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TO WHAT EXTENT DOES STORM INDUCED DEFORESTATION INFLUENCE RUNOFF FORMATION? RESULTS FROM A COMPARATIVE STUDY IN TWO SMALL TORRENT CATCHMENTS

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ABSTRACT

On the 26th of December 1999 the severe storm event Lothar caused great damage in several countries of Central Europe. Affected areas in prealpine regions of Switzerland offer an applicative basis to investigate the influence of storm caused damage on the hydrology of small torrent catchments. The research presented here is part of a joint project of the Swiss Federal Research Institute WSL and the Institute of Geography of the University of Berne (GIUB). The investigation area is situated within the watershed of the Sperbelgraben in the Emmental region (Swiss prealps) where studies in the field of Forest Hydrology have a history of 100 years. Two neighbouring sub-catchments with an area of approximately 2 ha each and a different extent of damage due to the storm have been equipped with a gauging station at their outlets. Additional information is acquired by the installation of 19 so-called surface runoff plots (50 to 110 m^2). Surface runoff measurements from summer 2002 at these plots are presented in this article.

Key words: forest hydrology, runoff generation, storm damage, deforestation

INTRODUCTION

The influence of forest coverage on runoff in river basins of various sizes represents a basic question in the field of forest hydrology. The first scientific measurements to investigate the effect of forest cover on runoff in Switzerland were carried out by Engler (1919) in the early 20th century. Based on comparative measurements in two very differently forested catchments in the Emmental region (Swiss prealps, canton of Berne), his statements revealed an important attenuating impact of the forest on intensive short-time flood events. This effect relates to both runoff volume and peak discharge. During persistent rainfall a slight or no effect at all was observed, depending on the water content of the soil before the event. Investigations in the Rappengraben and Sperbelgraben were carried on by Burger (1934, 1943, 1954) who also demonstrated an explicit influence of forest coverage on the mean annual water balance. The

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findings of all these studies strongly influenced the ideas in forest hydrology for several decades. A short review over some recent research on the topic of forest coverage influence on catchment scale hydrology is given in Badoux et al. (2003).
Runoff processes have also often been studied on a smaller scale than the catchment scale, prevalently by means of an artificial irrigation installation on areas of approximately 100 m^2. Ideally, the obtained information on the runoff processes of the irrigated site can be translated to sub-areas of entire catchments. In Badoux et al. (2002) some research on the topic of runoff formation using heavy rainfall simulation (e.g. Schwarz, 1986; Lang, 1995; Markart and Kohl, 1995) is shortly exposed.
An occasion to carry out an investigation regarding the effect of deforestation on the hydrology and erosion on different scales in Switzerland was brought about by a severe storm event. On the 26th of December 1999 the storm Lothar caused great damage in several countries of central Europe. In Switzerland, numerous regions featured large-scale damage to forested areas. In the whole country, trees with a total wood volume of 12.7 million m^3 on an area of approximately 46'000 ha were destroyed (WSL and BUWAL, 2001). Hence, small torrent catchments within such affected areas were predestined to investigate the topic.
In the study reported here, the investigation of the effect of storm originated deforestation on the hydrology is assessed on different scales. On the one hand, runoff and precipitation measurements are carried out in two differently affected sub-catchments (≈ 2 ha) within the Sperbelgraben catchment. On the other hand, 19 surface runoff plots (50 to 110 m^2) were implemented and irrigation experiments carried out on 14 soil profiles (1 m^2). This paper emphasises the results from the first year measurements on the surface runoff plots, described in detail in Ilg (2003). The research presented here is part of the overall project "Lothar and Mountain Torrents" of the Swiss Federal Research Institute WSL and the Institute of Geography of the University of Berne (GIUB). Specific details on this project are given in Badoux et al. (2002).

