Measurement and Modeling of Preferential Flow Under Controlled Conditions

B.P. Mohanty, P. Castiglione, P.J. Shouse, M. Th. van Genuchten

Abstract

Several conceptual models have been developed with different levels of complexity (e.g., equivalent continuum, dual porosity, and dual permeability approaches) to describe the macroscopic flow-transport process. However, no congruent conceptual model with a corroborating measurement technique is available to precisely describe this process. As gravity and/or capillary forces dominate the transport processes in the porous medium near saturation, various factors contribute to the initiation of macroscopic flow and its intensity, including pore geometry, distribution, and continuity. In addition to soil energy status, the nature of top and bottom boundary conditions and textural layering, play important roles. We quantified the effects of many of these factors on preferential flow and transport in a series of carefully controlled column experiments using novel designs. Existing dual permeability conceptual models will be tested with the new data sets, ultimately leading to the formulation of more realistic preferential flow models that contain physically-based and measurable parameters.

Keywords: Artificial macro pore, matrix flow, macropore flow, soil column, dual permeability model

Introduction

 Preferential flow can take several forms, most notably macropore flow [e.g., Mohanty et al., 1997, 1998] through biological channels (decayed roots, earthworm tunnels) in agricultural and forest soils. An important environmental implication of preferential flow is the accelerated movement of surface-applied fertilizers, pesticides, non-aqueous phase liquids, or other pollutants, into and through the unsaturated zone.

Conceptual Models for Water and Solute Transport in a Macroporous Medium

Process-based descriptions of preferential flow in structured media generally involve dual-porosity or dual-permeability type models. Such models typically assume that the medium consists of two interacting pore regions, one associated with the macro pore or fracture network, and one with the micropores inside soil aggregates or rock matrix blocks. Different formulations arise depending upon how water and solute movement in the micropore region are modeled, and how water and solutes between the micropore and macropore regions are allowed to interact. Early formulations in the soil science and hydrology literature generally assumed the presence of distinct mobile and immobile (non-moving) liquid flow regions. Several studies have extended these models to variably-saturated flow conditions. One such dual-permeability formulation was developed by Cerke & van Genuchten (1993, 1996) by assuming that the Richards equation for transient water flow and the advection-dispersion equation for solute transport can be applied to each of the two pore systems. The dual-permeability model contains two water retention functions, one for the matrix and one for the fracture pore system, but three hydraulic conductivities functions: \( K_{m}(h) \) for the fracture network, \( K_{f}(h) \) for the fracture, and \( K_{m}(h) \) for the matrix. Of these functions, \( K_{m}(h) \) is determined primarily by the structure of the fracture pore system, i.e., the size, geometry, continuity and wall roughness of the fractures, and possibly the presence of fracture fillings. Similarly, \( K_{f}(h) \) is determined by the hydraulic properties of single matrix blocks, and the degree of hydraulic contact between adjoining matrix blocks during unsaturated flow. Finally, \( K_{m}(h) \) is the effective hydraulic conductivity function for describing the exchange of water between the two pore systems. Estimates for the \( K_{f} \) and \( K_{m} \) functions may be obtained by assuming that \( K_{f} \) is primarily the conductivity function in the wet range, while \( K_{m} \) is the conductivity in the dry range [Peters & Klute, 1983; Durner, 1994].

Measurement of Flow and Transport in a Macroporous Medium

Although multidomain approaches are often based on a conceptual analysis of the underlying flow and transport processes, most available techniques for measuring soil hydraulic properties (conductivity and retention) can neither distinguish between the different flow domains and their relative contribution to flow (Luxmoore et al., 1990), nor

be used to determine the between-domain exchange terms during variably saturated flow, except perhaps when using some type of inverse procedure built upon many simplifying assumptions [Durner, 1994]. This limitation makes the conceptual models suspect as to their validity or applicability. Column studies have inherent bottlenecks in their design including wall flow effects, limited profile information in terms of soil properties and their dynamic retention/energy state, and boundary effects, whereas field studies usually show significant uncertainties over space and time that limit a true (repeatable) description of preferential flow.

Objective

Based on the above discussion and recognizing the enormous gap between conceptual modeling and experimental efforts, we propose to measure preferential flow and transport processes in a biporous soil system using improved experiments with better control, design, and rigor, followed by the testing of applicable conceptual models. Specific objectives include: (1) Design and construct repacked soil columns with different macropore/matrix domain configurations, precisely control top and bottom boundary conditions, and monitor domain-specific soil water conditions in terms of pressure head, water content, and resident chemical concentration. (2) Measure domain-specific (anidimensional) water flow and conservative chemical transport with different fractions of (open and buried) macroporosity under different initial and top/bottom boundary conditions. (3) Analyze the data in terms of equivalent continuum, dual-porosity, and dual-permeability type models, and develop new conceptual models as needed. In this paper we will focus on objectives 1 and 2 only.

