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Runoff generation regionalization: analysis and a possible approach to a solution

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Abstract The runoff generation mechanisms operating at a given location in a basin depend heavily on different controlling factors (topography, soil type, vegetation, land use, river network, precipitation, etc.). We seek an understanding of this process, which results from the particular combination of attributes of the controlling factors. Further, we want to identify homogeneous areas or units in which a certain process of runoff formation dominates. To do this we need an upscaling procedure for solving a classification problem: the role that the individual factor plays within the combination of all controlling factors has to be evaluated. The upscaling approach we use is a rule-based model. In order to derive it we used extensive experimental findings in our research basins. The simulation results—limited to the two kinds of overland flow (infiltration excess and saturation excess)—are in close accordance with the measurements.

INTRODUCTION

The analysis of spatially distributed runoff generation in hydrological catchment areas belongs to scale problems in hydrology which are difficult to solve. We are mainly concerned with the so-called quick runoff components representing the direct response to a storm event and including surface runoff—Hortonian overland flow and saturation excess surface runoff (Dunne & Black, 1970; Dunne, 1978)—and interflow. These quick runoff components occur predominantly in mountainous regions where the hillslope response, rather than network response, prevails (Wooding, 1965a, 1965b, 1966; Kirkby, 1976; Beven & Wood, 1993).

The main runoff generation mechanisms operating at a given site within the catchment under consideration depend heavily on the various controlling factors. Factors such as precipitation and evapotranspiration determine the initial soil moisture, and topography; soil type, vegetation, land use and the river network each play a decisive role in the overall runoff generation process. Amongst these influencing factors the topography, the soils and the vegetation show a considerable degree of spatial heterogeneity. Very dissimilar value combinations of these variables naturally result in differing runoff generation mechanisms. From this we derive the first goal of our investigation. We seek an understanding of the runoff production process at the local scale which results from the particular combination of attributes of the controlling factors. This will also show great spatial variability across the scales from the site or field, through the hillslope to the subcatchment and the catchment. Therefore we have to scale up the process identified in the first task. This leads to the second and major objective of our paper: we want to identify such homogeneous areas or units in which a certain process of runoff formation dominates. To do this we need an upscaling procedure for solving a classification problem: the role that the individual factor plays within the combination of all the controlling factors has to be evaluated.

The upscaling approach we use is a rule-based model or a knowledge-based system. In order to derive this model we used extensive experimental findings in our research basins. However, in this paper we limit ourselves to the study of only two runoff generation mechanisms, Hortonian overland flow and saturation excess surface runoff, in order to determine the response units within a catchment from which these two runoff components originate. The question of using these units to simulate the runoff hydrograph at the catchment outlet is not addressed in this paper.

Another problem must be treated as well. Apart from the spatial heterogeneity of the controlling factors, the antecedent soil moisture shows a considerable temporal variability that also highly influences the runoff generation. The contributing saturated areas can change widely depending on the initial soil moisture and the characteristics of the storm event.

Should our approach be given the label regionalization or scaling? Blöschl (1996) has pointed out: "Regionalization ... involves the transfer of information from one catchment (location) to another. Clearly, regionalization focuses on the space domain while scaling refers to both space and time". From this it would appear that we are addressing more a problem of scaling runoff generation. Kubota & Sivapalan (1995) and Robinson & Sivapalan (1995) recently dealt with similar problems of runoff generation scaling but used other models.

ANALYSIS OF BASIN RESPONSES

We have obtained our experimental findings in the representative and research basins Triebenbach (TB) and Upper Wernersbach (UWB), small adjacent mountainous basins of area 1.55 km^2 and 0.93 km^2 respectively. From the precipitation measured by a network of six stations we have calculated the average precipitation which is representative for both basins. These basins are situated in eastern Germany near Dresden in a forested region (Tharandter Wald) with an altitude 322–424 m a.m.s.l. Slightly sloping hillsides are characteristic; steeper slopes are only of local importance. The geological structure is heterogeneous with porphyry as the predominating rock type and cretaceous formations. The soil cover mainly consists of cohesive weathering products of porphyry (loamy grit, loam) and loamy Pleistocene depositions. Shallow soil profiles with a high stone content and high porosity, in addition to rooting, increase the hydraulic conductivity. These shallow profiles alternate with deeper profiles of less permeable, nearly saturated soils, sometimes with standing water. Table 1 shows properties of these two basins that are particularly important for runoff generation. It is striking that the UWB-basin has a significantly greater percentage of less permeable gleys than the TB-basin. In the permeable brown soils we find a reverse relationship. The higher percentage of steeper slopes in the TB-basin is considerable.

