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ORIGINAL PAPER

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# Influence of storm damage on the runoff generation in two sub-catchments of the Sperbelgraben, Swiss Emmental

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**Abstract** The project "Lothar and Mountain Torrents" investigates the effect of storm-originated deforestation on the hydrology on three scales within the Sperbelgraben catchment (Swiss Prealps). This article focuses on runoff measurements during a 3-year period in two differently affected sub-catchments (≈2 ha) and on 2-year surface runoff measurements on smaller plots (50–110 $m^2$). The link between these two scales and the results of irrigation experiments on 1 $m^2$ areas are interpreted using a detailed map of forest site types describing soil and vegetation characteristics. Plot results show that surface runoff is generated in two distinct ways. On the one hand, high amounts of saturation overland flow were observed on wet areas of gleyic soils. On the other hand, hardly any surface runoff was measured on Cambisols, with the exception of a short hydrophobic reaction at the beginning of storms occurring on areas with a thick organic litter layer (temporary Hortonian overland flow). On the long term, the lightly damaged sub-catchment (SC1) yields less runoff than the highly damaged one (SC2). This is confirmed when direct runoff volumes during flood events are considered. However, short and intensive showers surprisingly lead to higher discharge peaks in SC1. This occurrence is explained by different geomorphologic characteristics (mainly the channel density) and the spatial distribution of the moist to wet forest site types. Effects of deforestation and local soil compaction due to forest clearing remain small on both plot and sub-catchment scale.

**Keywords** Forest hydrology · Runoff generation · Storm damage · Forest coverage · Forest site types · Surface runoff

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## Introduction

The influence of forest coverage on runoff in river basins of various sizes represents a basic question in the field of forest hydrology (McCulloch and Robinson 1993). Nowadays, it is widely accepted that an increase in forest cover leads to a change in the water balance of a hydrological catchment, namely to an increase in annual evapotranspiration and thus to a decrease in annual runoff. The nature and extent of runoff change likely to result from a modification in forest cover has been investigated in studies all over the world and under very different conditions (e.g. Huang et al. 2003; Fahey 1994; Hornbeck et al. 1993; Cosandey 1992). One of the most established studies concerning this matter is probably the work by Bosch and Hewlett (1982) reviewing 94 catchment studies from a multitude of locations—an update of an earlier review mainly focussing on North America by Hibbert (1967). In this study, a remarkable variability in the totality of the results regarding changes in annual runoff was perceived. Nevertheless, the approximate magnitude of change within an experiment could be estimated due to systematic differences when studies were separated by forest cover type. A decreasing influence on annual runoff was noted for coniferous forests (ca. 40 mm), deciduous hardwoods (ca. 25 mm) and scrub (ca. 10 mm).

In contrast, the effect of forest cover on floods is more ambiguous: already in the first true catchment study, started in 1903, Engler (1919) pointed out the necessity of differentiation in his conclusions. Based on comparative measurements in two differently forested catchments in the Swiss Emmental region, his statements revealed an important attenuating impact of the forest on intensive short-duration flood events related to both runoff volume and peak discharge. However, during long duration and less intensive rainfall, a slight reduction or no effect at all was observed, depending on the water content of the soil before the event. Subsequently, the role of forests as a variable reducer of peak flow has often been confirmed and is undeniable in many specific cases (e.g. Richard 2002; Fahey and Jackson 1997; Beschta et al. 2000; Hornbeck 1973). Nevertheless, these findings cannot be generalised and do not apply in all circumstances. The complexity in rainfall-runoff processes makes it virtually impossible to predict the effect of deforestation or afforestation without a profound understanding of the hydrological behaviour of the studied site (Cosandey et al. 2005). McCulloch and Robinson (1993) note that depending amongst others on forest management methods, "forest may reduce small floods but, not extreme events". Furthermore, it is essential to distinguish between the influences of land cover change and logging operations in forest clearance (Reinhart 1964).

Many authors associate the mitigating influence of forests on flood generation with their soil properties (e.g. Engler 1919; Cosandey and Robinson 2000; Chang 2003; Weinmeister 2003). Generally, and if similar initial conditions are considered, forest soils have a larger water storage capacity than soils below arable land or pasture due to a higher content of organic material, less compaction and an usually more porous soil structure up to larger rooted depths. Burch et al. (1996) could not statistically demonstrate an overall effect of the forest on runoff coefficient and peak discharge in three forested catchments and smaller experimental plots in the Alptal (Swiss Prealps), not even for short and intensive showers. Hence, they linked this finding to the flysch soils predominating in this region; all Alptal sites are located on shallow and wet soils lying on similarly impermeable flysch bedrock. In such locations, potential difference in hydrological behaviour of forested areas and e.g. pasture is therefore attenuated due to small water retention capacity. Burch's findings stand in obvious contradiction with the conclusions of Engler (1919) and more generally with the paradigm in forest hydrology influencing Swiss forestry from the early 19th century until today (Germann and Weingartner 2003).

The assumption that forest influence highly depends on the local situation necessitates a spatial differentiated approach (Badoux et al. 2005; Hegg et al. 2004). The present study aims to provide such a differentiated view on forest effects on the runoff from small torrential catchments. Our objective is to explore dominant runoff processes at three different scales: sub-catchments ($\approx$20,000 m$^2$), surface runoff plots (50–110 m$^2$) and soil plots (1 m$^2$). Finally, the respective impact of severe storm damage on runoff mechanisms of the two larger scales is estimated and discussed. The research presented here is part of the overall project "Lothar and Mountain Torrents" (Hegg et al. 2004).

## Materials and methods

### Experimental site

Our investigation was carried out in a torrential catchment in central Switzerland. The Sperbelgraben catchment is situated in the hilly Emmental region (Prealps) and drains from northeast to southwest (Fig. 1). It has an area of 0.544 km$^2$, which is quasi entirely forested and ranges from 911 m asl at the gauging station to 1,203 m asl at its highest point. Main tree species in the area include fir (*abies alba*), spruce (*picea abies*), beech (*fagus sylvatica*) and sporadically maples (*acer pseudoplatanus*). Forest stands are for the most part well stratified and have a close to nature structure. Geologically, the Sperbelgraben is located in the molasse zone and consists of mainly conglomerate layers crossed by marl layers. 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, although steep slopes have only developed Regosols. Water-saturated soils, typically Gleysols, are largely restricted to gentle slopes with high clay content situated on the terraces. The mean annual precipitation (measured in the immediate proximity of the gauging station of the Sperbelgraben catchment) for the period from 1961 to 1999 amounts to 1,660 mm. Temperature measurements on a forested site within the Sperbelgraben from 1937 to 1957 indicated a mean annual temperature of 6.7°C (Casparis 1959). Full particulars about the torrential catchment of the Sperbelgraben are given in e.g. Engler (1919) or Burger (1954).

Inside the Sperbelgraben we focussed on two neighbouring sub-catchments of approx. 2 ha size (Fig. 1). They are located in the southeast zone of the ridge of the Sperbelgraben catchment at an elevation between 1,075 and 1,160 m asl. Apart from some soaked zones with nearly impermeable Gleysols, ca. 23% in sub-catchment 1 and ca. 37% in sub-catchment 2, the investigation area is principally characterised by Cambisols with partly limited and partly unlimited permeability. The most important parameters of the two sub-catchments are listed in Table 1.

