

Hydrometric approaches to gain a better understanding of saturation excess overland flow

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Abstract This paper examines how hydrometric approaches can be used to obtain information about the spatial variability of runoff processes, especially saturation overland flow. This quick runoff component reflects the interaction between subsurface and surface flow and catchment features such as topography and soil properties, weather characteristics like rainfall intensity and amount, and antecedent soil moisture. We measured transects across the stream with both spatially integrated measurements and point measurements. This kind of experimental investigation provides data of a new quality and additional process knowledge needed for a better understanding of runoff production. With detailed mapping of the dominant runoff processes in combination with the most important influencing parameters, an improved construction of submodels becomes possible.

INTRODUCTION

Runoff production is an important environmental process, by which precipitation is divided into overland flow and infiltration, the infiltrated water into interflow, soil moisture storage and deep percolation. Surface runoff may originate either from precipitation intensity exceeding the soil infiltration capacity or from the rainfall amount exceeding available storage capacity of the soil profile. This saturation excess occurs on a variable contributing area (Dunne & Black, 1970; Dunne, 1978).

The factors affecting runoff production vary both spatially and temporally. A spatially distributed meteorological input, differing land use and management and heterogeneity of physical basin features combine to form a complex and variable system output. Temporal variability is mainly due to meteorological variables and changes in antecedent wetness. To capture this complexity, detailed knowledge of the main driving processes and their spatial and temporal variability is required. Such investigations need field data of a new quality, measured across a variety of basin scales.

A further demand for more and better data results from the application of mathematical models in hydrology. Models have become useful tools in many fields of hydrology, even though their usefulness as instruments to predict the impact of climate or land use change remains questionable, because these predictions refer to conditions outside the calibration period. The usual split-sample test to validate a model is then not an adequate test of the model structure (Klemes, 1986; Kuczera *et al.*, 1993). Many parameter sets may produce nearly identical streamflow predictions although the individual contributing variables may vary significantly, therefore new and more powerful calibration strategies are necessary (Refsgaard & Knudsen, 1996; Refsgaard,

1997; Mroszkowski *et al.*, 1997). Models also provide simulated catchment responses other than streamflow. If equivalent data became available, a better scrutiny of the model structure could be expected. Multiple response data are needed to better test the model structure including piezometric levels, soil suction, soil moisture, spring outflow and sub-basin streamflow.

In particular the objective of this paper is to improve a better understanding of saturation overland flow and to show how a model calibration using multiple response data may work.

AREA OF INVESTIGATION

We conducted our experimental research in the mountainous catchment of the Wernersbach brook (Fig. 1) (Peschke *et al.*, 1990; Etzenberg *et al.*, 1997; Peschke, 1997). This basin is located in eastern Germany (latitude of the centre 50°58'N,

