

Topographical and ecological controls of runoff generation and lateral flows in mountain catchments

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Abstract We review results of research on runoff generation mechanisms and lateral flows from three case studies in catchments in the Harz mountains (central Germany), the Appalachian mountains (eastern USA), and Southern Alps (New Zealand). The studies consider the role of topography, including bedrock topography, land use, soil and hydrogeological conditions for runoff generation and partitioning into lateral flow components. Advanced investigation and monitoring techniques are briefly characterized and requirements for future research outlined.

INTRODUCTION

Brammer & McDonnell (1996), in reviewing the evolution of perceptual models of hillslope subsurface flow, showed that with increasingly sophisticated monitoring, new ideas concerning the age, origin and pathways of subsurface flow were proposed. Early studies using small hillslope pits and subsurface flow collection suggested a need for a simple model which represents the hillslope system as entirely pipeflow channelling of new water past the soil matrix to the channel (Anderson & Brooks, 1996; Uhlenbrook & Leibundgut, 1997). Later, monitoring using isotopic tracers (e.g. Pearce *et al.*, 1986) suggested that matrix water was displaced into the stream during events. More recent work that has coupled recording tensiometer data with other hydrometric techniques and isotope and chemical tracing, and sometimes with modelling, has revealed the importance of preferential flow of old water through macropores at the soil-bedrock interface (McDonnell, 1990; Peters *et al.*, 1995; Uhlenbrook & Leibundgut, 1997) and through weathered bedrock in steep upland areas (Anderson *et al.*, 1997).

This paper reviews results of three case studies in quite different hydrological regimes. These studies emphasize the essential, often dominating role of macropore flow (pipe flow) and piston flow, in connection with temporary water saturation on less permeable layers, in particular on bedrock, as major contributors to direct subsurface lateral flow (interflow). These flows often dominate direct overland flow (Hortonian infiltration excess and overland flow from impervious and temporarily saturated areas), at least under certain conditions.

SOIL STRUCTURE AND LAND COVER CONTROL OF RUNOFF GENERATION MECHANISMS AND LATERAL FLOWS

Borchardt (1980) initiated field investigations on runoff generation mechanisms in two experimental basins with similar relief, soil and hydrogeological conditions in the Harz mountains in central Germany: The Schäfertal basin (1.44 km²; 94% agricultural use), and the Waldbach basin (0.35 km²; totally forested). In the Schäfertal, a wall of concrete down to the bedrock was built at the basin outlet to capture total basin discharge. In addition to standard instrumentation, three transects of groundwater level recorders were established vertically to the river channel (i.e. along the north and south slopes of the valley). In the Waldbach basin, about 1 km away, basin discharge was recorded for comparison.

Flood hydrographs during wet initial moisture conditions were used to develop an improved understanding of runoff generation mechanisms (Becker, 1989). Figure 1 shows a typical example of discharge and groundwater level records for three short rainfall events. The first event on 8 May totalled 9.5 mm within 4 h; the second on 9 May totalled 12.4 mm within 7 h, and a third event on 12 May totalled 20 mm within 8 h. Figure 1 shows the basin discharge of the Schäfertal catchment and below it the corresponding groundwater levels recorded in the lower sections of the northern and southern slope and in the central valley. Discharge recorded at the Waldbach gauge during the same period is also shown in Fig. 1.

In both basins, immediate short-term rises and recessions of basin discharge can be observed during, and a few hours after the rainfall events. They are interpreted as direct overland flow from the roads and pathways and a few impermeable or saturated subareas in the basins. Significant secondary discharge rises and delayed peak flow of about two days were recorded in the Schäfertal for the third event, and more remarkably in the Waldbach for all events (in particular for the second and third event). They are interpreted as an interflow component most probably due to pipeflow through macropore systems and piston flow.