Table 1 Comparison of the important runoff generation properties of the Triebenbach and Upper Wernersbach basins.

		Upper Wernersbach:		Triebenbach:	
		absolute (km^2)	relative (%)	absolute (km^2)	relative (%)
Soil types	Floodplain soil	0.08	8.5	0.16	10.0
	Stagnogley	0.5	53.0	0.53	34.0
	Brown pseudogley	0.1	11.0	0.14	8.8
	Brown earth	0.25	27.0	0.74	47.0
Roads		2.6 [km]	1.4		
Slope	0 – 1°	0.18	19.3	0.086	5.5
	>1 – 3°	0.47	50.3	0.63	40.5
	>3 – 5°	0.24	25.7	0.54	34.7
	>5 – 7°	0.043	4.6	0.19	12.2
	>7°	0.001	0.1	0.11	7.1

In addition to these differences one feature of the UWB-basin is significant in the understanding of runoff generation mechanisms: this basin has roads with an impermeable surface about 2.6 km in length altogether (cf. Fig. 6), which transform the rain into Hortonian overland flow. Ditches on both sides of the roads catch the generated overland flow and drain it very quickly to the stream network and the outlet of the basin without great losses. The different form of these two adjacent basins can be seen in Fig. 6. In the following let us consider the various responses of these basins to rain storms.

Low antecedent soil moisture

Figure 1 shows the different discharge hydrographs of the two basins in response to a short but very intensive precipitation, typical of rain events in summer. The runoff from the UWB-basin increases sharply and reaches a significantly higher peak than the

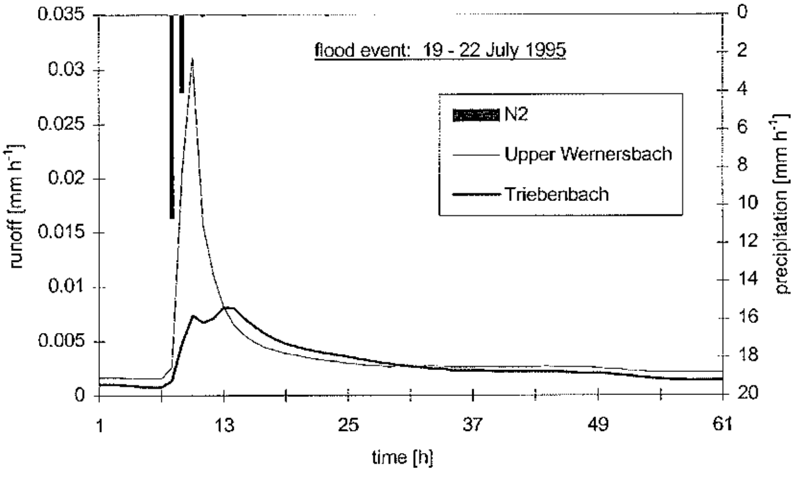

Fig. 1 During a low moisture state a short precipitation of high intensity causes quite different responses of the adjacent Upper Wernersbach and Triebenbach basins.

more moderate temporal course of the TB-hydrograph. This demonstrates that different runoff generation mechanism must be at work. Owing to differences in the controlling features between the two catchments as presented above, the Hortonian overland flow formed on the roads could cause the rapid and higher response of the UWB-basin. A closer look reveals that the precipitation of 10.7 mm h^{-1} during the first hour and of about 4.1 mm h^{-1} in the second hour, generated an overland flow of nearly 1×10^5 l, which yields 0.108 mm when related to the whole area of the basin. In this we have used a runoff coefficient of about 0.5 to 0.6 taking into account the losses due to moistening and infiltration in the drainage ditches on both sides of the roads. The comparison with the measured direct runoff of 0.11 mm confirms the supposition that the response of the UWB-basin is caused mainly by the overland flow from the roads.

In order to explain the distinctive response of the TB-basin we postulate that the runoff originates from the saturated area around the stream in the lower part of the basin (Fig. 6). Within this saturated area a station measuring soil moisture yields the results shown in Fig. 2. The measured minimum water content profile is related to the driest state of this location during the observed period, whereas the maximum profile reflects the complete saturation of the soil throughout the whole depth. The difference of about 13 mm represents the amount of rain necessary to fill up the free pore space of the soil. The rain excess forms overland flow.

