in soil properties at a variety of spatial scales. Most field soils exhibit different types of spatial heterogeneity, such as soil spatial variability and soil structure, which often also coexist. Within the concept of continuum models (e.g. Bear, 1972), spatial variability relates to the spatial distribution of macroscopic model parameters, such as the hydraulic conductivity, while in structured soils microscale effects sometimes become so dominant that they affect macroscopic scale flow and transport processes. In principle, both spatial variability in soil hydraulic properties and structure-induced heterogeneity can contribute to the initiation of preferential pathways. The challenge is to adequately account for both types of spatial heterogeneity in simulation models.

Structured soils and fractured rock formations contain a highly-permeable macropore or fracture pore system through which water and dissolved solutes can move at considerably higher velocities than in the porous matrix. Consequently, local nonequilibrium conditions in the transient pressure head and solute concentration distributions may develop (we use the term ‘local’ here to indicate a sub-REV scale, i.e. a scale smaller than that of the representative elementary volume (REV) in continuum approaches). Such preferential phenomena severely limit the prediction of water and solute movement in structured or macroporous soils, as well as in fractured rock systems. Preferential flow related to structure has been widely reported in soils containing wormholes, root channels, and inter-aggregate fissures (e.g. Ehlers, 1975; Bouma, 1981; Beven and German, 1982; Brusseau and Rao, 1990; Wang, 1991; Thoma et al., 1992; Flury et al., 1994; Liu et al., 1998; Pruess 1999; Vervoort et al., 1999; among many others).

Additional types of preferential flow have been linked to textural differences rather than structural effects. Two types of preferential flow phenomena that belong to this category are fingering (Hill and Parlange, 1972; Hillel, 1987) and funneled flow (Kung, 1990; Steenhuis et al., 1990; Walter et al., 2000). The evolution of finger-type preferential flow paths is associated with gravity-driven flow instability (Raats, 1973; Parlange and Hill, 1976; Glass et al., 1989). Fingering occurs in water repellent soils, when water percolates from a fine-textured into a coarse-textured layer, or when the air pressure increases ahead of infiltration front (Hendrickx et al., 1993; Ritsema et al., 1993; Ritsema et al., 1998; Dekker and Ritsema, 1994; Nieber, 1996; Bauters et al., 1998; DiCarlo et al., 1999).

Small-scale heterogeneities related to soil structure can be modeled either by using a discrete fracture network model (e.g. Sudicky and McLaren, 1992; Therrien and Sudicky, 1996) or a multi-continuum approach (e.g. Gwo et al., 1995, 1996). Within the discrete fracture network concept, a map of the structural geometry must be known, while with the multi-continuum approach two or more continua, representing matrix and fracture systems, share the same space domain.

Heterogeneity in continuum models can be simulated using both single- and dual-porosity or -permeability approaches. Multi-dimensional single-porosity models assume that preferential pathways may develop as a result of spatially variable distributed soil hydraulic properties. Spatially distributed soil hydraulic properties, for example generated deterministically or as random functions of the spatial coordinates, lead to characteristic patterns of relatively low and high flow velocities within the domain (e.g. Roth, 1995; Roth and Hammel, 1996; Tsang et al., 1988, 1996; Webb and Anderson, 1996; Birkhölzer and Tsang, 1997). In this case, local equilibrium is assumed and a single Richards’ equation is solved. The inclusion of randomly generated preferential pathways has for instance been used by Hopmans et al. (1988) and Vogel and Hopmans (1992) to improve predictions of drainage from a furrow-irrigated soil profile.

The dual-porosity approach (Barenblatt et al., 1960), on the other hand, assumes that the medium consists of two domains with different hydraulic and transport properties. The term dual-permeability is used to indicate that flow takes place in both domains in contrast to dual-porosity approach, which is often used in the context of mobile-immobile-type solute transport modeling. Water flow and solute transport in dual-permeability models are described using separate flow and transport equations for the fracture and matrix pore systems (e.g. Dykhuizen, 1987; Jarvis et al., 1991; Gerke and van Genuchten, 1993a). Crucial components of these types of models are transfer terms governing the exchange of water and/or solutes between the fracture and matrix pore systems. Empirical (Othmer et al., 1991) and semi-empirical (Gerke and van Genuchten, 1993b) expressions exist that are applicable to transient unsaturated flow.

Field scale studies of preferential flow from glacial till agricultural soils to tile drains (Villholth et al., 1998; Villholth and Jensen, 1998) show that both flow in macropores and spatial variability may affect measured tile outflow and solute output. Failure to describe the experimentally determined curves using the MACRO model of Jarvis et al. (1991) was attributed to the fact that a hydraulic resistance at the aggregate surface was not included. However, their modeling approach did not allow testing the hypothesis that the observed spatial variability may well have contributed to the discrepancies.

In addition to domain-internal heterogeneity, the geometry of field boundaries may be irregular, the soil surface shaped, and the boundary conditions spatially distributed. While field-scale transport processes are essentially 3D, they may, at times, be simplified and reduced to 2D descriptions.

In this paper we extend the 1D approach of Gerke and van Genuchten (1993a,b) to a 2D dual-permeability water flow and solute transport model by modifying the SWM II finite element code of Vogel (1987). The model allows for 2D two-domain simulations involving water and solute transfer between the fracture and matrix domains. The most important feature of the model is its ability to distinguish explicitly between heterogeneities due to macro-scale variability in the soil hydraulic properties and heterogeneities caused by micro-scale soil structural effects. Specific objectives of this paper are to compare the effects of a single- with those of a dual-permeability approach to simulate spatial heterogeneity, and to demonstrate the usefulness of combining dual-permeability features with a 2D model that considers spatially distributed hydraulic properties. We present a simulation example to illustrate the interplay of the two types of subsurface heterogeneity.

