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An analysis of the effects of spatial variability of soil and soil moisture on runoff

Bruno Merz
GeoForschungsZentrum Potsdam, Potsdam, Germany

Erich J. Plate
Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Karlsruhe, Germany

Abstract. Hydrological variables and processes usually exhibit a large spatial variability. Often this variability includes aspects of organization and randomness. Because any hydrological modeling has to deal with the question of spatial variability, methods that quantify the effects of spatial variability are valuable. Moreover, it is important to identify the situations where the spatial variability can be reduced (e.g., by using an "effective" value). For a small and well-instrumented catchment in a loess area in southwest Germany effects of spatial variability of the initial soil moisture and soil hydraulic properties on the runoff are investigated. The analysis is performed with a process-oriented rainfall runoff model. It is shown that organization in spatial patterns of soil moisture and soil properties may have a dominant influence on the catchment runoff. The simulations suggest that spatial variability can result in a complex, event dependent, behavior. It cannot be expected that a model with inputs based on mean parameters or mean initial conditions leads to mean outputs for heterogeneous fields. The analysis of different events shows the changing influence of spatial variability on the runoff with changing storm size. For very small and for large events spatial variability plays a negligible role. A large influence is found for medium-sized events.

1. Introduction

1.1. Spatial Variability and Runoff

Numerous field experiments have revealed that hydrological processes and parameters can show considerable spatial variability. Concerning soil parameters, *Warrick and Nielsen* [1980] compiled the results of different field studies and found coefficients of variation of 90–190% and 170–400% for saturated and unsaturated hydraulic conductivity, respectively. Because of the complexity of spatial patterns of soil, topography, meteorological boundary conditions, and vegetation, the soil moisture within a catchment is expected to be highly variable in space [e.g., *Lehmann*, 1995]. Determining if and how this variability should be considered in hydrological models is an active field of research. Recently, the scale-dependent nature of spatial variability has received increased attention [e.g., *Blöschl*, 1996].

Blöschl [1996] distinguished four aspects of spatial variability: (1) randomness, (2) periodicity, (3) discontinuity with discrete zones, and (4) convergence and preferential flow. Usually, the spatial patterns of hydrologic properties and state variables show aspects of randomness and organization. The high degree of organization often observed in natural catchments is attributed to interactions between ecosystem characteristics such as geology, topography, climate, and vegetation.

There is a large number of studies that have dealt with the effects of spatial variability. Demonstrations of the importance of organization in infiltration properties have been given by *Smith and Hebbert* [1979] and *Hawkins and Cundy* [1987]. *Freeze* [1980] used a stochastic-conceptual mathematical model of hillslope processes to study the influence of the spatial stochastic properties of the hillslope parameters on the statistical properties of the runoff events. He found that the representation of a heterogeneous hillslope by an "equivalent" homogeneous hillslope may lead to large errors in the statistical properties of the runoff. *Blöschl et al.* [1993] and *Grayson et al.* [1995] used the process-oriented rainfall runoff model THALES to investigate the effects of random and organized patterns of hydrologic variables on hillslope and catchment runoff. Similar questions were posed by *Kupfersberger and Blöschl* [1995] concerning groundwater flow. *Woolhiser et al.* [1996] showed that runoff hydrographs are strongly affected by trends in hydraulic conductivity. *Seyfried and Wilcox* [1995] pointed out that organization is commonly not captured in physically based, hydrologic models. *Merz and Bárdossy* [1997] used the process-oriented model SAKE (Simulationsmodell des Abflußverhaltens Kleiner Einzugsgebiete) to study the rainfall runoff behavior of a small loess catchment and showed the dominant influence of the spatial variability.

The work of *Wood et al.* [1988] on the scale-dependent nature of variability has been widely noticed. They introduced the concept of the representative elementary area (REA), which is defined as "a critical area at which implicit continuum assumptions may be used without knowledge of the patterns of parameter values although some knowledge of the underlying distributions may still be necessary" [*Wood et al.*, 1988, p. 31]. At scales smaller than the REA the actual patterns of variability are important in determining the hydrological response. At larger scales a statistical description of spatial variability should suffice. Recently, an increasing number of researchers have been dealing with the idea of the REA [*Blöschl et al.*,

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1995; *Fan and Bras*, 1995; *Woods et al.*, 1995]. *Fan and Bras* [1995] concluded that "the REA concept has limited utility in catchment hydrology" [*Fan and Bras*, 1995, p. 821] because of its dependence on storm characteristics and of the presence of multiscale heterogeneity. This aspect has been illustrated by *Seyfried and Wilcox* [1995] by discussing field examples. They argued that characterization of variability may change with scale. For each example, they found a deterministic length scale, which separates stochastic variability, described with stochastic methods, and deterministic variability, described with position-specific data. The examples showed that the deterministic length scale "depends on the scale of interest, the processes involved, and the local ecosystem characteristics" [*Seyfried and Wilcox*, 1995, p. 174]. *Blöschl et al.* [1995] performed process-oriented simulations for different assumptions of infiltration and precipitation. They concluded that the size of the REA will be specific to a particular catchment, climate, and application.

1.2. Purpose and Methods

The purpose of this paper is the investigation of the effects of spatial variability of infiltration parameters and initial soil moisture on the rainfall runoff process. Particularly, it looks at the role of event characteristics: Is there a threshold where the effects of spatial variability are decreasing to a negligible size? Because it has to be expected that effects of spatial variability depend on the particular application and catchment, this work concentrates on the rainfall runoff behavior in a particular catchment. The investigated catchment is a well-equipped, small catchment in southwest Germany. A process oriented model is used for simulating the runoff behavior. The base of the investigation is a large amount of collected field data. This paper is a continuation of the work of *Merz and Bárdossy* [1997]. By using the same modeling system and data and starting from their results, we extend their work to other types of spatial variability, to a larger area, and to other runoff events.

Section 2 contains an introduction of the study area and of the modeling system and describes the model application. Section 3 consists of four parts: the description of the heterogeneous fields and the effects of spatial variability at the subcatchment scale, at the catchment scale, and the event dependency of the effects of spatial variability. The paper closes with a discussion.

2. Study Area and Modeling

2.1. Description of the Study Area

The investigated area, the Menzingen area, is a subcatchment of the Weiherbach, which is located in the gently rolling Kraichgau region in southwest Germany. The Weiherbach catchment has been extensively investigated in the framework of a multidisciplinary research project which started 1989 and studies transport processes in rural areas. Since the beginning of the Weiherbach project much field data has been collected, for example, soil data and land use categories. Meteorological data is collected at a central measuring station. Precipitation is gathered at six rain gauges with a high temporal resolution. Once per week at 60 locations of the 6.3 km^2 Weiherbach catchment the soil moisture at four different depths is measured by the time domain reflectometry method. At different test hillslopes, soil moisture, water tension, and infiltration have been measured together with other variables for verification of hillslope and catchment models for simulating transport of water and substances like pesticides.

The Weiherbach catchment has a topography with smaller and steeper subcatchments in the eastern part and larger and less steep subcatchments in the western part of the basin. This valley asymetry was caused by periglacial processes in the Pleistocene, resulting in steeper west-facing, highly eroded slopes and gentler east-facing, loess-covered slopes. Figure 1 shows the topography of the Menzingen area (3.4 km^2). The area is dominated by intensive agricultural land use. Fifty-five percent of the area is covered with wheat and 3% is covered with forest; 3.5% is occupied with farmyards. The main soil types are loess soils (German taxonomy: "Pararendzina," "Parabraunerede," and "Kolluvium"). The Weiherbach catchment has a mean annual rainfall of 830 mm and a mean annual evaporation of 640 mm.