During the storm event "Lothar" the two sub-catchments were affected very differently. Sub-catchment 1 (SC1) showed little damage, whereas in sub-catchment 2 (SC2) the majority of the trees were damaged or destroyed. Furthermore, SC2 was partially cleared with afforestation machinery. To quantify the magnitude of storm-caused damage in the two sub-catchments, healthy and damaged trees featuring a diameter at breast height (dbh) larger than 20 cm were surveyed and mapped. The stand density in the two areas prior to the storm Lothar was properly the same at 205 trees per hectare. Table 2 gives an overview of the effect of the storm on the forest stand in the two sub-catchments. On the whole, damage in SC2 is roughly three times larger than in the adjacent

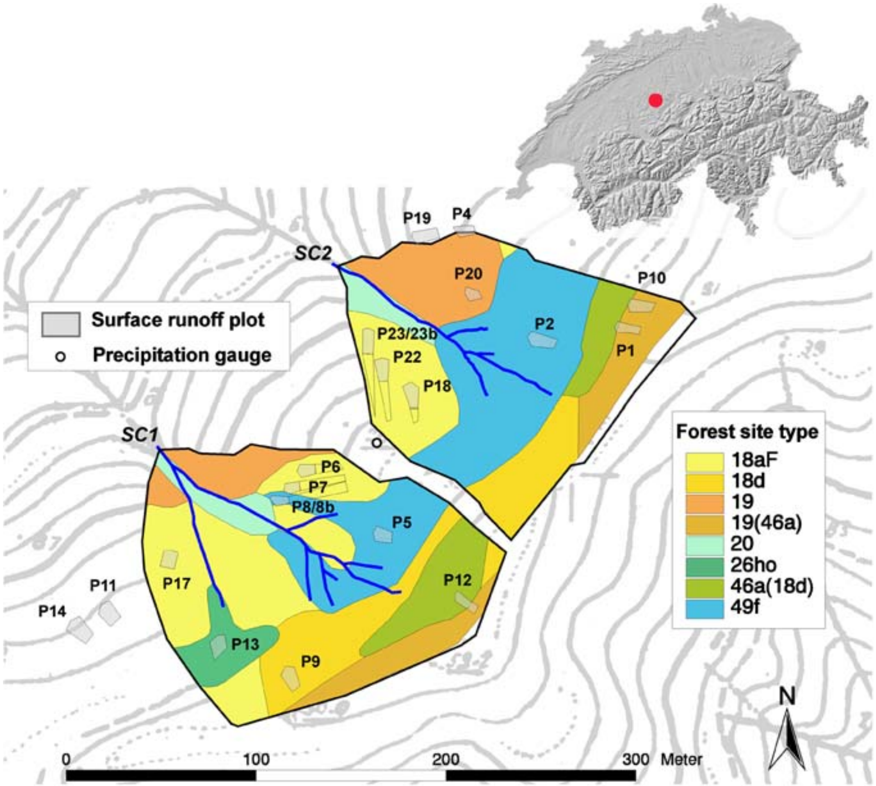


**Fig. 1** Overview over the investigation area showing the position of the 19 surface runoff plots (*numbered*) and the precipitation gauge (description of forest site types see Fig. 2 and Table 3 )

sub-catchment. Basal area after the storm amounts to 23.7 $m^2\,ha^{-1}$ in SC1 and 8.6 $m^2\,ha^{-1}$ in SC2 (dbh > 20 cm considered).

**Table 1** Characteristics of the lightly (SC1) and the heavily (SC2) damaged sub-catchment

| | | SC1 | SC2 |
|---|---|---|---|
| Area | ($m^2$) | 20,250 | 17,620 |
| Mean elevation | (m asl) | 1,130 | 1,128 |
| Exposition | | NW | NW |
| Mean slope | (°) | 25.3 | 25.7 |
| Maximal slope | (°) | 61.8 | 64.5 |
| Circumference | (m) | 550 | 540 |
| Form factor (Horton 1932) | | 0.54 | 0.49 |
| Channel density | (km $km^{-2}$) | 17.3 | 11.0 |
| Fraction of area with (moist to) wet soils | (%) | 22.8 | 36.7 |
| Damaged trees after storm | (%) | 21.4 | 62.7 |

## Forest site types

A map of forest site types of the entire Sperbelgraben catchment was established in spring 2001 by a professional company according to guidelines by Burger et al. (1996). These guidelines on the implementation of vegetation mapping are based on detailed descriptions of forest site types by Ott et al. (1997) and Ellenberg and Klötzli (1972). A forest site type represents the summary of the characteristics of similar forest sites grouped according to topographic and geomorphologic location, soil characteristics, floristic composition etc. The generated map at scale 1:5,000 was the basis for determining the location of all soil profiles and surface runoff plots.

Forest site types of the Sperbelgraben are different in soil moisture and soil acidity (Fig. 2) which implicates varying hydrological reactions of these areas. Higher soil water content (higher antecedent soil moisture) leads to

**Table 2** Tree survey after storm Lothar (only trees with a dbh > 20 cm considered, also for basal area calculation)

| | SC1 | | SC2 | |
|---|---|---|---|---|
| | Number | Percentage | Number | Percentage |
| Total trees | 416 | 100 | 362 | 100 |
| Undamaged trees | 327 | 78.6 | 135 | 37.3 |
| Overthrown trees | 66 | 15.9 | 176 | 48.6 |
| Broken trees | 12 | 2.9 | 28 | 7.7 |
| Cleared trees | 11 | 2.6 | 23 | 6.4 |
| Total damaged trees by storm | 89 | 21.4 | 227 | 62.7 |
| Basal area after storm ($m^2\,ha^{-1}$) | 23.7 | | 8.6 | |

**Table 3** Soil parameters for two groups of forest site types

| Forest site type (abbr.) | Slope (°) | Silt/clay (%) | PH ($CaCl_2$) | Litter layer (cm) | Rooting depth (cm) | Stagnic properties[a]/Gleyic properties[b] | Main soil type |
|---|---|---|---|---|---|---|---|
| 18d, 18aF, 19, 46a | 24–33 | 15–30/2–15 | 2.7–4.4 | 2–8 | > 100 | > 50 cm below surface/none | Cambisol |
| 26ho, 49f | 12–15 | 28–37/12–25 | 4.5–5.5 | 0–2 | < 30 | none/ > 20 cm below surface | Gleysol |

[a] Stagnic properties are related to soil saturation by surface water
[b] Gleyic properties are related to soil saturation by groundwater

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 spatial distribution of the forest site types in the sub-catchments is shown in Fig. 1.

Forest site types can be characterised regarding their runoff behaviour by distinguishing two main groups on the basis of the prevalent soil parameters measured in the investigation area (Table 3, Fig. 2). The forest site types 26ho (*Aceri-Fraxinetum adenostyletosum*) and 49f (*Equiseto-Abietetum fraxinetosum*) are typical for moist to wet areas. Dry to moist areas consist of forest site types 18aF (*Abieti-Fagetum typicum, with Festuca altissima*), 18d (*Aceri-Fraxinetum hylocomietosum*), 19 (*Abieti-Fagetum luzuletosum*) and 46a (*Vaccinio-Abietetum typicum*). Not assigned to one of these groups is type 20 (*Abieti-Fagetum polystichetosum)* characterised by small soil depths and restricted to steep areas along the channels.

