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Temporal variability of subsurface stormflow formation*

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Abstract

Subsurface storm flow (SSF) can play a key role for the runoff generation at hillslopes. Quantifications of SSF suffer from the limited understanding of how SSF is formed and how it varies in time and space. This study concentrates on the temporal variability of SSF formation. Controlled sprinkling experiments at three experimental slopes were replicated with varying precipitation intensity and varying antecedent precipitation. SSF characteristics were observed with hydrometric measurements and tracer experiments. SSF response was affected in different ways and to varying degree by changes of precipitation intensity and antecedent precipitation. The study showed that the influence of antecedent soil moisture on SSF response depends on the type of SSF formation. Formation of subsurface stormflow was hardly influenced by the increase of precipitation intensity. As a consequence, subsurface flow rates were not increased by higher precipitation intensity. Different soil structures determined runoff formation at different precipitation intensities. Saturation and flow formation occurred at the base of the soil, but also within the topsoil during high precipitation intensity. This implies that timing and magnitude of flow response can change substantially at different precipitation intensities.

1 Introduction

Fast subsurface flow (SSF) in shallow lateral preferential flow paths can play a key role for the runoff generation at hillslopes (reviews in Jones and Connelly, 2002; Weiler et al., 2006). Quantifications of SSF are difficult due to the high spatial variability of subsurface flow paths and the limited understanding of how SSF is formed. Hence, considerable research has been directed to the conceptual understanding of SSF formation (e.g. McDonnell, 1990, Sidle et al., 2000; Kienzler and Naef, 2007) as well as to the question where subsurface flow occurs (Jones et al., 1997; Scherrer and Naef, 2003) and how to detect the spatial variability of subsurface flow paths (Woods and

Rowe 1996). However, few studies concentrated on how the formation of SSF varies in time and is influenced by antecedent precipitation and precipitation intensity in individual rainfall events.

In general, temporal variance of precipitation is important for runoff formation mechanisms related to saturation. Kirkby (1969) described overland flow as a result of saturation excess of the soil and pointed out the significance of antecedent soil moisture for this process. The relation between saturation and SSF formation was conceptualized by McDonnell (1990). He explained the initiation of lateral subsurface flow in soil pipes as a result of perched saturation above impermeable bedrock. Correlation of SSF formation with antecedent precipitation has been shown by several studies (Whipkey, 1967; Lynch et al., 1979; Uchida et al., 1999). Beven and Germann (1982) pointed to the relation between antecedent soil moisture and preferential infiltration in that "higher initial soil moisture contents in the soil may also allow deeper penetration along the macropores by reducing the lateral losses." Similarly, Bouma et al. (1982) named soil water content as a crucial parameter for the "magnitude of bypass flow". Experimental evidence for this hypothesis comes from Weiler (2001), who observed reduced flow from macropores into the soil matrix, when the soil was wetted before the experiment. Thus, more intense and faster start of SSF can be expected under wet preconditions, as infiltrating water reaches lateral flow paths quicker and less water is required to trigger subsurface flow.

In a similar way, increased precipitation intensity as a result of a switch from matrix infiltration to macropore infiltration could lead to a subsequent faster onset of SSF. Beven and Germann (1982) hypothesized that the initiation of macropore flow is related to the precipitation intensity. They proposed that macropore flow is initiated from water ponding at the soil surface as soon as the infiltration capability of the soil matrix is surpassed. This conceptual model of macropore flow initiation has since been applied in many detailed numerical models of infiltration and runoff formation (e.g. Zuidema, 1985; Bronstert and Plate, 1997). In fact, experimental studies gave evidence for the correlation between precipitation intensity and macropore flow (Trojan and Linden, 1992). However, initiation of macropore flow has been observed even during low precipitation intensity as a result of subsurface saturation (Weiler and Naef, 2003).

This study aims to illuminate the relevance of antecedent precipitation and precipitation intensity for SSF formation. For this purpose, controlled sprinkling experiments at three different experimental slopes were replicated with varying precipitation intensity and antecedent soil moisture. SSF characteristics were observed with hydrometric measurements and tracer experiments. SSF response was affected in different ways and to varying degree by changes of precipitation intensity and antecedent soil moisture. It is discussed, which site-specific properties were responsible for the different responses and some general conclusions are drawn that may help to assess the temporal variability of SSF in individual rainfall events.