To find out what subsurface conditions allow such large amounts of interflow to be generated, a detailed soil survey was undertaken (Altermann, 1985). About one third of the Schäfertal basin had an upper permeable soil layer of about 40–50 cm thick above a less permeable second layer of 30–70 cm. Below it, on top of the bedrock, a more permeable schist zone with weathered rock exists and appears capable of transferring lateral subsurface flows downslope rather quickly (as pipeflow or macropore flow). The other non-valley parts of the basin are quite similar. In addition to flow through macropores, it appeared that temporary saturated subsurface layers above the second less permeable soil layer and/or above bedrock developed. They develop not only in the upslope parts of the basin near to the watershed divide where slopes are rather low, but also in the lower and steeper sections of the slope as confirmed by groundwater level rises of up to 1–1.5 m (middle part of Fig. 1). The groundwater level record taken in the central valley near to the channel indicated that apart from the short initial peaks, which may be caused by the water level rises in the channel, a rather stable rise in groundwater level occurred which produced increased exfiltration into the channel, in addition to that from the lower slope sections.

Thus, according also to recent findings of other researchers (McDonnell, 1990;

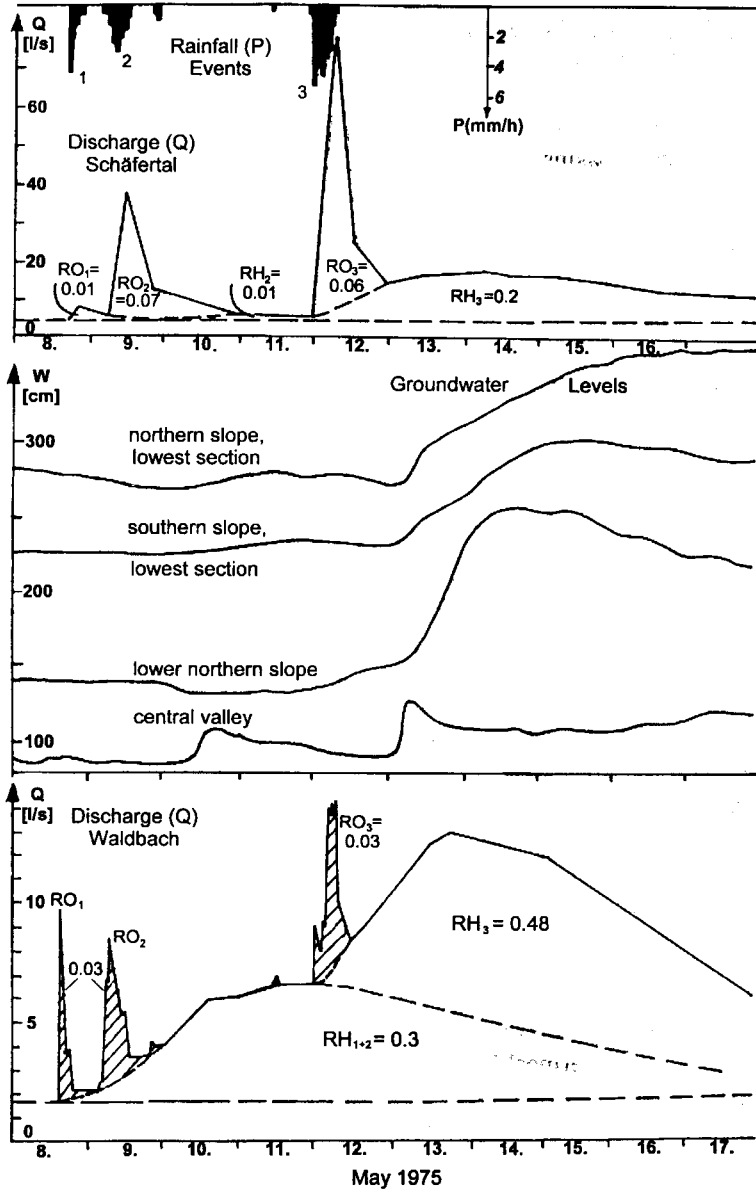


Fig. 1 Hydrographs recorded in the Schäferfetal (upper and middle part of figure) and Waldbach basins (lower part) during three subsequent rainfall events, as represented at the top of the figure (Explanation of the symbols: RO = direct overland flow runoff; RH = interflow runoff.)