In order to determine the amount of overland flow we start with 0.16 km^2 of floodplain soil (cf. Table 1). The rain excess of 1.8 mm would generate potential runoff on this area of 2.88×10^5 l. However, it seems to be realistic to assume again a runoff coefficient of about 0.5. The remaining runoff of 1.44×10^5 l results in a value 0.09 mm when related to the basin size of 1.55 km^2. Compared to a measured value (cf. Fig. 1) of about 0.08 mm the data correspond well and confirm our thesis.

The intensive two hour rain produces various runoff generation mechanisms in the dry adjacent basins UWB and TB that can be well explained on the basis of differing basin properties.

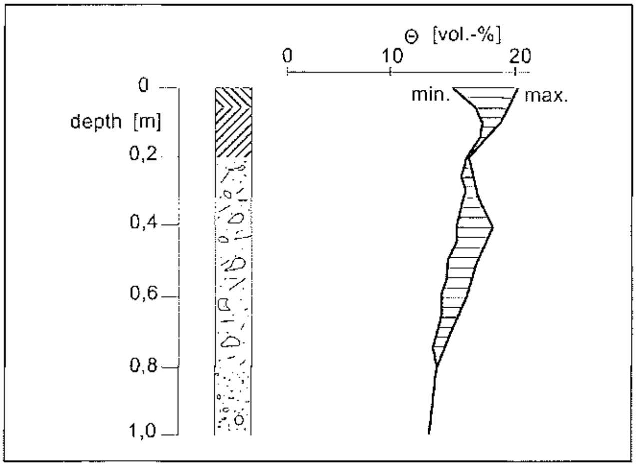

Fig. 2 Minimum and maximum profiles of soil moisture θ within the saturated area of the Triebenbach basin.

High antecedent soil moisture

We regard the runoff q_0 at the beginning of the rain event as a measure of the antecedent soil moisture. This runoff q_0 amounts to $5\ \mathrm{l\ s^{-1}\ km^{-2}}$ for the precipitation-runoff event presented in Fig. 3, in other words to the power of ten compared with the event in Fig. 1. While these two adjacent basins were moist, precipitation of long duration and medium intensity (only in the beginning was there an intensive one-hour rainfall) generates basin responses that are more similar than those in Fig. 1. Thus we see that during intensive rainfall the catchment features are less important then the actual precipitation characteristics. The differences in the runoff generation mechanisms as discussed with regards to Fig. 1 lose their significance. Now the ability of the basins to extend the contributing saturation area is dominant. This ability is quite different. Owing to the steep slopes—especially in the lower stretches of the TB stream—the saturated area quickly reaches its boundary and remains confined to the valley bottom. However, in the relatively flat UWB-basin the contributing area can expand further. The behaviour of the two basins is well reflected by their responses in Fig. 3 and also in Fig. 4. The latter illustrates that the dependence of the runoff coefficient on the antecedent soil moisture shows a saturation effect and approaches about 20% (TB) and 40–45% (UWB). Although the interflow component may be included in the runoff coefficient in very moist conditions, the results of Fig. 4 seem to be clear evidence for the greater expansion of the contributing saturated area in the UWB-basin.

THE RULE-BASED MODEL

The problem of identifying automatically areal units in which one runoff generation process dominates is not uniquely solvable. There are several approaches to treat such

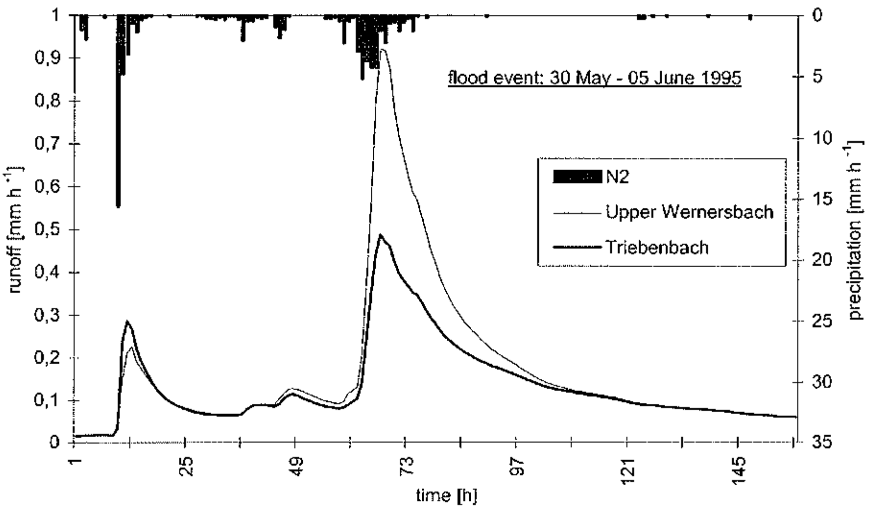

Fig. 3 The catchment responses of the adjacent Upper Wernersbach and Triebenbach basins are very similar during a wet period and as a consequence of prolonged rainfall.

