Journal of Hydrology 522 (2015) 418–427

Contents lists available at ScienceDirect

Journal of Hydrology

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

Temperature effect on the transport of bromide and *E. coli* NAR in saturated soils

B. Gharabaghi [a], A. Safadoust [b], A.A. Mahboubi [a,*], M.R. Mosaddeghi [c], A. Unc [d], B. Ahrens [e], Gh. Sayyad [f]

[a] School of Engineering, University of Guelph, Guelph, Ontario N1G 2W1, Canada
[b] Department of Soil Science, College of Agriculture, Bu-Ali Sina University, Hamadan 6517833131, Iran
[c] Department of Soil Science, College of Agriculture, Isfahan University of Technology, Isfahan 84156-83111, Iran
[d] Plant and Environmental Sciences, New Mexico State University, Las Cruces, NM 88003-8003, USA
[e] Department of Geography, University of Guelph, Guelph, Ontario N1G 2W1, Canada
[f] Department of Soil Science, College of Agriculture, Shahid Chamran University of Ahvaz, 831351-61357, Iran

ARTICLE INFO

Article history:
Received 1 August 2013
Received in revised form 26 October 2014
Accepted 1 January 2015
Available online 9 January 2015
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Rizlan Bernier-Latmani, Associate Editor

Keywords:
E. coli NAR
Weathering
Saturated condition
Preferential flow
Temperature
Tension infiltrometer

SUMMARY

In this study we investigated the transport of nalidixic acid-resistant *Escherichia coli* (*E. coli* NAR) and bromide (Br^-) through two soils, a sandy loam (SL) and clay loam (CL). Soils were repacked in columns (45 cm length × 22 cm diameter) and subjected to physical (freeze/thaw, and wet/dry cycles) and biological (by earthworms, *Eisenia fetida*) weathering for 12 months. Saturated flow conditions were maintained using a tension infiltrometer. Tests were carried out at either 5 or 20 °C. After steady-state flow conditions were established, a suspension containing *E. coli* NAR and Br^- was sprayed onto the surface of soil columns. Leachate was sampled at three depths, 15, 30 and 45 cm. Time to maximum concentration (C_{max}) of *E. coli* NAR was greater for SL at all depths. Both tracers had rapid breakthrough curves (BTCs) shortly after the suspension injection followed by prolonged tailing indicating the presence of preferential pathways and thus soil heterogeneity regenerated after the induced physical and biological weathering. About 40% of the *E. coli* NAR and 79% of the Br^- leached through the entire 45 cm soil columns during the experiments. Leaching with cold water (5 °C) led to lower hydraulic conductivity and flow rate and consequently enhanced bacterial filtration for both soils. Very low values for the detachment coefficient for *E. coli* NAR at 5 °C suggest an irreversible process of bacterial attachment in heterogeneous soils. BTCs were well described by the mobile–immobile model (MIM) in HYDRUS-1D. Soil texture/structure and temperature had a significant effect on the model's fitted parameters.

1. Introduction

Bacterial transport through saturated soils plays an important role in the dispersal of pathogenic microorganisms and enhancement of biorestoration of contaminated water resources. The processes through which viable bacteria reach deep into soil or geological layers and arrive at aquifers are dependent on a complex set of factors. Several review articles (Jamieson et al., 2002; Unc and Goss, 2004; Foppen and Schijven, 2006; Or et al., 2007) have comprehensively described the factors and mechanisms governing bacterial transport through soil, and their persistence in soils, as mitigated by environmental conditions, water and bacteria-source characteristics.

The significance of temperature-dependent water viscosity ought to be evaluated for any water-mediated transport processes. Hydraulic conductivity (K) is a function of fluidity (K = fluidity × intrinsic permeability) which is inversely proportional to fluid viscosity. As flux density is directly related to the hydraulic conductivity of the medium the temperature could indirectly affect the contaminant transport processes. Rahi and Jensen (1975) reported that variations of soil–water diffusivity in low-swelling soils due to thermal effects can be explained on the basis of temperature dependence of surface tension and viscosity. It was also observed that water infiltration into soil increased with water temperature. This was partly attributed to decreased water viscosity (Jaynes, 1990; Duke, 1992). Lentz and Bjorneberg (2002) found that diurnal and seasonal changes in the temperature of irrigation water could significantly alter furrow infiltration and stream flow. This observation was used to imply that the rate of water advance in the furrow and uniformity of water infiltration would be increased for evening irrigation rather than morning irrigation.