2 Experimental setup

Infiltration and runoff formation were monitored at three experimental slopes during sprinkling experiments on areas of 100 m^2. Follow-up experiments with similar precipitation intensity were conducted on adjacent days to study the influence of antecedent precipitation on SSF. In each case, the first experiment was conducted under dry weather conditions and the second experiment on the following day with the antecedent precipitation of the first experiment. Table 1 lists details on the antecedent moisture and precipitation intensity of the different experiments. Follow-up experiments with high (40–50 mm h^{-1}) and low (10 mm h^{-1}) precipitation intensities were conducted. Table 2 lists precipitation intensity and antecedent moisture during the different experiments. Subsurface flow was measured above the bedrock in a trench at the lower end of the sprinkled area. Surface runoff and outflow from larger pipes and macropores were measured either with 100 ml tipping bucket gauges or with 45° Thompson weirs. Soil moisture and matric potential were recorded in different depths and at different locations with TDR-probes and tensiometers. Piezometers recorded water levels within the soil. To determine event and pre - event water fractions in the different runoff components the sprinkling water was traced with the flourescent dye naphtionate. The natural tracer Radon-222 allowed assessing pre-event water percentages in SSF during natural rainfall events. Figure 1 depicts the experimental setup. Locations of the devices varied slightly at the different experimental slopes. At Lutertal, soil moisture was monitored more closely with 30 additional TDR probes (Retter et al., 2006). Details on the experimental setup and uncertainties of the methods can be found in Kienzler and Naef (2007).

3 Experimental slopes

The experiments were replicated across three hill slopes in the Swiss Plateau with different soils and geology to cover different subsurface flow mechanisms. At all sites, substantial SSF was expected according to the decision scheme of Scherrer and Naef (2003). The three test sites, listed in Table 3, were situated in the Swiss Plateau. Mean annual temperature in this area is between 6°C and 8°C, mean annual precipitation ranges from 1000 mm to 1500 mm and evapotranspiration is about 40% of annual precipitation. The Swiss Plateau is mainly formed by "Molasse", deposited at the border of the Alps and consisting of sandstones, marl, and conglomerates. These sedimentary rocks are in large parts overlain by glacial till and fluvial deposits. Details on geology and soil properties are given in Table 4. As all three sites are extensively used as meadow, vegetation is similar and consists of plants typical for middle-Europe rich pastures.

The formation of SSF as well as fractions of pre-event water in SSF varied substantially at these sites (Fig. 2). The individual response depended on the degree of direct or indirect feeding of SSF (Kienzler and Naef, 2007). Direct feeding of SSF means that precipitation feeds directly an extended system of large and well-connected preferential flow paths with little interaction with the soil matrix. Therefore, SSF responds quickly, shows high flow velocities and contains little pre-event water (site Koblenz in Fig. 2). Indirect feeding, as observed at Im Sertel, means that water infiltrates first into the soil matrix and that subsurface flow originates from the saturated soil matrix. In this case, SSF responds delayed to precipitation and contains little event water. Response at Lutertal and Schluessberg was between these extremes. At Schluessberg, parts of the subsoil saturated during low-intensity rainfall and SSF response was moderately delayed and contained about 60% of pre-event water. Also at Lutertal, SSF responded moderately delayed and contained about 50% of pre-event water. Here, outflow from individual soil pipes started at different times and contained different amounts of pre-event water. Delayed pipes had higher concentrations of pre-event water than pipes starting quickly. This indicates that the latter were fed directly from precipitation, whereas the former were fed indirectly from saturated parts of the soil (Kienzler and Naef, 2007).

4 Antecedent precipitation and SSF formation

Figure 3 (left) compares cumulative runoff coefficients in response to the follow-up experiments. Soil drainage after the first experiment is depicted by Fig. 3 (right). With regard to the influence of antecedent precipitation, the different sites showed distinct differences. During the two experiments, runoff response was similar at Schluessberg as well as at Lutertal. Contrary, no runoff at all was produced at Im Sertel during the first experiment, whereas subsurface flow from a thin weathered layer above the underlying sandstone started after a few mm of precipitation during the follow-up experiment (Fig. 3, left). Small differences of antecedent soil moisture were detected between the first and the second experiment at Schluessberg as well as at Lutertal. Contrary, at Im Sertel antecedent soil moisture is substantially increased before the second experiment in comparison to the first experiment (Table 1). Figure 3 (right) shows, that drainage at Im Sertel was considerably delayed in comparison to Schluessberg and Lutertal.