2. 2D dual-permeability model

The model of Gerke and van Genuchten (1993a) for water and solute movement in a variably-saturated structured medium assumes that all properties of the bulk porous medium are composed of two local properties, one associated with the fracture (subscript f) and one with the matrix (subscript m) pore system. Bulk and local properties are related by

$$\varepsilon = w_f \varepsilon_f + w_m \varepsilon_m \tag{1a}$$

$$\theta = w_f \theta_f + w_m \theta_m \tag{1b}$$

$$\mathbf{q} = w_f \mathbf{q}_f + w_m \mathbf{q}_m \tag{1c}$$

$$\theta c = w_f \theta_f c_f + w_m \theta_m c_m \tag{1d}$$

where ε is porosity (L^3L^{-3}), θ the water content (L^3L^{-3}), $\mathbf{q}$ the fluid flux density (LT^{-1}), c the solute concentration (ML^{-3}), and w_f is the relative volumetric proportion of the fracture pore system, $w_m = 1 - w_f$. Flow of water in the dual-permeability medium is described by means of two coupled Richards' equations as follows

$$C_f \frac{\partial h_f}{\partial t} = \nabla\cdot(\mathbf{K}_f \nabla h_f) + \nabla\cdot(\mathbf{K}_f \nabla z) - \frac{\Gamma_w}{w_f} \tag{2}$$

$$C_m \frac{\partial h_m}{\partial t} = \nabla\cdot(\mathbf{K}_m \nabla h_m) + \nabla\cdot(\mathbf{K}_m \nabla z) + \frac{\Gamma_w}{w_m}$$

where h is the pressure head (L), $\mathbf{K}$ the hydraulic conductivity tensor (LT^{-1}), C the specific water capacity (L^{-1}), z the vertical coordinate taken positive upward (L), t time (T), and Γ_w is the transfer term (T^{-1}) for water exchange between the two pore systems. The exchange of water between the matrix and the fracture pore systems is assumed to be proportional to the pressure head difference between both pore systems

$$\Gamma_w = \alpha_w (h_f - h_m) \tag{3}$$

where α_w is the first-order water transfer coefficient ($L^{-1}T^{-1}$). The local transient exchange of water causes a decrease in pressure in the drained domain and a corresponding increase of pressure in the receiving domain consistent with the respective water retention curves and the

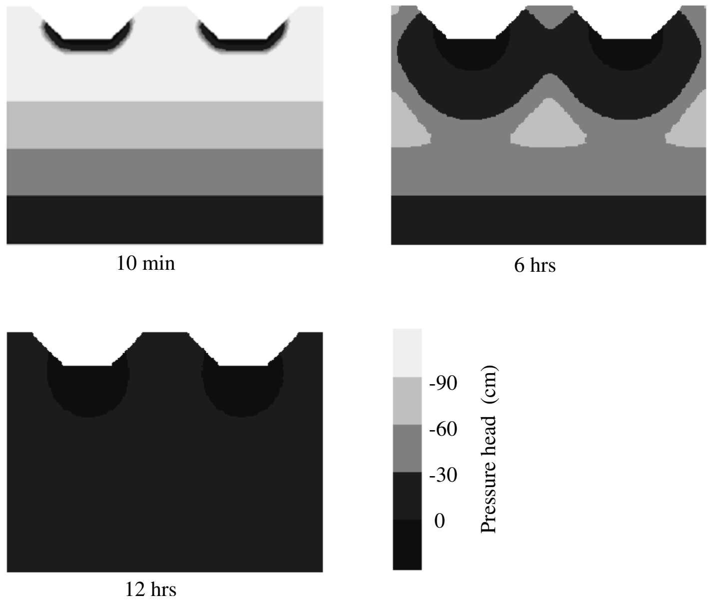

Fig. 1. Pressure head profiles at 10 min, 6 and 12 h after the beginning of furrow irrigation in a single domain system with uniform hydraulic properties (Scenario SU). The size of the flow domain is $2.0 \times 1.5\ \mathrm{m}^2$.

immediate flow conditions in the domains as prescribed by Eq. (2). Gerke and van Genuchten (1993b) obtained the following general expression for the water transfer coefficient:

$$\alpha_w = \gamma_w \frac{\beta}{a^2} K_a \tag{4}$$

where a is the characteristic radius or half-width of the matrix structure (L), β the dimensionless geometry coefficient, K_a the hydraulic conductivity (LT^{-1}) of the matrix at or near the surface of the fracture pore system, and γ_w is a corrective coefficient. A single average value of 0.4 for γ_w was found to be applicable for different hydraulic properties and initial conditions (Gerke and van Genuchten, 1993b). The geometry coefficient β was evaluated by Gerke and van Genuchten (1996) to be 3 for rectangular slabs.

Similar to Eq. (2), the transport of solutes in a dual-permeability medium, with the solutes subject also to linear equilibrium adsorption and first-order decay, is governed by two coupled convection–dispersion equations as follows

$$\begin{aligned} \frac{\partial}{\partial t}(\theta_f R_f c_f) &= \nabla\cdot(\theta_f \mathbf{D}_f \nabla c_f) - \nabla\cdot(\mathbf{q}_f c_f) - \theta_f \mu_f c_f - \frac{\Gamma_s}{w_f} \\ \frac{\partial}{\partial t}(\theta_m R_m c_m) &= \nabla\cdot(\theta_m \mathbf{D}_m \nabla c_m) - \nabla\cdot(\mathbf{q}_m c_m) - \theta_m \mu_m c_m + \frac{\Gamma_s}{w_m} \end{aligned} \tag{5}$$

where $\mathbf{D}$ is the dispersion coefficient tensor (L^2T^{-1}), μ a first-order decay coefficient (T^{-1}), R the retardation factor (dimensionless), and Γ_s is the solute mass transfer term ($ML^{-3}T^{-1}$) evaluated as (Gerke and van Genuchten, 1993b)

$$\Gamma_s = \pm \Gamma_w c_f + \alpha_s w_m \theta_m (c_f - c_m) \tag{6}$$

where α_s is the first-order solute mass transfer coefficient (T^{-1}). The first term on the right-hand side of Eq. (6) defines the advective contribution to Γ_s, while the second term gives the diffusive contribution. The first-order mass transfer coefficient is of the form (Van

Genuchten and Dalton, 1986)

$$\alpha_s = \frac{\beta}{a^2} D_a \tag{7}$$

where β and a are the same as for water, and D_a is the effective diffusion coefficient (L^2T^{-1}) of the soil matrix at the fracture/matrix interface.

