This is not a peer-reviewed article.
Pp. 129-132 in Preferential Flow Water: Movement and Chemical Transport in the Environment, Proc. 2nd Intl. Symp. (3-5 January 2001, Honolulu, Hawaii, USA), eds. David Bosch & Kevin King, St. Joseph, Michigan: ASAE. 701P0006

Preferential Flow in Water Repellent Sandy Soils: Principles and Modeling Approaches

Coen J. Ritsema[1]*, Jos C. van Dam[2], John L. Nieber[3], Louis W. Dekker[1], K. Oostindie[1], and Tammo S. Steenhuis[4]

Abstract

Leaching risks of surface-applied agrichemicals in water repellent soils can only be quantified with an acceptable degree of accuracy if knowledge of the underlying principles and an appropriate simulation model are available. The present study aimed to investigate water flow and solute transport processes in a water repellent sandy soil, and to introduce and apply new modeling approaches. Automated TDR measurements revealed that preferential pathways develop rapidly during severe rain storms, causing infiltrating water to be preferentially transported to the deeper subsoil. Furthermore, preferred pathways recurred at the same sites during all rain events. Simulations with a 2-D, numerical finite element flow and transport model indicate that preferential flow paths will only form during infiltration into dry water repellent soils, i.e. in the range below the so-called critical soil water content. Incorporation of hysteresis is essential to generate the formation and recurrence of preferential flow paths with the model. The process of preferential flow and transport has been incorporated in the well-known SWAP model also, and applied to field data of tracer transport through a water repellent sandy soil in the Netherlands. Results indicate early arrival times of bromide in the subsoil in case preferential flow is taken into account.

Keywords. Soil water repellency, Modeling, Preferential flow and transport, Rapid transport

Introduction

Soil water repellency is currently receiving increasing attention from scientists and policy makers, due to the adverse and sometimes devastating effects of soil water repellency on environmental quality and agricultural crop production (Ritsema and Dekker, 2000). Soil water repellency often leads to irregular wetting and rapid leaching of surface-applied agrichemicals. Attempts to model flow and transport in water repellent soils have been undertaken by Van Dam et al. (1990) and De Rooij (1995). In both cases, however, analytical approaches were used which neglected specific processes like hysteresis in the water retention function, which is of crucial importance in water repellent media. The aim of the present study is to investigate water flow and solute transport processes in the unsaturated zone of a water repellent sandy soil, with special attention to i) monitoring the formation of preferential flow paths during successive rain events, and ii) development and application of new modeling approaches for simulating flow and transport in water repellent media.

Materials and Methods

Soil Characteristics

Field experiments were carried out on a grass-covered water repellent sandy soil, near Ouddorp, the Netherlands. The soil consists of an approximately 10 cm thick humous surface layer, on top of fine dune sand. Water repellency in the upper 50 cm of the Ouddorp soil is extremely high, except in the shallow surface layer. Deeper in the profile water repellency is absent (Dekker and Ritsema, 1994). The Ouddorp soil becomes water repellent when dry, i.e. below the so-called critical soil water content (Ritsema et al., 1997a). Figure 1 shows the critical soil water content versus depth for the Ouddorp soil, and indicates when the soil is wettable or water repellent, and when uniform or preferential flow occurs.

[1] Alterra, Droevendaalsesteeg 3, 6700 AA, Wageningen, Netherlands
[2] Wageningen Agricultural University, Nieuwe Kanaal 11, 6709 PA, Wageningen, Netherlands
[3] University of Minnesota, 1390 Eckles Ave., St.Paul, MN55108, USA
[4] Cornell University, Riley-Robb Hall, Ithaca, NY 14853-5701, USA
(* Corresponding author; tel: 31.317.474266; fax: 31.317.419000; email: c.j.ritsema@alterra.wag-ur.nl)

TDR Measurements

An automated TDR device has been used to measure volumetric water contents of the soil within a 2 m long and 0.7 m deep vertical transect (Ritsema et al., 1997b). The probes were placed 15 cm apart in the horizontal direction at depths of 4, 12, 20, 30, 40, 55 and 70 cm. Every 3 hours, the TDR device automatically started a measurement series, and, in total, measurements continued for around 8 months. Almost 200,000 volumetric soil water content values were recorded, which were used to construct two-dimensional water content distributions for every 3 hour time-step. In all, around 2,000 graphs were made, a selection of which is presented in the present study.

