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An experimental tracer study of the role of macropores in infiltration in grassland soils

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Abstract:

Water flow in macropores is an important mechanism of infiltration in natural soils and, as such, is crucial for the prediction of runoff generation. The major flow processes controlling macropore flow are the initiation of macropore flow (water supply into macropores) and the water transfer from the macropores into the surrounding soil matrix (interaction). The water movement during infiltration and the resulting flow paths were studied with combined sprinkling and dye tracer experiments under different rainfall intensities and initial soil moisture conditions. The dye tracer was continuously applied with the sprinkling water on 1 m^2 plots. After the sprinkling, horizontal and vertical soil sections were prepared for surveying dye patterns, which showed the cumulated flow pathways in the soils. These experiments were carried out on four hillslope sites covered with grassland, where earthworms mainly built the macropore system. The evaluation of the flow processes in the soil was based on classified dye patterns and measurements of water content and matric potential. The results illustrate how flow in earthworm channels influences general hydrological flow processes during extreme rainfall events. Macropore flow was initiated from the soil surface or from a saturated or partially saturated soil layer. Transfer of water from the macropores into the soil matrix was mainly influenced by the soil properties and soil water content. The permeability of the underlying bedrock in combination with this transfer of water controlled the drainage of the macropores. Finally, major effects of macropore flow processes on the hydrological response were extracted. Infiltration excess overland flow was reduced if water bypassed the less permeable layer through macropores, saturation excess overland flow was less affected by macropores, and subsurface flow was activated very rapidly because the infiltrated water bypassed the soil matrix. This study highlights the most important processes that have to be considered in order to understand better and to model infiltration in natural soils in the future. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS macropore flow; initiation; interaction; dye tracer; runoff generation; experiments; infiltration; preferential flow

INTRODUCTION

An important mechanism that strongly influences infiltration in natural soils is water flow in macropores. Macropores are voids formed by soil fauna, decay of plant roots, wetting and drying processes, freeze–thaw cycles, or the erosive action of subsurface flow (Beven and Germann, 1982). The effect of macropores on water flow and transport in soils is an important research area in soil science (e.g. Ghodrati and Jury, 1990; Bootlink *et al.*•, 1993; Li and Ghodrati, 1997; Perret *et al.*, 2000). Hillslope hydrologists have especially discussed the effect of macropore flow on runoff generation (McDonnell, 1990; Smettem *et al.*, 1991; Tsuboyama *et al.*, 1994; Faeh *et al.*, 1997; Tani, 1997; Weiler *et al.*, 1998; Bronstert, 1999; Sidle *et al.*, 2000). Yet, macropore flow processes are often not considered in hydrological rainfall-runoff models, where soils are usually treated as a continuous porous medium and flow depends only on the hydraulic conductivity and the water content in the soil. Some models take into account macropore flow by defining a higher conductivity and a possible Q1

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bypassing of the soil, if a threshold of the rainfall intensity is exceeded (Katzenmaier *et al*., 2000). However, the main and relevant processes controlling macropore flow, especially the initiation of macropore flow and the water exchange between the macropores and the soil matrix, are not adequately considered and parameterized. This disregard leads to an unrealistic parameterization of soil properties in hydrological models in order to compensate for the influence of macropore flow (Grayson *et al*., 1992) and an incorrect prediction of flow pathways in catchments where macropore flow is an important process. The prediction of the flow hydrograph in the river may still be acceptable, but the internal hydrological behaviour in the catchment and the prediction of the water flow pathways are insufficient.

In this paper, the effects of macropores on flow processes in grassland soils, where earthworms mainly built the macropore system, are studied in detail. Combined sprinkling and dye tracer experiments with different rainfall intensities and initial soil moisture conditions were carried out on four different sites. The main objective was to investigate the initiation of macropore flow, the flow of water in the macropores, and the water transfer from the macropores into the surrounding soil matrix by combining information from the dye patterns and hydrologic measurements. Finally, a conceptual outline of the observed flow processes and the hydrological response is presented.

FLOW PROCESSES IN SOILS CONTAINING MACROPORES BUILT BY EARTHWORMS

The following short review on macropore flow in earthworm channels introduces the issue and also aims at justifying the experimental set-up. Infiltration into soils takes place through the soil matrix or the macropores. At many grassland sites in Switzerland, macropores developed by earthworms tend to generate a vertically oriented, continuous network of channels, and the flow rate in these macropores can be very high compared with the flow rates in the soil matrix. Even for unfavourable conditions the flow rate in wormholes is always higher than the rainfall intensity (Bouma *et al*., 1982; Wang *et al*., 1994). Thus, wormholes can significantly influence the infiltration rate and storage capacity of soils, if flow in the macropores is initiated and the water in the macropores is not immediately absorbed into the surrounding soil matrix. The initiation of macropore flow (water supply into macropores) and the water transfer from the macropores into the surrounding soil matrix (interaction) are the main controls on the infiltration in macroporous soils (Beven and Germann, 1982; Faeh *et al*., 1997; Buttle and House, 1998).

Macropore flow initiation is a function of initial water content, rainfall intensity and amount, hydraulic conductivity, and surface contributing area (Trojan and Linden, 1992). There is still a large demand for experiments to explore the causes and extent of macropore flow initiation (Flühler *et al*., 1996). Water can flow into macropores from the soil surface or from a saturated or partially saturated soil layer. Léonard *et al*. (1999) investigated surface initiation with laboratory experiments and used the results to verify a flow model. Ruan and Illangasekare (1998) studied surface initiation with a model that coupled overland flow and infiltration into macropores. Subsurface initiation was studied in the laboratory (Phillips *et al*., 1989; Ela *et al*., 1992; Li and Ghodrati, 1997) and could also be detected in the field (Weiler *et al*., 1998). Some studies verified that macropore density and the slope and roughness of the soil surface mainly influence surface runoff (Trojan and Linden, 1992; Léonard *et al*., 1999).

The water transfer from macropores into the surrounding soil matrix (interaction) was also referred to as lateral infiltration from the macropores (Beven and Clarke, 1986). Interaction is one of the critical processes describing water flow in macroporous soils (Logsdon *et al*., 1996; Faeh *et al*., 1997). Factors influencing interaction can be subdivided into properties of the soil matrix and properties of the macropores. Horizontal water flow in an unsaturated soil matrix is governed by the soil characteristics, like the unsaturated and saturated hydraulic conductivity, and the initial soil moisture condition (Chen and Wagenet, 1992). Another property of the macropores, apart from the macropore density and geometry, is the interface between the macropores and the soil matrix.

