The influence of wind storm deforestation on the runoff generation at various scales in a torrential catchment

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
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Alexandre Badoux

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Summary

Forest cover reduces annual water yield as well as, under certain conditions, flood flows. This second ability is of large interest in forest management and natural hazard mitigation. Earlier work has suggested that forest influence on floods seems to be more controlled by the forest soils than by forest vegetation type, age or state. Deforestation in the torrential Sperbelgraben catchment (Swiss Emmental) caused by the winter storm Lothar in December 1999 provided an investigation area for studying this topic. A nested approach was applied to evaluate the dominant runoff processes and mechanism at various scales and to estimate to what extent these are affected by deforestation.

The main objectives of this thesis were (1) to determine dominant runoff generation processes during artificial and natural rainfall events at the point and plot scale and to compare this information with a Swiss map of forest site types; (2) to evaluate the runoff mechanisms during flood events in two sub-catchments differently affected by the wind storm and thus to assess the impact of storm damage at this scale; (3) to verify the assumptions developed from (1) and (2) by applying a distributed hydrological model (PREVAH) at sub-catchment and catchment scale. Furthermore, the suitability of this conceptually structured model for small scale environments was tested.

Chapter II contains an analysis of soil profiles which were artificially irrigated on an area of 1 m^2. In addition, surface runoff during natural rainfall events was studied on experimental plots of 50 – 110 m^2 size. Two distinct surface runoff processes were observed. Large production of saturation overland flow was registered on wet areas of gleyic soils (runoff coefficients for sprinkling experiments: 0.39 – 0.94). On the other hand, almost no surface runoff was measured on Cambisols with the exception of local hydrophobic reaction after dry periods. The amount of Hortonian overland flow occurring at some sites remained small though (coefficients for artificial irrigation: 0.01 – 0.16). This pattern was observed at both scales. However, the signal of the water repellent litter layer was less distinctive on the larger experimental plots. During the sprinkling experiments, shallow lateral subsurface flow was detected on Gleysols only. On the well drained Cambisols along the steep slopes, percolation in greater depths dominated. The determined runoff behaviour at the two scales corresponded well with information deduced from a detailed forest site type map describing soil and vegetation characteristics.

In chapter III, the emphasis is placed upon the runoff behaviour of two sub-catchments (≈ 2 ha) of the Sperbelgraben differently affected by the wind storm. The sub-catchment runoff data collected during a three-year period was interpreted taking into account runoff information from the 50 – 110 m^2 plots. The link between these two scales was interpreted using the map of forest site types mentioned above. On the long term, the lightly damaged sub-catchment (SC1) yielded less runoff than the highly damaged one (SC2). The same applies to direct runoff volumes during flood events. Yet, it is not possible to assign the observed differences to the diverse magnitude of storm damage in the sub-catchments, as the water balances of SC1 and SC2 indicate an unknown amount of water loss from the catchments due to seepage. At plot scale however, local soil disturbance and sparse soil compaction (due to forest clearing) had a rather restricted impact. Hydrological behaviour of the two sub-catchments during periods of high flows is dominantly influenced by small scale geomorphological factors: (i) During short and intense showers the channel system is decisive. For such events higher discharge peaks are registered in the sub-catchment with a larger channel density (SC1). (ii) With longer and less intense rainfall, the spatial distribution of the moist to wet forest site types becomes crucial and controls the runoff hydrographs.

Chapter IV focuses on hydrological model experiments carried out in the Sperbelgraben investigation area. The water balance in general and storm discharge in particular were investigated at catchment and sub-catchment scale. The hydrological model PREVAH was applied to the Sperbelgraben catchment (54 ha) based on 25x25 m^2 grid cells aggregated to hydrological response units and running at one hour time resolution. Water balance simulations indicated a seepage loss of roughly 200 mm per year, which was in accordance with previous studies. The provided set of calibrated model parameters yielded stable results with satisfactory linear efficiency. The parameters were then adopted for the modelling of two sub-catchments (≈ 2 ha) applying smaller grid cells (2x2 m^2). Simulations confirmed the applicability of PREVAH even for these very small catchments. However, this could only be achieved by adding a new conceptual dynamic term in the runoff module that allows for a rapid drainage of small catchments during intensive rainfall. Moreover, modelling results substantiated the occurrence of considerable water losses due to seepage also in the sub-catchments. A comparison of simulated surface runoff with field measurements revealed the need of more profound process knowledge in conceptual hydrological modelling.

Forests like the one of the Sperbelgraben have a better capability than expected to cope with natural disturbances such as the wind storm Lothar. Hence, the effect of storm damage on the runoff processes was surprisingly small. At sub-catchment scale, water losses as a result of draining limit the evaluation of the impact of deforestation on flood flow. However, considering an experimental plot or a hillslope, the influence of the storm and the subsequent clearing operations on runoff generation was found to be very limited. The forest soil was affected locally as a result of toppled trees, but on a larger scale the hydrologic function of the soil remained widely maintained. Furthermore, compaction of the topsoil caused by afforestation machinery was rather moderate.

Zusammenfassung

Wald reduziert den Jahresabfluss sowie, unter gewissen Voraussetzungen, Hochwasserabflüsse. Diese zweite Eigenschaft ist für die Forstwirtschaft und für das Management von Naturgefahren von grosser Bedeutung. Wissenschaftliche Arbeiten weisen darauf hin, dass der Waldeinfluss auf Hochwasser stärker vom Waldboden abhängt als vom Typ, Alter oder Zustand des Bestandes. Nach dem heftigen Wintersturm Lothar im Dezember 1999 ergab sich eine Möglichkeit, Untersuchungen zu diesem Forschungsthema im schweizerischen Emmental (Kanton Bern) durchzuführen. Dort hatte der Orkan im Wildbacheinzugsgebiet des Sperbelgrabens erhebliche Waldschäden verursacht. In einem so genannten «nested approach» wurden die dominanten Abflussprozesse und Abflussmechanismen auf verschiedenen Massstabsebenen untersucht und abgeschätzt, in welchem Ausmass die Waldschäden diese beeinflussen.

Hauptziele der vorliegenden Dissertation waren, (1) die dominanten Abflussprozesse während künstlichen Beregnungen oberhalb von Bodenprofilen und während natürlichen Niederschlagsereignissen auf etwas grösseren Parzellen zu ermitteln; zudem wurden die Resultate dieser Untersuchungen mit einer Waldstandortskarte verglichen und deren Eignung zur Abschätzung hochwasserrelevanter Flächen getestet; (2) die Abflussmechanismen während Hochwasserereignissen in zwei von Lothar unterschiedlich beeinträchtigten Kleineinzugsgebieten zu beurteilen und den Einfluss der Sturmschäden auf dieser Massstabsebene abzuschätzen; (3) die unter (1) und (2) gewonnen Erkenntnisse durch die Anwendung eines hydrologischen Modells (PREVAH) zu überprüfen. Des Weiteren wurde die Eignung dieses konzeptionellen, hydrotopbasierten Modells für kleinskalige Einzugsgebiete getestet.

In Kapitel II ist die Analyse von Bodenprofilen und die jeweilige Beregnung von 1 m^2-Flächen unmittelbar oberhalb dieser Profile beschrieben. Diese Untersuchungen wurden durch Messungen des Oberflächenabflusses auf Plots (50 bis 110 m^2) ergänzt. Die Resultate legen nahe, dass Oberflächenabfluss im Untersuchungsgebiet ausschliesslich auf zwei Arten generiert wird. Auf vergleyten Flächen verursacht eine rasche Bodensättigung «saturation overland flow» von beträchtlichem Ausmass (Oberflächenabflusskoeffizienten bei Beregnung: 0.39 – 0.94). Demgegenüber führen auch Stauschichten in unterschiedlichen Tiefen auf den gut durchlässigen Braunerden nie zur Wassersättigung des Bodens. Stattdessen entsteht Oberflächenabfluss als «Hortonian overland flow», wenn eine hydrophobe, organische Auflage vorliegt (Abflusskoeffizienten bei Beregnung: 0.01 – 0.16). Dieses Muster konnte auf beiden

betrachteten Massstabsebenen beobachtet werden. Abflüsse, die durch hydrophobe Reaktionen der Auflage entstehen, waren auf den Plots jedoch weniger ausgeprägt zu beobachten. Während den Starkregensimulationen wurde oberflächennaher Zwischenabfluss ausschliesslich auf den vernässten Gleyböden festgestellt. Auf den Braunerden entlang steiler Hänge dominierte hingegen die Sickerung des aufgetragenen Wassers in grössere Tiefen. Das ermittelte Abflussverhalten auf beiden Ebenen lässt sich anhand der die Böden und die Vegetation beschreibende Waldstandortkarte gut ableiten.

In Kapitel III wurde das Abflussverhalten zweier vom Sturm Lothar verschieden stark betroffener Kleineinzugsgebiete (≈ 2 ha) untersucht. Die während einer dreijährigen Messperiode erfassten Abflussdaten aus den Einzugsgebieten wurden unter Berücksichtigung der Resultate der Oberflächenabflussplots interpretiert. Dazu kam auch die Waldstandortkarte zum Einsatz, um Plotinformationen auf grössere Flächen anzuwenden. Langfristig lieferte das schwach beschädigte Kleineinzugsgebiet (SC1) weniger Abfluss als das stark beschädigte (SC2). Dies gilt auch für die bestimmten Direktabflussmengen während Hochwasserereignissen. Dennoch war es nicht möglich, die beobachteten Unterschiede auf das unterschiedliche Schadenausmass in den Kleineinzugsgebieten zurückzuführen, da die Bilanzen von SC1 und SC2 Wasserverluste durch Tiefensickerung in beiden Gebieten zu erkennen gaben. Untersuchungen auf der Massstabsebene der Plots ergaben jedoch, dass örtlich auftretende Bodenstörung sowie die Verdichtung der Oberböden (mechanisierte Räumung) bloss eine limitierte Wirkung auf die Oberflächenabflussbildung haben. Das hydrologische Verhalten der Kleineinzugsgebiete während Hochwasserereignissen wird jedoch stärker von kleinskaligen geomorphologischen Faktoren beeinflusst: (i) Während kurzen und intensiven Regenfällen erwies sich das Gerinnesystem als entscheidend. Bei solchen Ereignissen wies meist dasjenige Kleineinzugsgebiet mit der grösseren Gerinnedichte die höheren Abflussspitzen auf (SC1). (ii) Während lang anhaltenden und wenig intensiven Niederschlägen spielte hingegen der Anteil der Feuchtflächen am Einzugsgebiet eine ausschlaggebende Rolle und führte zu höheren Abflussvolumina in SC2.

Das Kapitel IV bezieht sich auf die für das Untersuchungsgebiet durchgeführten hydrologischen Modellierungsexperimente. Dabei wurden einerseits die Wasserbilanzen des gesamten Sperbelgraben Einzugsgebietes (54 ha) sowie der Kleineinzugsgebiete (≈ 2 ha) simuliert und andererseits ein besonderes Augenmerk auf die Nachbildung einzelner Ereignisse in SC1 und SC2 geworfen. Die Modellierung des Sperbelgrabens mit PREVAH in stündlicher Zeitauflösung basierte auf 25x25 m^2 Rasterzellen, welche zu Hydrotopen aggregiert wurden.

Simulationen der Wasserbilanz ergaben einen Wasserverlust infolge Tiefensickerung aus dem Gebiet von rund 200 mm pro Jahr, was mit früheren Studien übereinstimmt. Der kalibrierte Modellparametersatz lieferte stabile Resultate und befriedigende lineare Gütekriterien. Dieser wurde in der Folge für die Modellierung der Kleineinzugsgebiete unter Anwendung kleinerer Rasterzellen (2x2 m^2) übernommen. Die Berechnungen bestätigten die Anwendbarkeit von PREVAH selbst für diese sehr kleinen Gebiete. Dies konnte aber nur mittels der Einführung eines neuen konzeptuellen dynamischen Terms bewerkstelligt werden, der eine schnelle Drainage von kleinen Einzugsgebieten während gewitterartigen Niederschlägen zulässt. Ausserdem bestätigten die Modellergebnisse das Auftreten von beträchtlichen Wasserverlusten infolge Tiefenversickerung auch auf dieser Massstabsebene. Der Vergleich von simuliertem Oberflächenabfluss mit Messungen auf den Plots zeigte schliesslich den Bedarf nach einem noch fundierteren Prozessverständnis in der konzeptuellen Modellierung auf.

Die Untersuchungen im Rahmen dieser Arbeit ergaben, dass in naturnahen Wäldern, wie jenen im Sperbelgraben, die natürlichen Störungen durch den Wintersturm Lothar besser bewältigt wurden als zu erwarten war. Die festgestellten Auswirkungen auf die Abflussprozesse waren erstaunlich gering. Wasserverluste aufgrund von Tiefensickerung in den Kleineinzugsgebieten erschwerten die Abschätzung des Einflusses der Sturmschäden auf Hochwasserabflüsse auf dieser Massstabsebene. Betrachtet man jedoch einzelne Plots oder ganze Hänge, fielen die Auswirkungen von Lothar und der damit verbundenen mechanisierten Räumungsarbeiten sehr begrenzt aus. Die Waldböden wurden zwar lokal von umgeworfenen und gebrochenen Bäumen in Mitleidenschaft gezogen, ihre hydrologischen Eigenschaften blieben jedoch grossflächig weitgehend bestehen. Die Räumung von Sturmholz verursachte nur an vereinzelten Stellen des Untersuchungsgebietes Bodenverdichtung und eine damit verbundene (vermutlich mittelfristige) erhöhte Oberflächenabflussbildung.

Chapter I

General Introduction

1.1 Background of this thesis – "Lothar and Mountain Torrents"

On 26 December 1999 the violent winter storm Lothar hit Western Europe. It caused enormous damage notably in France, Germany as well as in Switzerland. Alone in Switzerland fourteen people lost their lives during the storm. Forests sustained the most damage, amounting to 12.7 million m^3 of timber over an area of approximately 46'000 ha. This corresponds to ca. 3 % of the growing stock for all of Switzerland and is estimated at more than CHF 750 million (WSL and BUWAL, 2001). Due to the large extent of damage caused, long-term consequences were expected for Swiss forests. Potential consequences could, among other things, affect the frequency and magnitude of natural hazards in forested torrent catchments. In this context, the project "Lothar and Mountain Torrents" (Hegg et al., 2004) was implemented dealing with the effect of deforestation on hydrology and erosion in Switzerland at different scales. The project, a cooperation of the Swiss Federal Research Institute WSL and the Institute of Geography of the University of Berne (GIUB), was carried out within the framework of the basis programme LOTHAR of the Swiss Agency for the Environment, Forests and Landscape (SAEFL) and was also funded by SAEFL.

The primary objective of "Lothar and Mountain Torrents" was to illustrate the effect of storm deforestation on hazardous processes typical for small torrential catchments in Switzerland. To this end, the following sub-projects were established:

1. "Hydrologic Studies in Sub-Catchments" (WSL and GIUB)
2. "Forest development, root penetration and distribution, soil structure" (WSL)
3. "Vegetation Effects on Superficial Soil Movements" (WSL)
4. "Slope - Channel Interactions" (GIUB)

Together with the hydrologic studies (1), the pedologic investigations (2) were carried out in the Sperbelgraben catchment, Swiss Emmental. So were parts of the investigations dealing with the storm induced changes in the sediment budget of steep slopes (4). The bigger part of this survey though was conducted on a heavily damaged slope of the Spissibach (GIUB investigation site in the Bernese Oberland) as described in Gertsch and Kienholz (2004). As for the issue of vegetation influence on soil stability (3), it was conceived as basic research and mainly addressed in the soil laboratory (e.g. Frei et al., 2003).

The present thesis deals with the hydrological issues of the overall project “Lothar and Mountain Torrents” and was fully carried out in the Sperbelgraben investigation area. An intensive cooperation was maintained with the soil ecology group of WSL that addressed the pedologic investigations (2). Several results, provided mainly in Chapter II of this thesis, were acquired in close collaboration.

The work presented here looks at the hydrology at different scales in a hilly torrential catchment that has partially been affected by the violent winter storm Lothar. Due to storm-induced deforestation mainly in the southeastern part of the Sperbelgraben catchment, the storm led to changes in land-use. In a sense, Lothar is comparable to forest logging, at least when considering its result. By contrast to an anthropogenic intervention, the diminution of forest coverage occurred as a result of extreme meteorological condition though. In addition, soil compaction and disturbance was widely prevented, as only destroyed trees within reach of existing forest roads and paths were extracted by skidder after the storm. However, it is quite difficult to compare the present deforestation in the Sperbelgraben to a certain type of silvicultural treatment. In two main areas, the storm nearly performed a “clearcut”, breaking or overthrowing all large trees and leaving only a couple of young and flexible trees standing. Yet, the undergrowth on those areas was mostly left intact. Beside those heavily affected areas, several individual trees within widely unaffected stands were also damaged.

In the following sections of this introduction, a brief overview on the history of forest hydrology is given first in order to show the important role of experimental catchment studies in 20th century hydrological research. Second, relevant results regarding the influence of forest cover on annual water yield and flood flows will be reviewed. Third, more recent hydrological process research, arising from the increasing demand on process knowledge in the past decades, will be presented and discussed. Finally, the overall subject of the thesis will be addressed and the aims and research questions derived thereof described.

1.2 History of forest hydrology

Europe

In the early 19th century, forests were in a poor condition in much of Europe, including Switzerland, due to the increasingly large demand for fuel. Several severe floods occurred in the same period, e.g. in 1834, 1839, 1860 and 1868. After the 1868 flood, experts concluded that although intensive rainfall and high temperatures were the main contributing factors, over-harvested forests were also a factor (e.g. Landolt, 1869). The Swiss Forestry Union started lobbying for a forest law to provide financial support for reforestation and forest maintenance (Schmid, 2001). The law, enacted in 1876, prohibited any further decrease of the total forest cover in Switzerland and enabled federal authorities to financially support forestry activities, including reforestation and management practices intended to increase protection against natural hazards. To provide scientific support for forestry activities, the Swiss Forestry Research Institute, a predecessor institution of WSL, was founded in 1885. In addition providing a sound basis for general forestry, this institute received one important additional task from the government: to support the solution of important "forest - meteorological" questions, as forest hydrology was called at that time (Wullschleger, 1985).

In April 1903, continuous measurements of discharge and runoff were started in two 0.5 km^2 catchments in the Bernese Emmental region. The main objective was to investigate the influence of forests on hydrological processes. A first and comprehensive publication on the influence of forest on hydrological processes was presented by Engler (1919), who showed that the Sperbelgraben catchment, which was almost completely forested, produced much less runoff during short and intense thunderstorms than the nearby Rappengraben catchment, which was only 35% covered with forest. Engler also explained that during long-duration rainfall only slight to no effects were observed, depending on the water content of the soil before the event. The findings of this study influenced the ideas in forest hydrology for several decades during which Engler's work in the Emmental was carried on mainly studying the forest's influence on the water balance and flood runoff generation and therewith refining his results (e.g. Burger, 1954, Casparis, 1959).

In the post-war years, forest hydrologic research was initiated in the German Upper Harz mountains. As a part of the imposed reparations, timber was gained by means of large scale clearcutting. Following such an operation, two catchments were instrumented in 1948, one of them being the clearfelled Lange Bramke catchment (Liebscher, 1972). Since then, long-term investigations of different hydrological aspects (water balance, streamflow chemistry and runoff processes) have been carried out. Also in Germany, the Kroftdorf forest experiment, a multiple paired catchment study, was started in the late Sixties. Following a ten year calibration period, the changes in water quality and quantity were investigated after the partial felling of beech stands in two of the four small catchments investigated (Brechtel and Führer, 1991; Balász and Brechtel, 1974).

In Great Britain, the British Hydrological Research Unit was created in 1962 (and later on developed into the Institute of Hydrology), at a time when it became obvious that profound knowledge of the hydrological effect of afforestation of the high-altitude watersheds was required (McCulloch and Robinson, 1993). Subsequently, the Institute of Hydrology started catchment experiments at Plynlimon (Wales) and Coalburn (northern Britain). While at the Plynlimon study site, the hydrology of established forest, clearcut forest and grassland has been compared (Robinson and Dupeyrat, 2005; Kirby et al., 1991), the Coalburn study focuses on the effects of forestry growth on streamflow, from planting through to canopy closure (Robinson, 1998; 1986). Furthermore, the influence of catchment drainage (before conifer planting) are well investigated in the latter.

North America

In the 20th century, the interrelation between forest cover and discharge from catchments has particularly and very intensively been investigated in North America under different climatic conditions as well as in various forest types. This research field strongly benefited from the established practice of large scale clearcutting in North American forest management. Such operations are likely to cause changes in the water budgets of watersheds due to the considerable reduction of forest coverage.

In the US, the assumed role of the forests in regulating the flow of streams provided the basis for an 1911 act that allowed the government to buy private lands for national forest in the East. At this time, there was important debate about the influence of forest upon regulation of runoff in general and flooding in particular (Douglass and Hoover, 1988). The demand for quantitative data led the US Forest Service together with Weather Bureau to start the first experiments measuring streamflow before and after tree removal at Wagon Wheel Gap (CO, USA) in 1909 (Bates and Henry, 1928). Streamflow from two watersheds as well as further factors (e.g. temperature, humidity etc.) were monitored during eight years, after which one watershed was cleared. In the seven years following the harvesting, annual runoff of this catchment increased by an average of about 25 mm or 15 %. These changes in streamflow were ascribed to the reduction in forest cover. Controversy over the role of forests culminated after the 1927 Mississippi River flood. Subsequent extensive surveys revealed erosion and flood problems and accentuated the need for investigations on factors controlling those (Douglass and Hoover, 1988).

In the following decades many forest treatment experiments with controlled forest cover change were conducted throughout North America, many of them being summarised in Hibbert (1967) and later on in Bosch and Hewlett (1982). Best known are probably the studies carried out at Coweeta Hydrologic Laboratory (NC, USA) on some 25 small catchments since 1934 (Swank et al., 2001; Swank and Crossley Jr., 1988). At this site, approximately 70 years of data have been collected on the relationship between forest treatment and water resources. The Coweeta experience inspired research at many other sites including investigations in the notheastern USA (Hornbeck et al., 1993) such as those conducted at Hubbard Brook Experimental Forest (Hornbeck et al., 1997; Federer et al., 1990) and Fernow Experimental Forest (Adams et al., 1993; Patric and Reinhart, 1971).

Other activities

Catchment experiments have not exclusively been carried out in Europe and North America. As reported in Bosch and Hewlett (1982), activities were undertaken in many parts of the world e.g. in Australia, New Zealand, Kenya, South Africa, and Japan. In New Zealand for instance, large areas covered with exotic forest represent an economic resource that has substantially contributed to the growth of the country. Projected afforestation rates of 50’000 ha per year underline the importance of this vegetation form in the future. Typically, native forest, scrub, tussock grassland and pasture is converted to plantation forests (mainly pine). Thus, hydrological consequences of plantation forestry have received large attention from foresters and hydrologists and has evolved into an important research topic in New Zealand. Results from several catchment studies were summarised by Fahey (1994) and Rowe et al. (1997).

In the east African countries of Kenya, Uganda and Tanzania, water has always been the fundamental environmental variable deciding upon whether crop can be grown or not. Thus, the hydrological consequences of land use options (such as the replacement of indigenous bamboo forest and outliers of montane rain forest by commercially viable softwood plantations or pasture) were regarded as of great importance (McCulloch and Robinson, 1993). Results from Kenya showed that the conversion of bamboo forest to pines or montane forest to tea gardens have only lightly altered the hydrological response to rainfall and the evapotranspiration from a catchment. Full results from the East African Catchment Area Research project were summarised by Edwards and Blackie (1981).

Bruijnzeel (1990) reviewed the effect of tropical forest conversion, definitely the largest change in forest area over the past decades. In the short term, the impact of tropical forest removal depends on the intensity and manner of the clearance operations. He points out that there is a large difference between techniques adopted for research purposes and those applied in practice. Over the long term, the new land use form and its management determine the consequences of forest conversion (well managed plantations showing a smaller impact than pastureland or arable cropping).

1.3 Forest influence on annual water yield and floods: some results

Streamflow characteristics from catchments are primarily determined by precipitation. Long-term as well as short term runoff behaviour are also influenced by the catchment properties such as geology, morphology, soils and vegetation. Anthropogenic management of catchment streamflow is only possible by means of changes in the vegetation cover (aside from technical interventions in streams and soil deterioration through bad harvesting techniques). Considering the potential range of the different catchment properties, vegetation alone has a rather restricted effect on streamflow. During heavy rainfall for instance, interception losses by forest cover do not considerably have an effect. In addition to interception, a vegetation cover can influence runoff generation and erosion indirectly through e.g. root penetration, soil structure, pore volumes and aggregate stability (Moeschke, 1998). When forest coverage is reduced by (careful) logging, all these factors remain largely the same in the near future. This could explain why deforestation sometimes has so little impact, and brings out the importance of forest soil, even if the forest soils cannot be isolated from the development of the forest itself (Cosandey et al., 2005).

The influence of the vegetation type on the water balance of a catchment is multi-faceted. Here, the effect on annual water yield as well as on floods will be considered a bit closer in the following, whereas no emphasis is placed on the influence of forest coverage on low flows (e.g. Robinson and Cosandey, 2002; Keller, 1968), the snow cover (e.g. Gustafsson et al., 2005; Bründl et al., 1999) as well as on evapotranspiration (e.g. Zhang et al., 2001; Calder and Newson, 1979; Germann, 1976).

Annual water yield

Today it is widely accepted that an increase in forest cover leads to a change in the water balance of a hydrological catchment, namely increasing the annual evapotranspiration and thus decreasing the annual runoff. This topic has been investigated in studies all over the world and under very different conditions as reported in a series of reviews shortly described in the following.

In the decades after the first American paired catchment study by Bates and Henry (1928), many forest treatment experiments were carried out in diverse US regions and a zenith was reached in the 1960s. Hibbert (1967) summarised 39 forest treatment studies (all the results available by that time). The investigation showed that the upper limit of annual runoff increase was 4.5 mm for each percentage of reduction in forest cover. Most treatments produced less than 2.5 mm increase per year though. First-year responses to complete clearfelling varied from 34 mm to 457 mm of increased runoff while most produced less than 300 mm.

Apparently, first-year increases for thirty experiments did not reveal any strong relation between increased water yield and percentage of forest reduction. Hibbert (1967) drew the following generalizations: (1) A reduction of forest cover increases water yield; (2) an establishment of forest cover (afforestation) on sparsely vegetated land decreases water yield and (3) the response to treatment is highly variable and, for the most part, unpredictable.

Hibbert's review was updated by Bosch and Hewlett (1982) with the addition of 55 studies for a total of 94 forest clearing or planting experiments. Even though a remarkable variability in both data sets regarding annual yield changes remained, the approximate magnitude of change within an experiment could be estimated due to systematic differences when studies were separated by forest cover type. Thus, the authors question Hibbert's statement that water yield responses to afforestation and deforestation is largely unpredictable. They conclude that coniferous forest and eucalyptus, deciduous hardwood, scrub and grassland have, in that sequence, a decreasing influence on water yield of the source areas compared to bare ground. Yield changes per 10 % of land cover change amount to ca. 40 mm for coniferous forest, ca. 25 mm for deciduous hardwood and ca. 10 mm for scrub. No error limits on the coefficients are provided in the article. However, the authors state that more careful design as well as expansion of experiments to further regions would augment statistical inference.

After the publication of the major review by Bosch and Hewlett (1982), catchment experiments continued to be carried out with undiminished intensity. This led Sahin and Hall (1996) to carry on the effort of the previous authors in reviewing catchment experiments applying both classical and fuzzy techniques of linear regression analysis. Based on the 94 experiments investigated in 1982, the data base was expanded to 145 studies with particular focus on tropical rainforests and eucalyptus forests. A series of generalised relationships was developed which can be used to anticipate water yield changes following alteration in vegetative cover of a catchment. Determined changes per 10 % reduction in cover for conifer-type and eucalyptus-type forest were lower than those previously published (increase of 20-25 mm and 6 mm respectively). In contrast, values for deciduous hardwood were largely in line with earlier estimates and calculations for rainforest result in a yield change of approximately 10 mm. However, even in this latest review, the variance of the estimates remains high. Furthermore, Sahin and Hall (1996) as well as Bosch and Hewlett (1982) indicate that reductions in forest cover of less than 20 % are not detectable by streamflow measurements.

Floods

Compared to the influence of forest cover on annual catchment yield, the effect of forest cover on floods is a bit more ambiguous. In the worldwide first catchment study, Engler (1919) focussed on the necessity of differentiation in his conclusions, namely the important attenuating impact of the forest for intensive short-duration rainfall events, and the slight reduction for long-duration, low-intensity events. Many studies on the influence of forest cover on floods have been conducted in North America, Europe and other parts of the world since Engler's time. Thereby, the role of forests in reducing peak flows has been confirmed in many specific cases and locations (e.g. Cosandey et al., 2005; Guillemette et al., 2005; Beschta et al., 2000; Fahey and Jackson, 1997; MacDonald and Hoffman, 1995; Hornbeck, 1973; Maruyama and Inose, 1952).

In a review of the effects of forest cover reduction on peak flows, MacDonald et al. (1997) come to the following conclusions: (a) changes in the size of peak flows seem to decrease with increasing annual precipitation sum; (b) about 10-15 % of a watershed has to be cleared in order to cause a detectable rise in peak flows; (c) the percent change generally diminishes with floods of increasing return period; and finally (d) the percent change is normally more important in the growing season. Yet, results are variable because of factors such as topography, soil characteristics and species (as well as age) of the trees felled. Furthermore, they also depend on the forest management techniques adopted (Guillemette et al., 2005; McCulloch and Robinson, 1993). Thus, these findings should not be generalised and can not apply to all circumstances.