## Measurement set-up

A nested approach was applied in the present study. Investigations on three different levels (soil profile, runoff

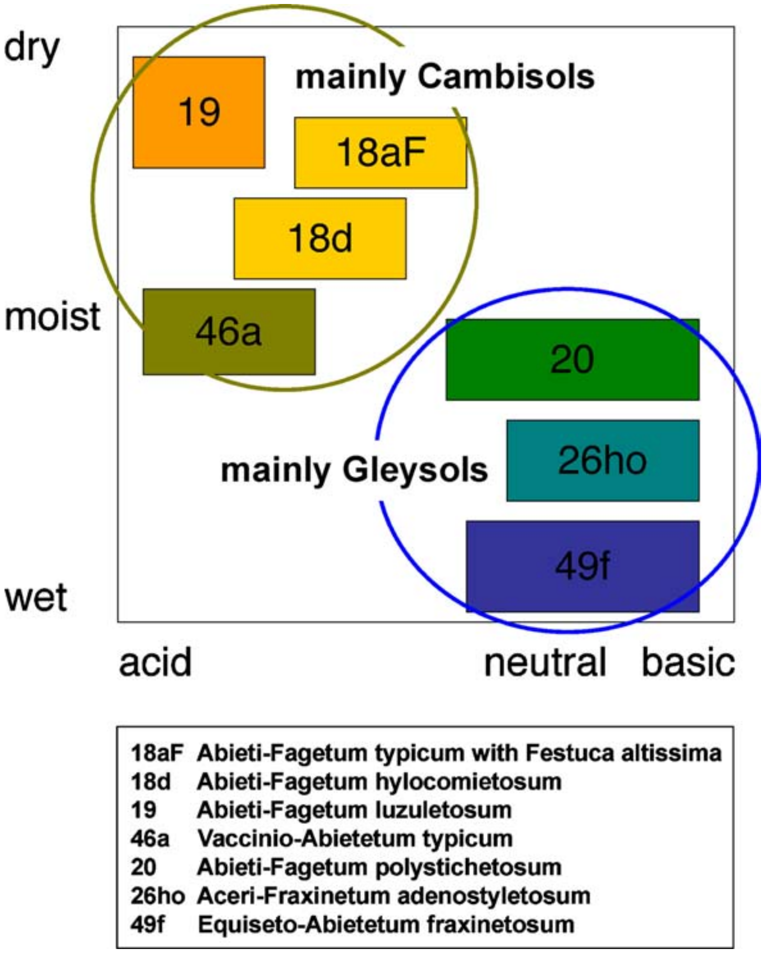


**Fig. 2** Wetness and acidity (pH) of selected forest site types in an elevation range from 1,000 to 1,300/1,400 m asl (from Burger et al. 1996; modified)

plot and sub-catchment) have been carried out to determine the hydrological characteristics within the sub-catchments. The map of forest site types, as described in the section above, allows for up- and downscaling of information between the different investigation levels.

### *Soil profiles and irrigation experiments*

The basic level in this approach consists of 17 soil profiles representing areas with similar forest and soil properties. Every profile has been classified according to the FAO–UNESCO soil classification system (FAO 1997). To determine the hydrologic properties of the site, irrigation experiments have been carried out just above most of the soil profiles. Total amount of overland flow and changes in water content were measured. Thus, the water-holding capacity of a soil and the total amount of water which forms sub-surface flow and deep percolation could be assessed. The results of these investigations are discussed in Witzig et al. (2004) and Badoux et al. (2005).

### *Surface runoff plots*

Nineteen surface runoff plots with an area of 50–110 $m^2$ were installed in 2002. The plots were distributed over the different forest site types in both sub-catchments and most of them are in the immediate vicinity of a soil profile. The plots 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 gutter which leads into a small gauging station. There, the water level is measured every minute and stored as ten minutes averages.

To investigate the behaviour of surface runoff from the top towards the bottom of the same slope, two so-called cascades have been installed. A cascade consists of three surface runoff plots, which are arranged parallel and vertically staggered on a slope. These surface runoff plots do not have an upper delimitation with PVC plates. Therefore the further down the slope a plot is situated, the larger its drainage area gets. The cascade in the lightly damaged sub-catchment (SC1) is composed of P6, P7 and P8 and the one in the heavily damaged sub-catchment (SC2) consists of P18, P22 and P23 (Fig. 1). Details about the setup of the surface runoff plots are to be found in Badoux et al. (2004).

In addition to the surface runoff investigations, two sub-surface runoff plots were installed in 2003 (23b, 8b). They do not have lateral delimitations and the PVC plates at the bottom were installed right above an impermeable soil layer at a depth of about 70 cm. Everything else of the measurement setup is identical to the surface runoff plot installations.

### *Sub-catchments*

Runoff measuring stations were installed at the outlet of both sub-catchments in early 2001. They have been equipped with a water level recorder, an instrument measuring electrical conductivity and a water temperature sensor. The measurement interval of all these devices is 10 min. To minimize data loss during wintertime, a gas heating was installed which prevented the water within the channel from freezing. Maintenance of the stations is carried out weekly, including a manual runoff measurement to verify the zero mark of the gauge and the water level–runoff relationship. More detailed information about the construction of these runoff-gauging stations is to be found in Badoux et al. (2002). In April 2001, a precipitation gauge (weighing principle) with an integrated data logger was installed and is operated since in the strip between the two sub-catchments.

## Data analysis

In 2002 and 2003 surface runoff on plots was measured from spring to autumn. From these two measurement series, only precipitation events during which surface runoff occurred at least on one plot were taken into account for further analysis. According to this, 51 surface runoff events occurred in 2002 and 46 in 2003. For every single surface runoff plot several parameters were determined where the most important are the amount of precipitation during an event, the surface runoff coefficient and the specific runoff peak value. The surface runoff coefficient was calculated by dividing the measured surface runoff volume by the event precipitation.

In the two sub-catchments, flood events that occurred between April 2001 and December 2003 and that exceeded a certain threshold of approx. $60\ l\ s^{-1}\ km^{-2}$ were taken into account for the investigation. Further analysis only included events that were fully registered by both runoff measuring stations, which was the case for the most part, except in some cases at the beginning of the study. The selected flood events were classified according to the characteristics of the triggering precipitation event. Three event types are differentiated: (1) intensive precipitation type featuring high 10-min intensities and short duration, (2) long-duration precipitation type with lower intensities and (3) flood events including snowmelt. For every single event, different rainfall-runoff parameters were calculated. The direct runoff volume during an event was determined by means of the software CODEAU (EPFL, Lausanne). The direct runoff coefficient was calculated by dividing this value by the event precipitation. The time lag between the beginning of precipitation and the start of direct runoff is termed reaction time.

The investigation period included an extraordinary meteorological situation, the very hot and quite dry summer of 2003 (Schär et al. 2004). For the investigation area in specific, this period can be defined from mid-June to the end of September. The nearby MeteoSwiss station Napf (7 km linear distance) recorded only 64% of its average precipitation in this period. And mean monthly temperatures from June and August exceeded longtime averages by not less than 7.5 and 6.4°C, respectively (MeteoSwiss 2003a).

## Results

### Water balance of the sub-catchments

In Fig. 3 runoff data from the lightly damaged sub-catchment 1 and the heavily damaged sub-catchment 2 are aggregated to daily runoff values and compared to each other. In general, SC2 yields more runoff than SC1. Daily values in the heavily damaged site exceed those from the lightly damaged site by an average of roughly 60%. This especially applies for medium to high values but not implicitly for low ones. During dry periods with daily runoff rates around 1 mm, there seems to be no more difference between the two catchments. In fact, the one-to-one-line intersects with the regression line at a threshold of about 0.6 mm. Thus, under pronounced low flow conditions, the lightly damaged sub-catchment 1 produces more daily runoff than its neighbour. Nevertheless, during the very hot and dry summer of 2003, it was precisely this sub-catchment that ran dry on a total of 11 days whilst the heavily damaged sub-catchment 2 showed a minimum of runoff throughout this extraordinary period.

Daily runoff data were aggregated to monthly and annual runoff values (Table 4). In some cases, this calculation was made impossible when longer gaps (measuring failure or ice-formation in the station in winter) occurred in the data set. In the event of short data gaps of a couple of hours, missing data were interpolated. The first year of investigation in 2001 was left apart since measurements were only started in April and technical problems led to a loss of data in September.

In terms of precipitation, the 2 years differ from each other quite distinctively. While the ca. 1,780 mm in 2002 exceed the longtime annual average of the MeteoSwiss rain gauge Kurzeneialp (at the outlet of the Sperbelgraben) by roughly 10%, the 2003 value of ca. 1,220 mm, which corresponds to about 75% of the longtime average, stands out because it is very low (MeteoSwiss 2003b). The last time such a small amount of precipitation was registered at Kurzeneialp was in 1976.