INVESTIGATION AREA

The investigation area consists of two neighbouring sub-catchments and their surroundings within the torrential catchment of the Sperbelgraben. During the storm event the two sub-catchments were affected in a very different way. In sub-catchment 1, little damage was registered, whereas in sub-catchment 2 the majority of the trees were destroyed. The damaged sub-catchment was partially cleared with afforestation machinery. Figure 1 gives an overview of the location of the investigation area.
The Sperbelgraben transversal valley is situated in the hilly Emmental region in the Swiss prealps. It has an area of 0.544 km^2, is quasi entirely forested and ranges from 911 m a.s.l. at the gauging station to 1203 m a.s.l. at its highest point. Geologically, the Sperbelgraben is located in the molasse zone and features mainly conglomerate layers crossed by marl layers. The variable susceptibility to weathering of the two different layer types led to the terrace shapes that can be observed all around the area. In the soils, the clay content varies with the fraction of marl in the bedrock, and contents of lime are low. The Sperbelgraben is principally characterised by Cambisols, but steep slopes have only developed Regosols. Water saturated soils, typically Gleysols, are largely restricted to gentle slopes with high clay content. The mean annual precipitation (measured in immediate proximity of the gauging station of the Sperbelgraben catchment) for the period from 1961 to 1999 amounts to 1660 mm.

Fig. 1: Location of the investigation area within the catchment of the Sperbelgraben; reproduced by permission of swisstopo (BA035612)

As mentioned in the Introduction, first scientific measurements to investigate the influence of the forest on runoff were carried out in the Sperbelgraben and Rappengraben by Engler (1919). Hydrological measurements and studies have a history of 100 years there. In 1902 both catchments were equipped with flow measuring stations and precipitation gauges; permanent measurements were subsequently taken up in 1903. Full particulars about the torrential catchment of the Sperbelgraben are given in Engler (1919), Burger (1934, 1943, 1954) and Casparis (1959).

The small sub-catchments are located in the south-east zone of the ridge of the Sperbelgraben catchment at an altitude between 1075 and 1160 m a.s.l. (Fig. 1). Their most important parameters are listed in Table 1. Apart from some soaked zones with nearly impermeable Gleysols, the investigation area is principally characterised by Cambisols with partly limited and partly unlimited permeability. The 19 surface runoff plots situated in the vicinity of the sub-catchments are listed and described in the following Methods section.

Tab. 1: Summary on some parameters of the lightly damaged sub-catchment 1 and the heavily damaged sub-catchment 2

		sub-catchment 1	sub-catchment 2
Area	[m^2]	20250	17620
Mean elevation	[m a.s.l.]	1130	1128
Circumference	[m]	550	540
Mean slope	[°]	25.3	25.7
Maximal slope	[°]	61.8	64.5
Channel density	[km km^{-2}]	17.3	11.0
Fraction of area with wet soils	[%]	22.8	36.7
Damaged trees after storm	[%]	21.4	62.7

METHODS

A nested approach was applied in the present study. The two selected sub-catchments were equipped with runoff gauges. While total runoff is measured on the sub-catchment scale, a broad study of the surface runoff characteristics is carried out on a smaller scale. For this purpose, 19 surface runoff plots were implemented in and around the sub-catchments, as seen in Figure 2. The basic level in the approach is characterised by 14 soil profiles chosen to be representative for areas with similar hydrologic properties. The hydrologic properties have been assessed with a forest site type map. This map gives an overview of the prevalent forest site types that can be found in the investigation area. The mapping was based on the Swiss state of the art procedure described in Burger et al. (1996). Every soil profile is associated with a surface runoff plot or plot group and has moreover been classified according to the FAO-UNESCO soil classification system (FAO, 1997). Just above every profile irrigation experiments have been carried out on 1m^2 to determine the hydrologic properties of the soil.

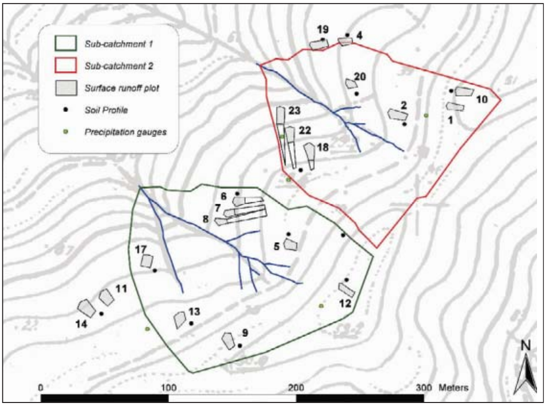

Fig. 2: Overview of the investigation area showing the position of the 19 surface runoff plots (numbered), the soil profiles and the precipitation gauges

As this article focuses on the results of the surface runoff plots, only the respective installations will be presented in this section. Furthermore, a very brief overview is given on the forest site types found in the investigation area. The soil profiles and the results of the irrigation experiments are elaborately described in Badoux et al. (2003) while the further installations, most notably the runoff gauges in the sub-catchments, are presented in Badoux et al. (2002).

