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Characterizing soil preferential flow using iodine–starch staining experiments and the active region model

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SUMMARY

Preferential flow in the unsaturated soil is an important and common phenomenon, which is difficult to characterize. The major objective of this study was to analyze preferential flow distributions using visualized soil water flow patterns and the active region model (ARM), which has been developed recently. Thirteen infiltration experiments were conducted in the field, including different soils, various initial and boundary conditions controlling the infiltration processes, and measurement sizes. An iodine–starch staining method was applied to visualize flow paths in the soils. Distributions of stained coverage and soil water saturation within the stained region (the active region) were used to determine the key parameter (γ) of the ARM. Results showed that the ARM was able to capture the major features of the observed flow patterns under different infiltration conditions. Low initial soil water contents resulted in more heterogeneous flow distributions, corresponding to larger γ values. The applied amount of infiltrating water affected the flow heterogeneity more complexly. A small amount of infiltrating water resulted in a relatively homogeneous flow pattern. As the infiltration amount increased, the flow patterns became more heterogeneous. With increasing infiltration amount to a certain point, the flow distributions became less heterogeneous and finally relatively homogeneous. Corresponding to the flow pattern changes, γ values of the ARM increased first and then decreased with increasing applied water amount within a relatively narrow range. The relatively small changes of γ values within the measurement sizes seemed to indicate that the soil flow heterogeneity was independent of the measurement scales within a certain range.

Introduction

Because of soil spatial variability and flow instability, it is challenging to characterize flow patterns in unsaturated soils. Preferential flow is one important and common phenomenon in unsaturated soils (Doughty, 1999; Hagedorn and Bundt, 2002; Simunek et al., 2003) and fractured media (Su et al., 2001; Zou et al., 2003), which is difficult to capture. Even for homogeneous soils, attributed to high non-linearity of unsaturated flow processes, an infiltration front can become unstable and split into fingers, resulting in preferential flow (Glass et al., 1988; Liu et al., 1998; Pruess et al., 1999; de Rooij, 2000).

A variety of modeling approaches have been developed to describe preferential flow in the soil. These are mainly continuum and discrete approaches (Liu et al., 2003, 2005). Simunek et al. (2003) reviewed several commonly used continuum-based models, from single-porosity models to more complex dual-porosity, dual-permeability, and multi-region type models. Though the continuum approaches are relatively simple and straightforward to implement, they are incapable of characterizing preferential flow paths caused by fingering and the spatial variability of soil properties (Liu et al., 2005). On the contrary, the discrete approaches, such as the diffusion-limited aggregation model (Witten and Sander, 1981; Flury and Flühler, 1995; Persson et al., 2001) and the random cascade model (Olsson et al., 2002), have been successfully used to represent field observations of preferential flow. The success of discrete approaches in characterizing preferential flow mainly relies on their capability of generating fractal or multi-fractal patterns. However, the discrete approaches are limited to small-scale applications and the physical mechanisms underlying these approaches are still not totally clarified (Ewing and Berkowitz, 2001).

To properly characterize heterogeneous water flow processes in the soil and benefit from the combined advantages of the continuum and discrete approaches, Liu et al. (2005) incorporated the fractal theory with the traditional continuum approaches and developed the active region model (ARM). The ARM is an extension of the active fracture model (Liu et al., 1998, 2003). Similar to the dual-domain model (van Dam et al., 1996; Larsson et al., 1999), the ARM divides the whole flow region into an active (mobile) region and an inactive (immobile) region. Water flow occurs in the active region exclusively, allowing the inactive region to be simply

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bypassed. Different from the dual-domain model, in the ARM the active region is fractal and changeable, and the relative portion of the active region is expressed as a power function of the water saturation within the flow region. While some previous field studies (van Dam et al., 1990; Larsson et al., 1999; Öhrström et al., 2002) support the fractal theory, an in-depth evaluation on the ARM has not yet been conducted.

The random cascade model has been successfully used to describe preferential flow patterns in the field (Wang et al., 2006). Both the random cascade model and the ARM were developed based on the assumption of fractal distribution of preferential flow in the soil. Therefore, a comparison of the models with field experimental data should be useful for a better characterization of flow patterns in the soil, and in turn to reveal some intrinsic physical structures of the models.

To compare the ARM with field experimental data, it is essential to visualize the flow and non-flow regions. For flow path visualization, dye infiltration experiments have been utilized, commonly using food-grade dye pigment Brilliant Blue as the tracer (e.g., Yasuda et al., 2001; Morris and Mooney, 2004; Öhrström et al., 2004). Nevertheless, the dye is adsorbed by soils with high clay and organic carbon contents (Ketelsen and Meyer-Windel, 1999; Kasteel et al., 2002; Öhrström et al., 2004). Other factors, such as pH and calcium content, also affect the dye adsorption (Flury and Flühler, 1995). Iodine–starch staining is an alternative technique used to investigate flow pathways (van Ommen et al., 1988; Lu and Wu, 2003; Hangen et al., 2004; Bogner et al., 2007). In addition to the advantages of limited toxicity, distinct visibility, and similar transport properties to water (Flury and Flühler, 1994), high water solubility and anionic properties provide the iodide ion with high mobility and low adsorption, and make the iodide ion an ideal tracer, especially in heavy clay soils.

