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Modelling the Hydrological Response of Extreme Floods in Sweden

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Hydrological models are today used for simulating extreme floods with the purpose of designing dams and spillways. In doing so, an extrapolation beyond the floods of the calibration period is made. This paper addresses this problem in connection to the HBV hydrological model. The model component describing flood dynamics, the runoff-response function, is studied. The methodology has been to calibrate different runoff-response functions over small to moderately large floods and to verify the performance over independent periods containing large experienced floods. Furthermore, the different model versions were run with extreme rainfall in order to generate design floods. It was found that the five-parameter response function of the original HBV model could be replaced by nonlinear functions including fewer parameters. However, it was difficult to select any response function formulation as significantly better than the others when extreme floods larger than those of the calibration period were simulated.

Introduction

The hydrologic cycle consists of innumerable, extremely complex phenomena. Nature shows large variability, which makes generalization of small-scaled process studies to the catchment scale difficult. However, the dynamics of the rainfall-runoff processes can be approached from a system's viewpoint by considering the catchment as a hydrologic system. There are many definitions of a system. Chow *et*

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al. (1988) define a system as "a set of connected parts that form a whole. The hydrologic cycle may be treated as a system whose components are precipitation, evaporation, runoff, and other phases of the hydrologic cycle." By using the system concept, investigation of input, output relationships are made rather than detailed process descriptions with exact physical laws. In many situations, the immediate need to solve a practical problem requires the use of a systems approach (Singh 1988).

Hydrological models are approximations of the actual hydrologic system. The fundamental water balance equation for a catchment model is

$$Q(t) = P(t) - E_a(t) - \frac{dS}{dt} \tag{1}$$

where

Q – discharge,
P – precipitation,
E_a – evapotranspiration,
S – water stored within the catchment, and
t – time.

This equation involves no approximation as long as no groundwater crosses the system boundaries (Fig. 1). The idea of hydrological modelling is to establish simple relationships between these variables, so that the water-balance dynamics can be simulated. The most familiar and well established hydrological model in Sweden is the HBV model (Bergström 1976).

In the HBV model, the water balance equation is simulated in the following way: Areal precipitation P is calculated by weighting rain gauge measurements according to a Thiessen or a isohyetal method. The areal precipitation is then distributed over the elevation zones by applying a correction factor for altitude. Depending on whether the mean air temperature T is below or above a threshold temperature TT, the precipitation will fall as snow or rain.

Snowpack S_{sp} is the first component constituting the general storage variable S. When the temperature rises above a threshold value, the snowpack begins to melt. Meltwater Q_m is not released from the snow, however, until the retention capacity of the snow pores is reached. This capacity is normally set to 10 % of the snowpack water equivalent. Snowmelt is calculated with a degree-day equation, according to

$$Q_m(t) = CF_{max}\,(T(t)-TT) \tag{2}$$

where

CF_{max} – the degree-day factor.

The general storage variable S is also formed by the soil moisture storage S_{sm}. Percolation of excess water from the soil moisture storage Q_s is related to the

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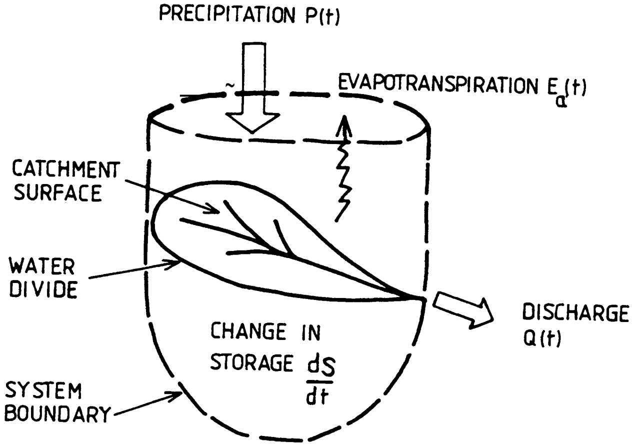

Fig. 1. The catchment as a hydrologic system.

precipitation and the computed soil moisture storage as given in Eq. (3). Rain or snowmelt generate small contributions of excess water from the soil when the soil is dry and large contributions when conditions are wet.

$$Q_s(t) = \left[\frac{S_{sm}(t)}{Fc}\right]^{\beta} P(t) \tag{3}$$

where

Fc – soil saturation threshold and
β – model parameter.