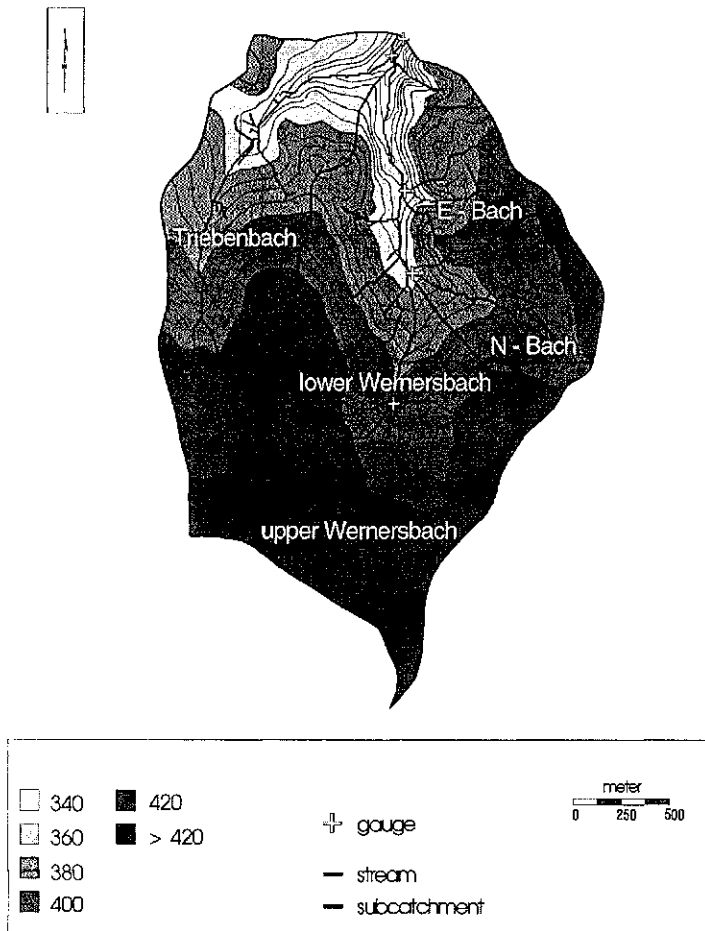


Fig. 1 The Wernersbach basin with zones of altitude, the main stream network and the sub-basins.

longitude 13°28'E, altitude from 322 to 424 m a.m.s.l.). The area is 4.6 km². The predominant rock is porphyry, but Cretaceous formations are also typical in this catchment. Some of these rocks form sandy soils with good infiltration properties and a low storage capacity, but they occupy only a small part of the catchment area. Quick lateral runoff components (overland flow, interflow) do not appear in these soils. The vertical exchange of moisture (infiltration, percolation, evapotranspiration) is dominant in these areas. The main part of the basin is covered by a cohesive skeletal soil (loamy

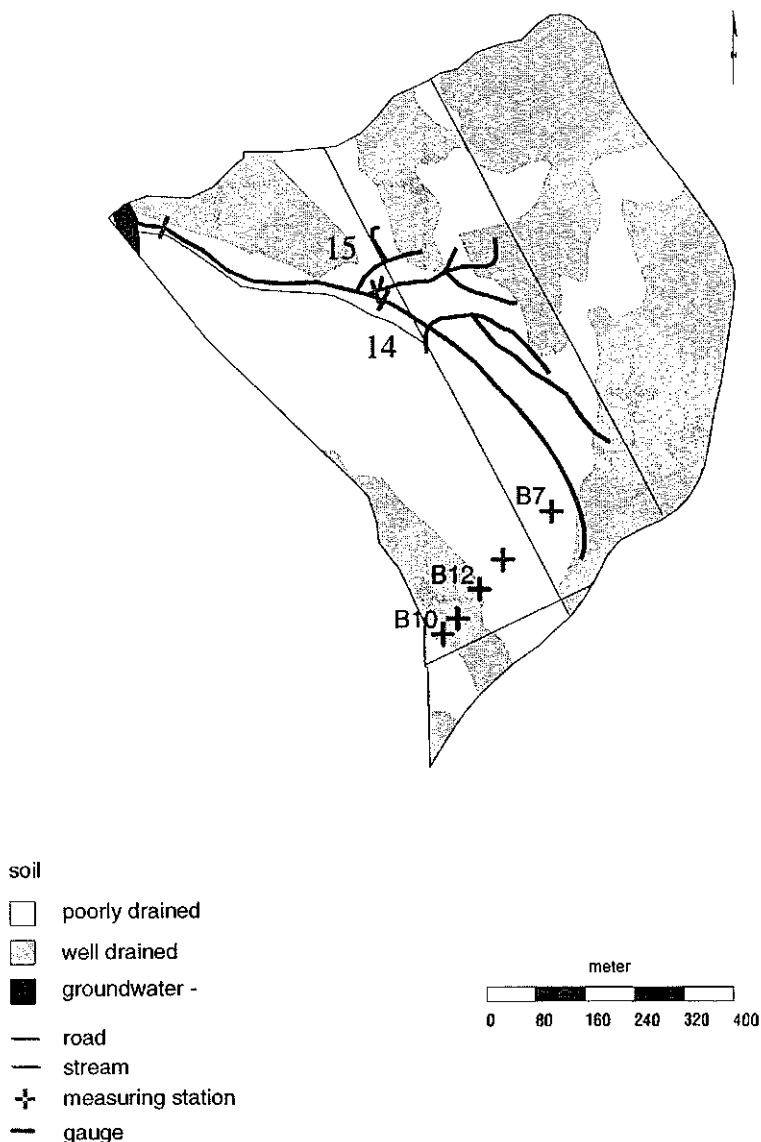


Fig. 2 The N-Bach sub-basin with some soil characteristics, the stream network, the transect of the measuring stations from B7 to B10 and gauging stations 14 and 15 further subdividing the sub-basin.

