Dye tracer experiments and modeling of infiltration patterns in a contaminated water repellent sandy soil

Kai Lipsius¹, Wolfgang Durner¹ and Sacha J. Mooney²

¹ Institute for Geoecology, TU Braunschweig
² School of Biosciences, University of Nottingham

Abstract

Water repellency of soils near the surface leads to preferential flow and transport, because it prevents water from entering hydrophobic areas and concentrates water fluxes in hydrophilic areas. Heterogeneity in the flow field is the main problem for the prediction of contaminant transport. To investigate the flow patterns in a sandy soil, which was contaminated with hydrophobic tar oils and heavy metals, tracer experiments were conducted. Brilliant Blue FCF tracer was irrigated at different irrigation heights at three dates. Dye coverage maps were produced using image analysis. The variability of dye coverage was calculated. In all profiles infiltrating water was heterogeneously distributed in the first 10 cm. Areas with high water repellency coincided with very low water contents and were not stained. Water infiltrated where the top layer was less water repellent staining these areas. In the subsoil preferential flow was also found, although it was throughout not water repellent.

A two-dimensional numerical transport model was used to analyze the influence of the heterogeneous water flux in the soil on the leaching and transport of contaminants. It is found that, in the early phase, the contaminant flux towards the groundwater is enhanced as compared to the homogeneous case. For solutes applied with the precipitation the differences in leaching masses between preferential flow paths and other areas increased constantly. For the contaminants situated in the soil, the overall transport of contaminants is quickly greatly reduced. Firstly much of the contamination is effectively preserved because in the bypassed area it is protected from leaching. Secondly, in preferential flow paths the contaminant concentration is already strongly reduced by leaching. For low adsorbing contaminants complete leaching from the soil is much faster under homogeneous flow conditions. The simulation further shows that sampling of soil solution by suction cups at certain points in the profile or sampling of sub regions of the soil for predicting the risk of ground water contamination can yield extremely different results, depending on whether the sampling position is situated in a preferential flow region or not.

Introduction

The risk of ground water pollution from contamination of the soil is difficult to predict. This is mainly due to the heterogeneity of the subsurface, causing spatial and temporal variance of contaminant transport in the vadose zone (Johnson et al., 2003; Hillel, 1998). Durner et al. (2004) found that volumes extracted with suction devices were orders of magnitude below those expected for homogeneous infiltration volumes and were highly variable in space and time. Typical preferential flow fields can largely increase danger for the ground water. Preferential flow must not necessarily lead to preferential transport. A decreased risk for the ground water is achieved, if leaching from contaminated areas is prevented. This is often found, since the concentrations in areas of preferential leaching decline rapidly (Kung et al., 2000; Allaire-Leung et al., 2000). However, when the dissolved contaminants are preferentially transported in flow paths, large parts of the unsaturated zone are by-passed and therefore not filtering contaminants on their transport through the soil (Flühler et al., 1996).
A possible cause for heterogeneous infiltration is water repellency. Evidence of unstable flow in field soils caused by water repellency has been reported by numerous researchers, including Ghodrati and Jury (1990), Dekker and Ritsema (1994), Ritsema et al. (1998), Doerr et al. (1998), and DeBano (2000). Anthropogenic contamination with hydrophobic substances such as wood preservatives can also cause severe water repellency (Bauters et al., 2000; Quium et al., 2002). The leachate of wood preservatives and its effect on the flow patterns in the soil has not been investigated (Hingston et al., 2001; Poppe et al., 2002).

In order to describe solute transport in the field, experimental data is needed. However extraction of samples from the soil and chemical analysis is costly. Various researchers have therefore used dye tracers to visualize the flow patterns in the soil (Flury et al. 1994; Aeby et al., 1997; Mooney et al., 1999; Flury and Wai, 2003). Images of stained soil profiles can easily be classified into stained and unstained areas using image analysis. This allows a semi-quantitative measure of the flow patterns, the so-called dye coverage (Flury et al. 1994; Petersen et al., 1997; Reichenberger et al., 2002).

This paper deals with the dye tracer experiments conducted on a contaminated sandy soil. The dye coverage is identified and analyzed. The flow patterns are simulated with two-dimensional solute transport models. By simulation of the structured heterogeneity as well as stochastic heterogeneous profiles the leaching amounts and concentrations are compared between homogenous and heterogeneous soils.

**Material and Methods**

**Site Description**

The soil on the site of the Pfleiderer company in Neumarkt in der Oberpfalz (N: 49°15´13´´, E: 11°28´46´´), is contaminated by storage of freshly impregnated wood. Precipitation leached wood preservatives containing heavy metals and tar oils into the top soil, rendering the soil water repellent. Soil texture is homogeneous sand, with less than 1% clay and gravel respectively. Soil type is an anthropogenically modified podsol.