Evapotranspiration E_a is computed as a function of the soil moisture conditions and the potential evapotranspiration E_p. However, when the soil moisture exceeds a storage threshold Lp, water will evaporate at the potential rate. The equations are

$$E_a(t) = \begin{cases} \dfrac{E_p \, S_{sm}(t)}{Lp} & \text{if } S_{sm} \leq Lp \\ E_p & \text{if } S_{sm} > Lp \end{cases} \tag{4}$$

Snow and soil moisture modelling is made separately for each type of land use and elevation zone. But the runoff generation is formed by transforming excess water from the soil plus direct precipitation over open water bodies with a lumped runoff-response function. It results from the assumption that the catchment response behaves like two linked tanks (Fig. 2). The lower tank is a linear reservoir, representing base flow. It is filled by percolated water from the upper tank PERC plus

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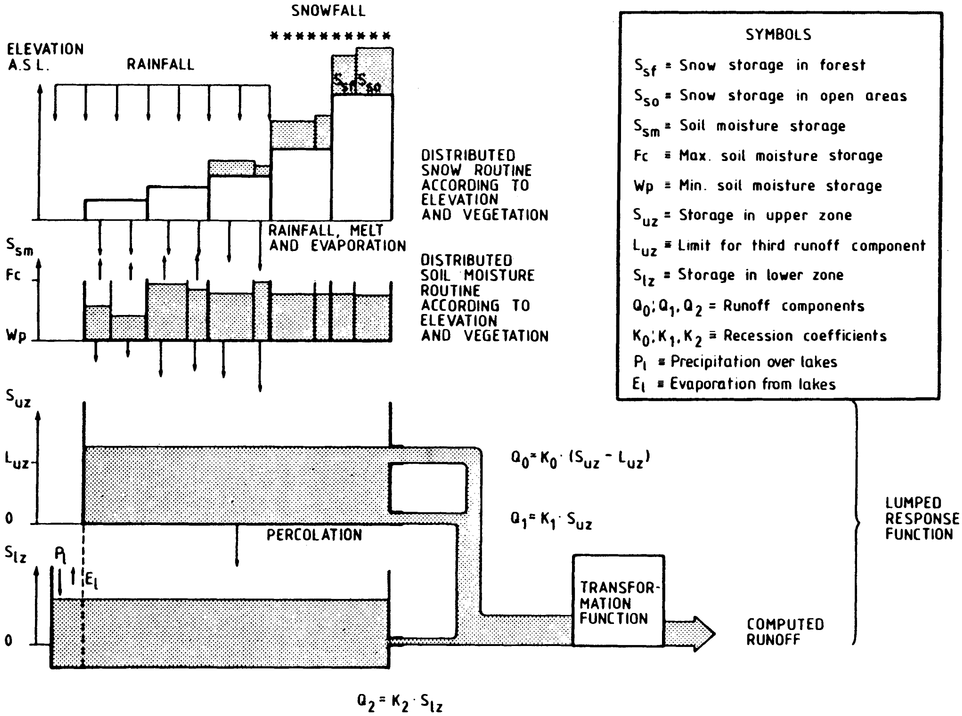

Fig. 2. The basic structure of the original HBV model.

precipitation over open water bodies P_l and responds to discharge and evaporation from lakes E_l.

If the excess water from the soil exceeds the percolation capacity, the upper tank starts to fill. This tank simulates the catchment response to flood events and has two recession coefficients separated by a threshold in storage (Fig. 2). Storage in the response function is the third component of the general storage variable S in Eq. (1). Thus the total storage $S = S_{sp} + S_{sm} + S_{uz} + S_{lz}$.

By simulating the hydrological cycle conceptually as described, one is forced to calibrate the model parameters by matching the model output with the observations. In order to get stable and representative parameter values it is essential to restrict the parameter number and to formulate the model equations so that the parameters are independent of each other. In model development and calibration it is important to split the available data set and save an independent period to verify the model performance. If this principle is followed and repeated for several areas, confidence in the model formulation can be gained (Bergström 1991).

Hydrological models are today not only used for regular inflow forecasting to reservoirs, but also for extending runoff series, filling in gaps of missing data, studying the effects of a hypothetical change in climate, and for simulating extreme

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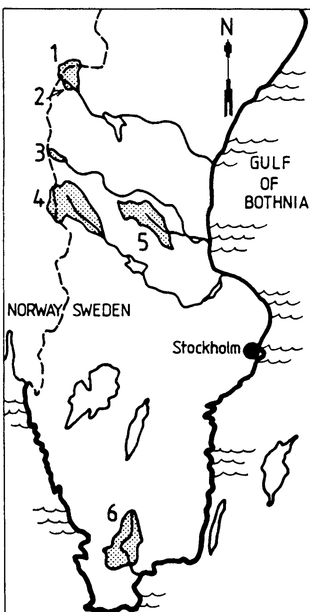
floods for designing dams and spillways. This means that the modeller takes a step into the unknown and the results can not be checked against observations. In Sweden, the HBV model is currently used for simulation of design floods. These floods are well beyond the observed floods used in the calibration process (Bergström *et al.* 1989). Consequently, an extrapolation is made and model structure and calibration will influence the magnitude of the generated design floods.