* Corresponding author. Tel.: +98 (519) 824 4120x58451; fax: +98 (519)836 0227.
E-mail address: mahboubi@uoguelph.ca (A.A. Mahboubi).

http://dx.doi.org/10.1016/j.jhydrol.2015.01.003
0022-1694/

Nomenclature

Br	bromide
BTCs	breakthrough curves
C	effluent (M L^{-3})
C_0	influent (M L^{-3})
D1	depth of 15 (L)
D2	depth of 30 (L)
D3	depth of 45 (L)
E. coli NAR	nalidixic acid-resistant *Escherichia coli* strain
EC	electrical conductivity (dS m^{-1})
C_{max}	maximum concentration of Br or *E. coli* NAR recovered in effluent sample (ML^{-3})
PV_{Cmax}	pore volume at C_{max}
D	dispersion coefficient (L^2 T^{-1})
K	hydraulic conductivity (LT^{-1})
v	pore water velocity (L T^{-1})
λ	dispersivity (L)
q	darcy water flux density (LT^{-1})
θ	volumetric water content (L^3 L^{-3})
θ_m	mobile volumetric water content (L^3 L^{-3})
t	time (T)
x	distance (L)
ρ_b	bulk density (M L^{-3})
α	solute exchange coefficient between mobile and immobile regions (T^{-1})
k_{att}	first-order attachment coefficients (T^{-1})
β	empirical factor controlling the shape of the spatial distribution (–)
k_{det}	first-order detachment coefficients (T^{-1})
k_{str}	first-order straining coefficients (T^{-1})
ψ_t	time-dependent blocking coefficient for straining process
ψ_x	depth-dependent blocking coefficient for straining process
SL	sandy loam
CL	clay loam
s_1	concentration at adsorption site that describe attachment/detachment process (N_c M^{-1})
s_2	concentration at adsorption site that describe irreversible straining process (N_c M^{-1})
s_{max}	maximum solid phase concentration of colloids on sorption sites (N_c M^{-1})
d_c	mean median of grain size (L)
x_0	initial straining status (L)

Lower air temperature would lead to colder furrow stream which minimizes infiltration and thus maximizes furrow stream. A field study conducted by Ronan et al. (1998) has shown lower stream flow in the afternoon, which was attributed to increased infiltration rates. Increased infiltration rates for warmer waters are mainly linked to viscosity effects on soil hydraulic conductivity.

Lo et al. (2002) observed that temperature affected bacterial retention in bentonite–sand mixtures. Greater bacterial recovery at 4 °C compared to 22 °C was attributed to lack of bacterial motility at the lower temperature. Increased ambient temperature could thus possibly be reflected in greater attachment and removal of bacteria from an aqueous flux. In recent years the assessment of risk of groundwater pollution due to application of liquid manure in the fall or spring has been the subject of debate. Bacterial densities in leachate from intact soil columns after fall manure–application were significantly ($p < 0.1$) lower (due to bacterial die-off) than those after spring manure–application during second, third, or fourth irrigation events (Warnemuende and Kanwar, 2002). In some cold regions (e.g. the Upper Midwest in USA, or much of Canada), livestock producers might prefer to spread the manures in the cold season as a means of reducing storage needs, providing more time for the application and reducing soil compaction when compared to the spreading on wet non-frozen soils in the spring. However, winter application of manure is rarely recommended, as early spring excess runoff, from non-infiltrating frozen soils, may carry off manure nutrients and bacteria to nearby surface waters (Foppen et al., 2005).

Intact soil columns have been commonly used in microbial and solute transport studies. However, the soil structure is often affected during core sampling (Dousset et al., 1995; Pires et al., 2007). Employing soil columns that were subjected to simulated physical (freeze/thaw and wet/dry cycles) and/or biological weathering similar to what happens in the nature, allows natural formation of aggregates and pore networks (Safadoust et al., 2012).

The objective of this study was to document and compare saturated flow transport of a non-reactive tracer, Br^-, with a bacterium, *Escherichia coli*, in weathered soil columns as affected by the ambient temperature.

2. Materials and methods

2.1. Site description and column preparation

Soil samples were collected in April 2008 from two sites in the province of Hamadan, western Iran. The region has a semi-arid climate, with long-term average annual precipitation of 328 mm. Most of precipitation occurs during the winter months. Monthly mean air temperature ranges from a high of 37.5 °C in July to a low of −30 °C in January. The areas from where we sampled the clay loam soil (Gavkhuni) and the sandy loam soil (Azandarian) have been under dryland farming cropped to wheat over 50 years. Soil samples were taken after harvesting prior to primary tillage. The two soils were a clay loam (CL) classified as clayey skeletal carbonatic mesic Typic Xerorthents and a sandy loamy (SL) classified as fine loamy mixed (calcareous) mesic Typic Xerorthents (Soil Survey Staff, 2010). Selected properties of the studied soils are summarized in Table 1.

Leaching experiments were conducted in laboratory using repacked soil columns in PVC cylinders (45 cm length × 22 cm diameter) under saturated flow condition. Each cylinder was filled with the soil which had been taken according to the soil profile's strata using 5 mini-columns with the height of 10, 10, 10, 10 and 5 cm, respectively and the same diameter as of the of main column. This repacking procedure reproduced the actual soil profile stratification.

The fresh soil from each mini-column was passed through an 8-mm sieve (with minimal destruction of aggregates) to remove any gravel or stones and poured gently in successive layers into the main PVC cylinder. The repacked soil columns did not have any macro-structural feature, such as macropores and cracks, but retained micro-structural features, such as intra-aggregates micropores. Soil columns had a final dry bulk density of 1.55 Mg m^{-3} for SL and 1.36 Mg m^{-3} for CL, similar to mean value of the field (natural) dry bulk densities (along the soil profiles) as measured using the standard core sampling method (Blake and Hartge, 1986). For this task the soil columns were repacked based on the average bulk density of five sampled layers. The bulk density values of five consecutive sampled layers for SL were .53,