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Multi-criterial validation of TOPMODEL in a mountainous catchment

A. Güntner,[1]* S. Uhlenbrook,[2] J. Seibert[3] and Ch. Leibundgut[2]

[1] *Potsdam-Institute for Climate Impact Research, PO Box 60 12 03, 14412 Potsdam, Germany*
[2] *Institute of Hydrology, University of Freiburg, Fahnenbergplatz, 79085 Freiburg, Germany*
[3] *Uppsala University, Department of Earth Sciences, Hydrology, Villavägen 16, 75236 Uppsala, Sweden*

Abstract:

The need for powerful validation methods for hydrological models including the evaluation of internal stages and spatially distributed simulations has often been emphasized. In this study a multi-criterial validation scheme was used for validation of TOPMODEL, a conceptual semi-distributed rainfall–runoff model. The objective was to test TOPMODEL's capability of adequately representing dominant hydrological processes by simple conceptual approaches. Validation methods differed in the type of data used, in their target and in mode. The model was applied in the humid and mountainous Brugga catchment (40 km^2) in south-west Germany. It was calibrated by a Monte Carlo method based on hourly runoff data. Additional information for validation was derived from a recession analysis, hydrograph separation with environmental tracers and from field surveys, including the mapping of saturated areas. Although runoff simulations were satisfying, inadequacies of the model structure compared with the real situation with regard to hydrological processes in the study area were found. These belong mainly to the concept of variable contributing areas for saturation excess overland flow and their dynamics, which were overestimated by the model. The simple TOPMODEL approach of two flow components was found to be insufficient. The multi-criterial validation scheme enables not only to demonstrate limitations with regard to process representation, but also to specify where and why these limitations occur. It may serve as a valuable tool for the development of physically sound model modifications.

KEY WORDS rainfall–runoff models; multi-criterial validation; TOPMODEL; saturated areas; distributed modelling

INTRODUCTION

In recent years, many spatially distributed hydrological models have been developed. They have become valuable tools in research and operational hydrology, e.g. for water balance studies, flood forecasting and computations of design floods. However, physically based distributed models are very complex and have an enormous data demand (e.g. Beven, 1989). It is not reasonable to assume that all model parameters can be determined for each location over the entire catchment area. Conceptual models are easier to apply because their model structure is simpler and their data requirements are lower. Complex hydrological processes are conceptualized by storage approaches. Some of these models are semi-distributed, meaning that processes and quantities are not simulated with explicit spatial discretization or lateral interactions, but are simplified by, for instance, distribution functions.

The TOPMODEL approach (Beven and Kirkby, 1979; Beven *et al.*, 1995) combines some advantages of different types of models. It allows one to make use of a semi-distributed concept for some hydrological

* Correspondence to: Dr A. Güntner, Potsdam Institute for Climate Impact Research (PIK), PO Box 601203, 14412 Potsdam, Germany. E-mail: guentner@pik.potsdam.de

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processes and requires only few driving variables and parameters. The integration of topographic information within the conceptual model structure allows one to simulate the spatial distribution of soil water content or groundwater levels for each modelling time-step. The variable source area concept enables a dynamic distinction between saturation excess overland flow (Cappus, 1960; Dunne and Black, 1970) as the fast and subsurface flow as the slow runoff component. The model has been used in numerous applications all over the world during the last years (Beven, 1997). However, as emphasized by Beven (1997), several simplifications and underlying assumptions restrict the physical basis of TOPMODEL and require that the model be used with care.

Model validation, i.e. testing the capability of a model to produce reasonable results with sufficient accuracy, is an essential step in model applications. Strategies for the validation are dependent on the type of results that are expected, i.e. the intended objective of the application, and on the type of the model itself. As an extension of the classical split-sample test, Klemes (1986) proposed a hierarchical scheme for model validation, including different catchments and changes of catchment characteristics or climatic conditions. However, applied, for instance, by Refsgaard and Knudsen (1996) for different hydrological models, it is a single-variable testing scheme considering runoff only. The need for extended methods of model validation has often been pointed out, calling for the evaluation of internal stages and spatial patterns (e.g. Rosso, 1994; Grayson *et al*., 1995; Refsgaard and Storm, 1996; Beven, 1997; Mroczkowski *et al*., 1997; Piñol *et al*., 1997; Refsgaard, 1997). In order to evaluate the goodness of runoff simulations during different hydrological conditions, different statistical measures and combinations of them have been proposed (Sefe and Boughton, 1982; Sorooshian and Gupta, 1995; Lindström, 1997; Seibert, 1997). Refsgaard (1997) summarizes the different validation requirements for lumped conceptual and distributed physically based models, stressing the importance of multi-criterial and multi-scale validation methods for the latter model type. Ambroise *et al*. (1995) presented the validation of a semi-distributed model including a wide range of information. However, such comprehensive validations are rare, partly due to lack of suitable data. In the case of TOPMODEL, comparisons of model concepts or results with spatially distributed data were carried out on the basis of groundwater levels (Lamb *et al*., 1997; Seibert *et al*., 1997), hydromorphic soil characteristics (Merot *et al*., 1995; Rodhe and Seibert, 1998) and of saturated areas, derived from both field surveys (Ambroise *et al*., 1996b; Güntner *et al*., 1998), isotopic runoff separation (Holko and Lepistö, 1997) and remote sensing data (Franks *et al*., 1998). For modelling tasks related to land use changes or to water quality influenced by flow pathways, for instance, an extended examination of the validity of the model for a specific site is required. This includes evaluating the model structure with regard to the representation of processes that are relevant to the modelling task. But in the case of a conceptual model, internal stages such as the contents of a storage can often not be directly validated against measured data. Furthermore, evaluating single quantities is usually not sufficient to assess complex processes. From that arises the quest for an examination of various model outputs on different temporal, spatial and thematic scales in order to obtain, by this integration, a closer assessment of the adequacy of the model structure to be applied for a certain task.

In this study, a multi-criterial scheme was used for validation of the rainfall–runoff model TOPMODEL. The study is part of a research project where different existing models were tested with respect to their representation of hydrological processes (Mehlhorn, 1998; Uhlenbrook *et al*., 1998). TOPMODEL, as an example of semi-distributed conceptual approaches, was applied to a mountainous catchment in south-west Germany with a size of 40 km^2. With humid climatic conditions, pronounced topography and the presence of saturated areas, the fundamental prerequisites for the application of TOPMODEL seemed to be fulfilled in the study area. The model was evaluated with regard to its capability of representing dominant hydrological processes by simple conceptual means in an adequate way. The focus was particularly on those components in which the model is specialized, which are the variable source area concept and saturation excess overland flow. The validation of TOPMODEL is presented as an example to demonstrate possible ways for a multi-criterial validation of conceptual, (semi-)distributed models. Results specific to TOPMODEL contribute, with additional experience, to the vigorous debate on applications of this model.

Dimensions of model validation

Multi-criterial model validation comprises a combined application of different validation methods. These methods differ with regard to their target, mode and the type of additional information taken into account. A structured overview on these dimensions of model validation (Table I) illustrates the broad range of possible approaches, also pointing out the need to decide carefully which type to use with regard to a certain objective of model application. For each type, examples for the validation of TOPMODEL in this study are given in Table I. The three basic dimensions of model validation, i.e. what is being validated, how is the validation being performed and what kind of information is used, can be characterized as follows (see Table I).