Interaction has been measured in single artificial or natural cylindrical macropores in the laboratory (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 determined the water exchange between macropores and the soil matrix at various depths. Their method seems to be an alternative to laboratory experiments to investigate the interaction process under natural conditions. Dye tracers were also successfully used in field experiments to visualize the continuity and the hydrological effectiveness of macropores (Bouma and Dekker, 1978; Flury *et al*., 1994). There is also experimental evidence that water flows through macropores when the soil matrix is unsaturated (Phillips *et al*., 1989). This behaviour can be theoretically explained if we assume a higher flux in the macropore than the interaction flux. As rainfall intensity and initial soil moisture content influence the infiltration into soils with macropores (van Stiphout *et al*., 1987; Bouma, 1990; Trojan and Linden, 1992), studies should be performed to consider their influence (Beven and Germann, 1982; Bouma, 1990).

EXPERIMENTAL METHODOLOGY

Study sites

To study the flow processes in macroporous soils at the plot scale for extreme rainfall events, experimental sites have to be selected and an adequate experimental set-up has to be designed. The study was restricted to grassland, which is a common land-use type in Switzerland, and the experimental sites were selected to fulfil the following criteria:

- To be covered by grassland, preferably meadow, that has not been disturbed for the last 20 years. In undisturbed grassland soils, macropores are primarily formed by large (>2 mm diameter), vertically oriented earthworm borrows (Syers and Springett, 1983).
- To be located on a gently sloping hillside. Thus, overland flow produced during the experiments, can be collected and measured at the bottom end of the sites.
- To aim to select sites with different exchange of water from the macropores into the soil matrix. Some sites were already localized in previous experiments (Faeh *et al*., 1997); other sites were selected based on soil types and bedrock.

Table I shows an overview of the soil properties, the parent material and macropore properties of the four selected sites in northern Switzerland.

Field methodology

The experimental set-up was designed to allow the:

- uniform application of a dye tracer to the experimental plots;
- measurement of overland flow;
- measurement of soil water content and matric potential by inserting probes laterally from the trench beside the experimental plot, thus avoiding disturbance of the soil surface;
- application of different rainfall intensities;
- experiments to be carried out under different initial soil moisture conditions.

Thus, four combined tracer and sprinkling experiments with different rainfall intensities and different initial soil moisture conditions were carried out at each site. The two selected rainfall intensities correspond to an extreme convective and an advective event. Convective processes are short-time rainfall events of high intensity, whereas advective events last several hours with a moderate intensity. Therefore, around 75 mm

Table I. Soil properties of the four experimental sites

Site	Soil classification[a]	Geological parent material	Average values at 30–80 cm depth			
			Density (g cm^{-3})	Soil texture[b]	Macroporosity (%)[c]	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

[a] Food and Agricultural Organization (1974).
[b] Soil Survey Staff (1951).
[c] Determination using the classified macropores larger than 1 mm^2 of the horizontal soil sections.

of water was applied at a constant rate within 1 h for the high-intensity rainfall experiment and within 6 h for the low-intensity rainfall experiment. The two different initial soil moisture conditions of the experiments were obtained by the following procedure. For the dry condition, the soil was protected with a tarp against rainfall for 3 weeks prior to the sprinkling experiment. For the wet condition, the soil was sprinkled with around 75 mm of water 1 day prior to the experiment.

Prior to the sprinkling experiments, two to three time domain reflectometry (TDR) probes and four to six tensiometers were installed in the instrumentation plot. The TDR probes (Model MP-917, Type PRB-H, ESI Environmental Sensors Inc.) are long rods with five 15 cm long segments taking measurements at 2 min intervals. They were installed slightly inclined to horizontal from a trench below the instrumentation plot to measure the water content at depth intervals of around 10 cm. The tensiometers were installed horizontally from the same trench at different depths with a smaller spacing in the topsoil. The careful installation of the TDR probes and the tensiometers from the trench left the surface of the instrumentation plot unaffected, avoided vertical flow along the tubes, and reduced temperature effects (Buchter *et al.*, 1999). The tensiometer tubes were 120 cm long and the tensiometer cups were 60 mm long and had an outer diameter of 22 mm (Type 2630-1, Soilmoisture Equipment Corp.). Matric potential was measured with temperature-compensated pressure transducers (Type 5301, Soilmoisture Equipment Corp.).

The sprinkling device was designed to apply water mixed with a liquid dye tracer on an area of 1·1 m by 2·7 m. The spray bar of the device consisted of 15 flat-spray nozzles (JATO, F I–R 1/4″, size 0·5) with a spray angle of 90° spaced at intervals of 180 mm. The bar was installed 100 cm above the ground and moved 180 mm between two mountings driven by an electric linear actuator. With the movement of the bar and the nozzles spraying orthogonal to the bar, a uniform application was achieved. In all cases the uniformity coefficients for different intensities and rainfall amounts were above 0·85. The coefficients agree with values found in other studies of different rainfall simulators (Lascelles *et al.*, 2000). The pressure at the nozzle inlet was 320 kPa, resulting in a sprinkling intensity of 60–70 mm h^{-1}. The lower intensity was achieved with repeated intermittent sprinkling. The mountings and the actuator were fixed on two poles that had been drilled orthogonally to the soil surface into the ground at 3 m distance. The device was protected with a tarp to minimize wind effects and to prevent tracer losses. The set-up of the four plots with the different initial and boundary conditions at each experimental site and the location of the instrumentation plot are shown in Figure 1.

