Verification of flow processes in soils with combined sprinkling and dye tracer experiments

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Abstract. Water flow in soils is influenced by macropores, by the heterogeneity of the soil matrix, and by the exchange of water between macropores and the soil matrix (interaction). The degree of interaction influences the runoff generation process in soils with macropores during extreme rainfall events. Despite a well developed macropore network, rapid overland flow can be generated due to low interaction in combination with low permeability in the subsoil. Low interaction in combination with permeable lateral flow pathways in the subsoil, however, results in bypassing of the topsoil and the generation of rapid subsurface flow. The water movement during infiltration and the resulting flow paths were studied with sprinkling experiments and dye tracing under different rainfall intensities and soil moisture conditions. The dye tracer was continuously applied with the sprinkling water on 1 m2 plots. After the sprinkling, cross-sections of the soil were prepared for surveying horizontal and vertical dye patterns, thus displaying the cumulated flow path in the soils. These experiments were carried out on sites, where different runoff generation processes were expected. The experimental results illustrate the influence of the water exchange between macropores and the soil matrix on runoff generation. The observed flow processes in macroporous soils depended on the water content of the soil matrix, the soil structure, the rainfall intensity and the water repellence near the soil surface. The verification of flow processes in the field was improved with combined sprinkling and dye tracer experiments.

1 Introduction

Infiltration into natural soils takes place either through the soil matrix or through preferential flow paths, called macropores. Macropores, which are voids formed, for example, by soil fauna, decay of plant roots, wetting and drying processes, freeze-thaw cycles, or the erosive action of subsurface flow (BEVEN & GERMANN, 1982)), can significantly influence the infiltration rate and storage capacity of soils. In recent years, macropore flow processes have been studied with intact soil columns (HEATHMAN ET AL., 1995; BOOTLINK ET AL., 1993) or with artificial macropores in the laboratory (PHILLIPS ET AL., 1989; GHODRATI ET AL., 1999). Little is known, however, about how macropore flow on field sites is initiated (water supply to the macropores) and how water transfer between macropores and the surrounding soil matrix (interaction) takes place. But these relationship controls the degree of macropore flow and thus infiltration into natural soils (BEVEN & GERMANN, 1982; BUTTLE & HOUSE, 1998; FAEH ET AL., 1997).

Macropore flow is initiated either at the soil surface or within the soil. Flow in macropores that extend to the soil surface is initiated when the hydraulic conductivity of the soil matrix is less than the rainfall intensity or when the soil near the surface is saturated. In macropores not open to the soil surface, flow can be initiated at a near-surface saturated horizon (WEILER ET AL., 1998; LI & GHODRATI, 1997). The amount of water that flows into each macropore is different, because the surface topography determines macropore flow initiation at the soil surface and the density and distribution of macropores determine initiation in the soil.

Different types of macropores have different lining material that can modify the water exchange between macropores and the soil matrix. Earthworm deposits produce a lining material high in clay and silt content (BANSE & GRAFF, 1968). Macropore lining in holes formed by root decay is created from bark material or translocated clays and oxides (SCHOENBERGER & AMOOZEGAR, 1990). A lining material of clay, silt or humus particles is created by deposition of downward moving particles from the soil surface in hydrologically active macropores, like cracks.

The hydraulic conductivity of the interface between the macropores and the soil matrix controls the water exchange between the two domains. Interaction has been measured in single artificial or natural macropores in the laborator (SMETTEM, 1986; GHODRATI ET AL., 1999). VAN STIPHOUT ET AL. (1987) carried out field experiments with dye tracers and soil water measurements under dry and wet initial soil moisture conditions. They could determine the water exchange between macropores and the soil matrix at various depths. Their method seems to be at the appropriate hydrological scale to investigate the interaction process. Dye tracers were also used successfully in field experiments to visualise the continuity and the hydrological effectiveness of macropores (BOUMA & DEKKER, 1978; FLURY ET AL., 1994).

In addition to soil properties, there are other factors that influence macropore flow. Water can also flows through macropores when the soil matrix is unsaturated (PHILLIPS ET AL., 1989). Rainfall intensity and initial soil moisture content can influence the infiltration in soils containing macropores (VAN STIPHOUT ET AL., 1987; BOUMA, 1990; TROJAN & LINDEN, 1992). Therefore, macropore infiltration studies should be performed with different rainfall intensities and initial soil moisture conditions (BEVEN & GERMANN, 1982; BOUMA, 1990).