Table I. Dimensions of model validation and examples for the application of TOPMODEL in this study

Dimension of validation	Example in this study
Target — validation of:	
Model structure	Concept of soil zone, concept of variable contributing areas based on the topographic index
Parameter set	calibrated parameter set
Single parameter	$S_{e\,max}$, T_0, t_d, m
Information — validation with:	
Spatial scale:	
Point data	Plant-available water capacity
distributed data, complete coverage of study area	Saturated areas
integrative data	Runoff (volume and components)
Temporal scale:	
continuous data	Runoff (volume and components)
data from single observations	Spatial extension of saturated areas
Derivation:	
data directly measured	Runoff
data directly deduced from measurements	Recession constant
data derived from measurements via auxiliary model	Runoff components from environmental tracers
Type:	
exact value	Contribution of runoff component
statistical property	Mean percentage of saturation excess overland flow areas
qualitative information	Field observations of runoff generation
Mode — validation by:	
Single variable	—
Multi-variable	Runoff volume, runoff components and saturated areas
Single site	—
Multi-site	Spatial distribution of saturated areas
Stationary conditions	No apparent changes of land use or climate
Instationary conditions	—
Single objective functions	—
Different objective functions	R_{eff}, R_{log} and R_{com}
Quantitative measures	Objectives functions
Qualitative measures	Visual check of flow recessions
Direct method	Physically based parameter by measurements
Indirect method	Subsurface zone concept by recession analysis
Internal method	Sensitivity analysis (response surfaces)
External method	Split-sample test

What is being validated? — Target. The term ‘model’ is often used with a twofold meaning, which is important to recognize when talking about validation of a model. First, the aim of model validation might be to evaluate the applicability of a hydrological model code for given physiographical conditions, including tests of the model structure as a whole or of single components, e.g. the conceptualization and corresponding assumptions of a runoff generation process. Secondly, the term model validation may be used with a more limited meaning, that is the check of a specific realization of a given model code in a study area, defined by a particular parameter set. Checking single parameters may give indications about the validity of model structure, as inappropriate concepts might be reflected in unreasonable parameter values.

What kind of data is used? — Information. Data used for model validation can be grouped into various categories depending on their information content. These are the spatial and temporal scale of data, the way data were derived and their type, ranging between crisp numerical values and qualitative information. The power of a certain validation method will considerably depend on the conformity of these characteristics of validation data with the objective of model application.

How is the model being validated? — Mode. Validation methods can be ordered according to the number of variables or sites that are used in parallel, and according to the extent and type of instationarities that are taken into consideration, e.g. deforestation or changing climate. Even when regarding only one variable (e.g. runoff) for validation, different criteria for goodness of simulations that are evaluating separately different aspects of this variable (e.g. low flow periods and floods) might give insight into the validity of the underlying model concepts. In the case of an indirect validation method, the type of the validated model component (e.g. the conceptualization of a groundwater storage) does not correspond to that of the additional information taken into account (e.g. recession characteristics of the hydrograph during dry periods). Often, in this category, fairly qualitative measures of model goodness are used, whereas quantitative measures can be used in the case of direct validation methods, which relate simulated variables to corresponding measurements. Finally, when applying an internal validation scheme, boundary conditions like input data are retained and only parameters or model components are altered, whereas with external methods, the reaction of the model to changing external forcing is examined, leaving the applied model structure and the parameter set unchanged. Every specific validation method is characterized by each of these modes, thereby defining its applicability and power for a specific validation task.

MATERIAL AND METHODS

Theory of TOPMODEL

Detailed descriptions of TOPMODEL and its mathematical formulation can be found elsewhere (e.g. Beven and Kirkby, 1979; Beven *et al*., 1995). Only a short description of the basic modelling concepts and some specific features of the version used in this study are given in this paper.

Total runoff is calculated as the sum of two flow components: saturation excess overland flow from variable contributing areas (Cappus, 1960; Dunne and Black, 1970) and subsurface flow from the saturated zone of the soil. For the saturated zone, it is assumed that: (1) its dynamics can be represented by a series of steady states; (2) its hydraulic gradient can be approximated by the local slope of ground surface $\tan\beta$. On the basis of these two assumptions a relationship between mean storage deficit $\bar{D}$ [m] of a catchment and local storage deficit D_i [m] at any point within the catchment can be derived [Equation (1)].

$$D_i = f(\bar{D}, T_{0i}, I_i, \bar{I}, m) \tag{1}$$

T_{0i} [m^2 h^{-1}] is the local lateral transmissivity when the saturated zones reaches the ground surface, I_i and $\bar{I}$ are the local and the catchment averaged value of the topographic index $a/\tan\beta$ (Kirkby, 1975), where a [m] denotes the upslope hillslope area per unit contour length. Parameter m [m] defines the variation of saturated hydraulic conductivity with depth. Different formulations presented by Ambroise *et al.* (1996a) can be selected in this model version (linear or exponential decline with soil depth or constant value with step function decline to zero). Areas with $D_i \leqslant 0$ are contributing areas for saturation excess overland flow. Precipitation or snowmelt on saturated areas contributes completely and immediately to runoff.

Actual evapotranspiration E_a [m] is calculated as a function of potential evapotranspiration E_p [m] and the content of a soil storage, S_e [m], with maximum capacity $S_{e\,max}$ [m] [Equation (2)]. This storage represents water available for evapotranspiration from the root zone, the interception storage and from microtopographic depressions.

$$E_a = E_p\left(\frac{S_e}{S_{e\,max}}\right) \tag{2}$$

In the model version used in this study, evapotranspiration demand exceeding the contents of storage S_e was additionally supplied by the unsaturated zone storage S_u [m] below the root zone if water was available in this storage.

Vertical flux, q_v [m h^{-1}], to the saturated soil zone is calculated according to a formulation proposed by Beven and Wood (1983)

$$q_v = \frac{S_u}{\bar{D} \cdot t_d} \tag{3}$$

S_u is the storage in the unsaturated zone and t_d [h m^{-1}] is a delay factor. Contrary to other versions of TOPMODEL (e.g. Beven *et al.*, 1995), the vertical flux in Equation (3) is calculated lumped for the entire catchment, based on the mean storage deficit $\bar{D}$ instead of the respective local storage deficits D_i. This approach was considered to be more consistent with the assumption of a spatially uniform recharge rate. With the usually applied equations, where recharge is a function of local groundwater levels, water is implicitly redistributed after each time-step, which is physically unreasonable (Seibert, 1998).

Snow accumulation and snowmelt is represented by a simple temperature index method (Bergström, 1976). However, periods with snowfall and snowmelt were mostly excluded in this study.

Runoff transformation in the channel network is described by a triangular weighting function (Bergström, 1976). Parameter c defines the number of succeeding time-steps over which the runoff generated in a certain time-step is distributed.

Study site

The mountainous Brugga basin (40 km^2) is located in the Black Forest in south-western Germany, about 20 km east of Freiburg. It is characterized by a high relief intensity, with elevation ranging from 440 to 1493 m a.s.l. Three topographic units can be distinguished: narrow valley floors (5% of total basin area), steep slopes of the valley sides (75%) and hilly uplands (20%). The bedrock consists of gneiss and anatexits, covered by debris, soils and drift of varying depth. Mean annual precipitation is approximately 1750 mm, generating a mean annual discharge of about 1250 mm. Especially on steep slopes the basin is widely forested (75% of total basin area), whereas the valley floors and the uplands are mainly used as pasture. The portion of settlements amounts to 2%, where only a small part of this area is sealed due to the rural structure of the villages.