What was the reason for the different influence of antecedent precipitation at different experimental slopes? It can be understood by considering the different types of

SSF formation (see Sect. 3). At Im Sertel, SSF responded delayed despite the high density of vertical macropores and the existence of a highly permeable layer. There was no direct preferential flow from the soil surface to the trench. Instead, infiltration from vertical macropores into the soil matrix occurred and lateral subsurface flow was initiated only after large parts of the subsoil were saturated. Therefore, during the first experiment, nearly all precipitation was retained in the subsoil, which reached almost saturated conditions. After this first experiment, the saturated parts of the soil drained slowly (Fig. 3, right). Consequently, a small amount of precipitation could trigger SSF from the saturated subsoil during the follow-up experiment. At the two other sites, SSF was formed differently. As the interaction of preferential flow with the surrounding soil matrix was limited, the initiation of SSF was less dependent on saturation. SSF started already from small, saturated patches within the soil. After the experiment, these small patches were drained fast and effectively by preferential flow. Therefore, the soils showed a similar retention capacity during follow-up experiments and also antecedent moisture was comparable for both experiments.

Also Scherrer et al. (2007) concluded from sprinkling experiments on 18 different sites, that "the impact of antecedent wetness on the runoff volume depends on the runoff process encountered." At some sites of their study, "a faster reaction under wet conditions was prevented by an efficient drainage system, which lowered the water table in the soil within a few hours.", whereas other sites "reacted quite sensitively to antecedent wetness. "

These findings imply that the influence of antecedent precipitation on runoff response depends on how SSF is formed. They show that parameters like the "antecedent precipitation index" have to be applied with caution in hydrological modeling, as high antecedent precipitation implies increased runoff response and high antecedent soil moisture for a limited number of hillslope settings only.

5 Precipitation intensity and SSF formation

At all experimental slopes, substantial subsurface flow occurred during low as well as during high intensities, whereas (nearly) no overland flow occurred during low intensities but large amounts during high intensities (Fig. 4, left). At Schluessberg and at Im Sertel, additional subsurface flow paths were activated during high precipitation intensities.

At Im Sertel, outflow from a thin weathered layer directly above the sandstone bedrock and from a soil pipe in 0.7 m depth was observed during low precipitation intensity. Both flow components contained high percentages of pre-event water. During the high intensity experiment, the same flow paths were activated again with high fractions of pre-event water. In addition, shallow subsurface flow from several macropores in 15–25 cm depth was observed with low percentages of pre-event water. Discharge of deep SSF was similar during both intensities (Fig. 4, right).

Different subsurface flow components were also observed at Schluessberg, where shallow subsurface flow to a depth of 40 cm and deep subsurface flow to a depth of 150 cm were measured separately. During high precipitation intensities, shallow subsurface flow from several small soil pipes was observed with low pre-event water content of 27% similar to overland flow. These pipes were not activated during sprinkling with 10 mm h^{-1}, while deep subsurface flow occurred with more than 62% of pre-event water. Increasing the intensity to 20 mm h^{-1} triggered overland flow and a slight increase of SSF (Fig. 4, right).

At Lutertal, overland flow and subsurface flow occurred during both intensities. Like at the other sites, pre-event water content in SSF was similar during the different intensities (Kienzler and Naef, 2007). Also, maximum SSF discharge was similar during different precipitation intensities and started after similar amounts of precipitation (Fig. 4, right).

To test, whether a switch from matrix infiltration to macropore infiltration occurred, amounts were compared of infiltrated water before soil moisture and soil suction started to increase at different tensiometers and TDR-probes in different depths (Fig. 5). For the calculation of the cumulative amount of infiltrated water, overland flow was subtracted from precipitation. This comparison shows comparable results for the different intensities (Fig. 5).

While this analysis revealed quick infiltration into the whole soil profile, the amplitude of soil moisture increase varied distinctly at different depths (Fig. 6). At all sites, increase of soil moisture was observed mainly in the uppermost layer of the soil as well as in the subsoil above the underlying bedrock material. During high intensity, mainly topsoil moisture content increased strongly, while subsoil moisture content responded less pronounced. In contrast, during low intensity, subsoil moisture content increased strongly and topsoil water content increase was less pronounced.