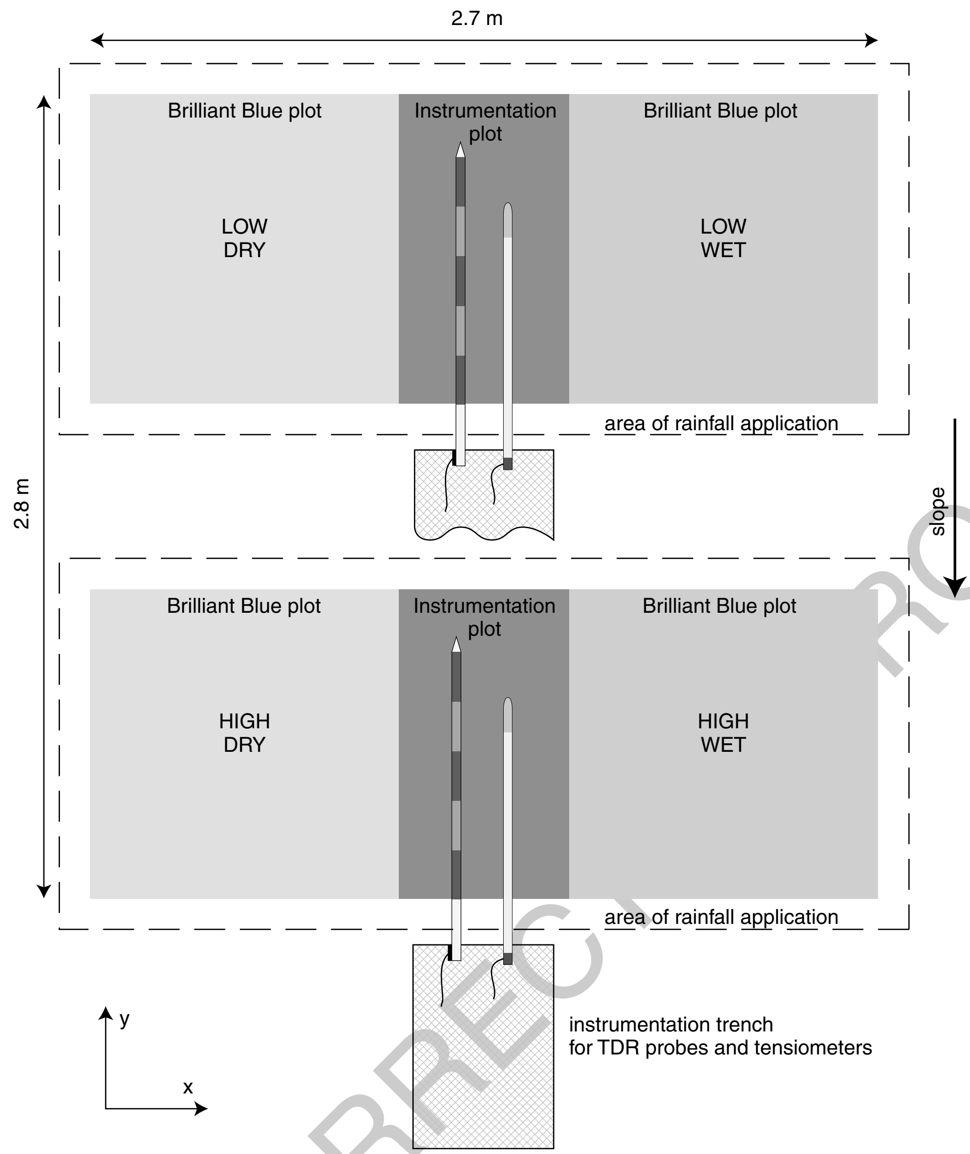

Figure 1. Set-up of the experimental plot (LOW: low rainfall intensity; HIGH: high rainfall intensity; DRY: low initial water content; WET: high initial water content)

Water fluxes and change in soil water content during the experiments were determined as follows. The actual rainfall was estimated by subtracting the measured losses during sprinkling from the total water application. The overland flow from the plot was collected and measured with tipping buckets. The measurements of the TDR probes were used to determine the total change of the water content in the soil profile. Because the water content was not surveyed consecutively from the surface to 100 cm depth, the available TDR measurements were interpolated to approximate the total water content change within the upper 100 cm of the soil profile. This value is somewhat approximate, because of an error of 0·023 to 0·034 $m^3 m^{-3}$ for the TDR measurements (Hook and Livingston, 1995), the limited region of influence around the TDR probes, and the interpolation between the TDR measurements.

The temporal measurements of the TDR probes at different depths were used to obtain the space–time distribution of soil water content changes. Because the TDR probes were not calibrated for every soil at each site, only relative values were used. The data of the TDR measurements were prepared as follows:

- data from segments of TDR probes that were found to have been exposed to vertical flow along the rods were removed;
- the surveyed depth locations of the segments were assigned to the depth ranges to each of the segments;
- the water content value at the beginning of the sprinkling was subtracted from the later observations for each probe segment to obtain the water content changes;
- the values between two consecutive measurements were linearly interpolated because the water content was measured at irregular time intervals.

The resulting soil water content changes for each experiment are shown in a depth–time graph in the left column of Figures 2 to 5. The water content changes are coded with different grey levels and illustrated for the depth range of each segment. Light grey shaded areas reflect depths at which the water content was not monitored. In addition, the tensiometer readings are shown by bars indicating the duration and the depth of the measured saturation.

The dye tracer Brilliant Blue FCF (C.I. 42090) added to the sprinkling water was used to visualize the cumulative flow pattern of the infiltrating water (e.g. Flury *et al*., 1994). This tracer is well suited to visualize flow pathways in vadose zone hydrological studies, because of its low toxicity, high visibility, and high mobility (German-Heins and Flury, 2000). Brilliant Blue FCF fronts are sharp and produce a strong colour contrast with the soil material, due to a self-sharpening effect (German-Heins and Flury, 2000). A concentration of 4 g l^{-1} ensured that the dye was still visible after dilution and adsorption (Flury and Flühler, 1995; Ketelsen and Meyer-Windel, 1999).

The same experimental procedure was applied twice at each site, once with the low rainfall intensity and another time with the high intensity. On the first day, the experiment started with sprinkling of around 75 mm of water without tracer on the wet and instrumental plot only (Figure 1). In this run, the measured soil water regime gives the results for the dry plot, and wet initial conditions were produced on the wet plot. The next day, water with Brilliant Blue was applied to the wet, dry, and instrumental plot. In this step, the measured soil water regime gives the results for the wet plot. On the third day of the experimental procedure, four to five vertical soil sections of 100 cm depth by 100 cm wide were cut from both the dry and wet plots, parallel to the lower border and starting 15 cm away from the lower border. The spacing of the vertical sections was 5–7 cm. The following day, four to five horizontal soil sections of 100 cm by 50 cm were prepared at different depths parallel to the soil surface with a closer spacing near the soil surface. The sections were carefully cut with a spatula and loose particles were removed with a vacuum cleaner. Thus, the macropore openings became clearly visible, allowing the determination of the macropore density and macroporosity.

Dye pattern analysis

The photographic recording of each soil section was done according to Forrer *et al*. (1999). The pictures of the soil profiles were taken by daylight under a whitish opaque foil (light tent) to diffuse the light and to avoid direct radiation. A grey frame with a ruler and a Kodak grey and a colour scale were attached to frame the soil profile. A Kodak Ektachrome Elite 200 colour slide film without optical filter 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 mm^2 for the vertical sections and 0·25 mm^2 for the horizontal sections. 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 difference was compensated for by 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 (Weiler, 2001).

Only the vertical dye patterns were used in this study for further analysis. The depth functions of the dye coverage with a vertical resolution of 1 mm were calculated for all four or five vertical dye patterns of each experiment. After the average soil surface ($z = 0$) was determined for each dye pattern, the depth function $f(z)$ of the dye coverage was related to the real soil depth. Thus, an averaged depth function for all vertical dye patterns of one experiment was calculated.

Apart from the dye coverage, the separated stained objects were also used for analysing the vertical dye patterns. The object width for a given depth of the vertical dye pattern is used as a proxy for the size of the object at this soil depth. Because the object width describes the extension of a stained flow pathway, it is referred to as stained path width (SPW). The depth function of the SPW for each object is evaluated for each vertical dye pattern. This procedure results in a frequency distribution of SPWs for each soil depth. The SPW was then classified into three classes (<20 mm, 20–200 mm, >200 mm) and the dye coverage of all objects within each class was calculated. The SPW classes were sorted according to their size. The second column in Figures 2 to 5 illustrates the resulting depth functions of SPW for each experiment. Because the SPW classes are shown as percentage of dye coverage, the maximum value is equal to the value for the total dye coverage.