3. Numerical experiments

As an illustrative example we consider furrow irrigation involving two furrows (Fig. 1). Water infiltrates into a 1.5-m deep soil profile from two adjacent furrows over a 12-h period. The water level in the furrows during the simulation period is kept 10 cm above the soil surface, thus resulting in constant pressure head boundary conditions. The water table at the bottom of the soil profile is also kept constant, leading to a zero pressure head boundary condition. Zero-flux flow conditions are imposed on all remaining boundaries. The profile was assumed to be initially at equilibrium with the water table (which means that all water fluxes were zero). The initial condition for solute transport was taken to be zero concentration, while along the wetted perimeter of the furrows the solute concentration of the infiltrating water was set equal to unity. A zero concentration gradient was imposed along the bottom boundary, thus enabling solute to exit the profile with draining water.

We compare five different flow scenarios: a single domain with uniformly distributed soil hydraulic properties (SU), a single domain with randomly generated hydraulic conductivities (SR), a two-domain dual-permeability system with uniformly distributed hydraulic properties (DU), a two-domain dual-permeability system consisting of a uniform matrix and a fracture domain having randomly generated hydraulic conductivities (DRF), and a two-domain dual-permeability system with a uniform fracture domain but a randomized matrix domain (DRM). The soil hydraulic parameters, the finite element grid, and the statistical parameters of the random conductivity field used in our numerical experiments, were taken from the simulation study presented by Vogel and Hopmans (1992).

3.1. Soil hydraulic and transport properties

The soil hydraulic properties were described by the equations (Van Genuchten, 1980)

$$\theta = \theta_r + (\theta_s - \theta_r)[1 + (-\alpha h)^n]^{-m} \tag{8}$$

$$K(S_e) = K_s S_e^{1/2}[1 - (-S_e^{1/m})^m]^2, \quad m = 1 - 1/n,$$

$$S_e = (\theta - \theta_r)/(\theta_s - \theta_r) \tag{9}$$

where θ_r and θ_s are the residual and saturated water contents, respectively; K_s the saturated hydraulic conductivity (LT^{-1}), and α (L^{-1}) and n the empirical fitting parameters. The dispersion coefficient for solute transport was considered to be of the form

$$D = D_0\tau + \lambda\frac{|q|}{\theta} \tag{10}$$

where D_0 is the molecular diffusion coefficient (L^2T^{-1}), λ is the dispersivity (L), and $\tau = \theta^{7/3}/\theta_s^2$ (Millington and Quirk, 1961) is a tortuosity factor. The hydraulic conductivity and dispersion tensors were both assumed to be isotropic, and hence fully determined by scalar functions.

The solute transport and soil hydraulic parameters, except for the saturated hydraulic conductivity, were assumed to be the same for all domains: $D_0 = 0.01\ \mathrm{cm^2 min^{-1}}$, $R = 1$, $\mu = 0$, $\lambda = 5$ cm, $\theta_r = 0.24$, $\theta_s = 0.45$, $\alpha = 0.019\ \mathrm{cm^{-1}}$, and $n = 1.83$. The average saturated hydraulic conductivities for the single, matrix and fracture domains were taken to be equal to 0.01, 0.0002, and 0.2 cm $\mathrm{min^{-1}}$, respectively. Transfer parameters determining the exchange of water and solute between the domains were set at $w_f = 0.05$, $K_a/K_m = 0.01$, $a = 1$ cm, $\gamma_w = 0.4$, $\beta = 3$, and $D_a/D_0 = 0.01$.

3.2. Random generation of the hydraulic conductivity field

A log-normally distributed autocorrelated scaling factor, defined as $\alpha_K = K_s/\bar{K}_s$, was generated to create subregions of high and low conductivity in the particular flow domain. A first-order Markov process (Haan, 1982) was used to randomize conductivities in a horizontal direction

$$y_{i+1} = \mu_y + \rho_y(y_i - \mu_y) + t_{i+1}\sigma_y(1 - \rho_y^2)^{1/2} \tag{11}$$

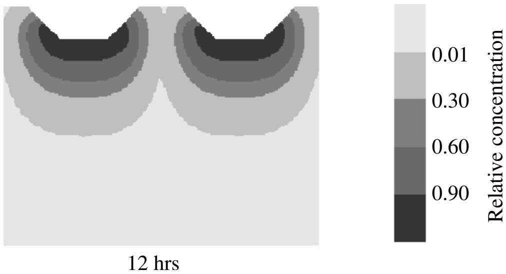

Fig. 2. Concentration profile at 12 h after the beginning of furrow irrigation in a single domain system with uniform hydraulic properties (Scenario SU).

where $y_i = \ln \alpha_K$ is the value of y for a particular nodal point i, μ_y and σ_y are the mean and standard deviation, respectively, t is $N\{0,1\}$, and ρ_y is the autocorrelation coefficient between y-values which are one lag apart. The lag was assumed to be 3 cm, corresponding with the element size of the finite element mesh. Parameters of the random process were: $\mu_y = -1.5$, $\sigma_y = 1.7$, and $\rho_y = 0.8$. The value of ρ_y, together with the lag, determines the shape of the Markov autocorrelation function. The parameter ρ_y can be determined by fitting the autocorrelation function to a set of autocorrelation data, obtained by geostatistical analysis of a measured hydraulic conductivity field.