Figure 1 shows the location of the two discharge gauges and the division into 12 subcatchments with areas ranging from 4.5 to 54.1 ha. Typical time series of rainfall and discharge are plotted in Figure 2. Most simulations have been performed for subcatchment 5 (Neuenbürger Pfad), because for this area (32 ha) much more data have been collected compared to the other subcatchments. The brook in the Neuenbürger Pfad area has an ephemeral flow regime. In that area the groundwater table is approximately 25 m deep. At low rainfall intensities runoff is generated mainly by rain falling on small impervious areas near the gauge. At high intensities overland flow due to infiltration excess occurs. The hydrograph at the Menzingen gauge shows a constant base flow component, superimposed by very fast and high runoff peaks in case of intensive rainfalls. The base flow is relatively constant throughout the year. The mean annual runoff coefficient of the hydrological years 1992–1994 was 15%. Large runoff peaks occur in summer, mostly caused by short and intensive thunderstorms. Winter events with long duration and modest rainfall intensity lead to small runoff peaks. These observations agree with the collected data (e.g., infiltration experiments) showing that the main runoff-producing mechanism in the Menzingen area is infiltration excess overland flow. This is attributed to small infiltration rates of the loess soils, soil-crusting effects, and the lack of distinct impeding soil layers. At heavy rainfall, soil erosion has been observed. Within the hydrological years 1992–1994 the runoff coefficients ψ of 36 storm events have been analysed, after separating the base flow by the straight line method. For 30 events, ψ was smaller than 2% and for six times ψ was larger than 2%. The lag time to peak is in the order of 1 hour. Details about the Weiherbach project and the wealth of collected field data are given by *Plate* [1992].

2.2. Rainfall Runoff Modeling

2.2.1. Outline of the modeling system. For modeling the rainfall runoff process the model SAKE/FGM has been used. It consists of two components: SAKE and FGM.

SAKE (Simulationsmodell des Abflußverhaltens Kleiner Einzugsgebiete) is a quasi-three-dimensional, process-oriented rainfall runoff model for small catchments. A brief description of SAKE is given in section 2.2.2; for further details, see *Merz* [1996].

FGM (Flussgebietsmodell) is a software package for modeling the rainfall runoff behavior of river systems. Runoff production and concentration is modeled by system hydrological approaches. FGM is extensively used by practicing engineers in Germany and is described by *Plate et al.* [1988].

To simulate the direct runoff component of the Menzingen area, SAKE and FGM have been coupled. SAKE has been

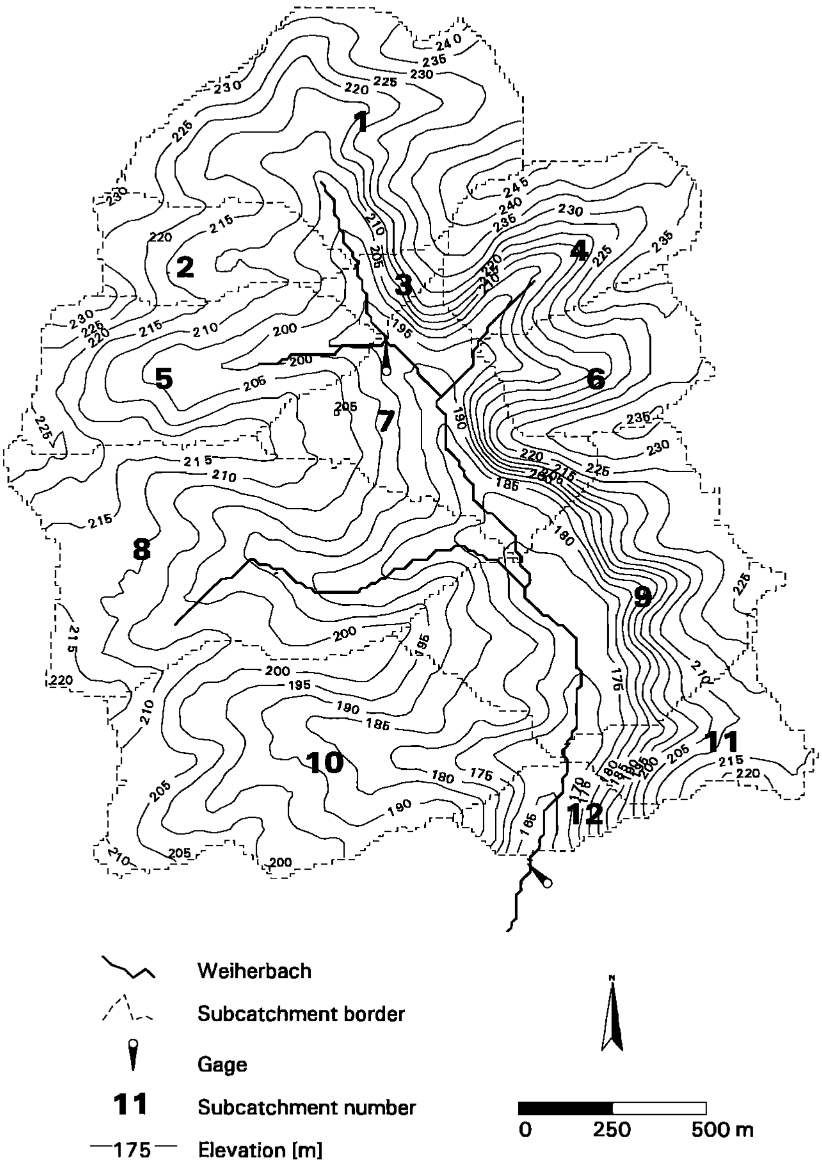

Figure 1. Topography, subcatchments, and discharge gauges of the Menzingen area.

used to simulate the subcatchment flow processes, and the resulting hydrographs have been linked by FGM. Runoff from the impervious areas of the farms and the flood routing in the Weiherbach brook have been calculated by FGM. The flood routing has been performed by the Kalinin Miljukov model [e.g., *Plate et al.*, 1977].

2.2.2. The process-oriented model SAKE. SAKE is a quasi-three-dimensional, process-oriented model. For the calculations in this study the following processes have been incorporated: interception, infiltration, overland flow, and flow in channels. For modeling interception a simple overflow model is used. The canopy storage capacity is calculated by the regression model of *Hoyningen-Huene* [1983] and depends on the leaf area index and the rainfall amount.

The one-dimensional infiltration module of SAKE considers infiltration into the soil matrix and into the macropores. The flow process in the macropores is governed by gravity, and effects of capillarity can be neglected. Macropores can lead to high infiltration rates, which have been observed in nature and cannot be explained by the matrix conductivity. Infiltration into the soil matrix is described by the potential flow theory. By use of the Richards equation [*Richards*, 1931], SAKE simulates the vertical soil water movement:

$$C\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K\frac{\partial h}{\partial z} - 1\right] + S_{mi} \quad (1)$$

where C is the specific moisture capacity, h is the matrix potential, K is the unsaturated hydraulic conductivity, z and t are the spatial (vertical) and temporal coordinates, and S_{mi} is a sink term. The soil hydraulic properties are incorporated by the model of *van Genuchten* [1980]:

$$\frac{\theta - \theta_R}{\theta_S - \theta_R} = \left[\frac{1}{1 + (\alpha h)^n}\right]^m \quad (2)$$

$$\frac{K(\theta)}{K_S} = \left(\frac{\theta - \theta_R}{\theta_S - \theta_R}\right)^{0.5}\left[1 - \left[1 - \left(\frac{\theta - \theta_R}{\theta_S - \theta_R}\right)^{1/m}\right]^m\right]^2 \quad (3)$$

with the saturated water content θ_S, the saturated hydraulic conductivity K_S, the residual water content θ_R, and the curve parameters n, α, and m ($m = (n - 1)/n$).