silt) and by loamy Pleistocene deposits. In near-stream areas there are clayey soils and shallow groundwater tables.

The Wernersbach basin is completely forested. Spruce [*Picea abies* (L.) Karst.] of different ages dominates and is mixed with deciduous species in some stands. The basin generates all types of runoff and has well-defined boundaries. The surface and subsurface watersheds differ only slightly, therefore water loss to adjacent areas appears minimal. A nearly impermeable bedrock reduces deep percolation.

Since the late sixties we have measured all meteorological variables driving the water cycle at two stations, the precipitation at six additional sites and the heat balance at two other locations. We record runoff at the basin outlet by using a wall across the stream valley that forces water to flow completely through the measuring station. In extended field studies soil properties, vegetation parameters and stream network have been mapped in detail (Etzenberg *et al.*, 1997).

The basin was subdivided into four sub-basins and partly subdivided again, thus creating a nested system of first- and second-order sub-basins. The main area we describe in this paper is the sub-basin N-Bach. Figure 2 shows this sub-basin, the soil types and a transect of measuring stations across the stream valley. Along this transect we measured the piezometric water level, the pressure potential and soil moisture.

RESULTS AND DISCUSSION

We analyse the flood discharge of events that occurred simultaneously in both basins. A statistical summary of the streamflow relationship between the entire Wernersbach basin and the N-Bach sub-basin is plotted in Fig. 3. Under dry catchment conditions, the different dominant runoff components lead to a great variety of the contribution of the N-Bach sub-basin to the Wernersbach runoff. With increasing moisture, the runoff

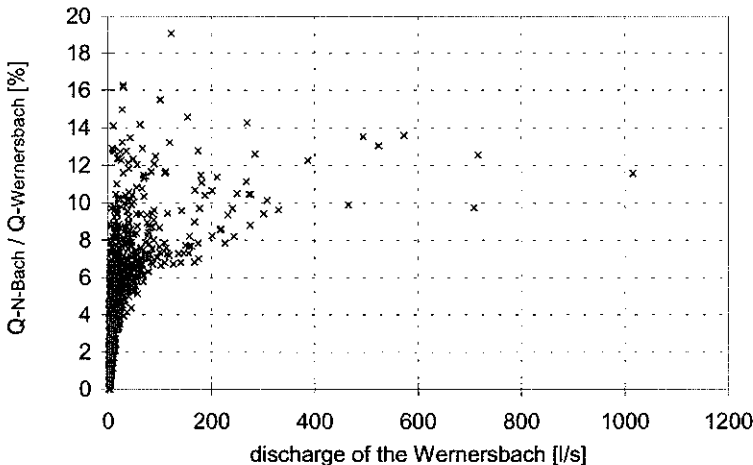


Fig. 3 Relation of the N-Bach flood discharge Q_{N-Bach} to the flood discharge of the whole Wernersbach basin $Q_{Wernersbach}$ (diurnal values) vs antecedent moisture state represented by the discharge of the Wernersbach brook at the beginning of the flood event.

generation becomes more uniform, and the percentage of the N-Bach streamflow on the Wernersbach discharge has an approximated boundary value of about 12%. This corresponds to the relationship of the areas of the basins.