In hydrological models, soil is often considered as a continuous porous media, where the water flow depends on the hydraulic conductivity and the water content of the soil. Some models take into account macropore flow and define a higher conductivity and a possible bypassing of the soil when a threshold of the rainfall intensity is exceeded. However, the role of the initiation of macropore flow and the role of the interaction between the macropores and the soil matrix are only implemented in some special models (e.g. FAEH ET AL., 1997).

The objective of this study is to observe and analyse flow processes in soils containing macropores with combined sprinkling and dye tracer experiments. Different rainfall intensities and initial soil moisture conditions are investigated on four sites with different soil and macropore properties. Especially, the effects of the initiation of macropore flow and the water transfer between macropores and the surrounding soil matrix on the resulting flow processes is discussed.

2 Field Experiments

The experiments presented here were designed to study macropore flow and factors that influence it at the field scale. We used combined tracer and sprinkling experiments with different rainfall intensities and initial soil moisture conditions. The four sites selected for the experiments shared three features:

1.)They were located in catchments where some unexpected large floods have occurred.

2.)They were covered by pasture, where an undisturbed development of a macropore system by earthworms was possible.

3.)They were situated on slopes to make overland flow possible.

The soil properties, the parent material and macropore properties of the sites are summarised in Table 1.

The experiments were performed with a sprinkler device covering an area of 1.5 m^2. TDR probes, tensiometers and facilities to measure overland flow were installed (Fig. 1). At each

Table 1 Properties of the soils of the four sites

Site	Soil Classification *	Geological parent material	Average values at 30-80 cm depth			
			Density ($g\ cm^{-3}$)	Soil texture†	Macroporosity ‡ (%)	Number of macropores per m^2
Rietholzbach	Mollic Cambisol	Conglomerates (molasse)	1.30	loam / clay loam	0.35	228
Heitersberg	Umbric Cambisol	Moraine	1.65	loam	0.41	357
Koblenz	Eutric Cambisol	Moraine	1.50	silt loam / loam	0.58	698
Niederweningen	Eutric Cambisol	Sandstone (molasse)	1.45	sandy clay loam / sandy loam	0.77	623

* Food and Agricultural Organization (1974)
† Soil Survey Staff (1951)
‡ Determination using the classified macropores larger 1 mm^2 of the horizontal cross-sections

site, four experiments were carried out. Two different rainfall intensities were applied on four plots with two different initial soil moisture conditions. We chose a 'high' rainfall intensity of 72 mm h^{-1} for 1 hour (corresponding to a 100 year rainfall in Northern Switzerland) and a 'low' rainfall intensity of 12 mm h^{-1} for 6 hours (corresponding to a 25 year rainfall). The initial 'dry' soil had not seen any rainfall for at least 2 weeks and the initial 'wet' soil had received an intense rainfall one day before the experiment.