For this study we used only one realization of the random process. The same realization was subsequently used to randomize the single-permeability domain, the fracture domain, and the matrix domain. The randomized saturated hydraulic conductivity field is shown in Fig. 3. Notice that the high conductivity regions create a pipe-like pattern. This feature allows water to flow from the top part of the soil profile to the groundwater table without any blockage by low-conductivity regions. The topsoil and the bottom parts of the flow region were not randomized. The top part of the soil profile was kept homogeneous (e.g. due to cultivation) to prevent a direct connection of the high-conductivity regions with water in the furrows. The homogeneous bottom part assures natural horizontal equilibration of pressure heads in soil profile with the water table.

Fig. 3. Randomly generated saturated hydraulic conductivity field in the analyzed soil cross-section of 2.0 m width and 1.5 m depth. The scaling factor, α_K, is equal to the local conductivity divided by the average conductivity.

3.3. Simulation results

Figs. 1 and 2 illustrate how water and solute move in the single domain with uniformly distributed hydraulic parameters (Scenario SU). Fig. 1 shows the more or less classical development of the pressure head profile during furrow irrigation. Water flow at the end of simulation (12 h) is close to steady state, while the concentration front (Fig. 2) has reached a depth approximately half-way to the water table.

Results for the second case (Scenario SR) involving a randomized conductivity field (Fig. 3), are presented in Fig. 4. The hydraulic connection between the furrows and the water table is now established much faster. As a consequence, the solute concentration front now reaches nearly the bottom of the profile at the end of the simulation (12 h). The pipe-like hydraulic conductivity distribution leads to macro-scale water flow channeling, with solute transport occurring in the form of a finger-type front.

Different results are obtained with the two-domain simulation using a uniform distribution of soil hydraulic properties (Fig. 5). In this case (Scenario DU), water flow in the fracture domain reaches steady state relatively soon, while the water content in the matrix domain is increasing only relatively slowly, predominantly through the absorption of water from the fractures. Also, as expected, solute transport rates are significantly higher in the fracture than in the matrix pore system.

Fig. 6 present simulation results for the case of a two-domain system in which the fracture domain has a randomized hydraulic conductivity field (Scenario DRF). This case shows the most heterogeneous distributions, especially for the solute concentration. As compared to the previous example (DU), the water content in the fracture domain increased much faster. The randomization apparently provides high-flux

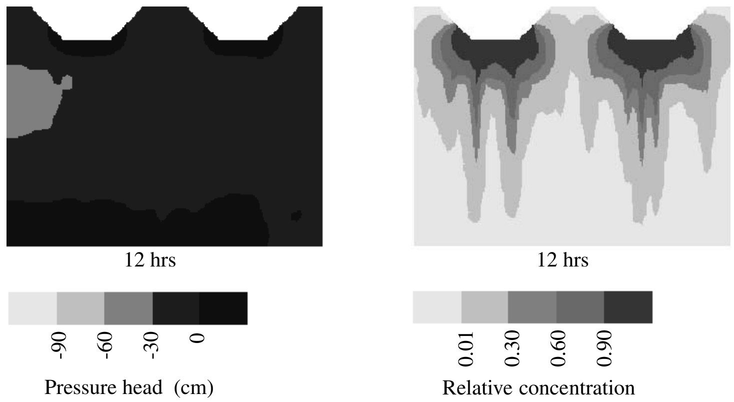

Fig. 4. Pressure head and concentration profiles in a single domain system with the randomly generated conductivity field (Scenario SR).

pathways for both water and the dissolved solute. Notice the extreme finger-type concentration front in both the fracture and matrix pore systems.

The DRM scenario illustrates the effect of employing a randomized conductivity field only for the matrix domain, while assuming the fracture system to remain uniform (Fig. 7). The results are quite similar to those obtained for the case with two uniform domains (DU). The pressure head profile in the matrix system still exhibits a somewhat distinctive preferential flow pattern. However, the matrix pressure head distributions remain relatively isolated and 'passive' in that they do not greatly affect solute displacement in the matrix domain.

Fig. 8a shows the calculated drainage rates during the irrigation for the five scenarios. The water fluxes for this purpose were integrated along the bottom boundary. In case of two-domain simulations, the fluxes in the fracture and matrix domains were combined using Eq. (1c) to yield one overall infiltration or drainage flux for the soil profile. Total cumulative amounts of water and solute entering and

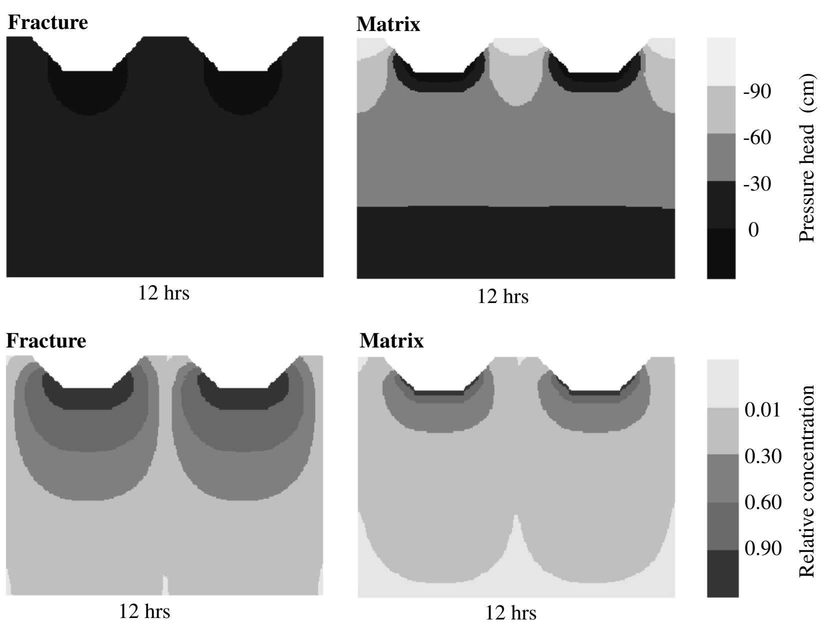

Fig. 5. Pressure head and concentration profiles in a dual-permeability system with uniform hydraulic properties (Scenario DU).

