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ScienceDirect
Catena 73 (2008) 204–211
CATENA
www.elsevier.com/locate/catena

A morphological approach to understanding preferential flow using image analysis with dye tracers and X-ray Computed Tomography

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Received 14 December 2006; received in revised form 28 August 2007; accepted 11 September 2007

Abstract

A key problem facing soil physics and hydropedology at present is some of the standard theories of water flow in soils do not fully reflect the processes at the pore scale, and thus, cannot be adequately used for prediction. As such, examination of soil structure is vital for hydropedologists. Realisation that solutes move preferentially through soil into groundwaters has meant research in this area has increased in importance. This paper describes a multi-scale approach to analyse transport mechanisms using visualisation techniques. Chloride and Brilliant Blue tracers were applied to undisturbed soil cores to examine the physical and morphological properties associated with preferential flow in a range of soil types. Following collection of serial digital images, it was possible to examine and quantify the nature of active water flow mechanisms in terms of both dye-stained pathways and spatial distribution of dye concentration, using image analysis. Preferential flow linked to water potential and soil structural discontinuity was observed in all but the coarsest textured soil which conformed to uniform flow theory. A high level of variability in flow patterns was noted between the soil types. Such information as to how a soil dynamically re-wets is key for hydropedologists involved in applications such as pollution modelling. This is especially significant when considering a wetting mechanism, such as preferential flow, that cannot be adequately described by conventional soil physics.

Keywords: Preferential flow; Image analysis; Dye tracer; Macropores; Solute transport; X-ray Computed Tomography

1. Introduction

There is little doubt that a combined hydropedological approach is especially suited to the examination of flow mechanisms in soils. Understanding the complex processes governing transfer of water and solutes in soil is key to solving problems of water quality. It is widely recognized flow processes in soils are strongly determined by soil structure (Vogel et al., 2005). This is unsurprising given the structure of soil is the three-dimensional (3-D) dynamic, heterogeneous framework in which and through which all soil processes occur (Young and Crawford, 2004). Therefore a key aspect of any hydropedology investigation is the examination of soil properties as they occur in the field.

Prediction of preferential flow pathways and their interactions with the soil matrix has been identified as a key area where synergies between pedology and hydrology are urgently needed (Lin et al., 2006). Preferential flow has been observed as rapid by-pass pathways in a range of soils (Bouma and De Laat, 1981). Rapid transport processes reduce solute residence time, and thus the time available for chemical degradation within the soil, and increase the risk of agrochemical pollution. Conventional physical flow theory has difficulties in accounting for preferential flow; flow is either saturated or unsaturated and the soil matrix regarded as both homogeneous and isotropic (Bouma, 2006). Considerable research over the past four decades has focused on examining mechanisms of solute transport and in particular, flow through macropores (e.g. Beven and Germann, 1982). Mechanisms of preferential flow have been studied in a range of soils both in the field (Droogers et al., 1998; Forrer et al., 2000) and under laboratory conditions (Aeby et al., 1997). Flury et al. (1994) found preferential flow was the rule, rather than the exception, in the soils examined and subsequent studies have shown as little as c. 1–10% of pore space may be utilised during soil water flow (e.g. Bouma and De Laat, 1981). As such it is vital non-equilibrium flow models are developed and parameterised accurately, preferably

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0341-8162/$ - see front matter.
doi:10.1016/j.catena.2007.09.003

with data that accounts for structural heterogeneity. Dual or multi-domain models have been widely used for modelling water flow in heterogeneous soils (see Feyen et al., 1998). Models such as MACRO (Jarvis, 1995) account for macropore and micropore flow, whereas multiple permeability models, such as Hutson and Wagenet (1995), describe a multi-region water flow that considers overlapping regions. Information concerning multi-scale porous architecture and its effect on soil function are urgently required to support such approaches.

Bouma et al. (1977) were among the first to use dyes to visualise flow patterns in field soils. Recent research has focused on the use of Brilliant Blue FCF as it provides the best combination of mobility, high visibility and low toxicity (Flury et al., 1994). Tracers allow flow patterns to be both visualised and quantified at different scales of observation. Their use has an advantage over traditional methods in allowing a distinction between areas of soil that participate in solute flow and those that do not (Droogers et al., 1998). When used in conjunction with image analysis, dye tracing is a powerful tool for characterising the interactions between morphological observations and physical processes in soil. At the field scale, image analysis techniques have been used both to visualise stained pathways and obtain a semi-quantitative description of flow patterns by determining concentrations of dye in stained soil (Aeby et al., 1997). Until recently, most studies of this type have been conducted at the centimetre scale and on a limited number of images (Forrer et al., 2000). However, it is necessary to examine flow at the pore scale in order to derive an improved understanding of solute flow, especially as we seek to identify so called 'triggers' or initiation mechanisms of preferential flow.