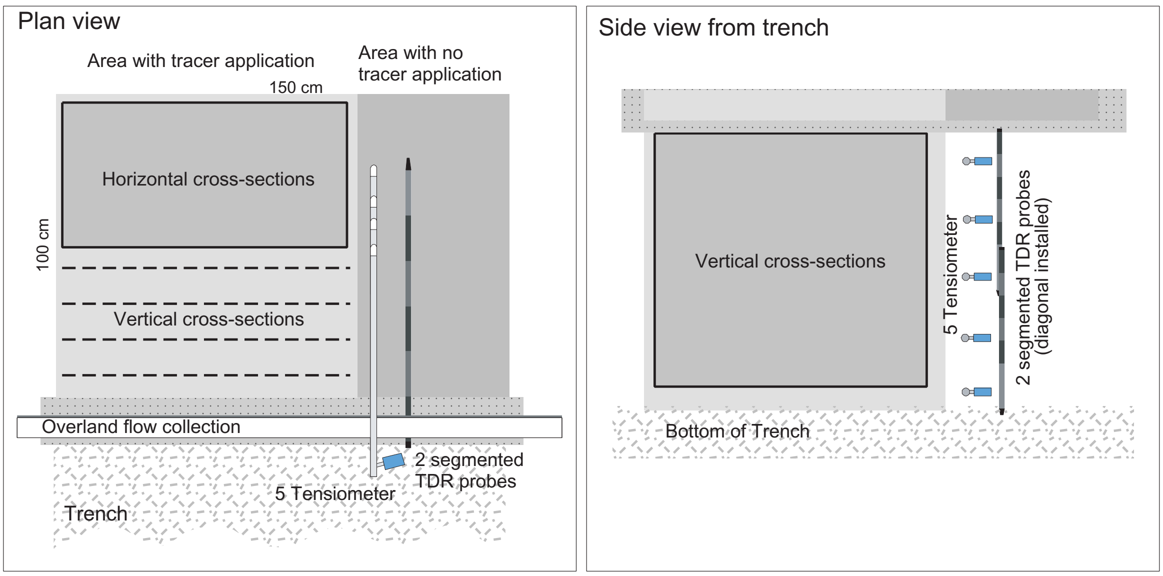

Fig. 1 Set up of the experimental plot

During the sprinkling experiments, the dye tracer Brilliant Blue FCF (C.I. 42090) with a concentration of 4 mg l^{-1} was continuously applied to produce a cumulative flow pattern of the infiltrating water in the so (GHODRATI AND JURY, 1990; FLURY ET AL., 1994). Brilliant Blue FCF provides a good compromise between mobility, visibility and toxicity (FLURY & FLÜHLER, 1995). One day after sprinkling, four to five vertical cross-sections 5-10 cm apart and four to five horizontal cross-sections at 5 to 70 cm depth were prepared and photographed, yielding 8 to 10 images per experiment. The vertical profiles covered an area of 100 by 100 cm, the horizontal profiles an area of 100 by 50 cm.

The soil water content and the matrix potential were measured at different depths. Diagonally installed segmented TDR probes monitored the soil water content (Fig. 1). Tensiometers, installed horizontally to prevent vertical preferential flow along the tensiometer tubes, measured the water potential in the soil matrix or in the macropores, depending on the position and the size of the porous cups (BOUMA, 1990).

The photographs of the cross-sections were evaluated as described by FORRER ET AL. (1999). The pictures were taken by daylight under a light tent to diffuse the light and to avoid direct radiation. A grey frame with a ruler and Kodak grey and colour scales were attached to frame the soil profile. A standard colour slide film (Kodak Ektachrome Elite 200) without optical filters was used. The pictures were scanned with a resolution of 3072 to 2048 pixels and corrected for geometric distortion using nearest neighbour resampling to yield a real resolution of 1 mm2 for the vertical profiles and 0.5 mm2 for the horizontal profiles. Because of the daylight conditions, the lower region of the vertical profiles and the corners of the horizontal profiles were darker than the other regions. This was compensated for using background subtraction based on the grey frame. Finally, the images were classified into stained, unstained and macropore areas using a conditional segmentation algorithm in the HSV colour space. The stained areas were further divided into three different concentration classes.

3 Results

Sprinkling experiments on the four different sites were used to illustrate the variety of flow processes in natural soils. The evaluation of the flow processes in the soil was based on observed and classified dye patterns and the measurements of water content and matric potential in the soil. Because the interpretation of all results of the experiments would go beyond the scope of this paper, only one experiment at each site was selected.

3.1 Site ‘Rietholzbach’

At the site 'Rietholzbach' the experiment with a high rainfall intensity on a 'dry' soil resulted in 23% overland flow of the total rainfall amount. Overland flow was observed 5 minutes after sprinkling had started, peaked after 10 minutes, and then slowly decreased. The dry soil near the surface (matric potential around 65 kPa) in combination with a water repellency of the organic material (verified with drop test) limited the infiltration into the soil matrix and therefore overland flow was produced. The non-wetting of the soil matrix near the surface can also be seen in the classified dye pattern (Fig. 2) of a vertical cross-section. Only a thin layer near the surface is stained in addition to the larger areas between 25-70 cm. Thus, the soil matrix was bypassed in the upper soil horizon by preferential flow paths and then partly wetted below 25 cm. This behaviour was supported by soil water content measurements, which showed a fast increase of the water content between 25-55 cm after 10-20 min, and matric potential measurements, which showed a sharp rise at 85 cm depth after 15 min.

