Visualization and modeling of preferential pathways in soils

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VISUALIZATION AND MODELING OF PREFERENTIAL PATHWAYS IN SOILS

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Flow patterns

Moisture and flow patterns are of utmost importance for matter transport and spatial distribution of pollutants and availability of nutrients in the soil compartment of ecosystems. They reflect and influence the habitat for soil organisms and control the (bio-) chemical environment of turnover processes to a high degree. Hagedorn et al. (1999) found, based on micro suction cup measurements, increased N transformations in preferential flow paths compared to the soil matrix. Bundt et al. (2001) found 15 –75 % higher concentrations of soil organic matter and total nitrogen in stained preferential flow paths of a dye tracer experiment compared to the soil matrix. They concluded that soil organic carbon is younger and N turnover faster in the preferential flow region than in the soil matrix. Soil structure, spatial variation of nonlinear material functions, and dynamics of upper boundary conditions are commonly accepted key factors of flow path formation (Vogel et al., 2006). Interactions of precipitation, vegetation, surface properties and soil structure result in complex flow patterns and preferential pathways dividing the flow area in slow and fast subregions (e.g. Šimůnek et al., 2003).

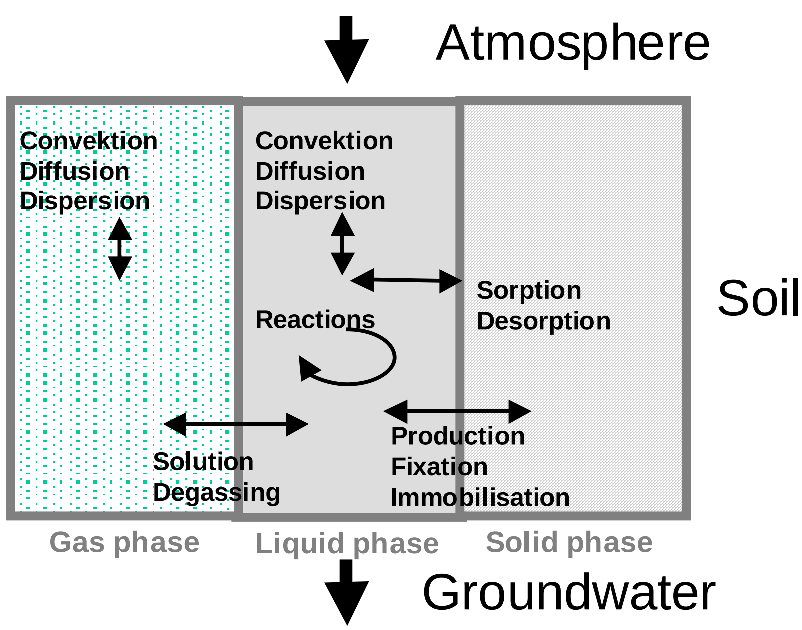

Figure 1: Schematic representation of flow and transport processes in an idealized soil.

Typical transport phenomena are fingering and macropore fluxes in cracks, earthworm tubes and along root channels. A comprehensive review on macropore processes can be found in Jarvis (2007). Flow patterns are often regarded as dynamical stochastic patterns. Surprisingly, Hagedorn and Bundt (2002) found that despite various boundary conditions at different sampling times, pathways of infiltrating water were relatively persistent with time in a forest soil. Water, energy and matter dynamics are further modified by agricultural and forest management measures like crop rotation, fertilization, tillage, forest thinning (e.g. by storm damages) or even clear-felling systems. Soil hydraulic material functions are nonlinear and exhibit pronounced hysteretical behaviour.