The similar responses of subsurface flow rate and pre-event water percentages in SSF indicate that (deep) subsurface flow was hardly influenced by precipitation intensity. Infiltration into the soil was similar and no switch to more preferential infiltration was detected. The maximum discharge of subsurface flow was already reached with low-intensity sprinkling and did not increase with higher precipitation intensity. However, the precipitation amounts and intensities applied in this study, correspond to extreme rainfall events, which occur with a return frequency of more than 50–100 years (10 mm h^{-1}) respectively 100–500 years (50 mm h^{-1}) in the study area (Röthlisberger et al., 1992). This implies that the observed subsurface flow with maxima between 3 mm h^{-1} (Im Sertel) and 6 mm h^{-1} (Lutertal) will deliver substantial contributions to storm flow during most flood events. Only, the relevance of subsurface flow will be low during very extreme and seldom events with high intensity precipitation, when overland flow will form the most part of total runoff. Uchida et al. (2001) listed similar maximum subsurface flow rates for several forested sites and attributed the limitations of the subsurface flow rates to geometry and hydraulic resistance of lateral subsurface flow paths. In our study, the occurrence of overland flow indicated that the limited infiltration rate could be responsible for subsurface flow limitation. However, it can only be speculated if subsurface flow is the cause of or the symptom for limited infiltration rates.

Overland flow was not the result of complete saturation of the soil, as it started while still large part of the pore volume was not filled and tensiometers indicated unsaturated conditions. However, saturated conditions were observed in the uppermost soil layers of all three experimental slopes during high intensity and partially also during low intensity (Fig. 6). Despite high macroporosity of the soil (Table 4), infiltration into the subsoil was limited and the topsoil saturated nearly independently from subsoil water content. Obviously, this topsoil saturation triggered overland flow. Also shallow subsurface flow at Schluessberg and Im Sertel originated from the saturated topsoil as indicated by the similar pre-event water content of overland flow and shallow subsurface flow. Infiltration into the subsoil was not completely inhibited and subsoil saturation developed above the underlying bedrock material. This saturation from below caused the formation of deep subsurface flow. Partially, e.g. at Lutertal, topsoil saturation and saturation from below occurred at the same time. As a consequence, both, overland flow and subsurface flow occurred during both intensities. At Schluessberg however, no subsoil saturation developed during high-intensity sprinkling and topsoil saturation was considerably delayed during low-intensity sprinkling. Consequently, here, overland flow and shallow subsurface flow occurred during high-intensity sprinkling, while deep subsurface flow formed during low-intensity sprinkling only. At Im Sertel, subsoil saturation and deep subsurface flow were observed during high intensity as well as during low intensity. Topsoil saturation and subsequent triggering of overland flow and shallow subsurface flow were observed during the experiment with high intensity only.

In summary, different parts of the soil controlled flow formation depending on precipitation intensity (Fig. 7). During low intensity, saturation above the underlying bedrock was the most relevant process and deep subsurface flow was the dominating runoff component. During higher intensity, topsoil saturation was the most relevant process and overland flow was the dominating runoff component. Such perched topsoil saturation has been observed repeatedly in podzolic soils with a thick organic O-horizon overlaying a distinctive impermeable hardpan layer (e.g. Brown et al., 1999). This study shows that the development of perched saturation can occur due to slight vertical vari-

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ations of macroporosity and packing density during high-intensity rainfall, influencing the different runoff components and the timing of these components. Overland flow and shallow subsurface flow occurred before saturation of the whole soil profile, as only part of the effective porosity of the whole soil was filled before runoff started. Deep subsurface flow drained the soil continuously and delayed or prevented therefore a complete saturation of the whole soil profile and the initiation of overland flow and shallow subsurface flow during low intensity.

6 Conclusions

The influence of antecedent precipitation on SSF response depends on how SSF is formed. Its influence is high, when SSF is initiated only after large parts of the soil have been saturated, which are drained slowly after a rainfall event. SSF is less dependent on saturation, where it is formed in a more direct way from small, saturated patches, which can be drained efficiently. Consequently, the influence of antecedent precipitation on SSF response is low at such sites. This implies for the application of antecedent precipitation in hydrological modeling, that antecedent precipitation correlates with antecedent soil moisture and runoff response for a limited number of hillslope settings only.