RESULTS

Table II lists the water fluxes and soil water content changes of all experiments. Total rainfall, rainfall intensity, overland flow, and change in soil moisture (ΔSM) within the upper 100 cm of the soil profile were derived from measurements. The difference between total rainfall and overland flow is the infiltrated water. Subsurface flow could not be measured, but qualitative conclusions on its importance were drawn from the observed staining of the bedrock or exfiltrating tracer into a neighbouring creek.

Overland flow at the Rietholzbach site is significant for the experiment with the high rainfall intensity and the dry initial conditions. The low amounts of observed overland flow at the Heitersberg site were not consistent with results of sprinkling experiments covering an area of 60 m^2 by Scherrer (1997), who observed high amounts of overland flow. Because runoff at this site is generated after saturation of the soil, boundary effects of the small experimental scale influenced the measurements of overland flow (Weiler, 2001). Overland flow of less than 2 mm was probably produced by small saturated or low permeable areas near the overland flow collector. The change in soil moisture ΔSM within the soil profile cannot be larger than the amount of infiltrated water. The discrepancies between infiltrated water and ΔSM in Table II reflect the uncertainties in the estimation of soil moisture changes within the soil profile. The uncertainty results from the error of the TDR measurement device, the interpolation between the TDR measurements, and from the small spatial resolution of the region of influence of the TDR probes compared with the irregular infiltration pattern produced by macropore flow.

The experiments with the high rainfall intensity at the Rietholzbach site produced some subsurface flow (Table II, last column). At the Heitersberg site, subsurface flow was more pronounced for the wet soil moisture conditions. For the dry soil moisture conditions, subsurface flow was negligible. At the Koblenz site, the subsurface flow was directly observed in the creek some hours after the beginning of the experiment. Dye-coloured water, percolating from the macropores into the saturated bedrock, reached the creek at 110 m distance downslope. The low values of the soil moisture changes support the hypothesis that a large amount of the infiltrating water left the soil profile. In contrast to the results from the Koblenz site, no soil was stained below 100 cm at the Niederweningen site. There, the high values of the soil moisture changes support the observations that stained water did not leave the soil profile.

The flow processes in the soil and the dynamics of water flow in the macropores and the soil matrix were analysed in detail for every experiment at the four sites. To derive a conceptual description of the initiation of macropore flow and the interaction, the high temporal resolution data from the tensiometer and TDR measurements were combined with high spatial resolution information from the vertical dye patterns.

Table II. Water fluxes and soil moisture changes of the experiments

Site	Experimental conditions		Total rainfall (mm)	Rainfall intensity (mm h^{-1})	Overland flow (mm)	Infiltrated water (mm)	ΔSM (mm)	Remarks on subsurface flow
Rietholzbach	high	dry	86·5	69·2 (±9·3)	19·1	67·4	74	Bedrock below
	high	wet	73·6	62·2 (±8·8)	2·7	70·9	104	100 cm depth stained
	low	dry	91·7	15·2 (±1·5)	0·0	91·7	130	Bedrock not stained
	low	wet	65·2	11·2 (±2·4)	0·0	65·2	85	
Heitersberg	high	dry	79·3	64·3 (±6·0)	1·0	78·3	83	Stained macropores
	high	wet	78·7	65·6 (±7·8)	7·0	71·7	17	below profile,
	low	dry	73·1	12·2 (±1·6)	0·0	73·1	53	bedrock deeper than
	low	wet	77·2	13·2 (±1·1)	0·0	77·2	27	120 cm
Koblenz	high	dry	74·4	61·2 (±3·8)	1·7	72·7	35	Creek stained 1 h after
	high	wet	77·6	62·1 (±5·8)	4·9	72·7	7	start of experiment
	low	dry	75·0	13·0 (±2·5)	0·0	75·0	59	creek stained 4·5 h after
	low	wet	68·7	13·1 (±1·7)	0·0	68·7	23	start of experiment
Niederweningen	high	dry	75·7	64·9 (±6·4)	0·0	75·7	58	No staining below
	high	wet	77·1	68·0 (±9·2)	0·8	76·3	82	100 cm
	low	dry	70·7	11·8 (±1·7)	0·0	70·7	94	No staining below
	low	wet	77·7	13·0 (±2·3)	0·0	77·7	53	100 cm

Rietholzbach site

The results for the four experiments at the Rietholzbach site differ considerably (Figure 2). In the experiment with high rainfall intensity and dry initial soil moisture conditions, the water content increased mainly between 20 and 50 cm depth, which is also reflected in the higher dye coverage at this depth. The infiltrated water reached this soil layer without significantly wetting the top layer. Overland flow amounted to 23% of the applied rainfall and was observed 5 min after sprinkling had started, peaked after 10 min, and then slowly decreased. The dry soil near the surface, in combination with a water-repellent organic material, temporarily limited the infiltration into the soil matrix. The limited infiltration is reflected in the dye pattern of a vertical soil section (third column, Figure 2), where only a thin layer near the surface is stained. The soil matrix in the upper soil horizon was bypassed by macropore flow in visible earthworm channels. Areas between 25 and 70 cm depth were again stained and interaction was high, resulting in a high percentage of SPW of the 20–200 mm class. The soil matrix was saturated below 70 cm depth after 20 min due to water bypassing the soil above in earthworm channels. After saturation, interaction was stopped, resulting in a low dye coverage and low SPWs.

For the high-wet experiment, the influence of the water-repellent topsoil was reduced due to the pre-wetting. Thus, the dye coverage near the surface is higher and water content started to increase after 10 min. The water flowing in the wormholes could infiltrate into the soil matrix between 10 and 70 cm depth until the matrix was saturated. Therefore, the dye coverage and the SPW are quite high within this depth. Interaction was limited below 70 cm because of the same effects as for the high-dry experiment.

In the experiment with low rainfall intensity and dry initial soil moisture conditions, the water content in the topsoil layer did not change within the first 2 h of sprinkling. However, the water content increased between 20 and 70 cm depth. Thus, water flow in the wormholes was initiated at the soil surface and a high interaction resulted in an increase of the water content of the soil matrix. The high interaction can also be seen in the vertical dye pattern and the SPW within this depth range. After the soil surface was wetted, water infiltrated directly into the soil surface, resulting in an increase of the water content in the top soil layer and a complete staining. The water content did not change anymore after 3 h in the soil below 30 cm depth.