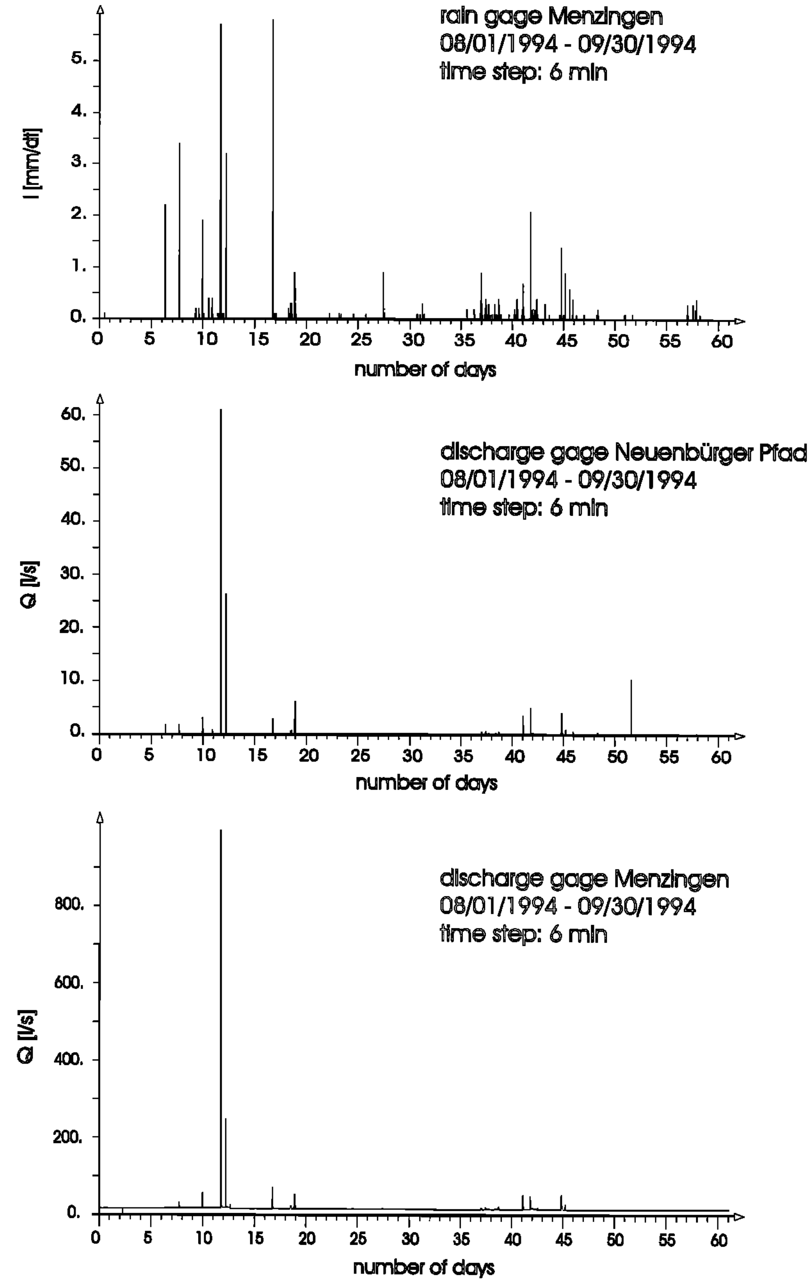

Figure 2. Time series of rainfall for the Menzingen area and of discharge measured at the gauges Neuenbürger Pfad and Menzingen.

Macropore infiltration is simulated by the kinematic wave approximation, proposed by *Beven and Germann* [1981]. The continuity equation for the macropore flow q_{ma},

$$\frac{\partial \theta_{ma}}{\partial t} + \frac{\partial q_{ma}}{\partial z} = S_{ma} \tag{4}$$

is combined with

$$q_{ma} = \alpha_{ma} \theta_{ma}^{\beta_{ma}} \tag{5}$$

where S_{ma} is the sink term of the macropore system, θ_{ma} is the macropore water content, and α_{ma} and β_{ma} are model parameters. At low rainfall intensities, all water infiltrates into the soil matrix. At rates higher than the matrix infiltration capacity, macropore infiltration starts. Ponding on the surface occurs when the rainfall rate is higher than the sum of matrix and macropore infiltration. The interaction between the two pore spaces is modeled assuming that water from the macropore system flows into the matrix according to the gradient of the hydraulic potential.

The two-dimensional overland flow module is based on the sheet flow assumption. To simplify the numerical treatment the diffusion wave model is used. The continuity equation reads

$$\frac{\partial h_o}{\partial t} + \nabla \cdot (\mathbf{v} h_o) = p - i \tag{6}$$

where h_o is the flow depth, $\mathbf{v}$ is the two-dimensional flow vector, p is the precipitation, and i is the infiltration rate. The simplified momentum equation reads

Table 1. Input Parameters for the Application of SAKE/FGM

Parameter	Symbol	Dimension	Value	Source of Data
		Interception		
Leaf area index	LAI	—	0–12	*Hoyningen-Huene* [1983]; *Maniak* [1993]
		Soil Hydraulic Parameters		
Saturated hydraulic conductivity	K_S	mm/h	3.0	*Montenegro* [1995]
Saturated water content	θ_S	cm^3/cm^3	0.40	*Montenegro* [1995]
Residual water content	θ_R	cm^3/cm^3	0.06	*Montenegro* [1995]
Curve parameter	α	1/m	1.5	*Montenegro* [1995]
Curve parameter	n	—	1.7	*Montenegro* [1995]
		Macropore Infiltration		
"Macropore system conductivity"	α_{ma}	m/s	0.5	*Merz* [1996]
Kinematic wave parameter	β_{ma}	—	2.0	*Germann and Greminger* [1981]
Macroporosity, forest	V_{ma}	%	2.0	···
Macroporosity, agricultural area	V_{ma}	%	0.4	···
		Overland Flow		
Manning's roughness coefficient	n	—	0.04–0.2	*Gerlinger* [1996], *Moore and Foster* [1990]
		Flood Routing Within Subcatchments		
Travel velocity	v_t	m/s	1.0	···
		Flood Routing (FGM)		
Manning's roughness coefficient	n	-	0.05	···

$$\nabla h_o + S_f = 0 \quad (7)$$

with S_f as the friction slope. S_f is evaluated using the Manning-Strickler resistance equation: $v = 1/nR^{2/3} S_f^{1/2}$. The hydraulic radius R is approximated by the flow depth h_o, and n is Manning's roughness coefficient.

For representing the flow in channels within subcatchments a simple translation approach has been chosen. Rainfall on the channel, or overland flow entering it, is simply transformed to the subcatchment outlet by a time lag. The travel time from each section is calculated using the distance to the outlet and a travel velocity. SAKE is intended to simulate the rainfall runoff process in small areas ($\leq$1 km^2). In such small areas channel flow has a very short response time. Because the processes with a longer response time dominate the runoff behavior, this simplified treatment has been adopted.

SAKE uses global and local time steps. Each process is independently simulated within the global time step, which has been set to 1 min. At the end of the global time step the global data is exchanged between the modules. In that way the different processes are coupled and for example, runon effects can be accounted for. The local time steps are chosen by the modules depending on the actual situation.

2.2.3. Model application. For simulating the runoff processes at the subcatchment scale, digital elevation data with a spatial resolution of 12.5 m were available. The data from a number of rain gauges, each having a temporal resolution of 6 min, have been used to obtain the rainfall input for the runoff events. For each subcatchment the rainfall time series have been obtained by the Thiessen polygon method. Within a subcatchment the rainfall has been assumed to be spatially homogeneous.

SAKE assumes that the leaf area index (LAI) and Manning's n for overland flow depend on the land use. LAI has been chosen according to literature data and n has been determined by erosion experiments [*Gerlinger*, 1997] and literature data. The parameter values and the data sources are listed in Table 1. *Montenegro* [1995] determined the soil hydraulic properties of the Weiherbach catchment by analysing soil samples, taken at different hillslope positions and depths. The data shows some relation between soil properties and morphometric position (e.g., increase of θ_S with upslope position). Because of the enormous variability of the samples, a clear relationship between morphometry and soil hydraulic properties is difficult to give. Therefore spatially constant values for the soil hydraulic parameters throughout the area have been chosen.

Concerning the influence of macropores on the infiltration in the Weiherbach area, *Merz* [1996] has shown that macropores are very effective in increasing infiltration rates during heavy rainfall. The most sensitive parameter of SAKE, given the characteristics of the Menzingen area, is the volume of the macropore system V_{ma}. V_{ma} of the agricultural areas has been selected as calibration parameter. Because the generation of the macropores in the Weiherbach catchment have mainly been attributed to worm activities [*Schmaland and Wohnlich*, 1992], no differences of V_{ma} for different crops have been made. Only for the small forested areas has a larger value for V_{ma} been chosen. The two remaining macropore infiltration parameters have been chosen from literature data.

As initial condition, SAKE needs an estimate of the soil moisture of every grid cell. For this purpose the measured soil moisture of the last measurement day before the rainfall event has been used for interpolating the areal moisture distribution. (The spatial interpolation of the soil moisture is documented by *Lehmann* [1995].) The periods from the soil moisture measurement day to the beginning of the rainfall event and from the end of the event to the next soil moisture measurement are bridged by an interevent module that keeps track of the soil moisture movement and the evapotranspiration [*Merz*, 1996].