The objective of this paper is to study catchment rainfall-runoff response and develop simple runoff-response functions with few calibration parameters. The problem of modelling extreme floods, well beyond the range of those of the calibration period is focused. The methodology has been to calibrate different runoff-response functions over small to moderately large floods and to verify the performance over independent periods containing large experienced floods. Furthermore, the model versions were run with extreme rainfall in order to generate design floods.

Study Catchments

Six catchments were studied, namely: Torrön, Äcklingen, Alfta, Ljusnedal, Trängslet and Torsebro (Fig. 3).

These catchments represent different parts of Sweden and their runoff records contain some exceptionally large rain floods. The Äcklingen and Ljusnedal catch-



CATCHMENT	(km^2) AREA	RIVER
TORRÖN 1)	1370	INDALSÄLVEN
ÄCKLINGEN 2)	157	RUTSÄLVEN
LJUSNEDAL 3)	340	LJUSNAN
TRÄNGSLET 4)	4483	ÖSTERDALÄLVEN
ALFTA 5)	3140	VOXNAN
TORSEBRO 6)	3676	HELGEÅN

Fig. 3.
Location and key data for the studied catchments.

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Table 1 – The alternative runoff-response functions to the HBV runoff-response function, tested at Äcklingen and Ljusnedal.

Runoff-response function	Number of tanks	Equations	Calibration parameters
1	two	*Upper tank:* $Q_u = K\,S_u^{\alpha}$ *Percolation between the tanks* = *PERC* *Lower tank:* $Q_l = K\,S_l$	K, α PERC
2	one	$Q = K\,T + K\,(S - T)^{\alpha}$ *if* $S > T$ $Q = K\,S$ *if* $S \leqslant T$	K, T α
3	one	$Q = e^{\alpha\,S} - 1$	α
4	one	$Q = e^{\alpha\,S^{\beta}} - 1$	α, β
5	two	*Upper tank:* $Q_u = e^{K_1\,S_u} - 1$ *Percolation between tankes* = *PERC* *Lower tank:* $Q_l = K_2\,S_l$	K_1, K_2 PERC
6	one	$Q \equiv K\,S^{(1\,+\,\alpha\,S)}$	K, α
7	one	$Q \equiv K\,S^{(1\,+\,\alpha\,\ln(S))}$ *if* $S > 0$ $Q = 0$ *if* $S = 0$	K, α
8	one	$Q \equiv K_1\,S + K_2\,S^2$	K_1, K_2

ments are fairly small and quick in response. For these catchments, recession analysis was performed and experiments with a large number of response function formulations were carried out (Table 1). In the hydropower developed catchments; Torrön, Trängslet and Torsebro the HBV model is operationally used for inflow forecasting to the reservoirs. At Alfta the model is used for flood forecasting and flood warning. Two of the response functions developed from the behavior of Äcklingen and Ljusnedal were calibrated and run over extreme rain floods at Torrön, Alfta, Trängslet and Torsebro.

Recession analysis

The shape of the hydrograph is a function of the catchment characteristics and the meteorologic/hydrologic inputs and outputs over time. It is normally analyzed as consisting of a base flow component and a flood component. The flood component is the portion of the hydrograph that responds quickly and is clearly related to a given storm or snowmelt period. Base flow is formed by the continuous outflow of groundwater and lake discharge in the catchment.

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The receding limb of the hydrograph is strongly related to storage and change in storage in the catchment after that the rainfall or snowmelt stops. The recession curve is often expressed as

$$Q_t = Q_0 \, e^{-K\,t} \tag{5}$$

where

Q_t – discharge at time t,
Q_0 – the discharge when $t = 0$, and
K – the recession coefficient.

Taking logarithms, Eq. (5) becomes

$$\ln Q_t = \ln Q_0 - Kt \tag{6}$$

which can be plotted as a straight line with the gradient $-K$ in semi-logarithmic scale. Eq. (5) is derived from a linear storage to outflow relation, equivalent to the formulation for the lower tank of the HBV model. On this basis many studies to define and analyze recession constants have been made (*e.g.* Bako and Hunt 1988; Tallaksen 1989; Schwarze *et al.* 1989; Petras 1986 and Brandesten 1987). Nathan and McMahon (1990) evaluated several automated techniques for base flow separation and recession analyses. A linear storage to outflow relation is normally not appropriate for modelling flood periods because K is rarely constant throughout a flood recession. In order to simulate the increase in recession rate with increasing storage, the HBV model contains an upper tank with two outlets.