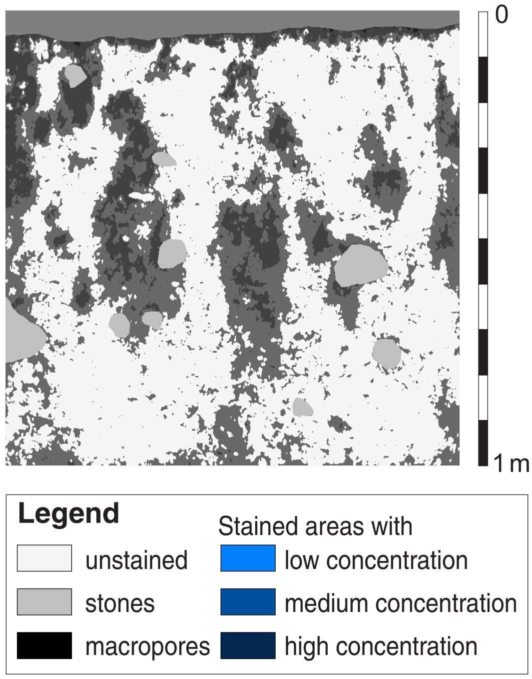

Fig. 2 Classified vertical dye pattern at site ‘Rietholzbach’.

Based on all observations, the flow processes during this experiment were evaluated (Fig. 3). The infiltration into the soil matrix was reduced due to its low permeability near the soil surface. Thus macropore flow was activated near the soil surface and controlled by the capacity of the macropore system and the interaction. The interaction was high due to a permeable matrix in the deeper soil layer.

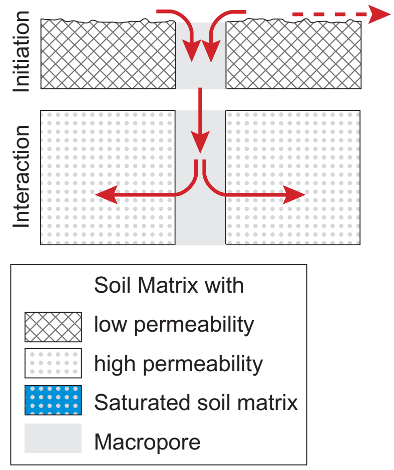

Fig. 3 Flow Processes during the experiment at site 'Rietholzbach'

3.2 Site 'Heitersberg'

Some results of the experiment with a high rainfall intensity on a 'wet' soil at the site 'Heitersberg' are shown in Fig. 4. The soil in the whole profile was nearly saturated prior to the experiment, with a matric potential of 1-4 kPa (Fig. 4a). After 20 minutes of sprinkling, the upper soil layer (0-30 cm) was saturated. As soon as the upper soil layer was saturated, surface runoff started and levelled off at a runoff coefficient of 15%. Thereafter, the matric potential in the soil below increased rapidly until the soil was saturated. Three classified dye patterns of horizontal cross-sections in different depths show that flow was restricted to a small percentage of the soil (Fig. 4b). The amount of staining decreased from the soil surface to deeper sections. The staining occurred mainly around visible macropores, in particular at the deepest cross-section.

The combination of the results of dye tracer experiments and soil water measurements allows an evaluation of the flow processes. Because the soil matrix was saturated quite rapidly, macropore flow determined the flow process in this experiment. The permeability of the soil in the upper 30 cm (A-horizon) was higher than the rainfall intensity, and the horizon could store the water during the first 20 min. After the top soil layer was saturated, macropore flow was initiated from this saturated horizon (Fig. 5). Because interaction was limited due to the satura-

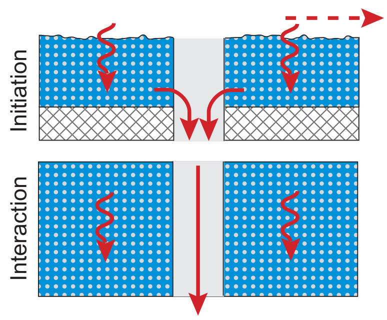

Fig. 5 Flow Processes during the experiment at site 'Heitersberg'