Bronstert, 1994; Uhlenbrook & Leibundgut, 1997), a perceptual model of runoff generation and lateral flows was developed: rain water infiltrates into the upper soil layer in most parts of the basin; it then quickly reaches the less permeable second soil layer and generates temporary saturation above it; this temporary saturation is perceived to have two effects:

- (a) It will generate quick lateral downslope flow through macropores in the upper soil layer (pipeflow), particularly in the steeper downslope sections of the valley. This lateral flow will represent a mixture of infiltrated event water and of pre-event water "pressed out" by the infiltrated event water, as described by McDonnell (1990).
- (b) It will cause percolation through the less permeable second soil layer at places where this layer is more permeable or penetrated (e.g. by roots etc.). The percolated water will then cause saturation on top of the bedrock with direct effects on basin discharge through pressure transfer to the valley floor and lower slopes. It will create immediate exfiltration of "old" pre-event water into the channel (piston flow), as described by Anderson *et al.* (1997)

In both cases, delays in peak flow of about two days are assumed to be caused by the time required for the percolation of water to and through the second soil layer, which may be rather short, and for the formation of saturated zones in the subsurface. This understanding is in agreement with the observation of large amounts of pre-event water in flood streamflow in similar basins (Herrmann *et al.*, 1986; Pearce *et al.*, 1986; McDonnell, 1990; Uhlenbrook & Leibundgut, 1997).

Finally the considerable differences in the observed direct runoff amounts (overland and interflow) deserve comment. In the Schäfertal, direct overland flow ranges from about 1% of precipitation (runoff/precipitation) for the first event up to 7% or 5.5% for the second and third events respectively (see Fig. 1). It is understood that this flow is generated from the few roads and pathways in the Schäfertal and from some impervious and temporarily saturated areas. In the Waldbach this component is more stable (about 3%) due to the fact that dynamically varying saturated areas did not occur during the three events.

More informative is the analysis of interflow runoff. During the first event interflow only occurred in the Waldbach with about 3% of precipitation. It increases here to nearly 50% of precipitation in the second and third events (see Fig. 1). In the Schäfertal basin an interflow component was observed only for the second event (about 1.6%), and up to about 20% for the third one. This difference is considered to be caused by the different land uses in the two basins; forest in the Waldbach and agriculture in the Schäfertal. Due to the more extensively developed and deeper root systems in the forest, larger amounts of infiltrated water may percolate to the permeable top layer of bedrock. Also in connection with the slightly steeper slopes in the Waldbach basin, this may generate larger amounts of interflow by the mechanisms as explained above. This illustrates not only the important role of land use in runoff generation, but also the role of direct subsurface flow contributions to flood flow, probably with a dominating proportion of pre-event water. Work is continuing to try to quantify this perceptual model.

ADVANCED MONITORING TECHNIQUES TO BETTER UNDERSTAND RUNOFF GENERATION AND IDENTIFY SUBSURFACE FLOW PATTERN

For many years, hydrologists have relied on surface topography to quantify patterns of downslope movement of water and solutes, since gravitational potential largely

dominates hydraulic gradients in steep terrain. Hence, with the increased availability of DTMs, surface topography has driven many popular hydrological models (e.g. TOPMODEL and TOPOG). While at the catchment scale this approximate description may be broadly reasonable, recent work by Freer *et al.* (1997) and Brammer & McDonnell (1996) has indicated that detailed flow pathways may deviate from those indicated by surface topography at the hillslope scale.

Most recently, McDonnell *et al.* (1996) and Freer *et al.* (1997) have explored the role of the bedrock surface topography in subsurface flow generation, using high resolution bedrock surface Digital Terrain Maps (DTMs) and extensive hillslope-wide trenching and flow measurement/quality analysis in the Panola Mountain research watershed in Georgia, USA (Fig. 2). They described results from a 20-m-long trench that was excavated down to saprolite bedrock (0.4–1.8 m) at the base of a 20×48 m hillslope, based on the design of Woods & Rowe (1996) at Maimai, New Zealand. The slope was then instrumented with a grid of recording soil physics instrumentation and soil sampling devices. The trench was divided into ten 2-m sections such that water arriving at each trench section could be routed separately through tipping bucket devices and sampled for major anions, cations and oxygen-18. The hillslope and its instrumentation were surveyed and the depth to the bedrock surface was obtained from a 2-m-grid rod survey. Both surface and bedrock topographies were used to compute the hillslope $\ln(a/\tan \beta)$ index, also called the topographical index, where a is the upslope contributing area to a point and $\tan \beta$ is the local slope angle. This index has been used as a measure of hydrological similarity (Beven & Kirkby, 1979). The pattern of the index can be used to indicate the propensity of a point to saturate. The related flow path information served as the basis for testing whether or not the downhill flow of water was controlled by surface topography or bedrock surface topography.

