Using the dye tracer experiment for characterisation of parameters of the dual-permeability model

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Abstract
This study is focused on the visualization of the preferential flow in different soil types and their horizons using a dye tracer experiment method. The field ponding dye infiltration experiments were performed on two soil types: Haplic Luvisol and Haplic Cambisol. The tension disc infiltrometer and the Guelph permeameter measurements were performed in the field on various horizons to study the impact of macropores on water flow. In addition, thin soil sections were made and micromorphological images were used to study soil aggregate structure and dye distribution at a microscale. The staining patterns within the vertical and horizontal sections documented very different natures of preferential flow in different soil types and also within the soil profiles. While preferential flow in Haplic Luvisol was caused by soil aggregation and biopores, preferential flow in Haplic Cambisol was caused only by biopores and large gravitational soil fractures. Micromorphological images showed that the dye was primarily distributed either in the interagregate pores and then in the pores inside the aggregates, or in the isolated large pores connected to the dye source and then into the matrix pores. Information about the dual-domain geometry and the dual-permeability models in HYDRUS 2/3D were then used to simulate preferential flow in studied soil types and to estimate parameters characterizing transport properties of bi-modal soil-porous medias.

Key Words
Soil structure, preferential flow, dye tracer experiment, micromorphological images, parameter optimisation

Introduction
It was observed that water flow and contaminant transport in structured soils is frequently influenced either by water and solute temporal immobilization or by preferential flow. To describe such non-equilibrium water flow and solute transport in soils, many numerical models have been recently developed. Overviews of non-equilibrium water flow and solute transport evidence, and various experimental and mathematical approaches to study and describe these phenomena were given by Gerke (2006), Jarvis (2007), Šimůnek and van Genuchten (2008), or Köhne *et al.* (2009a,b). Common physically based models for simulation of water flow and solute transport in structured soils assume (one) continuum and bi- or multi-continuum approaches. To apply various approaches, the properties characterizing water flow and solute transport must be specified. The numerical inversion and parameter estimation from the observed water flow and solute transport data are usually applied to obtain desired information. (See review articles mentioned above.) However, to obtain reliable results many parameters must be independently measured or determined from the literature. A summary of various approaches for independent parameter determination is given by Köhne *et al.* (2009a).

Various dye tracers are frequently used to study soil structure and preferential flow phenomena (Flury and Wai 2003). The most often applied dye is the food color Brilliant Blue FCF. There are many studies dealing with the food color Brilliant Blue FCF characteristics (Flury and Flühler 1995, Morris *et al.* 2008) and studies using this dye for visualization of non-equilibrium water flow and dye transport in soils (Flury *et al.* 1994, Kasteel *et al.* 2005, Sander and Gerke 2007).

Preferential water flow and herbicide transport was studied in the field and laboratory by Kodešová *et al.* (2008, 2009). They applied the dual-porosity and dual-permeability models in HYDRUS-1D (Šimůnek *et al.* 2008) to simulate observed data. Micromorphological images of studied soils were used to determine parameters describing dual-domains geometry. A goal of this study is to characterize dual-domain geometry of previously studied soils in macro and micro-scale using the dye tracer experiment. An additional goal is to use this information and measured transient flow data for characterization of parameters of the dual-permeability model.

Methods

The study was performed in Haplic Luvisol in Hněvčeves and Haplic Cambisol in Humpolec in the Czech Republic. Details of soil chemical, physical and transport properties are given by Kodešová *et al*. (2008, 2009). The field dye infiltration experiment was carried out in year 2009 using the similar procedure to that described by Sander and Gerke (2007). 100 (Haplic Luvisol) and 50 (Haplic Cambisol) liters of solution with food color Brilliant Blue FCF (5 kg m^{-3}) was infiltrated in a 1 x 1 m plot (applying an initial ponding depth of 10 and 5 cm, respectively) immediately after the wheat harvest. On the next day, one half of the plot was sliced horizontally and another half vertically to study the dye distribution within the soil profile to the depth of 100 cm. Micromorphology of soil structure and the dye distribution was studied on thin soil sections prepared from large soil aggregates, taken in the field. Thin sections were prepared according to the methods presented by Catt (1990). The tension disc infiltrometer (a disc radius of 10 cm) was used to measure cumulative water infiltration under unsaturated conditions created using the pressure head of -2 cm. The Guelph (well) permeameter was used to measure cumulative water flux under ponding conditions. Measurements were performed at various horizons to study possible impact of macropores. Therefore the depth of the drilled well was variable. The well radius was always 3 cm, and the well ponding depth was 5 cm.