Formation of subsurface stormflow was hardly influenced by the increase of precipitation intensity. As a consequence, subsurface flow rates were not increased by higher precipitation intensity. Such a limitation of subsurface discharge to site-specific maxima might be quite common.

Different soil structures determine runoff formation at different precipitation intensities as saturation may occur at the base of the soil, but also within the topsoil during high precipitation intensity. Thus, timing and magnitude of flow response can change substantially at different intensities. The identification of such processes is easy in cases, where distinct impermeable soil layers occur, however, this study showed that perched topsoil saturation during high precipitation intensity may be triggered also by slight changes of macroporosity and packing density.

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Table 1. Comparison of experiments with different antecedent precipitation. Details are given of antecedent soil moisture and precipitation intensity for each test slope.

Site	Schluessberg		Lutertal		Im Sertel	
Identification in text	first experiment	second experiment	first experiment	second experiment	first experiment	second experiment
Precipitation intensity [mm h^{-1}]	8	10/increase to 20	11.6	14.4	8.4	8.4
Precipitation sum [mm]	89	126	152	98	85	80
Antecedent soil moisture [mm]	220	240	125	140	540	584

Table 2. Comparison of experiments with different precipitation intensities. Details are given of antecedent soil moisture and precipitation intensity for each test slope.

Site	Schluessberg		Lutertal		Im Sertel	
Identification in text	low intensity	high intensity	low intensity	high intensity	low intensity	high intensity
Precipitation intensity [mm h^{-1}]	10/increase to 20	37	11.6	50.4	8.4	50.4
Precipitation sum [mm]	126	164	152	194	80	118
Antecedent soil moisture [mm]	240	237	125	138	584	613

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Table 3. Locations of the experimental slopes.

Site	Schluessberg	Im Sertel	Lutertal
Location (Long./ Lat:)	8°45′06″/47°16′48″	7°58′49″/47°14′17″	8°00′37″/47°14′10″
Altitude [m_asl]	520	540	690
Exposition	SW	NE	S
Slope [%]	28	40	30
Land use	meadow	meadow	meadow

Table 4. Soil characteristics of the experimental slopes. The pipette method was applied to determine percentages of sand (63 μm to 2 mm), silt (2 μm to 63 m) and clay (<63 μm). Packing density and percentage of coarse fragments were estimated according to Finnern et al. (1994). Macropore density was assessed by visual count in horizontal cross-sections of 2500 cm^2 at different soil depths.

Site		*Soil classification*			*Geological parent material*			
Depth [cm]	Horizon	particle size distribution [%]			coarse fragments [%]	packing density [$g\ cm^{-3}$]	macropore density [m^{-2}]	pH
		Sand	Silt	Clay				
Schluessberg		*Calcaric cambisol*			*Ground moraine*			
0–10	Ah	34	34	32	3	1.1	224	5
11–24	A/B	34	34	32	5	1.3	136	5
24–80	Bw	31	35	34	10	1.4	111	5
> 80	C	31	35	34	15	2	35	8
Lutertal		*Cambisol*			*Siltstone of "Oeningien" Molasse*			
0–10	A	26	51	23	< 1	1.2	184	5
10–25	B	26	51	23	< 1	1.3	248	6
25–40	B/Cv	26	51	23	2-5	1.4	132	6
> 42	C					2.2	0	7
Im Sertel		*Cambisol*			*Sandstone of "Helvetien" Molasse*			
0–20	A	41	29	30	< 1	1.2	284	5
20–80	B	47	29	24	< 1	1.3	216	5
80–160	B/Cv	51	27	22	< 1	1.3	344	5
160–270	Cv					1.8	126	8
> 270	C					2.2		8