A model with storage thresholds will be sensitive to the magnitude of the observed floods used for calibration. The highest recession coefficient K_0 in the HBV model, for example, is only active on the upper part of the flood hydrograph. But, when extreme floods are simulated, this parameter will dominate the model response. Since the HBV model response function has five calibration parameters and includes a storage threshold (L_{uz}), the calibration can result in several parameter combinations with equally good performance over a calibration period, but with considerable differences when simulating extreme floods (Harlin and Kung 1992). Gan and Burges (1990) arrived at similar conclusions. They simulated hydrologic response from extreme rainfall with a modified version of the Sacramento model. Their analysis was based on simulations for small (0.1-0.2 km^2) hypothetical homogeneous catchments. As reference, the output from the S-H model (Smith and Hebbert 1983) was used. They stressed the problems with storage thresholds and the dangers of simulating floods beyond the calibration range.

Fig. 4 shows recessions for undisturbed rain-generated floods, plotted as $\log_e$ discharge versus time for the Äcklingen and Ljusnedal catchments. It is evident from the recession plots that the slope of the curves change with discharge magnitude, hence a single linear relationship between storage and outflow for flood periods does not hold true. Lundin (1982) and Lind and Lundin (1990) report that

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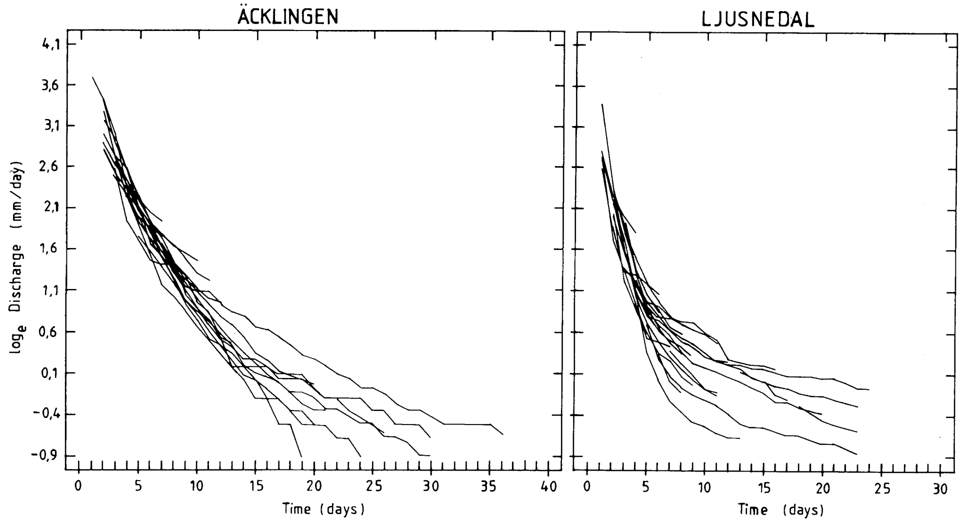

Fig. 4. Recession curves for rain floods as ln (discharge) versus time plots.

for Swedish tills the saturated hydraulic conductivity and groundwater flow are high close to the soil surface and decrease rapidly in deeper layers. At high storage the subsurface flow will occur close to the surface, hence an increase in recession rate should be expected.

If we draw an analogy with the hydraulics of channel flow, it is also seen that the flow conveyance increases with increasing storage. Considering the Manning equation for a broad channel, the flow per metre channel width is

$$q = \frac{1}{n} S_f^{\frac{1}{2}} y^{\frac{5}{3}} \tag{7}$$

where

n – Manning roughness coefficient,
S_f – friction slope, and
y – water depth.

The equation for runoff from a unit width surface of the length L will be

$$Q = \frac{S_f^{\frac{1}{2}}}{n\,L} y^{\frac{5}{3}} \tag{8}$$

which is the equation of a non-linear reservoir,

$$Q(S) = K\,S^{\alpha} \tag{9}$$

with $K = S_f^{1/2}/(\mathrm{n\ L})$ and the power $\alpha = 5/3$. Eq. (9) is also equivalent to the function for a single-valued rating curve used for discharge measurement.

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Selection of Alternative Runoff-Response Functions

Eight alternative runoff-response equations with non-linear storage to outflow properties, including fewer free parameters compared with the original HBV runoff-response function were formulated. Comparisons with the original HBV model equations by simulations in the catchments Äcklingen and Ljusnedal were made. The alternative runoff-response functions were both two-tank and single-tank functions, Table 1. Precipitation and evaporation from open water bodies was included in all alternative functions so that the remaining HBV model structure could be kept intact.

