DEVELOPMENT AND APPLICATION OF A CONCEPTUAL RUNOFF MODEL FOR SCANDINAVIAN CATCHMENTS

UTVECKLING OCH TILLÄMPNING AV EN BEGREPPSMÄSSIG AVRINNINGSMODELL FÖR SKANDINAVISKA NEDERBÖRDSOMRÅDEN

by Sten Bergström

SMHI Rapporter

HYDROLOGI OCH OCEANOGRAFI
Nr RHO 7 (1976)

SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT

DEVELOPMENT AND APPLICATION OF A CONCEPTUAL RUNOFF MODEL FOR SCANDINAVIAN CATCHMENTS

UTVECKLING OCH TILLÄMPNING AV EN BEGREPPSMÄSSIG AVRINNINGSMODELL FÖR SKANDINAVISKA NEDERBÖRDSOMRÅDEN

by Sten Bergström

SMHI Rapporter

HYDROLOGI OCH OCEANOGRAFI
Nr RHO 7 (1976)

SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT

Norrköping 1976

ERRATA

"Development and Application of a Conceptual Runoff Model for Scandinavian Catchments"

by Sten Bergström

Page	Location	Original	Should be
IV	Line 3	F_c	Fc
1	" 12	Linsley and Crawford	Crawford and Linsley
3	" 15	result	results
4	Line 5 and 17	Clarke (1972)	Clarke (1973)
5	Line 18	" "	" "
23	" 11	stationery	stationary
38	" 13	Steindalsvatn	Steinslandsvatn
45	" 21	C_{u1}-value	C_{u2}-value
50	" 18	starts.	starts,
60	" 3	fig. 7.3	fig. 7.13
60	" 8	$\frac{(S_{sm})^{\beta}}{Fc}$	$(\frac{S_{sm}}{Fc})^{\beta}$
64	" 14	value of s_{sm}	value of s_{act}
70	" 8	lower zones	lower zone
70	" 23	on	of
72	" 18	Roche (1970)	Roche (1971)
82	table 7.13 line 8	(p_w) 12.0	10.0
82	table 7.13 line 9	(p_w) 10.0	12.0
92	line 13	look	looks
103	" 29	1962-75	1963-75
126	" 25	cathcments	catchments
132	" 35	1975	1971

S U M M A R Y

The experiences of conceptual runoff modelling at the Swedish Meteorological and Hydrological Institute are summarized in the present work. The basic philosophy and the methodology when developing the HBV-model are discussed. The structure of the model is described with a discussion of its physical relevance and examples of alternatives. The sensitivity of the model to changes in parameter values is studied through mappings of the response surfaces of a sum of squares criterion of fit. Applications to a variety of catchments in Sweden and Norway are presented and the performance of the model is verified by a numerical criterion of fit, plottings of computed hydrographs and recorded ones, scatter diagrams of peak flows and flow duration curves. Examples of both short range and long range hydrological forecasting are given.

A general conclusion is that the HBV-model can be used for the reconstruction of the discharge in catchments of the presented type, if it is properly calibrated. The model can also be used for hydrological forecasting, if combined with meteorological forecasts or recorded climatic series.

S A M M A N F A T T N I N G

Erfarenheterna av begreppsmässiga avrinningsmodeller vid Sveriges Meteorologiska och Hydrologiska Institut summeras i föreliggande arbete. Den grundläggande filosofin och metodiken vid utvecklingen av HBV-modellen diskuteras. Modellstrukturen beskrives med en presentation av den fysikaliska bakgrunden och exempel på alternativ. Modellens känslighet för störningar av parametervärden studeras genom kartläggning av ett minsta kvadratkriteriums responsytor. Tillämpningar av modellen på ett antal avrinningsområden i Sverige och Norge redovisas och simuleringen utvärderas med ett numeriskt anpassningskriterium, uppritningar av den beräknade och observerade hydrografen, jämförelser mellan simulerade och beräknade flödestoppar samt varaktighetsdiagram. Exempel ges på hydrologiska lång- och korttidsprognoser.

En allmän slutsats är att HBV-modellen är användbar för rekonstruktion av

vattenföringsserier i den typ av områden, där den tillämpats, under förutsättning att den kalibreras på ett riktigt sätt. Modellen kan också användas för hydrologiska prognoser med hjälp av meteorologiska prognoser eller observerade klimatserier.