Surface runoff plots

Fig. 3: Surface runoff plot P1 located within the heavily damaged sub-catchment

Figure 3 shows a completely installed surface runoff plot within the heavily damaged sub-catchment. Generally, the plots feature a size of 50 to 110 m^2 and are delimited with rigid PVC plates at the top and laterally. At the bottom of a plot, the water that drains off on or very close to the surface is collected with PVC plates laid out parallel to the slope and is conducted into a gully which leads it into a small gauging box.

This gauging station consists of a plastic box of 0,6 metre length, 0,4 metre height and 0,4 metre width provided with an aluminium V-notch and a water level transmitter (pressure capsule). The soil and topographic characteristics of all surface runoff plots as well as their affiliation to a forest site type are given in Table 2.
In order to deduce the degree and the cause of a potential difference in surface runoff between the two sub-catchments, the location of the surface runoff plots was accurately determined. Plots were placed in as many different forest site types as possible, preferably in a damaged and non damaged site per type. A comparison of plots lying in the same unit of the forest site type map but with different elements respectively degree of damage allows for statements about the influence of storm caused damage on runoff. Furthermore, the study of surface runoff behaviour enables assessment of the extent to which the irrigation experiments are representative for larger areas within a single forest site type.

Tab. 2: Characteristics of the surface runoff plots

	Area [m^2]	Slope [%]	Exposition	Forest site type	Canopy closure [%]	Soil type	Silt [%]	Clay [%]	Humus form	Litter Layer [cm]	Rooting depth [cm]
P1	60	49	W	46a (18d)	0	Endostagnic Cambisols, podzolic properties, stagnic prop. > 70 cm	29	10	Mor	8	70
P2	90	29	W	49f	0	Dystric Gleysols	34	15	Muck	0.7	16
P4	54	44	W	19	60	Humic Cambisols	24	16	Moder	4.5	70
P5	67	24	W	49f	40	Dystric Gleysols	28	13	Muck	0.5	35
P6	106	50	W	18aF / 19	70	Dystric Cambisols	21	10	Moder	2	80
P7	139	55	W	18aF / 19	70	Dystric Cambisols	21	10	Moder	2	80
P9	80	51	NW	18d	60	Dystric Cambisols	23	5	Moder	1.5	90
P10	79	41	W	46a (18d)	40	Endostagnic Cambisols, podzolic properties, stagnic prop. > 70 cm	29	10	Mor	8	70
P11	88	40	NW	18aF	70	Dystric Cambisols	28	14	Mull	1.5	>100
P12	61	39	WNW	46a (18d)	50	Endostagnic Cambisols, stagnic prop. > 70 cm	33	7	Moder	2.5	65
P13	74	20	NNW	26ho	30	Umbric Gleysols	37	12	Muck	1	20
P14	110	51	NW	18aF	60	Dystric Cambisols	28	14	Mull	1.5	>100
P17	72	67	NNE	18aF	80	Dystric Cambisols	23	12	Moder	3.5	100
P18	106	53	N	18aF	0	Stagnic Cambisols, stagnic prop. > 40 cm	23	10	Moder	4	100
P19	80	57	WSW	19	80	Dystric Cambisols	23	7	Mull	4	130
P20	44	52	WSW	19	0	Dystric Cambisols	27	15	Mull	2	70
P22	145	54	N	18aF	0	Stagnic Cambisols, stagnic prop. > 40 cm	23	10	Moder	4	100

Forest site types

A map of forest site types of the entire Sperbelgraben catchment has been established by a professional company. This map gives an overview of the prevalent forest site types that are found in the investigation area. A forest site type represents the summary of the characteristics of similar forest sites grouped according to topographic and geomorphological location, soil characteristics, floristic composition etc. The generated map was the basis for determining the location of all soil profiles and surface runoff plots.