Weather characteristics, throughfall distribution, and the soil-atmosphere interface may considerably be affected by upcoming climate changes causing shifts in patterns and dynamics of water repellency, infiltration, evaporation, plant-availability of soil water and leaching of nutrients and pollutants. The role of boundary conditions have been extensively discussed in the context of surface sealing, crust formation, groundwater recharge, runoff generation, and soil erosion by water (Stolte et al., 1997; McDowell and Sharpley, 2002). However, they are also important for rapid flow phenomena in soil. Initiation and formation of preferential flow both depend on rainfall patterns and intensities. In forest ecosystems open field precipitation is transformed by canopy morphology and stem distribution of trees producing complicated infiltration patterns (Johnson and Lehmann, 2006).

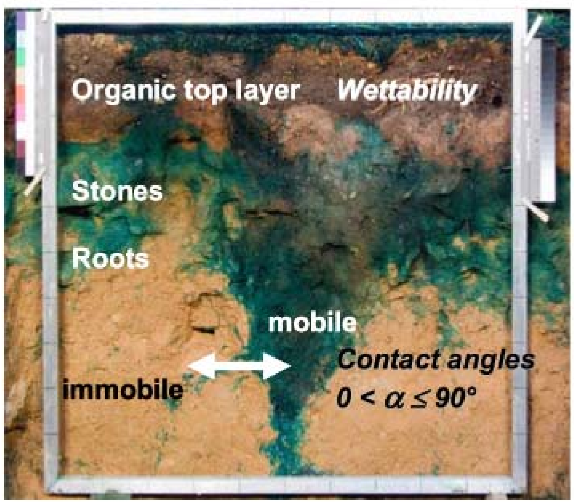

Figure 2: Prefential flow in a forest soil in the Fichtelgebirge mountains: factors and processes.

In Middle European forest ecosystems sealing of the soil surface normally is not a serious issue regarding runoff and erosion. However, soil – atmosphere interactions may have a considerable impact on the water and matter status of forest soils as well. Two mechanisms may be discussed in this context. The first is the likely role of spatial configurations of organic top horizons (thickness, litter orientation, discontinuities, and roots). Litter production and quality may change during global change (change in turnover processes, storm damages). The second is related to changes in the contact angle of infiltrating water and water repellency patterns. Figure 2 summarizes some important factors and processes concerning preferential flow in the soil of a forest ecosystem in the Fichtelgebirge mountains in Southern Germany.

Visualizing flow paths

To study water flow and solute transport in soils, dye tracer experiments are often performed (Ghodrati and Jury 1990). Brilliant Blue is frequently used for its low toxicity and good visibility against the background colour of most soils (Flury and Flühler 1995; German-Heins and Flury 2000). Usually, pictures of stained patterns serve for qualitative illustration of preferential flow. Recent works, however, propose a more quantitative approach based on modern image processing techniques (Forrer et al. 2000; Schwartz et al. 1999; Weiler and Flühler 2004). Most of the tracer experiments documented in literature were carried out on agricultural land. To the authors' knowledge, there are only few studies in stony forest soils (Buchter et al. 1997; Schulin et al. 1987a; Schulin et al. 1987b) or in tropical soils (Reichenberger et al. 2002; Renck and Lehmann 2004).

In this contribution we focus on the combination of computer based image analysis in combination with extreme value statistics as proposed by Schlather and Huwe (2005a,b). Results from three climatologically different sites will be presented: a) a tropical mountain rain forest in Southern Ecuador (Bogner et al. 2008), b) a forested site in the Fichtelgebirge Mountains in Bavaria (Germany; Bogner et al., 2007), and c) an agricultural site in Southern France (INRA, Avignon, unpublished). At each of the study sites, a plot of approximately 2m^2 was chosen. We eliminated litter and grass from the soil surface and applied a concentrated Brilliant Blue solution using a spray system similar to the one described by Ghodrati et al. (1990). Several vertical soil profiles were dug and photographed within a metallic frame of 1m^2.