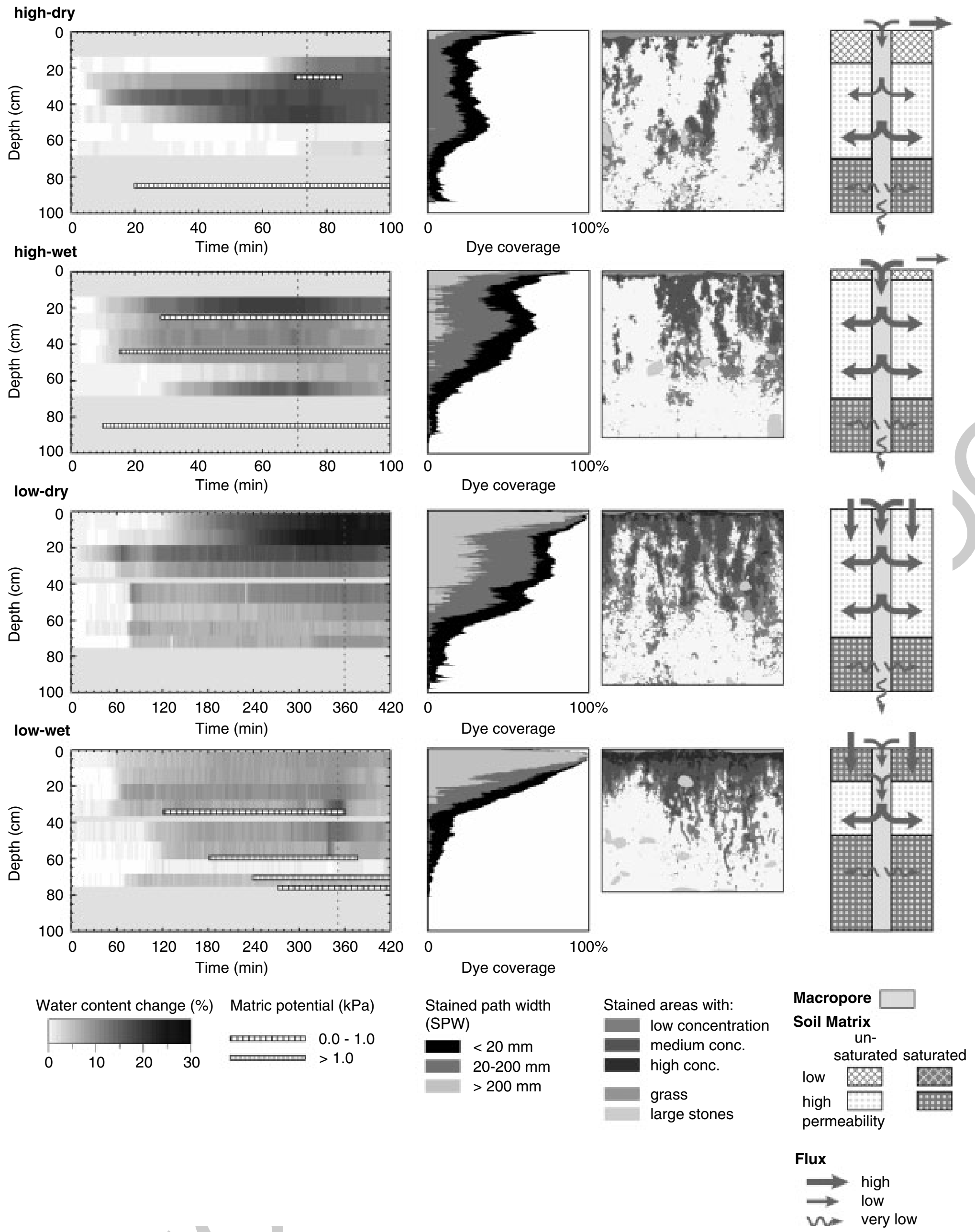

Figure 2. Experiments at the Rietholzbach site: depth–time plot of water content change and saturation (first column), depth function of dye coverage and stained path width (second column), example of a vertical dye pattern (third column), and conceptual model of the important flow processes (initiation and interaction) during sprinkling (fourth column)

For the low-wet experiment, the water content change and the saturation of the soil matrix started at the top and propagated to deeper layers. The tensiometer readings indicate that the soil was nearly completely saturated at the end of the experiment; however, no water table built up. The topsoil layer was completely stained due to water infiltrating in the soil matrix. At a depth of 30 cm, a sharp decrease of the dye coverage and the SPW was observed. This change of the flow regime in the soil was influenced by a partial wetting of the soil within the upper 35 cm and macropore flow initiation from saturated soil pockets. A low dye coverage and low SPW below 35 cm depth indicate that interaction was reduced.

A conceptual model of the important flow and runoff generation processes for the experiments at the Rietholzbach site was formulated (Figure 2, right column). The infiltration into the soil matrix was small, especially for dry initial conditions, due to the water-repellent soil surface. Thus, macropore flow was initiated at the soil surface, except for the low-wet experiment, where macropore flow was also initiated from saturated areas within the soil. Owing to initiation at the soil surface in combination with a low macropore density near the soil surface, only part of the water could enter the macropores, and the excess produced overland flow (Léonard *et al*., 1999; Weiler, 2001). The permeable matrix allowed a high interaction to a depth of 70 cm under non-saturated conditions. The soil matrix was nearly or completely saturated below 70 cm depth, resulting in a low interaction. Consequently, the site is generating surface runoff mainly after rainfall events with a high intensity after a longer dry period, a sequence that is frequent in summer when thunderstorms occur after a long dry period. Lateral subsurface flow on top of the bedrock (conglomerates), however, is generated if macropore flow exceeds interaction (usually for high rainfall intensities) and water bypasses the soil matrix in the wormholes.

Heitersberg site

At first sight, the results for the four experiments at the Heitersberg site look quite similar (Figure 3). The water content of the topsoil increased by 15 to 25% for the dry initial conditions and did not exceed 10% for the wet initial conditions. In accordance with the water content change, all experiments showed a pronounced staining of the upper soil layer, whereas the initial soil moisture conditions determined the thickness of the stained upper soil layer, especially for the experiments with the high rainfall intensity. The SPW in the topsoil is high, indicating a preferred infiltration into the soil matrix. The changes in water content below 30 cm depth are small (<5%) for all experiments. The dye coverage of the soil below 30 cm is low and the SPW is very small, indicating a low interaction from the wormholes into the soil matrix. The dye coverage of the subsoil is slightly higher for the low rainfall intensity.

The reactions of the matric potential for all experiments also show a similar pattern. A sharp rise of the matric potential in the topsoil was detected until this layer was saturated after the application of 30–40 mm of water for the dry initial conditions and 10–15 mm for the wet initial conditions. Then, the matric potential and the water content of the subsoil (below 40 cm depth) increased slowly, starting from the bottom up. This behaviour can be explained with a wetting front saturating the top layer, followed by initiation of macropore flow that continuously saturated the bottom layer. Depending on the rainfall intensity, a water table built up in the soil profile. When the water table reached the permeable topsoil, or even the surface during the high-intensity experiments, subsurface flow within the topsoil layer or overland flow started. Water flowing in the macropores could bypass the wet and low permeable soil matrix in the subsoil; however, drainage of the macropore system into the bedrock was not sufficient to drain the soil profile.