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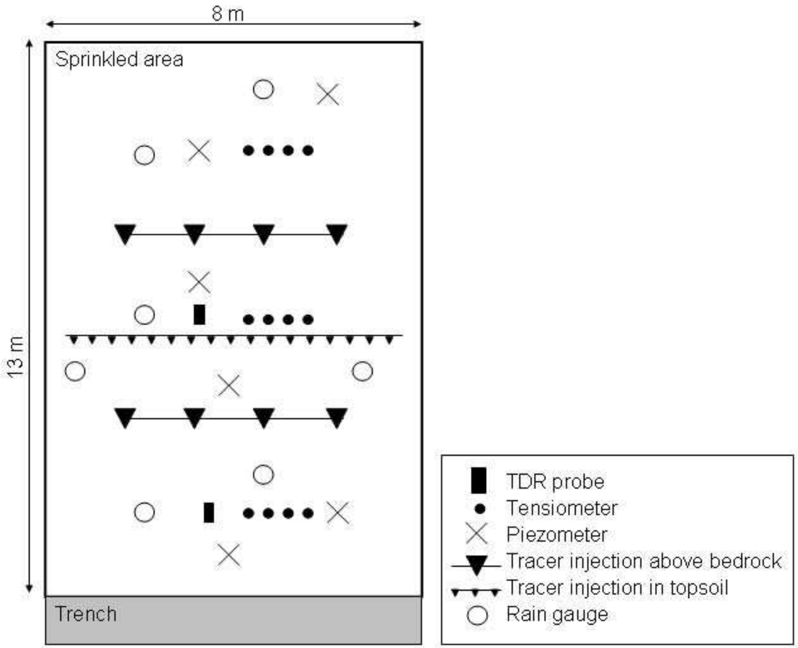

Fig. 1. Experimental set-up during the sprinkling experiments in a view from above. Installation depths of the probes and tracer injection varied at different experimental slopes according to soil depth.

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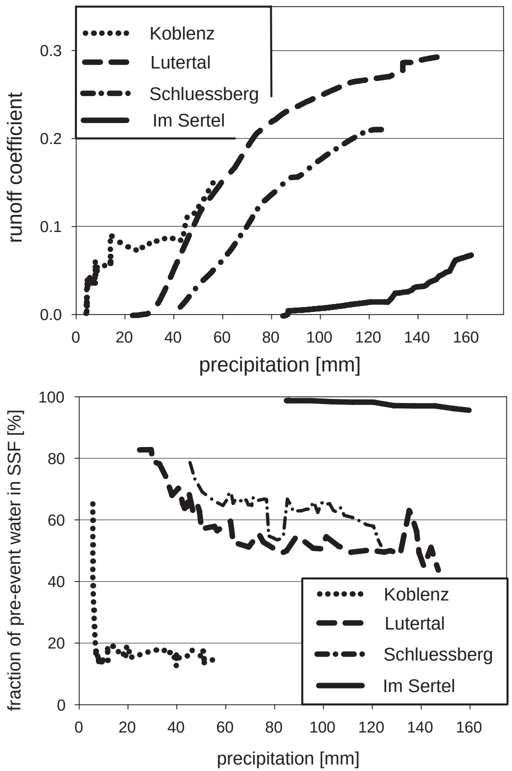

Fig. 2. Intercomparison of differently responding hillslopes (Kienzler and Naef, 2007). Directly fed subsurface storm flow starts quickly and contains little pre-event water (Koblenz). Indirectly fed subsurface storm flow starts delayed and consists mainly of pre-event water (Im Sertel). Experimental slopes Lutertal and Schluessberg responded in between these extremes. Results of pre-event water fraction and cumulative runoff coefficient are plotted against cumulated precipitation sum.