As a matter of fact, a considerable range exists in results from different studies. In southern France for example, at two different experimental sites, results are quite variable. Those from the Draix site are explicit in terms of flood. Flood runoff volumes on a forested catchment (Brusquet) are half as large as those from a mostly bare catchment (Laval) while discharge peaks (within the range of common frequencies) are even five times smaller at Brusquet. In contrast, in the Mont-Lozère experimental site, no notable difference between pre- and post-clearcutting high flood discharge could be detected, even though average flows increased (Cosandey et al., 2005). Several other investigations also did not indicate significant changes in peak flows following clearcuts of large parts of the catchment area (e.g. Robinson and Dupeyrat, 2005; Miller, 1984; Harr et al., 1982; Harr and McCorison, 1979).

In Plynlimon (Robinson and Dupeyrat, 2005), the negligible changes in peak flows may originate from the application of forest management guidelines designed to minimise soil damage during harvesting and hence reduce surface runoff generation. According to the authors, the lack of impact of the intervention could also indicate that the forest itself has a limited effect on flooding. The most radical increases in peak flow with forest cover reduction have often been attributed to soil compaction and disturbance leading to infiltration reductions (e.g. Cheng et al., 1975). Already Reinhart (1964) stated that, when judging hydrological conditions of logged areas, emphasis should not only be placed upon the amount of timber cut (or the size of the area cleared) and the condition of the forest stand, but perhaps as much upon forest road conditions and the forest floor disturbance resulting from the logging operations.

In summary, if in many environments forests reduce floods because rainfall infiltration into the soil is more effective through the forest canopy and the underlying litter than through crops or grassland, this does not apply everywhere. It has to be stressed that 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 environment under consideration (Cosandey et al., 2005). The general point of view on the role of forests as a flood reducer (especially for extreme events) is more widely acknowledged by the public opinion as by researchers.

1.4 Hydrological process studies

As reported and commented in McCulloch and Robinson's (1993) "History of forest hydrology", studying hydrological and water resource problems in the first half of the 20th century was not focussed on the whole of the hydrological cycle. Rather it was motivated by pragmatic engineering questions or geographical approaches on whole regions. Due to the fact that only two components of the water balance were capable of direct measurement (precipitation and runoff), restricted consideration was given to evaporation and storage (evaporation often being calculated 'by difference' or derived from empirical equations). When considering the many world-wide catchment area studies and trying to fully conceive their results, a sound knowledge of the physical processes within the catchments is indispensable. "Without this, the results are difficult to extrapolate, and the observations and conclusions may well be applicable only to situations where an identical set of processes is operating" (McCulloch and Robinson, 1993). That is practically nowhere, due to the uniqueness of every catchment. Hence, the understanding of physical processes in catchment area experimentation is a prerequisite for efficiently exploring hydrology in other (maybe ungauged) catchments.

In the past decades, a broad research community arose from the increasing demand on hydrological process knowledge. An objective often pursued is the derivation of hydrological modelling approaches for catchments and hillslopes from the field investigations. Studying the influence of different factors such as geology, soils, vegetation etc. in response to rainfall (i.e. the flow characteristics) of a headwater catchment, the runoff generation processes taking place on the hillslopes and in the immediate vicinity of stream or channel areas have to be considered. They control the lateral movement of water on top of the soil or within the unsaturated and saturated zones (e.g. Montgomery et al., 1997, McDonnell, 1990)

A sound summary on runoff processes is given e.g. in Bonell (1998) and Scherrer (1996). Commonly, runoff is classified in overland flow (runoff on the soil surface) and subsurface flow (runoff in the soil complex). Scherrer (1996) describes the further differentiation of these two classes and subdivides overland flow into (1) absolute, delayed or temporary Hortonian overland flow and (2) saturation overland flow. On the other hand, subsurface flow is produced through (3) matrix flow, (4) macropore flow, (5) pipe flow, (6) flow in highly permeable layers and (7) groundwater flow supplied by deep percolation through the soil. While fast water transfer of the categories 4 to 6 is also referred to as subsurface stormflow, subsurface flow that returns to the surface is called return flow. Details on these different flow types is given in Scherrer (1996).

Much progress in hillslope hydrology has been achieved due to a large number of experiments world-wide. An overview of this hydrological research on hillslopes is given in Gutknecht (1996), Anderson and Burt (1990) and Kirkby (1978). In the early days of process studies, it was believed that flood runoff in catchments was mainly produced due to infiltration excess overland flow (Horton, 1933), hereafter called Hortonian overland flow. In subsequent investigations though, precipitation intensities were reported to be too small to exceed infiltration capacity and effectively generate overland flow (e.g. Dunne and Black, 1970). Instead, flood runoff was thought to be largely produced on saturated areas created on sites with shallow soils (i.e. with a low storage capacity) or at the bottom of slopes and in valley bottoms. These studies led to the creation of the variable source area concept stating that the area contributing to flood runoff increases during a storm event and diminishes with decreasing rain fall (e.g. Hibbert and Troendle, 1988; Hewlett and Hibbert, 1967). Lately, investigations of Kirnbauer et al. (1996) demonstrate the importance of runoff processes on saturated areas for the flow regime of small sub-catchments in the alpine Löhnersbach catchment (Austria).

Several investigations emphasise the importance of subsurface flow during rainstorm events in small headwater catchments (e.g. McDonnell, 2003; Feyen, 1999; Peters et al., 1995; McDonnell, 1990; Wilson et al., 1990; Mosley, 1982 and 1979). With the use of artificial tracer methods, high subsurface flow velocities were identified and indicated preferential flowpaths in the soil (e.g. macropores, pipes, flowfingers). Thus, rapid subsurface flow through such flowpaths may considerably contribute to total stormflow. This can be very distinctive at the soil-bedrock interface, especially on slopes with thin soils (Peters et al., 1995). On the other hand, subsurface flow effects the beginning of surface runoff on saturated areas at the base of hillslopes. The crucial role of macropores and other preferential water flowpaths in runoff generation at hillslope scale has been demonstrated in many ingenious experiments (e.g. Weiler and Flühler, 2004; Weiler, 2001; Flury et al. 1994; Germann, 1990; Beven and Germann, 1982). However, bringing all this knowledge gained through experimentation in different geological, pedological, topographical and meteorological environments together to a common conceptualisation of hillslope hydrology has not yet been successful (Weiler and McDonnell, 2004).

The dominating runoff generation processes differ at various scales (e.g. Blöschl and Sivapalan, 1995). In larger (meso-scale) catchments, processes from smaller scales complexly combine to form an integrated response. Several studies show that different runoff processes may occur on close-by sites within a catchment (Scherrer, 1996; Faeh, 1997) and Beven (2001) even states that each hillslope is unique. Thus, identifying and delineating areas with the same dominant runoff generation processes is an important challenge in hydrological research (Uhlenbrook, 2004; Schmocker-Fackel, 2004; Scherrer and Naef, 2003). Approaches to map spatial patterns of runoff generation in catchments are described in Schmocker-Fackel (2004). They can be subdivided in three classes: approaches mapping either contributing areas and runoff coefficients, landscape units or runoff processes.

Several numerical models reproducing hillslope water fluxes have been developed (Seibert and McDonnell, 2002; McGlynn et al., 2002; Bronstert and Plate, 1997; Faeh et al., 1997). Applying the modelling system HILLFLOW, Bronstert and Plate (1997) consider most of the relevant hillslope processes. Three versions of the model are presented. While the 1D version copes with vertical (column type) soil water balances, the two others (hillslope and catchment) allow focussing on rapid soil water flow processes during storm conditions such as macropore infiltration, lateral subsurface stormflow and return flow. Considerations on the objectives of detailed hillslope hydrological modelling as well as conclusions about its limitations are given in Bronstert (1999). Weiler and McDonnell (2004) suggest a conceptualisation of the hillslope water balance accounting for first-order controls. Their model HillVi is able to realistically reproduce the water distribution across a (virtual) hillslope. It appears that the approach of Weiler and McDonnell (2004) goes in the right direction for improving process conceptualisation.

1.5 Aims and research questions of this thesis

In December 1999, the winter storm Lothar affected forests within the Sperbelgraben and thereby provided an opportunity to carry out scientific work at this site with a long hydrological history.

As explained in Section 1.3, the magnitude of forest influence on flooding in a given catchment is variable. It is, amongst others, related to the storage capacity of forest soils found there. As will be shown in Chapter II, forest cover (i.e. the trees) on shallow soils with a quite small storage capacity does not considerably increase this capacity. Hence, its effect on such locations is rather restricted during flood events. However, where mostly well drained and deep soils occur in the Sperbelgraben, it was broadly expected that the conditions were sufficient for the forest to exert a mitigating effect on flood generation in the investigation area.

Due to the ability of forest cover to augment the storage capacity of a soil (compared to when bare), it reduces the amount of storm precipitation that rapidly runs off on the soil surface and in the soil complex. This impact is important to forest management and natural hazard mitigation, as it affects total runoff at the outlet of a catchment. Consequently, an approach must be found to transfer the information on forest influence from a single point (e.g. a soil profile where soil hydrologic properties are assessed) to a sub-catchment or an entire catchment that generally shows partial areas with different properties. The method for identifying the hydrological properties (i.e. the dominant runoff processes) of an entire catchment is of primary importance (e.g. Schmocker-Fackel, 2004; Scherrer and Naef, 2003; Naef et al., 2002).

In the present project, the so-called map of forest site types was used for these purposes. A forest site type summarises similar forest sites grouped according to topographic and geomorphologic location, nature of soil, floristic composition etc. The mapping process is based on a detailed procedure (Swiss standard) described in Burger et al. (1996). While this map is widely used in several lines of action in Swiss forest management, it has yet never been applied for the purpose described here. Thus, the first exercise of this study was to verify whether the hydrological properties assigned to a given site by using the map conform with field observations.

In order to examine the impact of forest cover from a single point in the investigation area up to the outlet of a catchment, a nested approach was adopted (e.g. Figures 3-1 and 4-1). The smallest scale investigated is represented by several soil profiles. Dominant flow processes of these soils have been assessed by means of sprinkling experiments carried out on 1 m^2 rectangles above the profiles. Next to each soil profile, at least one larger experimental plot (approximately 60 m^2) was installed and equipped to measure surface runoff during natural precipitation events. On two locations, the installation was extended and subsurface flow was recorded in a ditch. Matching soil profiles and surface runoff plots were placed within the same forest site type to ensure the comparability of measurements with estimations derived from the applied forest site type map. It was decided to established a relatively large number of profiles (17) and plots (19) to give consideration to the variability (soils, topography, vegetation) of the investigation area. In return we decided not to carry out very intensive studies (e.g. permanent TDR measurement during natural rainfall events at the plots, application of tensiometers) at every of the selected sites.

Two instrumented sub-catchments (approximately 2 ha) constitute the next scale investigated in this study. They cover a large range of forest site types and contain several surface runoff plots each. The neighbouring sub-catchments are drained by first order streams that yield runoff throughout the year and were differently affected by the winter storm Lothar. While one suffered major damage and lost 63 % of its trees, the other was struck rather marginally with 21 % of the trees destroyed.

Lastly, the largest scale is represented by the torrential catchment of the Sperbelgraben (54 ha) that comprises the soil profiles, experimental plots and sub-catchments mentioned above. Wind storm damage covers only about 4-5 % of its area and therefore, no measurable change in flow behaviour was expected there (e.g. Bosch and Hewlett, 1982). Nonetheless, the Sperbelgraben was included in this study within the scope of the hydrological modelling experiment described in Chapter IV focussing on the simulation of discharge at sub-catchment and catchment scale. With the investigation we addressed the question (arisen in Chapter III) on the extent of water loss due to seepage in the two sub-catchments as well as in the entire Sperbelgraben. Due to information on sub-catchment leakage, we will be able to assess the accuracy of our statements about the influence of wind storm damage on the runoff behaviour. Moreover, hydrological modelling should help gaining knowledge on the composition of storm runoff formed by the different runoff processes along a typical slope or in an entire sub-catchment.

After this general introduction, the present thesis is divided into three chapters, followed by an overall synthesis. Chapters II to IV are dedicated to the different research questions mentioned above. Their specific objectives can be formulated as follows:

Objectives of Chapter II:

- to determine the runoff behaviour of different forest site types by means of hydrological and soil physical measurements at the point (1 m^2) and plot (ca. 60 m^2) scale,
- to answer the question of comparability between processes at profile and plot scale,
- to find out to what extent soil type patterns and dominating runoff processes can be deduced from the Swiss map of forest site types.

Objectives of Chapter III:

- to explore dominant runoff processes at the sub-catchment scale (ca. 20000 m^2) also including information from the smaller surface runoff plots (ca. 60 m^2),
- to estimate and discuss the impact of severe wind storm damage on the runoff behaviour of the experimental plots as well as of the Sperbelgraben sub-catchments.

Objectives of Chapter IV:

- to estimate seepage losses in the entire Sperbelgraben catchment and in two sub-catchments by applying the distributed hydrological model PREVAH,
- to asses the role of surface runoff during rainfall storms through comparison of model output with field measurements carried out on experimental plots,
- to evaluate, as a prerequisite to handle the first two objectives, if the distributed hydrological model PREVAH can tackle both the runoff characteristics of the Sperbelgraben catchment and of the sub-catchments.

For the investigations at the different scales described in Chapters II and IV, different measurement methods, mapping procedures and surveying methods were applied. They are each briefly described in the respective Chapters. In addition, Table 1-1 gives an overview on where full details on these methods and applications can be consulted. In several cases, they play an important role in diploma theses carried out within the scope of the project "Lothar and Mountain Torrents".

Table 1-1: Particulars on used methods and applications of this thesis.

Method / Application	Scale	Full description given in
Sprinkling experiments	Soil profile scale	Helbling, 2002 Sieber, 2002
Surface runoff measurements	Experimental plot scale	Könitzer, 2004 Ilg, 2002; Badoux et al., 2002a
Runoff gauging stations	Sub-catchments	Marti, 2002 Badoux et al. 2002b
GPS survey	Sub-catchments	Gertsch, 2002 Marti, 2002, Badoux et al., 2002a
Forest site type mapping	Sperbelgraben catchment	Burger et al., 1996 Ott et al., 1997 Hegg et al., 2004

Chapter II

Investigations on the runoff generation at the profile and plot scale, Swiss Emmental

Accepted for publication:

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2.1 Abstract

This article describes an investigation on runoff generation on different scales in the forested catchment of the Sperbelgraben in the Emmental region (Swiss prealps) where studies in the field of forest hydrology have a history of 100 years. It focuses on the analysis of soil profiles and the subsequent sprinkling experiments above them (1 m^2) as well as on surface runoff measurements on larger plots (50 to 110 m^2). In the Sperbelgraben investigation area, two very distinct runoff reactions could be observed. On the one hand, very high production of saturation overland flow was registered on wet areas of gleyic soils with runoff coefficients between 0.39 and 0.94 for profile irrigation. On the other hand, almost no surface runoff was measured on Cambisols with the exception, at some sites, of a hydrophobic reaction detected at the beginning of storms after dry periods (coefficients for profile irrigation: 0.01 – 0.16). This pattern was observed during 1 m^2 soil plot irrigation as well as on surface runoff plots. Apart from a less distinctive signal of the water repellent litter layer on the larger surface runoff plots, dominant hydrological processes at the two scales are the same. The determined runoff reaction at the two scales corresponds well with information from a forest site type map describing soil and vegetation characteristics and used as a substitute for a soil map in this study. Theoretical considerations describing forest influence on flood discharge are discussed and evaluated to be in good agreement with observations. These findings are a sound foundation for application in hydrological catchment modelling.

Key words: forest hydrology, runoff generation, storm damage, forest coverage, forest site types

2.2 Introduction

During the 19th century, flood catastrophes in the Alps were explained to be the result of forest destruction. Many treatises, travelogues and official reports forcefully pointed out the significance of the forest as water storage and runoff regulator. The causality between the occurrence of wide deforestation in the Alps and bad flood events was so obvious, that an experimental verification of the hydrological impact of the forest seemed to be superfluous (Germann and Weingartner, 2003; Brechtel and Krecmer, 1971). In Switzerland, following these natural disasters, federal forest legislation was introduced in 1876 and amended in 1902 (Schmid, 2001; Keller, 1988). At about the same time, federal water engineering legislation was adopted. Based on these regulations, structural measures were carried out in many rivers and torrents and large areas were afforested.

In the early years of the 20th century, a sound scientific base describing the forest influence on floods became more and more important to sustain the substantial financial contributions to forest management. Therefore, the newly founded Forestry Research institute in Switzerland (a predecessor institution of the Federal Research Institute WSL) started a comparative study of two basins (Emmental) with different forest cover in 1903. Engler (1919) published the first results of this study in a compendium of more than 600 pages. The study revealed an important attenuating impact of the forest on intensive short-time flood events (an example is given in Figure 2-1) which relates to both runoff volume and peak discharge. During persistent rainfall only a slight effect, if any at all, was observed, mostly depending on the water content of the soil before the event. However, the latter information found much less citation and did not alter the general understanding that forests reduce floods. Furthermore, Engler pointed out the fact that it is the forest soil – more than the vegetation cover – which causes reduced flood peaks. The Emmental project was continued and subsequent studies were published by Burger (1934, 1943 and 1954) and Casparis (1959).

Much of the afforestation established following the 1876 forest law was carried out in regions with flysch geology that are very flood prone due to their wet soils lying on similarly impermeable bedrock. In such a prealpine flysch area, the study site of the Alptal was put into operation by the WSL in 1968 (Keller, 1988). Three catchments with a forest cover varying from 20 up to 67 % were instrumented. Based on these measurements, it was statistically impossible to demonstrate an overall effect of the forest on flood discharge (Burch et al., 1996). Neither runoff volume nor peak discharge showed to be influenced by the forest fraction. The shallow flysch soils found at the Alptal site attenuate the difference in hydrological behaviour of forested areas and pasture during a storm event due to small water retention capacity in any case. In conclusion, Burch et al. (1996) suggest that it is rather the soil properties than the vegetation cover that defines the degree of protection against floods.

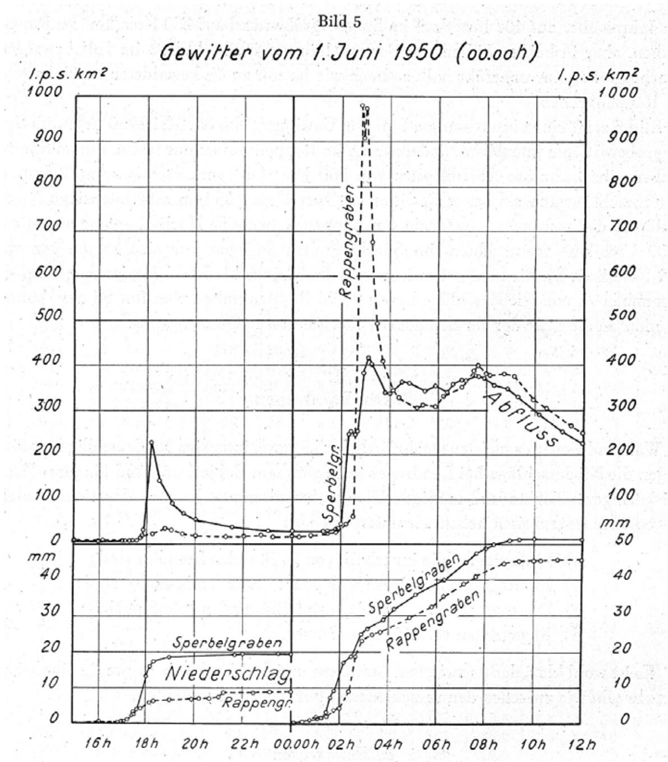

Figure 2-1: Hydrograph of the storm rainfall event on 1 June 1950. Specific discharge (l $s^{-1}km^{-2}$) is shown in the upper part, accumulated precipitation in the lower part (from Burger, 1954).

Feyen (1999) further investigated this hypothesis by carrying out irrigation and tracer experiments on two soil plots of 13 m^2 on forested sites. He compared the dominating runoff processes at three different scales (headwater catchment, sub-catchment and soil plots) and investigated the effect of vegetation, soil type distribution and drainage area on the runoff. His conclusion was that at different scales, different preferential flow processes dominate the runoff formation. On soil plots as well as on sub-catchments, runoff reacted very fast to natural and artificially irrigated rainfall.

Scherrer (1996) carried out many irrigation experiments on grassland and arable land in Switzerland under different geological conditions. They showed high variability in runoff generation depending on the local situation, mainly soil conditions and geological underground. Weiler et al. (1998), using the same experimental set up as Scherrer (1996), carried out artificial rainfall and tracer experiments in the Alptal and compared their results to simulations with the physically-based hillslope model QSOIL. Runoff processes were identified on two hillslopes (grassland and forested area) that show Gleysols developed from Flysch underground. On grassland, runoff generation was mainly controlled by a highly permeable A horizon and the vertical macropore system in deeper layers leading to bypass flow. In contrast, the forested site showed a bimodal poresize distribution resulting in a stronger subsurface flow response.

In another catchment with very different soils, Kohl et al. (1997) estimated runoff and infiltration characteristics of soils in spruce forests (Austria, Styria). Sites in two geological zones showing Cambisols were investigated by means of heavy rain simulation. Despite high irrigation intensity of 100 mm h^{-1} (comparable to the above mentioned irrigation studies) the infiltration capacity was never reached on any plot and neither surface runoff nor subsurface flow was observed. Depending on the geological underground, the soils showed very high percolation rates (Bänderamphibolit) or high retentiveness (Augengneis). Spruce stands in the upper Schesa catchment (Vorarlberg) also showed high infiltration behaviour and very low surface (and partly subsurface) runoff (Markart et al., 1997). In contrast to grazed and wet sites that yielded much higher surface runoff coefficients, most of the soils in the forest had favourable conditions regarding fast runoff mitigation.

In agreement on the important role of forest soil but working in diverse environments, Engler (1919) and Burch et al. (1996) made different statements regarding the influence of forest as a reducer of floods. As mentioned below runoff generation is expected to vary with different soil conditions. This obviously suggests that the flood protection efficiency of forests may vary considerably from one site to another and that the general understanding in this regard has to be replaced by a more differentiated approach.

Such differentiation is easiest implemented in practical applications if it relies on existing data or on data collected for other purposes. For selected Swiss forests, so called forest site types are mapped as described in Burger et al. (1996). A forest site type represents the summary of the characteristics of similar forest sites grouped according to topographic and geomorphologic location, nature of soil, floristic composition etc. To test this Swiss mapping procedure for hydrological purposes, the forest site type map replaces a standard soil map in this study.

The objectives of this paper are, first, to determine the runoff behaviour of different forest site types by means of hydrological and soil physical measurements at the point (1 m^2) and plot (ca. 60 m^2) scale. The second is to answer the question of comparability between processes at profile and plot scale. The third objective is to find out to what extent soil type patterns and dominating runoff processes can be deduced from the Swiss map of forest site types.

An occasion to continue the research on this topic was brought about by the severe storm event Lothar (26 December 1999) that caused serious damage in Switzerland (WSL and BUWAL, 2001) and several other countries of central Europe. Research funding by the Swiss

Agency for the Environment, Forests and Landscape enabled the implementation of the project "Lothar and Mountain Torrents" (Hegg et al., 2004) dealing with the effect of deforestation on hydrology and erosion in Switzerland at different scales. The work described here is part of these activities.

2.3 Investigation area

As an investigation area, two neighbouring sub-catchments were chosen within the torrential catchment of the Sperbelgraben. During the storm Lothar the two sub-catchments were affected in a very different way (light damage in sub-catchment 1, heavy damage in sub-catchment 2). Sub-catchment 2 was partially cleared with afforestation machinery. Figure 2-2 gives an overview of the location of the investigation area.

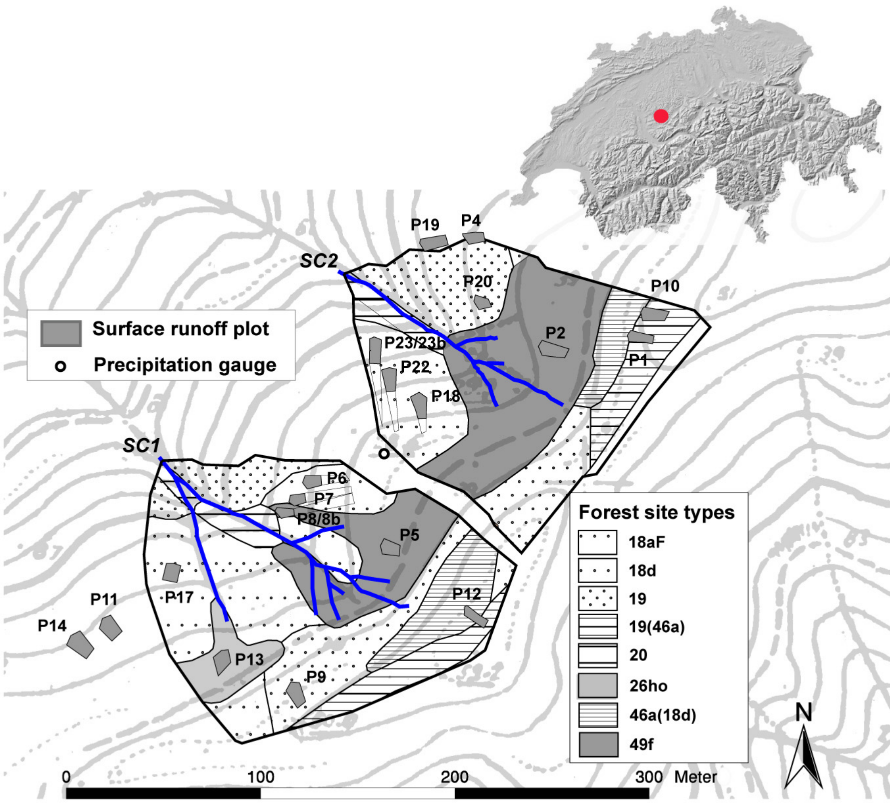

Figure 2-2: Overview over the investigation area showing the two sub-catchments (SC1 and SC2) and the position of the 19 surface runoff plots (numbered).

The Sperbelgraben catchment is situated in the hilly Emmental region in the Swiss prealps and drains from north-east to south-west. 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. In the soils, the content of clays 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 contents of clay. 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. Full particulars about the torrential catchment of the Sperbelgraben are given in Engler (1919), Burger (e.g. 1954) as well as in Hegg et al. (2004).

The small sub-catchments feature an area of 1.76 ha (heavily damaged) and 2.03 ha (lightly damaged) and are located in the south-east zone of the ridge of the Sperbelgraben catchment in an altitude between 1075 and 1160 m a.s.l. (Figure 2-2). 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 most important parameters of the two sub-catchments are listed in Table 2-1.

Table 2-1: Summary on some parameters of the lightly damaged sub-catchment 1 and the heavily damaged sub-catchment 2 (based on Marti, 2002).

		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
Fraction of area with wet soils	[%]	22.8	36.7
Fraction of damaged trees after storm Lothar [1]	[%]	21.4	62.7

1 Only trees with diameter at breast height (d.b.h.) larger than 20 cm were considered.

2.4 Methods

As mentioned above a nested approach was adopted in this study. Because the soil is a crucial factor in runoff generation, information on its characteristics is required in order to compare runoff generation processes at different scales. To test to what extent the Swiss forest site type map (Burger et al., 1996) can deliver soil information for hydrologic studies, such a map was established for the entire Sperbelgraben catchment and used as a substitute for a standard soil map. In contrast to the soil map, the map of forest site types includes a detailed description of the vegetation cover and additional information on topography and geomorphology.

The basic level in the nested approach is represented by 14 **soil profiles** chosen to be representative for areas with similar forest and soil properties within or in close vicinity to the two sub-catchments. Every profile has been classified according to the FAO-UNESCO soil classification system (FAO, 1997). Furthermore, the humus type, the rooting density and the rooting depth were determined. In addition, the pH (measured in $CaCl_2$ 0.01 M), the bulk density, the total soil pore volume and texture of all main horizons down to 1 – 1.5 m were measured.

Directly above 11 out of 14 soil profiles **irrigation experiments** have been carried out on 1 m^2 to determine the hydrologic properties of the site. The experimental setup was designed to measure (a) the total amount of overland flow and (b) the changes in water content (TDR-probes) in three to five depths down to 45 cm. The experimental setup is described in detail in Germann and Bürgi (1996). The registrations of the changing soil water content over time prior, during and after the irrigation experiment provides an indication of the dominant flow processes in a soil as described by Germann (1999). It is also possible to determinate the water holding capacity of a soil and the total amount of water which forms subsurface flow and deep percolation. At all sites three irrigation experiments were carried out on three consecutive days to assess the influence of changes in the initial soil moisture. As with every irrigation experiment a simulated rainfall of 60 mm in one hour was applied (precipitation event with a return period of 100 years in the Sperbelgraben), it can be assumed that the initial conditions for all sites are identical for the third consecutive experiment.

In the immediate vicinity of every soil profile at least one of a total of 19 **surface runoff plots** has been installed. Figure 2-3 shows two completely installed surface runoff plots 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 draining off on or very close to the surface is collected with PVC plates laid out parallel to the slope and is routed into a gully which leads it into a small gauging station. Furthermore, the two plots P8 and P23 were additionally equipped to measure subsurface flow above a less permeable soil layer (identified during soil profile analysis) at a depth of approximately 70 cm. These two installations are referred to as P8b and P23b. Surface runoff data will allow assessing to what extent the irrigation experiments are representative for larger areas. On the other hand, a comparison of plots lying in the same unit of the forest site type map but with different degree of wind storm damage allows for statements on the influence of deforestation on runoff formation.