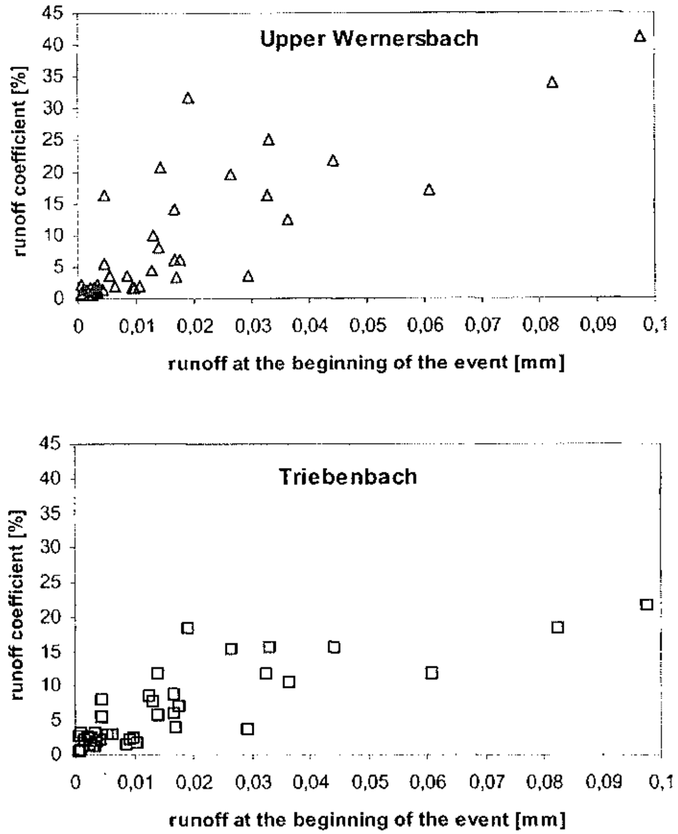

Fig. 4 Runoff coefficient against runoff at the beginning of the event; upper part: Upper Wernersbach basin, lower part: Triebenbach basin

a classification problem: e.g. neuronal networks, fuzzy logic, or binary logic. We decided on a binary approach realized by a knowledge-based system. This system has expert knowledge able to receive, to present and to process information using automatic reasoning and finally to make its conclusions available to the user.

In regard to the areal classification problem we have developed an expert system (XPS) (Peschke *et al.*, 1999) in which the GIS ARC/INFO and several rule blocks work together in close interrelationship (Fig. 5). The controlling factors of the runoff generation process such as morphology, soil type, vegetation, etc. show a high degree of spatial variability which is reflected by thematic maps of the areas under study. These maps may be overlaid by the GIS to yield areas or clusters of a specific combination of attributes. The smallest areal units formed by the geometric GIS-overlaying and without using any hydrophysical rules must be aggregated to process-predominant areas. This is achieved by the rules of the XPS.

The XPS is a physically based model that enables a qualitative analysis of the basin. It determines only which runoff generation process dominates in the area under consideration but gives no indication of the amount of runoff contribution. The XPS consists of the following components: (a) input information, (b) the first rule block, and (c) the second rule block.