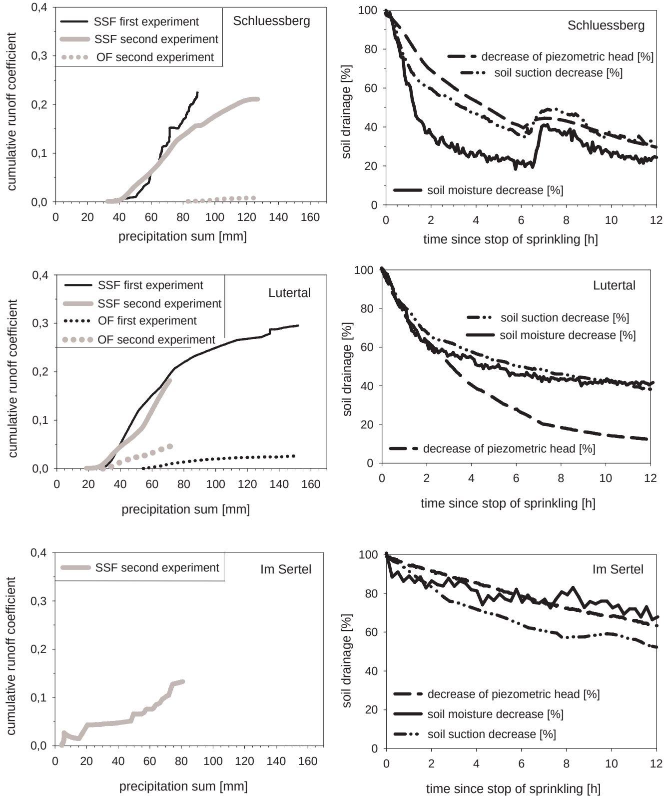

Fig. 3. Left: Comparison of cumulative runoff coefficients of overland flow (OF) and subsurface flow (SSF) in response to two follow-up sprinkling experiments with different antecedent precipitation. Right: Drainage after sprinkling. Measurements at single probes of soil moisture, soil suction and water level were averaged. To allow for comparison, not the absolute values, but percentages are given, where 100% corresponds to the maximum increase of a given parameter related to its value before the experiment.

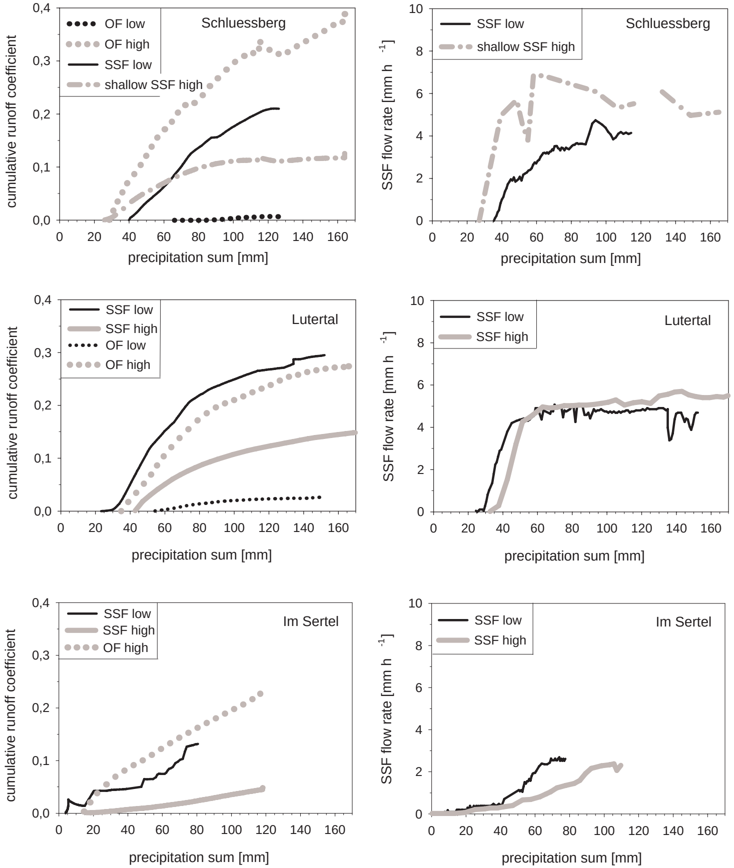

Fig. 4. Runoff response to low-intensity sprinkling and high intensity sprinkling. Compared are cumulative runoff coefficients (left) and SSF flow rates (right) for each test slope.

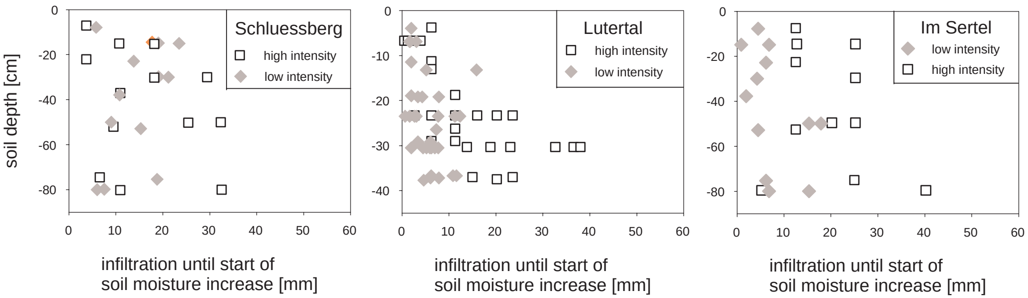

Fig. 5. Comparison of infiltration response to low-intensity and to high-intensity sprinkling. Depicted are sums of infiltration until start of soil moisture increase in different soil depths.