The relation between catchment and subcatchment may be clarified by a detailed inspection of individual flood events as presented in Figs 4 and 5. The basin responses to the same storm event of the whole Wernersbach catchment and the adjacent Etzenbach and N-Bach sub-basins (cf. Fig. 1) are compared. Under dry basin conditions these responses are quite different (Fig. 4). At the driest point observed (8 June 1992) the N-Bach sub-basin was nearly completely drained, indicating a lack of significant reservoirs of slow runoff components. We observe a weak response to the first rainfall event compared to the steeper increasing hydrographs of the Wernersbach and Etzenbach. We hypothesize that a spatially variable zone of surface

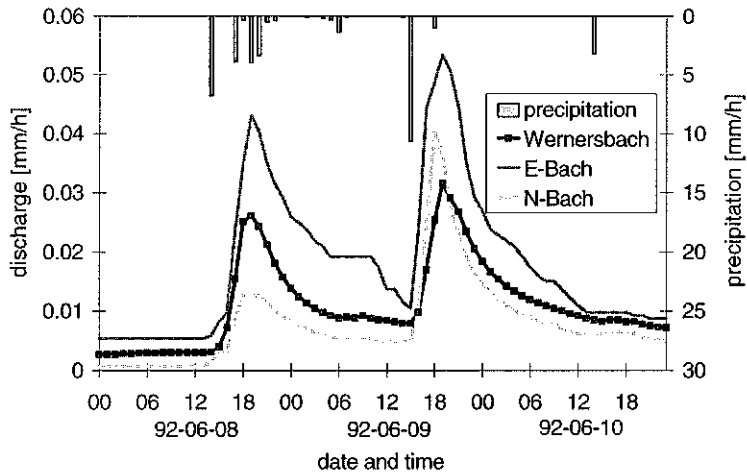


Fig. 4 Basin responses to the same two-peak storm event of the Wernersbach basin and the Etzenbach and N-Bach sub-basins.

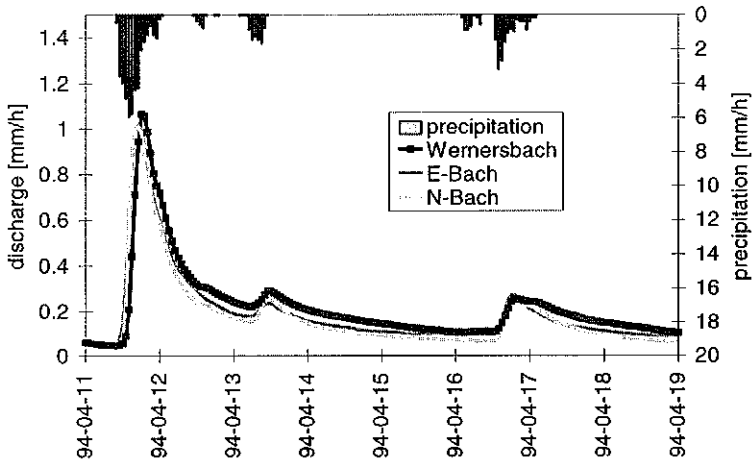


Fig. 5 Basin responses to the same heavy rainfall event after very moist pre-event conditions in the Wernersbach basin and the Etzenbach and N-Bach sub-basins.

saturated area can explain these results. The near-stream areas of the N-Bach offer good infiltration conditions and a shallow groundwater table. Approximately 20 mm of rain will activate small areas directly adjacent to the brook to produce saturation overland flow. In contrast to this situation, the antecedent soil moisture in the Etzenbach sub-basin is higher and thus the ability to generate saturation overland flow is greater. The hydrographs of the second rain event provide additional information: the N-Bach hydrograph exceeds the Wernersbach response, demonstrating the greater ability of the N-Bach basin to expand its saturated area. This can be confirmed by the observation that the N-Bach shows the greatest increase of the second peak discharge over the first one. If the wetting of the basins continues with both a large antecedent soil moisture and an increased amount of rain, the basin responses become similar (Fig. 5). In such a case, their shape is