Tracer investigations and field observations indicate that fast runoff components are generated on saturated areas and on mainly steep, highly permeable slopes, where macropore flow and pipe flow occur, and perched water tables may spread (Lindenlaub *et al.*, 1997; Güntner *et al.*, 1998; Mehlhorn *et al.*, 1998). In addition, displacement of soil water and of groundwater occurs. Hortonian overland flow was not observed except on small sealed areas. The slower runoff components are mainly generated in the deeper weathering zone and in the fractured hard rock aquifer (Lindenlaub *et al.*, 1997; Leibundgut *et al.*, 1998).

Model application

Two six-month periods were used for model calibration (July 1995–January 1996) and validation (April 1996–October 1996). The model ran with an hourly time-step. Basin-averaged precipitation was computed as the weighted mean of two stations. For estimates of potential evapotranspiration using the Penman equation, data from three meteorological stations at different elevations were available. The spatial distribution of the topographic index was computed using a digital elevation model with a grid size of $50 \times 50\ m^2$. A multiple flow direction algorithm (Quinn *et al.*, 1991) was used with a channel initiation threshold, g [m^2] (Quinn *et al.*, 1995), and a parameter h, modifying the slope-dependent weighting of downhill flow partition (Freeman, 1991; Holmgren, 1994). Best agreement of spatial distribution of calculated topographic index with mapped saturated areas was achieved for $g = 100\,000\ m^2$ and $h = 10$ (Güntner *et al.*, 1998).

Calibration was performed with runoff data measured at Oberried gauging station. As an objective function of model performance, the model efficiency, R_{eff} (Nash and Sutcliffe, 1970), evaluates mainly high flow conditions. The efficiency calculated with logarithm values of the discharge, R_{log}, lays a stronger stress on the performance of low flow simulations. In order to balance between the importance of both high and low flow periods for evaluation of model performance, a combined model efficiency, R_{com}, was used [Equation (4)]. Compared to an additive combination, multiplying R_{eff} and R_{log} requires both values to be large for a resulting overall good model performance.

$$R_{com} = \begin{cases} R_{eff} \cdot R_{log} & \text{for } R_{eff} \geqslant 0 \text{ and } R_{log} \geqslant 0 \\ 0 & \text{for } R_{eff} < 0 \text{ or } R_{log} < 0 \end{cases} \tag{4}$$

The number of parameters of the TOPMODEL main module is small compared with other rainfall–runoff models (four parameters: T_0, m, $S_{e\,max}$, t_d), but due to the incorporation of snowmelt and runoff routing modules the number of parameters increased to 10 for the model version used in this study.

For model calibration, the parameters of the snow routine were fixed to values obtained by Uhlenbrook *et al.* (1998) using the same routine for an application of the HBV model in the study area. Then, with the reduced number of free parameters, Monte Carlo simulations were carried out for the calibration period allowing the parameters to vary within wide ranges (Table II). These ranges were progressively reduced to locate the best parameter set in terms of R_{com}.

Additional information for validation — methods and previous results

Field mapping. An extensive mapping of saturated areas was performed for the entire catchment area (Güntner *et al.*, 1998). Pedological and geobotanical criteria allowed a consistent delimitation of permanently saturated areas for the whole catchment. In these areas hydromorphic characteristics can be found in the entire soil profile and wetness-indicating plants as classified by Ellenberg (1991) predominate. Of the total catchment area, 6·2% was mapped as saturated areas (Figure 1a) (Güntner *et al.*, 1998). In the present study, the field survey was used to compare the locations of mapped versus modelled saturated areas as well as to validate their simulated spatial variability. The spatial extension of single saturated areas was examined during different seasons and weather conditions.

Recession analysis. In order to derive an appropriate conceptualization of the saturated soil zone, a recession analysis of the measured catchment hydrograph can be used. As a result of the TOPMODEL formulations, the shape of the recession is determined by the assumed decline of hydraulic conductivity with

Table II. Initial parameter ranges for calibration with Monte Carlo simulations

T_0 [$m^2\ h^{-1}$]	$S_{e\,max}$ [mm]	m [mm]	t_d [$h\ m^{-1}$]	c [–]
10^{-2}–10^2	10^0–10^3	10^0–10^3	10^{-2}–10^1	10^0–10^1

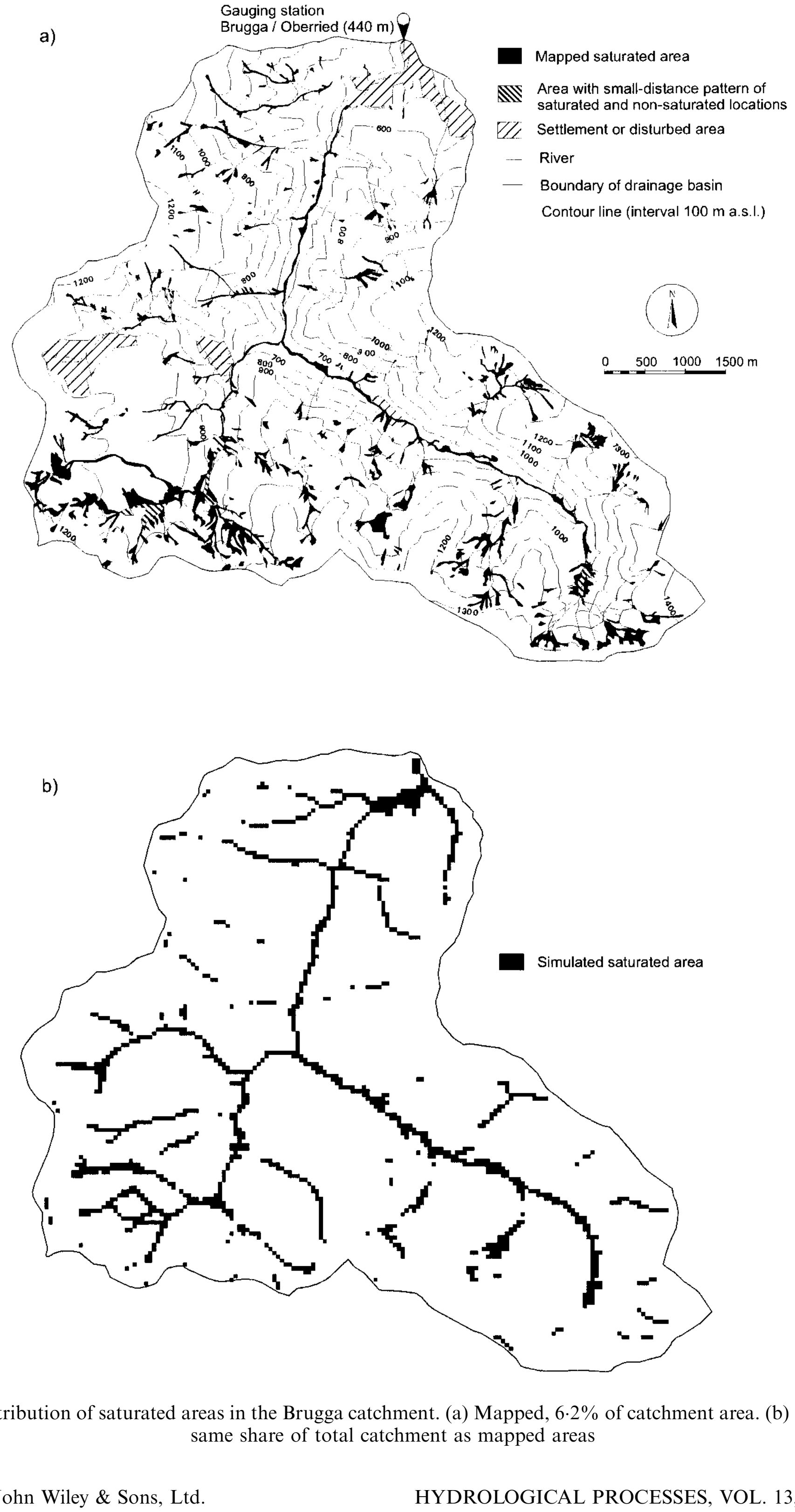

Figure 1. Spatial distribution of saturated areas in the Brugga catchment. (a) Mapped, 6·2% of catchment area. (b) Simulated, with the same share of total catchment as mapped areas

soil depth (Ambroise *et al.*, 1996a). Here, the recession analysis served to validate the assumed function of hydraulic conductivity versus soil depth and the respective model parameter m. Based on a 10-year time-series of daily runoff (1975–1984), not including the simulation period, a master recession curve for the Brugga catchment was constructed using the matching strip method (Toebes and Strang, 1964; Tallaksen, 1995). Periods directly influenced by precipitation or snowmelt were excluded.