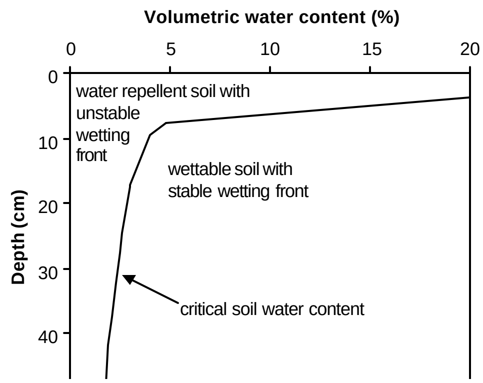

Figure 1. Critcial soil water content versus depth for the Ouddorp soil. In the zone left to the critical soil water contents, the soil is water repellent resulting in the formation of preferential flow paths during infiltration events. At higher soil water contents, the soil is wettable with uniform flow behaviour.

Tracer Experiment

A KBr tracer was applied uniformly to the surface of the Ouddorp experimental field (Ritsema et al., 1993). The unsaturated zone was sampled at several times after the tracer application using 0.1 m wide and 1 m long cylindrical cores. Each core was divided into sections, and all samples were used to determine soil water contents and bromide concentrations. Additionally, precipitation and groundwater levels were monitored too.

Modeling Approaches

First, water flow and transport were simulated using a two-dimensional finite element solution of Richards equation and the convection-dispersion equation, as described by Nieber (1996) and Ritsema et al. (1998). The flow solution method uses quadrilateral elements with a specialized downstream weighting of the hydraulic conductivities betwen adjacent node points. Hysteresis in the water retention characteristics was incorporated in the numerical solution.

Second, the well-known SWAP (Soil-Water-Atmosphere-Plant) model (Van Dam et al., 1997) has been adapted to account for preferential flow processes in water repellent soils. Basically, within SWAP, soil water flow is calculated using the Richards and conservation of mass equations, solved using the finite difference method. Solute flow is computed using a numerical solution of the convection-dispersion equation. In the adapted model, flow switches from uniform to preferential in case in a certain zone of the soil profile, water contents drop below the critical soil water content. The diameters of the preferential flow paths are calculated according to the relationship provided by Selker et al. (1991; 1996). The amount of fingers will depend on the actual amount and duration of the rainfall. Hysteresis is incorporated in the adapted SWAP model.

Results

TDR Measurements

In order to illustrate the process of preferential flow path formation and recurrence, a selection was made of two pronounced rainy periods. For each rainy period, the soil water content distributions measured within the TDR transect are shown just before, during (twice), and at the end (or after cessation) of the rainfall (Fig. 2).

Volumetric soil water contents before the rain events (Fig. 2, left hand side) were generally below 10% for the water repellent subsoil, and up to 10% to 25% for the humous layer, although there were some differences. No preferential flow patterns were present before the start of the rain events, but these emerged during both rainy periods. The preferential flow paths protruded through the water repellent layer and reached depths of around 60 to 70 cm. Observed patterns indicate that preferential flow paths recur at the same locations during successive rain events, due to the hysteretic water retention character of the Ouddorp sand. Persistent spatial preferential flow patterns like those found in the present study might develop in, for instance, untilled agricultural fields, golf courts, nature reserves and forests.