As a first step SAKE/FGM has been applied to the subcatchment Neuenbürger Pfad. Five summer storms of the hydrological years 1992–1994 have been selected. The calibration parameter, the macroporosity of the agricultural areas V_{ma}, has been held constant for all five events. Good agreement between measured and calculated hydrographs has been obtained for V_{ma} = 0.4%, resulting in a mean correlation coefficient of 0.83 and model efficiency of 0.73 (efficiency criteria of *Nash and Sutcliffe*, [1970]). (Two examples are shown in

Figure 6; the measured hydrographs have to be compared to the solid hydrographs, marked by "S".) Using process-oriented models, it is desirable to control the simulation results against internal data. In the present study the soil moisture data set has been used for internal validation. However, in the Menzingen area the soil moisture is a crude indicator of the event model performance. The five events had runoff coefficients ψ smaller than 2%. For an event with $\psi = 2\%$ a change of the event model parameters which doubles the volume of the fast runoff component results in a reduction of the infiltrated volume from 98 to 96%. In view of the uncertainties of the measurements and spatial interpolation of the soil moisture, such small differences do not contribute to the assessment of the performance of the event model.

After calibrating the model for subcatchment Neuenbürger Pfad (32 ha), it has been applied to the whole Menzingen area (352 ha). For the Menzingen area no parameter tuning has been done. The same values as shown in Table 1 have been used. The three largest storms of the hydrological years 1992–1994 have been simulated and plotted in Figure 3. The event characteristics are listed in Table 2. A very good agreement can be seen for the large event (June 27, 1994) with a runoff coefficient of 11.3%. It should be more difficult to accurately simulate events with smaller runoff coefficients and worse results have been obtained for the two other events with runoff coefficients of 2.5 and 2.7%, respectively. Another reason for the good agreement of the June 27, 1994, storm may be that at that day soil moisture measurements took place. Therefore the initial conditions provided for SAKE should be closer to reality than in the case of the two other storms, where an interevent module for the estimation of the initial soil moisture has been used. In case of the July 21, 1992, event the first runoff peak is not simulated by the model. This fast reaction could be explained by saturated areas and/or impervious areas which are not properly accounted for in the model. Given the procedure for calibration and validation (calibration of the model in a small subcatchment and transfer of the model to the whole Menzingen area) and given the very small runoff coefficients, the model gives a good description of the runoff behavior in the Menzingen area.

3. Spatial Variability

3.1. Heterogeneous Fields

In the presented study the effects of spatial variability of initial soil moisture and of soil hydraulic properties are investigated. For both quantities, field studies usually show an enormeous heterogeneity, and a description of the spatial distribution is difficult to obtain. For both characteristics, three options have been compared: (1) structured (S) (the data exhibit a structure or organization within its spatial distribution), (2) random (R) (by swapping the location of every value of case S in a random manner, a purely random pattern is established), and (3) spatially constant (C) (the arithmetic mean is assigned to every grid cell in order to obtain a spatially homogeneous field).

Other types of spatially heterogeneous fields could have been chosen, for example, *Kupfersberger and Blöschl* [1995], *Blöschl* [1996], and *Merz and Bárdossy* [1997] investigated correlated random fields. This study is limited to the three types above which represent extreme cases: S shows a clear spatial organization, R is completely random without any organization, and C shows no variability at all.

3.1.1. Initial soil moisture. The spatial variability of the moisture content of the upper soil layers can be attributed to (among other things) variations in soil characteristics, topography, and water routing processes. Several field studies [e.g., *Zaslaysky and Sinai*, 1981; *O'Loughlin*, 1981; *Moore et al.*, 1988; *Western et al.*, 1996] found some correlation between soil moisture and topography. Particularly, saturated areas often correlate with zones of topographic convergence. Such findings have led to the development of wetness indices, which predict the soil moisture as function of topography. *Beven and Kirkby* [1979] introduced a topographic index ln $(a/\tan\beta)$ with a as the local drainage area and β as the slope angle. Similar indices have been proposed by *O'Loughlin* [1981] and *Barling et al.* [1994].

Lehmann [1995], A. Bárdossy and W. Lehmann (Spatial distribution of soil moisture in small catchment, 1, Geostatistical analysis, submitted to *Water Resources Research*, 1997), and W. Lehmann and A. Bárdossy (Spatial distribution of soil moisture in small catchment, 2, Influencing factor and temporal variability, submitted to *Water Resources Research*, 1997) used the soil moisture data set of the Weiherbach catchment to analyze the spatial distribution of the soil moisture and to interpolate areal distributions from point measurements by different geostatistical methods. Some of the methods allow the consideration of physical knowledge in estimating soil moisture maps. *Lehmann* [1995] concluded that for the Weiherbach data set, the most appropriate method is the combination of a procedure called Bayes Markov updating and the topographic index ln $(a/\tan\beta)$ as additional information. This combination gave the most plausible soil moisture maps and the best results of the cross validation. For example, the soil moisture map of the layer 0–60 cm in Menzingen at June 20, 1994, is shown in Figure 4. The method has been used to produce similar maps for other measurement days as initial soil moisture distribution.

3.1.2. Soil hydraulic properties. Soils are an integral part of the landscape, and an interaction between the soil and the landscape position can be expected. This idea was promoted by Milne with the introduction of the catena concept [*Hall and Olson*, 1991]. *Pennock and Acton* [1989] observed that the soil characteristics had a close relation to the water movement on a hillslope, which also depends on the vertical and horizontal curvature. A field investigation in the hilly loess region of north China [*Li et al.*, 1995] revealed a topographic zonation of the infiltration: The infiltration rate decreased from the hilltop to the hillslope and further to the gully wall. For the Weiherbach area, *Montenegro* [1995] reported a decrease of θ_S (water content at saturation) with downslope position. At present, the spatial distribution within the Weiherbach catchment is investigated in more detail [*Schäfer*, 1996]. First results show that erosion of clay particles at the hilltop and sedimentation at the hillfoot have led to a decrease of K_S (saturated hydraulic conductivity) with downslope position. To study the effects of spatial variability of soil properties, K_S and θ_S have been chosen as spatially variable properties. In order to obtain organized K_S and θ_S patterns, these parameters have been inversely related to ln $(a/\tan\beta)$. Lower K_S and θ_S values are associated with downslope locations. Figure 5 shows the assumed spatial distribution of K_S. A similar map has been produced for θ_S.

It should be noted that the methods for deriving the spatial distributions of soil hydraulic parameters and soil moisture are different. The maps of K_S and θ_S are produced by relating the parameters to the topographic index. The soil moisture maps are