The conceptual evaluation of the flow processes for all experiments at the Heitersberg site is shown in the last column of Figure 3. The permeability of the soil in the upper 30 cm (A-horizon) was higher than the rainfall intensity, and water mainly infiltrated in the soil matrix. After the topsoil layer was saturated, macropore flow was initiated from this saturated horizon. The timing of macropore flow initiation depends solely on the saturation deficit of the topsoil and the rainfall amount. Because the low permeablity and saturation of the soil matrix reduced interaction and the low permeable bedrock prevented drainage of the macropores, the macropores filled up and then overland flow or subsurface flow in the permeable topsoil was generated. Because the saturation of the permeable upper soil layer mainly controlled the generation of runoff at this site, the initial soil moisture condition and the amount of rainfall determined the hydrological response of this site.

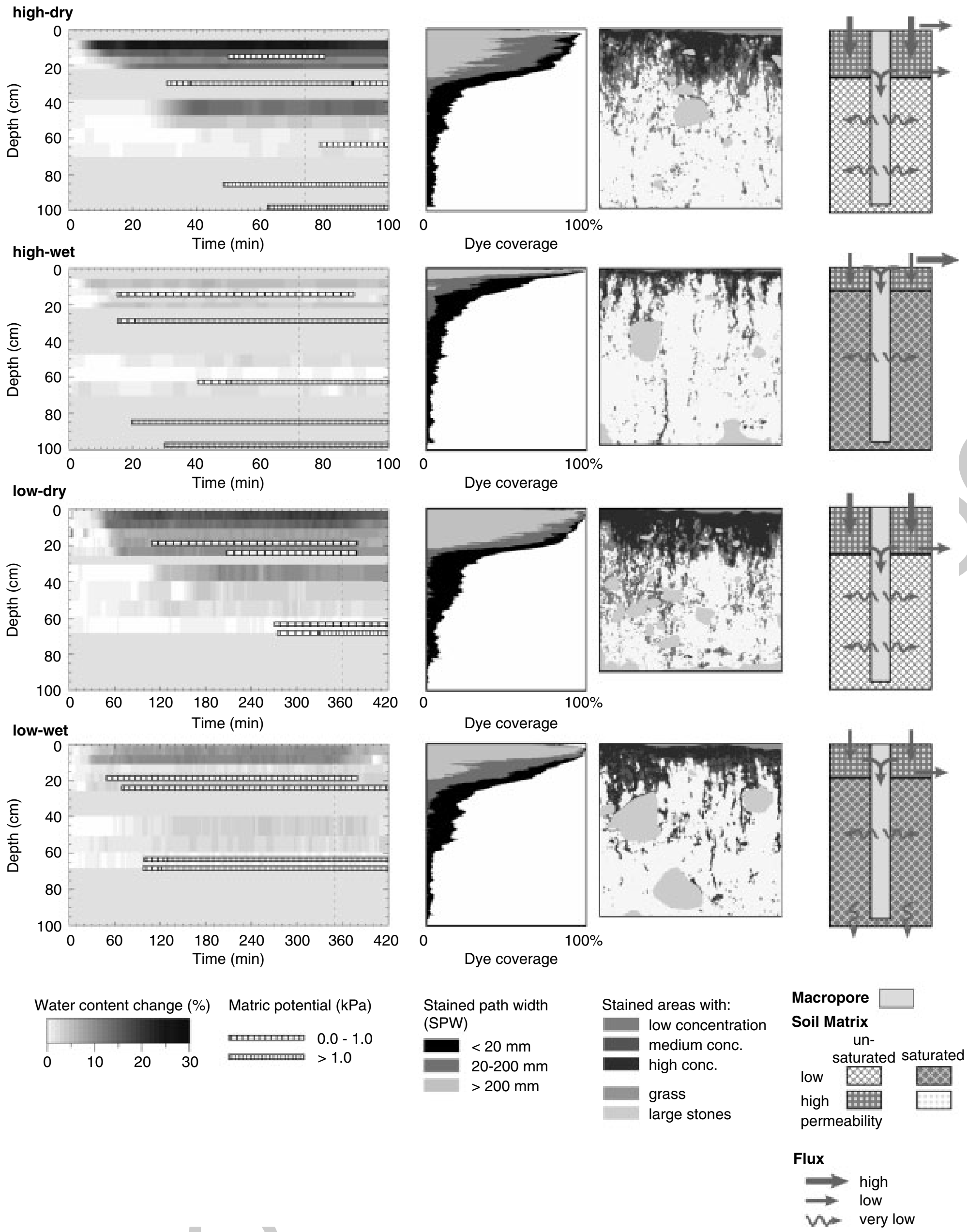

Figure 3. Experiments at the Heitersberg site: depth–time plot of water content change and saturation (first column), depth function of dye coverage and stained path width (second column), example of a vertical dye pattern (third column), and conceptual model of the important flow processes (initiation and interaction) during sprinkling (fourth column)

Koblenz site

Figure 4 illustrates the results of the Koblenz site. The results of the experiments with the high rainfall intensity were affected by a heavy rainstorm in the night after the experiment. Although the plot was protected by a tent, the groundwater table reached the soil surface. The groundwater leached the dye tracer from the