Hydrograph separation. For comparison with modelled runoff components, a two-component hydrograph separation based on electric conductivity, E_C, as environmental tracer was carried out. Pre-event water was assumed to be characterized by E_C as measured before the rise of the hydrograph. For event water, E_C was taken as $E_C = 10{\cdot}4\ \mu S\ cm^{-1}$, according to measurements of rain water. Owing to experimental problems while recording electrical conductivity, only data for a period of four weeks were available. Two relatively small flood events were suitable for model validation.

Soil data. Data on physical soil properties of the study area were available from pedological investigations (Stahr, 1979) and from experiments with dye tracers on hillslopes (Mehlhorn *et al.*, 1998).

RESULTS AND DISCUSSION

Calibration

A unique parameter set with best simulations according to the combined efficiency, R_{com}, could be determined (Table III, see also Figure 6a–c). Acceptable fits between measured and simulated runoff were obtained. However, considerable deviations could be observed during a wet interval in September 1995 and for periods influenced by snowfall or snowmelt (Figure 2).

Table III. Parameter values and objective functions for different simulations. (a) Calibration period (20 July 1995–27 January 1996). (b) Validation period (20 April 1996–29 October 1996). (c) Recalibration of the validation period (20 April 1996–29 October 1996). Q_{obs}: observed total runoff volume, Q_{sim}: simulated total runoff volume, Q_{sat}: simulated saturation excess overland flow, A_{sat}: percentage of simulated saturated areas on total catchment area

Simulation	Units	(a) Calibration period	(b) Validation period	(c) Validation period (recalibrated)
TOPMODEL main parameter				
T_0	$m^2\ h^{-1}$	1·6	1·6	1·6
m	mm	43	43	41
$S_{e\,max}$	mm	140	140	120
t_d	$h\ m^{-1}$	0·1	0·1	0·1
c	—	6·0	6·0	6·5
Objective functions				
R_{eff}	—	0·85	0·93	0·93
R_{log}	—	0·84	0·89	0·91
R_{com}	—	0·72	0·82	0·84
Summary statistics				
Q_{obs}	mm	588	497	497
Q_{sim}	mm	677	505	526
Q_{sat}	mm	69	52	54
Q_{sat}/Q_{sim}	%	10·1	10·2	10·3
Mean A_{sat}	%	5·0	5·8	6·0
Range A_{sat}	%	1·6–22·7	1·6–18·7	1·6–18·7

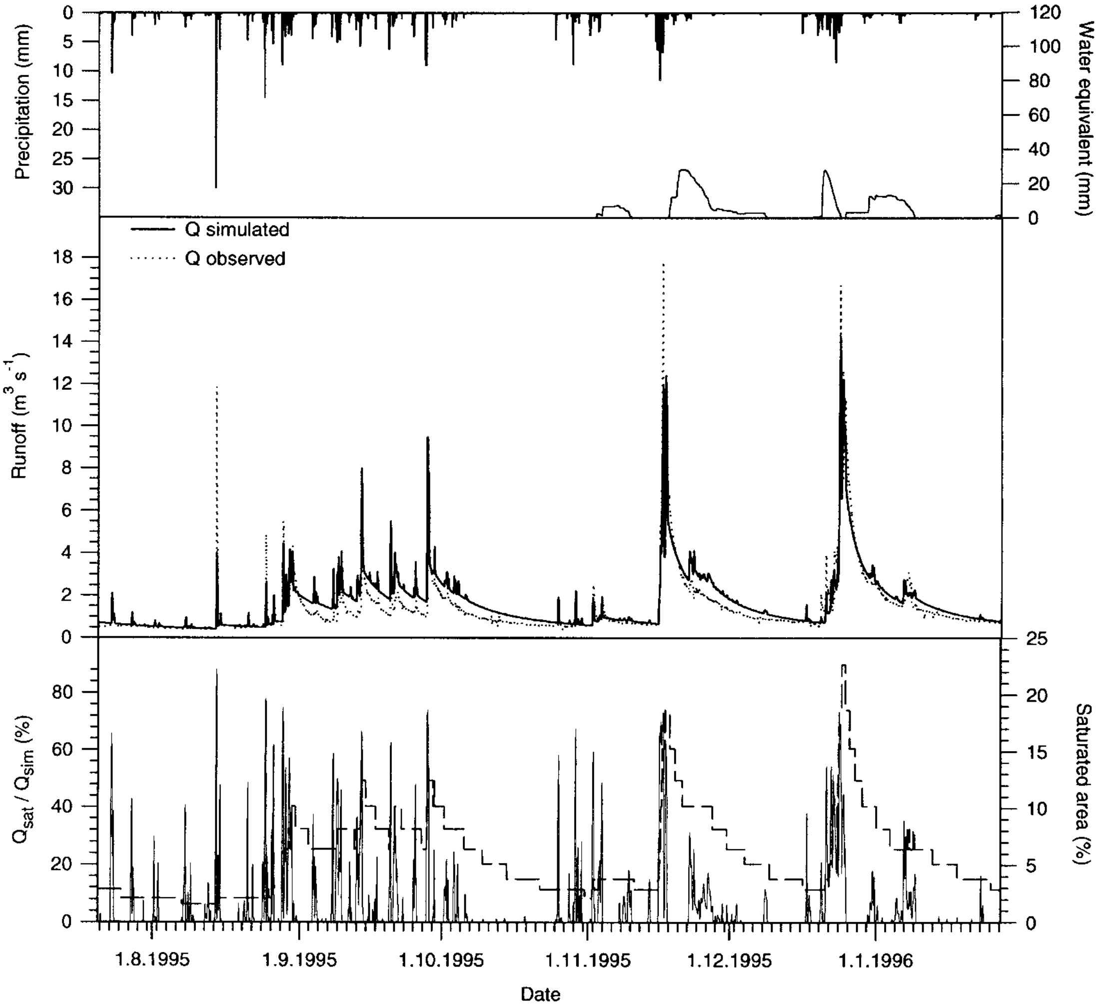

Figure 2. TOPMODEL simulations of the calibration period. Precipitation and water equivalent of simulated snow cover (upper plot). Measured and simulated runoff Q (middle plot). Percentage of simulated saturation excess overland flow, Q_{sat}, on total simulated runoff volume, Q_{sim}, and percentage of simulated saturated areas on catchment area (lower plot)

Additional methods

Recession analysis. A master recession curve for the Brugga catchment was derived (Figure 3a). Differences when evaluating separately the hydrograph recessions for summer and winter periods were not found. A first-order hyperbolic function fitted the master recession curve best (Figure 3b). Considering the outflow of the saturated zone storage of TOPMODEL, this recession form results from the assumption of an exponential decline of saturated hydraulic conductivity with depth. From the slope of the straight line in Figure 3b the model parameter m was derived as $m = 34$ mm (for theoretical details see Ambroise *et al.*, 1996a).