In both years the heavily damaged sub-catchment 2 had a higher annual runoff (Table 4). According to the findings from Fig. 3, higher values in SC2 predominate for wet to very wet periods. During the dry and hot summer months of 2003 (June–September), however, the two sub-catchments yielded similarly small amounts of runoff. Considered the fact that the stream in the lightly damaged sub-catchment 1 ran dry several times during this period, the comparison of those monthly runoff rates tends to surprise (e.g. July). Especially in July the higher total in sub-catchment 1 has to be attributed to the totally different behaviour of the two catchments during short but quite intensive showers with low antecedent rainfall. This subject matter, however, will be further discussed below when single flood events are addressed.

On the whole, the difference between the two sites of daily, monthly and annual runoff values is—at least partly—to attribute to a higher evapotranspiration in the less affected SC1 compared to SC2. Although

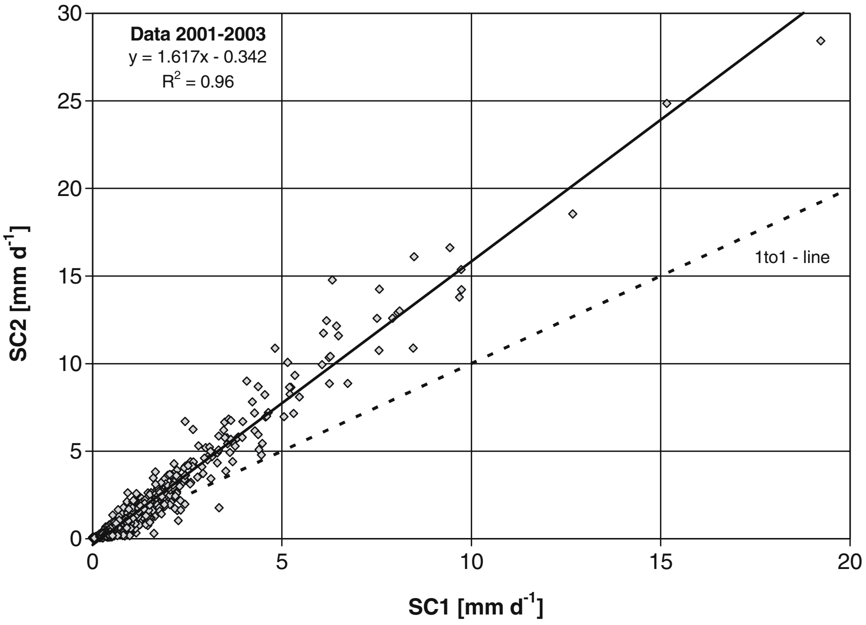


**Fig. 3** Daily runoff (from April 2001 till December 2003) of the lightly (*SC1*) and the heavily (*SC2*) damaged sub-catchments; the *full line* represents the regression line

**Table 4** Precipitation (P), runoff (R) and residual term (P–R) for the years 2002 and 2003 in the lightly (SC1) and the heavily (SC2) damaged sub-catchment

| | | J | F | M | A | M | J | J | A | S | O | N | D | Tot |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2002 | | | | | | | | | | | | | | |
| P (mm) | | 26 | 102 | 81 | 81 | 171 | 163 | 224 | 213 | 214 | 157 | 244 | 108 | 1,783 |
| R (mm) | SC1 | 16[a] | 39 | 32 | 15 | 40 | 33 | 67 | 55 | 59 | 52 | 87 | 35 | 530 |
| P–R (mm) | SC1 | 10 | 63 | 49 | 66 | 131 | 130 | 157 | 158 | 155 | 105 | 157 | 73 | 1,253 |
| R (mm) | SC2 | 12[a] | 52 | 39 | 16 | 56 | 44 | 91 | 81 | 87 | 74 | 131 | 47 | 731 |
| P–R (mm) | SC2 | 14 | 50 | 42 | 65 | 115 | 119 | 133 | 132 | 127 | 83 | 113 | 61 | 1,052 |
| 2003 | | | | | | | | | | | | | | |
| P (mm) | | 102 | 68 | 67 | 117 | 142 | 80 | 148 | 78 | 69 | 185 | 114 | 55 | 1,224 |
| R (mm) | SC1 | [b] | [b] | 59 | 28 | 33 | 13 | 14 | 5 | 4 | 28 | 15 | 17 | *230* |
| P–R (mm) | SC1 | – | – | 8 | 89 | 109 | 67 | 134 | 73 | 64 | 157 | 99 | 38 | *995* |
| R (mm) | SC2 | [b] | [b] | 70 | 34 | 41 | 14 | 7 | 4 | 2 | 41 | 17 | 15 | *260* |
| P–R (mm) | SC2 | – | – | −3 | 83 | 100 | 66 | 141 | 73 | 67 | 144 | 98 | 40 | *965* |

[a] In order to estimate the monthly runoff in January 2002, some daily values had to be interpolated

[b] Due to permanent ice formation in the measuring stations, no monthly runoff could be calculated for January and February 2003. Observations in the field lead to rough estimates of approx. 15 mm in each sub-catchment (both months together)

ground vegetation (e.g. *athyrium filix-femina*, *sorbus aucuparia*, *vaccinium myrtillus*) on damaged areas developed fast in the years after the storm event, it was not able to fully compensated for the missing trees in SC2. Hence, higher evapotranspiration leads to a higher average soil moisture deficit in the lightly damaged sub-catchment 1 and this site can therefore store more water in its soils. A fact that should also be observable when looking at single storm events (compare below). However, this explanation of differences in runoff premises impermeable catchments without any water losses as a result of seepage.

The centrally registered precipitation can permissibly be regarded as the areal precipitation for both sub-catchments. Hence, the residual term (P–R) of the water balance is considered as a rough estimate for the annual evapotranspiration (Table 4). Restrictions include the fact that measuring errors of runoff and precipitation add up in the residual term as well as variations of water storage in the soil and snowpack.

For both sub-catchments the residual terms (P–R) are very large in both years. They exceed by far the highest estimates for annual evapotranspiration in prealpine regions (Menzel et al. 1997; Lang 1978). A comparison of the sub-catchment data with data from the entire Sperbelgraben shows important differences in annual runoff and residual term. It emphasises how implausibly high the values of the smaller sub-catchments are. However, also (P–R) calculated for the total Sperbelgraben is quite high. The mean of the annual evapotranspiration estimates (1918–2000) amounts to 812 mm, whereas Casparis (1959) gives an average value of 856 mm for the period from 1927 to 1956. Penman (1959) questions the occurrence of such high values and suggests upper estimates of 550 mm for the Sperbelgraben. He mentions possible inaccuracies of the runoff gauge as an explanation approach. Most notably, though, he suspects an unknown degree of leakage from the Sperbelgraben.

Therefore, we conclude that the underground of the Sperbelgraben is not impermeable and accordingly water is lost due to seepage. This leakage problem was unexpected, as the gauging stations of the sub-catchments were built directly on the bedrock (that was believed to be impermeable based on field observations and previous descriptions). We cannot know if the amount of leakage in the two sub-catchments is the same and have to interpret the values in Table 4 with caution. Short-term flood events discussed in the section below are less affected by leakage, given that the runoff behaviour of a sub-catchment in such a case is dominated by fast runoff components.

## Short-term events in the sub-catchments

For every single event, several rainfall-runoff parameters were calculated. Table 5 shows the mean values of the most important parameters grouped by event type.

