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Transport of iodide in structured soil under spring barley during irrigation experiment analyzed using dual-continuum model**

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Abstract: Transport of radioactive iodide $^{131}\mathrm{I}^-$ in a black clay loam soil under spring barley in an early ontogenesis phase was monitored during controlled field irrigation experiment. It was found that iodide bound in the soil matrix could be mobilized by the surface leaching enhanced by mechanical impact of water drops and transported below the root zone of crops via soil cracks. The iodide transport through structured soil profile was simulated by the one-dimensional dual-continuum model, which assumes the existence of two inter-connected flow domains: the soil matrix domain and the preferential flow domain. The model predicted relatively deep percolation of iodide within a short time, in a good agreement with the observed vertical iodide distribution in soil. The dual-continuum approach proved to be an adequate tool for evaluation of field irrigation experiments conducted in structured soils.

Key words: breakthrough curve; dual-permeability model; field tracer experiment; preferential flow; solute transport; water flow

Introduction

Climate change poses the most serious threat to agriculture worldwide. Many areas of southern Slovakia are experiencing increases in the frequency and intensity of heavy rains following long hot, dry periods (Faško et al. 2008), leading to preferential flow, surface runoff, and soil erosion, hence to possible worsening quality of surface water and groundwater.

Agricultural production is dependent upon the addition of fertilizers. Soils have the ability to store nutrients for use in future years; excess nutrients leach out due to surface runoff and preferential flow. Preferential flow in soils develops when water and solutes travel at considerably high velocities through preferential pathways concurrently bypassing the porous matrix. This phenomenon has a direct influence on infiltration, drainage, and specifically on solute transport. Significant effects of preferential flow on solute transport were observed in soils from both ends of grain-size distribution spectrum: fingered flow induced by water repellency in sandy soils (e.g., Lichner et al. 2012) and macropore flow via soil cracks in clay and clay loam soils (e.g., Dohnal et al. 2009).

Mathematical models of water flow and solute transport could be used to characterize flowpaths and residence times in soils. However, reliable model predictions depend on soil hydraulic and transport properties, which are still difficult to estimate for soils with significant preferential flow effects (e.g., Gerke 2006). Unlike dye-staining techniques, restricted to single measurement due to destructive sampling, radioactive tracer techniques have the potential to deliver information from recurrent field experiments as the soil profile is disturbed negligibly (Lichner 1995). Thus, field irrigation experiment combined with radioactive tracer technique may provide valuable data (e.g., spatial and temporal variations of applied tracer), which serve for model calibration and validation (Alaoui et al. 1997).

Shetaya (2011) presented the distribution coefficient K_d of iodide for woodland and arable soil equal to 3.8 and 5.3 L kg^{-1}, respectively, and Mikolajków (2003) found that K_d of nitrate for brown, podsolic, and boggy soil were 5.22, 4.29, and 6.25 L kg^{-1}, respectively. As iodide and nitrate retardation in soils are similar, we used radioactive iodide as a tracer for nitrate movement in clay loam soil. Iodide is immobilized in soils in the form of organically bound iodine through the laccase-catalyzed oxidation (Seki et al. 2013). It was found that iodide was fully transformed into organic forms after 1 day of incubation in highly organic soils and was fully transformed in the studied soils after 60 days (Shetaya 2011).

The aim of this study was to predict iodide transport through clay loam soil during controlled field irrigation experiment following long hot, dry period using

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Table 1. Measured and estimated soil hydraulic properties. SM and PF refer to the soil matrix and preferential flow domain, respectively.

Domain	Depth (cm)	θ_r (cm^3 cm^{-3})	θ_s (cm^3 cm^{-3})	α (cm^{-1})	n (–)	K_s (cm d^{-1})	h_s (cm)	w_f (–)
SM	0–55	0.011	0.489	0.049	1.203	15.7	–0.08	–
	55–85	0.011	0.491	0.028	1.296	15.6	–0.16	–
	85–100	0.011	0.488	0.007	1.287	16.9	–0.68	–
PF	0–100	0.050	0.600	0.145	2.680	700.0	0.00	0.15

dual-continuum approach. The dual-continuum model invokes local nonequilibrium in pressure head and solute concentration between the two pore domains. This is achieved through dividing the liquid phase continuum into a preferential flow domain (further on abbreviated to the PF domain) and a soil matrix flow domain (the SM domain). Model predictions of iodide transport were compared with data from field irrigation experiment.