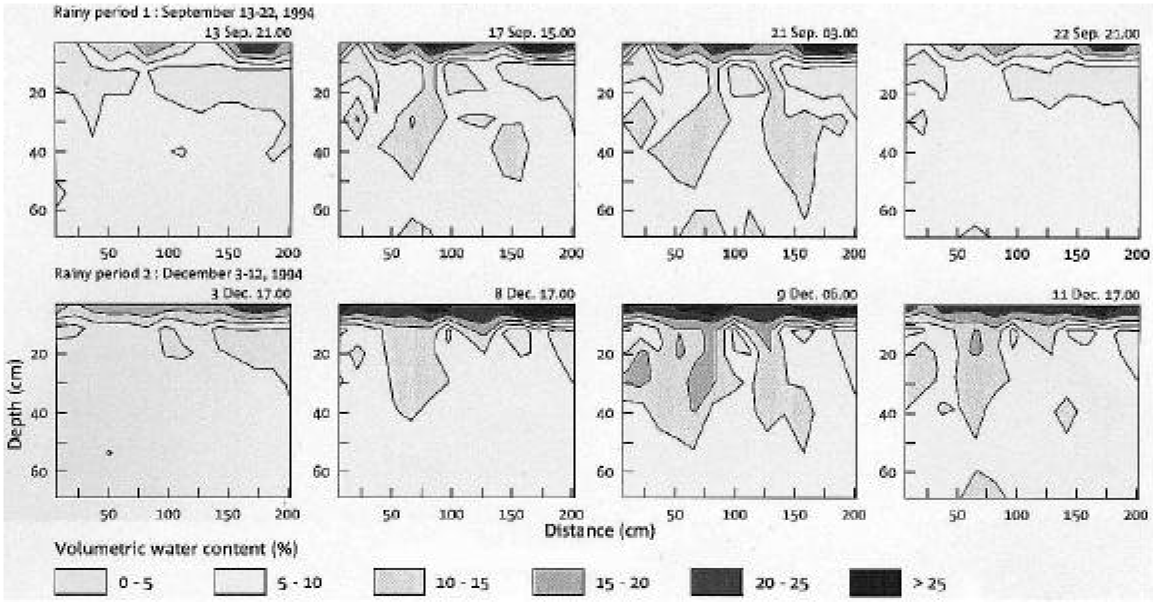

Figure 2. Spatial distributions of soil water content in the 2 m long and 0.7 m deep TDR trench before, during and after the rainy periods selected.

Tracer Experiment and Model Application

Fig. 3 shows simulation results of the 2-D numerical model for an infiltration event into water repellent soil, consisting of a wettable surface and bottom layer, and an extremely water repellent layer in between. The results show water content distributions at a specific time during the infiltration process. Preferential pathways are clearly visible. In the wettable, bottom layer, flow is dominated by diverging flow out of the bottom end of the preferred pathways.

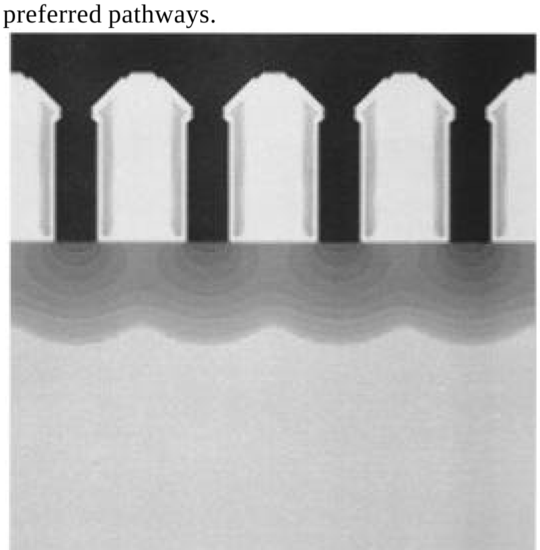

Figure 3. Formation of preferred pathways using the numerical 2-D model.

The adapted SWAP model has been used to simulate bromide transport through the Ouddorp experimental field. As an example, fig. 4 shows the bromide breakthrough curves at 105 cm depth simulated with both the traditional and adapted SWAP versions. Computed arrival time of bromide at 105 cm depth is much earlier in case the adapted SWAP model has been used, i.e. in case preferential flow is taken into consideration. In the situation of transport of reactive compounds, also the total receiving dose at 105 cm depth will be much higher compared with uniform flow because large parts of the unsaturated zone will be bypassed by the infiltrating water, reducing the potential neutralizing capacity of the soil significantly.