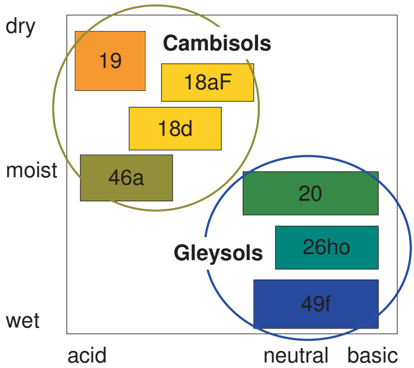

Fig. 4: Characteristics of selected forest site types found in the Sperbelgraben catchment (from Burger et al., 1996; modified)

Forest site types of the Sperbelgraben are different in soil moisture and soil acidity (Fig. 4) which implicates varying hydrological reactions of these areas. Higher soil water content (higher antecedent soil moisture) leads to a higher runoff coefficient as shown by Lynch et al. (1977). High soil acidity results in an accumulation of organic compounds on the surface (litter layer) due to a reduced decomposition rate. Under certain conditions, a hydrophobic litter layer may temporally reduce the infiltration capacity (Burch et al., 1989) and generate surface runoff. The driest and most acid soils in the investigated area are found on forest site type 19. The wettest and least acid soils are found on forest site type 49f.

RESULTS

The measurement of surface runoff from the plots started gradually in spring 2002, according to the completion of the installation of the different plots. Due to low temperatures, the operation of the plots was terminated on 7 Nov. 2002.
55 precipitation events that occurred between March and November 2002, which led to notable surface runoff in the plots were selected and divided into two categories: 21 intensive rainfall events and 34 persistent precipitation events. The partition resulted from the length and intensity of the rainfall events. For every single event and surface runoff plot several parameters were determined whereof the most important are the amount of precipitation, the surface runoff coefficient and the specific runoff peak value. Furthermore, the antecedent precipitation for 6, 24 and 72 hours was summed up.
Because the initiation of the surface runoff plots in the investigation area required a time span of several weeks, the data basis is not identical for the different locations. In addition, some data failures had to be tolerated with during the measuring period. As a consequence, only the 23 events during which every single plot was operational are considered in Figures 5 and 6. Moreover, surface runoff plot P5 had to be omitted due to technical problems. Detailed examination of this site in autumn 2002 displayed a leakage which could be attributed to mouseholes. It has to be assumed that a fair amount of surface runoff water was lost due to this corridor system. Site P5 has been repaired since.

Surface runoff generation in the investigation area

Figure 5 shows the surface runoff coefficients, compiled for every single surface runoff plot (cp. Fig. 2 and Tab. 2) on the basis of 23 precipitation events. The values are illustrated by means of box plots that are placed regarding the affiliation of the surface runoff plot to a forest site type.

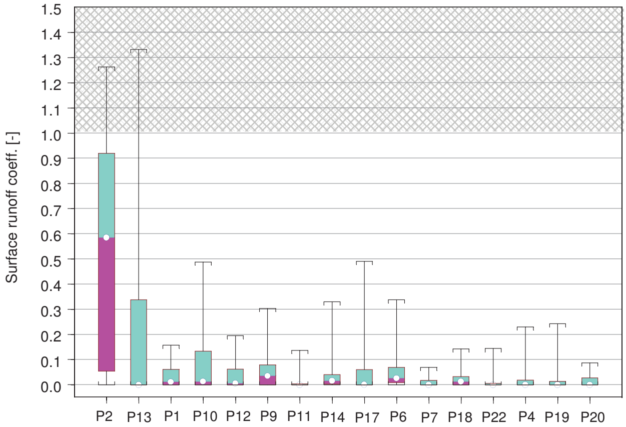

Fig. 5: Surface runoff coefficients for the 23 regarded rainfall events and each surface runoff plot; displayed box plots give range, quartiles and median

The surface runoff coefficients in Figure 5 reveal the considerable difference in behaviour of plots on humid to wet locations and those on rather dry locations. Considering the specific characteristics of each location, mainly two surface runoff processes have been identified: Surface runoff due to soil saturation (saturation overland flow) and surface runoff as a consequence of a hydrophobic reaction of the litter layer (temporary Hortonian overland flow).