Research Methods

Description of the Experimental Setup

The column consists of an acrylic cylinder, 22-cm internal diameter and 80-cm high. The setup is housed in a temperature and humidity controlled room. Important features of our experimental setup include: (1) using a graded and sieved non-swelling, non-shrinking, lean soil to create uniform particle size distributions of the repacked soil matrix, (2) maintaining a uniform bulk density across the column length by careful packing of the soil columns in layers, (3) creating 1-mm diameter 80-cm long uniformly distributed cylindrical macropores on half of the cross-section of the column (by carefully inserting hollow cylindrical stainless steel needles), thus producing two distinct flow transport regions, a matrix + macropore region and matrix-alone region, (4) preventing wall flow by passing this annular rings (2-3 mm thick) at different depths along the internal walls of the cylinder, thus forcing water to re-enter in the soil matrix, (5) controlling the pressure or flux at the top boundary by using a 21-cm diameter tension disc infiltrometer with contact used between the soil surface and the disc, (6) preventing the plugging of macropores due to caking of soil by using a cheese cloth on the soil surface, (7) minimizing erosion of the artificial macropores by applying a well-studied [Sorja and Lante, 1997] water-soluble polymer, polyanacrylamide (PAM), on the internal walls of the macropores with minimal alteration of its hydraulic and transport properties, (8) stabilizing macropore spaces inside soil matrix by applying a recommended dose of CaCl₂ solution, (9) controlling the gradient at the bottom boundary by using six detachable high-flow ceramic plates and/or stainless steel meshes with further provisions for glass-fiber wick sampler connections, (10) establishing good contact between soil and the bottom boundary by using high conductive diasom earthing material, (11) installing two sets of six (half-cross of the section, 10-cm long) TDR probes horizontally at 10 cm depth increments to monitor soil water and chemical concentration on the two flow transport regions (matrix+macropore, matrix-alone) of the column, (12) installing thirteen thin-walled pencil tensiometers with pressure transducers at 5-cm depth increments to monitor the profile soil water pressure head for the two regions concurrently, (13) preventing any mixing of outflow among flow transport zones containing different amount of macroporosity by placing 10-cm high stainless steel flow separators at the bottom creating six pre-chambers, (14) preventing air entrainment by locating peripheral air blinding valves at 40 and 70 cm depths, (15) monitoring outflow for the six chambers using an automated system, that includes separate fraction collectors for the miscible displacement experiment, and (16) multiplexing all instruments and recording the data at high resolution using data loggers and computer.

Results

Sample Experimental Findings:

Initially we conducted experiments to study the soil matrix properties of our repacked column. Macropores were

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Figure 1. Measured inflow, outflow, and soil water contents in the "macropore" and "no macropore" regions of the soil column for experiments 1 (left, open macropores) and 2 (right, buried macropores). Subsequently designed and created on half of the cross-section of the column. Next, several experiments were conducted under different initial and boundary conditions as well as with "open" and "buried" macropores. Some important findings from two of these prototype transient flow-transport experiments will be discussed here.

Experiment 1: This experiment was conducted with dry initial conditions. A zero tension was applied at the top boundary with the disc infiltrometer, and gravity drainage was allowed at the bottom boundary. Macropores were open at the soil surface.

Experiment 2: The same initial and top/bottom boundary conditions were used as for Experiment 1, but the macropores were now plugged to 1 cm depth from the soil surface. Figures 1 and 2 show soil water content and resident chloride concentrations versus depth and time for the two halves of the column (matrix + macropore ("macropore") region vs. matrix-alone ("no-macropore") region) for both experiments. Inflow and outflow across the top and bottom boundaries are also shown. Data indicate several interesting features: (1) differential rates of flow for "macropore" and "no-macropore" regions, (2) more time was necessary for preferential outflow to initiate from buried macropores condition as compared to the open macropores, (3) for the open macropore experiment 1, near surface (depth = 5 cm) soil water retention of the "no-macropore" region was higher than that of "macropore" region, indicating faster advective flow in the macropore region, (4) initially with depth, higher soil water contents were observed in the "macropore" region as compared to "no-macropore" region indicates higher flow in the "macropore" region, and (5) with time, diffusive transfer of water between the two regions established a trend of higher soil water contents in the capillary-dominated "no-macropore" region as compared to the gravity-dominated "macropore" region, and (6) for the buried macropore experiment 2, "macropore" and "no-macropore" regions showed no differences in the soil water content at early
times, and gradually established a similar pattern as observed in the open macropore experiment 1. Concurrently measured resident chloride concentration versus depth and time followed preferential flow pattern, thus reflecting differential transport for the two regions. Other characteristics features of the bimodal transport are clearly visible in these plots. A thorough mathematical analysis of these findings is needed to obtain insight into the mechanics of flow and transport processes under non-equilibrium conditions. This will strengthen our fundamental understanding and will provide a physical basis for modeling the preferential flow.

References


Figure 2: Measured resident chloride in the "macropores" and "no macropores" regions of the soil during the Experiment 2 (buried macropores).