The test runs at Äcklingen and Ljusnedal showed that most of the alternative functions could be calibrated to simulate flood periods with comparable results to the original HBV model.

However, Function 1, which has a lower tank identical to the HBV model but an upper tank described by a single non-linear reservoir was clearly less capable of modelling flood periods, compared with the original HBV model. Furthermore, the single tank Functions 2, 3 and 4 gave poor model agreement over base flow periods and were therefore less general in application.

Function 5 though, was easily calibrated and resulted in good model performance both for base flow and flood periods. This function was selected for further analysis and will in the following be referred to as the "E-box".

Function 6 was suggested by Lindström *et al.* (1990). This equation will respond with a linear recession rate at low storage values and an increasing recession rate with increasing storage. However, the recession rate increases tremendously fast with storage which makes the equation difficult to calibrate so as to model both base flow and flood periods correctly. To moderate the increase in recession with increasing storage a logarithm of the power term was introduced as given by runoff-response Function 7. Function 7 was selected for further analysis and will in the following be referred to as the "Ln-box".

Function 8 is a polynomial expression. It resulted in good model performance but was difficult to calibrate since the parameters have a large interdependence.

Table 2 – Model performance, expressed as R^2 values (%), for the original HBV model and the selected alternative runoff-response functions.

	Äcklingen		Ljusnedal	
	Cal.	Ver.	Cal.	Ver.
HBV	87.3	86.7	80.7	86.4
E-box	87.0	86.2	79.4	83.6
Ln-box	86.6	86.0	78.5	79.9

Cal. ≡ calibration period (1971-08-01 – 1981-07-31)
Ver. ≡ verification period (1981-08-01 – 1989-07-31)

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Table 2, shows the model performance for the HBV model with its original runoff-response function and the two alternative functions expressed by the R^2 criterion of fit, Eq. (10) (Nash and Sutcliffe 1970). All three functions were automatically calibrated over all flood and base flow periods with the POC calibration scheme (Harlin 1991).

$$R \equiv 100 \left[1 - \frac{\sum_{t=1}^{n} (Q_m(t) - Q_0(t))^2}{\sum_{t=1}^{n} (Q_0(t) - Q_{0m})^2} \right] \tag{10}$$

where

n – number of time steps,
Q_m – modelled runoff,
Q_0 – observed runoff, and
Q_{om} – mean observed runoff.

Results

Simulation of Observed Extreme Floods

The E-box and the Ln-box will have a non-linear increase in discharge with increasing storage, Fig. 5. This property will result in an increasing recession rate with flood magnitude when modelling extreme floods, Fig. 6.

In order to check the uncertainty due to model structure when modelling extreme floods, the three runoff-response functions: HBV, E-box and Ln-box, were

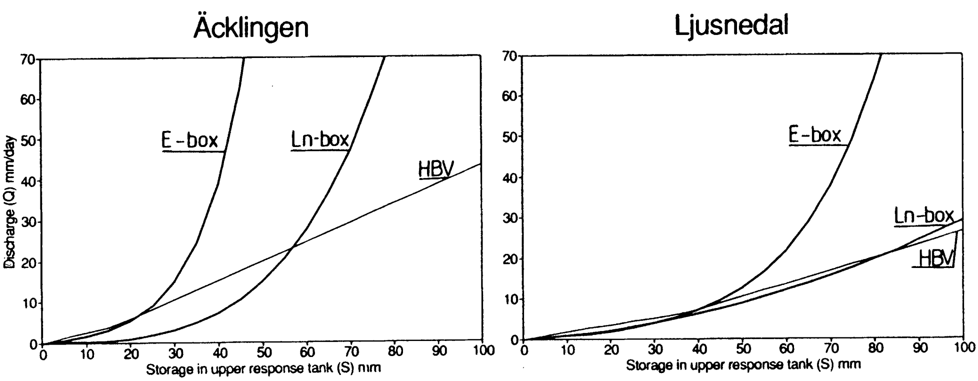

Fig. 5. The discharge to storage relation for the studied runoff-response functions. Only the storage in the upper tank is depicted for the HBV and E-box. For the Ln-box (which is a single tank formulation) the total storage is shown.