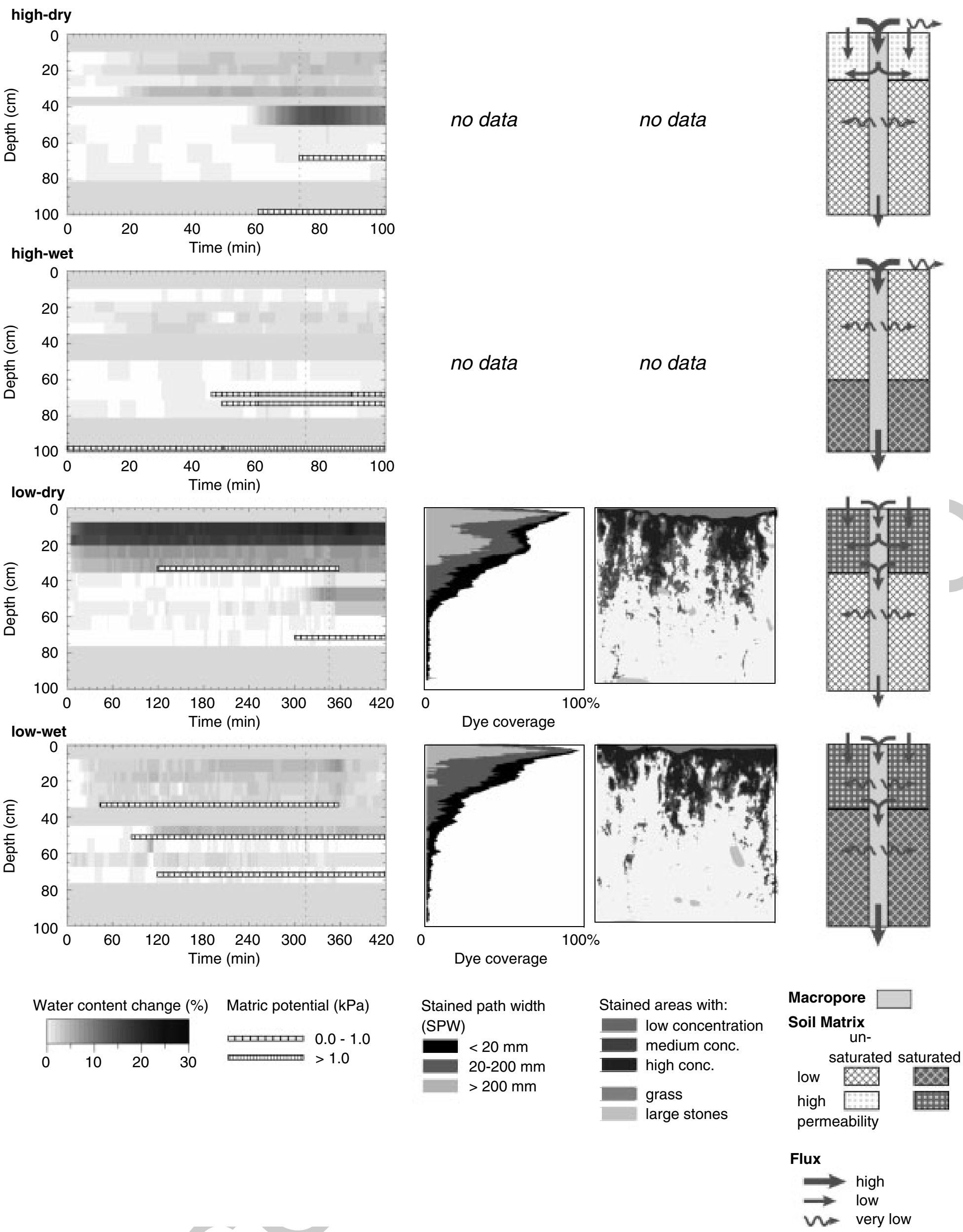

Figure 4. Experiments at the Koblenz site: depth–time plot of water content change and saturation (first column), depth function of dye coverage and stained path width (second column), example of a vertical dye pattern (third column), and conceptual model of the important flow processes (initiation and interaction) during sprinkling (fourth column)

soil under the experimental plot and delayed the preparation of the soil section by 1 week. Thus, no data are available for the dye pattern analysis.

The soil water content change is very low for all experiments ($<2\%$), except for the topsoil of the low-dry experiment. At the beginning of the experiments the groundwater table was at 100 to 120 cm depth. The soil profile was only saturated in the subsoil, never in the topsoil. The water table did not rise above 90 cm depth.

The intensity of the low rainfall experiments was lower than the permeability of the topsoil, resulting in a wetting front and a saturation of the top layer before the matric potential in the bottom layer reacted. Thus, macropore flow was mainly initiated within the saturated topsoil for the low rainfall experiments, whereas macropore flow was mainly initiated at the soil surface for the high rainfall experiments.

The dye coverages of the experiments with the low rainfall intensity show a quite extensive stained upper soil layer and a gradual decrease of the dye coverage with depth. The SPW is high near the soil surface, moderate in the topsoil, and very low in the subsoil, indicating a decrease of the interaction with depth.

The flow processes of this site are summarized in Figure 4. Owing to the intermediate permeability of the topsoil, macropore flow was mainly initiated at the soil surface for the high rainfall intensity and from the saturated upper soil layer for the low rainfall intensity. Macropore flow in wormholes dominated below 40 cm, despite a slightly unsaturated soil matrix. The low permeability of the soil matrix in combination with the low potential difference between the macropores and the soil matrix limited the interaction (Chen and Wagenet, 1992). Therefore, the water in the macropores bypassed the soil matrix and, owing to the efficient lateral subsurface flow pathways, it drained rapidly into the underlying bedrock. For the onset of subsurface flow, the initial soil moisture condition is only important for the low rainfall intensity when macropore flow is initiated in the topsoil. For the high rainfall intensity, subsurface runoff starts quickly.

Niederweningen site

Figure 5 shows the results of the experiments at the Niederweningen site. The water content primarily changed in the top layer (0–30 cm) and in the bottom layer (45–90 cm). The change of the top layer is pronounced for dry initial conditions. The change of the bottom layer is pronounced for wet initial conditions. The changes in water content between 30 and 50 cm are low; thus, the water bypassed the soil matrix of this layer and percolated to the bottom layer. Generally, the soil profile did not saturate; however, one tensiometer in the topsoil always showed a fast reaction and saturation. On excavating this tensiometer, it was found that the cup was connected to an earthworm channel. This reaction immediately after the beginning of the sprinkling can only be explained by an initiation of macropore flow at the soil surface.

The depth functions of the dye coverage differ distinctly from the other sites. The staining of the upper soil layer is more expanded for the dye patterns of the low rainfall intensity. At a depth of 30 to 40 cm, the dye coverage shows a local minimum. Below 40 cm, the staining increases again. The depth function is similar for the same initial soil moisture conditions but slightly different for the same rainfall intensity. The staining never reaches the bottom of the vertical soil section (100 cm). The SPW also shows a minimum at a depth of 30 to 40 cm. This area with a low interaction can also be seen in the examples of the vertical dye patterns. For the high-dry experiment alone, the dye coverage and SPW are low at a depth of 10 cm, which indicates macropore flow initiation at the surface due to a low permeable soil matrix. For the wet initial conditions, this behaviour is missing, however; for the low-dry experiment, the water content increase was delayed near Q2 the soil surface. This behaviour can be explained by a water-repellent soil surface, which may temporarily reduce the permeability of the topsoil for dry initial conditions.