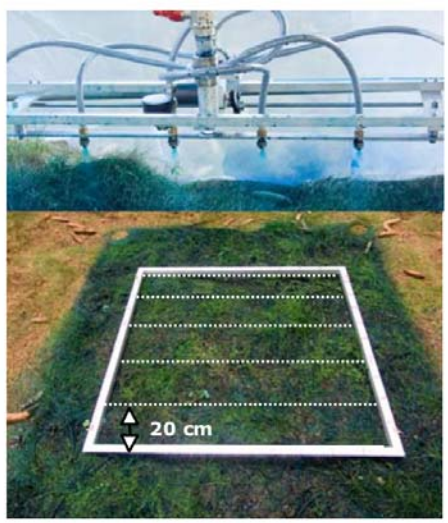

Figure 3: Performing a Brillant Blue dye tracer experiment on a forest soil (top: sprinkler unit; bottom: soil surface after tracer application; Fichtelgebirge, Germany, 2006)

An example of preferential flow is shown in figure 4. The Brillant Blue distribution clearly highlights the preferential flow zones in a tilled agricultural soil near Avignon in Southern France. Flow systems are strongly modified by tractor tyres and drought induced cracks.

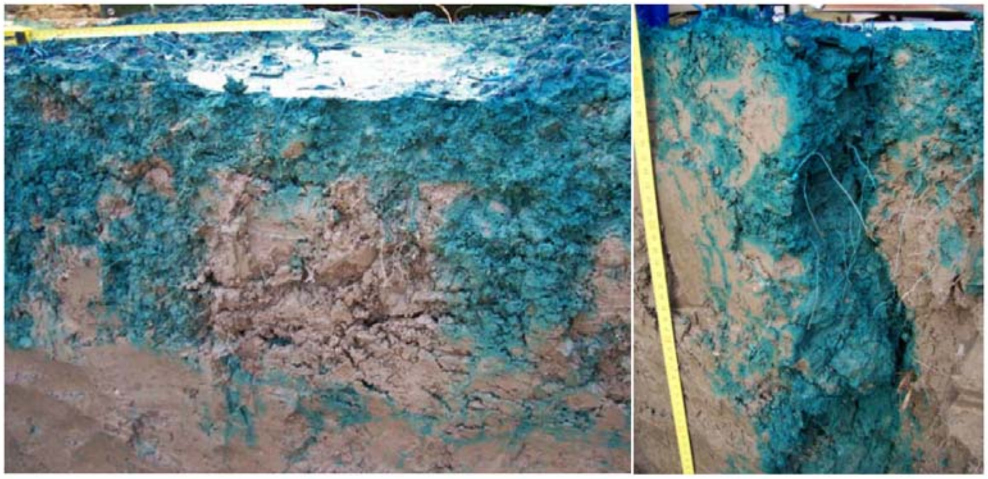

Figure 4: Example of flow systems in a tilled agricultural plot with compaction zone caused by tractor tyres (right) and with a drought induced deep crack (INRA, Avignon, 2007; Bogner 2007, unpublished)

Image analysis and risk index

After geometrical correction performed with the software PTLens (Niemann) and PTGui 5.5 (New House Internet Services B.V. 2005), the profiles within the frame were cut out. On some images, a part of the plot surface or a shadow of the frame was visible. These regions would disturb further processing and were cut away. Using the software Matlab 7.1 (The MathWorks, Inc. 2005a) and the Image Analysing Toolbox 5.1 (The MathWorks, Inc. 2005b), we extracted the blue patterns using colour-based segmentation with K-means clustering and generated binary images with stained parts in black and non-stained in white. From these images we estimated the risk index for soil leaching using the software package SoPhy ver 1.0.25 (Schlather 2005) written in R (Ihaka and Gentleman 1996).