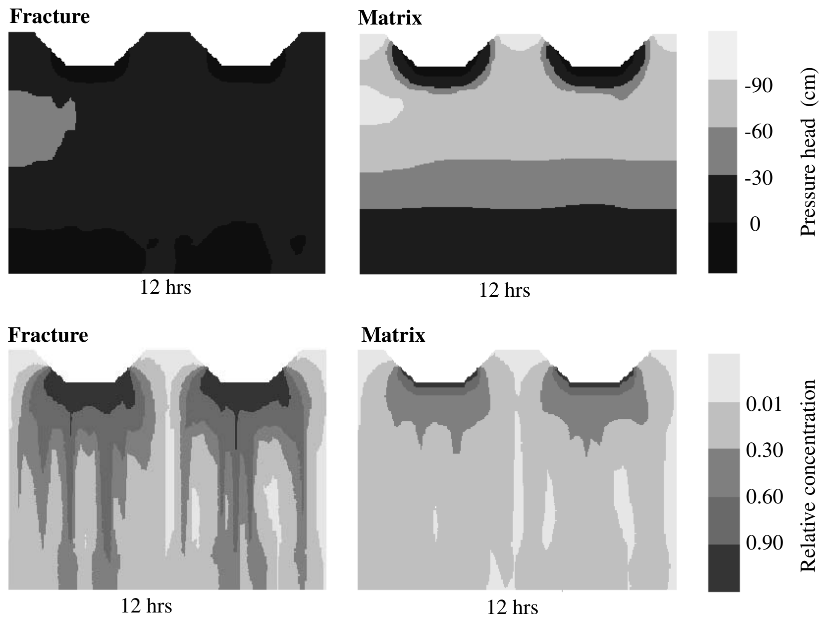

Fig. 6. Pressure head and concentration profiles in a dual-permeability system, in which the saturated hydraulic conductivity of the fracture domain was generated randomly (Scenario DRF).

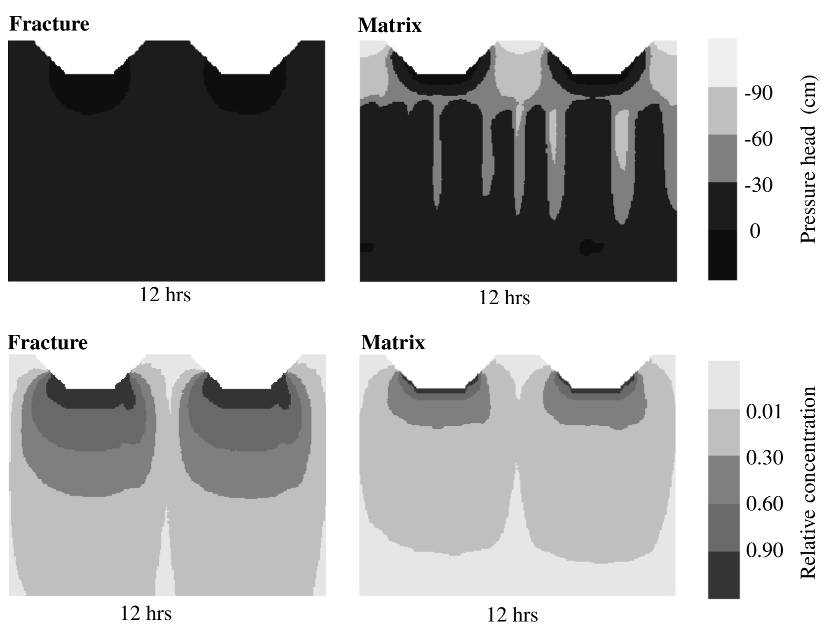

Fig. 7. Pressure head and concentration profiles in a dual-permeability system, in which the saturated hydraulic conductivity of the matrix domain was generated randomly (Scenario DRM).

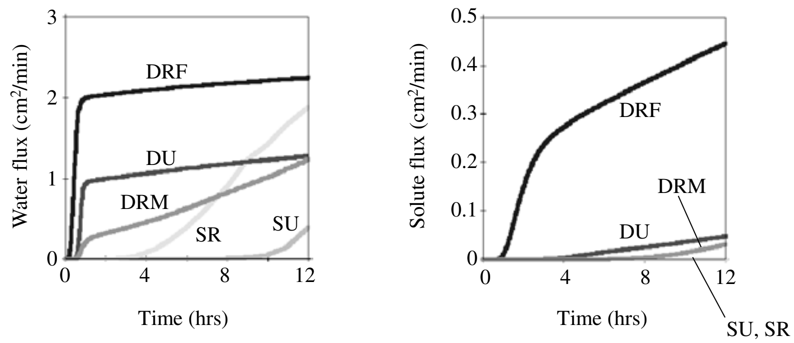

Fig. 8. Water and solute outflow from the lower boundary of the soil profile as computed for the respective flow scenarios: single uniform (SU), single with randomly generated conductivity (SR), dual uniform (DU), dual with randomly generated fracture conductivity (DRF), and dual with randomly generated matrix conductivity (DRM).

leaving the particular domains of the profile during the 12 h of irrigation are listed in Table 1. The values for the matrix and the fracture systems are provided separately after multiplication with their relative volumes, i.e. w_f and w_m, respectively. This guarantees additivity of the matrix and fracture contributions to the overall inflow/outflow amounts given in Table 1. The results indicate that the inflow rates are quite similar for all systems studied, but that the outflow rates vary considerably. The dual-permeability systems all exhibited a faster response in terms of drainage as compared to the single-permeability systems (Fig. 8a). The two-domain system with a randomized fracture domain (DRF) deviated the most from the homogeneous case by showing the earliest and largest outflow rates. Randomizing the hydraulic conductivity field of the single-porosity system (SR) also promotes early drainage, albeit to a lesser extent than use of a dual-permeability system.