Figure 2-3: Surface runoff plots P10 (left) and P1 (right). Lying close to each other, P10 was built up on an intact area, while P1 is situated on a heavily damaged area.

In every of the two **sub-catchments** a runoff measuring station was installed to verify how far the hydrologic properties of the slopes determined with irrigation experiments and surface runoff measurements on plots allow explaining the hydrologic reaction in these first order basins. To what extent is the hydrologic reaction modified by the channel network mapped in detail? The results of this part of the investigations in the Sperbelgraben are described in Badoux et al. (2005). A complete description of all permanent installations in the investigation area is given in Badoux et al. (2002a, 2002b).

2.5 Theory

Forests alter runoff generation both directly and indirectly. The direct influence is related to interception and evapotranspiration, the indirect influence to changes in soil properties. Many authors associate the main influence of forests on flood generation with changes in soil properties (e.g. Engler, 1919; Burch et al., 1996; Cosandey and Robinson, 2000, Chang, 2003; Weinmeister, 2003). Generally, and if similar initial conditions are considered, forest soils have a higher water storage capacity than grassland, pasture or cropland soils due e.g. to a higher organic material content and less compaction resulting in a generally better soil structure. This enables forest soils to store temporarily more water than other soils. As forests have a higher rate of evapotranspiration than many other vegetation types, this storage capacity is also emptied quicker.

Floods are normally associated with intensive rainfall. During such periods the air is very humid and therefore nearly no evapotranspiration takes place. Hence, all precipitation (*P*) that is not stored at least temporarily contributes to runoff, assuming that no deep percolation occurs and that infiltration is unlimited, a reasonable assumption for many forests. This runoff exceeding storage capacity (*QS*) is the sum of surface runoff (saturation excess overland flow) and quick lateral runoff in the soil. It can be described as follows:

$$QS = P - SC \qquad \text{with precipitation } (P) \geq \text{storage capacity } (SC) \qquad [1]$$
$$QS = 0 \qquad \text{with } P < SC$$

where *SC* represents the sum of the interception capacity of the vegetation and the water holding capacity of the soil. The runoff coefficient *PQ* describes the relation between precipitation and runoff as follows:

$$PQ = \frac{QS}{P} \qquad \text{generally } 0 \leq PQ \leq 1 \qquad [2]$$

However, under certain conditions *PQ* may exceed 1 (e.g. rain and snowmelt). As mentioned above, forests increase the storage capacity of a site due to increased interception and changes in soil properties by ΔSC_f. To consider this increase, equation [1] can be rewritten as follows:

$$QS_f = P - SC - \Delta SC_f \qquad \text{with } P \geq SC + \Delta SC_f \qquad [3]$$
$$QS_f = 0 \qquad \text{with } P < SC + \Delta SC_f$$

The runoff coefficient PQ_f can be determined in a similar way as described in equation [2]. The efficiency of the additional storage capacity of the forest can be described by the factor ΔPQ_f by which the runoff coefficient is reduced. It can be determined as follows:

$$\Delta PQ_f = \frac{PQ_f}{PQ} = \frac{QS_f}{QS} \qquad [4]$$

Using equations [1] and [2], this can be rewritten as:

$$\Delta PQ_f = 1 - \frac{\Delta SC_f}{P - SC} \qquad [5]$$

Curves describing the development of the runoff coefficient with (solid line) and without additional storage capacity ΔSC_f (dotted line) with increasing rainfall are shown in Figure 2-4. The dashed line represents the factor ΔPQ_f by which the additional storage volume reduces the runoff coefficient *PQ*.

The effect of an additional storage volume is limited. Even if storage capacity is doubled (Figure 2-4, left), the effect decreases below a 5 % reduction of the runoff coefficient rather quickly. This value of 5 % change in runoff coefficient may be considered as a reasonable lower limit that can be detected by very accurate hydrologic measurements.

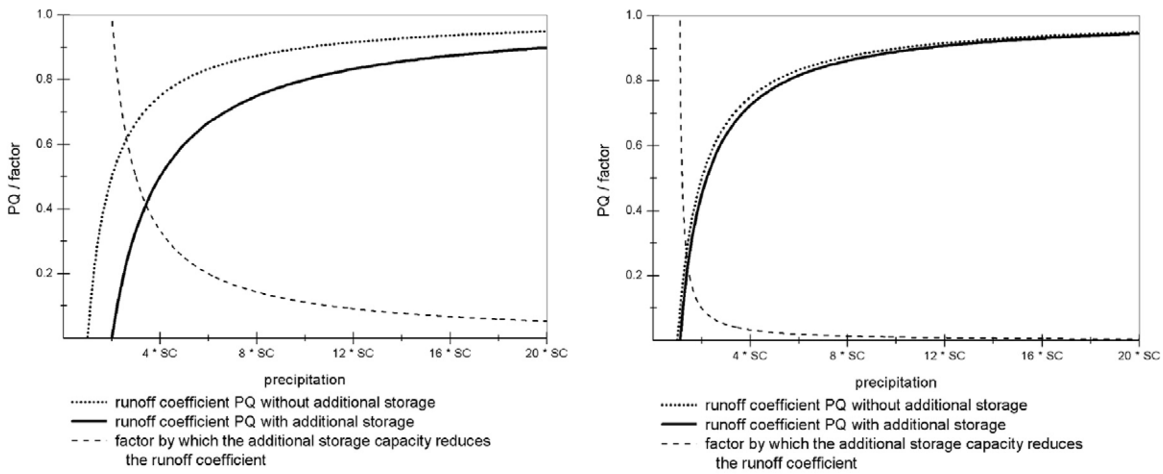

Figure 2-4: Schematic representation of the influence of additional storage on the runoff caused by storage excess runoff. Left: the storage capacity is increased by a factor of two; right: the storage capacity is increased by 10 %. The scaling of the x-axis is proportional to the storage capacity (SC) of the soil without considering forest influence.

The X-axis in Figure 2-4 is scaled proportional to *SC*, the water storage capacity available at the beginning of a rainfall event. This storage capacity is mainly dominated by soil properties as explained above. When plotting a single rainfall event in this graph, its position therefore depends not only of its rainfall volume but also on the soil properties of the studied site.

For events from the Alptal catchments, a small value for *SC* has to be used because of the very limited storage capacity of the soils. Therefore the events analysed by Burch et al. (1996) are situated in the rightmost part of Figure 2-4, where no influence of forests on floods can be detected. The influence due to the differences in the forest cover can only be detected with smaller rainfall events - events that have not been analysed by Burch et al. (1996), because they are normally not considered as floods. As these small events generally constitute a large portion of the annual water yield, forest influence is apparent in the water balance.

In the Emmental catchments however, the soils have higher storage capacities in many places and higher values for *SC* are applied in the x-axis of Figure 2-4. Rainfall events as analysed by Burch et al. (1996) are then located in the left part of the graph. As the events analysed by Engler (1919) have rainfall volumes in the same order of magnitude, these events are also located in the left part of the graph. Hence, it is reasonable that Engler (1919) showed that short rainfall events caused less runoff in the fully forested Sperbelgraben than in the Rappengraben with less forest cover. It is also intelligible why only a very small influence could be shown with long lasting rainfall events, because these events totalled a rainfall amount that was above the limit where forest influences can be detected.

2.5 Results

This paper reports on the hydrological characteristics and water balance of soils at point (profile) and plot scale (surface runoff plots) in two sub-catchments of the Sperbelgraben. Results are focused on surface runoff formation, caused by irrigation experiments and by natural intensive precipitation events, as well as on scale dependent differences.

a) Soil profiles and irrigation experiments

In the investigated area the soil types range from Cambisols to Gleysols. Cambisols are generally found in areas with steep slopes, whereas Gleysols are typically found on gentle slopes. Differences in soil moisture and acidity of the soils and forest site types present in the Sperbelgraben are shown in Table 2-2 and Figure 2-5. These factors implicate different hydrological response of these areas.

In general, the moist to dry Cambisols are very permeable. Main rooting depth ranges from 65 – 130 cm. Little surface runoff is expected on these sites based on their soil properties. However, 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 temporarily reduce the infiltration capacity (Burch et al., 1989) and generate surface runoff. In the investigated area the driest and most acid soils are found on forest site type 19 with a range of pH between 2.7 and 3.6 in the topsoils. There, thickness of the litter layer mostly exceeds 4 cm and thus infiltration capacity might be temporarily diminished. Hence, on such sites a hydrophobic reaction can be expected.

Table 2-2: Soil properties of soil profiles and surface runoff characteristics of artificial irrigation experiments.

Soil profile no.	Forest site type	Soil type	Silt (%)	Clay (%)	Litter layer (cm)	Humus form	Rooting depth (cm)	Surface runoff coefficient, 1. / 2. / 3. irrigation	Type of surface runoff
SP5	49f	Dystric Gleysols	28	13	0.5	muck	35	0.94 / 0.86 / 0.75	SOF[1]
SP13	26ho	Umbric Gleysols	37	12	1.0	muck	20	0.67 / 0.68 / 0.72	SOF[1]
SP2	49f	Dystric Gleysols	34	15	0.5	muck	15	0.39 / 0.48 / 0.57	SOF[1]
SPHN1	46a(18d)	Stagni-dystric Cambisols	25	16	4.5	moder	105	0.16 / 0.13 / 0.10	TH[2]
SP4	19	Humic Cambisols	24	6	4.5	moder	70	0.12 / 0.04 / 0.01	TH[2]
SP1	46a(18d)	Endostagnic Cambisols, podzolic properties	29	10	8.0	mor	70	0.06 / 0.02 / 0.01	TH[2]
SP19	19	Dystric Cambisols	23	7	4.0	mull/moder	130	0.03 / 0.02 / 0.01	TH[2]
SP6	19	Dystric Cambisols	21	10	2.0	moder	80	0.00 / 0.00 / 0.00	-
SP18	18aF	Stagnic Cambisols	23	10	4.0	moder	100	0.00 / 0.00 / 0.00	-
SP17	18aF	Dystric Cambisols	23	12	3.5	moder	100	0.00 / 0.00 / 0.00	-
SP15	18aF	Endostagnic Cambisols	23	7	5.0	mull/moder	100	0.00 / 0.00 / 0.00	-
SP14	18aF	Dystric Cambisols	28	14	1.5	mull	>100	0.00 / 0.00 / 0.00	-
SP12	46a(18d)	Endostagnic Cambisols	33	7	2.5	moder	65	0.00 / 0.00 / 0.00	-
SP9	18d	Dystric Cambisols	23	5	1.5	moder	90	0.00 / 0.00 / 0.00	-

1 Saturation Overland Flow (SOF)

2 Temporary Hortonian Overland Flow (TH)

Higher soil water content (higher antecedent soil moisture) leads to a higher runoff coefficient as shown by Lynch et al. (1977). In the Sperbelgraben the wettest and least acid soils (Gleysols) are typically found on forest site type 49f. They show a pH range of 4.8 – 5.2 in the topsoil. This indicates that the groundwater table is temporarily close to surface and reduces the rate of acidification. For Gleysols, rooting depth is restricted to 15 – 35 cm. Below this boundary, the soil is water saturated throughout the year. Therefore these sites may generate highest runoff coefficients.

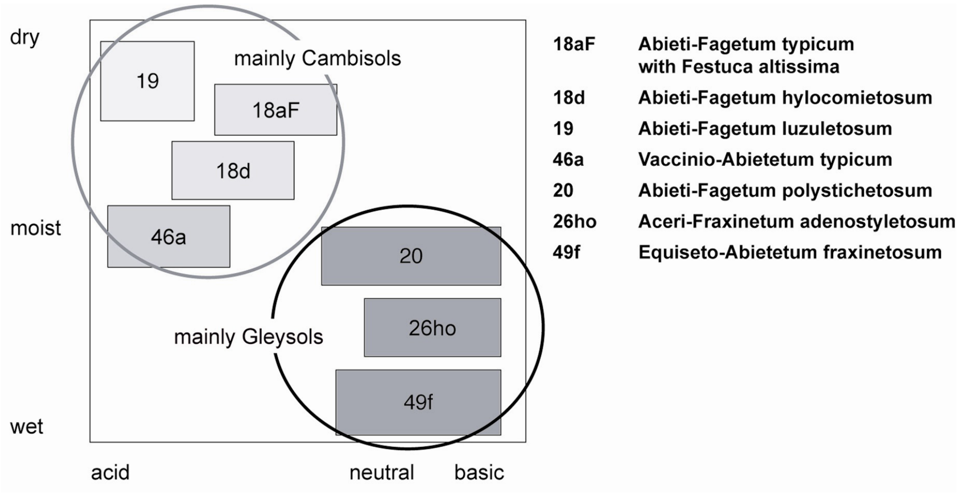

Figure 2-5: Characteristics of selected forest site types in an elevation range from 1000 to 1300/1400 m a.s.l. (from Burger et al., 1996; modified).

Water balance of soil profiles

11 soil profiles were irrigated and data on surface runoff and water content changes in depths to 45 cm were gained (Helbling, 2002; Sieber, 2002). Thus, a simple water balance can be calculated as follows:

$$P = Q_O + Q_{SSF} + S_Q + Q_D \quad [6]$$

with P as the applied rainfall of 60 mm in 1 hour and Q_O as the measured surface runoff. The temporal changes of the total soil water content (S_Q) between the beginning and 18 hours after the end of the irrigation experiment, was determined by summing up water content changes of the different soil layers. These changes were measured with TDR probes. The time frame of 19 hours was selected according to Germann (1999). The amount of water not measured as surface runoff and not stored in the observed soil profile resulted in deep percolation (Q_D) or lateral subsurface flow (Q_{SSF}). If no changes in water content were observed at the TDR probes in depths between 30 and 45 cm, lateral subsurface flow was assumed, otherwise deep percolation.

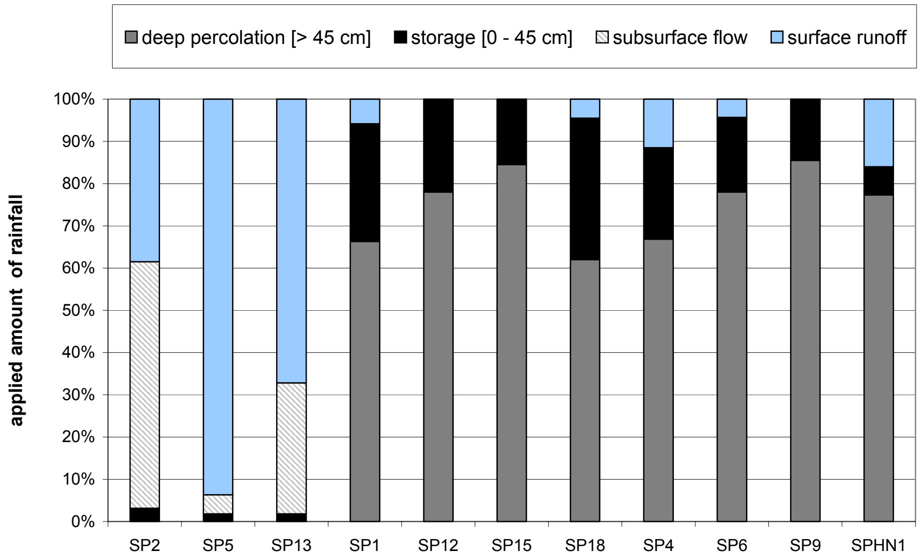

Figure 2-6: Water balance (surface runoff Q_0; lateral subsurface flow Q_{SSF}; storage S_Q; deep percolation Q_D) for 11 irrigated soil profiles of the *first* irrigation. Profiles SP2, SP5 and SP13 are located on Gleysols, all others on moist to dry soil types (Table 2-2).

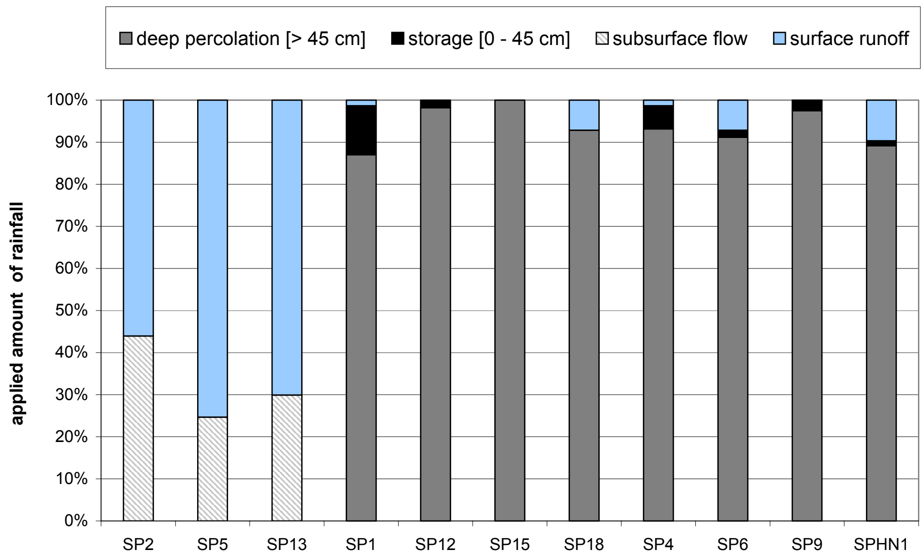

Figure 2-7: Water balance (surface runoff Q_0; lateral subsurface flow Q_{SSF}; storage S_Q; deep percolation Q_D) for 11 irrigated soil profiles of the *third* irrigation. Profiles SP2, SP5 and SP13 are located on Gleysols, all others on moist to dry soil types (Table 2-2).

Figure 2-6 shows the water balance of 11 profiles for the first irrigation. Because the first experiments took place at different dates, antecedent weather was different and therefore initial soil moisture contents are not directly comparable. Nevertheless, significant differences between the three soil profiles SP2, SP5 and SP13 (Table 2-2) and the remaining sites can be detected. Surface runoff and subsurface runoff are the dominating hydrological processes for the three mentioned profiles on gleyic soils. SP2 shows maximum discharge in form of subsurface flow (58.3 %), SP5 and SP13 as surface runoff (93.7 and 67.2 % respectively). In all three cases storage capacity is extremely limited to 1.8 – 3.2 % in the organic topsoil. In contrast, all other eight profiles (lying on moist to dry Cambisols) show deep percolation as the dominant process (62.0 – 85.5 %). Storage comes second (14.5 – 27.7 %) and surface runoff appears only on five sites and remains limited (< 11.5 %).

Figure 2-7 shows the results of the third irrigation experiment. Given the fact that both of the antecedent experiments took place within 48 h before the start of the third, initial soil moisture content is comparable. The results show a similar picture compared to the first day experiment, except for the storage capacity. This parameter is greatly reduced on the third day experiment for all profiles. The three profiles on gleyic soils (SP2, SP5, SP13) have no additional storage capacity. In the other profiles it is limited to a mean value of 3.3 % (values range from 0 – 11.7 %). Compared to first day experiment, the dominant processes of surface runoff on the humid and wet Gleysols as well as deep percolation in the moist to dry soils are even more pronounced. Hence, Figure 2-6 and Figure 2-7 show the different storage capacity of soils depending on the initial soil moisture content and on the forest site type.

Surface runoff generation:

A closer look to the surface runoff processes reveals three different types of surface runoff for the 11 irrigated soil plots:

High surface runoff coefficient: Three irrigation experiments on gleyic soils (SP5, SP13, SP2) result in high surface runoff coefficient between 0.39 and 0.94 (Table 2-2). These soils have slightly higher clay- and silt-proportion than all the other sites and are situated on a terrace with gentle slope. Rooting is restricted to only 15 – 35 cm because of underlying water logged horizons. The humus type is typically muck, indicating a high groundwater table. In these cases, surface runoff occurs after the saturation of the soil matrix. According to Kirkby and Chorley (1967) can be classified as saturation overland flow (SOF).

On the Cambisols, little or no surface runoff at all was observed. The units of the Swiss forest site type map allow for an additional differentiation:

*Low surface runoff coefficient***:** Two plots each of the forest site types 46a(18d) and 19 show low surface runoff coefficient between 0.01 and 0.16 (SPHN1, SP4, SP1, SP19) and declining values from first to third irrigation experiment (Table 2-2). Moist and acid soils are found on sites of forest site type 19 and 46a. Due to an extreme acid topsoil with a pH range of 2.7 –

2.8 the humus type is moder to mor. High soil acidity results in an accumulation of organic compounds on the surface because decomposition is limited. The thickness of the litter layer amounts on these sites to ≥ 4 cm. This litter layer of conifers reacts partially water repellent. Under these hydrophobic conditions a temporarily reduced infiltration capacity leads to a temporary Hortonian overland flow (TH) (Burch et al., 1989). Water repellence seems to increase with increasing thickness of the organic horizon. Once the litter layer is passed, deep percolation is not restricted due to well drained soils on slopes.

No surface runoff: On all four plots of forest site type 18aF (SP14, SP15, SP17, SP18) and on plots of forest site type 19, 46a(18d) and 18d (SP6, SP12, SP9) surface runoff does not occur at all. These plots show only a thin litter layer of ≤ 4 cm (except SP15) and a higher decomposition rate of organic material due to a higher pH range of 2.9 – 3.6. The humus type is therefore moder to mull. The infiltration capacity of these soils is higher than the irrigation intensity of 60 mm h^{-1}. Deep percolation is not restricted due to the good drainage of soils on slopes and acts as the dominant process in these soils.

Evolution of surface runoff with time:

Figure 2-8 shows the time dependent change in surface runoff for two selected profiles during the three successive irrigation experiments. Irrigation starts at t = 0 s and ends at t = 3600 s. Surface runoff is displayed as the proportion (%) of applied rainfall amount.

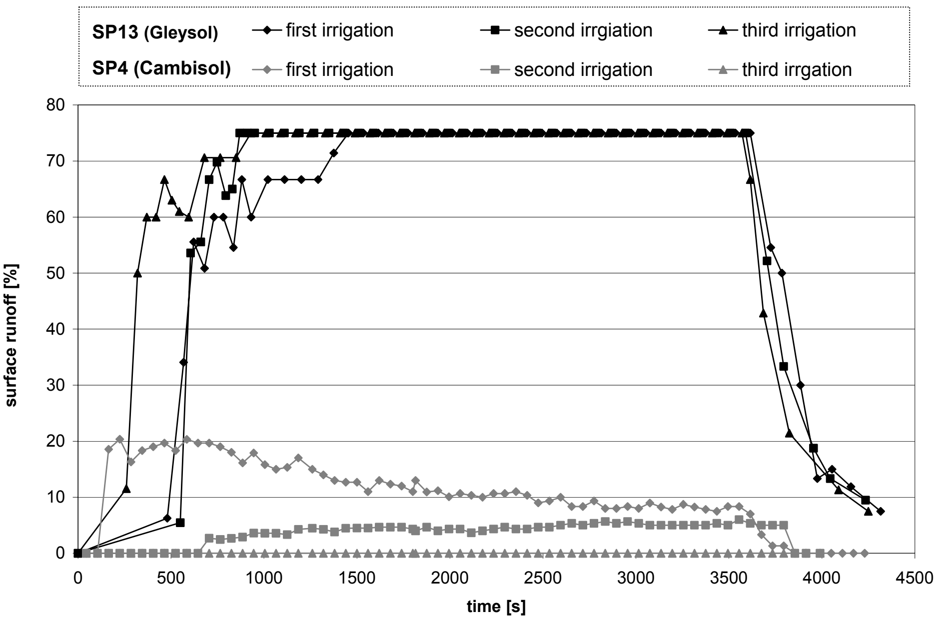

Figure 2-8: Surface runoff responses (as percentage of rainfall) of SP13 and SP4 during 60 min of artificial rainfall, calculated on the basis of the rainfall intensity of 60 mm h^{-1}.

Profile SP4 is an example of a hydrophobic soil producing “temporary Hortonian overland flow”. The first day experiment on SP4 shows a sharp rise of surface runoff and highest discharge values (20.4 % of applied rainfall amount) only 3 min after start. Thereafter, surface runoff slowly decreases until the end of irrigation. On the second day, surface runoff starts only after 11 min and never reaches the level of the first day. Surprisingly there is a light increase of surface runoff during irrigation but it remains in the range of tolerance. After the end of irrigation surface runoff stops immediately on the first as well as on the second day. On the third day, no surface runoff is generated at all. Hence, absolute surface runoff quantities decrease clearly from the first to the third day (Table 2-2).

SP13 in Figure 2-8 represents a soil showing high surface runoff coefficients. The difference to SP4 is evident. SP13 has a sharp increase of surface runoff, but maximum discharge is attained only after 24 min for the first day experiment. After this initial phase of increasing soil saturation, constant (maximum) runoff follows on a high level (75 %) till the end of the experiment. On the second day, the shape of the curve is quite similar to the first day curve but maximum discharge is attained 10 min earlier. On the third day, surface runoff rises even quicker and the maximum level is attained at the same time as on the second day. In all three experiments the shape of the SP13 hydrograph is similar when steady-state is attained. After the end of irrigation, runoff recession is much slower than on SP4 which can be related to the draining surface storage. Absolute surface runoff coefficients of SP13 increase from the first to the third irrigation. On such wet soils, only SP5 shows a decreasing surface runoff coefficient (Table 2-2). The reason for this unexpected result is to be found in a pipe that was clogged with sediment during first day irrigation. During the second experiment, sediment in the pipe was washed out and the water started immediately to flow out of the trench beside the experimental plot at a depth of 60 cm.

b) Surface runoff plots

Data gained from surface runoff plots in the 2002 and 2003 summer seasons show a distinct pattern in the surface runoff formation. Concerning the occurrence and magnitude of surface runoff, two different processes could be discerned (Badoux et al., 2004): (a) On moist to wet areas (typically Gleysols) considerable precipitation events saturate the soil quickly and lead to saturation overland flow. (b) Hydrophobic reactions were found to be the most significant processes producing surface runoff on dry to moist areas (typically Cambisols). Characteristic hydrographs feature peaks of temporary Hortonian overland flow at the very beginning of precipitation events. The range of generated surface runoff volume on these plots was far lower than on those producing saturation overland flow. Sites with a medium surface runoff reaction on precipitation events do not exist in the Sperbelgraben sub-catchments. Although poorly drained soil layers are observed at some profiles (e.g. endostagnic Cambisols), they are either not continuous or simply too deep to efficiently retain water, lead to saturation and eventually cause overland flow.

In Table 2-3, a selection of surface runoff plots operated in the investigation area is presented. Their geographical position is shown in Figure 2-2. The eleven plots listed can be divided into three classes: P2 and P13 stand for the moist to wet soils of the forest site types 49f and 26ho, they are the wettest plots operated. The plots P6, P7, P8 and P18, P22, P23 represent the steep hillslopes of the two sub-catchments (forest site types 18aF and 19), generally showing deep Cambisols. There, P8 and P23 are specially equipped in order to measure lateral subsurface flow above a poorly drained soil layer in a depth of approximately 70 cm too (P8b and P23b). For both groups, the three plots are arranged parallel and vertically staggered on a hillslope respectively. Finally, P1, P10 and P4 typify sites that regularly present temporary Hortonian overland flow (forest site types 46a and 19).

Table 2-3: Surface runoff plots and coefficients of total surface runoff volume during 2002 and 2003 events.

Surface runoff plot no.	Associated soil profile no.	Forest site type	Soil type	Forest storm damage	Slope [°]	Total surface runoff coefficient 2002 events[1]	Total surface runoff coefficient 2003 events[2]
P2	SP2	49f	Dystric Gleysols	totally damaged	16	0.70	0.13
P13	SP13	26ho	Umbric Gleysols	no damage	11	0.14	0.04
P6	SP6	18aF/19	Dystric Cambisols	no damage	26	0.06	0.00
P7	SP6	18aF/19		no damage	29	0.02	0.00
P8	SP6	18aF/19		no damage	29	-	0.01
P8b	SP6	18aF/19		no damage		-	0.00
P18	SP18	18aF	Stagnic Cambisols	totally damaged	28	0.03	0.05
P22	SP18	18aF		totally damaged	28	0.02	-
P23	SP18	18aF		totally damaged	30	-	0.00
P23b	SP18	18aF		totally damaged		-	0.00
P1	SP1	46a(18d)	Endostag. Cambisols, podzolic properties	totally damaged	26	0.05	0.03
P10	SP1	46a(18d)		no damage	22	0.05	0.01
P4	SP4	19	Humic Cambisols	no damage	24	0.04	0.05

1 Based on 23 events (early June till late November 2002) during which all listed plots were operated.

2 Based on 25 events(late June till early October 2003) during which all listed plots were operated.

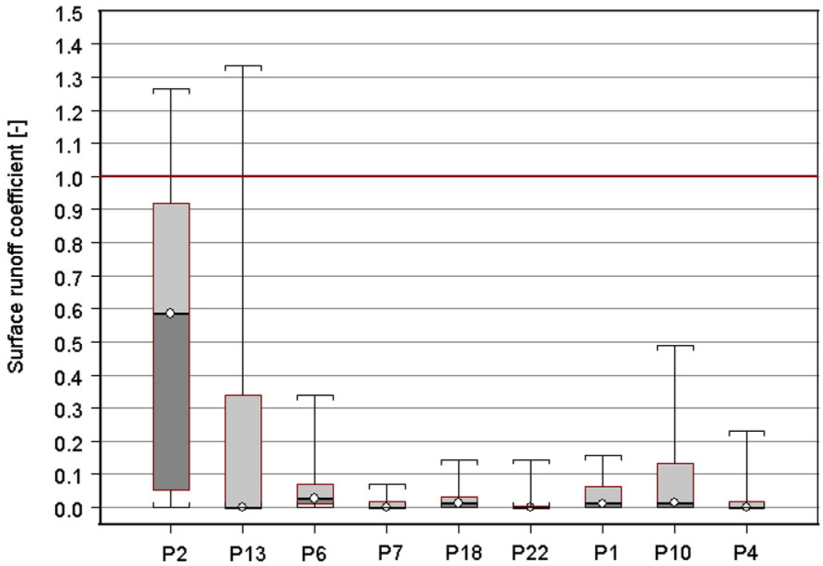

Figure 2-9: Surface runoff coefficients for 23 rainfall events in the 2002 investigation period and the surface runoff plots considered in Table 2-3; displayed box plots give range, quartiles and median.