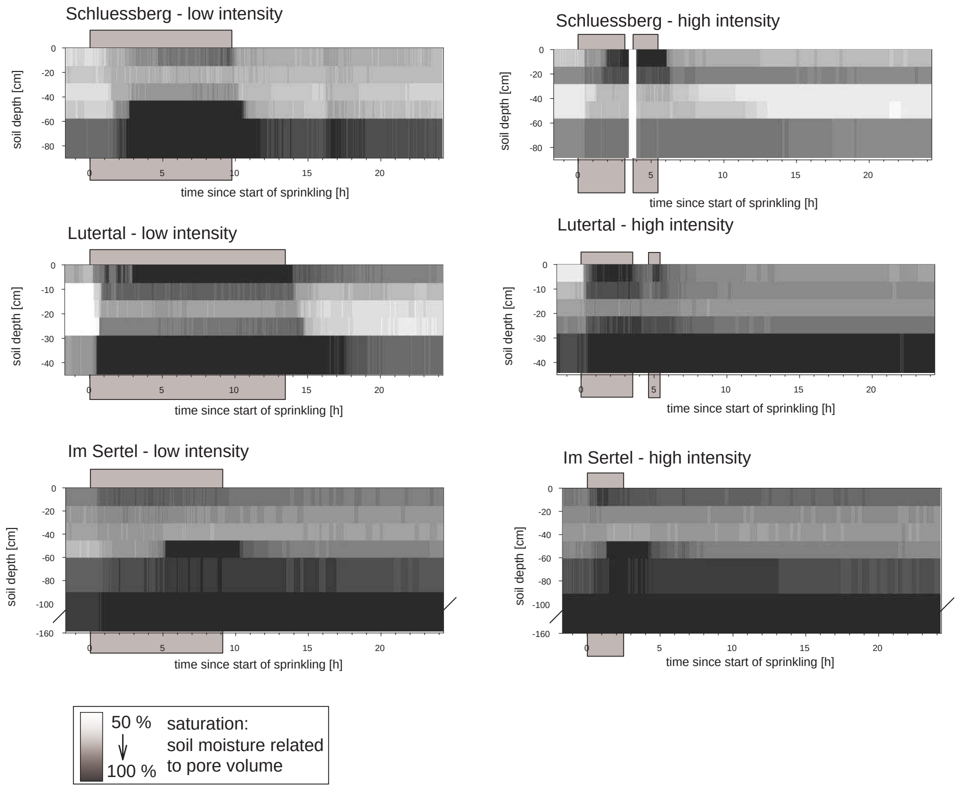

Fig. 6. Soil moisture dynamics at different sites in response to different precipitation intensities. Values of soil moisture are given in relation to pore volume, which was estimated according to Sponagel et al. (2005) from grain size distribution and packing density. Grey shaded boxes indicate sprinkling periods.

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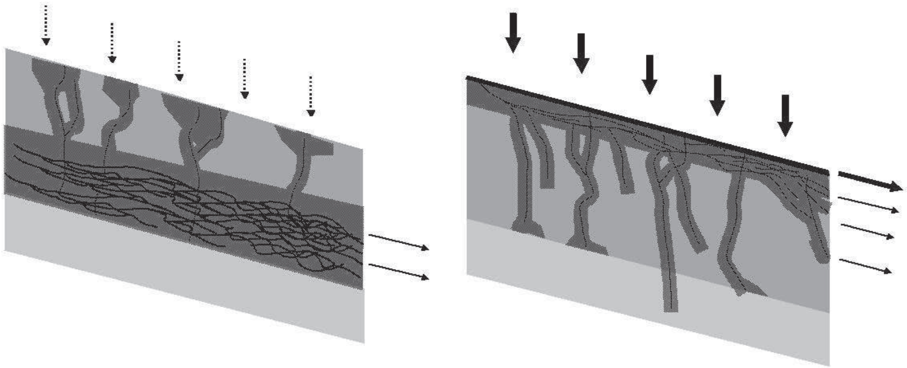

Fig. 7. Schematic concept of runoff formation during low precipitation intensity (left) and high intensity (right).