Freer *et al.* (1997) computed surfaces (topographic and bedrock) for the 20×48 m study hillslope, using a multiple flow direction algorithm to calculate the $\ln(a/\tan \beta)$ index. The downslope distribution of the accumulated area of each cell was controlled (or weighted) by the local topographic gradients. The accumulated area based on surface topography showed a clear and dominant “flow path” straight down the hillslope. In contrast, as illustrated in Fig. 2 from McDonnell *et al.* (1996) the bedrock-adjusted surface showed two distinct “snaking” flow paths converging approximately 10 m upslope from the trench. These different flow paths presented alternative routes for hillslope hydrological flux. Water-flow volume captured at the trench face and its resulting age and chemistry were used to “test” which pathway controlled flow. Freer *et al.* (1997) found that flow from the hillslope base and upslope water-table development were controlled by the bedrock surface. Trough flow from the predicted bedrock-controlled flow path was 85% greater than flow from any other slope sections, both in terms of total runoff volume and peak flow. The surface topography-inferred flow path carried much less flow and did not appear noticeably different from neighbouring trough sections. Accumulated areas at the trench face were derived for surface topography and bedrock topography. Again, the bedrock index and the bedrock accumulated areas closely resembled the spatial distribution of saturation on the hillslope and flow at the trench face.

