Journal of Hydrology 525 (2015) 536–546

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Modelling susceptibility of grassland soil to macropore flow

Abdallah Alaoui

Centre for Development and Environment (CDE), University of Bern, Hallerstrasse 10, 2012 Bern, Switzerland

ARTICLE INFO

Article history:
Received 1 February 2015
Received in revised form 7 April 2015
Accepted 11 April 2015
Available online 18 April 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Venkat Lakshmi, Associate Editor

Keywords:
Macropore flow
Dual-permeability modelling
Natural grassland
Well protection zones
Contaminant transport
Topsoil density

SUMMARY

Investigating preferential flow, including macropore flow, is crucial to predicting and preventing point sources of contamination in soil, for example in the vicinity of pumping wells. With a view to advancing groundwater protection, this study aimed (i) to quantify the strength of macropore flow in four representative natural grassland soils on the Swiss plateau, and (ii) to define the parameters that significantly control macropore flow in grassland soil. For each soil type we selected three measurement points on which three successive irrigation experiments were carried out, resulting in a total of 36 irrigations. The strength of macropore flow, parameterized as the cumulated water volume flowing from macropores at a depth of 1 m in response to an irrigation of 60 mm h^{-1} intensity and 1 h duration, was simulated using the dual-permeability MACRO model. The model calibration was based on the key soil parameters and fine measurements of water content at different depths. Modelling results indicate high performance of macropore flow in all investigated soil types except in gleysols. The volume of water that flowed from macropores and was hence expected to reach groundwater varied between 81% and 94% in brown soils, 59% and 67% in para-brown soils, 43% and 56% in acid brown soils, and 22% and 35% in gleysols. These results show that spreading pesticides and herbicides in pumping well protection zones poses a high risk of contamination and must be strictly prohibited. We also found that organic carbon content was not correlated with the strength of macropore flow, probably due to its very weak variation in our study, while saturated water content showed a negative correlation with macropore flow. The correlation between saturated hydraulic conductivity (K_s) and macropore flow was negative as well, but weak. Macropore flow appears to be controlled by the interaction between the bulk density of the uppermost topsoil layer (0–0.10 m) and the macroporosity of the soil below. This interaction also affects the variations in K_s and saturated water content. Further investigations are needed to better understand the combined effect of all these processes including the exchange between micropore and macropore domains.

1. Introduction

Experimental evidence has shown that preferential flow of infiltrating water through macropores may bypass most of the soil matrix (e.g., Beven and Germann, 1982), limiting the storage, filter, and buffer functions of soils (e.g., Clothier et al., 2008). Macropore flow is a subset of preferential flow that occurs in earthworm burrows, continuous root channels, fissures, or cracks in structured soil (e.g., Gerke, 2006; Hendrickx and Flury, 2001). Its initiation during infiltration depends on the initial matrix water content, the intensity and amount of rainfall, matrix conductivity, and the contributing area at the soil surface (e.g., Jarvis, 2007; Köhne et al., 2009a,b). Macropore flow is a widespread phenomenon known to strongly affect solute transport. It can be predicted to a certain extent from soil properties (e.g., texture, organic matter) and site attributes (e.g., land use and management, topography and vegetation) (Koestel et al., 2012; Ghafoor et al., 2013; Koestel and Jorda, 2014). However, little attention has been paid so far to the direct influence of soil hydraulic properties on macropore flow (Allaire et al., 2011; Dadfar et al., 2010; McLeod et al., 2008). Soil hydraulic and transport properties cannot be expected to produce accurate predictions at all scales, as they are in most cases spatially variable and involve nonlinear processes (Beven, 1995). In order to establish a link between soil hydraulic parameters and the soil's response to a given rainfall, it is advisable to directly consider the hydrodynamic functionality of soil macropores in conducting water and air, rather than dwelling on soil structure morphology (Alaoui and Goetz, 2008; Alaoui and Helbling, 2006; Larsbo et al., 2014).

Macropore flow in grassland soils can greatly accelerate transport of a range of contaminations to the groundwater, with serious consequences for groundwater quality. This follows from sensitivity analyses showing that in order to estimate local groundwater recharge in grassland it is sufficient to examine the topsoil to a

E-mail address: abdallah.alaoui@cde.unibe.ch

http://dx.doi.org/10.1016/j.jhydrol.2015.04.016
0022-1694/

depth of 0.70 m; the reason for this is that the roots of grassland vegetation typically do not reach any deeper and hence water stored in the subsoil is not available for evapotranspiration (Alaoui and Eugster, 2004). This potential for accelerating groundwater contamination makes macropore flow in grassland soils particularly worthy of investigation: An improved understanding of the susceptibility of different soil types to macropore flow would be helpful in assessing and managing risks of groundwater contamination at larger scales (e.g., catchment and landscape scale). In Switzerland, pumping wells are surrounded by three protection zones: (i) a zone immediately surrounding the pumping well, referred to in German as "S1", to prevent rapid and direct ingress of contaminants; (ii) a zone whose outer boundary is defined according to a minimum flow duration of ten days from a point source to the pumping well, referred to as "S2"; and (iii) a zone which is delineated based on hydrological boundary conditions, referred to as "S3" (FOEN, 2012).