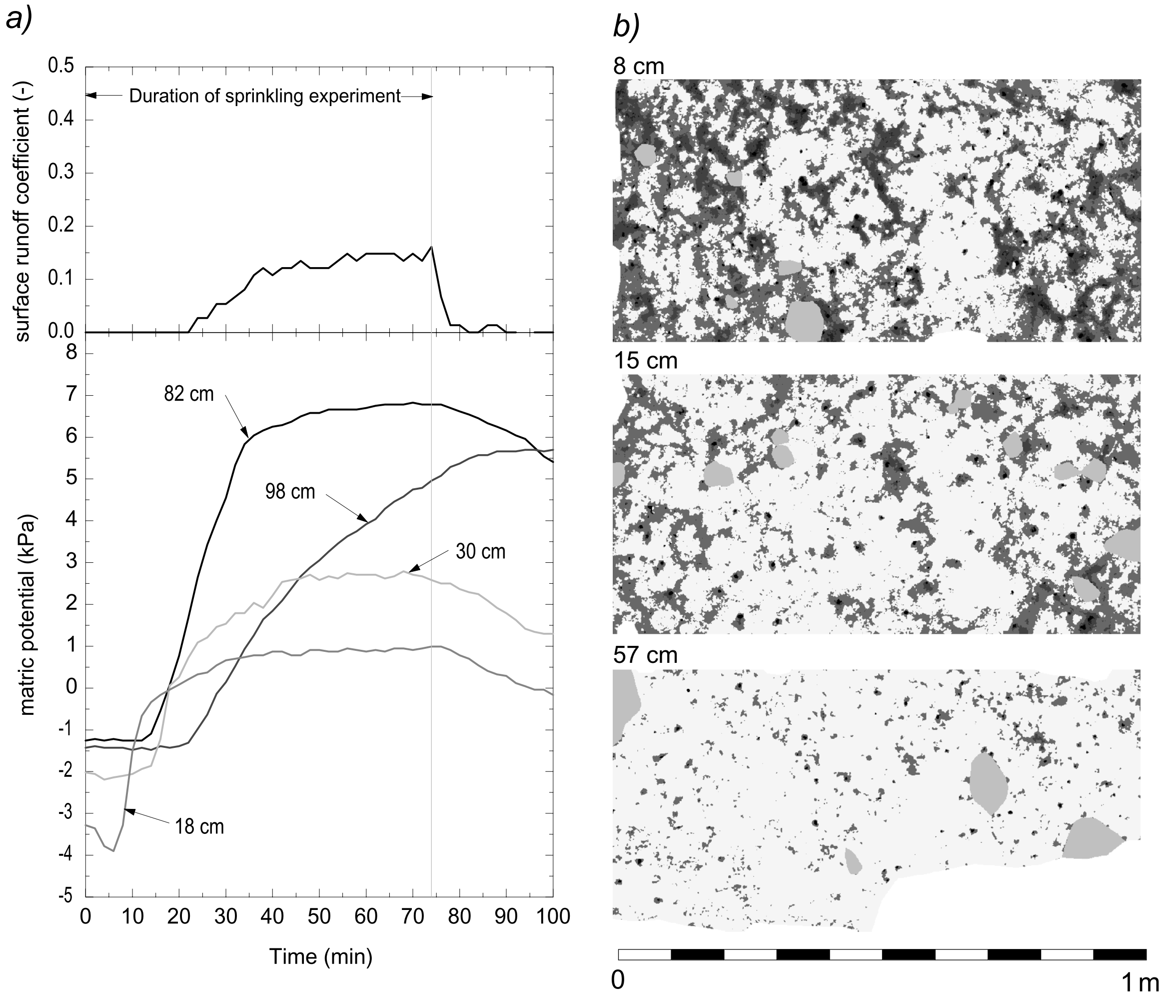

Fig. 4 a) Surface runoff and matric potential during sprinkling and b) classified horizontal dye patterns in three depth at site 'Heitersberg' (for legend see Fig. 2).

tion of the soil matrix, the drainage of the macropores into the geological bedrock material and into the macropore system controlled the infiltration rate and thereby the surface runoff.