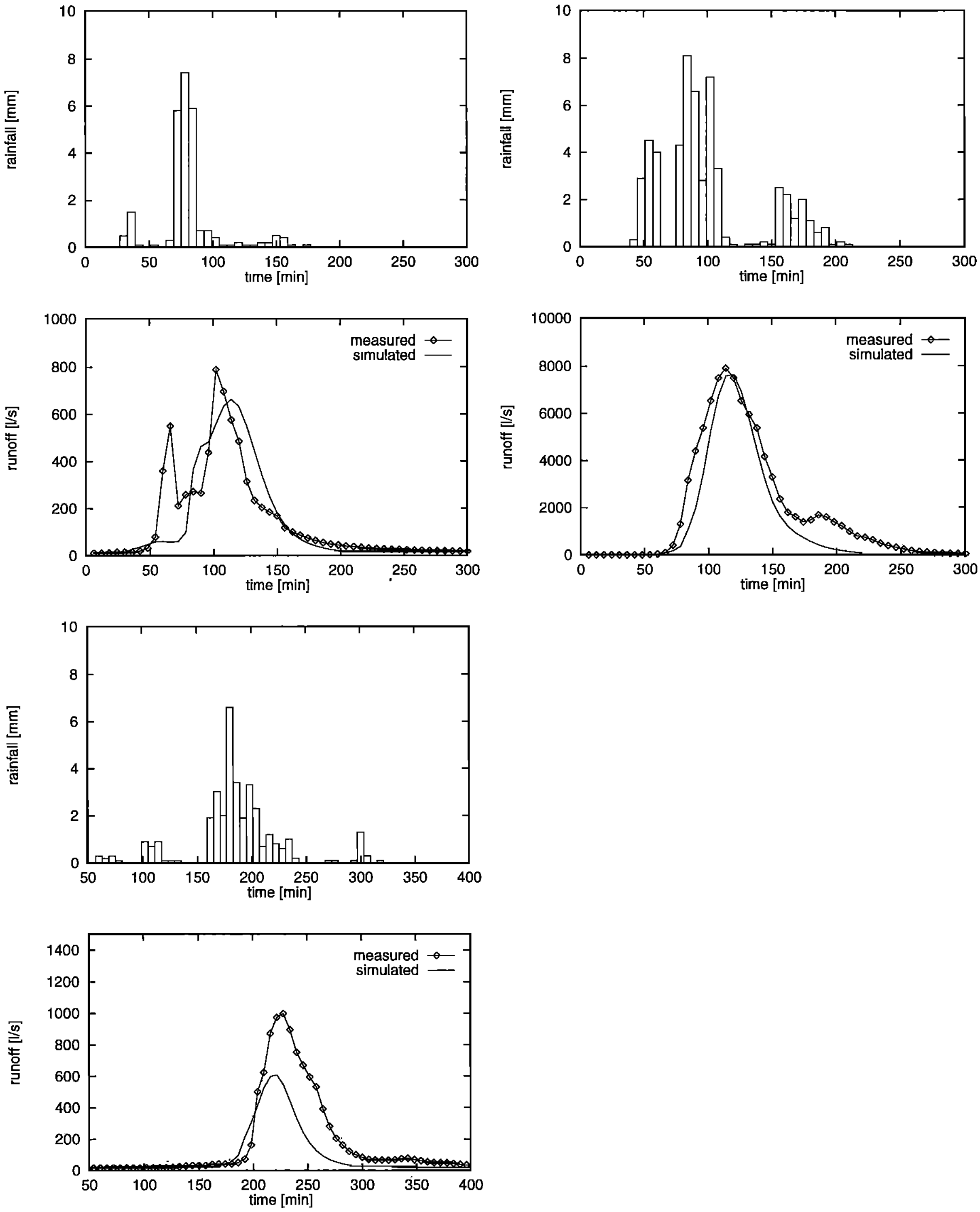

Figure 3. Comparison of measured and simulated runoff for three storms of the Menzingen area.

the result of an interpolation method based on up to 60 soil moisture measurements and on the topographic index as additional information. At the measurement location the value of the interpolated moisture map and the measured value coincide.

3.2. Simulation Results for Subcatchment Neuenbürger Pfad

To study the effects of spatial variability in the subcatchment Neuenbürger Pfad, the events of July 21, 1992, and August 12, 1994 (see Table 2), have been chosen. The combination of the two storms with three scenarios of spatially heterogeneous fields (initial soil moisture, soil hydraulic properties, soil moisture, and soil hydraulic properties) yields six different simulations, which are listed in Table 3. For each simulation the hydrographs resulting from the structured, the random, and the spatially homogeneous distributions have been plotted in Figure 6. For the random case, 50 realizations of the heterogeneous fields have been generated and 50 hydrographs have

Table 2. Characteristics of Three Summer Storms in the Menzingen Area

	July 21, 1992	June 27, 1994	Aug. 12, 1994
Rainfall, mm	26.7	83.0	34.8
Rainfall duration, hours	1.9	2.5	3.5
Mean initial soil moisture, vol. %	23	27	27
Runoff coefficient, %	2.5	11.3	2.7
Peak runoff, L/s	788	7899	997

been calculated. For a given time t, the 50 discharge values $(Q_1(t), Q_2(t), \cdots, Q_{50}(t))$ have been used to calculate the mean $(\bar{Q}(t))$ and the standard deviation $(\sigma_Q(t))$. For the random case, $\bar{Q}(t)$ and $\bar{Q}(t) \pm 2\sigma_Q(t)$ are plotted in Figure 6.

For the Menzingen area with usually low runoff coefficients, only a small part of the catchment contributes to the discharge at the outlet. Local variations in infiltration capacity, which depend on the soil, soil moisture, and land use, lead to different rates of infiltration excess. Moreover, overland flow, generated at locations further away from the channel, can reinfiltrate on its way downhill. These runon effects seem to be important in Menzingen where runoff coefficients are often smaller than 2%. Overland flow generation and runon effects lead to contributing areas which extend from the channel upslope. Their extent varies from event to event. The idea of the contributing area has been promoted earlier. *Betson* [1964] introduced the term "partial area concept": The catchment discharge results mainly from infiltration excess of impervious or less permeable areas, whereas the residual areas do not contribute. Later, this concept was transfered to other runoff generating mechanisms [e.g., *Dunne and Black*, 1970a, b] and named "variable contributing area," "dynamic watershed concept," or "variable source concept."

The second row of Figure 6 shows the influence of the spatial distribution of the initial soil moisture. For simulations A1 and A2, the structured case (S) yields much higher runoff than cases C and R. This large deviation can be explained by the contributing area concept. The soil moisture at locations adjacent to the channel is mostly higher for case S than for case C and R. This means that in case S more infiltration excess is generated at locations with shorter flow paths to the channel, which results in distinctively higher runoff rates for the structured soil moisture patterns. The difference between S and C for the event of July 21, 1992, is larger than for the event at August 12, 1994. This effect is caused by the different event characteristics: on August 12, 1994, there was a rainfall with a somewhat lower intensity, but a higher initial soil moisture. The measured runoff is approximately the same, but the contributing area for August 12, 1994, is larger than that for July 21, 1992, so that in this area the deviation between the soil moisture of cases S and C is smaller. This tends to decrease effects of spatial variability.

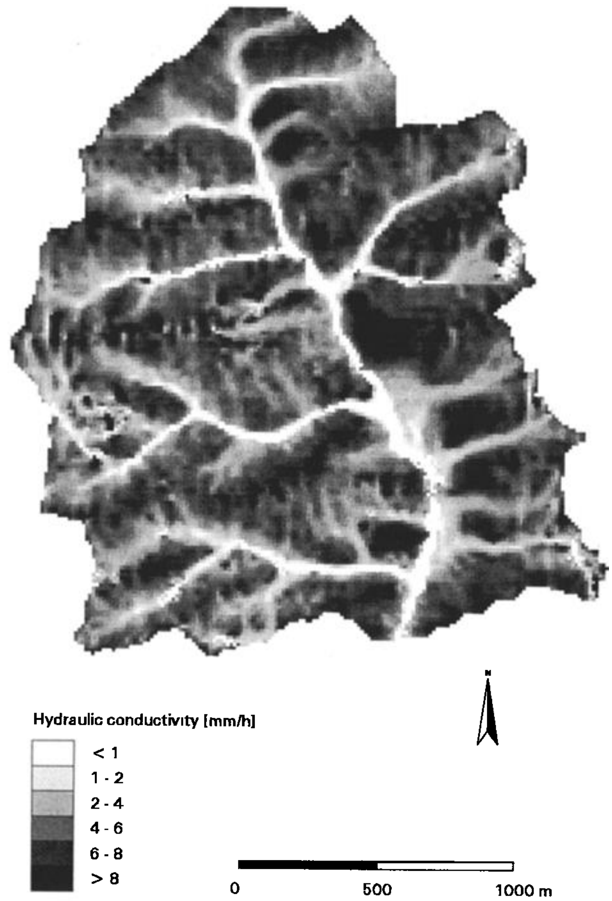

Figure 5. Assumed spatial distribution of saturated hydraulic conductivity.

