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Review

Quantifying preferential flow in soils: A review of different techniques

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SUMMARY

Preferential flow (PF) in soil has both environmental and human health implications since it favours contaminant transport to groundwater without interaction with the chemically and biologically reactive upper layer of soil. PF is, however, difficult to measure and quantify. This paper reviews laboratory and field techniques, such as breakthrough curves, dye tracing, and scanning techniques, for evaluating PF in soil at different scales. Advanced technologies, such as scanning techniques, have increased our capability to quantify transport processes within the soil with minimal soil disturbance. Important issues with respect to quantifying PF concern large-scale studies, frozen soil conditions, tracing techniques for particles and gases, a lack of simple mathematical tools for interpreting field data, and the lack of a systematic approach for comparing PF data resulting from different measurement techniques. Also, more research is required to quantify the relative importance of the various PF processes that occur in soil rather than the integrated result of all PF processes in soils.

Contents

Abbreviations: BTC, Breakthrough curve; FF, Finger flow; LF, Lateral flow; MF, Macropore flow; PF, Preferential flow.

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Introduction

Soil heterogeneity is responsible for the difficulty in predicting the movement of mass (solids, liquids and gases) in field situations at most scales. For example, it often results in faster movement of gas, water, solutes and particles than would be expected from the soil matrix properties (De Rooij, 2000; Lin and Zhou, 2008; Jamieson et al., 2002). This more rapid mass transport is associated with processes such as flow through earthworm burrows, cracks in soil, or flow associated with soil layering and hydrophobicity. These processes, together, are called preferential flow (PF).

There have been several studies of PF in soils during the last 30 years (Clothier et al., 2008; Flury et al., 1994). As a result, PF is now routinely included in models that predict water, solute, and particle transport in soils (Simunek et al., 2003). For reliable model prediction, characterizing PF is critical. This requires sampling and a method of measurement designed to avoid artefacts and bias. The characterization of the effectiveness, interaction, size, continuity, tortuosity, branching, number, and area of pores with respect to the importance of PF and the associated mass transport is difficult. Consequently, a wide selection of methods exists to evaluate PF depending upon the questions to be answered, available equipment and instrumentation, scale of interest, desired precision, and whether integrated PF or a specific type of PF is to measured.

This paper presents a review on various laboratory and field methods for assessing and quantifying PF in soil at different scales. It is intended for those who carry out field studies, manage the land, and need to choose a method to estimate PF for their research or for monitoring. It does not investigate the importance of PF for contaminant transport under various climate, soil, and agricultural conditions or discuss modeling approaches. These aspects have been covered in the review papers listed above.

Definitions

Preferential flow (PF): Refers to flow mechanisms where transport of water together with dissolved or suspended matter is primarily associated with a smaller fraction of the total pore network, at any scale much larger than the microscopic (μm) scale. PF may accelerate or delay the movement of matter depending upon the position of the matter compared to the position of PF paths. Four types of preferential flow are considered: crack flow (CF), burrow flow (BF), finger flow (FF), and lateral flow (LF).

Crack flow: Refers to PF along continuous cracks through an unsaturated soil profile (Blake et al., 1973). Cracking occurs during drying of certain duration in soils with significant clay content (Hendrickx and Flury, 2001).

Burrow flow: Refers to flow through channels created by soil fauna when runoff occurs (Zehe and Flühler, 2001).

Finger flow: Occurs when infiltrating water accumulates at the interface between two soil layers, usually in sandy soils, with a coarser layer underlying a finer layer (Starr et al., 1978). The water breaks into the subjacent layer through fingers (preferential flow paths) rather than uniformly through the entire layer (Rezanezhad et al., 2006).

Lateral flow: Occurs when infiltrating water moves laterally and locally along an inclined hydraulically restrictive layer such as along bedrock (McDonnell, 1990) or along lateral roots (Weiler and McDonnell, 2007).

Macropores: Refer to opening features larger than the microscopic scale in the soil that may cause non-equilibrium of mass movement. There is no accepted definition that characterizes a given soil pore as a macropore. Various authors have given diameter limits to define what they consider macropores and non-macropores (Beven and Germann, 1982; Chen and Wagenet, 1992; Jarvis et al., 1999). Common to all definitions of macropores is that their diameter is orders of magnitude larger than that of soil matrix textural pores (Greco, 2002).

Macroporosity: Refers to the percentage of soil volume occupied by macropores.

Macropore flow (MF): Refers to the mass movement through macropores, leading to non-equilibrium with the soil matrix. CF and BF together form macropore flow (MF).

Breakthrough curve (BTC): Describes the variation in solute concentration over time in leachate or in tile-drain effluent. The BTC of a given solute or particle type in a given soil under specific conditions is usually unique. BTCs are more readily compared when normalized. Solute or particle concentration is usually normalized by dividing the measured concentration with the applied concentration such that the concentration values are always between 0 and 1.0 (unitless). Time is normalized by calculating the pore volume ($T = vt/L$, unitless) which is the product of the velocity of water (v, m s^{-1}) and the time (t, s) divided by the length of the profile (L, m) or the distance of interest.

Considerations prior to choosing a technique

Studying mass flow in soil with an emphasis on PF requires careful planning with respect to equipment, instrumentation and technical expertise. The hypothesis, objectives and budget will, in part, dictate the sites and the scale at which PF will be measured.

Temporal and spatial scales of a study are determined by the hypotheses and processes of interest. A large variety of hypotheses associated with PF have been studied at microscale (e.g., difference in pore size that can trigger FF) to watershed scale (e.g., relationships between vertical and lateral flow processes), and to determine conditions required for PF to occur (i.e. initial soil moisture), for studying specific or bulk impacts of the PF processes (increased contaminant concentration in tile drain), and the short