Field survey of saturated areas. In addition to the results of Güntner *et al.* (1998) on the locations of saturated areas (Figure 1a), it was noticed in the field that transitions from saturated areas to locations with no wetness-indicating pedological or geobotanical characteristics were predominantly found within a very short distance (about 1 m). According to this observation it was supposed that seasonal or episodic spatial

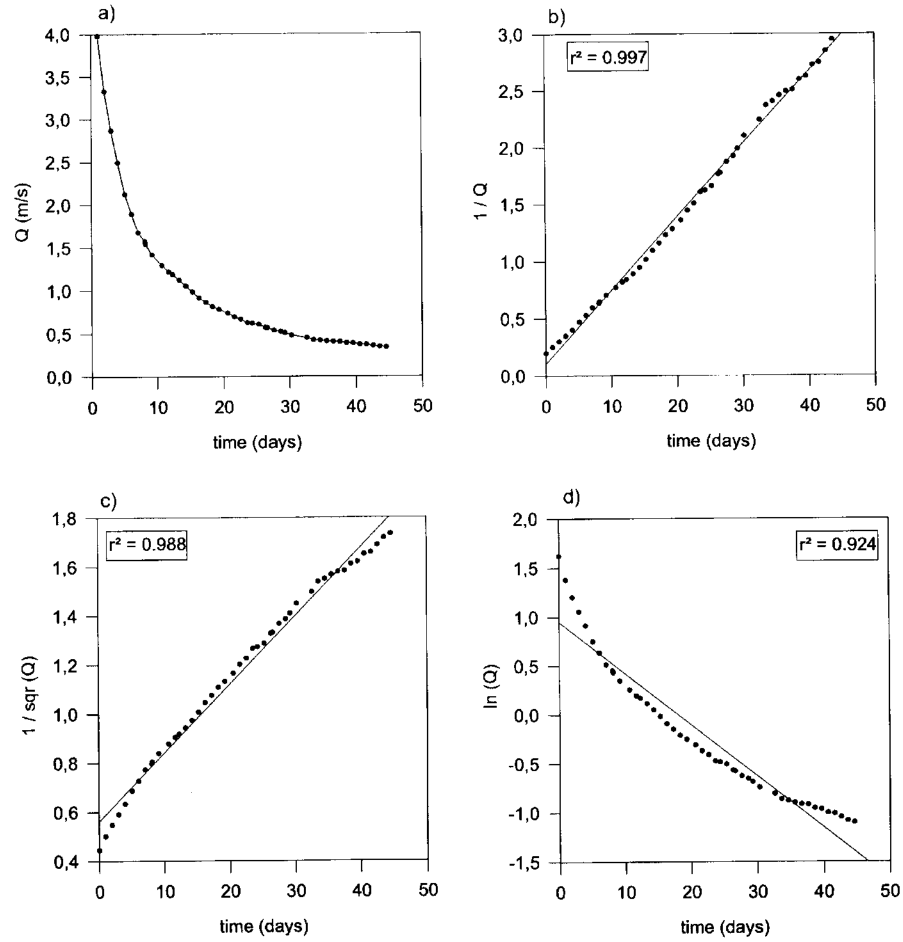

Figure 3. (a) Master recession curve of Brugga catchment. (b)–(d) Transformed master recession curve for different transformations of runoff axis, with linear regression and coefficient of determination (after Ambroise *et al.*, 1996a)

variability of saturated areas was small. This was confirmed when checking the extension of single saturated areas during different seasons and weather conditions. Saturated areas based on topography are mainly located in the narrow valley bottoms or in hollows of cirques of Pleistocene origin. These locations are bordered by steeply ascending slopes which impede an expansion of saturated areas. Perennial springs at fractures of underlying bedrock or at strata boundaries between massive bedrock and debris cover, as well as dense till deposits, are other explanations for the occurrence of saturated areas. Such saturated areas are sharply delimited, for instance, to the pit of a spring and a downhill strip along the hillslope below the spring. Therefore, they do not show significant variation in their spatial extension. Similar behaviour was observed in an alpine catchment by Kirnbauer *et al.* (1996).

Hydrograph separation. Event-water contribution to the selected flood events amounted to about 12% of total runoff volumes between the begin of rainfall on 1 November 1995 and the end of event-water contributions on 7 November 1995 (Figure 4). Maximum contributions were up to 25% for short periods during peak flow. These maxima occurred 2–3 hours after the peak of total runoff. During the falling branch of the hydrograph, contributions of event water were still found two days after the end of rainfall.

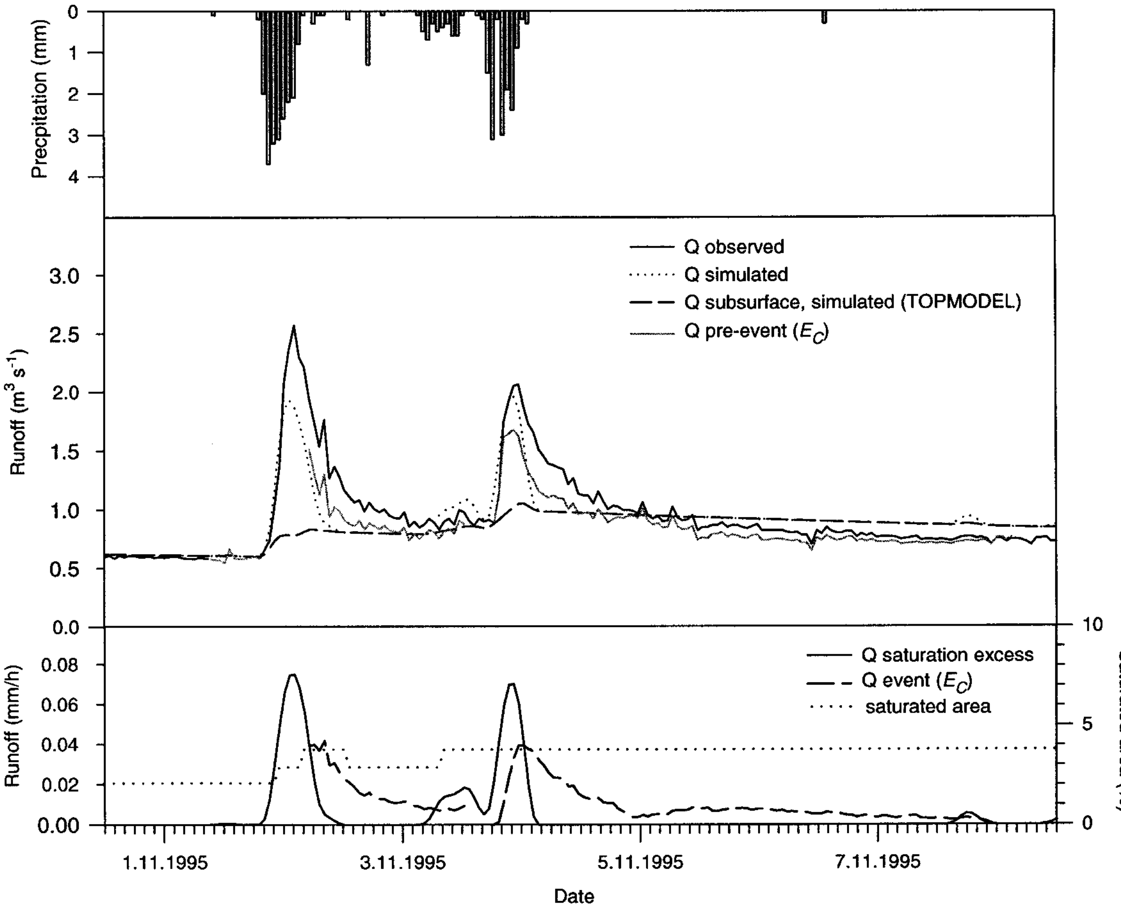

Figure 4. Hydrograph separation with electric conductivity E_C. Precipitation (upper plot). Total runoff Q and runoff components (middle plot). Runoff components and percentage of simulated saturated areas on catchment area (lower plot)