The major objective of this work is to characterize preferential flow in soils using observed soil water flow patterns from field experiments and the ARM. The study also tends to develop further insight into underlying relationships between flow patterns and the ARM parameter (γ). Specifically, we characterize preferential flow patterns in different soils with various initial and boundary conditions as well as measurement sizes, using iodine–starch staining experiments, and determine relationships between the ARM parameter (γ) and field test conditions. In addition, we also compare the ARM and the random cascade model with the field experimental data.

Methods and materials

Field experiments

Field experiments were conducted at two different field sites from June of 2006 to October of 2007 in Wuhan (30°37'N, 114°20'E), China. Before the experiment, Site I was used for vegetable production. The soil profile of Site I was relatively uniform without visual macropores and cracks. The top 40 cm of Site II was a mixture of soil and construction debris, which was removed before the experiment. At each site, undisturbed soil samples of 100 cm^3 were collected at the depth intervals of 0–10, 10–20, 20–50, and 50–100 cm to measure soil properties in the lab, including the soil texture, bulk density, porosity, and saturated hydraulic conductivity (Dane and Topp, 2002). Soil physical and hydraulic properties are summarized in Table 1. The residual soil water content was estimated from the soil texture and bulk density using RETC (van Genuchten et al., 1991). The calculated residual soil water contents were 0.07 and 0.12 $cm^3\ cm^{-3}$ for the loam (Site I) and silty clay (Site II) soils, respectively. The saturated water contents were assumed the same as their porosities.

An iodide indication solution was prepared with a concentration of 50 g L^{-1} (Lu and Wu, 2003). To make the iodide entirely oxidized (from I^- to I_2) under the atmospheric conditions, 40.40 g $Fe(NO_3)_3{\cdot}9H_2O$ was added to the starch solution.

Seven plots at the Site I and six plots at the Site II were set up for experiments. Infiltration conditions of the plots are listed in Table 2, including different soils (Site I: loam and Site II: silty clay), applied water depth (i.e., the initial ponding depths on the soil surface: 20, 40, 60, and 80 mm), and measurement sizes (i.e., the soil surface areas of inner frames: 100×100 cm^2, 100×200 cm^2, 100×400 cm^2). Within the three groups of Plots 1 and 2, 3 and 4, and 5 and 6, initial soil water contents were different in each group. The experimental design is schematically shown in Fig. 1a and b for Sites I and II, respectively. For the both sites, two rectangular frames were concentrically embedded into each plot (Fig. 1a). The outer frame was larger than the inner frame by 1 m in both length and width. The experimental design was similar to the double-ring infiltrometer (Ahuja et al., 1976; Yasuda et al., 2001). The water in the out frame was used to reduce the hydraulic gradient between the inner frame and the outside so that the lateral flow from the inner frame to the outside was restricted. Before infiltration, each plot was leveled to ensure a uniform surface condition. To avoid interference, the plots at the same site were placed at least 2 m apart from each other. The inner and outer areas were covered with plastic sheet. At the beginning of experiments, the inner areas were prepared by ponding a potassium iodide solution (20 g L^{-1}) on the top of the plastic sheet, with the outer border areas flooded with the same depth of fresh water. As the experiment started, the plastic sheet was removed immediately, creating an almost instantaneous ponding infiltration in both inner and border areas (Yasuda et al., 2001; Wang et al., 2006). Then the plots were covered to prevent evaporation and left for 12 h to complete the infiltration process.

After 12 h of infiltration, excavation of the plots was started. Because of difficulties to excavate horizontal layers in a soil with high

Table 1
Soil physical and hydraulic properties.

Site	Depth (cm)	Texture (%)			Bulk density ($g\ cm^{-3}$)	Porosity (%)	Saturated hydraulic conductivity ($cm\ s^{-1}$)
		>50 μm	2–50 μm	<2 μm			
I	0–10	29.4	49.2	21.4	1.38	38.8	3.4×10^{-4}
	10–20	28.2	49.4	22.4	1.40	40.2	1.2×10^{-4}
	20–50	31.3	46.2	22.5	1.44	40.6	1.1×10^{-4}
	50–100	32.1	44.8	23.1	1.45	44.4	1.1×10^{-4}
II	0–10	3.5	52.0	44.5	1.44	40.2	5.8×10^{-5}
	10–20	4.4	51.2	44.4	1.50	42.7	2.1×10^{-5}
	20–50	4.3	51.4	44.3	1.50	44.8	2.2×10^{-5}
	50–100	4.7	50.7	44.6	1.59	45.1	1.4×10^{-5}