Finally, Fig. 8b shows solute leaching rates to the groundwater table, obtained by integrating the solute flux across the lower boundary. The results are consistent with those in Fig. 8a in that the randomized fracture case (DRF) yields by far the largest amount of solute and the earliest breakthrough.

4. Discussion and conclusions

The dual-permeability approach used in this paper is based on two separate but interacting 2D flow domains. The model provides a useful tool for studying preferential flow in structured soils or unsaturated fractured rock. Both domains of the dual-permeability system can exhibit different spatial variabilities in their hydraulic properties, as well as different degrees of anisotropy. The further the two domains are removed from mutual local equilibrium, the more distinct the simulation results will be as compared to the single-porosity approach. The degree of local disequilibrium is controlled by the invoked values of transfer term parameters.

The effects of randomization on the one hand, and decomposition of the system into two domains on the

Table 1
Cumulative inflow and outflow amounts of water and solutes after 12 h of irrigation. The numbers in parenthesis indicate the value for the matrix multiplied by $w_m = 0.95$ and the numbers in brackets indicate the value for the fracture pore system multiplied by $w_f = 0.05$.

Flow system	Water/solute inflow (cm^2)	Water outflow (cm^2)	Solute outflow (cm^2)
SU	1896	37	0.000
SR	1956	500	0.009
DU	1717 (107) [1610]	762 (7) [755]	12 (0.01) [12]
DRF	2123 (118) [2005]	1483 (13) [1470]	207 (0.22) [207]
DRM	1823 (118) [1705]	465 (4) [461]	4 (0.00) [4]

other hand, are to a certain extent equivalent. The decision of which approach is more appropriate depends on the natural soil system being simulated, the preferred modeling concept, and our ability to relate the soil hydraulic properties to either macro-scale spatial variability or micro-scale structural effects. For example, fractured soil systems may be better modeled by using discrete fracture network models, and finely aggregated or biopores containing soils with the two-domain model. Unstructured soils with relatively small-scale variabilities in the hydraulic properties may be described either by the distributed parameters approach or by the two-domain approach. In addition to these conceptual criteria, selection of the particular approach should also be influenced by criteria of numerical efficiency. Macropore type heterogeneities at the scale of millimeters are difficult to model by means of a single-porosity or -permeability approach. Randomization in that case is not practical since the size of elements used for discretizing the flow domain would have to be significantly smaller than the autocorrelation length of the randomly generated hydraulic properties. This would require an excessive number of elements to cover the entire flow region.

Still, crucial to application of a multi-dimensional dual-permeability approach is the need for independent determination of the dual set of soil hydraulic and transport parameters, as well as of water and solute transfer parameters characterizing soil structure and the fracture/matrix interface. Since the parameters are random variables, additional data on spatial distributions and autocorrelations are required. In many natural systems structure-related preferential pathways are predominantly active at saturation and in a narrow range of negative pressure near saturation. This makes it possible to apply relatively straightforward procedures to determine the separate hydraulic properties of the fracture and matrix domains, for example by executing a simple two-stage transient flow experiment, in which during the first stage the preferential pathways remain inactive (dry) and the process is dominated by the matrix, while during the second stage (involving saturation) the flow process is strongly influenced by the preferential flow domain. The first stage is then used to estimate the matrix properties, while the second stage provides information necessary for the identification of the preferential flow domain parameters. The parameters can then be identified by solving the associated inverse problem for the dual set of Richards and convection-dispersion equations. Although simple in principle, the above-described inverse procedure may suffer from lack of uniqueness and likely needs to be complemented with additional (independent) information on soil structure, its spatial variability, and the fracture/matrix interface properties. The problem of identifying the dual-porosity and dual-permeability soil hydraulic parameters has been addressed by Durner (1994), Mohanty et al. (1997), Köhne et al. (1999), Vogel et al. (1999, 2000) and Schwartz et al. (2000), among others. A variety of experimental techniques for dual-permeability parameter identification are currently being developed by the authors.

Spatial variability in the soil hydraulic properties of a multi-dimensional dual-permeability system can be treated in a deterministic (e.g. by means of soil stratification) or stochastic manner (e.g. using autocorrelated random fields). The dual-permeability model described in this paper permits one to formulate and assess the usefulness of various alternative hypotheses about the spatial distribution of hydraulic properties by comparing model responses with real system observations.

Finally, we note that the 2D dual-permeability model proposed in this paper is capable of generating preferential flow patterns that qualitatively are in a good agreement with frequently observed distributions under field conditions (e.g. dye tracer studies by Cislerová et al., 1990; Villholth et al., 1998; and Larsson et al., 1999). The extension of the dual-permeability approach to a 2D (or even 3D) systems makes it possible to respect the natural spatial variability of hydraulic properties of the matrix as well as the preferential flow (fracture) domain, which in turn facilitates more realistic simulation of preferential flow processes at the field scale. The approach should help one to more effectively analyze the effects of soil structure and soil spatial variability on preferential flow, and design improved experiments for studying preferential flow processes.