Comparable to the artificially irrigated soil profiles, surface runoff plots P2 and P13 lying on forest site types 26ho, 49f show the strongest reaction to natural precipitation events (Figure 2-9). Particularly surface runoff plot P2 yields a considerably higher coefficient of total surface runoff (0.70 for 2002 events; 0.13 for 2003 events) than all the other plots which is especially pronounced for the year 2002 (Table 2-3). However, the two investigation periods 2002 and 2003 were substantially different. While the summer of 2002 was rather wet, the very hot and dry summer of 2003 represents a rare meteorological situation with an extremely low probability (Schär et al. 2004). Due to this condition, plots on moist to wet sites registered considerably lower surface runoff coefficients in 2003 than in 2002 as described in Badoux et al. (2005). Most of the considered events in Table 2-3 occurred during the mentioned heatwave when the water table of the Gleysols (normally close to the surface) was visibly lowered. Thus, rainfall water was stored or ran off as shallow subsurface flow but did not generate saturation overland flow.

In general, saturation excess overland flow from moist to wet forest site types is the most important surface runoff process observed in the investigation area, as shown in an exemplary event in Figure 2-10. The event consists of two successive and quite short rain storms yielding 14.5 mm and 18.8 mm respectively. Compared to the other plots considered in the graph, P2 and P13 show much higher surface runoff peaks as well as larger runoff volumes. Saturation of the upper soil (and thus surface runoff initiation) is reached shortly after the beginning of rainfall on such locations. On these sites, the groundwater table is mostly close to surface (depending on the weather conditions) as observed in profile holes and indicated by the grey colour of the Gley horizon close to the surface. However, peak runoff of plots P2 and P13 occurs later in the event as it highly depends on precipitation intensity as soon as soils are fully saturated. Apparently, storage capacity before the event was smaller on P13 compared to P2 as the first rainfall peak leads to higher runoff there. The further progression of P13 runoff is somewhat peculiar and could be influenced by lateral subsurface water input into the plot during the event. This assumption is supported by the occurrence of coefficients for single events higher than 1, as illustrated in Figure 2-9.

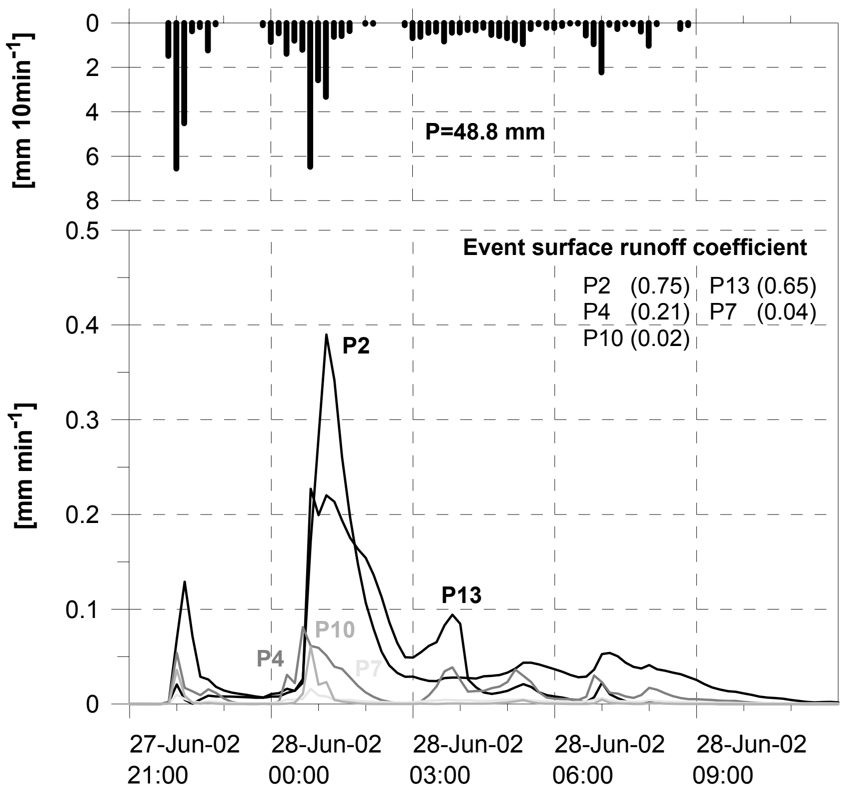

Figure 2-10: Surface runoff hydrograph of selected plots (Table 2-3, Figure 2-2) during the precipitation event of 27-28 June 2002. Plots P2 and P13 stand on Gleysols, whereas P4, P7 and P10 are located on moist to dry soil types.

On dry to moist forest site types (18aF, 18d, 19) with high infiltration capacity, surface runoff production is seldom and above all remains small (Figure 2-9). No plot shows a total surface runoff coefficient (for a single year) larger than 5 to 6 % (Table 2-3). During the very hot and quite dry summer of 2003, surface runoff on these plots situated on well drained Cambisols along the hillslopes is quasi negligible. Most of the plots showing typical hydrophobic characteristics (P1, P4 and partly P18, but not P10) yielded a similar range of surface runoff coefficients in both periods (Table 2-3). For single events (e.g. Figure 2-10), coefficients rarely exceed 0.20 to 0.25, a typical characteristic for the investigation area when surface runoff is generated due to water repellent reactions in the acid litter layer. For somewhat smaller plots, similar event coefficients are reported by e.g. Doerr et al. (2003) or Keizer et al. (2004), although their studies were carried out under different conditions (Portugal).

During 2003 measuring period, subsurface runoff plot P23b and P8b were activated throughout approximately 30 events. During none of these events monitored at these measuring boxes, subsurface flow was registered. On the basis of this observation, it was concluded that on the considered steep hillslopes, water infiltrates beyond 70 cm. Thus, the poorly drained soil layer is not continuous enough to lead to local saturation and subsequently to subsurface flow. Along the investigated hillslopes, lateral subsurface flow is likely to occur only at the soil-rock interface (Badoux et al., 2005).

Furthermore, pairs of surface runoff plots (e.g. P1/P10, P2/P13) within the same or very similar forest site types were compared (Badoux et al., 2004). Differences in factors that influence surface runoff formation (above all soil properties) are thus reduced to a minimum, and the compared plots only differ in the occurrence of storm damage. This comparative survey indeed revealed an influence of particular storm damage elements on the generation of surface runoff, but only very locally and of restricted magnitude. At one site, for instance, an overthrown rootstock laid open bare soil and thereby allowed temporary Hortonian overland flow generated upslope to infiltrate. At another site, though, a distinct soil compaction on a Cambisol (trace from hauled logs) did not lead to an increase and channelling of surface runoff. Generally, it can be stated that storm damage has a restricted influence on surface runoff generation on the investigated plots. Also, the successive ground vegetation arisen shortly after the wind storm on damaged areas was to a large extent capable of compensating the interception provided by the forest cover before the event.

2.6 Discussion and conclusions

Many irrigation experiments have been carried out all around the world. Even though some of these studies were conducted in forested catchments (e.g. Hornberger et al., 1991), most focussed on grassland or farmland. Recent investigations in Central Europe have been published by Scherrer and Naef (2003), Weiler and Naef (2003) or Markart and Kohl (1995).

The investigations within two sub-catchments of the Sperbelgraben on profile scale show different runoff behaviour of forest soils depending on their soil type and forest site type. Artificial high-intensity precipitation on 1m^2 plots leads to a high proportion of surface runoff (coefficients from 0.39 to 0.94) on humid to wet Gleysols. Such high surface runoff coefficients are rather unexpected for forest soils that often do not generate any surface runoff at all (e.g. Kohl et al., 1997; Markart et al. 1997; Schwarz, 1986). In contrast, the sprinkling experiments on dry to humid Cambisols result in no or only little surface runoff. For those experiments the coefficients (0.01 – 0.16) were found to be considerably higher after dry antecedent than after wet antecedent conditions. This strongly suggests the influence of water repellency. Looking at the corresponding soil profiles, the magnitude of the hydrophobic reaction seems to increase with increasing thickness of the organic horizon (also reported by e.g. Crockford et al., 1991; Scott and Van Wyk, 1990). In the Sperbelgraben, thick organic litter layers are most probable to occur on forest site type 19 (Table 2-2).

On steep slopes, the investigation area features a very high infiltration capacity, as has already been stated by Engler (1919) a long time ago. An exception is only made where temporary Hortonian overland flow occurs due to hydrophobic conditions. The effect of hydrophobicity is clearly visible at profile scale but only to a smaller degree at plot scale, due to the fact that the thickness and the composition of the litter layer observed on the soil profiles is spatially variable. As reported e.g. by Doerr et al. (2003) the influence of hydrophobic topsoils is most distinct at small scale and decreases with increasing size of the investigated area. We conclude that because of these spatial limitations and of its temporal limitation to the beginning of a rainfall event, temporary Hortonian overland flow does not contribute significantly to flood generation. Therefore, it can be ignored in the concept described in the theory chapter. These theoretical considerations on the forest influence on floods though stand in no contradiction to the findings made in the Sperbelgraben at profile and plot scale. The temporal and spatial variability of the influence of the water storage capacity of a forest soil on runoff generation can be explained therewith.

The comparability of responses at plot and profile scale is limited due to the different approach of investigations. While at profile scale, artificial rainfall intensity is identical for all experiments, natural precipitation events are considered at plot scale which vary in duration and intensity. Due to the non-linearity of hydrological processes, it is hardly possible to compare different rainfall events of profile and plot investigations. In addition, boundary effects increase with decreasing size of the tested areas. Their impact at plot scale is considerably smaller than at profile scale. Nevertheless, identical hydrological key processes were identified at the two different scales and surface runoff coefficients are found to be in similar order of magnitude for experiments on the same forest site types. Thus, we conclude that it is possible to derive from small scale irrigation experiments qualitative statements on main hydrological processes occurring in a specific soil type and to transfer them to larger areas under the conditions found in the Sperbelgraben.

The results of the irrigation experiments and surface runoff plots show that the map of forest site types (Burger et al., 1996) is a good tool for the determination of areas with similar hydrologic reactions. Its potential even goes beyond a standard soil map as it also allows identifying the predisposition of a site for hydrophobic behaviour. The inclusion of vegetation information into mapping procedures for hydrologic purposes, as this is the case with the Swiss forest site type map, therefore seems promising. Since such maps are widely used in Swiss forestry, they represent a potential to improve hydrological catchment modelling.

2.7 Acknowledgement

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Chapter III

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

Submitted to:

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3.1 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 three-year period in two differently affected sub-catchments (≈ 2 ha) and on two-year surface runoff measurements on smaller plots (50 to 110 m^2). The link between these two scales and the results of irrigation experiments on 1 m^2 areas is 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 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

3.2 Introduction

The influence of forest coverage on runoff in river basins of various size 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., 2002). 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 is highly site-specific, necessitates a new differentiated approach to investigate this topic. 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 (≈ 20000 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).

3.3 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 north-east to south-west (Figure 3-1). 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. 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 immediate proximity of the gauging station of the Sperbelgraben catchment) for the period from 1961 to 1999 amounts to 1660 mm. Temperature measurements on a forested site within the Sperbelgraben from 1937 to 1957 (recent measurements are inexistent) 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 focused on two neighbouring sub-catchments of approximately 2 ha size (Figure 3-1). They are located in the south-east zone of the ridge of the Sperbelgraben catchment at an elevation between 1075 and 1160 m a.s.l. 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 3-1.

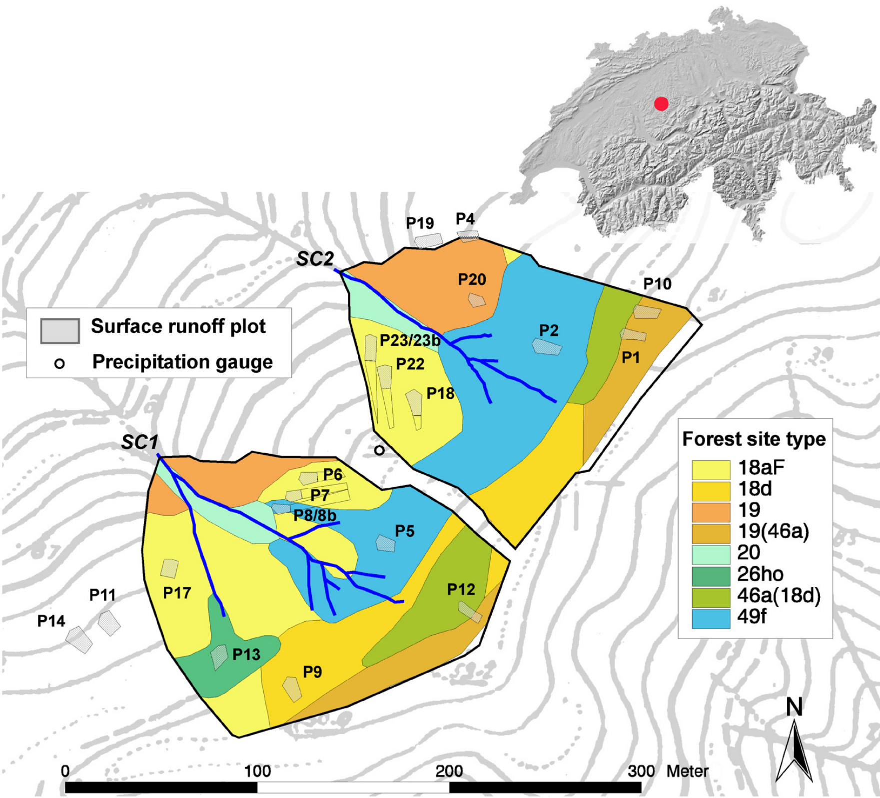

Figure 3-1: Overview over the investigation area showing the position of the 19 surface runoff plots (numbered) and the centrally located precipitation gauge.

Table 3-1: Characteristics of the lightly (SC1) and the heavily (SC2) damaged sub-catchment.

		SC1	SC2
Area	[m^2]	20250	17620
Mean elevation	[m a.s.l.]	1130	1128
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

Table 3-2: Tree survey after storm Lothar (only trees with a d.b.h. > 20 cm considered, also for basal area calculation). Based on data by Marti (2002) and Gertsch (2002).

	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	

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 (d.b.h.) 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 3-2 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 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 (d.b.h. > 20 cm considered).

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). 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 1:5000 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 (Figure 3-2) 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 temporarily 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 Figure 3-1.

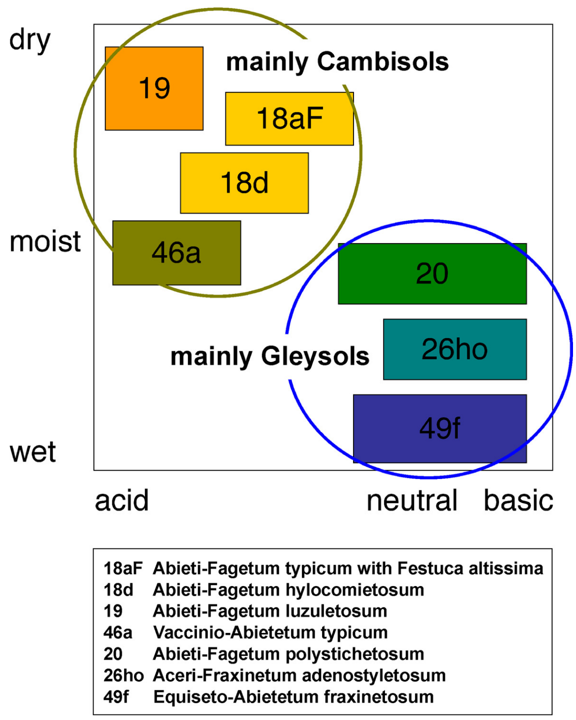

Figure 3-2: Wetness and acidity (pH) of selected forest site types in an elevation range from 1000 to 1300/1400 m a.s.l. (from Burger et al., 1996; modified).

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 3-3, Figure 3-2). 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.

Table 3-3: 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[(1)] / Gleyic properties[(2)]**	**Main soil type**
18d, 18aF, 19, 46a	24-33	15-30 / 2-15	2.7 – 4.4.	2-8	> 100	>50 cm / none	Cambisol
26ho, 49f	12-15	28-37 / 12-25	4.5 – 5.5.	0-2	< 30	none / >20 cm	Gleysol

1 Stagnic properties are related to soil saturation by surface water.

2 Gleyic properties are related to soil saturation by groundwater.

Measurement set-up

A nested approach was applied in the present study. Investigations on three different levels (soil profile, runoff 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 amount of water which forms subsurface flow and deep percolation could be assessed. The results of these investigations are discussed in Witzig et al. (2004) and Badoux et al. (2005a).

Surface runoff plots

19 surface runoff plots with an area of 50 to 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 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 (Figure 3-1). 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 subsurface runoff plots were installed in 2003 (P23b, P8b). 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 of these devices is 10 minutes. 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 are to be found in Badoux et al. (2002a). 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 2002 and 46 took place in 2003. For every single 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.

In the two sub-catchments, flood events that occurred between April 2001 and December 2003 and that exceeded a certain threshold of approximately 60 l s^{-1} km^{-2} were taken into account for the investigation. This value corresponds to twice the mean discharge of the entire Sperbelgraben catchment. 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: a) Intensive precipitation type featuring high 10-minute intensities and short duration, b) Long-duration precipitation type with lower intensities and c) 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 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 long time averages by not less than 7.5 °C respectively 6.4 °C (MeteoSwiss, 2003a).

3.4 Results

Water balance of the sub-catchments

In Figure 3-3 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 1to1-

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.

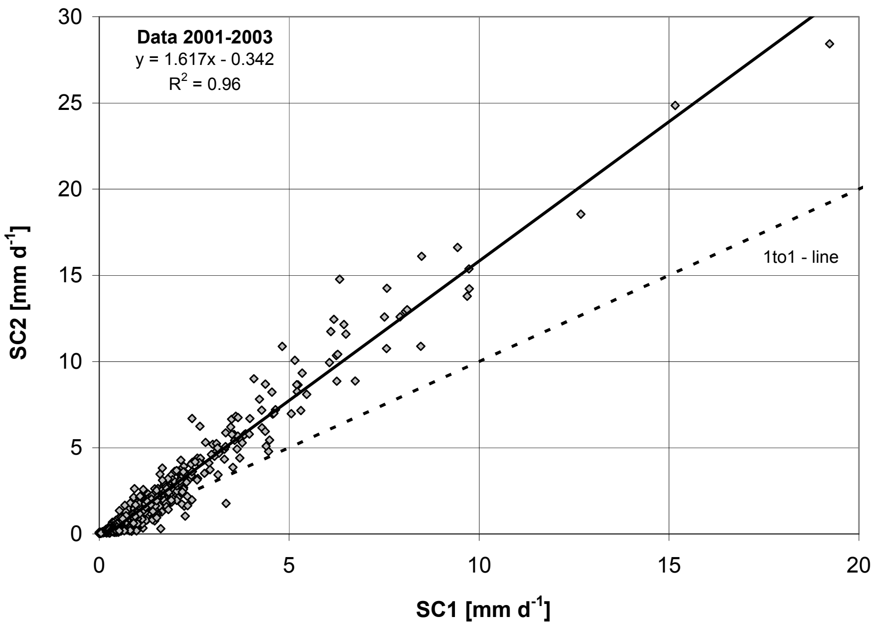

Figure 3-3: Daily runoff (from April 2001 till December 2003) of the lightly (SC1) and the heavily (SC2) damaged sub-catchment; the full line represents the regression line.

Daily runoff data were aggregated to monthly and annual runoff values (Table 3-4). 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 was interpolated. The first year of investigation 2001 was left apart since measurements were only started in April and technical problems led to loss of data in September.

In terms of precipitation, the two years differ from each other quite distinctively. While the ca. 1780 mm in 2002 exceed the long time annual average of the MeteoSwiss rain gauge Kurzeneialp (at the outlet of the Sperbelgraben) by roughly 10 %, the 2003 value of approximately 1220 mm stands out because it is very low (MeteoSwiss, 2003b). 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 3-4). According to the findings from Figure 3-3, higher values in SC2 predominate for wet to very wet periods. During the dry and hot summer months of 2003 (June to 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 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 approach to explain differences in runoff premises impermeable catchments without any water losses as a result of seepage.

Table 3-4: 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.

2002		**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Tot**
P [mm]		26	102	81	81	171	163	224	213	214	157	244	108	1783
R [mm]	SC1	16 (1)	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	1253
R [mm]	SC2	12 (1)	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	1052

2003		**J**	**F**	**M**	**A**	**M**	**J**	**J**	**A**	**S**	**O**	**N**	**D**	**Tot**
P [mm]		102	68	67	117	142	80	148	78	69	185	114	55	1224
R [mm]	SC1	(2)	(2)	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	(2)	(2)	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*

1 In order to estimate the monthly runoff in January 2002, some daily values had to be interpolated.

2 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).

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 3-4). 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 the highest estimates for annual evapotranspiration in prealpine regions by far (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 (1917 to 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 (sequence of conglomerate and marl layers that was believed to be impermeable based on field observations and previous descriptions). We do not know if the amount of leakage in the two sub-catchments is the same and have to interpret the values in Table 3-4 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 3-5 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 3-5). SC2 means exceed SC1 means by ca. 75 % for persistent precipitation events and by ca. 50 % for short and intensive rainfall events. However, direct runoff volumes are significantly different at the 95th percentile only for the long-duration, low-intensity event type and not for the short, high-intensity event type (Table 3-5). From a total of 54 persistent precipitation events only three showed higher direct runoff in SC1. Those all 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 3-4 gives four examples of single flood events in the Sperbelgraben sub-catchments. For the two low-intensity events, it is evident that direct runoff is much larger in the heavily damaged sub-catchment 2 than in 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 (Figure 3-4, top). 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. For the two high-intensity rainfall events, direct runoff volume is larger in SC2 (Figure 3-4, bottom). Compared to the events of the long-duration, low-intensity type, the difference between the two sub-catchments is less important though. The smaller size of this difference is caused by surprisingly higher runoff peaks in SC1 during short and intensive rainfall events, an occurrence described in detail below. However, in most of the events (mainly the larger ones), the slower runoff recession of SC2 compensates for the smaller specific peaks and leads to higher direct runoff values there. The July 2001 event in Figure 3-4 for example yielded 3.07 mm of direct runoff in SC2 and 2.13 mm in SC1 (coefficients: 0.15 and 0.10 respectively).

Table 3-5: 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.

		Persistent precipitation (54 events)		
Parameter	Unit	SC1	SC2	SD_{95}
Precipitation (P)	[mm]	29.0	29.0	-
Max. P-intensity	[mm $10min^{-1}$]	1.2	1.2	-
Length of direct runoff	[min]	2034	2226	n
Reaction time	[min]	95	170	y
Peak discharge	[l s^{-1} 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)		
Parameter	Unit	SC1	SC2	SD_{95}
Precipitation (P)	[mm]	17.3	17.3	-
Max. P-intensity	[mm $10min^{-1}$]	3.7	3.7	-
Length of direct runoff	[min]	608	749	y
Reaction time	[min]	49	79	y
Peak discharge	[l s^{-1} 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)		
Parameter	Unit	SC1	SC2	SD_{95}
Precipitation (P)	[mm]	16.4	16.4	-
Max. P-intensity	[mm $10min^{-1}$]	0.7	0.7	-
Length of direct runoff	[min]	3484	4153	n
Reaction time	[min]	-	-	-
Peak discharge	[l s^{-1} km^{-1}]	129	204	n
Direct runoff	[mm]	5.91	11.05	y
Direct runoff coefficient	[-]	-	-	-

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 Figure 3-5, 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 eleven 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 (Table 3-5). 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 the non-site specific parameter precipitation is deliberately being excluded. Thus, the site-specific 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 an univocal interpretation of the data. While for intensive showers the average peak of SC1 is higher than the one of SC2, it is the opposite for persistent precipitation events (Table 3-5). 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 3-4 (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 Figure 3-4 (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 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 (Figure 3-4, 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.

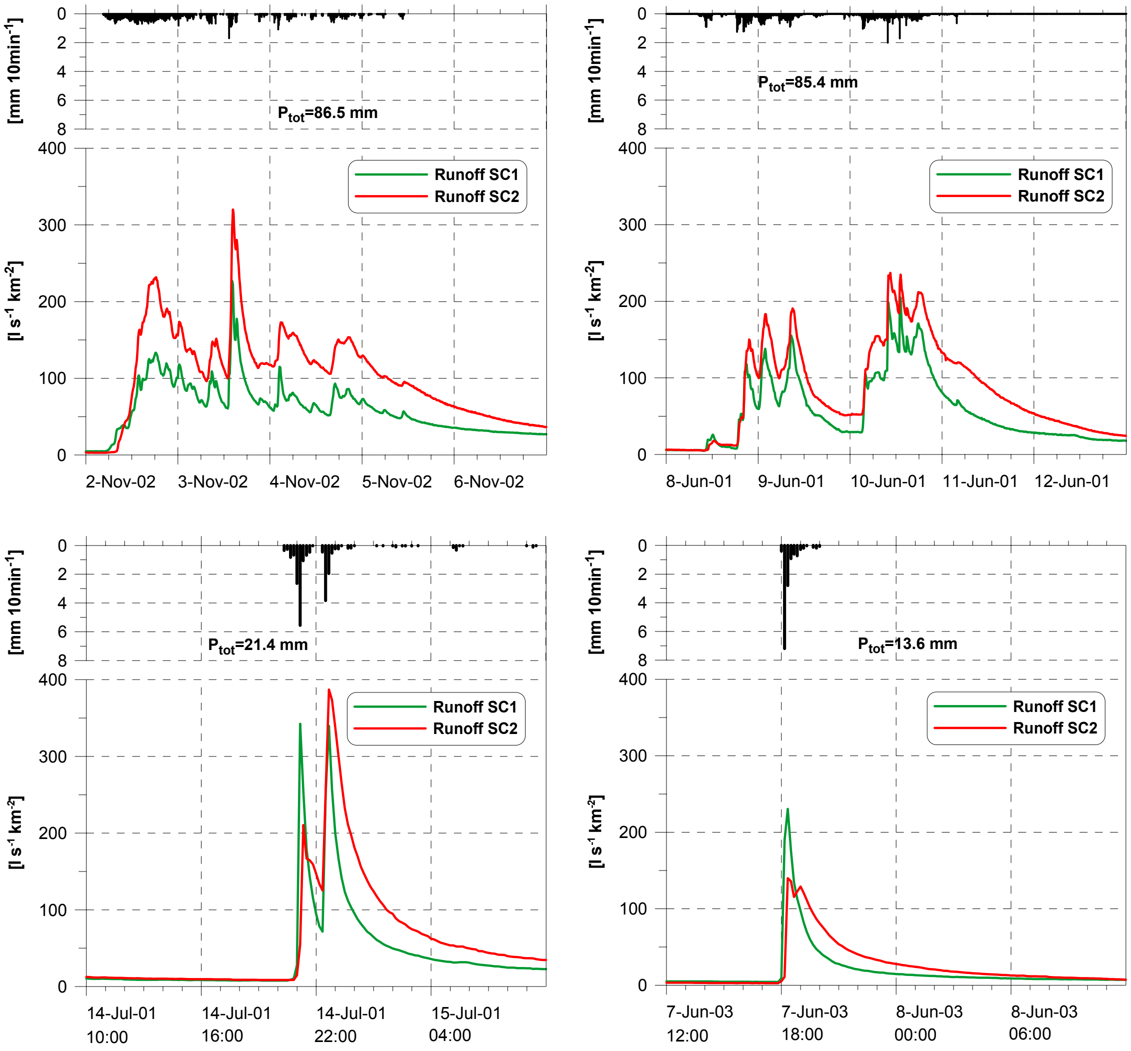

Figure 3-4: Typical examples of precipitation-runoff events in the sub-catchments: two long-duration, low-intensity events (top) and two short, high-intensity events (bottom).

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 run-off 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 3-5 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 3-5).

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 persists, the heavily damaged SC2 usually shows higher specific 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 Gustafsson et al. (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 damage 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 to 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 3-5). Furthermore, reduced radiation on the ground (canopy radiation interception) in SC1 causes lower snowmelt intensities when no rainfall is involved.

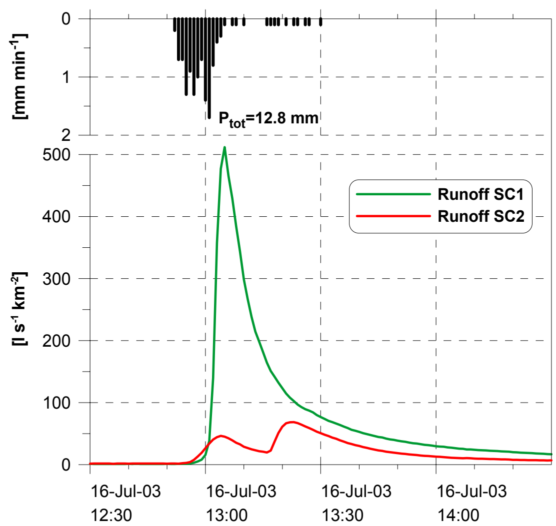

Figure 3-5: Very short intensive rainfall event during summer 2003 (available 1-minute runoff and precipitation data was used in this chart).

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: (a) 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. (b) 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 (Könitzer, 2004).

Summer season 2003

Compared to 2002 measurements, 41 % less summer precipitation was recorded in 2003 in the investigation area (April through September). But for all that, about the same amount of events were registered on the plots.