Although several studies have been dedicated to the methodology of delineating these protection zones (e.g., Bussard et al., 2005), the methods currently in use do not differentiate between travel time in the unsaturated zone and in the saturated zone. This differentiation is crucial, however, as the vertical flow rate can greatly affect total travel time from a point source to the pumping well. Moreover, there have been no investigations so far into the susceptibility of soils in protection zones to preferential flow that enables rapid transport of pollutants to the groundwater; nor have the different soil types composing these zones been systematically compared in terms of their susceptibility to preferential flow (e.g., Jiménez-Madrid et al., 2012).

Accordingly, this paper has two main aims. The first is to assess the susceptibility of four representative grassland soils – the most widespread on the Swiss plateau – to rapid contaminant transport. The second aim is to quantitatively define the relevant parameters controlling macropore flow in grassland soils, with a view to enabling prediction and management of contamination near the well. This may relate, for example, to the spreading of pesticides or herbicides in agricultural zones near pumping wells. In order to define the parameters, water flowing from macropores in response to irrigation experiments was simulated using the dual-permeability MACRO model (Stenemo and Jarvis, 2010). The total water volume flowing from macropores in response to 1 h of irrigation with 60 mm h^{-1} intensity at a depth of 1 m is used as an indicator of the strength of macropore flow. To enable meaningful comparative analyses of different soil types, we considered only natural grassland soils – that is, soils in natural (non-trafficked) grassland – thus excluding any effects of land management and cropping on soil structure. We believe that the values obtained under these specific conditions may be comparable to those for other land uses and land covers, which may exhibit greater or at least similar susceptibility to macropore flow. A shallow water table in some cases may accentuate this susceptibility.

2. Material and methods

2.1. Soil description

This study investigated macropore flow in four soil types at a total of twelve measurement points. According to local nomenclature and with World Reference Base for Soil Resources (WRB, 2014) classification names indicated in brackets, the four soil types investigated are: brown soils (cambisol hypereutric), para-brown soils (cambisol luvic), acid brown soils (cambisol dystric), and gleysols (eutric gleysol and cambic gleysol). These are the most widespread soil types on the Swiss plateau, which is Switzerland's main agricultural area. The selected gleysols were located on hill slopes where the water table was measured at a depth of about 0.90 m. Basic soil parameters are given in Table 1.

2.2. Irrigation experiments

Irrigation was supplied at each measurement point by a rainfall simulator. This consisted of a metallic disc with a surface of 1 m^2 that was perforated with 100 holes and attached to small tubes leading to a reservoir. The metallic disc was moved by a motor drive. Irrigation intensity was controlled by a flowmeter (Alaoui and Helbling, 2006). Three successive irrigations were conducted at each measurement point, enabling consideration of three different moisture levels. Irrigation intensity and duration differed between study sites in some cases (Table 2). The irrigation experiments were carried out in summer between April and August.

In order to measure water content and its variation in time and space, several time domain reflectometer (TDR) probes (CR10X & TDR100, Campbell Scientific Inc.) were inserted at different depths at each measurement point, with 0.20-m waveguides (two parallel rods of 6 mm diameter) (Table 2). Calibration was performed according to Roth et al. (1990). This calibration method minimizes the degree to which the uncertainty of volumetric water content calculated from the TDR measurements depends on water content. Nonetheless, large relative uncertainties were observed for low degrees of saturation, amounting to 16.0% for very dry soil at 8.0%, as opposed to only 1.2% for wet soil at 93% (Roth et al., 1990). TDR measurements were made every 60 s.

2.3. Laboratory analysis

Saturated hydraulic conductivity (K_s) was determined in samples of undisturbed soil with a diameter of 55 mm and a length of 42 mm, taken at 50-mm depth increments throughout the soil profile. Three to five samples per depth were taken. K_s was measured using a constant head permeameter (Klute and Dirksen, 1986). Porosity and bulk density were determined in samples of undisturbed soil with a diameter of 115 mm and a length of 98 mm. Porosity was determined by means of gravimetric water content measurements at full saturation, whereas organic matter content was determined by weight loss on ignition. Soil pH was measured at 1:2 (soil/0.01 M CaCl2) on a mass basis (Soil Survey Staff, 2004).

2.4. Model used

MACRO is a one-dimensional non-steady-state model of water flow and solute transport in field soils. A complete water balance is considered in the model, including treatments of precipitation (rain, snowpack, and irrigation), vertical unsaturated and saturated water flow, losses to primary and secondary field drainage systems, evapotranspiration, and root water uptake. The model divides the total soil porosity into macropores and micropores. Water flow in micropores is calculated using the Richards (1931) equation. Net rainfall is partitioned into an amount taken up by micropores and an excess amount of water flowing into macropores under non-equilibrium conditions, thereby bypassing the matrix. Water flow in the macropores q_{ma} is calculated by a modified kinematic wave approach Eq. (1) (Germann, 1985), where the macropores are assumed to drain by gravity, implying a unit hydraulic gradient and simple power law function to represent the unsaturated hydraulic conductivity:

$$q_{ma} = (K_s - K_b)\left(\frac{\theta_{ma}}{\theta_s - \theta_b}\right)^{n^*} \quad (1)$$

where the subscript "ma" refers to macropores, θ_{ma} ($m^3\,m^{-3}$) is the macropore water content, θ_s ($m^3\,m^{-3}$) is the saturated water