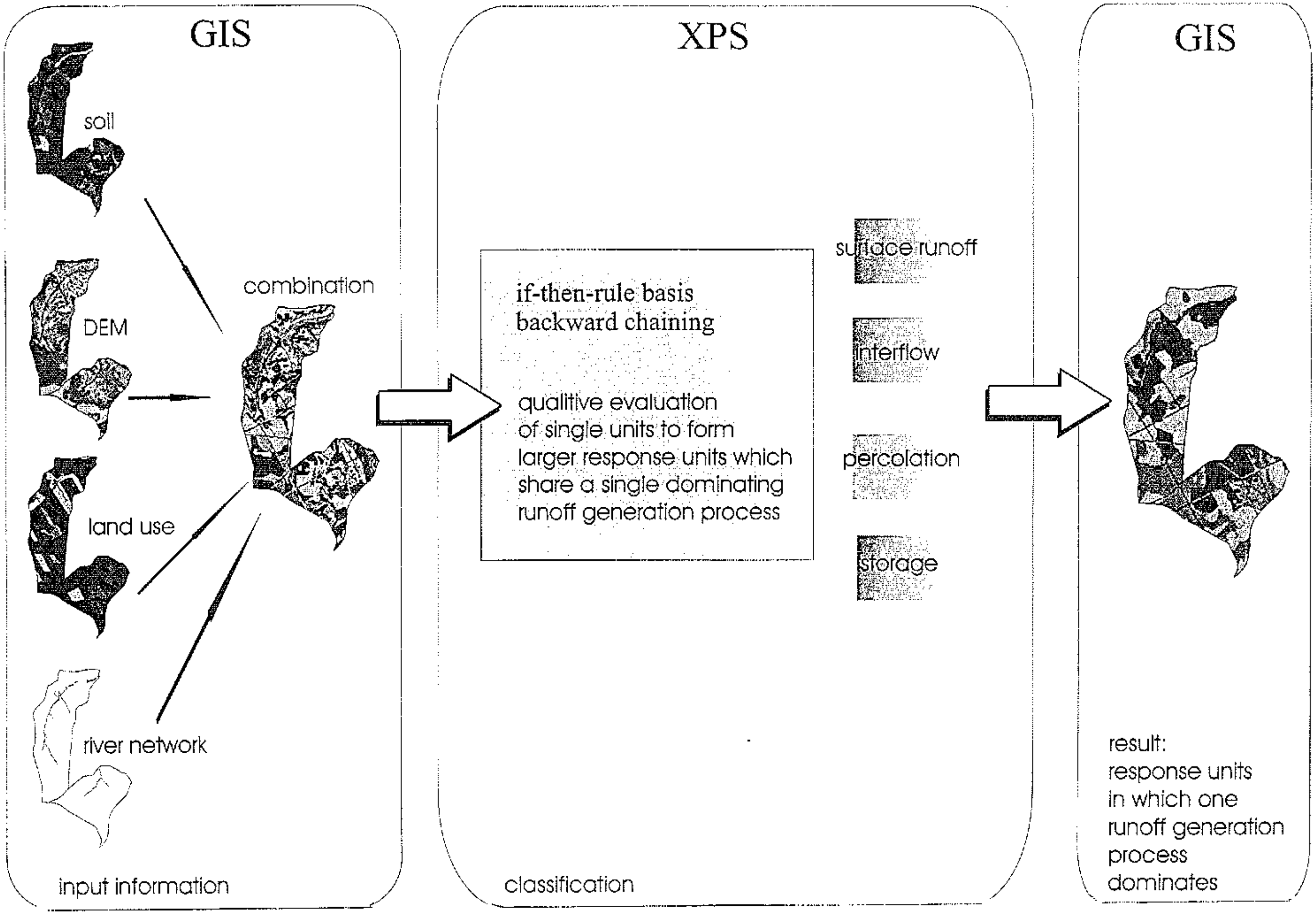

Fig. 5 Interrelationship between the GIS ARC/INFO and the rule based XPS.

Table 2 Example of a file with input information (excerpt).

Id. no.	Soil type	Stream network	Slope	Antecedent soil moisture	Humus content
1	Brown earth	Not known	1	1	6
2	Flood plain soil	Not known	5	n-rel	Not known
3	Pseudogley	2	3	Not known	12

The input information contains two files. The first of them comprises first of all the information about the areal units obtained by the GIS-overlaying, but it can be completed with further information by the user. Table 2 shows an excerpt of one example of input information. The second file comprises data of different precipitation events necessary for scenario-analyses in order to test areal responses to different precipitation impacts and thus to enable better classification.

The first rule block contains those rules that represent the output knowledge of physically based models as well as experiential knowledge obtained by long-term experimental observation. One example of a physically based rule is the necessary condition for generating Hortonian overland flow: the precipitation intensity must be greater than the saturated hydraulic conductivity of the topsoil. Table 3 presents examples of experiential knowledge. This first rule block is further divided into three sub-blocks corresponding to our rough assignment of the possible responses of an areal unit to a precipitation impact: overland flow (Hortonian and saturation excess), interflow, and infiltration and/or storage or groundwater recharge. The second rule block evaluates the result obtained from the three sub-blocks, and indicates the dominant process.

All the rules are if-then rules.

Output from the first rule block for a given area may show more than one response to a given precipitation impact. In such cases we seek the dominant or most probable response with the second rule block. GIS ARC/INFO then produces the graphic representation of the classification results.

