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Transition from the point scale to the small catchment scale: exemplified on the Weiherbach catchment

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Abstract The rainfall runoff process of a small catchment is described by developing the catchment model step by step from the point to the catchment scale. The concept is based on the view that it is, to a certain extent, possible to transfer results obtained at a smaller scale to a larger one. The paper gives an overview of the transition from the point to the small catchment scale for the Menzingen/Weiherbach catchment. At every scale the modelling concentrates on the important processes and on the appropriate representation of those processes.

INTRODUCTION

Hydrological models have to be applied at a wide range of scales. There is no model which is suitable for the whole range. At different scales the importance of hydrological processes may change, which can be illustrated by the example of flood routing. The runoff behaviour of very small catchments is dominated by hillslope processes. With increasing scale the influence of flood routing processes increase relative to the influence of the hillslope processes, which should be reflected in the model structure. Furthermore, at different scales different methods for describing the hydrological behaviour are applicable. Often at a small-scale physically based descriptions are chosen. With increasing scale much larger abstractions are appropriate. On the one hand the efforts necessary for a detailed physically based description may set limits, but on the other hand, new mechanisms may evolve at the larger scale which may conceal small-scale effects. From this discussion it follows that a scale dependent description should be sought.

The purpose of the present work is a scale dependent description of the rainfall runoff process in small catchments. Modelling starts at the point scale and continues to the grid scale, the subcatchment scale and the small catchment scale. The models and the consideration of spatial variability change from scale to scale. The concept is based on the view that it is possible to transfer results obtained at a smaller scale to a larger one.

The concept is exemplified in the Menzingen/Weiherbach basin, which is located in the gently rolling Kraichgau region in the southwest of Germany. The Menzingen area is a loess catchment with a size of 3.4 km^2. The area is dominated by intensive agricultural land use. The main runoff producing mechanism in the Menzingen area is infiltration excess overland flow. Details of the basin can be found in Plate (1992).

This paper focuses on the ideas underlying the project. For each spatial scale the dominant features and the investigations performed are outlined briefly, and followed by an example. Finally, the consequences for the larger scales are listed. Details can be found in Merz (1996), Merz & Bárdossy (1998) and Merz & Plate (1997).

POINT SCALE

Dominant features and investigations

At the point scale only vertical processes have to be considered. Infiltration is the dominant feature with regard to rainfall runoff behaviour and because of the small spatial extent, homogeneous soil properties are assumed. Within this project an infiltration model based on the one-dimensional (1D) vertical Richards equation (Richards, 1931) has been developed. The parameterization of such models is important. By performing a sensitivity and uncertainty analysis (Hornberger & Spear, 1981) the most sensitive parameters have been identified and the uncertainty of the model predictions determined.

Example: Uncertainty analysis

For the parameterization of the soil hydraulic properties Van Genuchten's method (1980) has been chosen. This uses five parameters: saturated water content θ_S, saturated hydraulic conductivity K_S, residual water content θ_R, and the curve parameters n and α. These parameters cannot be given with certainty. They have been assumed to be random variables with typical probability density functions and statistical parameters taken from Carsel & Parish (1988) (Table 1), and a Monte-Carlo simulation has been performed. Homogeneous initial soil moisture conditions (0.24 $cm^3\ cm^{-3}$) and a heavy rainfall (rainfall depth: 55 mm, duration: 3 h) have been chosen. Figure 1 shows the median (50%-quantile), the 1σ (16%, 84%) and 2σ (2.25%, 97.75%) quantiles of the soil moisture at the end of the rainfall event. The wetting front of the median moisture profile has reached a depth of 15 cm, compared to 45 cm depth of the wetting front of the 97.75-quantile. In addition, the histogram of the runoff coefficient in Fig. 1 illustrates the large uncertainty.

Consequences for larger scales

The simulations show that, for the level of data usually available, even predictions with a physical basis contain large uncertainties. To assess the reliability of simulation results these uncertainties should be quantified. Furthermore the sensitivity analysis

Table 1 Statistical parameters and probability density functions for the soil hydraulic parameters of a silt loam soil (Carsel &Parish, 1988).