Acknowledgements

The research was partly conducted within the framework of the CTU research project CEZ J04/98 211100002. Additional support was provided by NATO Collaborative Linkage Grant EST 974796.

References

Barenblatt, G.I., Zheltov, I.P., Kochina, I.N., 1960. Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks. J. Appl. Math. Mech. 24 (5), 1286–1303.

Bauters, T.W.J., DiCarlo, D.A., Steenhuis, T.S., Parlange, J.-Y., 1998. Preferential flow in water repellent sands. Soil Sci. Soc. Am. J. 62, 1185–1190.

Bear, J., 1972. Dynamics of Fluids in Porous Media. Elsevier, New York.

Beven, K.J., German, P., 1982. Macropores and water flow in soils. Water Resour. Res. 18, 1311–1325.

Birkhölzer, J., Tsang, C.-F., 1997. Solute channeling in unsaturated heterogeneous porous media. Water Resour. Res. 33, 2221–2238.

Bouma, J., 1981. Soil morphology and preferential flow along macropores. Agric. Water Manage. 3, 235–250.

Brusseau, M.L., Rao, P.S.C., 1990. Modeling solute transport in structured soils: a review. Geoderma 46, 169–192.

Cislerová, M., Vogel, T., Šimunek, J., 1990. The infiltration–outflow experiment used to detect flow deviations. In: Roth, K., Fluhler, H., Jury, W.A., Parker, J.C. (Eds.). Field-Scale Water and Solute Flux in Soils. Monte Verita, Birkhauser Verlag, Basel, pp. 109–117.

Dekker, L., Ritsema, C., 1994. How water moves in a water repellent sandy soil: 1. Potential and actual water repellency. Water Resour. Res. 30, 2507–2517.

DiCarlo, D.A., Bauters, T.W.J., Darnault, C.J.G., Steenhuis, T.S., Parlange, J.-Y., 1999. Lateral expansion of preferential flow path in sands. Water Resour. Res. 35 (2), 427–434.

Durner, W., 1994. Hydraulic conductivity estimation for soils with heterogeneous pore structure. Water Resour. Res. 30, 211–233.

Dykhuizen, R.C., 1987. Transport of solutes through unsaturated fractured media. Water Res 21 (12), 1531–1539.

Ehlers, W., 1975. Observations on earthworm channels and infiltration on tilled and untilled loess soils. Soil Sci. 119, 242–249.

Flury, M., Flühler, M., Jury, W.A., Leuenberger, J., 1994. Susceptibility of soils to preferential flow of water: a field study. Water Resour. Res. 30, 1945–1954.

Gerke, H.H., van Genuchten, M.Th., 1993a. A dual-porosity model for simulating the preferential movement of water and solutes in structured porous media. Water Resour. Res. 29 (2), 305–319.

Gerke, H.H., van Genuchten, M.Th., 1993b. Evaluation of a first-order water transfer term for variably saturated dual-porosity models. Water Resour. Res. 29 (4), 1225–1238.

Gerke, H.H., van Genuchten, M.T., 1996. Macroscopic representation of structural geometry for simulating water and solute movement in dual-porosity media. Adv. Water Resour. 19 (6), 343–357.

Glass, R.J., Parlange, J.-Y., Steenhuis, T.S., 1989. Mechanisms for finger persistence in homogeneous, unsaturated, porous media: theory and verification. Soil. Sci. 148, 60–70.

Gwo, J.P., Jardine, P.M., Wilson, G.V., Yeh, G.T., 1995. A multiple-pore-region concept to modeling mass transfer in subsurface media. J. Hydrol. 164, 217–234.

Gwo, J.P., Jardine, P.M., Wilson, G.V., Yeh, G.T., 1996. Using a multiregion model to study the effects of advective and diffusive mass transfer on local physical nonequilibrium and solute mobility in a structured soil. Water Resour. Res. 32, 561–570.

Haan, C.T., 1982. Statistical Methods in Hydrology. The Iowa State University Press, Ames, IA.

Hendrickx, J.M.H., Dekker, L.W., Boersma, O.H., 1993. Unstable wetting fronts in water-repellent field soils. J. Environ. Qual. 22, 109–118.

Hill, D.E., Parlange, J.-Y., 1972. Wetting front instability in layered soils. Soil Sci. Soc. Am. J. 36, 697–702.

Hillel, D., 1987. Unstable flow in layered soils: a review. Hydrol. Processes 1, 143–147.

Hopmans, J.W., Schukking, H., Torfs, P.J.J.F., 1988. Two-dimensional steady unsaturated water flow in heterogeneous soils with autocorelated soil hydraulic properties. Water Resour. Res. 24 (12), 2005–2017.

Jarvis, N.J., Jansson, P-E., Dik, P.E., Messing, I., 1991. Modelling water and solute transport in macroporous soil. I. Model description and sensitivity analysis. J. Soil Sci. 42, 59–70.

Köhne, M., Meyer-Windel, S., Gerke, H.H., 1999. Parametrizing a dual retention and conductivity model. Geophysical Research Abstracts, EGS 24th General Assembly, The Hague, vol. 1, no. 2, p. 329.

Kung, K.-J.S., 1990. Preferential flow in a sandy vadose zone. 2. Mechanisms and implications. Geoderma 46, 59–71.

Larsson, M.H., Jarvis, N.J., Torstensson, G., Kasteel, R., 1999. Quantifying the impact of preferential flow on solute transport to tile drains in a sandy field soils. J. Hydrol. 215, 116–134.

Liu, H.H., Doughty, C., Bodvarsson, G.S., 1998. An active fracture model for unsaturated flow and transport in fractured rocks. Water Resour. Res. 34 (10), 2633–2646.

Millington, R.J., Quirk, J.M., 1961. Permeability of porous solids. Trans. Faraday Soc. 57, 1200–1207.