Table 3 Conditions for generating Hortonian overland flow RO.

Height of ponding (mm)	Slope I	Potential RO (necessary conditions)	Micro-relief: 1 – effective, 0 – not effective	RO possible	Density of stream net-work (3 steps)	RO effective
0 – 1	all	no				
>1 – 3	>30°	yes	0	yes		
			1	no	3	RO
>3 – 5	>20°	yes	0	Yes		
			1	I >30° yes	3	RO
>5 – 10	>15°	yes	0	Yes		
			1	I >30° yes	2; 3	RO
>10 – 20	>10°	yes	0	Yes		
			1	I >20° yes	2; 3	RO
>20	all	yes	0	Yes		
			1	I >20° yes	2; 3	RO

RESULTS AND DISCUSSION

As mentioned above we limit ourselves in this paper to the identification of the two types of overland flow: Hortonian infiltration excess and saturation excess. The necessary condition for generating infiltration excess is only met on the roads with impermeable surfaces in the UWB- basin.

The criteria that must be fulfilled for an area to generate saturation excess are: the area must be flat (the decision whether slopes of less than 1°, or less than 3°, or less than 5° are defined as flat depends on the dominant soil type), have a soil type with poor permeability and/or shallow water table, and be closely connected to the stream network.

Results of the XPS-simulation are presented in Fig. 6, on the left-hand side for a dry state, on the right hand side for a very moist state. The chosen states approximate those of Fig. 1 and Fig. 3 respectively. It is clear that the TB-basin has only limited

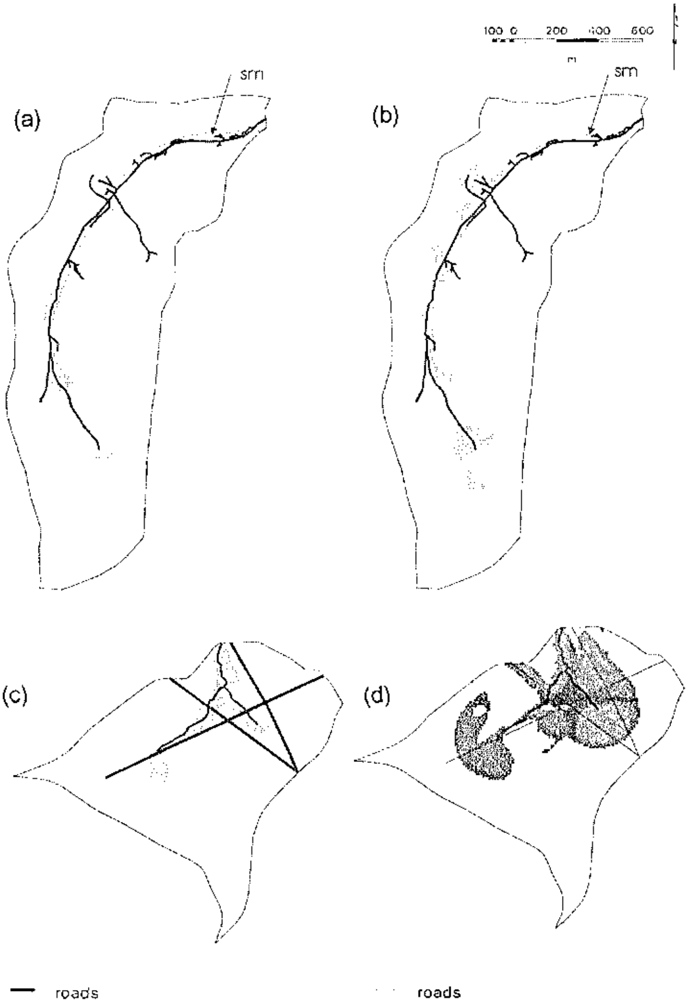

Fig. 6 Spatial distribution of overland flow simulated by the rule-based model. Left: low antecedent soil moisture, right: high antecedent soil moisture; upper part: Triebenbach basin, lower part: Upper Wernersbach basin. Hortonian overland flow—generated only on the roads of the UWB-basin—is only significant during dry conditions (c). The areas of saturation excess (shaded areas), increasing with soil moisture, extend in the UWB-basin (c) and (d) more than in the TB-basin (a) and (b). The arrow (sm) marks the soil moisture station (cf. Fig. 2).

ability to expand its saturated area. However, in the UWB-basin the contributing areas extend significantly with increasing moisture. Therefore these simulations confirm the conclusions that we draw from experimental findings.

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