Material and methods

Field experiment and soil

The study area was located at the Experimental Station of Research Institute of Irrigation at Most pri Bratislave village (48°08′27″ N, 17°14′41″ E). The station is about 133 m above sea level. The average annual air temperature is 9.7℃, the average annual precipitation is 554 mm. The soil is classified as a Chernozem (WRB 2006) and has a clay loam texture (Soil Survey Division Staff 1993). The soil profile consists of three relatively homogeneous horizons. Physical and chemical properties of the surface horizon were as follows: clay/loam/sand content was 53/46/1%, $CaCO_3$ content 11.2%, C_{org} content 1.9%, pH (H_2O) 8.2, and pH (KCl) 7.8.

The experiment was performed at a 1.4 m × 3.4 m plot after a two weeklong hot and dry period, which resulted in fissures and cracks in the soil profile. Spring barley (*Hordeum vulgare* L.) was growing on the field during the experiment. An original radioactive tracer technique (Lichner 1992) was used to measure the tracer distribution in the soil profile. The measuring probe, used to determine tracer concentrations, consists of a duralumin tube (inner diameter of 8 mm, outer diameter of 12 mm), in which the Geiger-Müller detector (with the length of 21 mm and the diameter of 6.3 mm) and the analog interface unit are connected to a nuclear analyzer with a coaxial cable. Owing to its small size the Geiger-Müller detector can be considered as a point detector. The counting rate recorded by the detector is directly proportional to the activity of the radioactive tracer. Eight probes were installed vertically to the depth of 1.5 m on the plot before the irrigation had started.

Around each of eight probes, a short pulse of $Na^{131}I$ solution with the activity of about 10 MBq was trickled by syringe (Lichner 1995). After the application, radioactive iodide ($^{131}I^-$), bound at the soil matrix, was leached by irrigated water. Water application was conducted manually with a watering can (100 mm in 10 h). The irrigation was then interrupted for 12 h to allow water and tracer redistribution within the soil profile. Following this interruption, another 100 mm of water was applied within 10 h. Vertical distributions of iodide in soil were measured four times during the irrigation experiment, together with the iodide breakthrough curve at the depth of 30 cm.

The soil-water retention curves for the three soil horizons were measured by standard pressure plate apparatus method on undisturbed soil samples and the hydraulic parameters were consequently obtained by fitting van Genuchten's modified prediction model (Vogel et al. 2000) to data points. The measurements of the saturated hydraulic conductivity K_s were carried out by tension infiltrometer at three depths. Five replicate measurements were conducted at each depth. The volumetric portion of the PF domain, w_f, was estimated as 15% of the bulk soil. The retention curve parameters of the PF domain were also estimated based on indirect soil and plot characteristics. The sensitivity of the dual-continuum model to uncertainties associated with preferential flow parameters was studied e.g. by Dohnal et al. (2012). Table 1 summarizes the soil hydraulic parameters for both flow domains. θ_r and θ_s are the residual and saturated water contents, respectively, h_s is the air-entry value of Vogel et al. (2000), and α and n are fitting parameters.

For solute transport, dispersivity value of 5 cm was used. The molecular diffusion coefficient was set equal to 1.3 cm^2 d^{-1}. The values of bulk density within the soil profile were taken from previous study (Nováková 2000). The distribution coefficients were estimated from batch tests performed on soils with similar organic content (Szabová & Čipáková 1988).

Flow and transport model

The dual-continuum approach (Gerke & van Genuchten 1993) assumes that the porous medium consists of two separate domains with specific hydraulic properties. One-dimensional variably saturated water flow in the dual-continuum model was described by a pair of Richards' equations for the PF and the SM domain pore systems. Similarly, a coupled pair of advection-dispersion equations was solved to model solute transport. The exchange of water and solute between the matrix and the fracture domains was assumed to be proportional to the local pressure difference and the concentration gradient between the two pore systems. The dual sets of governing equations for water flow and iodide transport were solved numerically with a finite element scheme using the computer code S1D (Vogel et al. 2010).

Initial and boundary conditions

The iodide tracer was placed at the top 0.1-cm depth of the profile as initial condition. Irrigation water was without iodide. The bottom boundary condition was set to zero concentration gradient, to allow the tracer to pass freely the lower boundary at the depth of 100 cm. Note that iodide concentration in the water entering the soil surface during the experiment was not measured; hence only relative concentrations and masses could be evaluated by the modeling (similarly as in Vogel et al. 2007).