Schlather and Huwe (2005a,b) formulated a model based on extreme value statistics. It describes $p(d_i)$, the number of stained pixels in depth d_i, as being an estimate of the probability to find stained pixels in at least this depth, up to a multiplicative constant m. The authors fitted the tail distribution 1–H to the function p(d)/m, H being the generalised Pareto distribution:

$$H(d, \xi_r, s) = 1 - \left(1 + \frac{\xi_r\, d}{s}\right)^{-1/\xi_r}$$

where $s > 0$, $\xi_r \in \mathbf{R}^+$ and d such that $1 + \xi_r\, d/s > 0$. They proposed ξ_r, called the form parameter of the generalised Pareto distribution, as a risk index for the vulnerability of groundwater by pollutants. The estimated risk index was interpreted as follows: for given experimental and pedological conditions

(1) If $\xi_r < 0$: H has an upper end point; the dye tracer does not exceed a certain depth.
(2) If $\xi_r > 0$: H has an infinite upper end point; the water table is surely reached.

(3) If $\xi_r = 0$: H decreases exponentially; the water table is reached, but the transported mass might be negligible.

We think that it is only possible to interpret the form parameter of the Pareto distribution directly as a risk index for groundwater vulnerability for regions with rather homogeneous geological material between the soil surface and the water table, like sedimentary basins with shallow water tables. Since a tracer experiment characterises the flow regime in the top one meter of soil, one can not expect that the Pareto distribution defined here will still be appropriate for greater depth when the geological layers change. In our study area, the ground water is not being monitored. So not knowing how deep the water table is nor what geological layers occur, we propose to interpret the form parameter of the Pareto distribution as a risk index of soil leaching and a characteristic of the flow regime for given experimental conditions.