Figure 3-6 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 3-6 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 mayor 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 heatwave.

As shown in Witzig et al. (2004), the Gleysols of the investigation area are water saturated throughout the year below a depth of 15 to 35 cm which corresponds to their restricted rooting depth. Depending on the weather, the groundwater table is temporarily 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 approximately 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 subsurface flow.

This explanation approach is confirmed by Figure 3-7 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 three 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 30 August) did not result in soil saturation. It was only in early October, when roughly 91 mm of precipitation fell in three days, that P2 generated surface runoff again.

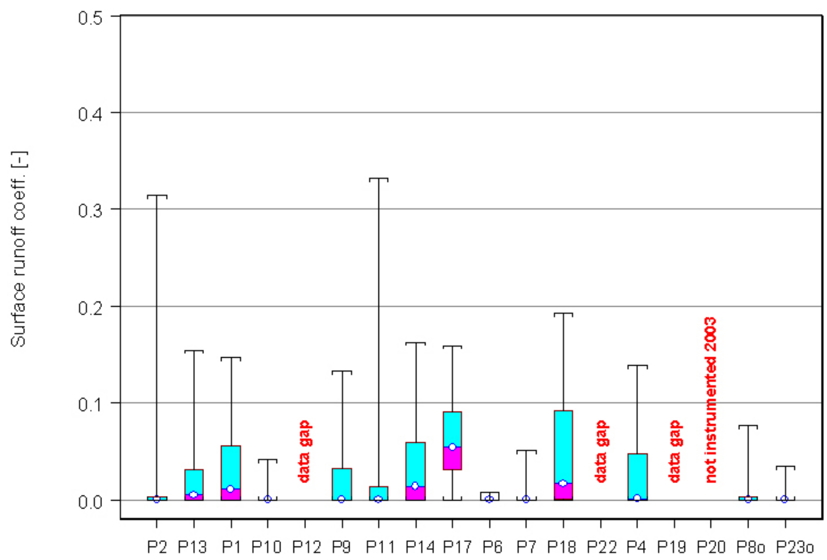

Figure 3-6: Surface runoff coefficients for 20 selected rainfall events and each surface runoff plot; displayed box plots give range, quartiles and median are placed regarding the affiliation of the plot to a forest site type; all events fall within the period from 30 June to 10 September 2003; plots P12, P19, P22 had to be omitted due to measuring failures during this period.

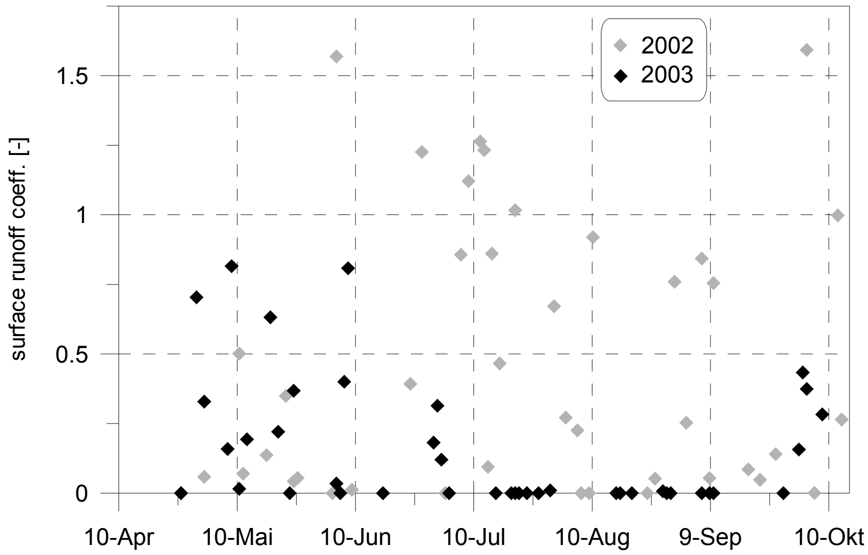

Figure 3-7: Surface runoff coefficients for plot P2 from events in 2002 and 2003.

In contrast, P13, the other plot situated on a moist to wet forest site type (26ho), did not react as drastic to the heatwave 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 (Figure 3-8). 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.

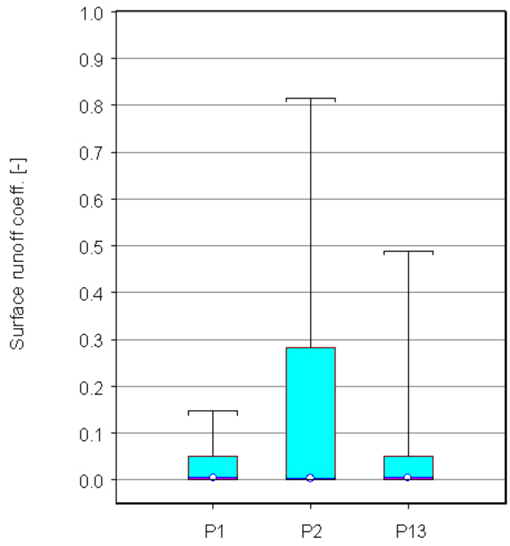

Figure 3-8: Surface runoff coefficients for the 42 events during which the plots P1, P2, P13 were operational (26 April until 8 October 2003).

Surface runoff measurements along the slopes (cascades)

For the most part, the plots of the two cascades (cascade in SC1: P6, P7, P8; cascade in SC2: P18, P22, P23; Figure 3-1) 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.

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.

Subsurface 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 subsurface flow above a less permeable soil layer (identified during soil profile analysis) at a depth of approximately 70 cm. These two installations are referred to as P8b and P23b.

Subsurface runoff plot P23b operated during 31 events and P8b throughout 37. During the events monitored at these stations, no subsurface 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 subsurface 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.

3.5 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 3-1), their runoff concentration should theoretically be comparable. However, the interaction of the local land-scape and geomorphic processes led to an approximately 60 % larger channel density in SC1 compared to SC2 (Table 3-1; Figure 3-1). 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 (Figure 3-1), 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 $km\,km^{-2}$ for SC1 compared to 20.1 $km\,km^{-2}$ 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 immediate channel vicinity. As neither large amounts of surface runoff nor fast subsurface 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 subsurface flow (assessed at the profile and plot scale). Because 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 3-1), 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 (Figure 3-7). 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 (Figure 3-5). 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 Figure 3-5, 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.

3.6 Conclusions

Regarding surface runoff generation in forested areas, there is no such thing as an uniform reaction to storm precipitation. Groups of forest site types (Table 3-3) 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. Whereas 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 heavily sub-catchment runoff is 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.

3.7 Acknowledgements

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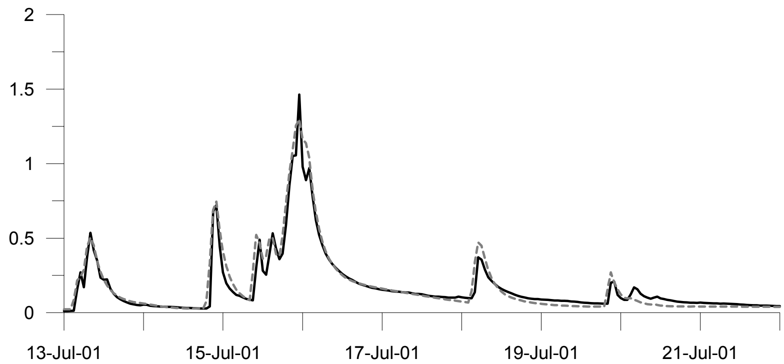
Chapter IV

Aspects of a multi-scale modelling experiment in a small, forested, storm damaged catchment, Swiss Emmental



Submitted to:

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4.1 Abstract

This study focuses on the hydrological simulation of discharge on two scales within a small torrential catchment in the Swiss Emmental. The hydrological model PREVAH was applied to the Sperbelgraben catchment (54 ha) based on 25x25 m^2 grid cells aggregated to hydrological response units and running at one hour time resolution. Water balance simulations for the period of 1982 to 2003 revealed a seepage loss of approximately 200 mm per year as argued by previous studies. The provided set of calibrated model parameters yielded stable results with linear efficiency of 0.80 and 0.73 for daily and hourly hydrograph respectively. The parameters were then adopted for the modelling of two sub-catchments (≈ 2 ha). There, smaller grid cells (2x2 m^2) were applied at a time step of an hour for the years 2001 to 2003. Calculations confirmed the applicability of the used model even for these very little catchments. However, this could only be accomplished by the introduction of a new conceptual dynamic term in the runoff module that allows a rapid drainage of small catchments during intensive rainfall. Furthermore, results point at the problem of water losses in the sub-catchments, not only as baseflow as believed so far, but also as interflow from the unsaturated zone. Hence, long-duration flood events are affected by leaking as well. The seepage losses observed in the sub-catchments are larger than the expected differences in hydrological behaviour forced by storm damages. Finally, a qualitative comparison of simulated surface runoff with field measurements points out that further steps are required to bring sound process knowledge into conceptual hydrological model.

Keywords: hydrological modelling, storm damage, multi-scale approach, water balance, runoff generation processes, internal verification

4.2 Introduction

Response to rainfall in small headwater catchments is largely determined by the runoff generation processes taking place at the hillslopes and in the immediate vicinity of stream or channel areas (e.g. McDonnell, 2003; Weiler et al., 2003; Selby, 1993). First order controls are represented by the processes that define the lateral movement of water on top of the soil or within the unsaturated and saturated zones. Hence, the soil properties and the land use are of decisive importance in such micro-scale catchments with areas smaller than 1 km^2 (Uhlenbrook et al., 2004). Moreover, the underlying bedrock also influences runoff generation (Freer et al., 2002).

Regarding catchment modelling studies at the micro-scale, the recent comparison of the original and the new dynamic TOPMODEL within the small forested Panola Mountain catchment (Georgia USA; 0.41 km^2) has to be mentioned (Peters et al., 2003). With the modelling system HILLFLOW, Bronstert and Plate (1997) consider most of the relevant hillslope hydrological processes. Three versions of the model are presented: 1D, 2D and 3D. While the 1D version copes with vertical (column type) soil water balances, the two others (hillslope and catchment) allow focussing on rapid soil water flow processes during storm conditions such as macropore infiltration, lateral subsurface stormflow and return flow. Considerations on the objectives of detailed hillslope hydrological modelling as well as conclusions about its limitations are given in Bronstert (1999).

Several investigations in micro-scale catchments emphasise on the importance of sub-surface stormflow during storm events (e.g. Peters et al., 1995; McDonnell, 1990; Wilson et al., 1990; Mosley, 1979). Fast subsurface flow can be generated and may represent a considerable part of total stormflow on slopes with soils showing high lateral permeability due to macropores, highly permeable layers or pipes. Lateral subsurface flow occurs principally at the interface of two soil layers with differences in permeability. This effect can be especially distinctive at the soil-bedrock interface and a very fast reaction is generated on slopes with thin soils (Peters et al., 1995). In contrast, investigations of Kirnbauer et al. (1996) within the alpine Löhnersbach catchment (Austria) demonstrated the dominant influence of runoff processes on saturated areas for the flow regime of small torrential sub-catchments.

Current knowledge about the influence of land use change on water quantity (and quality) in a river basin is widely based on experimental catchment studies (Bosch and Hewlett, 1982; Sahin and Hall, 1996) and on long-term observations (e.g. Swank and Crossley Jr., 1988; Hornbeck et al., 1993; Schwarze et al., 1994). Focussing on water balance issues, long-term land-use change as well as climate change impact studies applying distributed hydrological models have recently been carried out mainly at the meso- and macro-scale (e.g. Klöcking and Haberlandt, 2002; Wegehenkel, 2002; Lahmer et al., 2001; Fohrer et al., 2001; Schulla, 1997). Furthermore, event based modelling approaches have been conducted in different meso-scale catchments in order to asses the effects of different land-use scenarios on floods in a temporally more detailed way (e.g. Ott and Uhlenbrook, 2004; Niehoff et al., 2002).

The present paper deals with a special kind of land-use change: storm caused damage in steep forested areas within the torrential Sperbelgraben catchment (Swiss Emmental). This catchment is one of the investigation sites studied within the project "Lothar and Mountain Torrents" (Hegg et al., 2004). Previous investigations emphasised on artificial irrigation experiments above soil profiles (Witzig et al., 2004; Badoux et al., 2005a), surface runoff measurements on plots of 50 to 110 m^2 (Badoux et al., 2004) and the runoff behaviour of two 2 ha sub-catchments (Badoux et al., 2005b). Open questions remained with regard to the extent of water loss due to seepage in the two sub-catchments (as well as in the entire Sperbelgraben catchment) and the composition of storm runoff formed by the different runoff processes along a typical slope or in an entire sub-catchment. To explore these questions we decided to apply a distributed hydrological model to the investigation area.

Hydrological models that aim at simulating the impact of anthropogenic land use change or climate variation need an explicit and accurate framework. The controlling hydrologic processes must be described in such a way as to enable them to take into account the modified environmental conditions. Empirical models do not suit for this purpose and more physically-based approaches have to be opted for. The distributed hydrological model PREVAH (Precipitation-Runoff-Evapotranspiration-HRU model, e.g. Gurtz et al., 1999) was developed with the aim of taking into account as much as possible of the physical relationships within a catchment but also contains conceptual approaches, mainly with regard to runoff generation. The model PREVAH is well established at the meso- and macro-scale (e.g. Gurtz et al., 2003a), its application to the Sperbelgraben sub-catchments at very high resolution represents a challenge.

The objectives of this paper are, (1) to estimate seepage losses in the entire Sperbelgraben catchment and in two sub-catchments; (2) to asses the role of surface runoff during rainfall storms and (3) to evaluate, as a prerequisite to handle objectives one and two, if the distributed hydrological model PREVAH can tackle both the runoff characteristics of the Sperbelgraben catchment and of the sub-catchments. Its suitability for such modelling exercises in micro-scale catchments is put to the test.

4.3 Investigation area

The investigation area consists of the forested torrential catchment of the Sperbelgraben situated in the hilly Emmental region in the Swiss prealps. In particular, two neighbouring sub-catchments are considered that vary in their extent of forest damage in consequence of the storm event “Lothar” (Dec 1999).

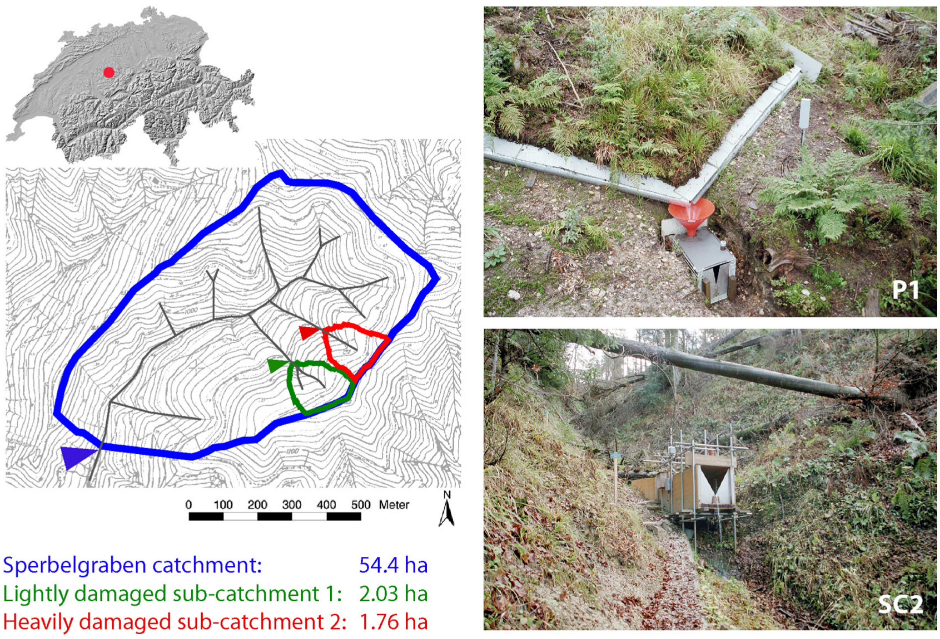

Figure 4-1: Left: Location of the investigation area. Right: Lower part of surface runoff plot P1 (above); downstream view on the gauging station at the outlet of the heavily damaged sub-catchment SC2 (below).

The Sperbelgraben catchment drains from north-east to south-west, has an area of 0.544 km^2 and ranges from 911 to 1203 m a.s.l. Main tree species in the quasi entirely forested area include fir, spruce, beech and sporadically maples. 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.

The two adjacent sub-catchments are located in the south-east zone of the ridge of the Sperbelgraben at an elevation between 1075 and 1160 m a.s.l., as shown in Figure 4-1 (left). With

2.03 ha, the lightly damaged sub-catchment (hereafter SC1) is somewhat larger than its heavily damaged neighbour (SC2). Basic parameters of the investigated catchments are listed in Table 4-1. Furthermore, forest damage in the two sub-catchments was quantified after the storm event, only considering trees with a diameter at breast height (d.b.h.) larger than 20 cm. While stand density in the two areas prior to the storm was properly the same at 205 trees per hectare, SC2 shows an overall damage that is roughly three times larger than the one of SC1 (Table 4-1). Present basal area amounts to 23.7 m^2 ha^{-1} in SC1 and 8.6 m^2 ha^{-1} in SC2 (for trees with d.b.h. > 20 cm). A more detailed description is given e.g. in Badoux (2005b).

Table 4-1: Characteristics of the entire Sperbelgraben (SP) catchment as well as of the lightly (SC1) and the heavily (SC2) damaged sub-catchments.

Characteristics	**unit**	**SP**	**SC1**	**SC2**
Area	[m^2]	544000	20250	17620
Mean elevation	[m a.s.l.]	1063	1130	1128
Exposition	[-]	SW	NW	NW
Mean slope	[°]	25.5	25.3	25.7
Circumference	[m]	2960	550	540
Form factor (Horton, 1932)	[-]	0.46	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

4.4 Materials and methods

Measurement set up

A nested approach was applied in the present study. Measurements on three different scales (sub-catchment, surface runoff plot and soil profile) have been carried out to determine hydrological characteristics of the sub-catchments.

SC1 and SC2 were equipped with runoff gauges as illustrated in Figure 4-1 (Badoux et al., 2002a). Furthermore, a broad study of the surface runoff characteristics was carried out on a smaller scale. For this purpose, 19 surface runoff plots (Figure 4-1) were installed in and around the sub-catchments (Badoux et al., 2004). In addition, 17 soil profiles representing areas with similar forest and soil properties were chosen. Each soil profile is associated with a surface runoff plot or plot group and has been classified according to the FAO-UNESCO soil classification system (FAO, 1997). The hydrologic properties of the soils have been assessed with a forest site type map and verified by carrying out artificial rainfall experiments on 1 m^2 right above the profiles (Witzig et al., 2004). The mentioned map gives an overview of the prevalent forest site types that can be found in the investigation area. The mapping was based on a detailed procedure (Swiss standard) described in Burger et al. (1996). Finally, runoff data from the entire Sperbelgraben was obtained from the Federal Office for Water and Geology (FOWG) that runs this station since 1958.

The model PREVAH

The model that has been used in the research presented here is the conceptually structured model PREVAH (Precipitation-Runoff-Evapotranspiration-HRU model, e.g. Gurtz et al., 1999) whose discretisation relies on hydrological response units HRUs (Ross et al., 1979; Flügel, 1997; Gurtz et al., 1999). PREVAH consists of several different components as shown schematically in Figure 4-2. A detailed model description is given e.g. in Gurtz et al., 1999 and Zappa, 2002.

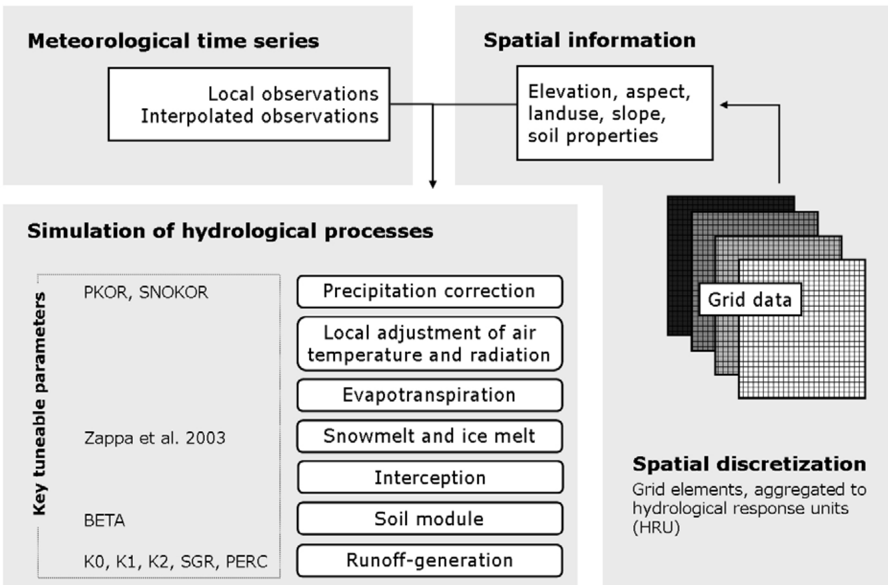

Figure 4-2: Scheme of the distributed hydrological model PREVAH (Precipitation-Runoff-Evapotranspiration HRU Model; Zappa, 2002; Gurtz et al., 1999). The declared parameter abbreviations are listed in Table 4-2.

Since the mid nineties, the model PREVAH has been applied in Swiss catchments of variable size and in very different environments. At the point scale, simulations of soil moisture, evapotranspiration and the water balance of single raster units have been carried out for the Rietholzbach lysimeter (Gurtz et al., 2003b). Moreover, soil moisture on several plots in the Riviera Valley (southern Switzerland) has been modelled (Zappa and Gurtz, 2003). At meso-scale, the pre-alpine research catchment Rietholzbach represents the object of many model-based investigations, namely a comparative study in modelling runoff and its components together with the alpine catchment Dischmabach (Gurtz et al., 2003a). Through the application of PREVAH to the Dischmabach, the spatial analysis and modelling of snowmelt runoff from high mountainous areas was further improved (Zappa et al., 2003; Klok et al., 2001). Experience in larger mountainous catchments was gained in modelling experiments focussing on the 1703 km^2 large Thur catchment (Gurtz et al., 1999). Finally, Zappa (2002) showed several model applications for water basins at different spatial scales, including a 20-year water balance simulation for the whole of Switzerland (41285 km^2).

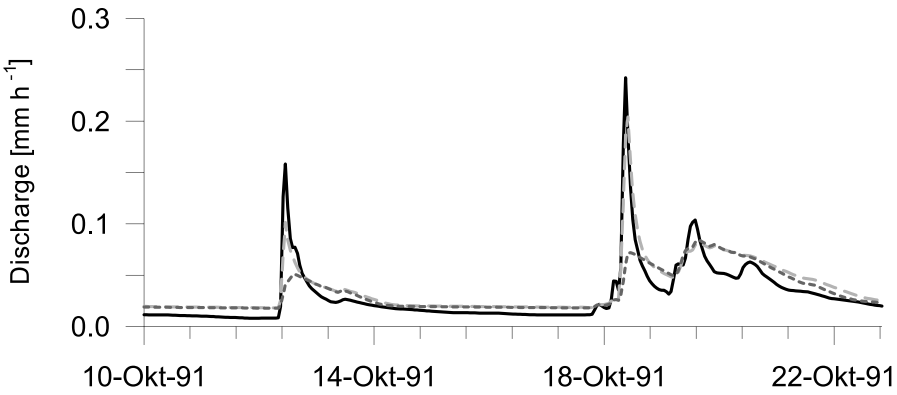

Figure 4-3: Example of observed (full line) and modelled (dashed lines) runoff hydrographs for the Sperbelgraben catchment. The graph shows how the new conceptual dynamic term allows a better description of quick response surface runoff generation (dashed line, light grey).

The original HBV-based runoff generation module (Bergström, 1976; Gurtz et al., 2003a) of PREVAH is not suited if a catchment reaction to rainfall is shorter than the integration time step of one hour as characteristic for the here studied sites. Therefore, a term enabling the production of a very fast surface runoff component was integrated to allow a rapid drainage of small catchments. In short, the new overland flow component is large on steep downslope areas of micro-scale catchments after intensive rain storms. Full description of this enhancement is given in the Appendix. Figure 4-3 shows how the implemented conceptual dynamic term allows a better description of storm runoff generation.

Modelling set-up and strategy

Simulations in the entire Sperbelgraben catchment

The criteria for aggregation of grid cells into HRUs were formulated based on knowledge about the spatial differentiation of hydrological processes and the structure of the selected catchments (Gurtz et al., 1999). HRUs were extracted according to elevation zone (50 meters bands), aspect, land-use and soil type (see below). For the Sperbelgraben catchment, a total of 158 HRUs were generated on the basis of the 854 25x25 m^2 grid cells which gives an average of 5.4 cells per HRU. This represents a higher catchment-internal spatial variability as compared to previous investigations, where more than 10 grid cells per HRU were aggregated for modelling the Rietholzbach and Dischmabach catchments (Gurtz et al., 2003a).

Regarding topography, the parameterisation of the model is based on information derived from gridded maps of elevation (GG25 © 2005 swisstopo, DV033492). Soil characteristics were assessed in detail within the Sperbelgraben sub-catchments. 17 soil profiles representing areas with similar forest and soil properties were analysed and described (Badoux et al., 2005a; Hegg et al., 2004). Thus, in-situ information on soil depth, plant available field capacity and hydraulic conductivity were gained and applied instead of large-scale data from generally available maps. These characteristics were then adopted for the entire Sperbelgraben by means of a small-scale forest site type map (1:5000) established according to guidelines by Burger et al. (1996). A forest site type represents the summary of the characteristics of similar forest sites grouped according to topographic and geomorphologic location, soil properties, floristic composition etc. The land-use has been derived from a regular small-scale forest map of the Sperbelgraben catchment, and integrated in the parameterisation process (Gurtz et al., 1999).

The model is forced by interpolated values of observed climatic variables. These are collected at different weather station and rain gauge networks run by MeteoSwiss. Six meteorological input variables at time steps of one hour or one day are required: precipitation, air temperature, global radiation, relative sunshine duration, wind speed in and water vapour pressure. Hourly data for the period 1981-2003 are available. In addition, local precipitation was measured from 2001 to 2003. The procedures adopted for spatial and temporal interpolation are based on detrended inverse distance weighting and ordinary Kriging (Sonderegger, 2004).

The experiment was calibrated for the years 1982 to 1986 while 1981 was used as initialisation year. The calibration procedure relies on the monitored maximisation of an acceptability score based on nine different objective functions (Sonderegger, 2004). The functions test the agreement between observed and simulated discharges (Nash and Sutcliffe, 1970; Legates and McCabe, 1999; Zappa et al., 2003) not only for the full calibration period, but also on a month-to-month and year-to-year basis. This allows for the identification of parameter sets that provide a similar agreement in all the different seasons of the year and in all years of the calibration period. Subsequently, the Sperbelgraben catchment simulation was verified for the years 1987 to 2003.

Table 4-2: Definition of internal variables of the hydrological model (plain records) and declaration of the calibrated model parameters (italic records) for different settings: P100 assumes no catchment leakage, P60 runs include leakage of 40 % of deep percolation. Abbreviations refer to Figures 4-2 and A1.

Parameter	**Abbr.**	**Unit**	**P100 (day)**	**P60 (day)**	**P60 (hour)**
Inflow in the soil model	P_b	[mm h^{-1}]	-	-	-
Plant available water storage in the aeration zone of the soil	SSM	[mm]	-	-	-
Plant available, maximal water storage in the aeration zone of the soil	SFC	[mm]	-	-	-
Surface runoff storage	SSR	[mm]	-	-	-
Water storage in the upper zone	SUZ	[mm]	-	-	-
Dynamic parameter for fast surface runoff	FSR	[-]	Equations in Appendix		
Rainfall adjustment	*PKOR*	[-]	-2.8	14.7	12.6
Snowfall adjustment	*SNOKOR*	[-]	1.9	-3.0	-1.4
Soil moisture recharge parameter	*BETA*	[-]	2.5	2.5	1.8
Storage coeff. for surface runoff	*K0*	[h]	18.5	28.5	27
Storage coeff. for interflow	*K1*	[h]	72	121	121
Storage coeff. for delayed baseflow	*K2*	[h]	2250	2300	2300
Storage coeff. for quick baseflow	*K3*	[h]	920	880	880
Threshold parameter for surface runoff	*SGR*	[mm]	27	47	38
Deep percolation	*PERC*	[mm h^{-1}]	0.08	0.095	0.095

Two different types of simulations (P100 and P60) were carried out. As will be explained in the following, serious doubts persist on the plausibility of the water balance when it is determined using the residual term method. These doubts stress the likelihood of leakage from the Sperbelgraben catchment. In the P100 simulation, it is assumed that the water balance is closed and no seepage losses occur. In contrast, in the P60 simulation the diversion of a certain amount of baseflow is enabled and thus a possible leaking allowed for. For both simulations, sets of calibrated parameters were determined (Table 4-2).

Simulations in the Sperbelgraben sub-catchments

For the simulation of the two Sperbelgraben sub-catchments, HRUs were newly extracted in conformity with elevation (smaller bands of 20 metres were used), aspect and the collected afore mentioned field information on land-use and soil types. The sector including the sub-catchments was surveyed using a global-positioning system GPS and a digital terrain model (DTM) with a resolution of 2 metres that meets the requirements of the small and varying terrain was generated. Thus, very small grid cells of 2x2 m^2 could be applied to the investigation area. Furthermore, every damaged as well as healthy tree located within the sub-catchments with a diameter of at least 20 cm was surveyed in order to receive accurate information on the forest coverage. A total of 402 and 387 HRUs were generated for the lightly (SC1) and the heavily damaged (SC2) sub-catchments. The interpolation of meteorological variables relies on the same data basis as used for the Sperbelgraben computations.