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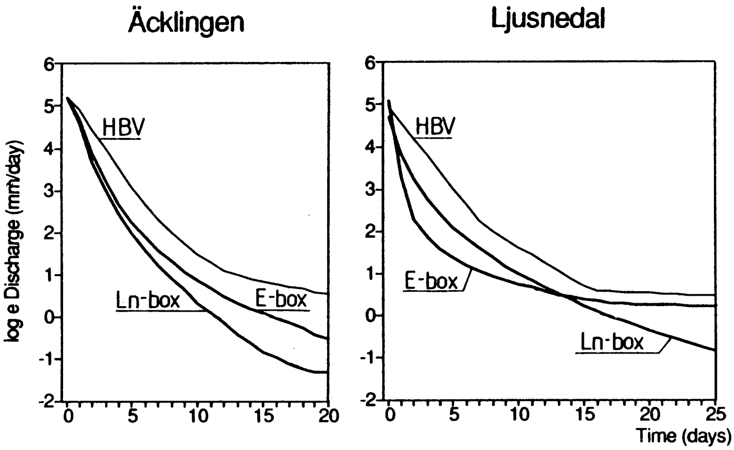

Fig. 6. Recession curves for the three studied functions as ln (discharge) *versus* time plots.

calibrated on small to moderate rain floods and verified on large observed rain floods at Torrön, Alfta, Trängslet and Torsebro, Figs. 7 and 8. Only rain floods were studied in order to reduce the influence of the snow routine of the model, and thereby receive a clearer picture of the runoff-response function behavior. During the simulations the original HBV model structure was used and only the runoff-response function was replaced when testing the E-box and Ln-box.

The verification flood for Alfta (Fig. 7) is one of the best known extreme floods in Sweden. It culminated the 11th of September 1985, with a peak flow of 360 (m^3/s) at Alfta in the Voxnan river (Fig. 9).

The September 1985 flood was caused by extreme rainfall over the provinces of Dalarna and Hälsingland in Central Sweden. During July and August rainfall was larger than normal which resulted in low soil moisture deficits and well filled reservoirs. The heavy rainfall prevailed in the beginning of September with the largest rainfall occurring the 6th of September. On the 6th of September about 70 (mm) of rain fell over the notheastern parts of Dalarna and a large part of Hälsingland. On the 7th of September an additional 10 (mm) of rainfall fell. Large floods resulted, mainly in the Ore and the Voxnan rivers. The resulting flooding was the largest observed for the past 100 years.

The most spectacular consequence of this flood situation was an overtopping of the Noppikoski embankment dam in the Ore river. In the early morning of September 7, the dam eroded and within 45 minutes the 1,000,000 m^3 of water stored in the reservoir emptied out. During the dam failure the total outflow was about 600 (m^3/s). Luckily no people were injured or killed but severe damage was caused to several bridges and to the down stream forests (Kommittén för undersökning av allvarliga olyckshändelser 1987).

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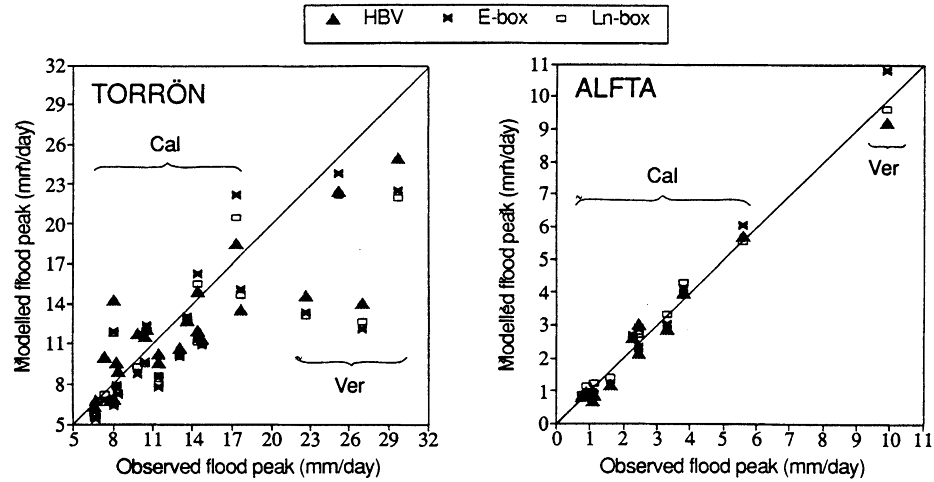
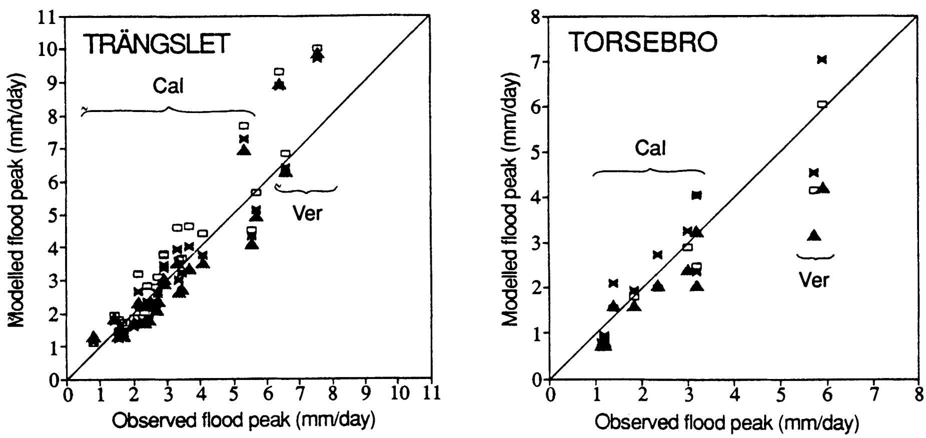