Mohanty, B.P., Bowman, R.S., Hendrickx, J.M.H., van Genuchten, M.Th., 1997. New piecewise- continuous hydraulic functions for modeling preferential flow in an intermittent flood-irrigated field. Water Resour. Res. 33 (9), 2049–2063.

Nieber, J.L., 1996. Modeling finger development and persistence in initially dry porous media. Geoderma 70, 209–229.

Othmer, H., Diekkrüger, B., Kutilek, M., 1991. Bimodal porosity and unsaturated hydraulic conductivity. Soil Sci. 152 (3), 139–150.

Parlange, J.-Y., Hill, D.E., 1976. Theoretical analysis of wetting front instability in soils. Soil Sci. 122, 236–239.

Pruess, K., 1999. A mechanistic model for water seepage through thick unsaturated zones in fractured rocks of low matrix permeability. Water Resour. Res. 35 (4), 1039–1051.

Raats, P.A.C., 1973. Unstable wetting fronts in uniform and nonuniform soils. Soil Sci. Soc. Am. Proc. 37, 681–685.

Ritsema, C.J., Dekker, L.W., Hendrickx, J.M.H., Hamminga, W., 1993. Preferential flow mechanism in a water repellent sandy soil. Water Resour. Res. 29, 2183–2193.

Ritsema, C.J., Dekker, L.W., Nieber, J.L., Steenhuis, T.S., 1998. Modeling and field evidence of finger recurrence in a water repellent sandy soil. Water Resour. Res. 34 (4), 555–567.

Roth, K., 1995. Steady state flow in an unsaturated, two-dimensional, macroscopically homogeneous, Miller-similar medium. Water Resour. Res. 31, 2127–2140.

Roth, K., Hammel, K., 1996. Transport of conservative chemical through an unsaturated two-dimensional Miller-similar medium with steady state flow. Water Resour. Res. 32, 1653–1663.

Schwartz, R.C., Juo, A.S.R., McInnes, K.J., 2000. Estimating parameters for a dual-porosity model to describe non-equilibrium, reactive transport in a fine-textured soil. J. Hydrol. 229, 149–167.

Steenhuis, T.S., Kung, K.-J.S., Parlange, J.-Y., Selker, J.S., Chen, X.X., 1990. Flow regimes in sandy soils with inclined layers. In: Morel-Seytoux, H. (Ed.). Proceedings of the 10th Annual Hydrology Days. Hydrology Days, Atherton, California, pp. 78–94.

Sudicky, E.A., McLaren, R.G., 1992. The Laplace Transform Galerkin technique for large-scale simulation of mass transport in discretely fractured porous formations. Water Resour. Res. 28 (2), 499–514.

Therrien, R., Sudicky, E.A., 1996. Three-dimensional analysis of variably-saturated flow and solute transport in discretely fractured porous media. J. Contam. Hydrol. 23, 1–44.

Thoma, S.G., Gallegos, D.P., Smith, D.M., 1992. Impact of fracture coatings on fracture/matrix flow interactions in unsaturated, porous media. Water Resour. Res. 28 (5), 1357–1367.

Tsang, Y.W., Tsang, C.F., Neretnieks, I., 1988. Flow and tracer transport in fractured media: a variable-aperture channel model and its properties. Water Resour. Res. 24, 2049–2060.

Tsang, Y.W., Tsang, C.F., Hale, F.V., Dverstorp, B., 1996. Tracer transport in a stochastic continuum model of fractured media. Water Resour. Res. 32, 3077–3092.

Van Genuchten, M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J. 44, 892–898.

Van Genuchten, M.Th., Dalton, F.N., 1986. Models for simulating salt movement in aggregated field soils. Geoderma 38, 165–183.

Vervoort, R.W., Radcliffe, D.E., West, L.T., 1999. Soil structure development and preferential solute flow. Water Resour. Res. 35 (4), 913–928.

Villholth, K.G., Jensen, K.H., Fredericia, J., 1998. Flow and transport processes in a macroporous subsurface-drained glacial till soil. I. Field investigations. J. Hydrol. 207, 98–120.

Villholth, K.G., Jensen, K.H., 1998. Flow and transport processes in a macroporous subsurface-drained glacial till soil. II. Model analysis. J. Hydrol. 207, 121–135.

Vogel, T., 1987. SWM II-Numerical model of two-dimensional flow in avariably saturated porous medium. Research report no. 87, Department of Hydraulics and Catchment Hydrology, Agriculture Univversity Wageningen, The Netherlands, 1987.

Vogel, T., Hopmans, J.W., 1992. Two-dimensional analysis of furrow infiltration. J. Irrig. Drain. Engng — ASCE 118 (5), 791–806.

Vogel, T., Cislerová, M., Stodolovská, A., 1999. Hydraulic parameters of acid brown soil by inverting infiltration-outflow experiment. Geophysical Research Abstracts, EGS 24th General Assembly, The Hague, vol. 1, no. 2, p. 305.

Vogel, T., Šanda, M., CÍslerová, M., 2000. Modeling structure related preferential flow component of subsurface runoff at the hillslope scale. GRA, EGS 25th General Assembly, Nice, vol. 2, p. 272.

Walter, M.T., Kim, J.-S., Steenhuis, T.S., Parlange, J.-Y., Heilig, A., Braddock, R.D., Selker, J.S., Boll, J., 2000. Funneled flow mechanisms in a sloping layered soil: laboratory investigation. Water Resour. Res. 36 (4), 841–849.

Wang, J.S.Y., 1991. Flow and transport in fractured rocks. Rev. Geophys. (Suppl), 254–262.

Webb, E.K., Anderson, M.P., 1996. Simulation of preferential flow in three-dimensional, heterogeneous conductivity fields with realistic internal architecture. Water Resour. Res. 32, 533–545.