**Dye Tracer Experiments**

To investigate the solute transport on the Pfleiderer Site, several dye tracer experiments have been conducted. To identify the general flow patterns, the causes of the preferential flow and the ideal method for the main experiments on the site where intensive sampling devices were installed (Durner et al., 2004) two preliminary experiments were conducted. The results served to optimize the design of the final experiment at the intensive sampling site. Brilliant Blue FCF was applied manually with watering cans (Fig. 1) on 8 m² in the preliminary studies and on 63 m² in the main experiment. Irrigation height was 50 mm. Degree of water repellency was measured with the Water Drop Penetration Time (WDPT) Test, which based on the gradual break down of hydrophobicity under the influence of water (Dekker und Ritsema, 1994; Doerr, 1998). Three water drops are place on the soil surface and time until complete infiltration is measured.

To analyze the dye experiments the pictures of the stained profiles were separated into stained and unstained areas yielding dye coverage maps. The image analysis steps are shown in Fig 2. The original image was divided into binary images for single channels. For each pixel it was tested if the value was above or below a threshold. The threshold was set as selective as possible. In the final dye coverage maps only those areas are defined as stained, for which all channels are classified as stained (Fig. 2).
Fig. 1: Pictures of Tracer application and profile preparation

Fig. 2: Image analysis steps to identify the dye coverage exemplarily shown for a 1 m wide profile (a) shows the original picture (b) the binary images for each of the 5 used channels and the respective threshold values and (c) the resulting dye coverage map, with the dyed area in black.

Modeling

Two-dimensional numerical modeling was used to compare the leaching of contaminants for homogeneous and heterogeneous flow fields. Flow and Transport parameters were determined in preliminary column experiments. The flow patterns identified in the dye tracer experiments were reconstructed. This is shown for one profile in Fig. 3. In a second group heterogeneity was caused by stochastic distribution of Miller-Miller similar scaling factors (Miller and Miller, 1956) to systematically investigate the impact of heterogeneous flow patterns on contaminant leaching. The correlation length and coefficient of variation of variance of the scaling factors was varied. One of the scenarios is shown in Fig 4. All simulation scenarios were compared to a homogeneous scenario, that otherwise had the same initial and boundary conditions. The water and solute transport modeling was conducted with Hydrus2D Version 2.05. (Simunek et al., 1999). Water transport is solved with the Richards equation (Richard, 1931) and solute transport with the convection dispersion equation (e.g. Hillel, 1998). Adsorption is modeled with...
the Freundlich isotherm, applying the local equilibrium assumption. The van Genuchten-Mualem parameterization of the hydraulic functions is selected (van Genuchten, 1980; Mualem, 1976). The parameters are derived from the ROSETTA pedotransfer function (Schaap et al., 1999) and from preliminary column experiments. The solutes considered were i) a low adsorbing solute, dissolved in the precipitation and initially not present in the soil with the properties of BB (own column experiments), ii) a low adsorbing solute, uniformly distributed in the soil, with the properties similar to Cr (VI), and iii) a strongly adsorbing solute, uniformly distributed in the soil, with properties similar to Cr(III) (USEPA, 1999).

Fig. 3.: On the left the Brilliant Blue concentration (mmol cm\(^{-3}\)) a model scenario for a profile with structured heterogeneity as identified in dye experiments, and on the right the dye coverage map of the same profile. Profiles are 4 m wide and 2.5 m and 2 m deep, respectively.

Fig. 4.: On the left the distribution of the scaling factor for water pressure heads for one of the model scenario with stochastic heterogeneity, and on the right Brilliant Blue concentration (mmol cm\(^{-3}\)) after 500 days. Profiles are 4 m wide and 2.5 m deep.

Results and Discussion

Dye Tracer experiments

Figure 5 shows two typical dye coverage maps. All profiles showed heterogeneous flow patterns. All samples from the first layer classified as unstained by image analysis exhibited actual and extreme potential water repellency. In stained areas the samples from the top soil are not water repellent or show low hydrophobicity. It seems to be sure to say, that water is directed to areas of low hydrophobicity and infiltrate there. This is in unison with the theory of flow in water repellent soils Ritsema and Dekker (1995). However in these experiments water was ponded on the surface and runoff took place. So water infiltrated in micro depressions. The strong negative
The identified flow patterns show that the scale of heterogeneity is in the decimeter scale and therefore above that of typical laboratory columns. Therefore it seems to be impossible to predict the heterogeneity with laboratory experiments. Using dye tracers in field experiments therefore seems to be a relatively cost-effective and fast alternative. However to obtain pictures of the infiltration patterns the soil needs to be disturbed at a relatively large scale. Furthermore dye tracer experiments do not show a lot of dynamics. This strongly limits its applicability for risk assessment of ground water pollution. In combination with numerical simulation these shortcomings can be overcome.