R^2-values
(10 years)
HBV 0.84
E-box 0.83
Ln-box 0.84

R^2-values
(8 years)
HBV 0.82
E-box 0.84
Ln-box 0.83

Fig. 7. Model performance for the tested runoff-response functions at Torrön and Alfta. The functions were calibrated and verified on rain floods only. R^2 values refer to calibration periods.



R^2-values
(16 years)
HBV 0.91
E-box 0.90
Ln-box 0.86

R^2-values
(10 years)
HBV 0.91
E-box 0.87
Ln-box 0.90

Fig. 8. Model performance for the tested runoff-response functions at Trängslet and Torsebro. The functions were calibrated and verified on rain floods only. R^2 values refer to calibration periods.

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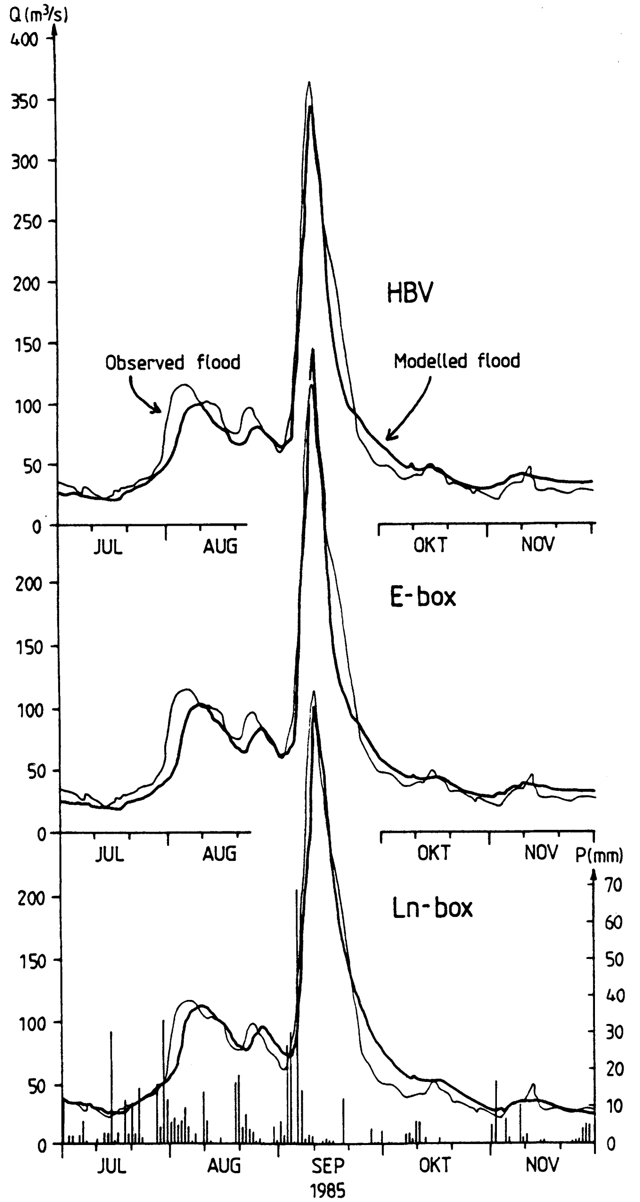

Fig. 9. Modelled (thick line) and observed (thin line) runoff at Alfta during the extreme rain flood in September 1985.

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Table 3 – Design flood simulation of the most critical autumn floods, using the HBV model with three different runoff-response functions. The table gives the resulting peak flow values (mm/day). The range is calculated with reference to the mean of the highest and the lowest peak value.