On average, the heavily damaged sub-catchment 2 yields more direct runoff than the lightly damaged sub-catchment 1, regardless of the event type (Table 5). The difference is more pronounced though when considering long-duration precipitation events compared to short and intensive rainfall events (SC2 means exceed SC1 by means of ca. 75 and 50%, respectively). As a matter of fact, direct runoff volumes are significantly different at the 95th percentile only for persistent precipitation events. From a total of 54 events only three showed higher direct runoff in SC1. All these occurred during the very dry summer of 2003. During 12 out of 45 intensive showers, SC1 produced a higher direct runoff than SC2, however, mostly for rather small events (direct runoff $<0.5$ mm). Interestingly, all five intensive shower events that took place from mid-June to late-September 2003 fall in this category.

Figure 4 gives four examples of single flood events in the Sperbelgraben sub-catchments. For the two

**Table 5** Arithmetic mean of precipitation–runoff parameters for the lightly (SC1) and the heavily (SC2) damaged sub-catchment; persistent precipitation events (top), intensive showers events (middle) and events including snowmelt (bottom) from April 2001 till December 2003; the column SD95 indicates whether the respective values are significantly different in the two catchments at the 95th percentile using the Mann–Whitney *U* Test

| Parameter | Unit | SC1 | SC2 | $SD_{95}$ |
|---|---|---|---|---|
| Persistent precipitation (54 events) | | | | |
| Precipitation (P) | (mm) | 29.0 | 29.0 | – |
| Max. P-intensity | (mm 10 $\text{min}^{-1}$) | 1.2 | 1.2 | – |
| Length of direct runoff | (min) | 2,034 | 2,226 | N |
| Reaction time | (min) | 95 | 170 | Y |
| Peak discharge | (l $\text{s}^{-1}$ $\text{km}^{-1}$) | 146 | 175 | N |
| Direct runoff | (mm) | 3.96 | 6.96 | Y |
| Direct runoff coefficient | | 0.111 | 0.199 | Y |
| Intensive showers (45 events) | | | | |
| Precipitation (P) | (mm) | 17.3 | 17.3 | – |
| Max. P-intensity | (mm 10 $\text{min}^{-1}$) | 3.7 | 3.7 | – |
| Length of direct runoff | (min) | 608 | 749 | Y |
| Reaction time | (min) | 49 | 79 | Y |
| Peak discharge | (l $\text{s}^{-1}$ $\text{km}^{-1}$) | 290 | 241 | Y |
| Direct runoff | (mm) | 1.17 | 1.77 | N |
| Direct runoff coefficient | | 0.068 | 0.098 | Y |
| Events incl. snow melt (18 events) | | | | |
| Precipitation (P) | (mm) | 16.4 | 16.4 | – |
| Max. P-intensity | (mm 10 $\text{min}^{-1}$) | 0.7 | 0.7 | – |
| Length of direct runoff | (min) | 3,484 | 4,153 | N |
| Reaction time | (min) | – | – | – |
| Peak discharge | (l $\text{s}^{-1}$ $\text{km}^{-1}$) | 129 | 204 | N |
| Direct runoff | (mm) | 5.91 | 11.05 | Y |
| Direct runoff coefficient | | – | – | – |

low-intensity events, it is evident that direct runoff is much larger from the heavily damaged sub-catchment 2 than from its neighbour. Actually, specific runoff is continuously higher in SC2 during these two events, apart from very short periods right at the beginning of precipitation. During the November 2002 flood, direct runoff amounts to 37.1 mm in SC2 and 18.2 mm in SC1 with direct runoff coefficients of 0.43 and 0.21, respectively. It represents the forth-largest event recorded for both sub-catchments regarding direct runoff volume. Also for short and intensive rainfall events, higher direct runoff was measured in SC2, even though with a minor difference (Fig. 4, bottom). This has to do with the fact that in general, the lightly damaged sub-catchment 1 surprisingly yields higher runoff peaks during this event type, an occurrence described in detail below. In most of the events (mainly the larger ones), however, the slower runoff recession of the heavily damaged sub-catchment 2 compensates for the smaller specific peaks and leads to higher direct runoff values. The July 2001 event in Fig. 4 for example yielded a discharge of 3.07 mm in SC2 and 2.13 mm in SC1 (coefficients: 0.15 and 0.10, respectively).

Under the very dry and hot conditions prevailing from mid-June till the end of September 2003, the two sub-catchments in the Sperbelgraben behaved somewhat differently than usual. As a matter of fact, all eight events registered in this period showed higher direct runoff volume in SC1. This occurrence is well illustrated by means of Fig. 5, showing a July 2003 event characterised by its very short duration but high rainfall intensity. Moreover, antecedent precipitation was extremely low, as it had not been raining for the previous 11 days.

Regarding direct runoff coefficients, the situation is more consistent. The values of the two catchments are significantly different for both persistent precipitation and intensive shower events. The difference between SC1 and SC2 is again more distinctive with persistent precipitation events. Direct runoff coefficient is calculated through the scaling with event precipitation. By this means, the influence of a non-site-specific parameter (precipitation) is consciously being excluded. Thus, the differences between the sub-catchments are better accentuated. In the present case, this leads to a statistically significant difference between the SC1 and SC2 coefficients during intensive shower events while for direct runoff this does not apply.

The comparison of the mean specific discharge peaks, though, does not allow for a univocal interpretation of the data. While for intensive showers the average peaks of SC1 are higher than those of SC2, it is the opposite for persistent precipitation events (Table 5). Although the difference with peak discharge between the two sub-catchments is statistically significant at the 95th percentile only for intensive shower events (and not for persistent precipitation events), SC1 and SC2 feature a diverse runoff behaviour depending on the event type.

For short and intensive precipitation events, discharge in SC1 increases faster and leads to higher peaks than in SC2. However, the discharge recession right after a peak is much slower for SC2. Figure 4 (bottom, right hydrograph) shows this typical behaviour of the two sub-catchments during a short and intensive precipitation event. Looking at the 14 July 2001 event of Fig. 4 (bottom, left hydrograph), it can be noticed that SC2 has a higher discharge peak following the second precipitation peak. This was caused by the slower runoff decrease