	α (cm^{-1})	n	θ_R (cm^3 cm^{-3})	θ_S (cm^3 cm^{-3})	K_S (cm h^{-1})
μ	0.020	1.41	0.067	0.45	0.45
σ	0.012	0.12	0.015	0.08	1.23
pdf	lognormal	normal	normal	normal	lognormal

yielded the following ranking of the importance of the soil hydraulic parameters: K_S, θ_S, α, n, θ_R. This order resulted from simulations with rainfall and soil data leading to infiltration excess overland flow. However, in catchments with other runoff generating mechanisms this order may change. This result has been used at larger scales, e.g. when looking at the influence of the spatial distribution of soil hydraulic properties at the grid scale, only the influence of the most sensitive parameter K_S has been investigated.

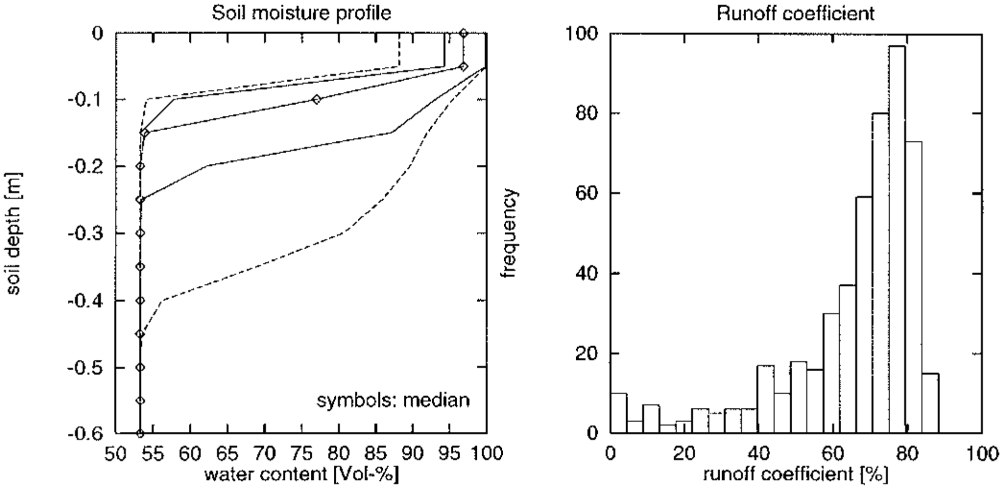

Fig. 1 Model uncertainty of soil moisture (2.25, 16, 50, 84 and 97.75% quantiles) and of the runoff coefficient, given uncertain soil hydraulic properties.

GRID SCALE

Dominant features and investigations

In the present work the grid scale is considered to have a horizontal extension of about 10 m. This magnitude is given by the resolution of the data in the Weiherbach basin. Within such an area, spatial heterogeneity has to be considered because of small-scale variability of the soil matrix and because of the influence of macropores. To study the influence of the small-scale variability on the mean infiltration, heterogeneous three-dimensional (3D) K_S-fields have been generated by Turning Band Simulations (Bras & Rodriguez-Iturbe, 1985). The 1D-Richards based model has been extended to a 3D version and 3D-flow fields have been simulated. The average flow behaviour has been compared to simulations with averaged or effective parameters.

The actual spatial correlation length for soil properties in a given area is very difficult to determine. To cover the whole possible range three correlation lengths have been assumed for the vertical direction: (a) the vertical correlation length $\lambda_v = 0$, i.e. there is no spatial correlation; (b) $\lambda_v = 0.25L_v = 0.25$ m, i.e. the correlation length equals 1/4 of the vertical extend of the flow field L_v; and (c) $\lambda_v >> L_v$, i.e. the flow field can be considered as vertically homogeneous. Similar assumptions have been used for the horizontal directions, yielding nine cases. Figure 2 illustrates a vertical profile of one realization for each of the three cases and gives an impression of the large range of heterogeneous fields considered in the analysis.

Furthermore the 1D-infiltration model has been supplemented with a macropore module, based on the kinematic wave approach proposed by Beven & Germann (1981). Data from 60 rainfall experiments were used to investigate infiltration into a natural soil.

