Available online at www.sciencedirect.com
SCIENCE @ DIRECT®

Journal of Hydrology 300 (2005) 1–19

Journal of Hydrology
www.elsevier.com/locate/jhydrol

Transport of conservative and reactive tracers through a naturally structured upland podzol field lysimeter

M.I. Stutter[a,e,*], L.K. Deeks[b,d], M.F. Billett[c,e]

[a]*The Macaulay Institute, Craigiebuckler, Aberdeen AB15 8QH, UK*
[b]*National Soil Resources Institute, Cranfield University, North Wyke, Devon EX20 2SB, UK*
[c]*Centre for Ecology and Hydrology, Bush Estate, Penicuik, Midlothian EH26 0QB, UK*
[d]*Soil-Plant Dynamics Unit, Scottish Crop Research Institute, Dundee DD2 5DA, UK*
[e]*School of Biological Sciences, University of Aberdeen AB24 3UU, UK*

Received 16 July 2003; revised 20 April 2004; accepted 26 April 2004

Abstract

Compared to agricultural soils, descriptions of solute transport in upland soils at scales smaller than catchments are scarce. This study evaluates data from three consecutive field tracer experiments in which Cl, Na and Ca (stepped rates of 4.5, 9 and 4.5 mm h^{-1}) were irrigated onto a ferric podzol monolith (3×2 m^2 and 0.6 m depth) isolated from the surrounding soil except at the base. For each individual experiment a one hour pulse of tracer was applied and subsequently washed through with water for approximately 1 pore volume and monitored using suction cup samplers located in the O and B horizons.

Breakthrough curves showed considerable heterogeneity in the response of both horizons and inferred that downward leaching would result in considerable temporal spreading of solute mass across wide time scales. Patterns of Cl and Na breakthrough were similar and were characterised by low peak concentrations (maximum C/C_0 of 0.05 Cl and 0.03 Na). Minimal Ca breakthrough was observed in the O horizon, although a higher breakthrough was observed in the B horizon. These factors suggest that isolated highly active pathways were controlling the O horizon response, although these were not captured by the sampler network. This was supported by more rapid mean times to peak in the B horizon. Lateral drainage, intercepted at the base of the O horizon on the downslope face, accounted for approximately 45% of solute volume and 25, 21 and 14% of Cl, Na and Ca tracer mass, respectively. This rapid drainage pathway comprised surface flow and flow along the organic mineral interface, likely fed from preferential flow pathways in the O horizon. The breakthroughs observed in the mineral soil, although heterogeneous, indicated a response for this horizon of sustained leaching to shallow ground waters.

Keywords: Solute transport; Breakthrough; Tracer; Preferential flow; Temporal; Spatial heterogeneity; Lysimeter; Podzol; Organic horizon

1. Introduction

The mechanisms that control the transport of solutes through soils into streamwaters and groundwaters are poorly understood. Descriptions of the impacts of soil physical structure on transport of water

* Corresponding author. The Macaulay Institute, Craigiebuckler, Aberdeen. AB15 8QH, UK. Tel.: +44-1224-498200; fax: +44-1224-311556.
E-mail address: m.stutter@macaulay.ac.uk (M.I. Stutter).

0022-1694/$ - see front matter
doi:10.1016/j.jhydrol.2004.04.026

and solutes and of surface chemistry on exchange interactions have been made, but are often confined to laboratory investigations. Studies of undisturbed soils at a scale encompassing field heterogeneity are rare. The runoff of fertilisers and pesticides applied to agricultural catchments has directed much of the research to managed systems (e.g. Bergstrom, 1990; Jury and Fluhler, 1992; Kumke et al., 2002). Comparably less is known about solute transport through unmanaged upland soils, despite their importance in the UK and their role in controlling river water quality in headwaters. Upland systems are chemically and hydrologically distinct from those of the lowlands, being characteristically steeper sloping, more organic-rich and with higher annual precipitation.

Translating data from repacked laboratory soil columns experiments to field soils may be misleading since such homogeneous soils are rarely encountered. The role of natural structural heterogeneity has recently been studied through the use of lysimeters and cores incorporating undisturbed soil (e.g. Bowman et al., 1994; Schoen et al., 1999; Bejat et al., 2000; de Rooij and Stagnitti, 2000; Strock et al., 2001). Studies have shown that a component of flow may move rapidly through discrete pathways termed ‘preferential flow’ (Luxmoore, 1981) attributed to soil structural, textural and hydraulic heterogeneities (e.g. Kung, 1990; Webb and Anderson, 1996), desiccation cracks, root channels and faunal burrows. The rapid movement of preferentially mobile water limits equilibration times of solutes at soil surfaces, thereby controlling the influence of soil chemistry on percolating solutions. Observations of high mobilities of reactive chemicals have been attributed to bypass flow in macroporous systems (Jury et al., 1986; Kladivko et al., 1991; Kung et al., 2000). Such transport contrasts with the slower, tortuous passage of solutes moving through the pore network of the bulk soil matrix, affected by processes such as diffusion, dispersion and ion exchange.

In comparison to managed agricultural soils, upland soils may be expected to retain more complex structural variability since features are not destroyed by cultivation. In addition, upland soils are commonly horizonated with organic-rich surface horizons. Since preferential flow provides a means of by-passing the buffering capacity of the soil system, their occurrence in organic soils will largely decide the fate and transport of many reactive chemicals from the atmosphere to surface waters. Variations in the infiltration capacity of surface peats will control the catchment hydrograph response to storm and baseflow conditions (Holden and Burt, 2002), with associated effects on the chemistry of waters entering streams.

As well as presenting the range of complimentary techniques that we employed in our approach, the principal objectives of this paper were (i) to provide a high resolution description of the spatial and temporal heterogeneity of breakthrough of surface applied solutes for an upland soil, (ii) to contrast the passage of reactive cation components of successive tracer applications with an unreactive accompanying anion, and (iii) to assess the role of the organic surface horizon in mediating water and solute interactions with the mineral subsoil. It was beyond the scope of the present study to apply modelling approaches to the data and we concentrate here on providing a full picture of the complexities of flow and interactions within the soil. The study therefore has implications for the incorporation of soil heterogeneity into modelling and the theoretical understanding of transport in upland ecosystems.

2. Methods

2.1. Study site and lysimeter design

The monolith (56° 55′N, 3° 0′W) was located within the Allt Roy catchment, a small nutrient-poor headwater of the River Dee, NE Scotland (Fig. 1). The catchment geology comprises pink granite (Fungle group, Mount Battock series) and the soils have formed over shallow, gritty drift material. The vegetation is dominated by mature *Calluna vulgaris* and the site has a mean annual precipitation and temperature of 1070 mm and 7 °C, respectively.

An undisturbed soil block ($2.4 \times 3.4\ m^2$ and ~ 0.6 m depth) was isolated on a gently sloping (6°), east-facing site (altitude 410 m), with its long axis parallel to the slope. The soil, a well-drained ferric podzol (FAO system), comprised an organic (O) surface horizon (0–0.25 m), a thin A horizon with slight illuviation (typically 0.25–0.30 m) and a slightly indurated Bs horizon (5YR5/8) extending to the base of