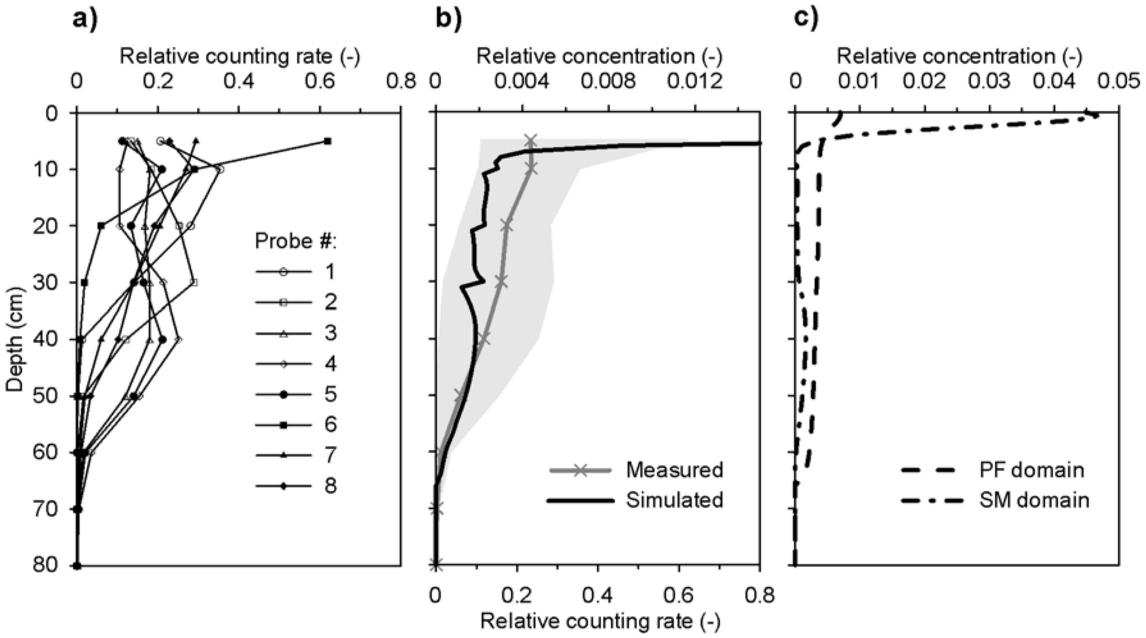

Fig. 1. Vertical iodide distributions in the soil profile: a) – measured iodide profiles along the individual probes for $t = 22$ h (cumulative infiltration rate of 100 mm); b) – simulated composite concentration and mean measured distribution with shaded area representing measurement variability among eight probes; c) – simulated liquid concentrations in the flow domains.

"Atmospheric boundary condition" was postulated at the soil surface. This type of condition allowed for switching between the Neumann and Dirichlet type conditions, i.e. when the top soil was not capable of transmitting water during irrigation, the flux condition was changed to pressure condition. The unit hydraulic gradient condition was used at the lower boundary, allowing water to leave the soil profile at the rate equal to unsaturated hydraulic conductivity. No rainfall had occurred for 14 days before the start of the infiltration experiment, so the initial soil water pressure was set to –700 cm throughout the entire soil profile. No evapotranspiration was taken into account for the simulated period.

Results and discussion

Figure 1 depicts observed and simulated vertical iodide distributions in the soil profile after irrigation of 100 mm water and the following 12 h redistribution period. It can be seen that iodide migrated down to the depth of 70 cm below the surface. Measurement variability among eight probes is clearly visible in Fig. 1a as each probe reflected different transport regime (either in the soil matrix and/or through preferential pathways and other structural soil elements). Simulated composite concentrations showed deep penetration of iodide (Fig. 1b), which is in relatively good agreement with the observed distribution pattern. The concentration increase in the SM domain below 30 cm depth could be attributed to the iodide transfer from the PF to the SM domain (Fig. 1c). Without considering preferential flow effects, iodide distribution was limited in the 0–20 cm part of the topsoil.