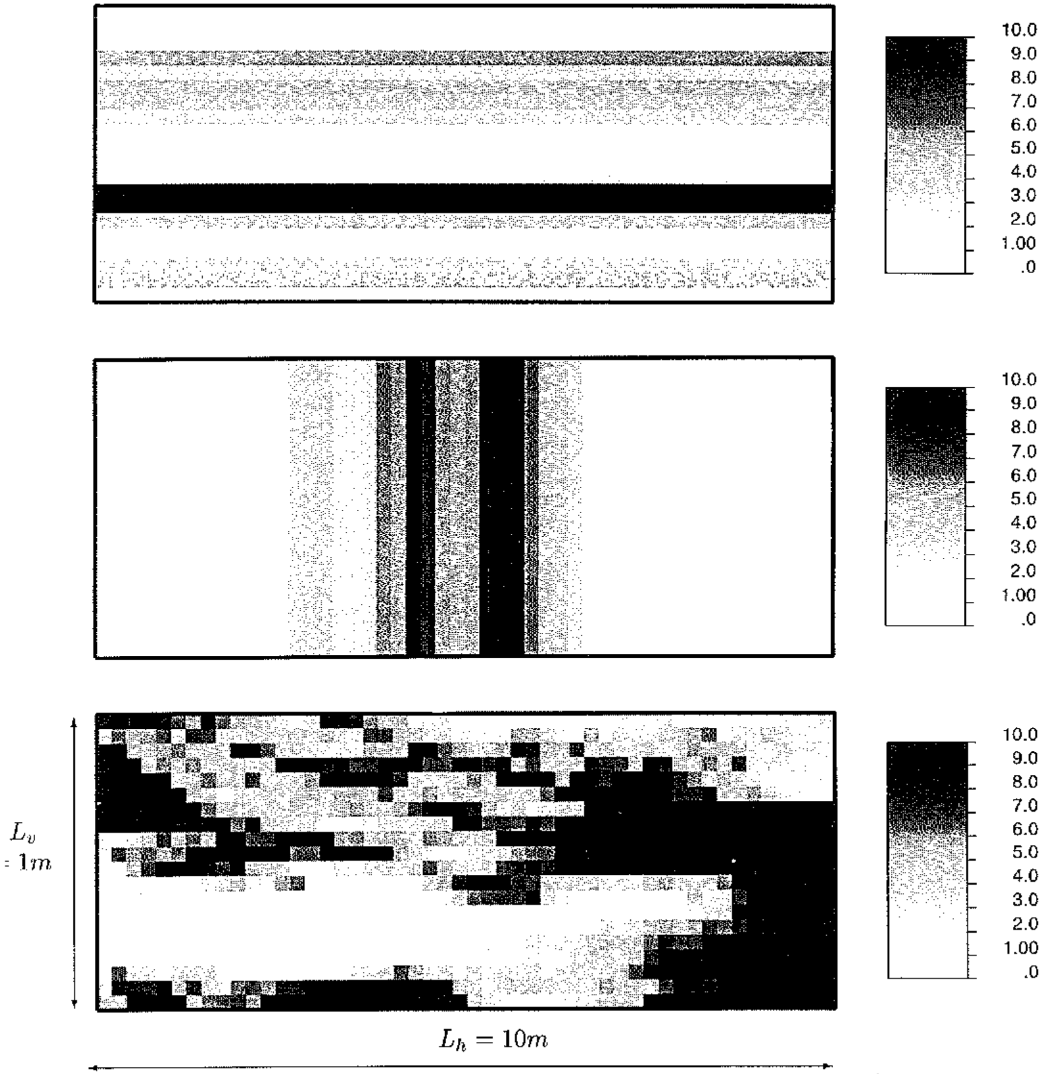

Fig. 2 Vertical profile of three heterogeneous K_S-fields (K_S, in mm h^{-1}).