3.3 Site 'Koblenz'

The experiment with a low rainfall intensity under 'dry' soil moisture conditions showed a dye pattern like that observed at the site 'Heitersberg' (Fig. 6a). The upper soil layer was nearly completely stained, whereas the soil below 30-40 cm was only stained near visible macropores. The matric potential of the upper soil layer increased rapidly, and the layer was saturated after 3 hours of sprinkling. However, the matric potential in the subsoil increased very slowly. The initial matric potential in the lower layer was 1-5 kPa and the soil was not saturated at the end of the experiment. However, the coloured water, which percolated from the macropores into the saturated bedrock, stained a creek, which was 110 m away from the site, within seven hours after the beginning of the experiment. An additional tracer experiment using NaCl was performed to measure the flow velocity of the fast subsurface flow pathways. The ion tracer was applied with three infiltrometer rings at the site in 70 cm depth to activate directly macropore flow. The conductance of the water in the creek was measured. The solute velocity was determined by fitting the transfer function model (JURY, 1982) to the breakthrough curve (Fig. 6b). The calculated velocity of 0.08 m s^{-1} showed, that the water flowed preferentially in the saturated bedrock.

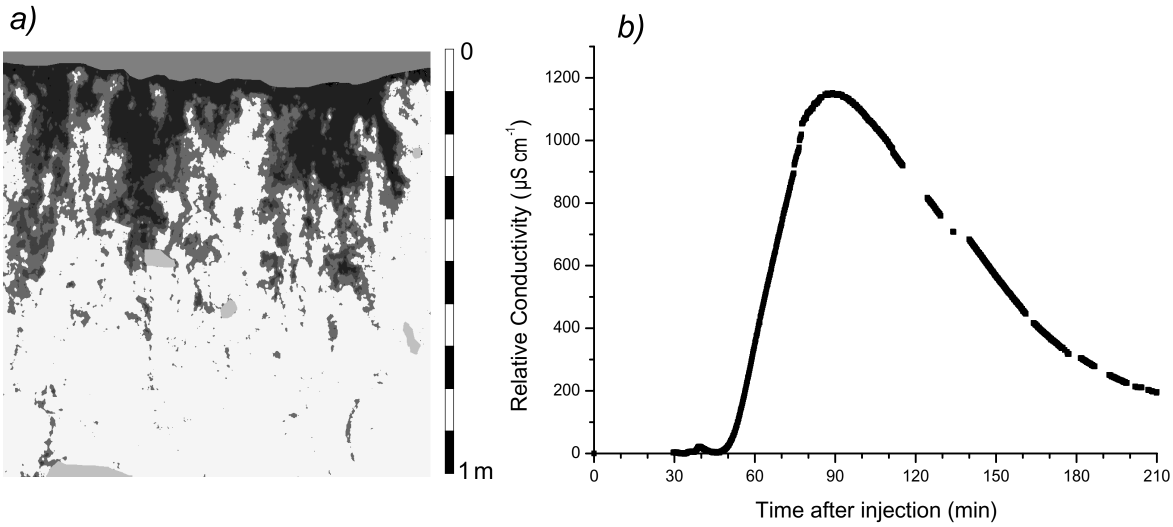

Fig. 6 a) Classified vertical dye pattern and b) breakthrough curve of NaCl at site 'Koblenz' (for legend see Fig. 2).

The evaluated flow processes of this experiment are summarised in Fig. 7. After saturation of the upper soil layer, macropore flow was initiated at the soil surface and from the saturated upper soil layer. Despite a slightly unsaturated soil matrix, macropore flow dominated below 40 cm. The low permeability of the soil matrix limited the interaction between the macropores and the soil matrix. However, the water in the macropore drained rapidly into the underlying saturated bedrock by efficient lateral subsurface flow pathways.

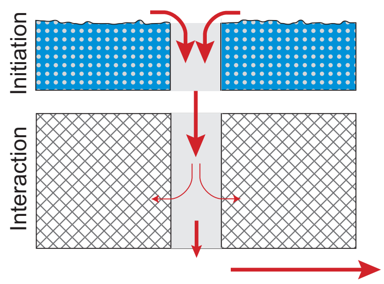

Fig. 7 Flow Processes during the experiment at site 'Koblenz' (f legend see Fig. 3).

3.4 Site 'Niederweningen'

Some results of the experiment with the low rainfall intensity under 'wet' soil moisture conditions are illustrated in Fig. 8. The water content increased rapidly near the soil surface (Fig. 8a) followed by an increase of the water content below 40 cm. The water content between 20-40 cm remained stable. The matric potential measurements showed a saturated upper soil layer and unsaturated conditions (3-12 kPa) between 20-40 cm. A classified vertical dye pattern illustrates the measurements (Fig. 8b). The upper soil layer is nearly completely stained. The layer between 20-40 cm shows only narrow linear features, which connect the upper soil layer with the layer below 40 cm. The soil layer below 40 cm shows an expansion of the staining.