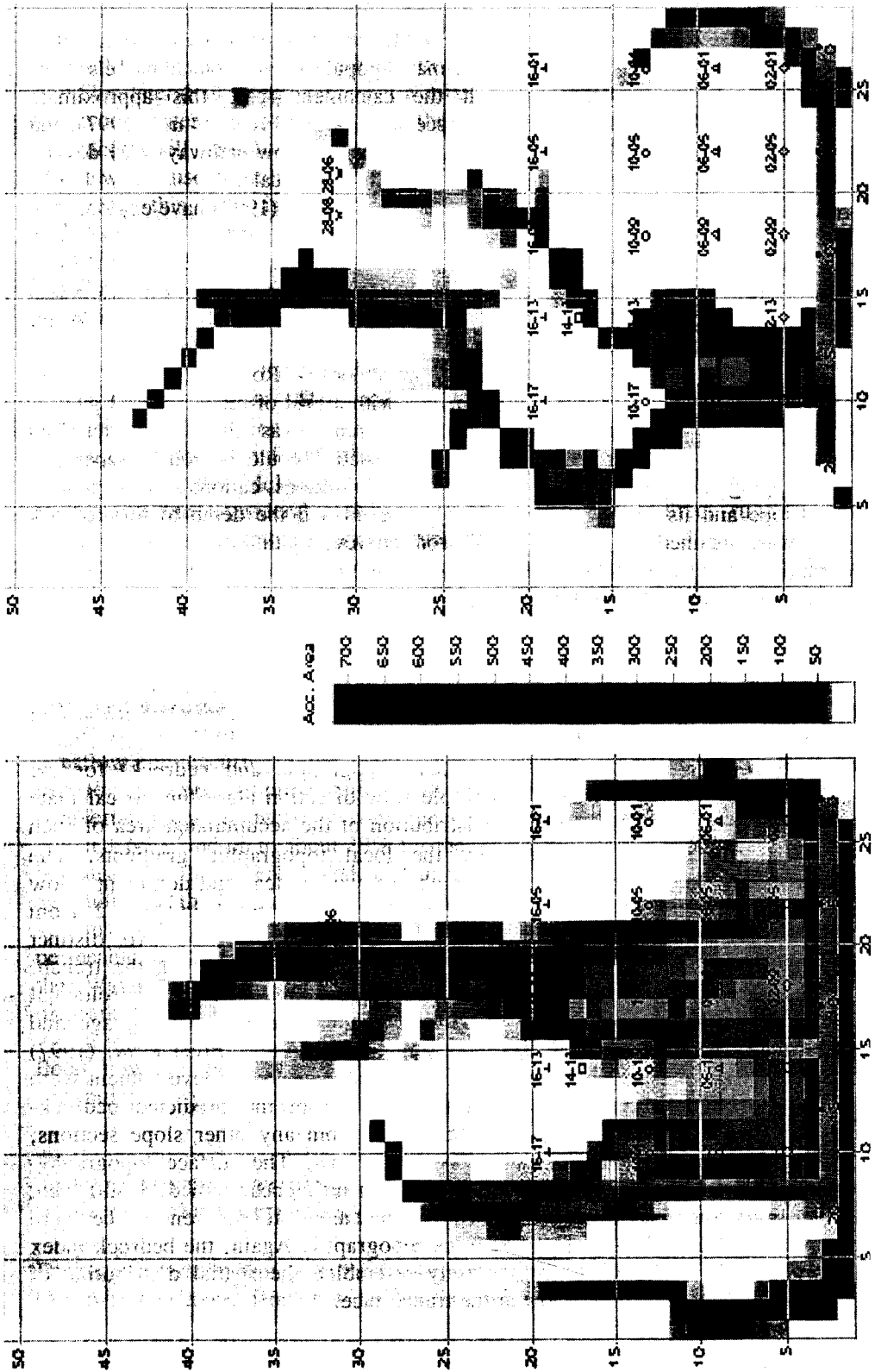


Fig. 2 Plan-view maps of the 20 x 48 m hillslope studied by Freer *et al.* (1997) at Panola. Plots show the two different flow paths, using an accumulated area multiple flow direction algorithm to calculate the topographic index. The *left-hand* plot shows the surface based on topography; the *right-hand* plot shows bedrock surface. The trench is located at the downslope portion of the hillslope. (Taken from McDonnell *et al.*, 1996).

Woods & Rowe (1996) studied the spatial variability of subsurface flow from a 50 m hillslope trough system at the Maimai catchment in New Zealand. Woods & Rowe (1996) demonstrated that flow varied considerably across an otherwise planar looking hillslope section. They found that there was "some positive correlation between flow and area but that the troughs (draining the greatest areas) do not dominate flow as might be expected". McDonnell (1997) indicated that this may be due to the fact that the bedrock surface controls flow direction during rainfall events on the hillslope, as described in recent studies by Brammer & McDonnell (1996) at the site and the McDonnell *et al.* (1996) and Freer *et al.* (1997) studies from Panola. McDonnell (1990) showed that water perches at the soil bedrock interface during most rainfall events at Maimai and that this saturated flow controls the rapid hillslope runoff response. Thus the process of interest in understanding subsurface flow is saturation from below; a wetting up from the bedrock surface into the soil profile. Differences in flow paths not immediately related or predictable by standard topographic surveys or topographically-based modelling approaches may result from the discrepancy between the bedrock surface and the soil surface topography. Freer *et al.* (1997) showed that the downslope accumulated areas to the trench face at Maimai based on surface topography and bedrock topography revealed a marked difference in the distribution at the trench face: there was a pronounced shift in accumulated area towards those trough subcatchments with the highest subsurface volume, as dictated by subsurface bedrock topography.

McDonnell (1997) reasoned that this may have explained the lower-than-expected contributions from troughs with the greatest upslope contributing area and some of the variability witnessed by Woods & Rowe (1996). McDonnell (1990) used recording tensiometers to show that water tables on the Maimai hillslope were extremely short-lived. Therefore between events, the surface topography may be the best surrogate for flow direction, since gravity and matric potential together control the gradient of total potential and resulting unsaturated flow direction, i.e. the bedrock surface may not be an important control on lateral flows under these conditions.

CONCLUSIONS

Research needs to be strengthened along the lines outlined in this paper and supplemented by the application of new measuring techniques such as, for instance, the knocking pole penetrometer technique (Yoshinaga & Ohnuki, 1995) combined with use of "ground penetrating radar" (GPR) for non-invasive characterization of soil characteristics and topography of the soil-bedrock interface (Collins *et al.*, 1989). Particular emphasis should be placed on investigating the combined effects of matrix flow, macropore flow, temporary perched subsurface water saturation (including small immobile pockets that are stable between events, but re-mobilized during subsequent events), and especially the role of the bedrock topography and less permeable soil layers on the spatial pattern and temporal variation of hillslope flow.

Considering the complexity and relatively high costs for the required field studies, they should more closely be coordinated where international programmes such as the IGBP Mountain Workplan may serve as a basis (Becker & Bugmann, 1997).

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