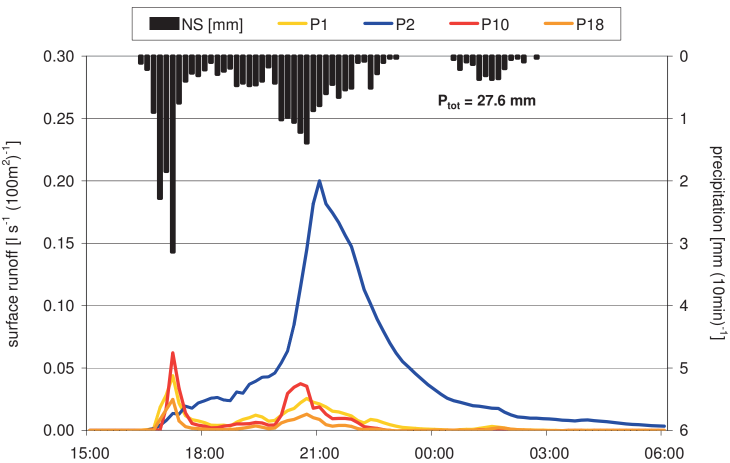

Fig. 6: Runoff hydrograph for a precipitation event amounting 27.6 mm on 12 may 2002; the two different mechanisms that lead to the formation of surface runoff can be well distinguished on the diagram.

The occurrence of saturation overland flow is confined to the plots P2 and P13 located within those zones of the investigation area that feature wet soils (forest site types 49f and 26ho). Their coefficients feature a much larger range of values than all the other installations as

shown in Figure 5. At these locations, the saturation of the soil (and subsequently surface runoff) is reached shortly after the beginning of a notable rainfall event. Nevertheless, there is a lag time of approximately 3 h before the peak runoff occurs. This is slow in comparison with certain other areas discussed below (cp. Fig. 6). Coefficients higher than 1 indicate an additional lateral water input, possibly originating from underneath the PVC demarcation. Large contributions of surface runoff on these plots could also be observed in terms of high specific surface runoff peaks, as shown by the hydrograph of plot P2 in Figure 6.
The effect of hydrophobicity was found to play an important role on a rather large area of the investigation area. After longer periods without any rainfall it was mainly P1, P10, P17 and P18 and to a smaller extent P4 where temporary Hortonian overland flow was observed. In the hydrograph this process is characterized by a clear peak of the surface runoff at the very beginning of the rainfall, followed by an only small contribution in the course of the event due to the gradual wetting of the litter layer (Fig. 6). In Figure 7, the close connection of the amount of antecedent rainfall and the resulting surface runoff coefficient on the strongly hydrophobic P1 is illustrated. The highest surface runoff coefficients (marked with a red ellipse) occurred during small precipitation events after periods with very little antecedent rainfall. The water repellence with enhanced surface runoff responses was caused by the initially dry organic compounds of the litter layer of these plots.

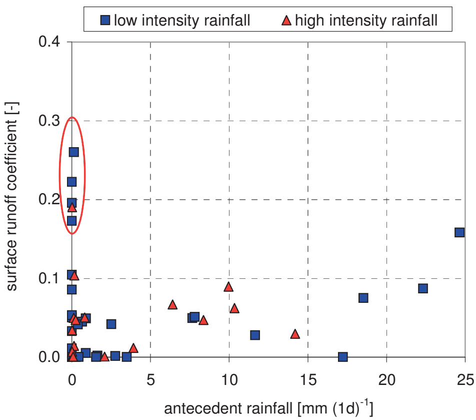

Fig. 7: Surface runoff coefficients against one day-antecedent rainfall amount for the strongly hydrophobic surface runoff plot P1; highest coefficients occur during rainfall events following dry periods (encircled values)

In the investigation area, there were no further characteristics identified generating significant amounts of surface runoff. Hence, if surface runoff occurs at all in the investigation area: Either there is an important response caused by zones with saturated soils or a small to moderate response indicates soils presenting hydrophobic reactions. Poorly drained layers are observed at different soil profiles but are either not continuous or simply too deep to efficiently retain the water and eventually cause saturation overland flow.