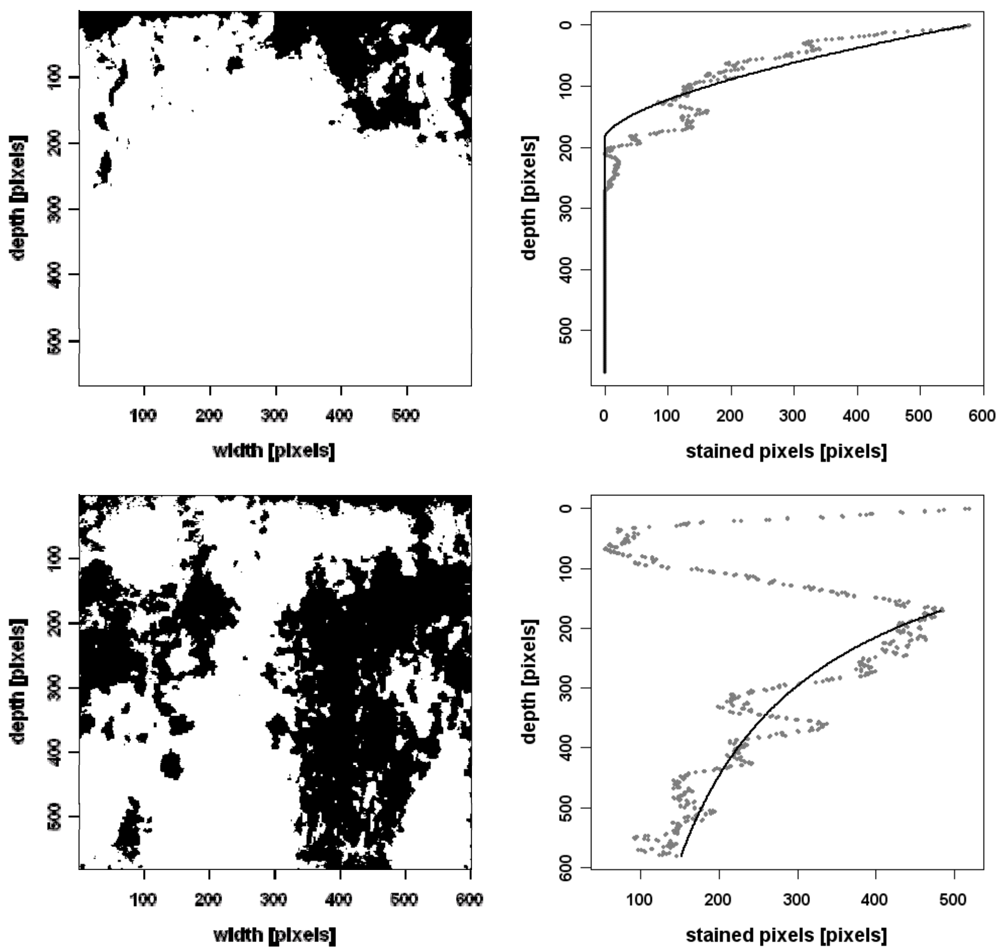

Figure 5: Results from image processing and nonlinear fit of the generalised Pareto distributions (Southern Ecuador, top row: new landslide, ξ = -0.62; bottom row: old landslide: ξ = 0.7; Bogner et al., 2008).

Examples for image analyses and risk indices are exemplary shown in figure 5 for soils in an old and new landslide of a tropical mountain rainforest landscape in Southern Ecuador. It should be noted that the risk index of the old landslide is positive while that of the new slide is negative.

Modelling flow systems

Modelling transport in heterogeneous, structured soil is still a demanding task. An overview can be found in Šimůnek et al. (2003). Promising approaches are two region models where flow in both regions is described by Richards' equation and structure information is condensed into the exchange term between the fast and slow flow region (Gerke, 2006). Measuring and modelling dynamics of macrostructure elements in soil like cracks and tubes is still in its early stages (e.g. Vogel et al., 2006). A stochastic modelling approach for three-dimensional simulation of flow paths is suggested by Schlather and Huwe (2005a) based on extreme value statistics and random field simulations.

Here we present to approaches. The first is process based and uses a forward modelling of processes with a detailed representation of spatial distribution of stones. The second is a stochastic model for spatially distributed flow paths.

Figure 6: Photograph of a 4 m x 1.5 m soil profile in a tropical mountain rain forest in Southern Ecuador. The red squares show two digitalised sections used for water flow simulations (Zeilinger 2008 in Bogner et al., 2008).

In the deterministic approach, matric potential-water content functions and the hydraulic conductivity functions were calculated with Rosetta, a computer program for estimating soil hydraulic parameters. It is based on artificial neural analysis and implements hierarchical pedotransfer functions which allow the estimation of van Genuchten water retention parameters and the saturated hydraulic conductivity using texture data (Schaap et al. 2001). Two-dimensional simulations were performed withHydrus-2D (Simunek et al. 1998), a model for water flow, heat and solute transport in two-dimensional variably saturated media that uses the finite element method to solve the following extended form of Richards' equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x_i}\left[K\left(K^A_{ij}\frac{\partial h}{\partial x_j} + K^A_{iz}\right)\right] - S \quad ,$$

where θ is the volumetric water content $[L^3L^{-3}]$, h is the pressure head [L], S is a sink term $[T^{-1}]$, x_i (i=1, 2) are the spatial coordinates [L], t is time [T], K^A_{ij} are components of a dimensionless anisotropy tensor K^A, and K is the unsaturated hydraulic conductivity function $[LT^{-1}]$ given by:

$$K(h, x, z) = K_s(x,z)\, K_r(h, x, z),$$

where K_r is the relative hydraulic conductivity and K_s the saturated hydraulic conductivity [LT^{-1}]. Two 40 cm x 40 cm large sections of the profile were chosen (red squares in figure 6) and the stones were digitalised and simulated as internal zero flux boundaries to investigate their influence on the flow regime. We applied the same constant infiltration rate of 2 cm/d on the upper boundary of each section.