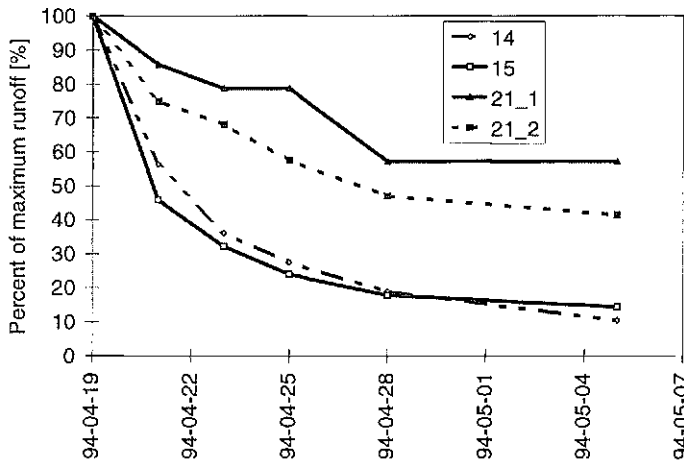


Fig. 6 Recession hydrographs of the two sub-basins (14 and 15) within the N-Bach sub-basin as compared with recession hydrographs of two sub-basins (21-1 and 21-2) within the Etzenbach sub-basin.

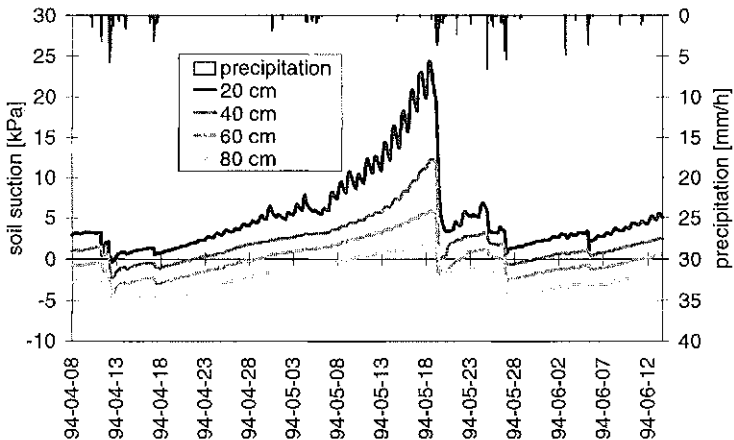


Fig. 7 Soil suction during and after the event in April 1994 measured at the B10 station.

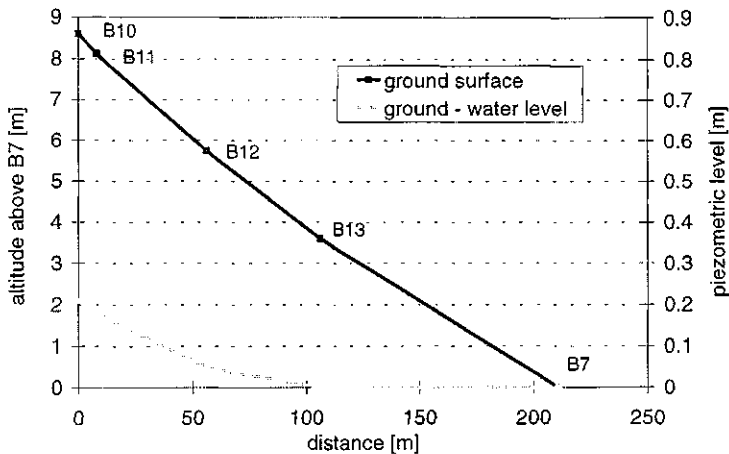


Fig. 8 Altitudes of the ground surface and the piezometric level along the B7 to B10 transect (cf. Fig. 3) during the April event in 1994. Near the B13 station the source area of saturation overland flow expanded during this extreme precipitation-runoff event.

governed primarily by the rain parameters, whereas the differences in the runoff generation mechanisms, caused by varied basin features are less significant. At this time the area contributing to the saturation overland flow had reached its upper limit.

In order to confirm this hypothesis we analyse measurements at the sub-basin and point scale. Figure 6 shows the recession of streamflow observed after the event in April 1994 (Fig. 5) at gauging stations 14 and 15 within the N-Bach sub-basin (cf. Fig. 2) as compared with the recession hydrographs at two sites in the adjacent Etzenbach sub-basin (cf. Fig. 1). The comparison shows a very fast drainage of the corresponding parts of the N-Bach sub-basin, confirming the absence of baseflow components, whereas the adjacent Etzenbach sub-basin is greatly influenced by slow runoff components.