Influence of deforestation on surface runoff

In the following, pairs of surface runoff plots within the same or very similar forest site types will be compared. Hence, the discrepancy between factors that influence surface runoff formation is reduced to a minimum, as the objects of comparison will only differ considerably in the extent of storm damage. Soil properties and present ground vegetation, on the contrary, are virtually identical. This procedure allows the characterisation of the influence of deforestation on the surface runoff from small plots. A short description of the surface runoff plot pairs is given below, followed by a brief summary of the findings in each case.

Plots P1 and P10: These two plots are situated next to each other within an area characterised by moist and acid soils. P1 shows a total loss of vegetation due to storm damage with essentially two large, slightly tilted rootstocks remaining (Fig.3). In contrast P10 stands on an undamaged site featuring seven firs (abies alba) with a diameter at breast height larger than 20 cm.
Based on 52 rainfall events with available data for both locations, the mean surface runoff coefficients and the mean specific surface runoff peaks of the two plots show very comparable magnitudes (unlike pictured in Fig. 5 where only 23 events could be considered). However, P10 features the wider range of values, with extremes lying much above those of P1, as demonstrated in Figure 8. The comparison of the specific surface runoff peaks of all 52 rainfall events shows that P10 often achieves the higher peaks than P1. These findings are confirmed by the compilation of peaks and coefficients for the 19 intensive rainfall events registered during the investigation period (see Tab. 3). The most noticeable discrepancy between P1 and P10 is achieved by peakflow maximum values.

The higher peaks on P10 cannot be explained by differences in the occurrence of temporary Hortonian overland flow due to water repellent reactions. This process, characterised by sizeable runoff responses at the beginning of events, is very pronounced on both locations P1 and P10. It is supposed that the two large rootstocks on P1 have a favourable effect on the infiltration. The bare soil exposed by the stumps provides an opportunity for the surface runoff water to infiltrate into the soil. In addition, branches lying in a pile tend to locally attenuate water repellent reactions. Hence, at this site, elements of storm damage have a mitigating effect on the generation of surface runoff. A finding not confirmed at other sites, as demonstrated below.

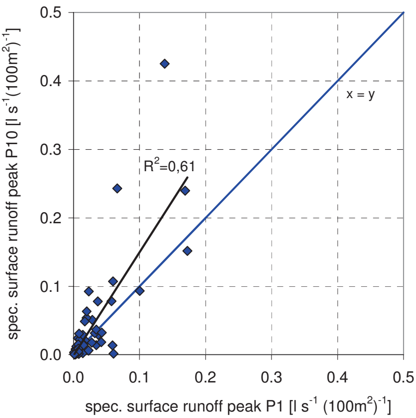

Fig. 8: Specific surface runoff peaks of P1 (x-axis) and P10 (y-axis) as pairs of values for the 52 rainfall events with available data for both plots

Plots P2 and P13: P2 lies in the middle of the storm damaged sub-catchment and contains one overthrown tree as well as two rootstocks from trees damaged prior to the storm Lothar. In contrast, P13 shows no damage with five spruces (picea abies), one fir and one alder (alnus incana) - all young growth. There is a distance of about 220 m between the two plots (Fig. 2). Nevertheless, the two locations are comparable with regard to their high soil moisture. However, P2 situated in the forest site type 49f presents the wetter soils.
Figure 5 and Table 3 accentuate the fact that the occurrence and magnitude of surface runoff are a lot more distinct at location P2 than on P13. As for the surface runoff coefficients achieved during all the 55 rainfall events, the difference between the two plots was found to be statistically significant (MANN/WHITNEY, tested at a 5 % significance level). Different