ACKNOWLEDEMENTS

The staff of the Swedish Meteorological and Hydrological Institute is gratefully acknowledged for valuable assistance in all phases of this work. In particular I wish to thank Dr. Arne Forsman for experienced advice and encouragements, Mr Stig Jönsson, partner on this project since September 1974, Mr Lars-Erik Eggertsson for valuable help with computer problems and Mrs Vera Kuylenstierna for typing the manuscript.

I also want to thank professor Gunnar Lindh at the Department of Water Resources Engineering, Lund Institute of Technology, who convinced me about the value in a summary of my work on conceptual modelling.

During the four years of work on conceptual runoff modelling valuable criticism and suggestions in the form of meetings or by more informal contacts, have been provided, both on a national and on an international basis. I am grateful to all those who participated in this process.

Parts of this work have been financed by the Swedish Natural Sience Research Council and Ångermanälvens Vattenregleringsföretag which is gratefully acknowledged.

Finally I want to express my gratitude to all those who have participated in the lengthy process of data collection and processing. Reliable records of meteorological and hydrological data are indispensable when developing conceptual runoff models.

LIST OF CONTENTS

LIST OF SYMBOLS

a_t	accumulated difference at time t.
B_{max}	maximum base in the transformation function.
B_q	actual base in the transformation function.
C_o	degree-day melt factor.
$C_{o\ inf}$	range in distribution of the degree-day melt factor.
$C_{o\ max}$	maximum in the distribution of the degree-day melt factor.
$C_{o\ min}$	minimum in the distribution of the degree-day melt factor.
C_1	general parameter.
C_2	general parameter.
C_{e1}	parameter in the snow evaporation equation.
C_{e2}	parameter in the snow evaporation equation.
C_{eff}	parameter relating melt rate to accumulated snowmelt.
C_{m1}	parameter accounting for windspeed in the snowmelt equation.
C_{m2}	parameter accounting for windspeed in the snowmelt equation.
C_{perc}	percolation capacity.
C_{route}	parameter in the transformation function.
C_{sf}	snow fall correction factor.
C_{u1}	parameter accounting for windspeed in the snow accumulation routine.
C_{u2}	parameter accounting for windspeed in the snow accumulation routine.
C_{wh}	water holding capacity of snow.
E_a	actual evaporation.
E_p	potential evaporation.
e_a	vapor pressure in the atmosphere.
e_s	surface vapor pressure.
F^2	sum of squares criterion of fit.
F_o^2	initial variance.
F_{abs}	alternative criterion of fit.

F_{diff}	alternative criterion of fit.
F^2_{mv}	alternative criterion of fit.
F_c	maximum soil moisture storage in the model.
Fc_{max}	max. value of Fc in a distributed routine.
Fc_{min}	min. value of Fc in a distributed routine.
f (x)	frequency distribution function of x.
H	elevation in the catchment.
i	general variable in time or space.
K	storage discharge parameter.
K_o	storage discharge parameter in the upper zone.
K_1	storage discharge parameter in the upper zone.
K_2	storage discharge parameter in the lower zone.
L_p	limit for potential evaporation.
L_{uz}	limit for slow drainage of the upper zone.
M	snowmelt.
P	precipitation.
P_{corr}	rainfall correction factor.
P_{lapse}	area-elevation correction of precipitation.
$\overline{P}_{lapse}$	average area-elevation correction of precipitation.
p_w	part of the model representing lakes, rivers and other wet areas.
Q	runoff.
Q_o	runoff generated from the upper zone.
Q_1	runoff generated from the upper zone.
Q_2	runoff generated from the lower zone.
Q_c	computed runoff.
Q_g	total generated runoff.
Q_{in}	inflow from an upstream situated reservoir.
Q_{loc}	local inflow to a reservoir.
Q_r	recorded runoff.
$\overline{Q}_r$	mean of recorded runoff.

Q_{tot}	total runoff from a reservoir.
R^2	criterion of fit.
r	alternative storage discharge description.
S	storage.
S_{act}	active storage in the soil moisture zone.
S_b	bottom storage under the snowpack of the model.
S_{ls}	storage in the lower zone of the model.
S_r	storage in a reservoir in a catchment.
S_s	storage of snow in the model.
S_{sm}	soil moisture storage in the model.
$S_{sm_{min}}$	minimum soil moisture storage for a given period of time.
S_{uz}	storage in the upper zone of the model.
s_{act}	relative active soil moisture storage for a given period of time.
T	temperature.
T_o	general temperature correction.
T_{lapse}	area-elevation correction of temperature.
t	variable in time.
t_o	initial time.
u	windspeed.
$\bar{u}$	average windspeed.
W_c	convective heat flux.
W_g	heat flux from the ground.
W_l	latent heat flux.
W_{lw}	net long wave radiation.
W_m	heat equivalent of the snowmelt.
W_p	contribution of heat from precipitation.
W_{sw}	absorbed short wave radiation.
W_t	change in the energy content of the snowpack.
Z	area of contributing zone in the distributed soil moisture routine.