Example: Effects of small-scale variability for the case of horizontal soil layers

Assuming a horizontal correlation length $\lambda_h >> L$ and a vertical correlation length $\lambda_v = 0$, a 1D-soil column with horizontal layers is derived. Again, the results of a field campaign in the Weiherbach area have been used to perform a Monte-Carlo simulation by generating 1000 realizations. Calculating the infiltration for every soil column and averaging the 1000 runs yields the mean infiltration behaviour which has been compared in Fig. 3 with three deterministic calculations: arithmetic mean K_S^{ari}, geometric mean K_S^{geo} and an "effective" value K_S^{eff}, which is determined by using the long-term infiltration rate of the mean infiltration (Fig. 3). The comparison for the soil moisture is shown in Fig. 4. Both figures show that the averaged flow behaviour cannot be described by one deterministic value of K_S. Furthermore, the small-scale variability reduces the mean infiltration.

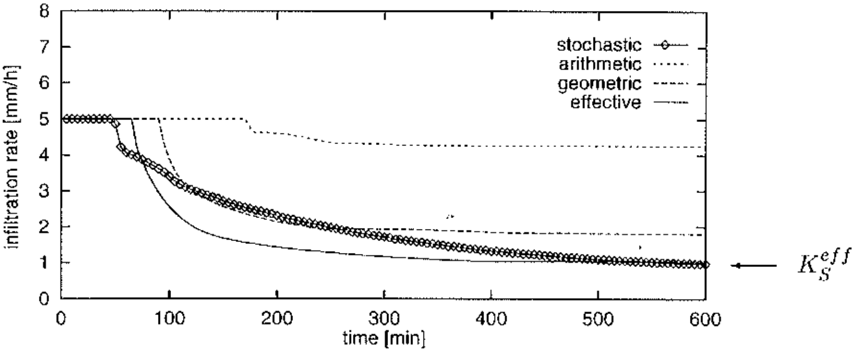

Fig. 3 Deterministic and stochastic infiltration (average infiltration obtained from 1000 realizations of heterogeneous fields).

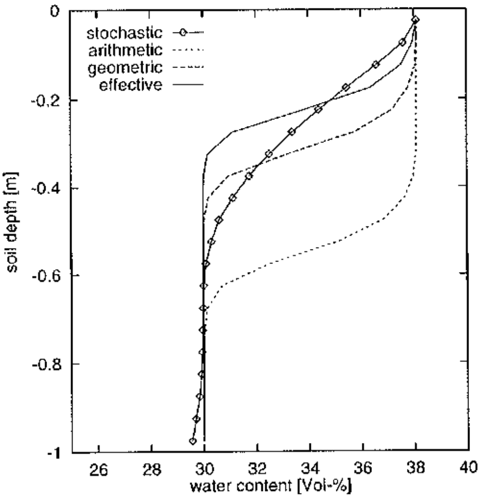

Fig. 4 Deterministic and stochastic soil moisture profiles (averages soil moisture profile obtained from 1000 realizations of heterogeneous fields).

Consequences for larger scales

The investigation of the small-scale variability of the soil matrix showed that the mean soil moisture profiles of heterogeneous fields cannot be described by a model with arithmetically or geometrically averaged parameters and that small-scale variability reduces the infiltration rate. At larger scales an effective K_S ($0.6\,K_S^{geo}$) has been used as a result of this study (see Merz, 1996). Furthermore the correlation length strongly affects the mean infiltration and a large effort is necessary to derive effective parameters for the mean infiltration behaviour.

The investigation of the effects of macropores shows that macropores are very effective in increasing the infiltration rate. An infiltration model for a soil containing macropores has been developed as an infiltration module at larger scales.

SUBCATCHMENT SCALE

Dominant features and investigations

At the subcatchment scale the 1D-infiltration model developed (for matrix and macropore infiltration) has been extended to account for interception, two-dimensional (2D) overland flow, and flow in channels and on impervious areas. Other components like groundwater flow are of no importance in the Neuenbürger Pfad subcatchment (32 ha). The resulting event-based model SAKE (Simulationsmodell des Abflußverhaltens Kleiner Einzugsgebiete) is a quasi-3D, process oriented, distributed grid based model. After looking at the parameter sensitivity, parameter interaction and model uncertainty, the calibrated model is used to study the influence of agricultural roads, the influence of the spatial variability of soil parameters and soil moisture, and the effects of land use changes on the runoff behaviour.