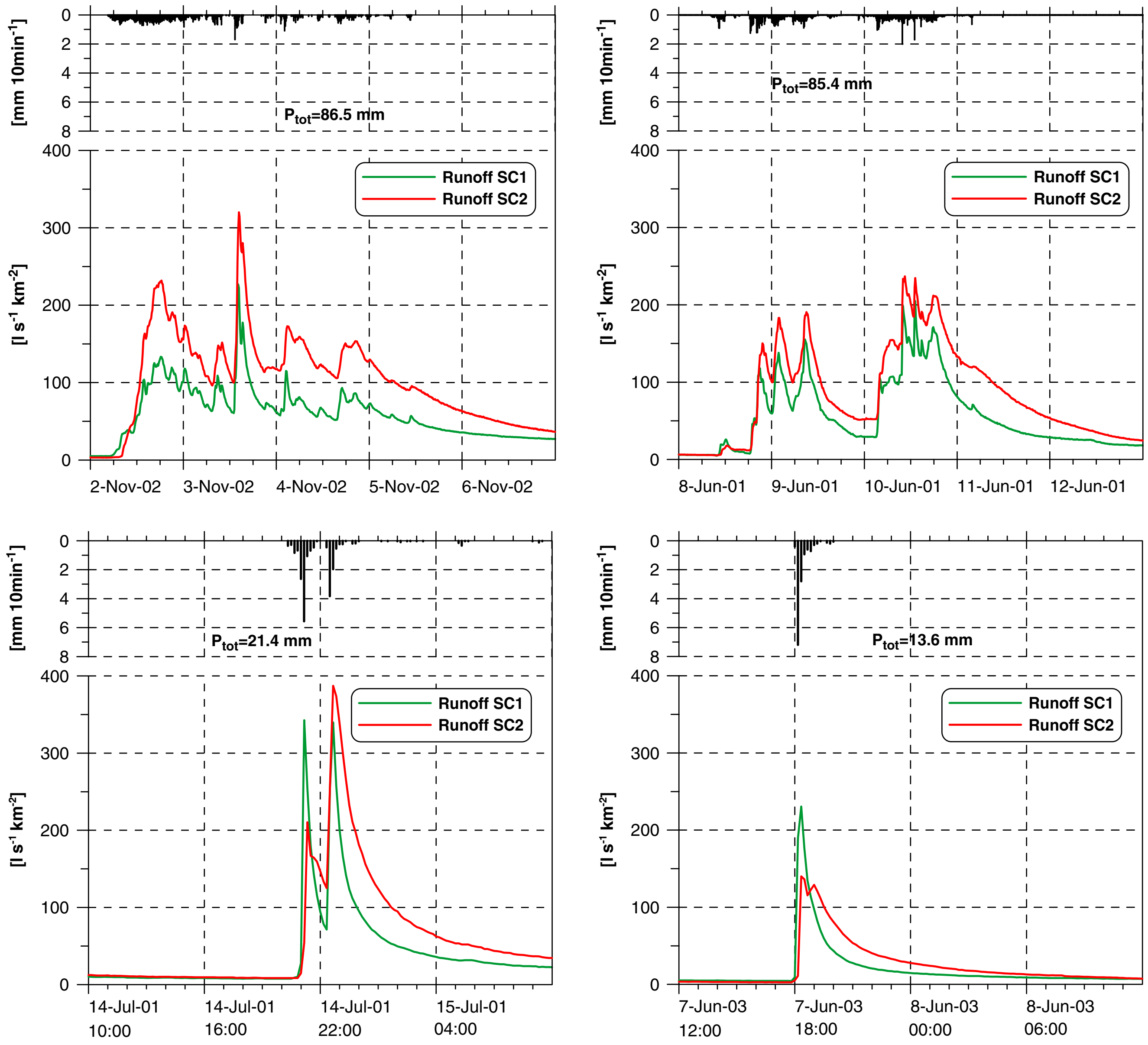


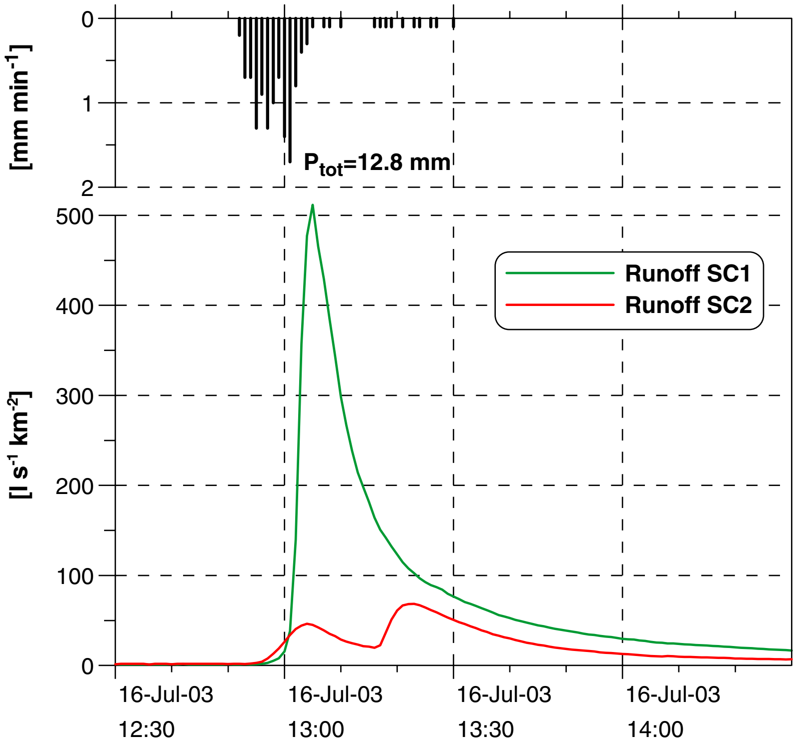
**Fig. 4** Typical examples of precipitation–runoff events in the lightly (*SC1*) and heavily (*SC2*) damaged sub-catchments: two long-duration, low-intensity events (*top*) and two short, high-intensity events (*bottom*)

there compared to SC1. Although the newly beginning rainfall led to similar reactions in both catchments, the different runoff levels at 22:30 led to a higher peak value in SC2. In contrast, peak discharge values for typical long-duration precipitation events are in general higher in the heavily damaged sub-catchment 2 (Fig. 4, top). Normally, the sub-catchments react weakly at the beginning of a low-intensity rainfall. After some time however, SC2 starts to yield higher runoff compared to its neighbour until a first peak is reached. During the further progression of an event, the catchments runoff responses resemble each other again, even though situated on a different flow level.

Looking at the specific event types, it can be stated that for short and intensive shower events the lightly damaged sub-catchment 1 normally shows a quicker and more distinct runoff reaction leading to higher peak discharge values. This pattern is all the more pronounced during dry periods when the antecedent precipitation is low, as illustrated in Figure 5 showing a short shower in July 2003. For such events, SC1 also has higher direct runoff coefficients than SC2. Generally, however, the sub-catchments behave conversely regarding direct runoff due to a slower runoff recession in SC2. This is a typical characteristic for this sub-catchment, which is also suggested by higher direct runoff duration compared to SC1 (Table 5).

In comparison, long-duration, low-intensity precipitation leads to a more consistent pattern of runoff behaviour in the two sub-catchments. After a quicker runoff reaction in SC1 and as precipitation persist, the heavily damaged SC2 usually shows higher specific

**Fig. 5** Very short intensive rainfall event during summer 2003 (available 1-min runoff and precipitation data were used in this chart)



runoff throughout a whole event. Thus, this causes higher peak discharge values as well as larger direct runoff volumes. The only exceptions to this standard occurred during the hot and dry summer of 2003 after long rainless periods.

For flood events generated due to a combination of rainfall and snowmelt (or rarely sole snowmelt), the two sub-catchments draw a classic pattern for differently forested basins. This was demonstrated e.g. by Stähli and Gustafsson (2005) for the Alptal study site in the Swiss Prealps or by Koivusalo and Kokkonen (2002) in Siuntio, southern Finland. In consequence of a higher snow interception compared to its neighbour, the lightly damaged sub-catchment normally features thinner snowpack and smaller water equivalent during the winter months. A fact that is documented by weekly field measurements in the winters of 2001/02–2003/04. In general, the less abundant snowmelt in SC1 due to lower snow water equivalent of the snowpack leads to smaller runoff during flood events compared to SC2 (Table 5). Furthermore, reduced radiation on the ground (canopy radiation interception) in SC1 causes lower snowmelt intensities when no rainfall is involved.

## Surface runoff events on the plots

### *Summer season 2002*

Data gained from surface runoff plots in 2002 show a distinct pattern in the runoff formation Badoux et al. (2004). Concerning the occurrence and magnitude of surface runoff, two different processes could be discerned: (1) on moist to wet areas (typically Gleysols) considerable precipitation events saturate the soil quickly and lead to saturation overland flow. Subsequently, peak values are normally reached at the time of the most intensive rainfall, (2) hydrophobic reactions were found to be the most significant processes producing surface runoff on dry to moist areas (typically Cambisols). Under water-repellent conditions following dry periods, typical hydrographs feature 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. The range of generated surface runoff volume on these plots was far lower than on those producing saturation overland flow. Also, the influence of hydrophobic layers is supposed to be restricted to a small scale (Doerr et al. 2003). Although poorly drained soil layers are observed at different profiles, they are either not continuous or simply too deep to efficiently retain water and eventually cause overland flow. An influence of particular storm damage elements on the generation of surface runoff in the investigation area could only be detected locally and to a restricted extent. Moreover, the successive ground vegetation grown after the storm on damaged areas was to a large extent capable of compensating the interception provided by the forest cover before the event.