The analytical expressions presented by Wooding (1968) and Zhang *et al.* (1998) are usually used to calculate *K* values from the tension disc and the Guelph permeameter, respectively. The radially symmetric single-porosity and dual-porosity models in HYDRUS 2/3D (Šimůnek *et al.* 2008) were applied here to estimate parameters of the soil hydraulic functions (van Genuchten 1980) of both models using both field experiments. First, the single-porosity flow model in HYDRUS 2D/3D was used to estimate the saturated hydraulic conductivity, K_s, via a numerical inversion of the data from the tension disc infiltrometer, and using the soil water retention curve parameters obtained in the laboratory from ponding infiltration test presented by Kodešová *et al.* (2009). Second, the dual-permeability flow model in HYDRUS 2D/3D was used to estimate the saturated hydraulic conductivity, K_{sf}, in the macropore domain using the Guelph permeameter cumulative infiltration. In this case, the parameters obtained from the tension disc infiltrometer experiment were used to describe the matrix domain, and the parameters characterizing water retention in the macropore domain and mass exchange between macropore and matrix domains were either set (at measured or average values) or optimized. Parameters characterizing the aggregate geometry were set based on the field ponding dye infiltration experiment and micromorphological study.

Haplic Luvisol in Hněvčeves **Haplic Cambisol in Humpolec**

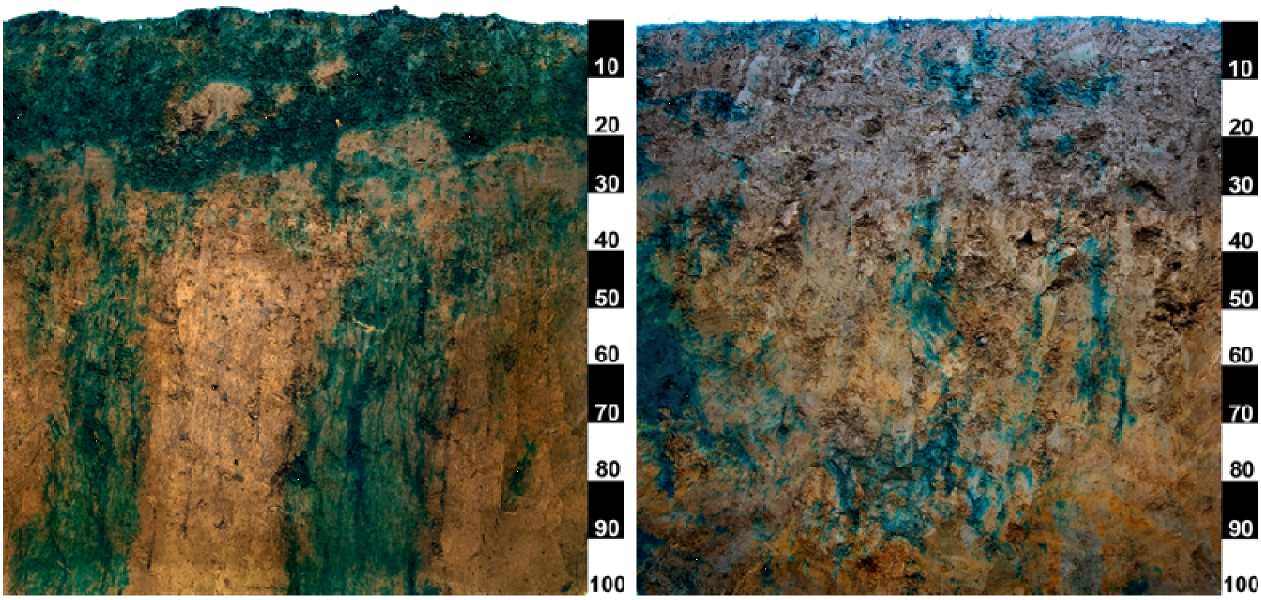

Figure 1. Examples of staining patterns within the vertical sections in Haplic Luvisol in Hněvčeves (left) and Haplic Cambisol in Humpolec (right). Diagnostic horizons of Haplic Luvisol: Ap_1 (0 – 25 cm), Ap_2 (25 - 35 cm), Bt_1 (35 - 75 cm) and Bt_2 (75 - 100 cm). Diagnostic horizons of Haplic Cambisol: Ap (0 – 33 cm), Bw (33 - 65 cm) and C (65 – 100 cm).

Results

Here we show only examples of staining patterns within the vertical sections in Haplic Luvisol in Hněvčeves

(Figure 1 left) and Haplic Cambisol in Humpolec (Figure 1 right). Left figure shows that while dye tracer was partly regularly transported and only some isolated domains were visible in the surface Ap_1 horizon, the significant preferential flow occurred in the subsurface horizons. The preferential flow in the upper subsurface Ap_2 horizon (plow pan) was caused by the gravitational biopores in the very compact matrix structure, which considerably slowed down the dye transport. In the case of deeper horizons (Bt_1 and Bt_2), the preferential flow occurred due to the gravitational biopores and extensively developed prismatic structure, which was highly affected by organo-mineral coatings. Right figure shows that the dye tracer transport in Haplic Cambisol was in all horizons (Ap, Bw, C) mainly affected by the preferential flow caused by the gravitational fractures and biopores.