Non-destructive imaging, such as X-ray Computed Tomography (CT), provides excellent opportunities to examine soil physical behaviour particularly in terms of characterising flow paths and residence times in soils (Wilding and Lin, 2006). X-ray CT can be used to create 3-D visualisations derived from 2-D attenuation scans. For the last decade, significant advances have been made in the quantification of 3-D soil structure (e.g. Vogel and Roth, 1998; Zhang et al., 2005). However, this research has often focused on theoretical considerations rather than addressing experimental issues which can, in part, be attributed to difficulties with access, resolution and costs. Even so, great potential has been demonstrated e.g. Perret et al. (1999) found 80% of a macropore network could be comprised of one independent macropore path. A concerted effort is urgently needed to quantify multi-scale soil porous architecture in a manner such that the data can be incorporated into models of flow and transport (Lin et al. 2006).

The aims of this study were to examine flow pathways in undisturbed soils at the column scale using image analysis of dye tracer patterns and to use quantified data from flow patterns and soil macroporosity to elucidate the underlying flow mechanisms at the macropore scale.

2. Materials and methods

2.1. Soil collection and tracer analysis

Soil samples were obtained from the University of Nottingham's experimental farms at Sutton Bonnington and Bunny (U.K.) from four contrasting textural groups; Newport series, a light sand, (brown soil), Dunnington Heath series, a sandy loam (Stagno Gleyic Luvisol), Fladbury series, a clay loam (Pelo-alluvial gley soil) and Worcester series, a heavy clay (argillic pelosol). Intact (length 170 mm, diameter 70 mm) cores were collected in the field for the measurement of saturated hydraulic conductivity. Selected physical properties for the soil types examined are listed in Table 1. Replicated (×3) intact soil blocks (200×200×200 mm) were collected following methods similar to those described by Quisenberry et al. (1994). The soils were sampled four to eight weeks after sowing with wheat, with the exception of the Worcester series which was under grass. As each soil had recently been used for arable agriculture no horizon differentiation was possible within the sampled volume due to ploughing. Aggregates were typically classified as angular blocky although some prismatic aggregates and massive areas were identified in the Fladbury series. Pedestals of soil were carved from the surface to a depth of c. 250 mm and a wooden box placed over the soil. The sides of the box were injected with polyurethane foam and left overnight to cure. After 24 h, soil columns were carefully removed and transported to the laboratory. Columns were placed under a rainfall simulator and leached with 0.01 M $Ca(NO_3)_2$ at a rate of 280 ml h^{-1} (7 mm h^{-1}), maintained throughout all experiments. An equilibrium between inflow and outflow was reached in all soils. Volumetric water content at three depths (50, 130 and 210 mm) was recorded throughout the wetting and tracer experiment, by three rod 200 mm TDR probes (4.8 mm diameter and 45 mm spaced) installed horizontally within soil columns (TDR100 Reflectometer, Campbell Scientific Inc.). Chloride breakthrough measurements were obtained by adding an additional 80 ml (2 mm) pulse of 0.1 M $CaCl_2$ and collecting the solute using a fraction collector. Samples were taken over a 24 h period, resulting in 200 samples per column. Chloride concentration was determined by automated colorimetry. Brilliant Blue dye was applied to intact soil columns using a peristaltic pump. The flow was maintained through 30 tubes equally distributed over the soil surface, at the same rate of 7 mm h^{-1}. The dye solution was applied at a concentration of 3 g l^{-1} and leached for 2 h (560 ml) to enable the dye to provide sufficient coverage for analysis. Complete dye breakthrough was not achieved in any of the soils. Hydrophobicity was measured in each soil type using the water drop penetration time (WDPT) method (Dekker and Ritsema, 1994).

Table 1
Selected soil physical properties for the studied soils

Soil series	% sand	% silt	% clay	Bulk density (g cm^{-3})	[a]Organic matter (%)	Saturated volumetric water content (cm^3 cm^{-3})	Saturated hydraulic conductivity (cm s^{-1})
Newport	78.7	9.4	11.9	1.49	2.26	0.44	3.69×10^{-3}
Dunnington Heath	66.4	18.0	15.6	1.56	4.53	0.44	1.86×10^{-3}
Worcester	31.1	34.5	34.4	1.40	5.49	0.52	6.31×10^{-5}
Fladbury	9.0	30.9	60.1	1.12	5.79	0.65	6.85×10^{-5}

[a] Measured by loss on ignition.