α	parameter in the distributed soil moisture routine.
β	parameter in the lumped soil moisture routine.
τ	period of time.

Appendix 1

ACC. DIFF.	accumulated difference between the computed and the observed hydrographs.
EVP	computed actual evaporation.
MELT	yield from the snow routine.
P	precipitation.
SM	computed soil moisture storage.
SNOWCOV	computed snow covered area.
SP	computed average snowpack.
TEMP	temperature.
Q	computed and recorded discharge.

Appendix 2

F^2	sum of squares criterion of fit.
n	number of values for the computation of F^2.
R^2	criterion of fit.
σ	mean error.

1. INTRODUCTION

The processes in nature governing the hydrological cycle have long attracted the attention of those working on the rational use of existing water resources. Particularly the processes converting the driving forces, precipitation and evaporation into runoff have been subject to great efforts by scientists and engineers.

In recent years the advent of electronic computers has made it possible to organize and analyze data and to carry out computations in a way previously inconceivable. This possibility has resulted in the development of mathematical hydrological models which in a conceptual way are capable of simulating the most significant components of the runoff generating processes. Among the pioneers in this field were Linsley and Crawford (1966) when presenting the Stanford watershed model, a model which today has found a lot of applications all over the world. Also well known is the SSARR model (Schermerhorn and Kuehl, 1968) developed for river regulations in the Columbia basin in the north-western of U.S.A. The SSARR model is also in operational use for forecasting purposes in Sweden (Danielsson and Wretborn, 1975) and in Poland (Bobinski, Piwecki and Zelazinski, 1975).

In the Scandinavian countries the first models were presented by Nyberg (1972), Nielsen and Hansen (1973) and Grip (1973). The first model from the Swedish Meteorological and Hydrological Institute (SMHI) was presented by Bergström (1972 A).

The increasing interest in hydrological models caused the World Meteorological Organization to initiate the project on "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting" in 1968 with ten participating models from different parts of the world. The final report from this project appeared in 1975 (WMO, 1975 B).

Mathematical runoff models can be applied to a vast field of water resource problems. Some of the most common applications are summarized in the following three points.

1. Simulation of natural discharge.
2. Operational forecasting.
3. Prediction of effects of future physical changes in a catchment.

Simulation of natural discharge means that the model is used to simulate runoff from meteorological input data available in the catchment or in its neighbourhood. The performance of the model is generally verified against a recorded runoff series. The model can be used to extend runoff records by means of long records of meteorological observations. It can also be used to tell artificial from natural variations in a catchment where human influence or other changes in the hydrological regime are suspected. A tempting, but rather difficult, application is the estimation of runoff in ungauged catchments. To do this with any certainty requires long experience with the model so that its components can be related to the physiographic characteristics of the catchment.

In operational forecasting, the model is first fitted and tested in order to verify its capability of runoff simulation from meteorological data. Then meteorological forecasts or recorded climatic series can be used to forecast discharge in rivers.

The most difficult point is to predict the effects of future physical changes in a catchment, as it requires not only an accurate runoff model but also that its components with certainty can be related to the characteristics of the catchments, such as degree of urbanization or percentage of clear cuttings in a forest. If so, the model can be used to study the possible effect on the hydrological regime of a proposed activity in the catchment.

1.1. The work at the Swedish Meteorological and Hydrological Institute (SMHI)

Since 1972 work on the development of an operational hydrological runoff model has been in progress at the SMHI. The efforts have been concentrated on the simulation of natural discharge and operational forecasting. The objective is to develop a model which is applicable to most Swedish catchments. This means that it must not require better data coverage than can generally be satisfied also in rather remote areas. Furthermore the intention is to make the model so flexible that it can be transferred from catchment to catchment without too much modification of its basic structure.

Initially a simple model for the snow-free season was developed, which showed encouraging results when applied to a few small basins. Since then the model has been tested in several catchments ranging in size from 4 to nearly 4 000 km^2. The model has been modified slightly as catchment size and other characteristics have changed, but the basic structure is still the same. It has been named the HBV-model, from the water balance section (HBV), where it was developed, followed by a number to identify different versions.