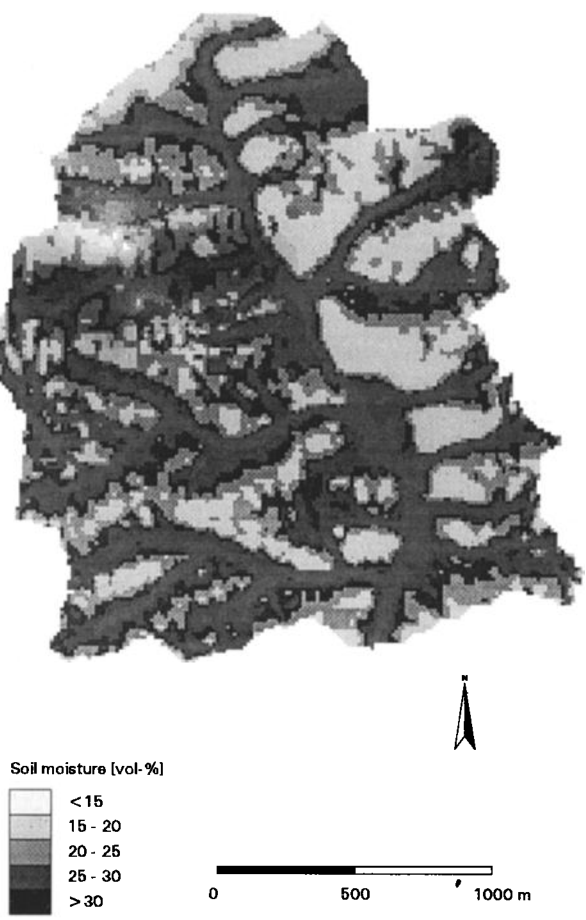

Figure 4. The measured/interpolated soil moisture of the 0- to 60-cm layer on June 20, 1994, in Menzingen.

Table 3. Simulations With Spatially Variable Soil Hydraulic Properties and/or Initial Soil Moisture

Spatial Heterogeneity	July 21, 1992	Aug. 12, 1994
Initial soil moisture	A1	A2
Infiltration parameters	B1	B2
Soil moisture and infiltration parameters	C1	C2

Comparing cases C and R, there is again some event dependency. For July 21, 1992, the mean random hydrograph almost equals case C. Even though, at a given location, the initial soil moisture can deviate dramatically from the mean, the catchment runoff process smoothes this variability. For August 12, 1994, the runoff of case R is much lower than the runoff of case C. Again, this phenomenon can be explained by runon effects and the size of the contributing area: The larger the contrib-

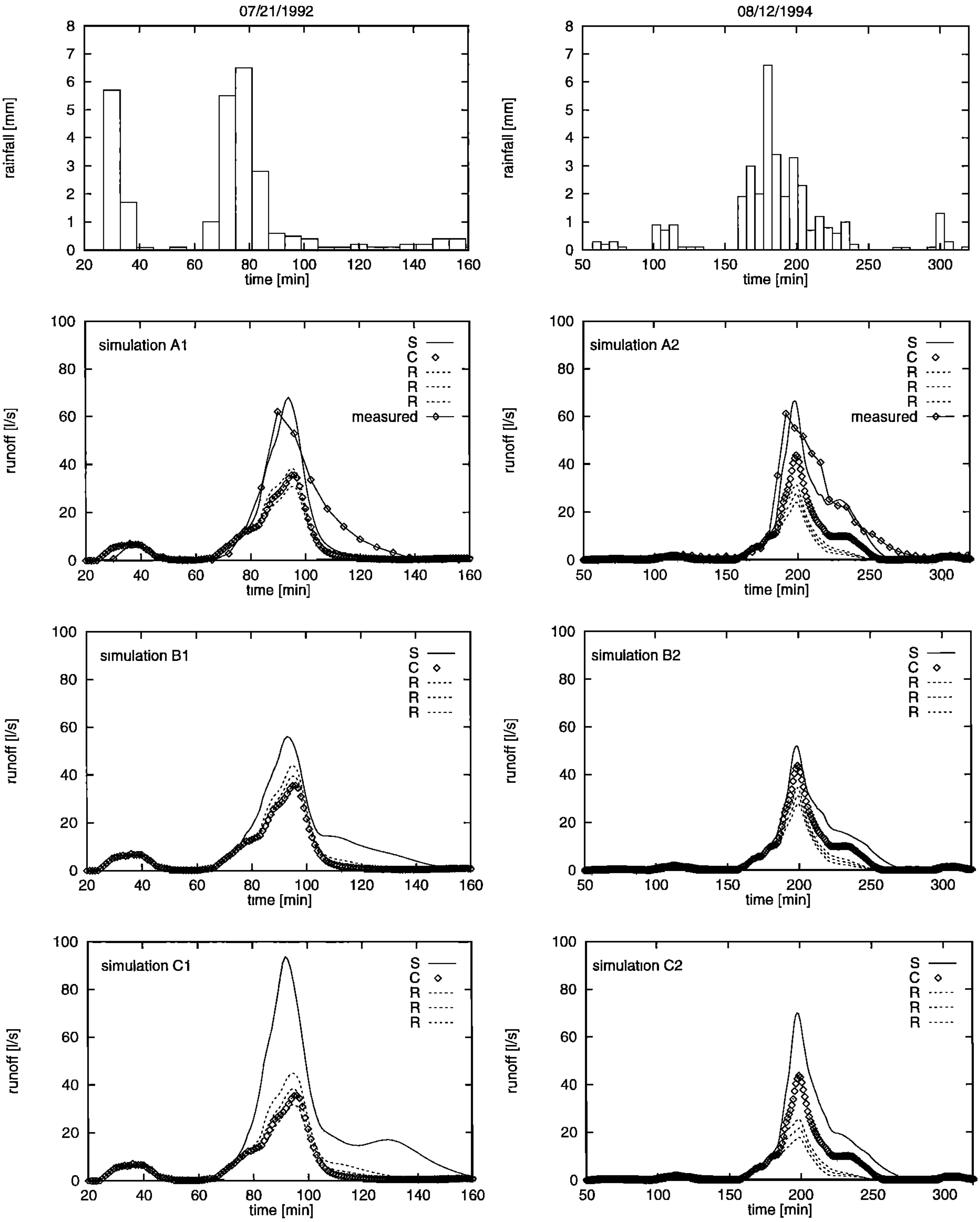

Figure 6. Subcatchment runoff resulting from different spatial patterns of initial soil moisture and soil hydraulic properties.

uting area, the longer are the flow paths and the larger is the possibility that an element with a very large infiltration capacity occurs along the flow path. This effect is superimposed on the different source areas for overland flow caused by the different spatial soil moisture patterns of S and C.

The third row of Figure 6 shows the results for the effects of spatially variable soil hydraulic properties, while the initial soil moisture has been assumed to be spatially homogeneous. Qualitatively, the same conclusions can be drawn. The inclusion of organization in the pattern of the soil properties increases the runoff. Because smaller K_S and θ_S values have been assumed at locations near the channel, more infiltration excess overland flow reaches the brook. However, this increase is much smaller than for the variable soil moisture case. The combined effects of initial soil moisture and soil hydraulic properties are shown in the bottom row of Figure 6. Organization in both fields increases the runoff which leads to runoff much higher than for cases C or R. Similar effects as for simulations A1 and A2 can be observed. These effects are much more pronounced because of the combined effect of soil moisture and soil hydraulic properties.

For all simulations of Figure 6 the $\pm 2\sigma_Q(t)$ range is very narrow: The hydrographs resulting from 50 realizations show only small variations. This means that at the given scale and for the given situation, the variability may be considered in a stochastic way, that is, by using the probability density function. It is not necessary to use the actual spatial distribution, that is, location-specific data.

From these simulations, and other simulations (other events and other heterogeneous fields) not shown here, it has to be concluded that for the given situation the effects of spatial variability on the runoff are very important.

3.3. Effects of Spatial Variability at the Catchment Scale

Simulations C1 and C2 which show the effects of spatial variability of initial soil moisture and soil hydraulic properties have been applied to different areas ranging from the subcatchment Neuenbürger Pfad (0.32 km^2) to the Menzingen area (3.52 km^2). For the subcatchment Neuenbürger Pfad it has been shown that the use of average values for soil moisture and soil hydraulic parameters may lead to large deviations in the runoff response. If the area is increased, local, random effects have smaller consequences on the runoff.