The calibrated model parameters (simulation of the entire Sperbelgraben) have been adopted for the simulation of the sub-catchments, too. Only parameters of the runoff-generation module have been re-calibrated in order to better match the reaction of the sub-catchments to long-duration, low-intensity precipitation as well as short and intensive storm rainfall. The simulation was calibrated for the years 2001 and 2002 while 2000 was used as initialisation year. Afterwards, model validation was carried out for the year 2003. Only observed discharge data from May to November were processed, as a parameter set had to be identified that provides good agreement during periods characterised by rainfall only. Events caused by snowmelt or by a mix of rainfall and snowmelt (typical for Spring months) are not emphasised here.

4.5 Results

Simulation of the Sperbelgraben water balance as we see it

The Sperbelgraben catchment mean annual water balance for the periods 1917-2003 (available measurement) and 1982-2003 (modelling period) is shown in Table 4-3. Data from the MeteoSwiss rain gauge Kurzeneialp at the outlet of the Sperbelgraben were adopted and catchment precipitation calculated (before 1958, two additional gauges were operated in order to account for the difference in elevation of 295 m).

Table 4-3: Mean annual water balance (precipitation P; evapotranspiration ET; simulated R_{sim} and observed R_{obs} runoff) for the Sperbelgraben catchment, including simulated surface runoff component (RS), storage change (DS) and average efficiency criteria r^2_{lin} and r^2_{log}. Enhanced model runs treat runoff generation considering the new dynamic term described in the Appendix.

Method	Period [a]	Res [b]	P	ET	R_{sim}	R_{obs}	RS	DS	r^2_{lin}	r^2_{log}
Kurzeneialp	1982-1986 1982-2003	-	1790 1652	-	-	-	-	-	-	-
Sperbelgraben [c]	1917-2003	-	1675	807	-	868	-	-	-	-
Sperbelgraben [c]	1982-1986 1982-2003	-	1870 1726	866 783	-	1004 943	-	-	-	-
Enhanced P100	1982-1986 1982-2003	day	1641 1570	665 652	1002 927	-	96 84	-26 -9	0.764 0.794	0.783 0.777
Enhanced P60d	1982-1986 1982-2003	day	1886 1811	710 691	996 926	-	113 101	180 194	0.788 0.800	0.827 0.804
Enhanced P60h	1982-1986 1982-2003	hour	1861 1785	669 654	1006 933	-	119 116	184 198	0.700 0.733	0.824 0.796
Original P60h	1982-1986 1982-2003	hour	1812 1760	648 644	951 909	-	59 43	213 207	0.596 0.622	0.800 0.761

(a) The year 1984 was left apart due to runoff measurement inaccuracies; model calibration 1982-1986, model application 1982-2003.

(b) The model was calibrated based on discharge data at different time resolution (Res).

(c) 1958-2003 catchment precipitation was calculated from the MeteoSwiss rain gauge Kurzeneialp (at the outlet of the Sperbelgraben) by multiplication with an altitude factor derived from 1903-1957 measurements (Casparis, 1959) at three points (Kurzeneialp 894 m a.s.l.; Kuttelbad 1062 m a.s.l., Bisegg 1150 m a.s.l.).

Simulation P100 implies that all precipitation input into the Sperbelgraben catchment that does not evaporate or is stored (soil, snowpack etc.), is gauged at its outlet. P100 was calibrated relying on daily runoff information (Tables 4-2 and 4-3). Whereas calculated annual catchment runoff (1982-2003) for P100 is only slightly smaller than the measured value and thus corresponds well, a large difference is noticeable in the components evapotranspiration and precipitation. As a matter of fact, theoretical considerations (Penman, 1959; Badoux et al., 2005b) speculate that the Sperbelgraben catchment might not be impervious.

Own estimations for the Sperbelgraben using the residual term method give a mean annual evapotranspiration (1917 to 2003) of 807 mm. Casparis (1959) calculated an average value of 856 mm for the period from 1927 to 1956. Values of this order of magnitude exceed even high estimates for annual evapotranspiration in prealpine regions (Menzel et al., 1997). In an article that discusses the evapotranspiration information for the two Emmental catchments Sperbelgraben and Rappengraben published by Casparis (1959) and Burger (e.g. 1954), Penman (1959) questioned the occurrence of such high values. Based on water balance considerations, he suggests an upper estimate of 550 mm for the Sperbelgraben. On the one hand, he mentions possible inaccuracies of the runoff gauge as an explanation approach. Most notably though, Penman (1959) suspects an unknown degree of leakage.

The evaluation of evapotranspiration in PREVAH has proved to be accurate in past studies on different scales (Gurtz et al., 2003b; Zappa and Gurtz, 2003). Evapotranspiration is determined based on the Penman-Monteith equation (Gurtz et al., 1999). Thus, as PREVAH is calibrated against measured runoff and generates a good annual runoff estimate, precipitation for the model run P100 is shortened during calibration in order to cope with the catchment leakage. Table 4-3 shows an average precipitation reduction of 82 mm per year for the model run P100 (1570 mm) within the period 1982-2003 compared to the closest rain gauge of Kurzeneialp (1652 mm). Such an adjustment is not plausible in an alpine environment, as precipitation is generally rather underestimated by measurements (e.g. Sevruk, 1997). In order to overcome this problem, it was decided to introduce a simple term enabling the simulation of water loss due to leakage. Hence, a fixed percentage of the water percolating to the groundwater storage is removed from the system. In the two P60 model runs, we assume that only 60 % of the actual percolation is reaching the runoff gauge as baseflow. The remaining 40% is taxed as loss by leakage.

For the two P60 runs, precipitation for the investigated period (1982-2003) is approximately 10 % higher than data from Kurzeneialp (Table 4-3), as a consequence of the calibrated rainfall and snowfall adjustments (Table 4-2). This raise is found to be in a reasonable range if uncertainty in precipitation measurement and interpolation is considered (e.g. Sevruk, 1986).

With 691 mm, calculated annual evapotranspiration for 1982-2003 from the simulation calibrated against daily discharge data (P60d) lies above the value determined with P100. In contrast, the P60h model run (calibrated against hourly discharge data) generates about the same evapotranspiration as P100. A value of 650 to 660 mm per year seems an appropriate estimate. However, compared to estimations by Penman (550 mm; Penman, 1959) or by the Swiss Hydrological Atlas (600 mm; Menzel et al., 1997), suggested evapotranspiration seems rather high. Nevertheless, values calculated by PREVAH are situated clearly below computations based on the residual term method (Table 4-3) and are of reasonable magnitude when compared to calculations in other small Swiss catchments. E.g. the hilly prealpine Rietholzbach catchment (ca. 25 % forest cover), where PREVAH assessed an annual evapotranspiration of 583 mm for the 1981-1998 period. On the Rietholzbach Lysimeter (grass cover) a value of 529 mm per year was observed for the same period.

For the P60 simulations, the storage change DS (Table 4-3) obtains a new sense. Beside the proper display of e.g. soil and snow storage changes it also represents the amount of water loss as a result of leakage from the Sperbelgraben catchment. This fraction of water not measured at the catchment outlet and already anticipated by Penman (1959) amounts to nearly 200 mm per year.

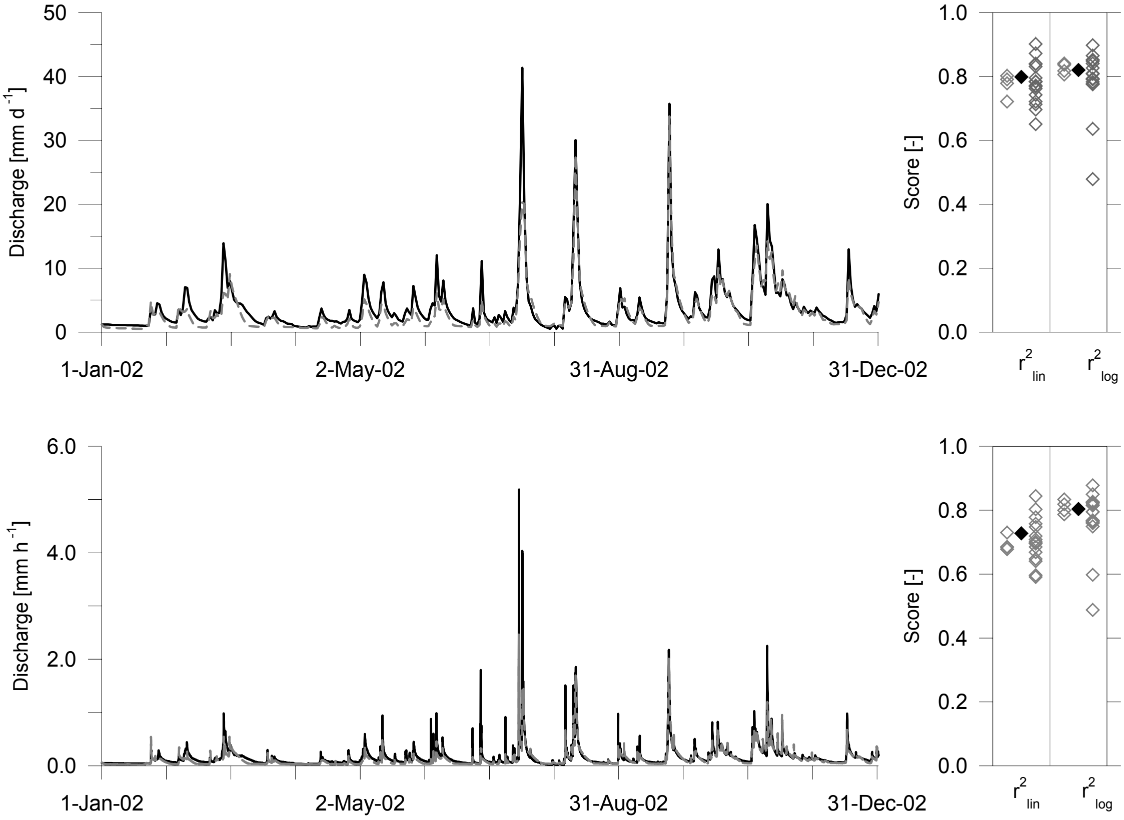

Figure 4-4: Daily (above) and hourly (below) runoff hydrograph of the Sperbelgraben catchment for the year 2002. Furthermore, the variability of the simulation performances (left r^2_{lin} and right r^2_{log}) is given for the calibration (column 1), the full investigated period (column 2) and the verification period (column 3).

For the full investigation period, both P60 simulations slightly underestimate annual runoff by ca. 10 to 15 mm (P60d: 926 mm; P60h: 933 mm) which indicates that the a further increase of catchment leakage should not be envisaged. Figure 4-4 displays the daily and hourly discharge hydrograph of the Sperbelgraben catchment for the year 2002 and the corresponding variability in both linear and logarithmic efficiency (calibration, verification as well as for the full year period). Generally speaking, the efficiency criteria achieved for discharge simulations are satisfying and reflect the fact that PREVAH with enhanced runoff generation (Appendix) is able to tackle the high spatial and temporal variability in hydrological behaviour for small catchments of less than 1 km^2 size. The linear criterion r^2_{lin} is better when the simulation is calibrated against daily discharge data (P60d). This implies that the model discloses some limitations in the simulation of high flows. In contrast, the low flow runoff behaviour of the Sperbelgraben is well reproduced as shown by the efficiency criteria r^2_{log} of 0.80 for both P60 model runs. Compared to the P100 experiment, better correspondence between model and observation regarding low flow conditions are obtained when water losses in the Sperbelgraben are considered. (r^2_{log} values in Table 4-3). The low variability of the efficiency in the calibration period demonstrates the suitability of the adopted calibration procedure (Figure 4-4). The provided set of tuneable parameters (Table 4-2) yields stable results, as confirmed by the efficiencies obtained in the validation period (apart from isolated outliers).

Modelling of the two separate Sperbelgraben sub-catchments

In the sub-catchments, we are facing larger water losses compared to the above suggested 200 mm for the entire Sperbelgraben. For the year 2002, observed precipitation (1780 mm) and runoff (SC1: 530 mm; SC2: 730 mm) as well as modelled evapotranspiration (SC1: 540 mm; SC2: 500 mm) are considered and an estimate for water loss through seepage is calculated. It amounts to 710 mm for SC1 and 550 mm for SC2. Consequently, it is to assume that the extent of water loss within the entire Sperbelgraben varies depending on the location. The different parts or sub-catchments show a different degree of leakage. Hence, for the modelling of the sub-catchments, the fixed percentage of water that is removed from the system instead of percolating to the groundwater storage (and thus the simulated water loss due to leakage) was increased. Compared to a value of 60 % for the entire Sperbelgraben simulation, only 20 % of the actual percolation is reaching the baseflow storage and eventually the runoff gauge in form of groundwater flow.

The set of calibrated model parameters for the Sperbelgraben (Table 4-2) was used for the simulation of the sub-catchments. The storage coefficients of the runoff components generated in the soil unsaturated zone (*K0, K1*), the threshold parameter for surface runoff (*SGR*) and the parameter controlling deep infiltration into the saturated zone (*PERC*) had to be re-calibrated to give consideration to the smaller size of the sub-catchments and their different degree of leakage among each other (Table 4-4). The main differences between the resulting runoff module parameters of SC1 and SC2 regard the storage coefficient for interflow (*K1*) as well as the percolation.

Table 4-4: Newly calibrated model parameters (runoff module) for the simulations of the lightly (SC1) and heavily (SC2) damaged Sperbelgraben sub-catchment. Abbreviations refer to Figures 4-2 and A1.

Parameter	**Abbr.**	**Unit**	**SC1**	**SC2**
Storage coeff. for surface runoff	K0	[h]	28.7	28.7
Storage coeff. for interflow	K1	[h]	143.4	85.4
Threshold parameter for surface runoff	SGR	[mm]	28.7	28.7
Deep percolation	PERC	[mm h^{-1}]	0.470	0.356

Since SC2 generally shows a slower runoff recession for any event type (Badoux et al. 2005b), higher storage coefficients for surface runoff and interflow would be expected there. Yet, the surface runoff storage coefficients are equal for both catchments and calibration generated a much higher storage coefficient for interflow for SC1 (Table 4-4). With a high *K1* value, the model is producing less subsurface flow per time step and accordingly has more water in the storage of the upper unsaturated zone *SUZ* (Figure A1). By this means, more water percolates within SC1. Accounting that the bulk part of this percolating water is designated to leave the system (shown above), less total runoff is generated in SC1. We suppose that this behaviour is owed to the fact that the sub-catchments are not only leaking baseflow but also a fraction of runoff generation from the unsaturated zone is not gauged at the outlets. The actual pathways of the water at the threshold between the saturated and the unsaturated zone are not fully understood yet and could not be determined in the framework of the project “Lothar and Mountain Torrents”. The model tries to deal with these processes by increasing the percolation parameter for SC1 compared to SC2 (Table 4-4) and thus in-directly accounts for losses from the unsaturated zone. This agrees with the previous consid-erations on the annual water loss for the year 2002.

Since this analysis focuses on rain fed flood events, only observed hourly data from 1 May through 30 November have been considered for model calibration and verification at sub-catchment scale. Table 4-5 displays the linear and logarithmic efficiency criteria of the model calibration (2001-2002) and verification (2003) period. Efficiency criteria obtained for discharge simulation is surprisingly good during the calibration period. This applies particularly for SC2 with linear and logarithmic efficiencies above 0.8. However, the criteria achieved for model verification are much lower, reflecting difficulties for the model in describing such small scale hydrological systems. Then, 2003 was a special year controlled by the impacts of a seldom summer heatwave over Europe (Schär et al., 2004). Further limitations may be charged to the short duration of calibration due to limited data availability.

Table 4-5: Average efficiency criteria r^2_{lin} and r^2_{log} for model calibration, verification and selected events in the lightly (SC1) and the heavily (SC2) damaged Sperbelgraben sub-catchment (events A1 to A3 were triggered by long-duration, low-intensity rainfall, B1 to B3 by short-duration, high-intensity rainfall).

Method	Period/ Begin	Duration	SC1 r^2_{lin}	SC1 r^2_{log}	SC2 r^2_{lin}	SC2 r^2_{log}
Calibration	2001-2002	Summer*	0.732	0.756	0.840	0.821
Verification	2003	Summer*	0.303	0.605	0.470	0.595
Event A1 (calibration)	13 Jul 2001	9 d	0.928	-	0.903	-
Event A2 (calibration)	02 Nov 2002	5 d	0.313	-	0.801	-
Event A3 (verification)	19 May 2003	4 d	0.148	-	0.449	-
Event B1 (calibration)	27 Jun 2002	48 h	0.723	-	0.658	-
Event B2 (calibration)	06 Aug 2002	24 h	0.522	-	0.738	-
Event B3 (verification)	08 May 2003	48 h	0.689	-	0.770	-

* 1 May through 30 November

Special interest was given to 20 flood events (or group of successive events) of two types (long-duration, low-intensity rainfall events and short-duration, high-intensity rainfall events). They allow testing if the model is able to reproduce a flood hydrograph at the micro-scale. The obtained linear efficiency criteria r^2_{lin} for all events and both sub-catchments are illustrated in Figure 4-5. Results from single events confirm calibration and verification results in the sense that events in SC2 are better simulated than in SC1. This applies in terms of lower variability and higher absolute values of efficiencies.

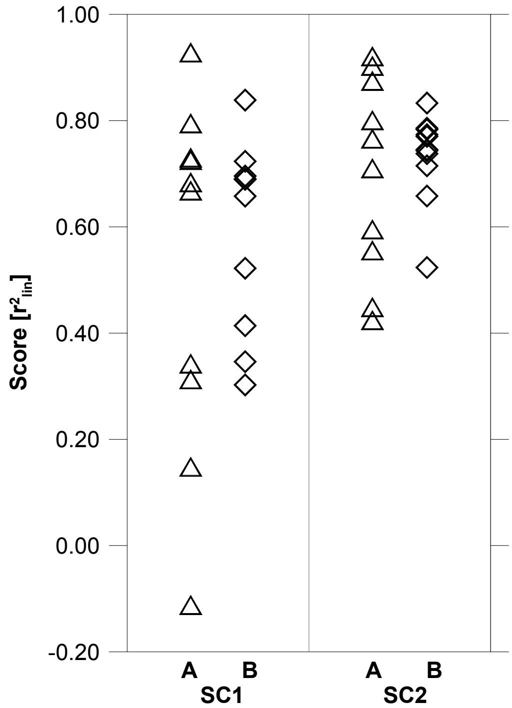

Figure 4-5: Variability of the efficiency score (r^2_{lin}) between observation and simulation for selected events in SC1 and SC2 (including A1–A3 and B1-B3) in the period from 2001 to 2003. Triangles represent long-duration, low-intensity rainfall events, diamonds show short-duration, high-intensity rainfall events.

Statistically, the short and intensive rainfall events are better modelled than long-duration, low-intensity events, no matter which catchment is considered. This finding should not be overrated though; as the used score (Nash and Sutcliffe, 1970) punishes in a minor way poor simulations when the average of the observations is a bad estimate for the event, as in the case of floods generated after intensive rainfall. The mean value is a better estimate of an event pattern when events are triggered by long lasting precipitation events. In such cases a simulation has to be much closer to the observed value in order to yield efficiency scores as high as in the case of flash flood events. A thorough discussion on the significance of 'goodness-of-fit' measures for model evaluation is presented by Legates and McCabe (1999). And as a matter of fact, our subjective visual evaluation prefers the simulations of persistent low-intensity events over the ones of short and intensive events. Six events from Figure 4-5 were selected and are diagrammed in Figures 4-6 and 4-7. The respective linear efficiency criteria of these events A1 to A3 and B1 to B3 are given in Table 4-5.

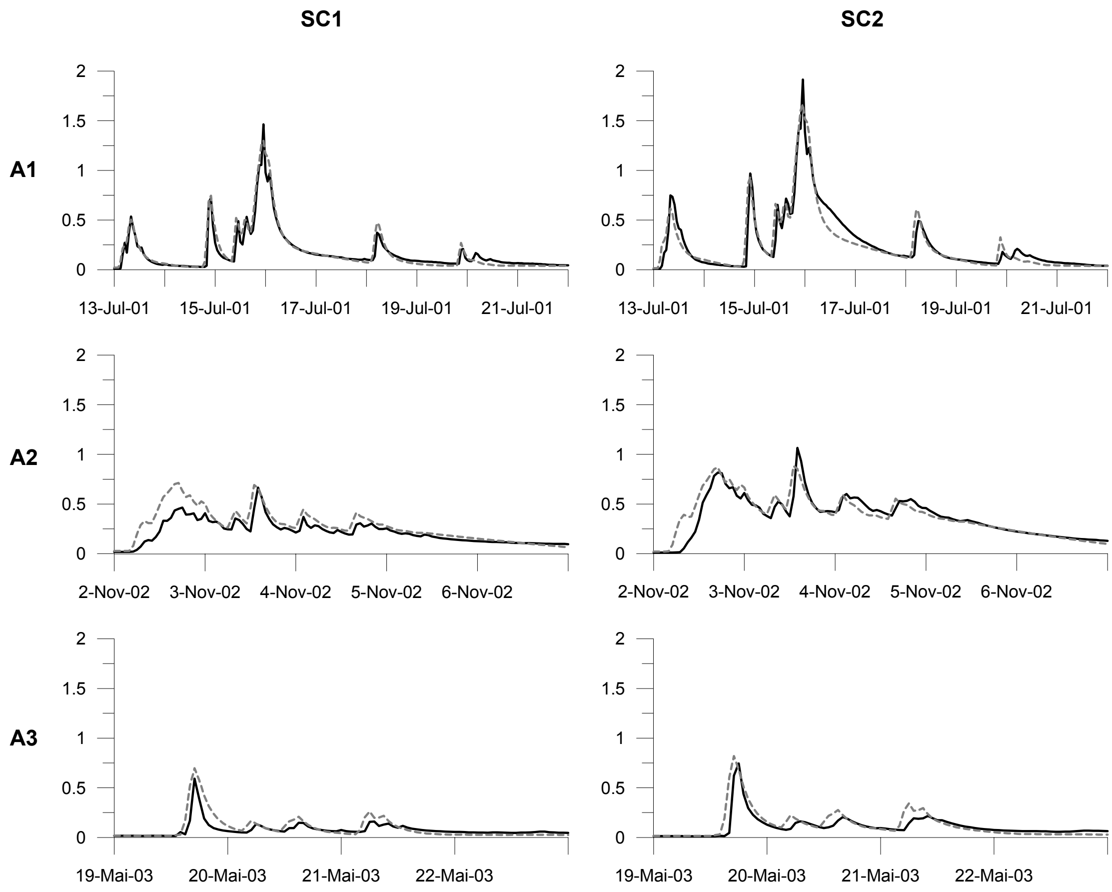

Figure 4-6: Modelled (dashed line) and observed (full line) runoff hydrographs for selected short-duration, high-intensity rainfall events, Sperbelgraben sub-catchments (compare Table 4-5).

The modelling of the sequential events starting on 13 July 2002 (A1) is an example of a well simulated hydrograph. In larger catchments such results would not surprise due to the experience gained with PREVAH in the past decade. Obtained in such small micro-catchments though, they reflect the large applicability of this distributed model. In general, however, discharge is rather overestimated during long-duration, low-intensity events (A1 to A3), especially for peaks and at the beginning of an event. In contrast, runoff recession is well reproduced in the majority of cases.

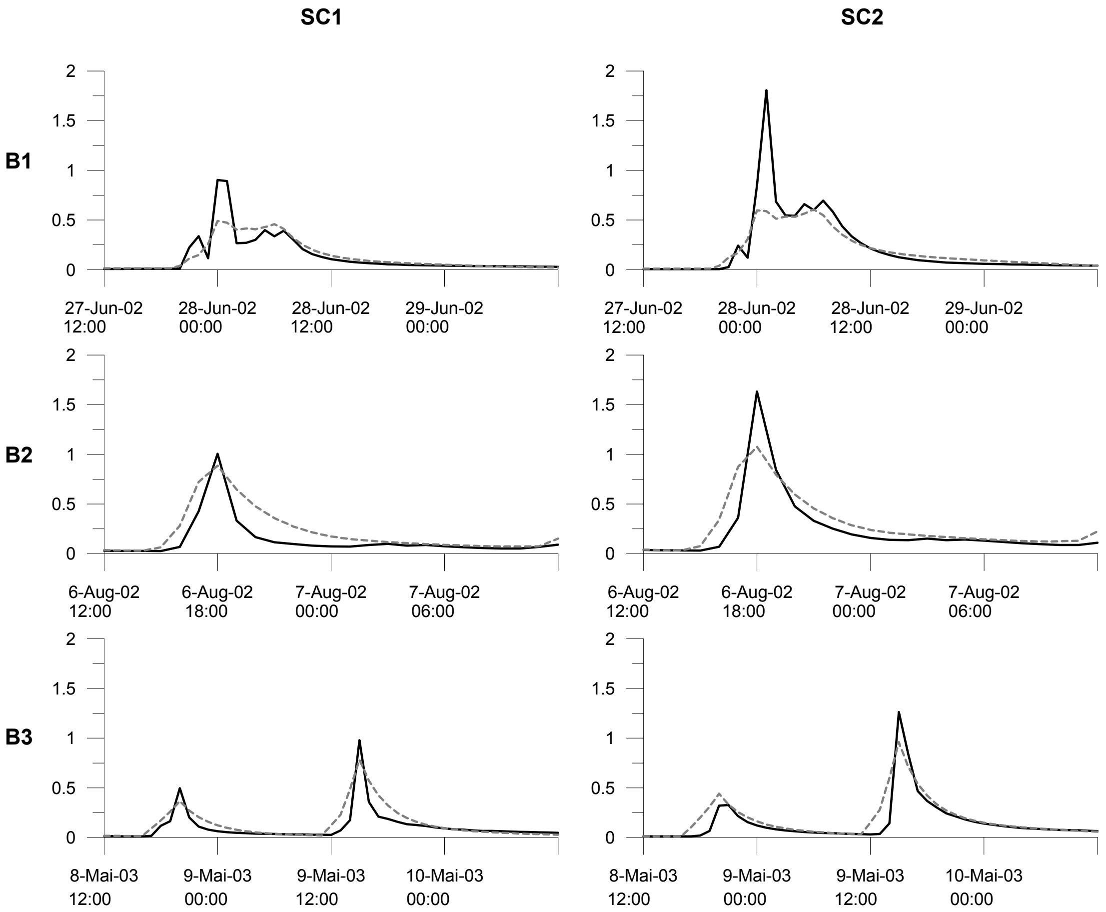

Figure 4-7: Modelled (dashed line) and observed (full line) runoff hydrograph for selected long-duration, low-intensity rainfall events, Sperbelgraben sub-catchments (compare Table 4-5).

For typical short-duration, high-intensity events (B1 to B3), modelled hydrographs are rather poor compared to observed data (Figure 4-7), even though event efficiencies are acceptable (Table 4-5). Discharge peaks are generally underestimated for those short storm events. The model often (over-)compensates for this missing water by calculating early hydrograph rises and too slow recessions which suggests too high storage coefficients for the fast runoff components. The poor agreement during runoff recession especially applies to SC1 that is characterised by narrow discharge peaks (Badoux et al., 2005b). Apparently, the model can not fully allow for the dominant influence of the channel density and other factors of the small scale geomorphology on runoff behaviour. In future applications, the possibility should be considered to adopt precipitation input data on a smaller time resolution (e.g. 10 minutes) and by this means account for quick runoff responses that can not be soundly parameterised at an hourly time step.

Comparison of simulated runoff generation with field data on surface runoff

In order to verify PREVAH simulations regarding runoff generation with other data than observed runoff at the sub-catchment outlet, surface runoff measurements from plots operated in the investigation area (e.g. Badoux et al., 2004) were additionally considered. This additional “soft data”, defined as proposed by Seibert and McDonnell (2002), will help to better utilise the information content gained from the experimental sub-catchments.

Five plots were selected (among them P1 in Figure 4-1) that represent different behaviour concerning surface runoff generation. Their location is given in Figure 4-8. Plots P2 and P13 lie on gently sloped Gleysols and produced large amounts of saturation excess surface runoff. In contrast, P6 and P18 situated on steep Cambisols on two different slopes produced nearly no surface runoff at all. Last, P1 on an endostagnic Cambisol with podzolic properties regularly generated small amounts of Hortonian overland flow due to hydrophobic reactions of its thick litter layer (Badoux et al., 2005a).