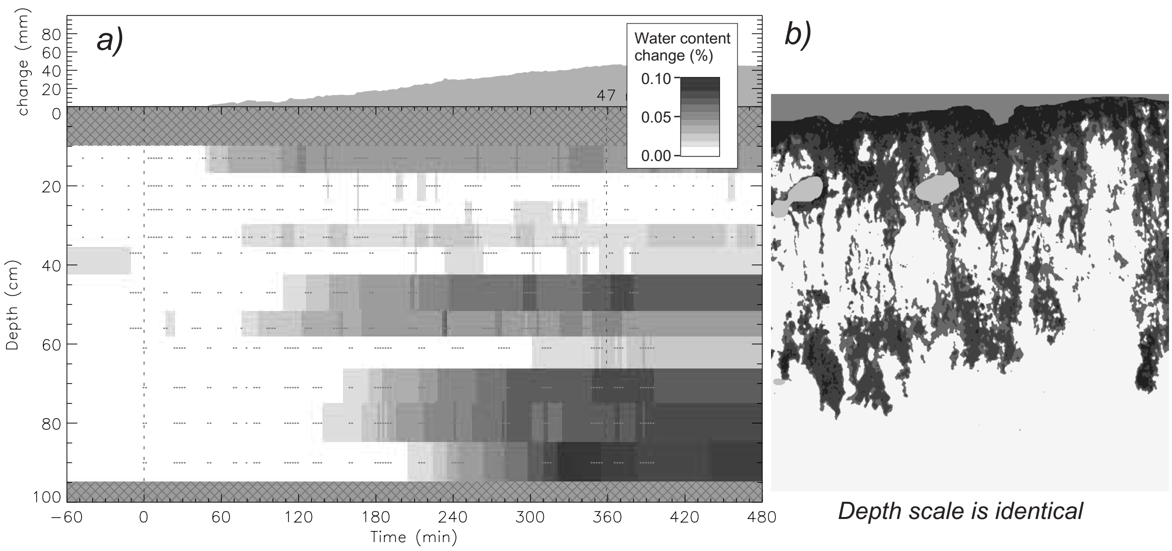

Fig. 8 a) Water content change during sprinkling and b) classified vertical dye pattern at site 'Niederweningen' (for legend see Fig. 2).

The flow processes, which were evaluated, were more multifaceted at this site (Fig. 9). Initiation of macropore flow occurred in the saturated upper soil layer. Between 20-40 cm the interaction was low and the water in the macropore was forced to flow to deeper soil layers. Because the soil texture changed at 40 cm (increase of sand, decrease of clay fraction), the interaction increased and the water flowed in the permeable soil matrix. Despite a lowly permeable soil matrix near the soil surface, infiltrating water bypassed this range in macropores and was stored in the subsoil. Because of these macropores, no overland flow was initiated.

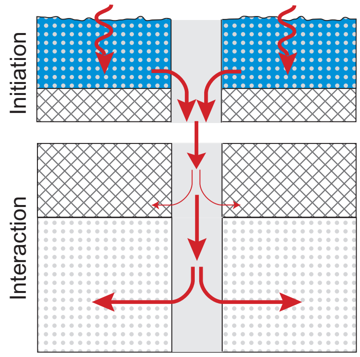

Fig. 9 Flow Processes during the experiment at site 'Niederweningen' (for legend s Fig. 3).

4 Conclusion

Flow processes in natural soils were observed and analysed with combined sprinkling and dye tracer experiments in the field. The results of the dye tracer experiments in combination with soil water measurements allowed a detailed evaluation of the flow processes that occurred during simulated extreme rainfall events. The flow processes, which were observed on the sites with similar soils, were quite different. The results imply that initiation of macropore flow and the water exchange between macropores and the soil matrix have a marked influence on the resulting flow processes. However, the processes of macropore flow initiation and interaction are not yet well enough understood to be correctly implemented into infiltration models. This study showed that water content of the soil matrix, soil structure, rainfall intensity, and water repellence near the soil surface influenced the flow processes in soils. Additionally, the study showed that macropore flow in natural soils dominates the flow processes. This study serves as an example to improve the understanding of macropore flow and to be able to model macropore flow processes more correctly in future.

5 References

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