The relative difference in the runoff volume between the heterogeneous cases (structured case S and one realization of the random case R) and the homogeneous case C have been calculated:

$$\Delta V_Q^{S,C} = \frac{V_Q^S - V_Q^C}{V_Q^C}\,100\%$$

$$\Delta V_Q^{R,C} = \frac{V_Q^R - V_Q^C}{V_Q^C}\,100\% \qquad (8)$$

and plotted versus area. Figure 7 shows the values for the 12 subcatchments and for additional locations at confluences along the Weiherbach brook. For simulation C1 there is a wide range of $\Delta V_Q^{S,C}$ values. There are subcatchments with a very sensitive runoff response to the spatial pattern, and there are subcatchments where the spatial variability has a much smaller effect. At the outlet of the Menzingen area the difference in the runoff volume between S and C is 100%. This means that the consideration of the organization augments the runoff volume by 100% compared to the spatially homogeneous case. For case R a qualitatively similar behavior is shown in Figure 7, but the differences are much smaller. The same effects can be observed for simulation C2. It is interesting to note that even at the catchment scale the effects of spatial variability depend on the event (e.g., 100% and 20% for case S of simulation C1 and C2, respectively) and on the type of the spatial pattern (e.g., 100% and 10% for simulation C1 for cases R and S, respectively). Again, the larger influence on the runoff of case S of simulation C1 compared to C2 can be explained by the smaller contributing area of the event.

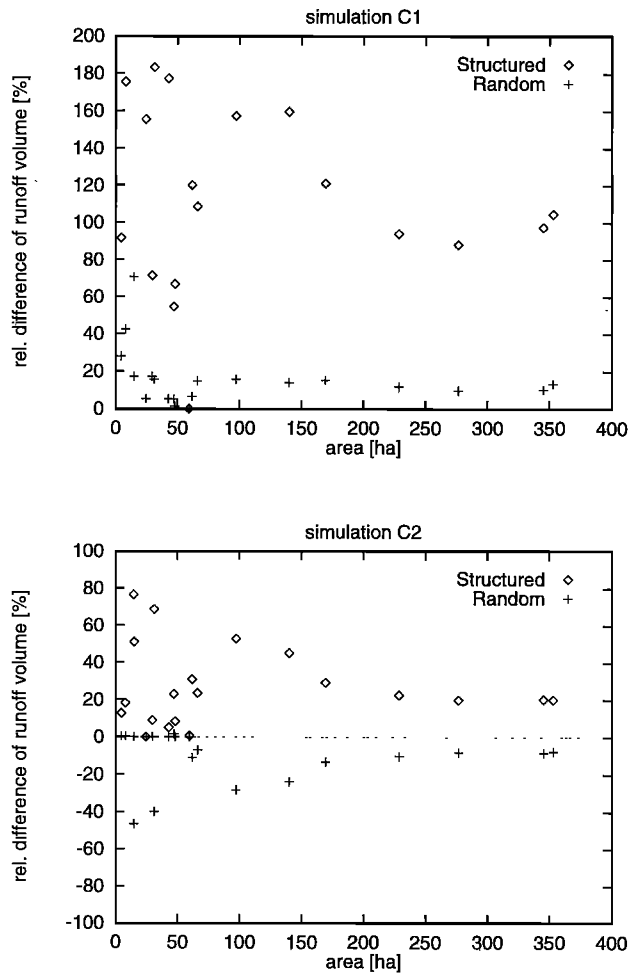

Figure 7. Difference in runoff volume resulting from spatially variable and spatially constant fields of initial soil moisture and soil hydraulic properties versus catchment area.

3.4. Event Dependency

The previous simulations showed that the effects of spatial variability are event dependent. *Grayson et al.* [1995] also found a large influence of storm characteristics (direction of moving storm and rainfall intensity) on the effects of random and organized initial conditions on catchment runoff. *Merz and Bárdossy* [1997] investigated the influence of different distributions of the initial soil moisture on the runoff. They found a large difference for a small runoff event, whereas the difference disappeared for a large event.

These observations lead to the question of whether there is a treshold above which the effects of spatial variability can be neglected. If such a threshold could be found, it would simplify the treatment of spatial variability in catchment hydrology. For events below the threshold the spatial variability has to be considered in detail, whereas for events above the threshold a simplified treatment or even a neglect of spatial variability should suffice.

Figure 8 shows the hydrographs of the subcatchment Neuenbürger Pfad for 10 rainfall runoff events, with the structured and the spatially homogeneous distribution of initial soil moisture and soil hydraulic properties. The different rainfall time series have been generated by stepwise decreasing or increasing the rainfall depth of a historical event while keeping the temporal distribution. Between events 1 and 10 there is an increase in peak flow of 2 orders of magnitude. For event 1 with low rainfall (20 mm), resulting in a very low peak runoff (Q_S = 9.5 L/s) and runoff coefficient (ψ = 0.3%), the two scenarios lead to almost identical hydrographs. Here mainly the precipitation falling directly onto the brook and on the impervious areas reaches the outlet. For rainfall event 2 the runoff peak of case S has more than doubled, while the hydrograph of case C has hardly changed. In case S the maximum rainfall intensity is large enough to generate infiltration excess on grid cells with low K_S and θ_S values and/or wet antecedent conditions. In case C the rainfall intensity has not yet reached this threshold. A further increase of the rainfall depth (which is tantamount to an increase in rainfall intensity) increases the difference between cases S and C. Starting from a rainfall height of 27.5 mm (event 4: ψ (case S) = 2.7%), the opposite effect can be observed: The differences in the hydrographs decrease until the hydrographs are quite similar (event 6: ψ (case S) = 7.3%). For larger events the spatial distribution effects the runoff only in a minor way.

For the runoff generation by infiltration excess, the ratio of the rainfall intensity to the "soil conductivity" (composed of matrix and macropore contribution under given antecedent conditions) determines the generation of overland flow. For storms 2–4 the values of rainfall intensity and "soil conductivity" are almost identical. Therefore runoff production is strongly effected by the spatial distribution of soil properties and initial soil moisture. For larger storms the rainfall intensity clearly exceeds the maximum infiltration rate and the spatial patterns of the "soil conductivity" are of lesser importance.

Figure 9 shows the difference in the runoff volumes of cases S and C for 40 rainfall events with a duration of 1.5 to 2.5 hours in two subcatchments versus the mean peak flow. Events of the same type (different only in rainfall depth) are assigned the same symbol and connected. Both areas show a similar behavior. For very small runoff events there is a very small influence of the spatial distribution. With increasing runoff this influence is increasing to large differences, until it descends again for large runoff values. The simulations shown in Figure 9 suggest a threshold (in terms of peak flow) of 350 L/s (11.2 L/s ha) and 900 L/s (18.8 L/s ha) for subcatchments 5 and 9, respectively.

4. Discussion and Conclusions

Hydrological state variables and processes usually exhibit a large spatial variability. Often this variability includes aspects of organization and randomness. For fields with large heterogeneity it is difficult to obtain a good mean value, it is more difficult to get a more complete stochastic description (e.g., higher-order moments, correlation structure), and the most difficult task is to obtain location-specific patterns. Because any hydrological modeling has to deal with the question of spatial variability, methods which quantify the effects of spatial variability are needed. Moreover, it is important to identify the situations where the spatial variability can be incorporated in a simplified way (e.g., by using the mean value): What effort has to be spent in order to get a satisfactory representation of the spatial variability?

For a small and well-instrumented catchment in a loess area in southwest Germany effects of spatial variability of the initial soil moisture and soil hydraulic properties on the runoff have been investigated. The analysis has been performed with a process-oriented rainfall runoff model. The model parameters have mainly been chosen according to field measurements and literature data. One infiltration parameter, the macroporosity of the acricultural areas, has been used as calibration parameter. By calibrating the model in a subcatchment (0.32 km^2) and transfering the calibrated model to the catchment (3.52 km^2), a good model performance has been obtained.