Example: Effects of spatial variability and event dependency

This example shows the influence of the spatial distribution for different rainfall events. In Fig. 5 the hydrographs resulting from the assumed spatial distributions (case S) of initial soil moisture and soil hydraulic parameters have been compared to the hydrographs resulting from spatially constant distributions (case C), where the arithmetic mean is assigned to each grid cell. Different rainfall time series have been generated by decreasing or increasing stepwise the rainfall depth of a historical event while keeping the same temporal distribution. For event 1 with a low rainfall depth (20 mm) and a very low peak runoff ($9.5\ \mathrm{l\ s^{-1}}$), the two scenarios lead to almost identical hydrographs. Increasing the rainfall depth increases the difference. If one starts from a rainfall depth of 27.5 mm (event 4), the opposite effect can be observed. The difference in the hydrographs decreases until the hydrographs are quite similar (event 6). For larger rainfall events, the spatial distribution affects the runoff only in a minor way.

This behaviour can be explained by the characteristics of the runoff generating mechanism in the Neuenbürger Pfad subcatchment. At low rainfall intensities only the

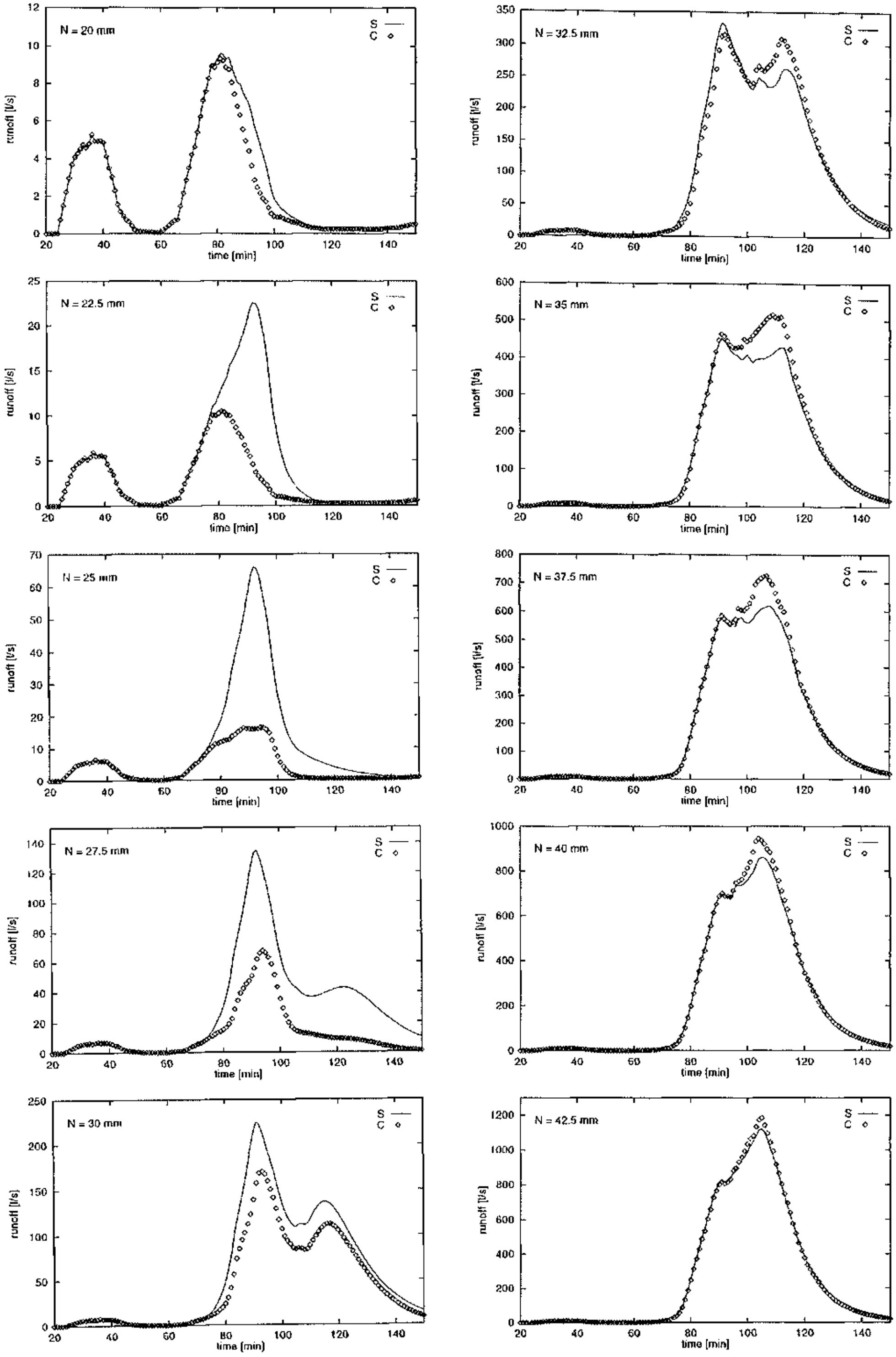

Fig. 5 Hydrographs simulated for the structured and spatially homogeneous distribution of initial soil moisture and soil hydraulic properties, for events with different rainfall depth.

precipitation falling in streams and impervious areas contributes to the runoff. Increasing the rainfall intensity leads to a larger contributing area. But only a small part of the catchment takes part in the runoff generation process. Overland flow generated at locations further away from the outlet re-infiltrates on its way downhill. For such medium-sized events the spatial distribution plays an important role. For large events where most or all of the subcatchment area contributes, the effects of spatial distribution are again small.

Consequences for larger scales

The simulations showed that areas close to the stream are particularly important for a sound simulation of the runoff process. The inclusion of an agricultural road in the model strongly improved model performance and points to the large contribution of impervious areas to the runoff in the Weiherbach catchment. The investigation of spatial variability showed that spatial variability can have a dominant influence on the hydrograph, especially if organization is present in the heterogeneous fields. From simulations with different types of heterogeneity it is concluded that spatial variability can result in a complex, event-dependent behaviour. A model with mean parameters does not necessarily represent the mean behaviour. Investigations concerning the event dependency of spatial variability showed that for very small and large events, the spatial variability may be neglected and mean values may suffice.