As the rooting depth of spring barley can hardly exceed 30 cm at the turn of April/May, it can be concluded that about 2% of iodide, bound in soil matrix and mobilized by the surface leaching enhanced by mechanical impact of water drops, could be transported below the root zone of crops via soil cracks after application of 100 mm water and the following 12 h redistribution period. It should be noted that 3 h precipitation of more than 127 mm was registered in this region e.g. on 10.7.1999. Hourly and daily precipitation data during heavy rain events measured at two meteorological stations in the southwest of Slovakia were presented by Lichner et al. (2006).

Figure 2 shows observed and simulated breakthrough curves at the depth of 30 cm. The simulated concentration increase after 4 h of irrigation is delayed compared to the mean observed breakthrough curve (Fig. 2b); nevertheless the simulated curve remained within the measurement variability. The PF domain showed steep increase of iodide concentrations in response to the first irrigation after 4 h (Fig. 2c). The iodide concentrations in the SM domain were characterized by gradual increase at this depth. The second irrigation induced a slight increase of concentration in the PF domain at about 24 h and negligible response in the SM domain. This could be explained by different vertical distribution of iodide in both flow domains at this time.

Conclusion

Transport of iodide tracer through structured soil during field irrigation experiment was analyzed using dual-continuum model. Observed iodide distributions in the soil profile (i.e., relatively deep percolation within a short time) could not be described with a model based on classical single continuum approach. The applied dual-continuum approach allowed more adequate ap-

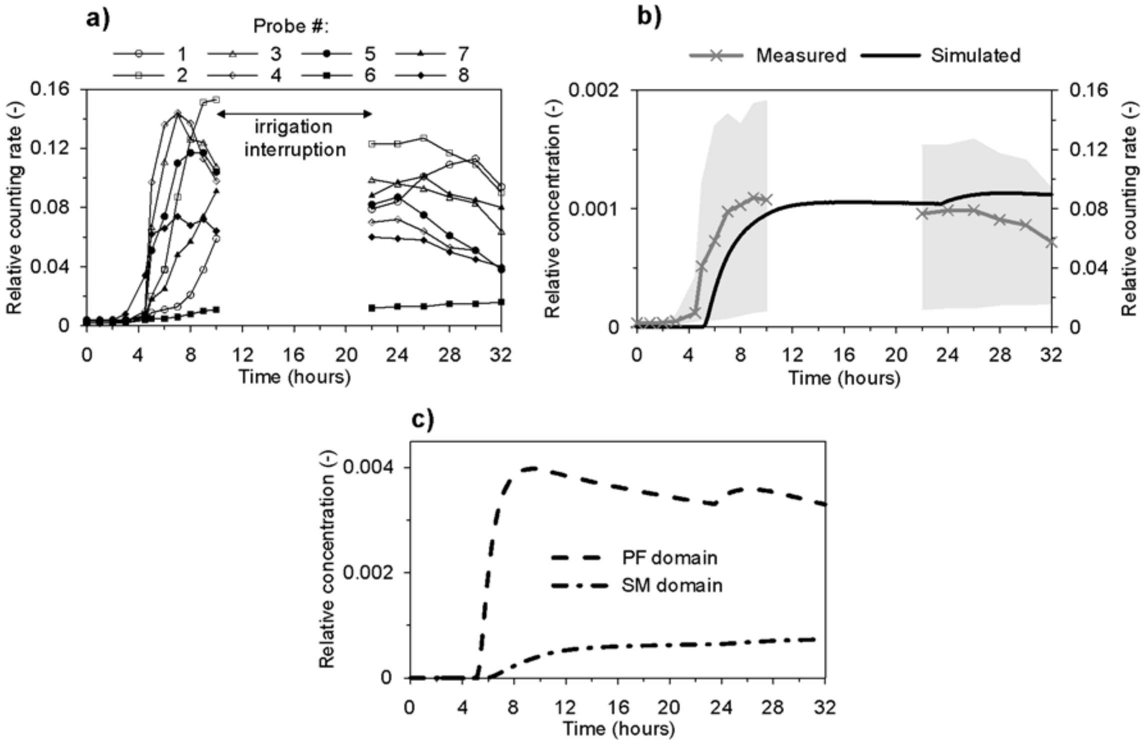

Fig. 2. Iodide breakthrough curves at the depth of 30 cm: a) – iodide concentrations measured by individual probes; b) – mean measured and simulated composite breakthrough curves (the shaded area represents the measurement variability among eight probes); c) – simulated domain-specific iodide concentrations.

proximation of the field data. The dual-continuum model proved to be a useful tool for evaluation of field irrigation experiments conducted in structured soils.

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