	Torrön (1983-10-16)	Alfta (1985-09-24)	Trängslet (1985-08-18)	Torsebro (1988-08-16)
HBV	63.3	14.2	19.6	10.1
E-box	113.1	18.5	31.8	14.3
Ln-box	91.5	16.6	25.1	13.0
Range	± 28 %	± 13 %	± 24 %	± 17 %

Simulation of Design Floods

The uncertainty in design flood simulation, due to model structure, was estimated by simulating the most critical autumn floods (after August 1st) according to the Swedish guidelines for design flood determination (Flödeskommittén 1990). Before the simulations, each response function was fine tuned over the largest of the observed rain floods. During the design flood simulation the soil moisture deficit was removed before the onset of the spring flood and the observed pricipitation was replaced by a 14-day design areal rainfall sequence at the most critical location in time. The resulting peak flows are given in Table 3.

Discussion and Conclusions

The recession analyses are done for undisturbed rain flood recessions, that are periods where no rainfall was recorded during the recessions. These periods are however not truly undisturbed. Rainfall can have occurred over parts of the catchment where no gauge is located. The assumption that evapotranspiration could be neglected is also a weakness in the approach. However, only flood period recessions were examined, not the base flow recessions. This means that the evaporation will be negligible.

It was found that the runoff-response function of the HBV model could be substituted with a great number of different equations without radically changing the model performance. However, the results from the experiments carried out in this study indicate that none of the alternative runoff-response functions clearly performed better than the origianl HBV model function. An advantage of the original HBV model response function is that the effect of each parameter is easy to identify and calibrate. The HBV model gave throughout the best agreement over calibration periods, in particular for base flow periods. The largest disadvantage of the HBV model runoff-response function is that the parameter number is fairly large (five) and that the highest recession rate K_0 is locked by the L_{uz} storage

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threshold. From this follows, that simulation of larger floods than those used in calibration will have the same recession as the largest floods of the calibration period.

In general the E-box response function generated the largest flood peak followed by the Ln-box and the HBV. The differences between the models increased when simulating design floods. In terms of simplicity of application the E-box and HBV were easier to calibrate than the Ln-box. This was due to the fact that the parameters of this function are strongly interdependent and that it was difficult to match the model to both base flow and flood periods with good results. In the Ljusnedal catchment this function performed poorly over base flow periods. It should however be borne in mind that the Ln-box is a single tank formulation with only two free parameters, which limits the degrees of freedom in calibration.

The E-box and the original HBV runoff-response function were found to be almost equivalent in application. The exponential increase in recession rate of the E-box could, however, possibly overestimate the recession rate of extreme floods. But this would require further research to be verified. If a runoff-response function with few parameters and with the ability of describing both floods and base flow periods is sought for, the E-box should be considered.

In formulating alternative response functions, the ambition was to reduce the number of free parameters and to formulate the equations so that the recession rate would increase with storage and flood magnitude. It was initially believed that such functions would be easier to calibrate correctly for extreme floods simulation since the equations would be active over all parts of the hydrograph. However, the results from calibration on small to moderate floods and verification over large observed floods (Figs. 7 and 8) indicate that it is difficult to select any response function as significantly better than the others. Futhermore, these figures show that the quality of the model performance over verification periods is linked to that over the calibration periods. It was also seen that for almost all of the verification period floods, the different response function formulations performed mutually similar. Either they all underestimated a certain flood or they overestimated the flood. The errors are therefore not only due to this model component but also to errors in model input and in the soil moisture routine. Another problem is that during extreme floods the rating curves have usually been extrapolated far beyond the range supported by direct measurements.

For the Torrön basin there occurred some snow accumulation during the largest flood, which also affects the results. Another problem in modelling the runoff from this catchment is that it has a fast runoff response. If for example, heavy rainfall starts in the evening one day and ends at midday the next day it will be split over two time steps (the time step used was 24 hours) in the model and thereby generate a smaller flood than the one observed. Design flood simulation according to the Swedish procedures avoid these problems, since all meteorological and hydrological inputs are preset on a daily time step. The Swedish guidelines for design flood

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determination state that a hydrological model with documented performance should be used in the simulations. In Sweden this means that the HBV model or similar is accepted. In Norway a simplified version of the HBV model is used for extreme flood simulation (Andersen *et al.* 1983). But the problem of how to assess the model error when extrapolating to such extremes as the design floods remains unsolved. This paper is an attempt to illustrate this uncertainty. The design flood simulations (Table 3) indicate that the modelling uncertainty is in the range of ± 20 % on an average. But nevertheless, further research focused on this problem is necessary before more precise estimates can be given.

The results showed that there is no clear tendency that the HBV model systematically underestimates extreme floods beyond the period of record. Therefore, as long as calibration is carried out with emphasis on the largest observed floods, the HBV model is appropriate for design flood simulations.

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