reasons may have lead to this result. On the one hand, forest site type 49f is supposed to show the wetter soil conditions than 26ho. Consequently, saturation surface runoff is to be expected earlier from plot P2. On the other hand, interception of rainfall on location P2 is only effected by ground vegetation (herbage, shrubs) that is (re-) growing as an after-effect of storm Lothar. In contrast, location P13 is partially closed with smaller trees and additionally features quite abundant ground vegetation. Thus, larger interception losses are probable there.
Surface runoff coefficients larger than one (cp. Fig. 5 and Tab.3) imply an additional lateral soil water input from underneath the PVC plates that reaches the plot surface as return flow. The values suggest a more important input in P2 than in P13. Nevertheless, it remains very difficult to estimate these lateral water flows on the basis of the spatial distribution of the forest site types or the geomorphology of the terrain. Possibly, the lateral inputs radically control the occurrence and the magnitude of surface runoff on these locations and consequently have a more important impact on the runoff formation than the different elements of damage. An influence of the gentle slope of P13 (Tab. 2) on the occurrence of surface runoff is not very likely, since the mean reaction times on the two locations are quite similar.

Plots P9 and P12: The two plots lie roughly one hundred metres from each other on very similar areas with moist to dry soils. The high infiltration capacity and permeability that characterises the two locations makes the occurrence of surface runoff improbable. Neither plots show any storm damage. However, P12 features a scar several metres long from when logs were hauled to the nearby forest path.
There are no considerable differences between the surface runoff coefficients of P9 and P12. The specific surface runoff peaks, however, are higher on location P9. A local reduction of the infiltration rate and a subsequent increase of surface runoff due to the trace from hauled logs are definitely not apparent on P12. The two plots are both located in moist to dry forest site types featuring soils with a high infiltration and permeability. It is assumed that the effect of soil compaction on the runoff formation is simply too small to be measured on these forest soils.

Tab. 3: Mean and maximum values of surface runoff coefficients, surface runoff peaks and reaction time based on intensive rainfall events only for the three plot pairs P1/P10 (19 events), P2/P13 (21 events) and P9/P12 (20 events)

Intensive rainfall events	Plot no.	Surface runoff coeff. [-]	Specific surface runoff peak [$l\ s^{-1}\ (100m^2)^{-1}$]	Reaction time [min]
Mean	1	0.04	0.055	16.8
	10	0.04	0.083	32.1
Maximum	1	0.19	0.172	-
	10	0.28	0.425	-
Mean	2	0.39	0.190	87.1
	13	0.08	0.107	78.1
Maximum	2	>1	1.716	-
	13	0.65	1.033	-
Mean	9	0.03	0.091	17.0
	12	0.02	0.056	32.0
Maximum	9	0.18	0.639	-
	12	0.12	0.347	-

CONCLUSIONS

The data gained from surface runoff plots during spring to autumn 2002 show a distinct pattern in the runoff formation. Concerning the occurrence and magnitude of surface runoff, two different processes could be discerned within the investigation area. On wet areas (Gleysols) serious precipitation events saturate the soil quickly and thus lead to saturation overland flow. After soil saturation, peak values are normally reached at the time of the most intensive rainfall. Hydrophobic reactions were found to be the most significant processes producing surface runoff on the moist to dry forest site types (Cambisols). Under water repellent conditions following dry periods, typical hydrographs feature high peaks of temporary Hortonian overland flow at the very beginning of precipitation events. Typically, the plots showing hydrophobic behaviour present a thick litter layer due to limited decomposition. Looking at the volume of the generated surface runoff, the range reached on these plots was far lower than on those plots producing saturation overland flow.
By means of comparative surveys with pairs of surface runoff plots, an influence of particular storm damage elements on the generation of surface runoff could be detected locally. At one site, the bare soil, laid open by overthrown rootstocks facilitates the re-infiltration of temporary Hortonian overland flow, while leftover branches attenuate hydrophobic conditions. On the whole, elements of storm damage have a rather restricted influence on surface runoff. Moreover, the successive ground vegetation arisen after the storm on damaged areas was to a large extent capable of compensating the interception provided by the forest cover before the event.
As a next step, the scale transition between the surface runoff plots and the sub-catchment will be studied. The main question in this respect is how far the insight into runoff generation gained with the analysis of the data from the surface runoff plots allows explaining the runoff reaction of the sub catchments.

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