Validation

Split-sample test. For the validation period, runoff simulations agreed well with observations except for extended recession periods (e.g. July 1996), which were simulated too flat (Figure 5, Table III, column b). The poorer simulation during the calibration period is probably caused by inconsistencies in the precipitation data and the lumped simulation of snow accumulation and melt. Recalibrating the validation period, which did not include any intervals influenced by snow, revealed only a small improvement of runoff simulations with slightly different parameter values (Table III, column c). Therefore it could be stated that: (1) including previously fixed parameters of the snow routine in the original calibration process did not considerably influence the obtained values of TOPMODEL's main parameters, and (2) the calibrated parameter set of Table III (column a) could be considered to be generally valid for the Brugga catchment.

Parameter sensitivity. As an internal method for validation of a rainfall–runoff model (Table I), its hydrologically sound response to changes of parameter values may be checked. This analysis was based on the response surfaces of different objective functions which evaluated the goodness-of-fit between measured and simulated runoff (Figure 6). When increasing $S_{e\,max}$ to values of 100 mm or more, thus providing larger amounts of water available for evapotranspiration, model performance was influenced significantly only during low flow periods (R_{log}, Figure 6h,i) but not during higher flow periods (R_{eff}, Figure 6e,f). This is

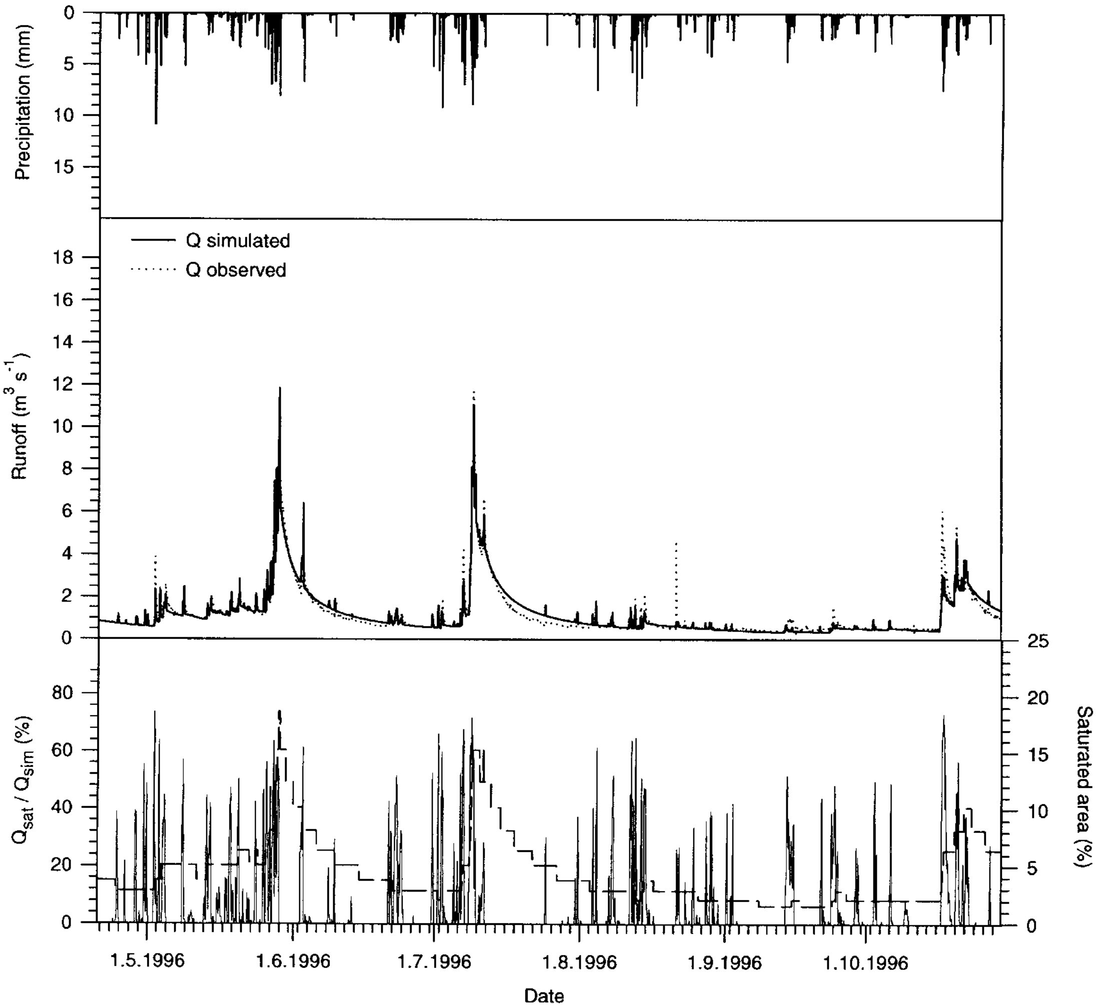

Figure 5. TOPMODEL simulations of the validation period. Precipitation (upper plot). Measured and simulated runoff Q (middle plot). Percentage of simulated saturation excess overland flow, Q_{sat}, on total simulated runoff volume, Q_{sim}, and percentage of simulated saturated areas on catchment area (lower plot)

reasonable, as the reduction of runoff corresponding to increased evapotranspiration only slightly affects the shape of the hydrograph with hourly resolution during high flow. An interdependence between parameters m and $S_{e\,max}$ existed (Figure 6f,i). During low flow periods (R_{log}) a larger value of $S_{e\,max}$ (higher evapotranspiration and reduced runoff) could be compensated by an increase of parameter m (flatter recession limbs of hydrograph) resulting in the same model performance. During higher flow periods (R_{eff}), however, an inverse relationship was noticed: increased runoff due to larger values of m is at least partly compensated by higher evapotranspiration in terms of larger $S_{e\,max}$. This qualitative analysis illustrated that model structure was sensitive to changes of some parameter values in a hydrologically sound manner. But it also revealed the common problem of interdependence of parameters and equifinality of parameter sets. Nevertheless, the combined model efficiency, R_{com}, provided a well-defined unimodal response surface (Figure 6a–c). This points out that considering multiple criteria for model performance in terms of runoff simulation and selecting an appropriate integrative objective function may constrain the range of possible