![Fig. 4: Vertical flow patterns of the 1 m x 1m profiles with stained areas in blue under 50 mm irrigation and 25 mm irrigation.](image)

**Modeling**

![Fig. 5: Time series of concentration of homogeneous profile (structured heterogeneity) at observation nodes in 1 m (red) and in 1.5 m depth (blue and black) at different positions in the profile](image)

Figure 6 shows the time series of the concentration of Brilliant Blue and Cr(VI) in six observation nodes for the homogeneous profile. For comparison the Cr(VI) concentration curves for one typical structured profile and one stochastically heterogeneous profile are shown in Fig. 7. Concentrations in observation nodes show extreme variances for both structural and stochastic heterogeneity compared to the homogeneous case. This is true to almost the same degree for
observation points in same depths and close to each other. A sampling of soil solution with at points therefore will not yield representative results under heterogeneous flow patterns.

![Graph](image.png)

**Fig. 7:** Time series of concentration of profile with structured heterogeneity (left) and stochastic heterogeneity (right) at observation nodes in 1 m (red) and in 1.5 m depth (blue and black) at different positions in the profile.

If the discharge loads from 1 m wide sections is considered (Fig. 8 for BB and Cr(VI) in the homogeneous case and Fig. 9 for Cr(VI) for exemplary heterogeneous profiles), the leaching rate and mass still deviates largely between the sectors. Compared to single observation nodes, however, the variance is decreased. If the typical scale of preferential flow paths lies around 10 cm, it can be seen (not shown here), that at observation points there is large variance, but in 1 m wide sections, the variance are somewhat balanced. This indicates that for these profiles sampling seepage in 1 m wide sections will be enough to reliably predict contaminant transport. So generally dye tracer experiments can help to predict the necessary scale for seepage sampling devices.

![Graph](image.png)

**Fig. 8:** Cumulative contaminant leachate of the homogeneous profile for Brilliant Blue (dissolved in precipitation) and Cr(VI) (initially uniformly distributed in the soil) averaged over 1 m wide sections.

The time lines of discharge loads for the heterogeneous profiles (Fig. 9) show distinct tailing. The rate of leachate decreases with time, because the contaminants leached at later times, are those that are preserved in increasingly less conductive sites. In the preferential flow paths the concentration is quickly largely reduced. The complete leachate of contaminants is faster under homogeneous flow fields, because bypassing of large regions prevents leaching of contaminants.
in the heterogenous profiles. In the beginning however leachate loads are higher under heterogeneous conditions, because of some preferential transport.

Besides the spatial variance in leaching also the temporal variance is high. This is true for homogenous flow fields as well. But under heterogeneous flow fields the temporal variance is also increased (not shown here). This is because some regions are only percolated under specific saturation conditions. Since no kinetically limited adsorption is considered the temporal variance is rather underestimated.

Fig. 9: Cumulative contaminant leachate of the profile with structured heterogeneity (left) and stochastic heterogeneity (right) homogeneous profile for Cr(VI) (initially uniformly distributed in the soil) averaged over 1 m wide sections.

Conclusions

The influence of hydrophobicity on preferential flow can be demonstrated by analyzing stained and unstained samples separately. Unstained areas correlate with low water repellency. However, hydrophobicity alone cannot explain the flow patterns on the site, since it is limited to the top 10 cm and preferential flow is also initiated below that. The flow patterns could be well described by the dye tracer experiments. The heterogeneity cannot be analyzed on the scale of usual laboratory experiments. To identify the impact on contaminant transport a numerical simulation is necessary.

The heterogeneity always causes preferential transport, leading to areas where leaching is faster than under homogeneous flow conditions. The discharge load deviates extremely spatially and temporally under structural and stochastic heterogeneity. Especially solutes entering the soil with precipitation show different discharge loads, since the solutes are preferentially transported in the preferential flow paths. Contamination from contaminants with limited reserve in the soil leads to quickly decreased concentrations in the flow paths and tailing caused by leaching of increasingly less percolated regions. The extreme variance makes a representative point measurement of seepage composition impossible. Without knowing the flow patterns conclusions for the whole profile are impossible. Some balancing of the variances takes place in 1 m wide sections. It is only significant if the scale of typical flow path width is around 10 cm. An investigation of flow patterns therefore can yield important insight into necessary scales of seepage sampling devices.

References


Poppe, M., Schroder, H.G., Woeste, W., 2002. Contamination of wood with chromium and
chromate. Gefahrst Reinhalt L 62 (7-8): 315-318
Schaap, M.G., 1999. Rosetta Lite, Version 1.0. U.S. Salinity Laboratory, USDA, ARS, Riverside, California