Various soil structures were also documented on micromorphological images of soil structure studied on thin soil sections prepared from large soil aggregates (not shown). The micromorphological images of the Haplic Luvisol soil samples showed higher-order aggregates of the Ap_1 horizon, dense structure of the Ap_2 horizon, well-developed soil structure affected by clay coatings of the Bt_1 horizon and isolated pores with clay coatings inside the large aggregates of the Bt_2 horizons. Aggregates in all horizons (Ap, Bw, C) of the Haplic Cambisol were poorly developed. The pore system did not show intrapedal or interpedal pores, pores were developed mainly along gravel particles. Correspondingly to the different soil structure compositions, dye tracer was differently distributed in the soil. Images did not show a regular dye distribution. It was evident that the dye was primarily distributed either in the interagregate pores and then in the pores inside the aggregates, or in the isolated large pores connected to the dye source and then into the matrix pores. Accumulated organic matter, clay coating, larger soil grains and isolated larger capillary pores, which initially did not contain the dye tracer, behaved as less-permeable or impermeable barriers.

An example of measured and simulated transient flow data using the dual-permeability model in HYDRUS 2/3D is shown in Figure 2. In this case, the K_{sf} value for the macropore domain of the dual-permeability model was estimated using the Guelph permeameter cumulative infiltration data measured in the Ap_1 horizon of Haplic Luvisol.

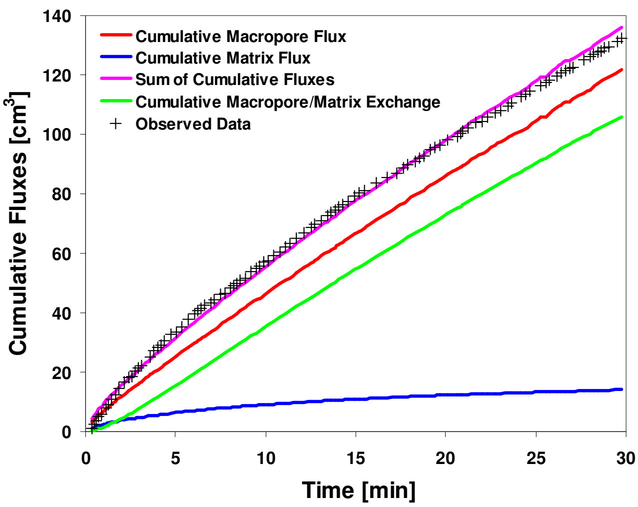

Figure 2. Measured and simulated (using the dual-permeability model) cumulative infiltrations for the Guelph permeameter test performed in the Ap1 horizon of Haplic Luvisol. Cumulative Macropore Flux = direct (from the infiltration well) cumulative infiltration into the macropore domain, Cumulative Matrix Flux = direct cumulative infiltration into the matrix domain, Sum of Cumulative Fluxes = Sum of direct cumulative fluxes, Cumulative Macropore/Matrix Exchange = cumulative infiltration from the macropore domain into the matrix domain.

Parameters characterizing the aggregate geometry (the shape factor for spherical aggregates β =15, the characteristic length of an aggregate a = 1.5 cm) and macropore domain fraction (f_w = 0.0277) were set based on the field ponding dye infiltration experiment and micromorphological study. The soil hydraulic parameters (θ_{rm} = 0 cm^{3}cm^{-3}, θ_{sm} = 0.428 cm^{3}cm^{-3}, α_m = 0.0124 cm^{-1}, n_m = 2.001, K_{sm} = 1.25 10^{-4} cm min^{-1}) obtained for the single-porosity model in HYDRUS 2/3D using the tension disc infiltrometer data were assumed to characterize the matrix domain. The parameters characterizing water retention in the macropore domain (θ_{rf} = 0 cm^{3}cm^{-3}, θ_{sf} = 0.428 cm^{3}cm^{-3}, α_f = 0.1 cm^{-1}, n_f = 3) were either equal to the parameters in the matrix domain or set to average values (characteristic macropore soil water retention curve shape parameters published in the literature). The saturated hydraulic conductivity (K_{sf} = 0.182 cm min^{-1}) was optimized together with the effective saturated hydraulic conductivity of the interface between the macropore and matrix domains (K_{sa}= 5.3 10^{-5} cm min^{-1}).

Conclusion
Information about the fraction of the macropores existing in studied soils and information about the shape and size of the aggregates, biopores and soil fractures were further used to describe the dual-domain geometry in the dual-permeability model, which was applied to simulate preferential flow in these soils.

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