On the basis of the preceding investigations, we interpret the dominant role of quick runoff components in the N-Bach sub-basin, to saturation overland flow. Finally, we examine this process knowledge using point measurements of soil suction at the B10 station (cf. Fig. 2) during and after the period of the event in April 1994 (Fig. 7). The pre-event conditions are characterized by nearly saturated soils. Only the tensiometers at depths of 20 and 40 cm indicate slightly unsaturated conditions. The piezometric level is 55 cm below ground. Following precipitation, the soil becomes saturated to a depth of 20 cm, and the saturated area expands from the near-stream region to the B10 station. From additional measurements of the suction, soil moisture and piezometric levels at stations along the transect B10 to B7 (cf. Fig. 2), we derived the piezometric level (Fig. 8). By comparing this with the surface slope we are able to determine the expansion of the saturation area and the groundwater level at each point of the transect. Because of the extremely high soil moisture during the April event the transect was at its maximum possible extension of the surface saturated area.

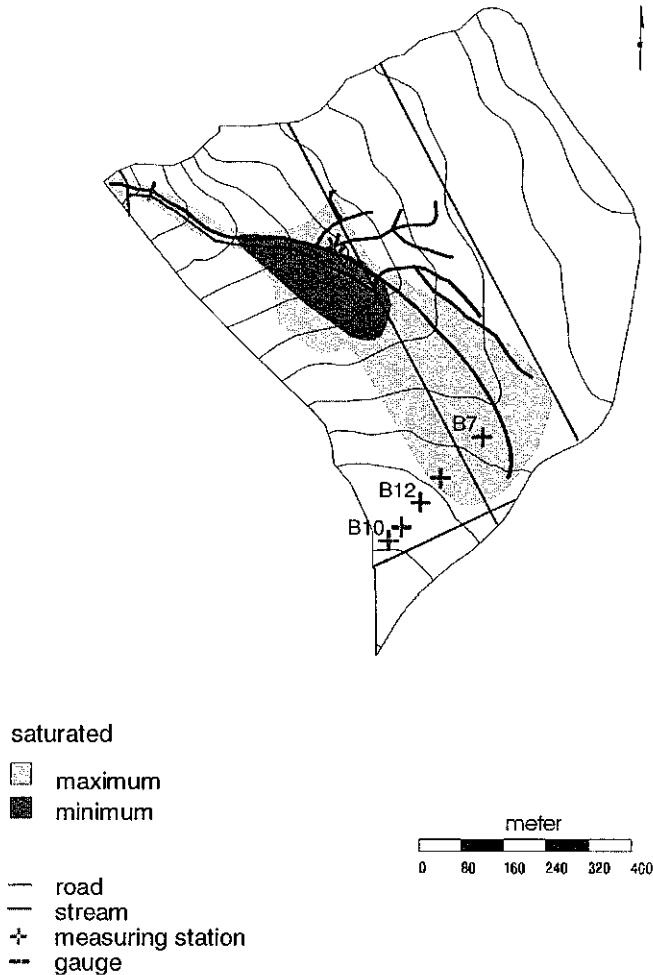


Fig. 9 Minimum and maximum source areas of the saturation overland flow in the N-Bach sub-basin.

Summarizing our knowledge gained through the evaluation of precipitation–runoff events in the basin, sub-basins of first and second order, and point scale, we conclude that there is no significant percentage of baseflow in the N-Bach sub-basin. Runoff production at the site is characterized by quick runoff components, in particular by saturation overland flow. This overland flow response does not occur immediately; considerable wetting is needed to reach its maximum possible contribution. This temporal development is associated with a significant expansion of the contributing source area of saturation overland flow.

We are now using the data collected in the GIS ARC INFO to interpolate the spatially discrete information about source areas of saturation overland flow (Fig. 9). Such a spatially distribution of saturation can be used in new calibration strategies (Peschke *et al.*, 1997, 1999).

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