### *Summer season 2003*

Compared to 2002 measurements, 41% less summer precipitation was recorded in 2003 in the investigation

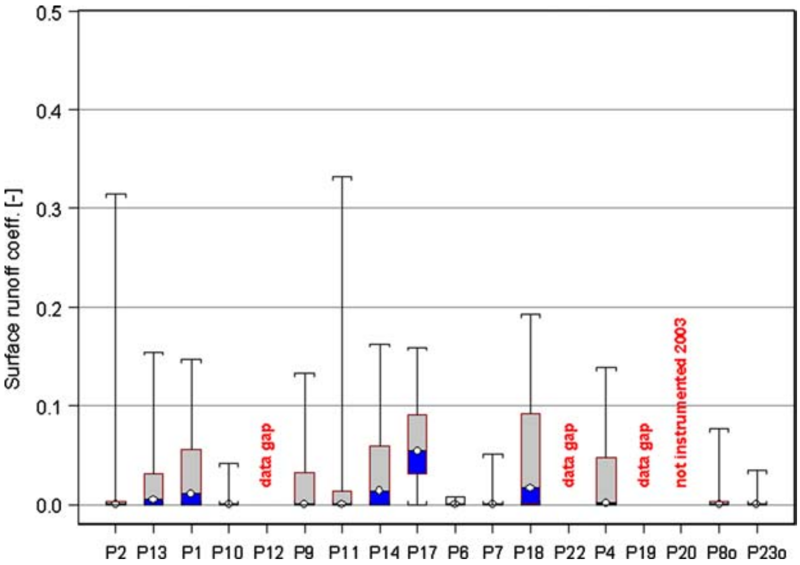


**Fig. 6** Surface runoff coefficients for 20 selected rainfall events and each surface runoff plot; displayed *box plots* give range, *quartiles and median* and are placed regarding the affiliation of the plot to a forest site type; all events fall within the period from 30 June to 10 September 2003; plots P12, P19, P22 had to be omitted due to measuring failures during this period

area (April through September). But for all that, about the same amount of events was registered on the plots.

Figure 6 displays the surface runoff coefficients of the plots operated in the Sperbelgraben investigation area on the basis of 20 selected 2003 precipitation events. In order to assure the comparability of the data, only events could be considered during which all plots were functional. Figure 6 shows no obvious difference between plots situated on moist to wet forest site types (P2, P13) and plots lying on dry to moist forest site types (others). This fact constitutes a major difference to the conclusions made concerning the 2002 data (Badoux et al. 2004). While plots on dry to moist sites performed similarly than in 2002, plots on moist to wet sites registered considerably lower surface runoff coefficients. A plausible explanation for this occurrence is the fact that many of the 20 considered events lie within the summer 2003 heat wave.

As shown in Witzig et al. (2004), the Gleysols of the investigation area are water saturated throughout the year below a depth of 15–35 cm which corresponds to their restricted rooting depth. Depending on the weather, the groundwater table is temporally very close to surface. As a result of the heat and very moderate precipitation, the water table of the Gleysols on gentle slopes in the heavily damaged sub-catchment 2 receded sensibly to a depth of approx. 35 cm. Consequently, these soils were able to store fair amounts of precipitation water without generating the site characteristic saturation overland flow. Moreover, some water might have run off as shallow sub-surface flow.

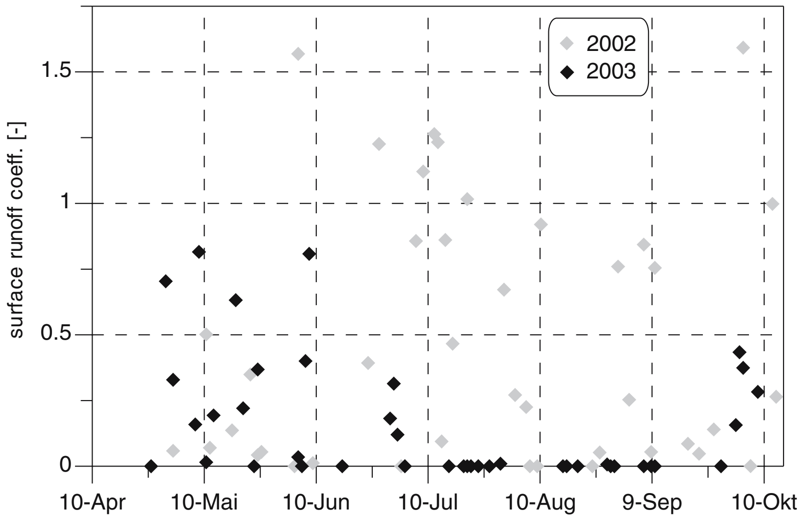
This explanation approach is confirmed by Fig. 7 that shows the progression of surface runoff coefficients on P2 (moist to wet forest site type 49f) during the 2002 and 2003 measuring seasons. Through spring and until the end of June 2003, P2 generated coefficients comparable to those of the preceding year. Then, after three last events with surface runoff in the first days of July, plot P2 did not show any notable reaction to rainfall for the next 3 months. During this period, the water table in these Gleysols was low enough that even the few considerable precipitation events (e.g. 42 mm on 30th August) did not result in soil saturation. It was only in early October, when roughly 91 mm of precipitation fell in 3 days, that P2 generated surface runoff again.

In contrast, P13, the other plot situated on a moist to wet forest site type (26ho), did not react as drastic to the heat wave as P2 did. In 2003 P13 responded more often to rainfall events by generating surface runoff (50% of the recorded events in 2003 compared to 31% in 2002) but on a quantity basis, produced a lot less surface runoff (roughly 50% of the 2002 volume).

Furthermore, it has to be mentioned that the occurrence and magnitude of surface runoff are a lot more distinct on P2 than on P13. This has already been shown in Badoux et al. (2004) for 2002 data and could be confirmed (Fig. 8). The main reason for this actuality is the fact that forest site type 49f is normally showing the wetter soil conditions than 26ho (Burger et al. 1996). Comparing the data ranges of P13 and P1 for the 42 considered events, no considerable difference appears (with the exception of a single P13 value). Nevertheless, the processes leading to the runoff pattern of these two plots are basically different.

Finally, in the 2003 measuring period, the plots situated on dry to moist forest site types did not show a basically different surface runoff behaviour compared to the preceding year. On the whole, the coefficients lay in the same range and reflect the pattern first observed in 2002. They never exceed 0.20, a typical characteristic when surface runoff is generated due to water-repellent reactions in the acid–litter layer.

**Fig. 7** Surface runoff coefficients for plot P2 from events in 2002 and 2003



*Surface runoff measurements along the slopes (cascades)*

For the most part, the plots of the two cascades did not show any surface runoff at all during the selected events. When surface runoff occurred on a plot and a coefficient could be determined, it remained small. The largest surface runoff coefficient registered within the considered events was 0.12 on P18 during a 40 mm long-duration precipitation. Furthermore, no rainfall event at all led to runoff on all six plots of the two cascades. Same picture when looking at the cascades separately: no event induced surface runoff simultaneously in all three plots along the slope of the lightly damaged sub-catchment 1; for the plots of the heavily damaged sub-catchment 2 two such events occurred, showing mostly very small amounts of runoff though.