SMALL CATCHMENT SCALE

Dominant features and investigations

At the small catchment scale the runoff behaviour of the Menzingen area (3.4 km^2) has been investigated. The catchment has been divided into subcatchments and the subcatchment processes have been simulated by SAKE. The hydrographs from the subcatchments have been linked by FGM, a software package for modelling the rainfall runoff behaviour of river systems (Plate *et al.*, 1988). After calibrating the model a simplified method for simulating the rainfall runoff process of the Menzingen area was developed.

Example: Simplified, process oriented model

The catchment area is split into two domains: the 3D convergence domain, which consists of all grid cells around the drainage line with merging flowpaths. The complete rainfall runoff model is used to simulate the runoff process within this domain. The hillslope domain consists of 2D hillslopes, which drain into the convergence domain. Runoff generated on those hillslopes is estimated by a simplified method, which is based on flow time as a parameterization of topography. In that way, the area which is particularly important, is modelled in detail, whereas the less important areas are lumped together by a simplified, statistical approach.

CONCLUSIONS

The paper gives an overview of the transition from the point to the small catchment scale for the Menzingen/Weiherbach catchment. At each scale the modelling concentrates on the important processes and on the appropriate representation of the processes. The effects of spatial variability and its scale dependent nature have been explored. Several results which have been obtained at a smaller scale could be transferred to larger scales.

The upscaling concept has some limitations which can be demonstrated by deriving the mean infiltration behaviour at the grid scale. This study has shown that the subgrid variability of soil hydraulic parameters reduces the mean infiltration. This shift in the mean behaviour is accounted for by reducing the saturated hydraulic conductivity at the larger scales. The limitations of this upscaling step are that much efforts is required to derive effective parameters and that the shift in the mean behaviour due to small-scale variability is small compared to the uncertainty of the rainfall runoff calculations at the larger scale. Furthermore, the use of effective soil parameters may be complicated by their dependency on event characteristics for some types of spatial variability. It seems that the derivation of an effective model, i.e. a new process description at the larger scale, would be more appropriate if such a description can be found. Nevertheless, the development of the simplified, yet process oriented catchment model has benefited greatly from the investigations at smaller scales.

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