It is remarkable that, despite the soil being extensively stained between 40 and 80 cm depth for of the high-dry experiment, the water content increased only slightly during the sprinkling. A possible explanation could be that the TDR rods were outside the spatially distinct stained areas and, therefore, did not show a reaction in water content change. Thus, the detailed spatial information of the dye patterns is necessary to analyse infiltration processes if the region of influence of the device (TDR probes) is smaller than the spacing between two adjacent preferential flow pathways (Ritsema and Dekker, 1996)

The conceptual outline of flow processes highlights that initiation of macropore flow occurred solely at the soil surface. Between 30 and 40 cm, the interaction was low and the water in the macropore was forced to flow to deeper soil layers, bypassing the upper soil layer. Infiltration in the soil matrix was reduced for dry initial

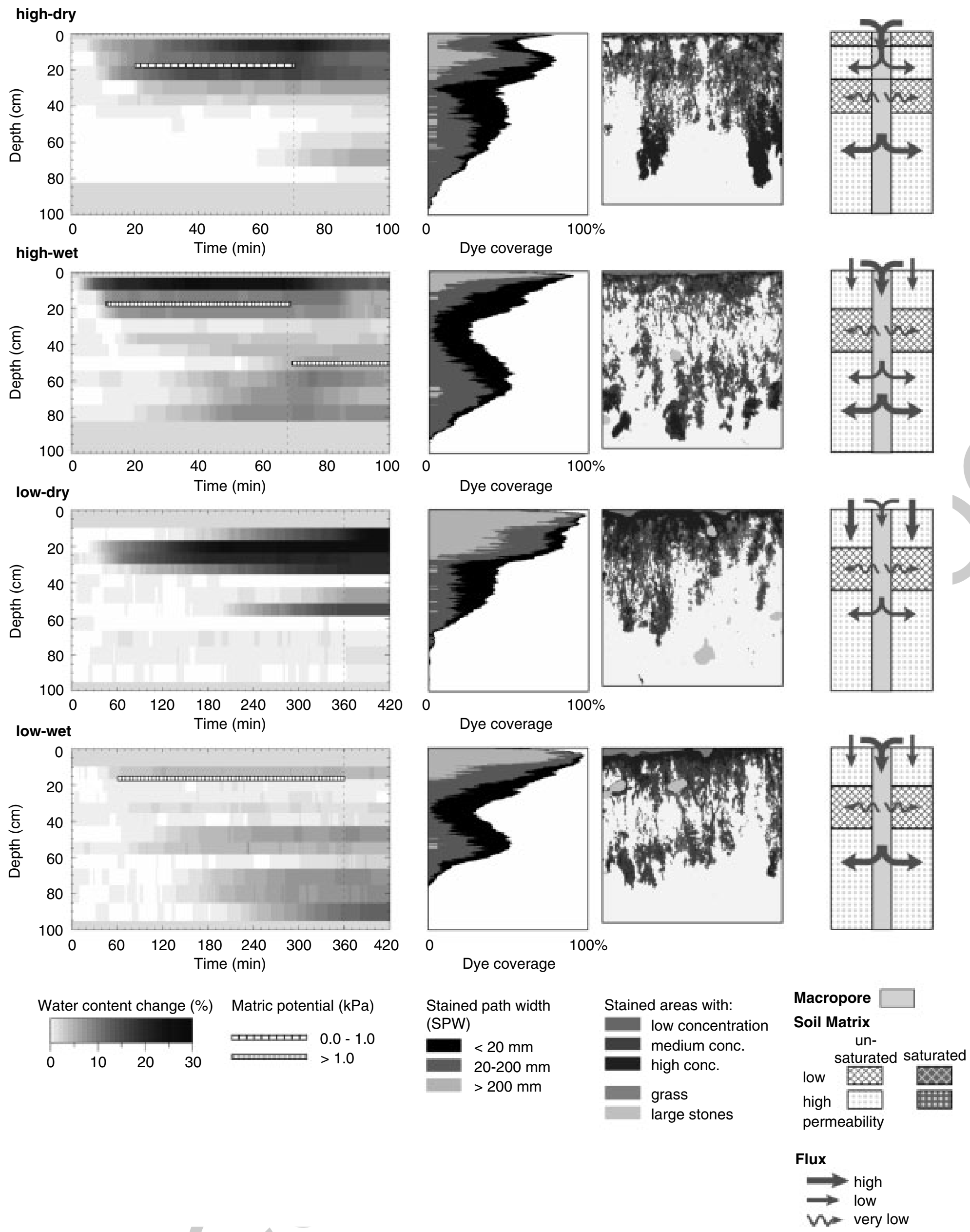

Figure 5. Experiments at the Niederweningen site: depth–time plot of water content change and saturation (first column), depth function of dye coverage and stained path width (second column), example of a vertical dye pattern (third column), and conceptual model of the important flow processes (initiation and interaction) during sprinkling (fourth column)

conditions due to a water-repellent soil surface. Because the soil texture changes at 40 cm depth (increase of sand, decrease of clay fraction), the interaction increased and the water could flow into the permeable soil matrix and was stored in the subsoil. Despite the low permeablity of the topsoil, no overland flow was generated and the storage capacity of the deeper soil layers was activated, due to continuous earthworm channels from the surface into the subsoil. Thus, the generation of runoff at this site was delayed.

CONCLUSIONS

The influence of macropores on flow processes in grassland soils was studied in detail with combined sprinkling and dye tracer experiments. At all sites investigated, a vertically oriented, continuous network of macropores formed by earthworms had developed that dominated the flow processes during extreme rainfall events. In general, macropores increase the overall permeability of the soil and tend to reduce overland flow generation. Despite the similar pedological classification of the soils at the four sites, the effects of macropore flow on runoff generation were quite different. A detailed description of flow processes could be derived with the unique experimental combination of high temporal resolution data from the tensiometer and TDR measurements and high spatial resolution information from the dye patterns.

The experiments confirm that macropore flow is initiated either at the soil surface or from a saturated or partially saturated soil layer. If the rainfall intensity exceeds the infiltration rate of the soil matrix, macropore flow is initiated at the soil surface. The subsurface initiation process depends on the presence of a saturated soil layer. Saturation of a soil layer can develop if the permeability decreases within the profile and the rainfall amount exceeds the saturation deficit of the soil layer. The experimental results further point out that interaction (water flow from the macropores into the surrounding soil matrix) is mainly influenced by the soil properties and soil water content. A high interaction due to a permeable soil matrix and a low initial soil water content results in storage of water in the soil. A low interaction due to a low permeable soil matrix or a nearly saturated soil matrix causes the infiltrating water to bypass the matrix. Finally, the interaction in combination with the permeability of the underlying bedrock controls the drainage of the macropores. If the interaction is low and the permeability of the underlying bedrock is high due to efficient lateral flow pathways, the macropore drainage is high. If the interaction and the bedrock permeability are low, drainage of the macropores is reduced and saturation of the macropore system occurs.

Macropores built by earthworms influence the hydrological response at the plot scale in different ways. Infiltration excess overland flow on sites with a topsoil of low permeability is reduced if water can bypass this layer in macropores. Water can then be stored in the subsoil, if the water transfer from the macropores into the soil matrix is high. Saturation overland flow is less affected by macropores. However, runoff generation is slightly delayed due to the additional storage in macropores. Subsurface flow is activated very rapidly because infiltrated water bypasses the soil matrix, especially when macropore flow is initiated at the soil surface and the interaction is low. These new insights on how macropores affect infiltration and flow processes in soils can contribute to a better understanding of the hydrological response at the plot scale and to an improvement of the simulation of runoff generation.

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