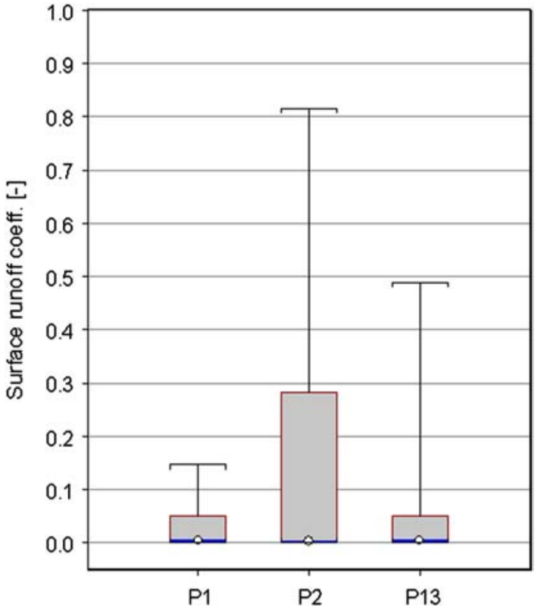


**Fig. 8** Surface runoff coefficients for the 42 events during which the plots P1, P2, P13 were operational (26 April until 8 October 2003)

Hence, in neither of the two cascades any kind of runoff generation pattern is detectable, least of all an increase of surface runoff in downhill direction. It is therefore believed that the high infiltration capacity of the observed Cambisols does prevent from any larger surface runoff generation along the slopes. Apart from P18, none of the plots showed frequent hydrophobic behaviour during the two measuring periods.

## Sub-surface flow

Irrigation experiments showed that on Cambisols, between 75 and 95% of the precipitation percolates deeper than 50 cm (Witzig et al. 2004). Therefore, the two plots P8 and P23 were additionally equipped to measure sub-surface flow above a less permeable soil layer (identified during soil profile analysis) at a depth of approx. 70 cm. These two installations are referred to as P8b and P23b.

Sub-surface runoff plot P23b operated during 31 events and P8b throughout 37. During the events monitored at these stations, no sub-surface flow was registered (with the exception of three negligible responses on P8b). As a result of this, we conclude that water infiltrates beyond 70 cm, confirming that this soil layer is not poorly drained enough to stop water from percolating, nor is it continuous over the whole slope. Taking into account further field observations that revealed similar soil characteristics up to large depths (in part >2 m), lateral sub-surface flow is likely to occur only at the soil–rock interface. However, not much is known about the bedrock depth and topography on these areas so far.

## Discussion

Not only runoff peaks after intensive showers, but also the average reaction times of the two sub-catchments to rainfall events seem to be unaffected by the different extent of storm damage. The lightly damaged sub-catchment 1 shows significantly quicker reactions than its neighbour for both event types. Thus, the effect of higher canopy interception in SC1 is not ascertainable. Since the two sub-catchments have a very similar form (Table 1), their runoff concentration should theoretically be comparable. However, the channel density in SC1 is approx. 60 % larger than in SC2 (Table 1; Fig. 1). This geomorphic parameter may well control the behaviour of these sites, allowing for a quicker reaction and a faster concentration in the lightly damaged sub-catchment 1. Furthermore, the existence of a secondary channel in SC1 enables a fast drainage of the western part of the sub-catchment during rainfall events (Fig. 1), while SC2 has a central and sparsely branched channel. Finally, wet zones (forest site types 49f and 26ho) are particularly well connected to the channel system in the lightly damaged sub-catchment. The channel density for these areas amounts to 30.1 km $\mathrm{km}^{-2}$ for SC1 compared to 20.1 km $\mathrm{km}^{-2}$ for SC2. The importance of the wet zones in reference to surface runoff generation on the plot scale has been demonstrated above.

Hence, it is assumed that for short intensive showers, the contributing areas in the sub-catchments are restricted to steep slopes with very shallow soils along the lower channels (forest site type 20) and the moist to wet areas in the immediate channel vicinity. As neither large amounts of surface runoff nor fast sub-surface flow were observed on the dry to moist areas that constitute the hillslopes of the sub-catchments, no contribution is to be expected from there.

When rainfall is more continuous but less intensive, peak values are generally not reached early in an event. Thus, fast runoff concentration in a well-branched channel system will not be the main catchment characteristic controlling the runoff progression. For such long-duration events, it is supposed that an increasingly large area featuring moist to wet soils contributes to the runoff formation by yielding both surface runoff and sub-surface flow (assessed at the profile and plot scale). Since soil saturation is widely reached there, little surface water will infiltrate on its way to the central channel system. At the outlet of the sub-catchment, a discharge peak is attained when virtually all areas showing forest site types 26ho and 49f are yielding runoff. Since SC2 has a larger fraction of these areas than SC1 (Table 1), higher peaks and larger direct runoff volumes are measured there. Accordingly, the spatial distribution of the moist to wet zones is of greater significance than any other catchment characteristic regarding runoff generation during long-lasting, low-intensity precipitation events. In contrast, the role of the dry to moist areas on the slopes of the sub-catchments is not evident when rainfall is continuous. On Cambisols typical for such areas, it could not be detected to what depth water percolates vertically and if or when the soil–bedrock interface is reached. The speed and orientation of a possible further lateral flow along this boundary is also uncertain, as bedrock structure could not yet be monitored.

Extreme meteorological conditions, however, can sensibly modify the characteristics of runoff generation in the investigated sub-catchments. At least a part of the generally wet Gleysols in SC2 (forest site type 49f) generated almost no surface runoff between mid-June and the end of September 2003 (Fig. 7). Due to the heat and drought, the water table of plot P2 receded sensibly and the increased storage capacity prevented the production of saturation overland flow. On the other hand, P13 (forest site type 26ho) within SC1 was less affected by the meteorological conditions. These circumstances on the plot scale partly explain the irregularities observed on the sub-catchment scale. Specifically, the eight sub-catchment events that occurred from mid-June till the end of September 2003 were all characterised by an unusual runoff behaviour compared to all the other sub-catchment events recorded during this investigation (Fig. 5). In fact, the lightly damaged SC1 yielded more direct runoff than SC2, even during the three long-duration precipitation events. The lack of large amounts of surface runoff from areas on forest site type 49f in SC2 led to an overall low level of total runoff there. Furthermore, the slow runoff recession typical for intensive showers in SC2 did not occur in summer 2003 as shown in Fig. 5, probably because even the Gleysols close to the channel system did not react to the rainfall peaks. In contrast, SC1 was less affected because the areas on forest site type 26ho were at least yielding small amounts of runoff.

## Conclusions

Regarding surface runoff generation in forested areas, there is no such thing as a uniform reaction to storm precipitation. Groups of forest site types (Table 3) studied within the investigation area show a totally diverse behaviour during flood events. The dry to moist forest site types (18aF, 18d, 19 and 46a) produce virtually no surface runoff, aside from locally occurring temporary Hortonian overland flow. While on the moist to wet forest site types (26ho and 49f), large amounts of saturation overland flow can be generated under normal conditions. Sites with a medium surface runoff reaction on precipitation events do not exist in the Sperbelgraben sub-catchments.

Forests like the ones found in the Sperbelgraben sub-catchments have a much better capability to cope with natural disturbances than expected. And thus, the effects of deforestation on the runoff processes are surprisingly small. In general, the forest soil is affected locally when e.g. a tree is overthrown and consequently the soil structure damaged on this specific site. On a larger scale, however, the hydrologic function of the soil remains largely maintained. Considering a hillslope or a sub-catchment, no increase of surface runoff generation could be discerned as a result of the storm and the following clearing operations. More dominantly, the hydrological behaviour of the two investigated sub-catchments is influenced by small-scale geomorphology such as the channel density and the spatial distribution of wet areas.

Hence, it can be stated that: (1) beside steep slopes with very shallow soils along the channels (forest site type 20) only the moist to wet areas in the immediate vicinity of the channel system contribute to sub-catchment runoff during intensive showers; (2) the longer the rainfall event lasts, the more the sub-catchment runoff is increasingly affected by the surface runoff and fast subsurface runoff production on these Gleysols.

Future investigations could evaluate the loss of water due to seepage. The unknown extent of leakage of groundwater out of the sub-catchments makes it impossible to draw conclusions regarding the influence of storm damage on the water balance. Furthermore, it is not possible to asses to what degree (if at all) seepage affects sub-catchment runoff during long-duration precipitation.

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