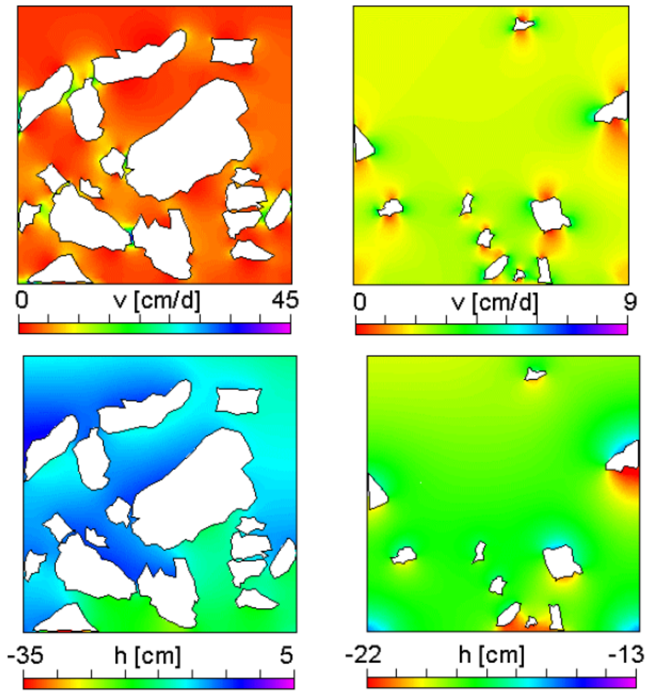

Figure 7: Results of water simulation run 2: Distribution of flow velocities (top) and matric potential (bottom) in the two digitalised sections (figure 1) at steady state. Boundary conditions: top: constant infiltration rate of 2 cm/d; bottom: free drainage; stones: internal boundaries of zero flux(Zeilinger 2008 in Bogner et al., 2008).

Simulation results clearly show that stones have a high influence on the flow regime. This is an important aspect as in our mountainous study area soils have a high stone content. Figure 7 shows flow velocities and pressure heads of a steady state simulation of the square regions in figure 6. We observed complex patterns in the distribution of flow velocities and matric potential, with pronounced differences between the two sections. A high stone content leads to high velocities near the stones and especially in the gaps between them causing preferential flow paths. Stones create a higher grade of differentiation in the soil with relatively wet areas on their tops and dryer areas between them. As a consequence, they modify water and solute transport like nutrients and pollutants as well as chemical reactions.

The stochastic modelling approach is based on several concepts and assumptions described in Schlather and Huwe (2005a). The potential depth of the infiltration or dye tracer is determined by the heterogeneous availability of water at the surface, but also by other factors like the pore size, hence the velocity of the infiltrating water. The depth can be modelled by a stationary and isotropic random field for fields without slope. Water is assumed to infiltrate at certain locations that are Poisson distributed. Here we allow for many more infiltration points to account also for matrix flux. Paths, especially those of the preferential flow, are not vertical, but have a complicated geometry, assuming a simple, 3-dimensional path with stochastic variations. For simplicity, we assume that the radius is constant in depth. Concentrations are not discriminated.

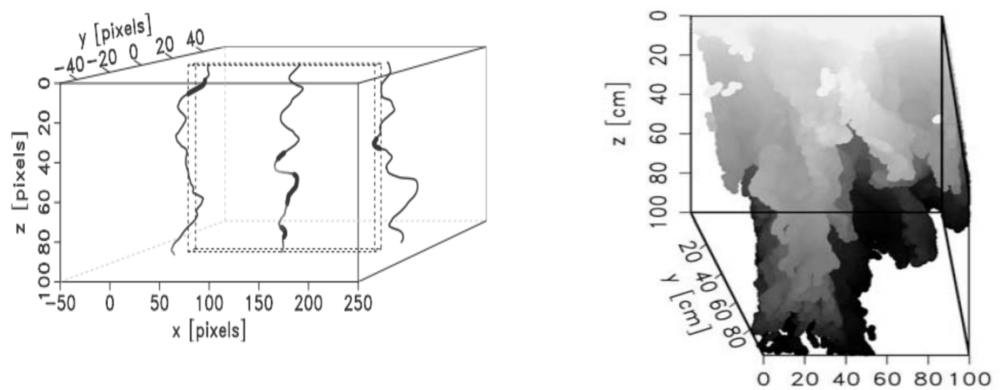

Figure 8: Stochastic modelling of flow paths (left: principle; right: example; Schlather and Huwe, 2005a,b)

Principles of the path modelling are shown in figure 8. An exemplary simulation result (one realisation of the stochastic process is given on the right side of figure 8 with the view point below the soil profile. Figure 9 show four realisations of the same stochastic path generating process. Here two-dimensional slices are cut out of the threedimensional flow system. From figure 9 it becomes clear that a correct assessment of the risk of groundwater pollution for a field site with preferential flow systems is quite a difficult task.