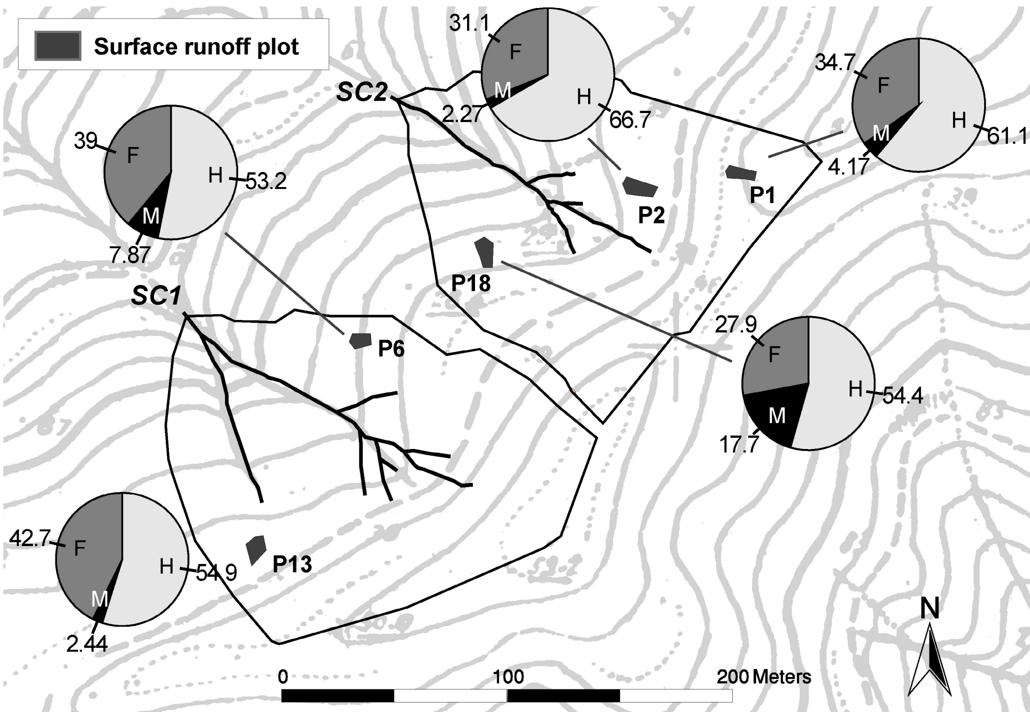

Figure 4-8: Comparison between modelled (PREVAH) and measured (plots P1, P2, P6, P13 and P18) surface runoff occurrence in the sub-catchments SC1 and SC2. Abbreviations in the pie charts denote Hits, Misses and False alarms (Jasper and Kaufmann, 2003).

For each plot, three HRUs characteristic for the site were chosen. The comparison of modelled HRU surface runoff and the measured plot runoff is carried out qualitatively for each registered event in the measuring periods of 2002 and 2003. This means that the occurrence of surface runoff for a given rainfall event and site is considered and not its quantity. This comparison is supposed to show us if the model realistically describes the processes within the sub-catchments.

The results of the evaluation are illustrated in Figure 4-8 in form of pie charts. According to von Storch and Zwiers (2001) hits (H), misses (M) and false alarms (F) were calculated for each plot as follows: (i) If both simulation and measurement feature surface runoff for a certain event, a hit is counted; (ii) if only the simulation indicates surface runoff, a false alarm is recorded; (iii) an exclusive runoff response from field measurements represents a miss. The pie chart values displayed in Figure 4-8 correspond to the percentages of hits, false alarms and misses for one investigated site compared to total cases (H+F+M). For each plot, an integral value of the three considered HRUs was used. The percentage of hits coincides with the critical success index CSI as defined by Schäfer (1990) and used e.g. in Jasper and Kaufmann (2003):

$$CSI = \frac{H}{H + F + M}$$

CSI is the number of correct event forecasts (or simulations) divided by the number of cases forecasted and/or observed. CSI is a skill measure that is not dominated by non-events. A perfect score of 1 indicates that all events were correctly simulated, and all simulations correspond to measured events (Zappa, 2005).

PREVAH simulates surface runoff too often compared to field observations. This fact is pointed out by the percentage of false alarms that lies between 28 and 43 % for all five sites (Figure 4-8). In contrast, the model rarely produces surface runoff when in reality nothing occurs. And thus, the percentage of registered misses remains small for most of the plots (except for the 18 % of P18). Best results are achieved for plots P2 and P1 with a CSI of 0.67 and 0.61 respectively, the other three plots score around a CSI of 0.54 which is quite weak (slightly over the half of events show a match of simulations and observations).

There is no pattern discernible in the result, except maybe for the fact that plots that regularly produce considerable amounts of saturation overland flow (P2 and P13) yield very few misses. However, surface runoff on all plots remains quite difficult to predict using the process description currently implemented in the adopted model. The main cause of this is the high linearity in the simulation of surface runoff generation. The model reacts non-linearly only if the soils are strongly unsaturated.

4.6. Discussion and conclusions

The hydrological simulations presented here were carried out with the conceptually structured model PREVAH that is generally applied to mesoscale catchments of 10 to 1000 km^2 size (Gurtz et al., 1999). Here in contrast, it was used for investigations on much smaller catchments at two different scales. The model PREVAH was chosen for this investigation because of two main reasons. First, the detailed climatic and soil data required to yield good results with a hillslope model (Bronstert, 1999) were not available for all investigation areas. Then, it was a declared objective of the study to apply the same model at both scales, including the entire Sperbelgraben, a catchment not suited for the use of a detailed hillslope model due to its size of 0.54 km^2.

PREVAH managed to well reproduce discharge hydrographs of the Sperbelgraben, yielding linear efficiency criteria between 0.7 and 0.8 (Table 4-3). The newly integrated enhanced runoff generation module makes it possible to cope with the high spatial and temporal variability of the dominating processes in the torrential catchment. Modelling the sub-catchments (1.8 and 2.0 ha) at high resolution implied more problems. Although good scores were achieved for model calibration during the 2001 and 2002 summers (May through November) including the satisfying simulation of several flood events, the model revealed limitations when operated in such small areas or when dealing with special situations such as the 2003 summer heatwave. Nevertheless, questions on the loss of water and on its origin at both scales could be answered. The high evapotranspiration estimates (ca. 860 mm) for the Sperbelgraben presented by Burger (1954) and Casparis (1959) were clearly contradicted. We propose a value of 650 mm for the 1981 to 2003 period and thus conclude that the amount of water lost due to leakage adds up to approximately 200 mm a year. Penman's assumption on the Sperbelgraben water balance (Penman, 1959) could thus be confirmed and catchment leakage quantified.

For the 0.54 km^2 catchment, water loss is primarily caused by vertical leakage from the saturated zone. All gauging stations are placed directly on the solid rock of the channel bed to avoid water losses. However, the weathered conglomerate bedrock apparently offers possibilities for the water to deeply drain past the stations. Proportionally, leaking is larger in the sub-catchments compared to the Sperbelgraben. It is expected that drained water emerges further downstream along intermediate marl layers and is gauged at larger scale catchments (i.e. Kurzeneibach, Emme). Furthermore, a contribution to the losses through lateral flow along the soil-bedrock interface can not be excluded. Authors suggest that bedrock topography can control the spatial variation of lateral subsurface flow (e.g. Freer et al., 2002; Peters et al., 1995) in small catchments. However, the very steep topography with strongly incised channels of SC1 and SC2 probably limits the extent of water that bypasses the gauging station at the soil-bedrock interface.

Annual sums of runoff and precipitation as well as simulation results reveal a more pronounced leakage, either lateral or vertical, from SC1 compared to SC2. This hypothesis is backed by the interpretation of the calibrated model parameters and geomorphological characteristics. First, PREVAH yields a higher storage coefficient for interflow and a higher percolation for SC1, both leading to a larger loss from this sub-catchment. In addition, the lower fraction of wet soils in SC1 (Table 4-1) also points at more important water losses. On the well drained Cambisols, water more easily reaches the conglomerate bedrock and then might vertically seep. Hence, the most probable unequal degree of leakage makes any assumption about the concurring influence of storm caused deforestation on peak flows impossible. This applies primarily for long-duration, low-intensity events. At this stage, it should be kept in mind that the identification of runoff components in the sub-catchments is not fully understood. Due to the small scale, water losses can not be distinctly attributed to whether a classic baseflow or a faster subsurface flow component. Model based separation of runoff components might be strongly related to the model structure (Gurtz et al., 2003a).

Processes controlling runoff generation at the hillslope scale (e.g. Wilson et al., 1990; Gutknecht, 1996) such as overland flow, infiltration, macropore flow, return flow, percolation, capillary rise (e.g. Beven and Germann, 1982; Weiler and Naef, 2003) are obviously better described in dedicated models like HILLFLOW (Bronstert and Plate, 1997; Bronstert, 1999) or perceptual models designed for specific micro catchments (e.g. Seibert and McDonnell, 2002) than in the model applied here. PREVAH and similar models were originally developed to cope with the hydrological cycle at meso-scale, where sub-catchments like SC1 and SC2 represent at most one out of thousands of grid cells. Though, it was a challenge to explore with PREVAH a new research field. Through the multi-scale modelling experiment we had to concede that the smaller an investigated catchment is, the more perceptual knowledge is required. In the present case, catchment leakage had to be considered and a quick runoff component had to be created in order to tackle local runoff generation characteristics. This allowed for satisfactory simulation of the majority of the observed hydrographs, both in case of short and intensive as well as long-lasting rainfall events.

PREVAH being a distributed model, only internal verification can confirm its real skill (Grayson et al., 2002). Thus, the model representation of surface runoff generation was evaluated using field measurements as "soft data" (Seibert and McDonnell, 2002). It revealed that the non-linearity of the runoff generation processes is not properly described by the model. The attained correspondence demonstrates that further steps are required to bring sound process knowledge into models.

4.7 Acknowledgements

We would like to thank E. Frick, L. Indermaur, M. Jeisy and K. Steiner for their generous contribution in the field as well as for their support regarding the handling of hydrological data. Furthermore we are very indebted to B. Fritschi for the management of the measurement equipment in the Sperbelgraben. The project "Lothar and Mountain Torrent" of the Swiss Federal Research Institute WSL and the Institute of Geography of the University of Berne GIUB was financially supported by the Swiss Agency for the Environment, Forests and Landscape SAEFL.

4.8 Appendix

Implementation of overland flow generation in small catchments

Some of the conceptual equations governing the water flows within the unsaturated zone of PREVAH are shortly summarized. The schematic representation of the flows is displayed by Figure A1. Such flows are computed for each HRU^i at each time step. Key variables and parameters of the soil and runoff-generation modules are declared in Table 4-2. The inflow PP_b^i into the storages of the runoff-generation module is regulated by SFC^i:

$$PP_b^i(t) = P_b^i(t) \cdot \left(\frac{SSM^i(t-1)}{SFC^i} \right)^{BETA} \tag{A.1}$$

BETA is a dimensionless non-linearity parameter that controls the redistribution of the presently available water supply P_b^i [mm·dt^{-1}] between the plant available soil moisture storage reservoir (SSM^i), the overland storage reservoir (OSR^i) and the upper storage reservoir of the unsaturated zone of the soil (SUZ^i). SUZ^i and OSR^i are the part of the soil moisture content that exceeds the field capacity and contributes to the runoff-generation (Figure A1). The soil moisture recharge (SMR^i) is the difference between P_b^i and PP_b^i. SMR^i increases with increasing *BETA*.

$$SMR^i(t) = P_b^i(t) - PP_b^i(t) \tag{A.2}$$

A new conceptual dynamic term enables the production of overland surface runoff component before available water reaches the upper runoff storage SUZ^i. Such overland flow allows a rapid drainage of small catchments and was so far not accounted by PREVAH. This component is generated in an additional runoff storage (OSR^i, Figure A1) whose water supply is controlled by the factor fsr^i [-]:

$$fsr^i = \left(1 + \log\left(\frac{P_b^i}{\sqrt{A_e}} \right) \right) \cdot \frac{a_{TI}^i}{10} \cdot \left(\frac{SSM^i}{SFC^i} \right) \tag{A.3}$$

with P_b^i [mm h^{-1}] as present available water supply for a HRU, A_e [km^2] as size of the investigated catchment, SSM^i [mm] as present field capacity for the HRU and SFC^i [mm] as its maximal field capacity. The factor a^i_{TI} corresponds to the following equation:

$$a_{TI}^i = \frac{TI^i - TI_{MIN}}{TI_{MAX} - TI_{MIN}} \tag{A.4}$$

with TI^i [-] as topographic index (Beven and Kirkby, 1979) for the i-th HRU, TI_{MIN} [-] as minimal topographic index of the investigated catchment and TI_{MAX} [-] as maximal topographic index.

Hence, the regulator fsr^i (and thus the inflow to the overland flow storage) is large in the following cases: (1) after very yielding rainfall events that boost the available water supply (most notably when soil moisture is high); (2) above all for small catchments and (3) for HRUs that have a high topographic index. According to this, the new, very fast surface runoff component shows the largest effect on steep downslope areas of micro-scale catchments after intensive rain storms. This factor fsr^i applies for catchments between 1 ha and 50 km^2, whereby its influence for catchments larger than 10 km^2 is rather limited.

$$DOSR^i(t) = PP_b^i(t) \cdot fsr^i \qquad \text{(A.5)}$$

$$DSUZ^i(t) = PP_b^i(t) \cdot \left(1 - fsr^i\right) \qquad \text{(A.6)}$$

fsr^i regulates the separation of the water volumes available for runoff generation PP_b^i. The storage reservoirs SUZ^i and OSR^i are incremented by $DSUZ^i$ and $DOSR^i$ respectively. SUZ^i is then emptied by deep percolation *PERC,* by surface runoff, and by interflow. The generation of surface runoff and interflow is governed by the storage coefficients K_0 and K_1. OSR^i is emptied by very fast overland flow, governed by the storage coefficient K_0^* which is parameterized as the tenth part of K_0. If K_0 is equal to 30 hours then K_0^* is equal to 3 hours.

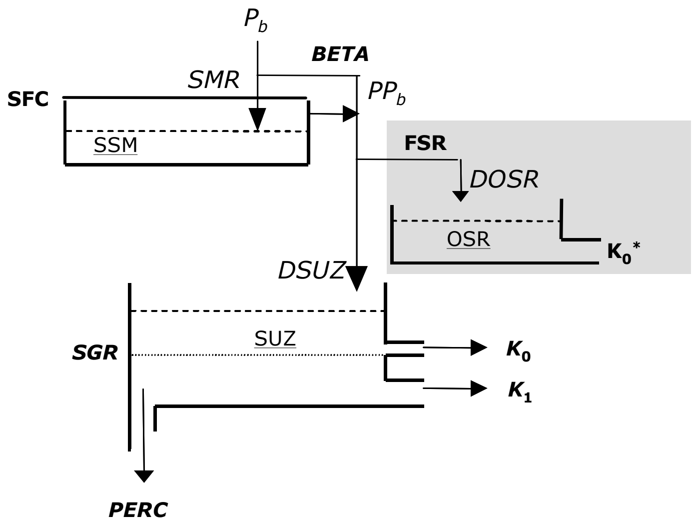

Figure A1: Schematic representation of the water flows in the enhanced runoff module of PREVAH (abbreviations are given in the text and in Table 4-2).

The effects of the newly implemented conceptual dynamic term are displayed in Figure 4-3 and Table 4-3. During rainfall events, it permits a better reproduction of fast runoff responses in small catchments. This improvement is also reflected by the linear criterion r^2_{lin} (Table 4-3). The P60h model run obtained with the enhanced model version considerably outscores the original P60h simulation for both the model calibration and application period (both simulations verified against data at time resolution of one hour).

Chapter V

Synthesis

The goal of this thesis was to evaluate the hydrologic consequences of the wind storm Lothar on the affected areas. We carried out investigations on different scales from the point (single irrigated soil profile) to the entire torrential catchment (0.54 km^2 large Sperbelgraben catchment). The following conclusions can be drawn.

Two types of surface runoff generation were identified in the Sperbelgraben investigation area by means of artificial irrigation experiments (1 m^2 area above soil profiles) conducted on three successive days each (Sieber, 2002; Helbling, 2002). On the moist to dry forest site types (typically Gleysols), soil saturation was reached rapidly due to the high intensity of the rainfall applied (60 mm h^{-1}) and abundant saturation overland flow occurred subsequently. Surface runoff coefficients of 0.50 and more were usually reached thereby. These soils showed extremely limited storage capacity already for the first experiment. Dry to moist areas (typically Cambisols) yielded a small amount of temporary Hortonian overland flow with coefficients below 0.20. These sites are characterised by high soil acidity, resulting in a thick organic litter layer (limited decomposition) with hydrophobic properties. However, when sprinkling experiments were repeated, runoff values decreased. On the less acid Cambisols, no surface runoff at all was observed. Instead, all artificial rainfall infiltrated and a large portion percolated deeper than 45 cm (range of TDR probes). The water storage in the soils was limited on all dry to moist areas, especially during the second and third irrigation experiments. As for shallow subsurface flow, it occurred exclusively on the Gleysols.

The surface runoff processes identified at the point scale were widely confirmed by the surface runoff measurements on experimental plots of 50-110 m^2. Surface runoff coefficients above 0.2 were only registered on the moist to wet forest site types. On the overall most yielding plot, runoff coefficients larger than 1.0 were determined, suggesting the occurrence of return flow and thus of considerable lateral water flows not only on the soil surface but also in the soil. Hortonian overland flow was identified on plots with dry to moist soil conditions. Some plots regularly showed hydrophobic behaviour, on others it was virtually never observed, according to the composition and thickness of the present litter layer. Generally, Hortonian overland flow was more pronounced at the point scale though. For both processes producing surface runoff, a considerably larger variability in the results was registered at the plot scale compared to the point scale. This can be attributed to the fact that the triggering events were natural precipitation events instead of artificial rainfall with a constant intensity and fixed duration. The volumes of the natural rainfall events (of various durations) ranged from less than 10 mm up to 110 mm. Furthermore, a large difference in climatic characteristics was observed between the two investigation periods at plot scale. While precipitation and temperature in the 2002 summer months were normal, the very hot and dry summer of 2003 represented a very rare meteorological situation.

Along two typical steep slopes with well drained Cambisols, the surface runoff generation from top towards the stream of each slope was compared. In neither of the two observed slopes any kind of pattern was detectable as virtually no surface runoff at all was observed on any plot due to the high infiltration capacity. Moreover, subsurface flow (measured in a depth of 70 cm at the bottom of the two mentioned slopes) did not occur at any time during the 2003 measuring period. Most probably, a large fraction of the water moved vertically beyond 70 cm and to the bedrock via preferential flow pathways in these well drained Cambisols. Hence, we conclude that sub-surface flow occurs only at the soil-rock interface which can be situated up to large depths (in part > 2 m). Water flow measurements right above the bedrock were not conducted in this study, mainly because such deep trenches could not be realised on steep slopes like the ones investigated. Thus, the characteristics of deep subsurface runoff and the mechanisms by which it reaches the channel remained unclear. However, it became evident that subsurface water contributes to storm flow in the sub-catchments (this applies mainly for long-duration events) in spite of the fairly deep soils.

At the sub-catchment scale (≈ 2 ha), the assessed flow characteristics did not conform to the expected pattern (generally higher discharge peaks from clearcut basins). We presumed that the heavily damaged sub-catchment (SC2) would yield higher discharge peaks and runoff volumes during flood events mainly due to a lower soil moisture deficit as a result of a reduced evapotranspiration from the affected forest coverage. However, for short and intensive shower events the lightly damaged sub-catchment (SC1) typically showed a more rapid and distinct runoff response often leading to higher peak discharge. In contrast, for long-duration, low intensity events peak values were higher in SC2 than in SC1. As for runoff volume, it was virtually always larger in SC2, regardless of event type.

Sub-catchment runoff behaviour could partly be explained by geomorphological factors. A substantially higher channel density as well as a better connection of the wet zones to the channel system caused a faster concentration of water and thus a quicker runoff reaction in SC1. With more continuous and less intense precipitation, peak discharge was usually not reached at the beginning of a flood event. This indicates that the spatial distribution of the moist to wet soils gains importance during such event types. In the sub-catchments, a peak is reached when virtually all areas with Gleysols yield large amounts of surface flow and shallow sub-surface flow. As SC2 has a higher fraction of Gleysols, larger storm flow volumes and higher peaks were registered there. The role of deep subsurface flow along the interface of dry to moist soils with bedrock during flood events could not be clarified. It was not possible to determine if this flow component contributed differently to flood flows in SC1 and SC2.

The smaller runoff volumes in SC1 during flood events could also originate from a larger water loss due to leakage. Seepage losses were identified by water balance calculations for SC1 and SC2. Although annual sums of runoff and precipitation indicated that they were higher in SC1, their respective magnitude was not determinable due to the short measurement period (2001-2003). We addressed this question by carrying out hydrological modelling experiments. For this purpose, the distributed hydrological model PREVAH was applied to both the entire Sperbelgraben catchment and the two sub-catchments. PREVAH managed to well reproduce the runoff characteristics of the Sperbelgraben. The integration of a new conceptual dynamic term in the runoff routine helped to deal with the high spatial and temporal variability of runoff generating processes typical for small torrential catchments. Even though the model showed limitations to cope with rare situations such as the summer 2003 heatwave, most of the flood events at sub-catchment scale were satisfyingly simulated. But most importantly, answers regarding the question on the loss of water through leakage could be provided. While losses amount to roughly 200 mm per year in the Sperbelgraben, they are considerably higher in the sub-catchments. Furthermore, the interpretation of the calibrated model parameters affirms the assumption of larger seepage losses in SC1 compared to SC2 stated above.

Hence, it is not only the larger fraction of wet Gleysols producing saturation overland flow and shallow sub-surface flow that caused more yielding runoff responses in SC2 during flood events. It is also the smaller fraction of dry to moist soils in this sub-catchment that leads to less abundant seepage losses. On the well drained Cambisols, a certain portion of water that reaches the weathered conglomerate bedrock deeply drains through vertical fissures and cracks, is stopped only by intermediate marl layers and emerges further downstream without being measured at the gauging station.

This unequal degree of water losses due to leaking in the sub-catchments limits our estimations of the impact of deforestation on flood runoff. Nonetheless, it became obvious that the influence of wind storm damage is restricted in the Sperbelgraben investigation area. In conclusion, the following statements can be made:

- Forests like the one of the Sperbelgraben have a much better capability to cope with natural disturbances such as the wind storm Lothar than it was supposed. The impact of deforestation on the dominant runoff processes remained surprisingly small. The forest soil was affected locally as a result of toppled trees and consequently the soil structure was damaged on several small and delimited areas. On a larger scale though, the hydrologic function of the soil remained widely maintained.
- Considering an experimental plot or a hillslope, the influence of the wind storm on runoff generation was very limited. Furthermore, soil disturbance and compaction of the topsoil due to clearing operations with afforestation machinery remained moderate and occurred only on small areas within the investigation area. For example, scars from hauled logs did sporadically canalise surface flow along steep slopes, but this water rapidly infiltrated below the scar.
- The successive ground vegetation quickly arisen after the storm on damaged areas was to a large extent capable of compensating the interception provided by forest cover before the event. Moreover, it helped preventing surface sealing.

Open questions remain regarding the exact role of the subsurface flow component along the soil-bedrock interface. It's contribution to stormflow at sub-catchment scale could not be fully clarified. Field measurements (trenches down to the bedrock) are complicated to carry out due to the very steep slopes in the Sperbelgraben. Modelling experiments could not resolve this question either as the identification of the runoff components in the sub-catchments is not fully understood. For example, water losses as a result of leakage could not be distinctly attributed to a classic baseflow or a more rapid subsurface flow component because the model based separation of runoff components is strongly related to the structure of the model used. Finally, the comparison of measured and simulated surface runoff showed the difficulty to simulate non-linear runoff processes and confirmed that further integration of process knowledge into hydrological models is needed.

References

Adams, M.B., Kochenderfer, J.N., Wood, F., Angradi, T.R. and Edwards, P., 1993. Forty years of hydrometeorological Data from the Fernow Experimental Forest, West Virginia, US Forest Service General Technical Paper NE-184.

Anderson, M.G. and Burt, T.P. (Editors), 1990. Process Studies in Hillslope Hydrology. Wiley, Chichester, 539 pp.

Badoux, A., Hegg, C., Kienholz, H. and Weingartner, R., 2002a. Investigations on the influence of storm caused damage on the runoff formation and erosion in small torrent catchments. In: Proceedings of the Int. Conference on Flood Estimation, Bern, CHR Report II-17: 39-47.

Badoux, A., Hegg, C., Kienholz, H. and Weingartner, R., 2002b. Investigations on the influence of storm caused damage on the runoff formation and erosion in small torrent catchments. In: Congress Publication of the Interpraevent 2002 in the Pacific Rim, Matsumoto, Vol. 2: 961-971.

Badoux, A., Ilg, H., Hegg, C., Witzig, J., Kienholz, H. and Weingartner, R., 2004. To what extent does storm induced deforestation influence runoff formation? Results from a comparative study in two small torrent catchments. In: Congress Publication of the Interpraevent 2004, Riva del Garda, Vol. 1(II): 1-12.

Badoux, A., Witzig, J., Germann, P.F., Kienholz, H., Lüscher, P., Weingartner, R. and Hegg, C., 2005a. Investigations on the runoff generation at the profile and plot scale, Swiss Emmental. Hydrological Processes, (accepted).

Badoux, A., Jeisy, M., Kienholz, H., Lüscher, P., Weingartner, R., Witzig, J. and Hegg, C., 2005b. Influence of storm damage on the runoff generation in two sub-catchments of the Sperbelgraben, Swiss Emmental. European Journal of Forest Research, (submitted).

Balász, Á. and Brechtel, H.M., 1974. Wieviel Wasser kommt aus dem Wald? Allgemeine Forstzeitschrift (München), 29(49): 1083-1090.

Bates, C.G. and Henry, A.J., 1928. Second phase of streamflow experiment at Wagon Wheel Gap, Colorado. Monthly Weather Review, 56(3): 79-85.

Bergström, S., 1976. Development and application of a conceptual runoff model for Scandinavian catchments. Bulletin Series A, No. 52. University of Lund.

Beschta, R.L., Pyles, M.R., Skaugset, A.E. and Surfleet, C.G., 2000. Peakflow responses to forest practices in the western cascades of Oregon, USA. Journal of Hydrology, 233: 102-120.

Beven, K.J. and Kirkby, M.J., 1979. A physically based, variable contributing area model of basin hydrology. Hydrological Sciences Bulletin, 24(1): 43-70.

Beven, K.J. and Germann, P.F., 1982. Macropores and water flow in soils. Water Resources Research, 18(5): 1311-1325.

Beven, K.J., 2001. On fire and rain (or predicting the effects of change). Hydrological Processes, 15(7): 1397-1399.

Blöschl, G. and Sivapalan, M., 1995. Scale issues in hydrological modelling - a review. Hydrological Processes, 9: 251-290.

Bonell, M., 1998. Selected challenges in runoff generation research in forests from the hillslope to headwater drainage basin scale. Journal of the American Water Resources Association, 34(4): 765-785.

Bosch, J.M. and Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology, 55: 3-23.

Brechtel, H.M. and Krecmer, V., 1971. Die Bedeutung des Waldes als Hochwasserschutz. Österreichische Wasserwirtschaft, 23: 166-177.

Brechtel, H.M. and Fuehrer, H.-W., 1991. Water yield control in beech forest - a paired watershed study in the Krofdorf forest research area. International Association of Hydrological Sciences (IAHS) Publication, 204: 477-484.

Bronstert, A. and Plate, E.J., 1997. Modelling of runoff generation and soil moisture dynamics for hillslopes and micro-catchments. Journal of Hydrology, 198(1-4): 177-195.

Bronstert, A., 1999. Capabilities and limitations of detailed hillslope hydrological modelling. Hydrological Processes, 13(1): 21-48.

Bruijnzeel, L.A., 1990. Hydrology of moist tropical forests and effects of conversion: A state of knowledge review. Free University, Amsterdam, 224 pp.

Bründl, M., Schneebeli, M. and Flühler, H., 1999. Routing of canopy drip in the snowpack below a spruce crown. Hydrological Processes, 13(1): 49-58.

Burch, G.J., Moore, I.D. and Burns, J., 1989. Soil hydrophobic effects on infiltration and catchment runoff. Hydrological Processes, 3: 211–222.

Burch, H., Forster, F. and Schleppi, P., 1996. Zum Einfluss des Waldes auf die Hydrologie der Flysch Einzugsgebiete des Alptals. Schweizerische Zeitschrift für Forstwesen, 147(12): 925-937.

Burger, H., 1934. Einfluss des Waldes auf den Stand der Gewässer; 2. Mitteilung; Der Wasserhaushalt im Sperbel- und Rappengraben von 1915/16 bis 1926/27. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 18. Band, 2. Heft: 311-416.

Burger, H., 1943. Einfluss des Waldes auf den Stand der Gewässer; 3. Mitteilung; Der Wasserhaushalt im Sperbel- und Rappengraben von 1927/28 bis 1941/42. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 23. Band, 1. Heft: 167-222.

Burger, H., 1954. Einfluss des Waldes auf den Stand der Gewässer; 5. Mitteilung; Der Wasserhaushalt im Sperbel- und Rappengraben von 1942/43 bis 1951/52. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 31. Band, 1. Heft: 9-58.

Burger, T., Danner, E., Kaufmann, P., Lüscher, P. and Stocker, R., 1996. Standortkundlicher Kartierschlüssel für die Wälder der Kantone Bern und Freiburg. Kommentar und Anwenderschlüssel, ARGE Kaufmann+Partner / Burger+Stocker und Forstliche Bodenkunde WSL, Solothurn, Lenzburg, Birmensdorf, Schweiz.

Calder, I.R. and Newson, M.D., 1979. Land use and upland water resources in Britain - a strategic look. Water Resources Bulletin, 16: 1628-1639.

Casparis, E., 1959. 30 Jahre Wassermessstationen im Emmental. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 35. Band, 1. Heft: 179-224.

Chang, M., 2003. Forest hydrology: An introduction to forest and water. CNC Press, Boca Raton, 373 pp.

Cheng, J.D., Black, T.A., deVries, J., Willington, R.P. and Goodell, B.C., 1975. The evaluation of initial changes in peak streamflow following logging of a watershed on the west coast of Canada. International Association of Hydrological Sciences (IAHS) Publication, 117: 475-486.

Cosandey, C., 1992. Influence de la forêt sur le cycle de l'eau. Hydrol. continent, 7(1): 13-22.

Cosandey, C. and Robinson, M., 2000. Hydrologie continentale. Armand Colin, Paris, 360 pp.

Cosandey, C., Lavabre, J., Martin, C. and Mathys, N., 2002. Conséquences de la forêt méditerranéenne sur les écoulements de crue. Synthèse des recherches menées en France. La Houille Blanche - Revue Internationale de l'Eau, 2002-3: 38-42.