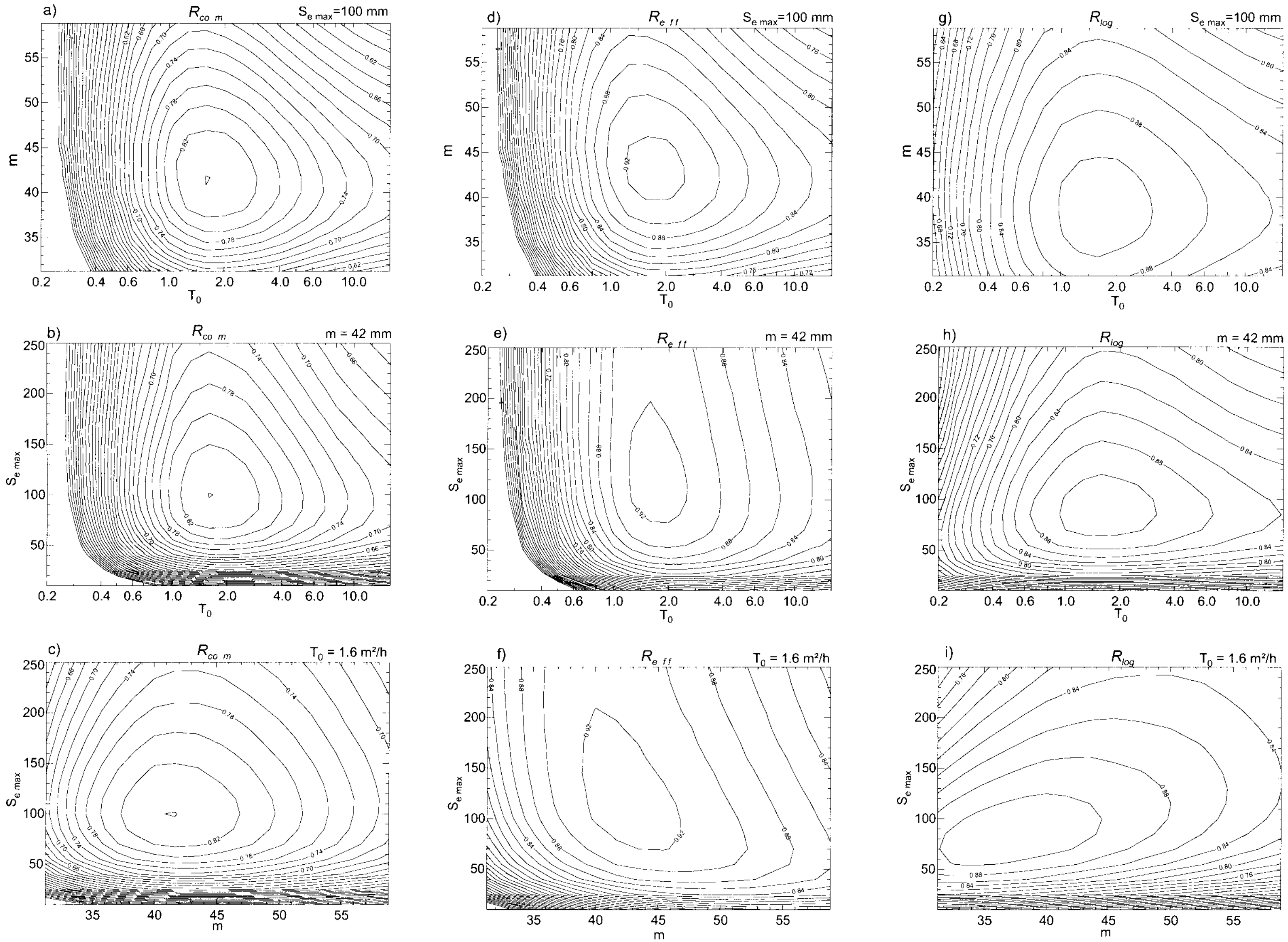

Figure 6. Response surfaces of different objective functions (first column: R_{com}, second column: R_{eff}, third column: R_{log}) for parameters T_0, $S_{e\,max}$ and m. Recalibration of the validation period

parameter values and allow one to select a single parameter set as being optimal for that specific objective of the model application.

Parameter values versus basin characteristics and processes. A direct method of model validation (Table I) is to compare calibrated parameter values with experimental data. In principle, this is feasible in the case of TOPMODEL, as its parameters are considered to be related to measurable terrain characteristics (e.g. Beven *et al*., 1995). Nevertheless, it should be noted that the parameters are effective at the basin scale, which integrate spatial variability as well as simplifications and inadequacies of the model structure. $S_{\mathrm{e\,max}}$ can roughly be compared to the plant-available water in the root zone. As measurements in the study area are in the range of 50–220 mm (Stahr, 1979), the calibrated value of $S_{\mathrm{e\,max}} = 140$ mm is reasonable. Assessing T_0 in view of field values of transmissivity is much more difficult, because T_0 values depend on the grid resolution of the digital elevation model (DEM) used for derivation of the topographic index (e.g. Bruneau *et al*., 1995; Wolock and McCabe, 1995; Franchini *et al*., 1996; Saulnier *et al*., 1997), and a reliable estimate of transmissivity for saturated soils at the catchment scale is hardly achievable. Approximate values of $T_0 = 36\ \mathrm{m^2\,h^{-1}}$ derived from tracer experiments on steep slopes with high effective porosity (Mehlhorn, 1998) can be regarded as an upper limit of transmissivity in the study area. Assuming considerably lower values in compact till deposits in other parts of the catchment, the calibrated $T_0 = 1{\cdot}6\ \mathrm{m^2\,h^{-1}}$ is within a physically reasonable range. For both $S_{\mathrm{e\,max}}$ and T_0, however, the ranges of reasonable values were rather large and thus the calibrated values being within these ranges was no rigorous validation criteria.

The delay parameter t_{d} is part of a very simple formulation of vertical soil water movement and has no direct physical counterpart. Its reciprocal value may be considered as a measure of hydraulic conductivity. In this study, t_{d} had to be selected so small in order to obtain good model performance in terms of runoff simulations (Table III), so that incoming rainfall reached the saturated subsurface zone within one modelling time-step, i.e. one hour. Iorgulescu and Jordan (1994) reported similar calibration results. With this parameterization, modelled subsurface runoff reacted immediately to rainfall events. Except for some parts of the catchment with very coarse soil texture, including stones and debris, this fast passage of the unsaturated zone is not realistic. However, the required parameterization of t_{d} indicated that other processes generating fast subsurface flow were of importance. These may be preferential flow, translatory flow or groundwater ridging (for process description see, e.g. Bonell, 1993). Field studies including tracer methods confirm these processes to be of great importance in the Brugga catchment (Lindenlaub *et al*., 1997; Mehlhorn *et al*., 1998). Thus, the calibrated value of $t_{\mathrm{d}} = 0{\cdot}1\ \mathrm{h\,m^{-1}}$ must be interpreted as an effective parameter value which integrates various processes that are not captured explicitly by the simple model formulation. Although thereby ensuring an adequate response in terms of overall dynamics of generated runoff, the simple representation of subsurface zone in TOPMODEL did not agree with the real situation referring to runoff generation mechanisms or flow pathways.

For validation of parameter m, results derived from the recession analysis could be used. The calibrated value of 43 mm (Table III, column a) differed notably from the value derived by recession analysis (34 mm). A visual comparison of the simulated and observed hydrograph, representing a qualitative mode of model validation (Table I), revealed that with the calibrated values for m recession limbs were simulated too flat (Figure 5). Using a value of 34 mm for m, recession limbs matched the observed hydrograph markedly better. On the other hand, peak discharges were then considerably overestimated. In addition, simulated saturated areas were taken into account. Their mean simulated percentage on total catchment area was about 5·5% (Table III) which corresponded well to the mapped percentage of 6·2%. On the other hand, the simulated percentage of saturated areas was highly variable with time (Figure 5 and Table III). During high flow periods it reached nearly 20%. This was in contrast to the field observations, where spatial variability of the extension of saturated areas was small. A percentage higher than 10% was not reasonable in the study area, except for extreme situations, which did not occur during the study period. In the model, because of the large percentage of simulated saturated areas during floods, overland flow rates and consequently total runoff would be simulated too high. For compensation, parameter m had to be calibrated to a large value in order to better match observed peak flow at the expense of the performance of recession simulation. This is due to the function of this parameter to control the dynamics of subsurface runoff, with lower m reducing the range of subsurface flow rates and, thus, diminishing peak flow but also flattening out recessions. In summary, the poor correspondence of calibrated m to its value derived from the recession analysis revealed that the calibration of m was influenced by inadequacies of the model structure for the study area, i.e. an overestimation of the dynamics of saturated areas.