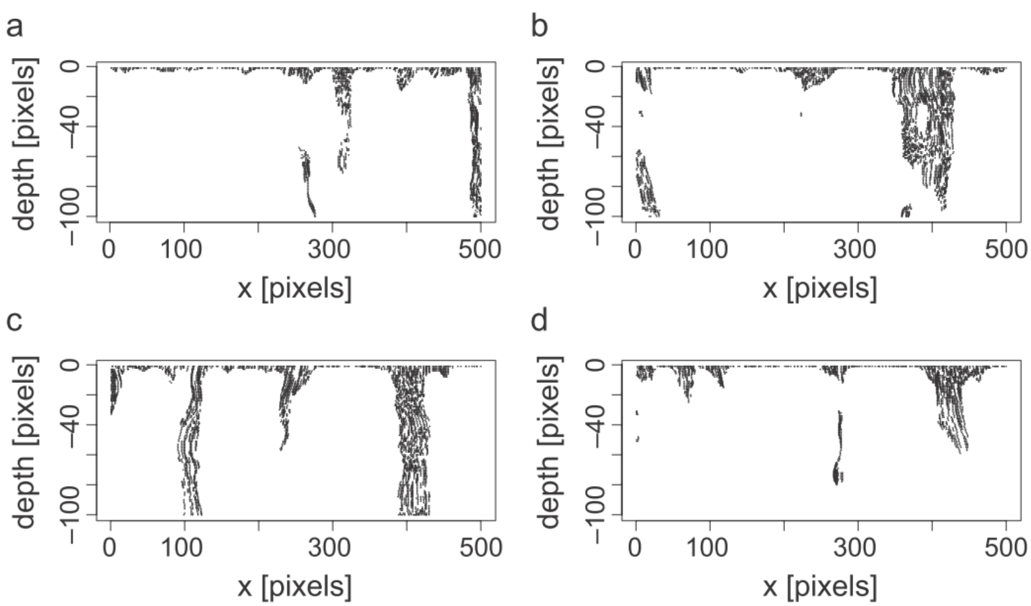

Figure 9: Four realisations of stochastic simulations of flow paths for flow system with $\xi = 1.5$ (Schlather and Huwe, 2005a)

Perspectives

There is good evidence that soil structure, precipitation intensity and plant roots are key factors for preferential flow of water. But the quantitative role of specific factors like tillage, crack formation, litter structure and stone content for flow processes most often remains unknown under field conditions. Furthermore, we still need to understand how the relevance of these key factors changes under extreme atmospheric boundary conditions and whether further factors (such as small-scale wettability in macropores) may gain in importance.

Experiments done by Bundt et al. (2001) and Hagedorn et al. (1999) showed that chemical processes in preferential flow paths can differ from those in the soil matrix. Preferential flow creates different compartments for chemical reactions, but consequences for leaching of nutrients and solutes and for C- and N-turnover are still poorly understood. And we do not know how these processes will change under extreme atmospherical boundary conditions. We need detailed knowledge on spatial small-scale variability of chemical parameters (C, N, Fe, Mn, cation exchange capacity, soil texture, soil water content and bulk density) to appreciate the difference between processes in the soil matrix and preferential flow paths and to quantify possible effects for larger-scale processes. Non invasive and image generating methods like ground penetrating radar, electrical soil tomography or VIS/NIR – spectroscopy together with spatial modelling of material properties and heterogeneous process modelling could possibly be helpful tools to tackle these demanding tasks.

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