Acknowledgements

This work has been executed within the framework of Contract FAIR6-CT98-4027, financed by the European Commission and the Netherlands Ministry of Agriculture, Nature Management, and Fisheries.

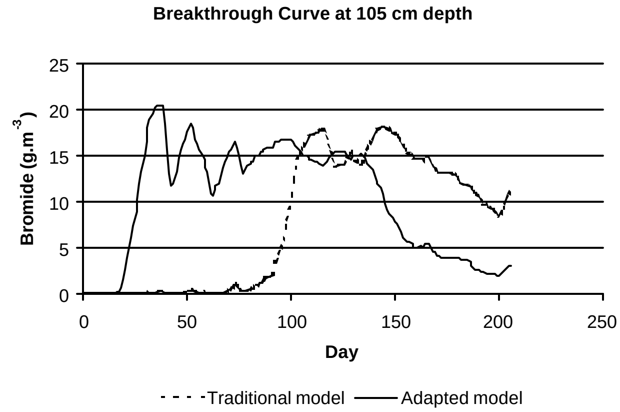

Figure 4. Breakthrough curves of bromide at 105 cm depth computed with the traditional and adapted SWAP model, i.e. without and with accounting for preferential flow, respectively.

References

Dekker, L.W. and C.J. Ritsema. 1994. How water moves in a water repellent sandy soil. I. Potential and actual water repellency. Water Resour. Res. 30, 2507-2517.

De Rooij, G.H., 1995. A three-region analytical model of solute leaching in a soil with a water repellent top layer. Water Resour. Res. 31, 2701-2707.

Nieber, J.L., 1996. Modeling finger development and persistence in initially dry porous media. Geoderma 70, 207-230.

Ritsema, C.J. and L.W. Dekker (Eds.) 2000. Special issue: Water Repellency in Soils. J. Hydr. 231-232, pp. 450.

Ritsema, C.J., L.W. Dekker, J.M.H. Hendrickx, W. Hamminga. 1993. Preferential flow mechanism in a water repellent sandy soil. Water Resour. Res. 29, 2183-2193.

Ritsema, C.J., L.W. Dekker, A.W.J. Heijs. 1997a. Three-dimensional fingered flow patterns in a water repellent sandy field soil. Soil Sci. 162, 79-90.

Ritsema, C.J., L.W. Dekker, E.G.M. van den Elsen, K. Oostindie, J.L. Nieber, T.S. Steenhuis. 1997b. Recurring fingered flow pathways in a water repellent sandy field soil. Hydrology and Earth System Sciences 4, 777-786.

Ritsema, C.J., L.W. Dekker, J.L. Nieber, T.S. Steenhuis. 1998. Modeling and field evidence of finger formation and finger recurrence in a water repellent sandy soil. Water Resour. Res. 34, 555-567.

Selker, J.S., T.S. Steenhuis, J.-Y. Parlange. 1991. Estimation of loading via fingered flow. In: Irrigation and Drainage: Conference Proceedings; July 22-26, Honolulu, Hawaii, USA, edited by W.F. Ritter, pp. 81-87.

Selker, J.S., T.S. Steenhuis and J.-Y. Parlange. 1996. An engineering approach to fingered vadose pollutant transport. Geoderma 70: 197-206.

Van Dam, J.C., J.M.H. Hendrickx, H.C. van Ommen, M.H. Bannink, M.Th. van Genuchten, L.W. Dekker, 1990. Water and solute movement in a coarse-textured water-repellent field soil. J. Hydr. 120, 359-379.

Van Dam, J.C., J. Huygen, J.G. Wesseling, R.A. Feddes, P. Kabat, P.E.V. van Walsum, P. Groenendijk, C.A. van Diepen. 1997. Theory of SWAP version 2.0. – Simulation of water flow, solute transport and plant growth in the Soil-Water-Atmosphere-Plant environment. Tech. Doc. 45, DLO Winand Staring Centre, Wageningen, Netherlands. pp. 167.