Concept of runoff generation. The recession analysis showed, furthermore, that an exponential decline of saturated hydraulic conductivity with depth was an appropriate conceptualization of the soil zone (Figure 3b). This could be stated on the basis of the TOPMODEL assumption of a single and homogeneous aquifer covering the entire catchment area. However, when examining Figure 3d in more detail, a better fit could be obtained when using three straight lines with different slopes, instead of one single line. This corresponds to three linear reservoirs, connected in parallel. These reservoirs could be associated with different source areas of subsurface runoff, which agrees with the perceptual model of the Brugga basin as proposed by Lindenlaub *et al*. (1997), Mehlhorn *et al*. (1998), where an underlying fractured hard rock aquifer, lower and upper debris cover are hydrological storages with different outflow behaviour. Thus, model validation by recession analysis indicated that even if one exponential storage for subsurface runoff gave acceptable runoff simulations, a more complex model structure would be needed for a more realistic representation of subsurface runoff.

When comparing the spatial distribution of mapped and simulated saturated areas (Figure 1), their patterns were in a satisfying correspondence at a rough visual check. However, only 34% of simulated areas covered exactly the mapped saturated areas. This poor agreement could partly be attributed to methodical problems of comparison, i.e. relating grid and polygon data, and to the resolution of the digital terrain model used for modelling, which was too coarse to reflect small-scale patterns in the catchment. A closer comparison revealed some characteristic differences between the patterns of simulated and mapped saturated areas. The occurrence of mapped saturated areas on steep slopes or close to the top of valley sides was systematically not represented by the model. These differences could be associated with factors other than topography as captured by the topographic index that are important for the generation of saturated areas, such as geology (fractures, strata boundaries), spatially variable transmissivity and climatic conditions varying with elevation (for details see Güntner *et al*., 1998).

Comparison of simulated runoff components with those derived from hydrograph separation is another type of model validation. In this case it has to be considered that the validation data themselves are based on a model (Table I) with certain assumptions, which may reduce the power of validation. In this study, this refers to the crude assumption of event water retaining its electric conductivity of rain water on the way to the catchment outlet, resulting in an overestimation of pre-event components. Nevertheless, for single flood events, some clear differences between modelled and separated runoff components appeared (Figure 4).

(1) Modelled saturation excess overland flow occurred earlier than contributions of event water as determined by hydrograph separation (time of first appearance and timing of peak).
(2) Peak contributions of simulated saturation excess overland flow were larger than peak contributions of event water.
(3) There was a contribution of event water during hydrograph recession whereas no saturation excess overland flow was simulated.
(4) Owing to point (3), the volume of event water integrated over the entire second flood in Figure 4 was about twice as large as the volume of modelled saturation excess overland flow.

Looking at descriptions of the TOPMODEL approach (e.g. Beven and Kirby, 1979; Beven *et al*., 1984, 1995), saturation excess overland flow as it is simulated within TOPMODEL should be interpreted as pure event water since 'any rain falling upon the saturated source area is taken to be runoff' (Beven *et al*., 1995,

p. 633). Following this interpretation, the simulated saturation excess overland flow always should be equal or less than the event water contribution. Therefore, the first two differences between the runoff components indicate a major failure of the model and suggest that other runoff generation processes which are not explicitly conceptualized within TOPMODEL, for instance, subsurface storm flow, are of importance in the study area.

One may argue that there is an exchange between surface and subsurface water and that it is only the amount of a fast flow component, but not its source and flow path, that is determined by TOPMODEL using the rainfall on the portion of saturated areas, i.e. flow from the saturated areas is also generated by displacement of pre-event water (Robson *et al.*, 1992). The differences between the results of the hydrograph separation and the TOPMODEL simulations imply that the latter interpretation should be applied to the Brugga catchment. However, as in this case the procedural model (i.e. the formulation of model equations) no longer corresponds to the perceptual model of runoff generation in saturated areas, the physical foundation of the model is restricted. Thus, with this vague definition of the runoff component, TOPMODEL cannot be validated against tracer data and much of TOPMODEL's point, in distinguishing between two components, is lost.

CONCLUDING REMARKS

The multi-criterial validation of TOPMODEL allowed a comprehensive evaluation of its capability to capture hydrological processes in a mountainous catchment. Satisfying runoff simulations were obtained after calibration, similar to many other applications in humid catchments (Beven *et al.*, 1995). An overall physically reasonable model response in terms of runoff when changing parameter values was found by means of a sensitivity analysis using different objective functions. The incorporation of spatial information on saturated areas complies with the repeatedly made request for a distributed model to be validated by adequate spatial data (e.g. Rosso, 1994; Grayson *et al.*, 1995; Beven, 1997). The comparison of simulated and observed spatial patterns of saturated areas allowed characteristic differences to be derived. In this way, the importance of factors other than topography, as captured by the topographic index, for the generation of saturated areas could be demonstrated for the study area. Validation of parameter values and dynamics of contributing areas against field observations, and the results of a recession analysis, revealed that the dynamics of the extension of saturated areas was overestimated by the model. A hydrograph separation indicated that the TOPMODEL approach of two runoff components was too simple with regard to important processes of runoff generation in the study area.

Prior to the application of TOPMODEL, important prerequisites for its use were supposed to be met in the study area, which is similar to other regions where TOPMODEL had been applied successfully [e.g. the Vosges (Ambroise *et al.*, 1996b)]. The intention throughout this paper has been to validate the model by a variety of methods and a broad range of supplementary independent information. This approach not only enabled a clear demonstration that application of the model was limited with regard to the objective of representing the dominant hydrological processes, but also allowed us to specify where and why these limitations occur. Taking an inverse point of view, model results derived on the basis of well-defined model assumptions, e.g. on the occurrence of a certain runoff process if distinct physiographic conditions are fulfilled in the catchment, may validate or broaden the perceptual understanding of the hydrological behaviour of a catchment, when compared with field observations. An example in this study is the spatial pattern of saturated areas. The mapped areas were compared with respective simulation results, which were based on the strict assumption that only topography determines the location of saturated areas, while soil characteristics like transmissivity were assumed to be homogeneous throughout the entire study area. Consequently, characteristic differences between both information layers highlight other factors, which amplifies, at least qualitatively, the hydrological knowledge about the catchment. Thus, combining both points of view, strategies for modifications of the model to better reflect the hydrological properties of the study area could be worked out. In future investigations, including stepwise modifications of the model or within a hypothesis-testing framework on the hydrological response of a catchment (see also Piñol *et al*., 1997), a multi-criterial validation scheme may serve as a valuable tool for identification of relevant model components. Modifications of the modelling concepts towards a more realistic representation of the hydrological behaviour of the catchment will most probably require more parameters. An adequate model extension, however, could at the same time enable incorporation of additional information for model validation. Furthermore, additional spatially distributed validation data like soil moisture or snow cover are assumed to constrain parameter values and different process representations (see also Franks *et al*., 1998). In general, this allows one to proceed in accordance with a top-down approach of model development: an initially simple and low-parameterized model, as TOPMODEL in this example, will successively be extended and adapted to the most important catchment characteristics, thereby ensuring concentration on dominant processes and keeping the number of parameters low.

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