Cosandey, C., Andréassian, V., Martin, C., Didon-Lescot, J.F., Lavabre, J., Folton, N., Mathys, N. and Richard, D., 2005. The hydrological impact of the mediterranean forest: a review of French research. Journal of Hydrology, 301(1-4): 235-249.

Crockford, S., Topalidis, S. and Richardson, D.P., 1991. Water repellency in a dry Sclerophyll Eucalypt forest - measurements and processes. Hydrological Processes, 5: 405–420.

Doerr, S.H., Ferreira, A.J.D., Walsh, R.P.D., Shakesby, R.A., Leighton-Boyce, G. and Coelho, C.O.A., 2003. Soil water repellency as a potential parameter in rainfall-runoff modelling: experimental evidence at point to catchment scales from Portugal. Hydrological Processes, 17: 363-377.

Douglass, J.E. and Hoover, M.D., 1988. History of Coweeta. In: W.T. Swank and D.A. Crossley Jr. (Editors), Forest Hydrology and Ecology at Coweeta, Ecological Studies 66, Springer, New York, pp. 17-31.

Dunne, T. and Black, R.D., 1970. Partial area contributions to storm runoff in a small New England watershed. Water Resources Research, 6(5): 1296-1311.

Edwards, K.A. and Blackie, J.R., 1981. Results of the East African catchment experiments 1958-1974. In: R. Lal and E.W. Russel (Editors), Tropical Agricultural Hydrology, Wiley, Chichester, pp. 163-188.

Engler, A., 1919. Einfluss des Waldes auf den Stand der Gewässer. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 12. Band: 1-626.

Faeh, A.O., 1997. Understanding the processes of discharge formation under extreme precipitation. A study based on the numerical simulation of hillslope experiments. Mitteilungen der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie der ETH Zürich, Nr. 150.

Faeh, A.O., Scherrer, S. and Naef, F., 1997. A combined field and numerical approach to investigate flow processes in natural macroporous soils under extreme precipitation. Hydrology and Earth System Sciences, 4: 787-800.

Fahey, B.D., 1994. The effect of plantation forestry on water yield in New Zealand. New Zealand Forestry, 39(3): 18-23.

Fahey, B.D. and Jackson, R., 1997. Hydrological impacts of converting native forests and grasslands to pine plantations, South Island, New Zealand. Agricultural and Forest Meteorology, 84: 69-82.

FAO-UNESCO, 1997. Soil map of the world. Unesco, Paris.

Federer, C.A., Flynn, L.D., Martin, C.W., Hornbeck, J.W. and Pierce, R.S., 1990. Thirty years of hydrometeorologic data at the Hubbard Brook Experimental Forest, New Hampshire, US Forest Service General Technical Paper NE-141.

Feyen, H., 1999. Identification of runoff processes in catchments with a small scale topography. PhD Thesis no. 12868, ETH Zurich, Switzerland, 147 pp. [available online at: http://e-collection.ethbib.ethz.ch/cgi-bin/show.pl?type=diss&nr=12868].

Flügel, W.A., 1997. Combining GIS with regional hydrological modelling using hydrologic response units (HRUs): An application from Germany. Mathematics and Computers in Simulation, 43: 297-304.

Flury, M., Flühler, H., Jury, W.A. and Leuenberger, J., 1994. Susceptibility of soils to preferential flow of water: A field study. Water Resources Research, 30(7): 1945-1954.

Fohrer, N., Haverkamp, S., Eckhardt, K. and Frede, H.-G., 2001. Hydrologic response to land use changes on the catchment scale. Physics and Chemistry of the Earth (B), 26(7-8): 577-582.

Freer, J., McDonnell, J.J., Beven, K.J., Peters, N.E., Burns, D.A., Hooper, R.P., Aulenbach, B. and Kendall, C., 2002. The role of bedrock topography on subsurface storm flow. Water Resources Research, 38(12): art. no.-1269.

Frei, M., Böll, A., Graf, F., Heinimann, H.R. and Springman, S.M., 2003. Quantification of the Influence of Vegetation on Soil Stability. In: C.F. Lee and L.G. Tham (Editors), Proceedings of the International Conference on Slope Engineering, Hong Kong, Vol. II: 872-877.

Germann, P.F., 1976. Wasserhaushalt und Elektrolytverlagerung in einem mit Wald und einem mit Wiese bestockten Boden in ebener Lage. Mitteilungen der eidgenössischen Anstalt für das forstliche Versuchswesen, 52. Band, 3. Heft: 163-309.

Germann, P.F., 1990. Macropores and hydrologic hillslope processes. In: M.G. Anderson and T.P. Burt (Editors), Process studies in hillslope hydrology, Wiley, Chichester, pp. 327-363.

Germann, P.F. and Bürgi, Th., 1996. Kinematischer Ansatz zur in-situ Erfassung des Makroporenflusses während Infiltrationen. Kulturtechnik und Landentwicklung, 37: 221-226.

Germann, P.F., 1999. Makroporen und präferenzielle Sickerung. In: H.P. Blume, P. Felix-Henningsen, W.R. Fischer, H.G. Frede, R. Horn and K. Stahr (Editors), Handbuch der Bodenkunde, Ecomed, Landsberg, pp. 1-14.

Germann, P.F. and Weingartner, R., 2003. Hochwasser und Wald - das forsthydrologische Paradigma. In: F. Jeanneret, D. Wastl-Walter, U. Wiesmann and M. Schwyn (Editors), Welt der Alpen - Gebirge der Welt, Haupt Verlag, Bern, pp. 127-141.

Gertsch, E. and Kienholz, H., 2004. Geomorphodynamik sturmgeschädigter Waldhänge – Eine Aufnahmemethodik und erste Ergebnisse (Geomorphodynamics in storm damaged forested slopes – Monitoring methods and first results). In: Congress Publication of the Interpraevent 2004, Riva del Garda, Vol. 1(III): 123-134.

Grayson, R.B., Blöschl, G., Western, A.W. and McMahon, T.A., 2002. Advances in the use of observed spatial patterns of catchment hydrological response. Advances in Water Resources, 25(8-12): 1313-1334.

Guillemette, F., Plamondon, A.P., Prévost, M. and Lévesque, D., 2005. Rainfall generated stormflow response to clearcutting a boreal forest: peak flow comparison with 50 world-wide basin studies. Journal of Hydrology, 302(1-4): 137-153.

Gurtz, J., Baltensweiler, A. and Lang, H., 1999. Spatially distributed hydrotope-based modelling of evapotranspiration and runoff in mountainous basins. Hydrological Processes, 13(17): 2751-2768.

Gurtz, J., Zappa, M., Jasper, K., Lang, H., Verbunt, M., Badoux, A. and Vitvar, T., 2003a. A comparative study in modelling runoff and its components in two mountainous catchments. Hydrological Processes, 17(2): 297-311.

Gurtz, J., Verbunt, M., Zappa, M., Moesch, M., Pos, F. and Moser, U., 2003b. Long-term hydrometeorological measurements and model-based analyses in the hydrological research catchment Rietholzbach. Journal of Hydrology and Hydromechanics (Svk), 51(3): 162-174.

Gustafsson, D., Stähli, M. and Lehning, M., 2005. Towards an improved snow interception model for sub-alpine forests. European Journal of Forest Research, (submitted).

Gutknecht, D., 1996. Abflussentstehung an Hängen - Beobachtungen und Konzeptionen. Österreichische Wasser- und Abfallwirtschaft (ÖWW), 48(5/6): 134-144.

Harr, R.D. and McCorison, F.M., 1979. Initial effects of clearcut logging on size and timing of peak flows in a small watershed in Western Oregon. Water Resources Research, 15(1): 90-94.

Harr, R.D., 1982. Streamflow changes after logging 130-year-old Douglas-fir in 2 small watersheds. Water Resources Research, 18(3): 637-644.

Hegg, C., Thormann, J.J., Böll, A., Germann, P.F., Kienholz, H., Lüscher, P. and Weingartner, R. (Editors), 2004. Lothar und Wildbäche. Schlussbericht eines Projektes im Rahmen des Programms "LOTHAR Evaluations- und Grundlagenprojekte", Eidg. Forschungsanstalt WSL, Birmensdorf, 79 pp.

Hewlett, J.D. and Hibbert, A.R., 1967. Factors affecting the response of small watersheds to precipitation in humid areas. In: W.E. Sopper and H.W. Lull (Editors), Forest Hydrology, Pergamon, Oxford, pp. 275-291.

Hibbert, A.R., 1967. Forest treatment effects on water yield. In: W.E. Sopper and H.W. Lull (Editors), Forest Hydrology, Pergamon, Oxford, pp. 527-543.

Hibbert, A.R. and Troendle, C.A., 1988. Streamflow generation by variable source area. In: W.T. Swank and D.A. Crossley Jr. (Eds.), Forest Hydrology and Ecology at Coweeta, Ecological Studies 66, Springer, New York, pp. 111-127.

Hornbeck, J.W., 1973. Storm Flow from Hardwood-Forested and Cleared Watersheds in New Hampshire. Water Resources Research, 9(2): 346-354.

Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S. and Lynch, J.A., 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern USA. Journal of Hydrology, 150: 323-344.

Hornbeck, J.W., Martin, C.W. and Eagar, C., 1997. Summary of water yield experiments at Hubbard Brook Experiment Forest, New Hampshire. Canadian Journal of Forest Research, 27: 2043-2052.

Hornberger, M.G., Germann, P.F. and Beven, K.J., 1991. Throughflow and solute transport in an isolated sloping soil block in a forested catchment. Journal of Hydrology, 124: 81-99.

Horton, R.E., 1932. Drainage basin characteristics. Trans. Am. Geophys. Union, 13: 355-361.

Horton, R.E., 1933. The role of infiltration in the hydrologic cycle. Trans. Am. Geophys. Union, 14: 446-460.

Huang, M., Zhang, L. and Gallichand, J., 2003. Runoff responses to afforestation in a watershed of the Loess Plateau, China. Hydrological Processes, 17(13): 2599-2609.

Jasper, K. and Kaufmann, P., 2003. Coupled runoff simulations as validation tools for atmospheric models at the regional scale. Quarterly Journal of the Royal Meteorological Society, 129(588): 673-692.

Keizer, J.J., Coelho, C.O.A., Shakesby, R.A., Domingues, C.S.P., Malvar, M.C., Perez, I.M.B., Matias, M.J.S. and Ferreira, A.J.D., 2004. The role of soil water repellency in overland flow generation in pine and eucalypt forest stands in coastal Portugal. Australian Journal of Soil Research, (accepted).

Keller, H.M., 1968. Zur Frage des Einflusses von Wald auf das Niederwasser. Schweizerische Zeitschrift für Forstwesen, 119(10): 750-751.

Keller, H.M., 1988. European experiences in long-term forest hydrology research. In: W.T. Swank and D.A. Crossley Jr. (Editors). Forest Hydrology and Ecology at Coweeta, Ecological Studies 66, Springer, New York, pp. 407-414.

Kirby, C., Newson, M.D. and Gilman, K., 1991. Plynlimon research: the first two decades., Institute of Hydrology, Wallingford.

Kirkby, M.J. and Chorley, R.J., 1967. Throughflow, overland flow and erosion. Bull. intern. Assoc. Sci. Hydrology, 12: 5-21.

Kirkby, M.J. (Editor), 1978. Hillslope Hydrology. Wiley, Chichester, 389 pp.

Kirnbauer, R., Pirkl, H., Haas, P. and Steidl, R., 1996. Abflussmechanismen - Beobachtung und Modellierung. Österreichische Wasser- und Abfallwirtschaft (ÖWW), 48(1/2): 15-26.

Klöcking, B. and Haberlandt, U., 2002. Impact of land use changes on water dynamics - a case study in temperate meso and macroscale river basins. Physics and Chemistry of the Earth (B), 27(9-10): 619-629.

Klok, E.J., Jasper, K., Roelofsma, K.P., Gurtz, J. and Badoux, A., 2001. Distributed hydrological modelling of a heavily glaciated Alpine river basin. Hydrological Sciences Journal, 46(4): 553-570.

Kohl, B., Markart, G., Stary, U., Proske, H. and Trinkaus P., 1997. Abfluss- und Infiltrationsverhalten von Böden unter Fichtenaltbeständen in der Gleinalm (Stmk.). Berichte der Forstl. Bundesversuchsanstalt Wien, 96: 27-32.

Koivusalo, H. and Kokkonen, T., 2002. Snow processes in a forest clearing and in a coniferous forest. Journal of Hydrology, 262: 145-164.

Lahmer, W., Pfützner, B. and Becker, A., 2001. Assessment of land use and climate change impacts on the mesoscale. Physics and Chemistry of the Earth (B), 26(7-8): 565-575.

Landolt, E., 1869. Die Wasserverheerungen in der Schweiz im September und Oktober 1886. Schweizerische Zeitschrift für Forstwesen, 20(1): 1-9 / (2): 17-23 / (3): 33- 37.

Lang, H., 1978. Die Verdunstung in der Schweiz (Zusammenfassender Bericht). Beiträge zur Geologie der Schweiz – Hydrologie, 25: 11-31.

Legates, D.R. and McCabe, G.J., 1999. Evaluating the use of "Goodness-of-Fit" measures in hydrologic and hydroclimatic model validation. Water Resources Research, 35: 233-241.

Liebscher, H.-J., 1972. Results of research on some experimental basins in the Upper Harz Mountains. International Association of Hydrological Sciences (IAHS) Publication, 97: 150-162.

Lynch, A.J., Corbett, E.S. and Sopper, W.E., 1977. Effects of antecedent soil moisture on stormflow volumes and timing. Surface and Subsurface hydrology. Proceedings of the 3rd Int. Symposium on Theoretical and Applied Hydrology. Fort Collins, CO. Water Res. Publ.: 89–99.

MacDonald, L.H. and Hoffman, J.A., 1995. Causes of peak flows in northwestern Montana and northeastern Idaho. Water Resources Bulletin, 31: 79-94.

MacDonald, L.H., Wohl, E.E. and Madsen, S.W., 1997. Validation of water yield thresholds on the Kootenai National Forest. Dept. of Earth Resources, Colorado State University, Fort Collins, CO, 197 pp.

Markart, G. and Kohl, B., 1995. Starkregensimulation und bodenphysikalische Kennwerte als Grundlage der Abschätzung von Abfluss- und Infiltrationseigenschaften alpiner Boden-/Vegetationseinheiten. Berichte der Forstl. Bundesversuchsanstalt Wien, 89: 1-38.

Markart, G., Kohl, B. and Zanetti, P., 1997. Oberflächenabfluss bei Starkregen - Abflussbildung auf Wald-, Weide- und Feuchteflächen (am Beispiel des oberen Einzugsgebietes der Schesa-Bürserberg, Vorarlberg). Centralblatt f. d. ges. Forstwesen, 114: 123-144.

Maruyama, I. and Inose, T., 1952. Experiment of forest influence upon streamflow at Kamabuti, First Report on Government Forest Experiment Station Publication 53, Meguro, Tokyo, pp. 1-46.

McCulloch, J.S.G. and Robinson, M., 1993. History of forest hydrology. Journal of Hydrology, 150: 189-216.

McDonnell, J.J., 1990. A rationale for old water discharge through macropores in a steep, humid catchment. Water Resources Research, 22: 2821-2832.

McDonnell, J.J., 2003. Where does water go when it rains? Moving beyond the variable source area concept of rainfall-runoff response. Hydrological Processes, 17(9): 1869-1875.

McGlynn, B.L., McDonnell, J.J. and Brammer, D.D., 2002. A review of the evolving perceptual model of hillslope flowpaths at the Maimai catchments, New Zealand. Journal of Hydrology, 257: 1-26.

Menzel, L., Lang, H. and Rohman, M., 1997. Mittlere jährliche aktuelle Verdunstungshöhen 1973-1992. In: Hydrologischer Atlas der Schweiz, Tafel 4.1, Bern, Switzerland.

MeteoSwiss, 2003a. Witterungsberichte der MeteoSchweiz (Monate Juni, Juli, August, September). Zürich.

MeteoSwiss, 2003b. Niederschlagsbulletin der MeteoSchweiz (das Jahr 2003). Zürich.

Miller, E.L., 1984. Sediment yield and storm flow response to clear-cut harvest and site preparation in the Ouachita Mountains. Water Resources Research, 20(4): 471-475.

Moeschke, H., 1998. Abflussgeschehen im Bergwald - Untersuchungen in drei bewaldeten Kleineinzugsgebieten im Flysch der Tegernseer Berge. Forstliche Forschungsberichte, 169. Forstwissenschaftliche Fakultät der Universität München und Bayrische Landesanstalt für Wald und Forstwirtschaft, München, 276 pp.

Montgomery, D.R., Dietrich, W.E., Torres, R., Anderson, S.P., Heffner, J.T. and Loague, K., 1997. Hydrologic response of a steep, unchanneled valley to natural and applied rainfall. Water Resources Research, 33(1): 91-109.

Mosley, M.P., 1979. Streamflow generation in a forest watershed, New Zealand. Water Resources Research, 15: 795-806.

Mosley, M.P., 1982. Subsurface flow velocities through selected forest soils, South Island, New Zealand. Journal of Hydrology, 55: 65-92.

Naef, F., Scherrer, S. and Weiler, M., 2002. A process based assessment of the potential to reduce flood runoff by land use change. Journal of Hydrology, 267(1-2): 74-79.

Nash, J.E. and Sutcliffe, J.V., 1970. River flow forecasting through conceptual models (1), a discussion of principles. Journal of Hydrology, 10: 282-290.

Niehoff, D., Fritsch, U. and Bronstert, A., 2002. Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology, 267(1-2): 80-93.

Ott, B. and Uhlenbrook, S., 2004. Quantifying the impact of land-use changes at the event and seasonal time scale using a process-oriented catchment model. Hydrology and Earth System Sciences, 8(1): 62-78.

Ott, E., Frehner, M., Frey, H.-U. and Lüscher, P., 1997. Gebirgsnadelwälder: praxis-orientierter Leitfaden für eine standortgerechte Waldbehandlung. Haupt Verlag, Bern, Stuttgart, Wien, 287 pp.

Patric, J.H. and Reinhart, K.G., 1971. Hydrologic Effects of Deforesting Two Mountain Watersheds in West Virginia. Water Resources Research, 7(5): 1182-1188.

Penman, H.L., 1959. Notes on the Water Balance of the Sperbelgraben and Rappengraben. Mitteilungen der Schweizerischen Anstalt für das forstliche Versuchswesen, 35. Band, 1. Heft: 99-109.

Peters, D.L., Buttle, J.M., Taylor, C.H. and LaZerte, B.D., 1995. Runoff production in a forested, shallow soil, Canadian Shield basin. Water Resources Research, 31(5): 1291-1304.

Peters, N.E., Freer, J. and Beven, K.J., 2003. Modelling hydrologic responses in a small forested catchment (Panola Mountain, Georgia, USA): a comparison of the original and a new dynamic TOPMODEL. Hydrological Processes, 17(2): 345-362.

Reinhart, K.G., 1964. Effect of a commercial clearcutting in West Virginia on overland flow and storm runoff. Journal of Forestry, 62: 167-171.

Richard, D., 2002. Forêts et crues. La Houille Blanche - Revue Internationale de l'Eau, 2002-3: 54-58.

Robinson, M., 1986. Changes in catchment runoff following drainage and afforestation. Journal of Hydrology, 86: 71-84.

Robinson, M., 1998. 30 years of forest hydrology changes at Coalburn: water balance and extreme flows. Hydrology and Earth System Sciences, 2(2): 233-238.

Robinson, M. and Cosandey, C., 2002. Impact de la forêt sur les débits d'étiage. La Houille Blanche - Revue Internationale de l'Eau, 2002-3: 59-63.

Robinson, M. and Dupeyrat, A., 2005. Effects of commercial timber harvesting on streamflow regimes in the Plynlimon catchments, mid-Wales. Hydrological Processes, (in press).

Ross, B.B., Contractor, D.N. and Shanholtz, V.O., 1979. A finite element model of overland and channel flow for assessing the hydrologic impact of landuse change. Journal of Hydrology, 41: 11-30.

Rowe, L., Fahey, B., Jackson, R. and Duncan, M., 1997. Effects of land use on floods and low flows. In: M.P. Mosley and C.P. Pearson (Editors), Floods and Droughts: the New Zealand Experience, New Zealand Hydrological Society, Wellington (NZ), pp. 89-102.

Sahin, V. and Hall, M.J., 1996. The effects of afforestation and deforestation on water yields. Journal of Hydrology, 178(1): 293-309.

Schäfer, J.T., 1990. The Critical Success Index as an Indicator of Warning Skill. Weather and Forecasting, 5(4): 570-575.

Schär, C., Vidale, P.L., Lüthi, D., Frei, C., Häberli, C., Liniger, M.A. and Appenzeller, C., 2004. The role of increasing temperature variability in European summer heatwaves. Nature, 427: 332-336.

Scherrer, S., 1996. Abflussbildung bei Starkniederschlägen – Identifikation von Abflussprozessen mittels künstlicher Niederschläge (Runoff generation during intense rainfall – Identification of runoff processes using sprinkling experiments). PhD Thesis no. 11793, ETH Zurich, Switzerland., 180 pp.

Scherrer, S. and Naef, F., 2003. A decision scheme to indicate dominant hydrological flow on processes on temperate grassland. Hydrological Processes, 17: 391-401.

Schmid, F., 2001. Politische Konsequenzen aus dem Unwetterereignis von 1868 - Anfänge des eidgenössischen Hochwasserschutzes. Schweizerische Zeitschrift für Forstwesen, 152(12): 521-526.

Schmocker-Fackel, P., 2004. A method to delineate runoff processes in a catchment and its implications for runoff simulations. PhD Thesis no. 15638, ETH Zurich, Switzerland, 187 pp. [available online at: http://e-collection.ethbib.ethz.ch/show?type=diss&nr =15638].

Schulla, J., 1997. Hydrologische Modellierung von Flussgebieten zur Abschätzung der Folgen von Klimaänderungen. Zürcher Geographische Schriften, Heft 69. ETH Zurich, Switzerland.

Schwarz, O., 1986. Zum Abflussverhalten von Waldböden bei künstlicher Beregnung. In: G. Einsele (Editor), Das landschaftsökologische Projekt Schönbuch, DFG–Forschungsbericht, VHC–Verlagsgesellschaft, Weinheim, pp. 161-179.

Schwarze, R., Herrmann, A. and Mendel, O., 1994. Regionalization of runoff components for central European basins. International Association of Hydrological Sciences (IAHS) Publication, 221: 493-502.

Scott, D.F. and Van Wyk, D.B., 1990. The effects of wildfire on soil wettability and hydrological behaviour of an afforested catchment. Journal of Hydrology, 121: 239-256.

Seibert, J. and McDonnell, J.J., 2002. On the dialog between experimentalist and modeler in catchment hydrology: Use of soft data for multicriteria model calibration. Water Resources Research, 38(11): art no. 1241.

Selby, M.J., 1993. Hillslope materials and processes. Oxford University Press, Oxford, 451 pp.

Sevruk, B. (Editor), 1986. Correction of precipitation measurements. In: ETH/IASH/ WMO Workshop on the Correction of Precipitation Measurements, Zürcher Geographische Schriften, Heft 23. ETH Zurich, Switzerland.

Sevruk, B., 1997. Regional dependency of precipitation-altitude relationship in the Swiss Alps. Climatic Change, 36(3-4): 355-369.

Swank, W.T. and Crossley Jr., D.A. (Editors), 1988. Forest Hydrology and Ecology at Coweeta. Ecological Studies 66, Springer, New York, 469 pp.

Swank, W.T., Swift Jr., L.W. and Douglass, J.E., 1988. Streamflow changes associated with forest cutting, species conversions, and natural disturbances. In: W.T. Swank and D.A. Crossley Jr. (Editors), Forest Hydrology and Ecology at Coweeta, Ecological Studies 66, Springer, New York, pp. 297-312.

Swank, W.T., Vose, J.M. and Elliott, K.J., 2001. Long-term hydrologic and water quality responses following commercial clearcutting of mixed hardwoods on a southern Appalachian catchment. Forest Ecology and Management, 143(1-3): 163-178.

Uhlenbrook, S., 2004. An empirical approach for delineating spatial units with the same dominating runoff generation processes. Physics and Chemistry of the Earth, 28: 297-303.

Uhlenbrook, S., Roser, S. and Tilch, N., 2004. Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. Journal of Hydrology, 291(3-4): 278-296.

von Storch, H. and Zwiers, F.W., 2001. Statistical Analysis in Climate Research. Cambridge University Press, Cambridge, 494 pp.

Wegehenkel, M., 2002. Estimating of the impact of land use changes using the conceptual hydrological model THESEUS - a case study. Physics and Chemistry of the Earth (B), 27(9-10): 631-640.

Weiler, M., Naef, F. and Leibundgut, C., 1998. Study of runoff generation on hillslopes using tracer experiments and a physically-based numerical hillslope model. International Association of Hydrological Sciences (IAHS) Publication, 248: 353-360.

Weiler, M., 2001. Mechanisms controlling macropore flow during infiltration. Dye tracer experiments and simulations. Schriftenreihe des Instituts für Hydromechanik und Wasserwirtschaft der ETH Zürich, Band 7, 150 pp.

Weiler, M. and Naef, F., 2003. An experimental tracer study of the role of macropores in infiltration in grassland soils. Hydrological Processes, 17(2): 477-493.

Weiler, M., McGlynn, B.L., McGuire, K.J. and McDonnell, J.J., 2003. How does rainfall become runoff? A combined tracer and runoff transfer function approach. Water Resources Research, 39(11): art. no.-1315.

Weiler, M. and Flühler, H., 2004. Inferring flow types from dye patterns in macroporous soils. Geoderma, 120(1-2): 137-153.

Weiler, M. and McDonnell, J.J., 2004. Virtual experiments: a new approach for improving process conceptualization in hillslope hydrology. Journal of Hydrology, 285(1-4): 3-18.

Weinmeister, W., 2003. Fähigkeiten des Waldes zur Verminderung von Hochwasser und Erosionsschäden. In: Hochwasserschutz im Wald, Berichte aus der Bayrischen Landesanstalt für Wald und Forstwirtschaft (LWF), 40: 15-29.

Wilson, G.V., Jardine, P.M., Luxmoore, R.J. and Jones, J.R., 1990. Hydrology of a forested hillslope during storm events. Geoderma, 46: 119-138.

Witzig, J., Badoux, A., Hegg, C. and Lüscher, P., 2004. Waldwirkung und Hochwasserschutz - eine standörtlich differenzierte Betrachtung. Forst und Holz, 59(10): 476-479.

WSL and BUWAL (Editors), 2001. Lothar. Der Orkan 1999. Ereignisanalyse. Eidgenössische Forschungsanstalt WSL und Bundesamt für Umwelt, Wald und Landschaft BUWAL, Birmensdorf, Bern, 365 pp.

Wullschleger, E., 1985. 100 Jahre Eidgenössische Anstalt für das forstliche Versuchswesen 1885-1985, Teil 1: Die Geschichte der EAVF. Mitteilungen der eidgenössischen Anstalt für das forstliche Versuchswesen, 61. Band, 1. Heft: 163-309.

Zappa, M., 2002. Multiple-response verification of a distributed hydrological model at different spatial scales. PhD Thesis no. 14895, ETH Zurich, Switzerland, 167 pp. [available online at: http://e-collection.ethbib.ethz.ch/show?type=diss&nr=14895].

Zappa, M., Pos, F., Strasser, U., Warmerdam, P. and Gurtz, J., 2003. Seasonal Water Balance of an Alpine Catchment as Evaluated by Different Methods for Spatially Distributed Snowmelt Modelling. Nordic Hydrology, 34(3): 179-202.

Zappa, M. and Gurtz, J., 2003. Simulation of soil moisture and evapotranspiration in a soil profile during the 1999 MAP-Riviera campaign. Hydrology and Earth System Sciences, 7: 903-919.

Zappa, M., 2005. On the use of skill measures based on 2x2 contingency-tables for the evaluation of spatially distributed snow cover simulations. Advances in Water Resources, (submitted).

Zhang, L., Dawes, W.R. and Walker, G.R., 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, 37(3): 701-708.

Unpublished diploma theses

Gertsch, E., 2002. Geomorphodynamik ausgewählter Lotharschadenhänge im Spissibach und Sperbelgraben. Diploma Thesis at the Institute of Geography of the University of Bern, 195 pp.

Helbling, A., 2002. Infiltrationsverhalten, Speichervermögen und Grobporenanteil der Böden verschiedener Waldstandortstypen. Diploma Thesis at the Institute of Geography of the University of Bern, 94 pp.

Ilg, H., 2003. Untersuchungen zum Oberflächenabfluss in vom Sturm Lothar unterschiedlich beschädigten Testparzellen im Sperbelgraben, Emmental. Diploma Thesis at the Institute of Geography of the University of Bern, 148 pp.

Könitzer, C., 2004. Untersuchungen zur Abflussbildung im Sperbelgraben, Emmental. Diploma Thesis at the Institute of Geography of the University of Bern, 87 pp.

Marti, Ph., 2002. Niederschlag und Abfluss im Sperbelgraben: Untersuchungen zu Einfluss der Lothar-Sturmschäden auf den Wasserhaushalt. Diploma Thesis at the Institute of Geography of the University of Bern, 99 pp.

Sieber, S., 2002. Beregnungsversuche im Sperbelgraben: Folgen des Sturms "Lothar" auf den Bodenwasserhaushalt. Diploma Thesis at the Institute of Geography of the University of Bern, 117 pp.

Sonderegger, C., 2004. Rainfall/Runoff modelling of a sub-catchment of the Yangtze in China. Diploma Thesis, ETH and University Zurich, Switzerland, 103 pp.

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