At the subcatchment scale the inclusion of organization strongly influences the runoff. The simulations show a strong event dependency: The inclusion of organization leads to a much larger increase in runoff for a thunderstorm with dry antecedent conditions compared to a storm with higher initial soil moisture and somewhat lower rainfall intensity. This difference can be explained by the different size of the contributing area. For the thunderstorm event the source areas for overland flow generation are expected to be smaller. The smaller the contributing area, the more it concentrates around topographic convergence zones which tend to produce more overland flow because of the spatial patterns of soil moisture and soil properties. An opposite effect can be observed for the random fields. For the thunderstorm event the mean runoff hydrograph resulting from 50 realizations resembles the hydrograph of case C (spatially constant). For the event with a larger contributing area case R (random) yields less runoff than case C. Here the larger contributing area and the longer flow paths lead to a higher possibility that an element with a large infiltration capacity occurs along the flow path which reduces the overland flow by runon infiltration. At the catchment scale different spatial patterns may also lead to large deviations in the runoff. The simulations suggest that spatial variability can result in a complex, event-dependent behavior. It cannot be expected that a model with mean parameters or mean initial conditions represents the mean behavior resulting from heterogeneous fields.

The analysis of different events showed that effects of spatial variability are small for very small and for large runoff events. A large influence has been found for medium-sized events. For events with low rainfall intensity, mainly the impervious areas contribute and the effects of spatial variability are small. Increasing the rainfall intensity leads to a sensitive range with a small difference between rainfall intensity and "soil conductivity." Under these conditions, runoff is very sensitive to the spatial pattern of infiltration. A further increase of the rainfall intensity leads to an expansion of the source areas for overland flow generation and to a smaller influence of the spatial pattern of infiltration.

It should be noticed that these findings are obtained from measurements and simulations in a small catchment which is distinguished by infiltration excess overland flow as main runoff generating mechanism and small runoff coefficients. Furthermore the assumed spatial patterns of the soil hydraulic properties may be criticized as not very realistic. However,

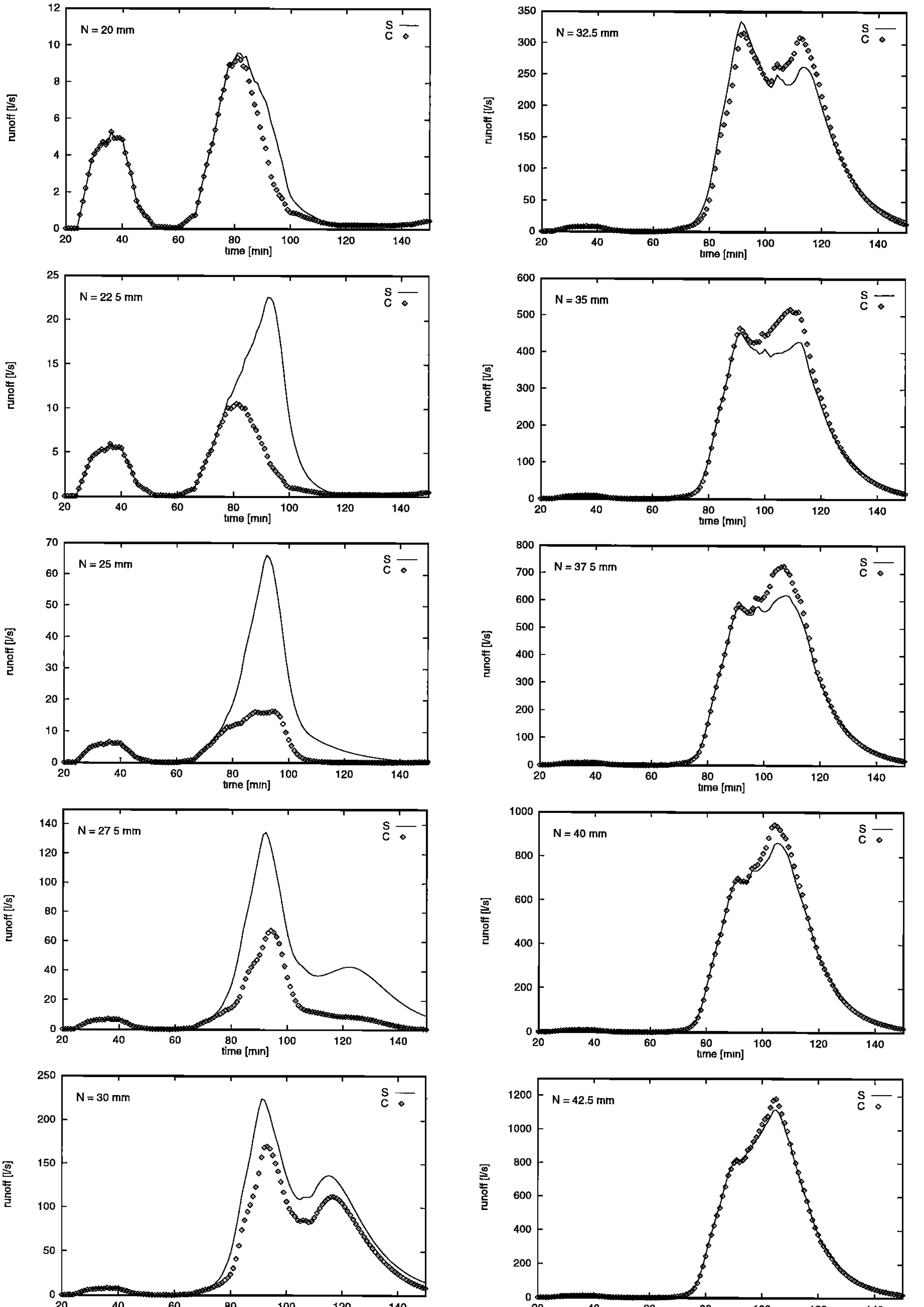

Figure 8. Hydrographs simulated for structured and spatially homogeneous distribution of initial soil moisture and soil hydraulic properties for events with different rainfall depth.

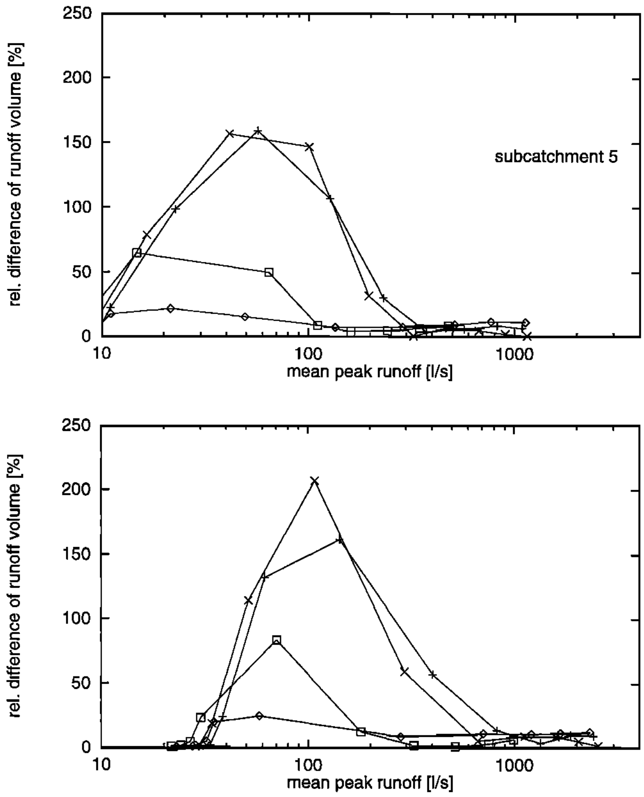

Figure 9. Difference in runoff volume for structured and spatially constant distribution of initial soil moisture and soil hydraulic properties as function of mean peak runoff for 40 events in two subcatchments.

Merz and Bárdossy [1997] studied the influence of other spatial patterns of soil parameters on the runoff in the subcatchment Neuenbürger Pfad, and their results agree with the present study.

The analysis indicates that organization in spatial patterns of soil moisture and soil properties may have a dominant influence on the catchment runoff. Furthermore, the changing influence of the spatial variability with changing storm size is shown. The simulations suggest that for the Menzingen area the spatial variability of soil moisture and soil properties may be neglected for storms with a return period larger than 10 years. If the task is to predict floods with return periods larger than 10 years, it is not necessary to invest much manpower or money for deriving the spatial distribution.

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B. Merz, GeoForschungZentrum Potsdam, Telegrafenberg A 17, 14473 Potsdam, Germany. (e-mail: bmerz@gfz-potsdam.de)

E. J. Plate, Institute for Hydrology and Water Resources Planning, University of Karlsruhe, Kaiserstrasse 12, 76128 Karlsruhe, Germany.

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