The present work intends to give some insight into the philosophy and methodology in the development of the HBV-model, to discuss the structure and to show some practical applications. As development and application are closely related, examples from different catchments will be used as illustrations in case they have had significant impact on the methodology or structure of the model. A more systematic presentation of the result is given in a separate chapter, No. 8, and some graphs of computed and observed discharge are presented in appendix 1.

2. DEFINITIONS

In the following text some expressions that might not be self-explanatory will be used. Therefore it was felt appropriate to give some clarifications. For more complete definitions of the terms in hydrological modelling, reference is made to, for example, Clarke (1972).

A system has a very broad meaning. It can be defined in a simple way as by von Bertalanffy (1968, page 55): "A system can be defined as a set of elements standing in interrelations". Dooge (1973, page 4) gave a more specified definition: "A system is any structure, device, scheeme, or procedure, real or abstract, that interrelates in a given time reference, an input, cause, or stimulus, of matter, energy, or information, and an output, effect, or response, of information, energy, or matter".

A linear system is defined as one where the principle of superposition holds, which means that if $y_1(t)$, $y_2(t)$ are the outputs corresponding to the inputs $x_1(t)$, $x_2(t)$, the outputs corresponding to $x_1(t) + x_2(t)$ will be $y_1(t) + y_2(t)$.

A model can be defined according to Clarke (1972) as "a simplified representation of a complex system". This simple definition applies to the use of the term model in this text.

A mathematical model is defined as a set of mathematical expressions and logical statements combined in order to simulate the behaviour of a given system.

A deterministic model is a model where two equal sets of inputs will always yield the same output, if run through the model under identical conditions. The model has no component controlled by chance.

A stochastic model has some component of random character. Identical inputs may result in unequal outputs, if run through the model under identical conditions.

A black box model is developed without any considerations of the physical processes in the catchment. The model is merely based on analysis of input and output.

A conceptual model is based on some considerations of the physical processes in the catchment. In a hydrological model the use of a lower zone representing ground water and an upper zone representing quicker runoff, for example, will give the model a conceptual status.

A routine, function or procedure is a part of a model, for example the simulation of snowmelt or the soil moisture accounting procedure.

A lumped model or routine is one where the catchment is regarded as one unit without any consideration of the geographical or statistical distribution of its properties.

A distributed model or routine is accounting for the statistical or geographical distribution of properties within the catchment.

Ambiguous use of the terms parameter and variable sometimes causes confusion when discussing mathematical models. The definitions below have, however, become practice in hydrological modelling. They have been suggested by Clarke (1972) among others.

A parameter is a constant in the mathematical expressions or logical statements of the mathematical model. It remains constant in time. Alternatively the terms coefficient, constant or factor will be used in this text.

A variable is a quantity which varies in time. It can be a series of input to or output from the model but also a description of the conditions in the different components of the model.

In this text the parameters will be classified further as free or confined depending on their use in the model.

A free parameter is found empirically during the calibration of the model. Alternatively the term empirical coefficient will be used.

A confined parameter is estimated from the map or other information about the catchment. It is kept constant during the calibration procedure.

3. STRATEGY

The runoff modelling problem can be approached from two extreme standpoints. One is the analysis of time series of input and output and construction of the model without any notice of the known or unknown physical properties of the catchment. This is sometimes called the "black box" approach. The other is represented by the school advocating for, if not a complete, then at least a thorough understanding of the physical processes before any model can be established.

The most famous example of the black box approach in hydrology is probably the instantaneous unit hydrograph (IUH) as described by Dooge (1973) among others. The elegant mathematical solutions are attractive, but the determination of the excess water that will form the runoff is a very weak point. This problem is sometimes overcome by an antecedent precipitation index (API), meaning that the length of the dry period preceding precipitation is a factor reflected in the response. A model of the latter type is not, however, to be regarded as a black box model any longer as the effect of a soil moisture deficit is accounted for implicitly.

The black box approach has its main drawback in its incapability to account for the general knowledge which we have about the catchment and the different physical processes. It is therefore strongly felt that the application of pure black box methods is a waste of information.

On the other hand the school advocating that a runoff model can be developed only with a thorough knowledge of the physical laws and mechanisms of the runoff generating process, will run into unsurmountable problems due to shortage of information. Detailed knowledge of the physical laws at one spot in the catchment will be more or less impossible to extrapolate to areal behaviour because of limited knowledge of the distribution of the physical characteristics over the catchment.

Most runoff models are compromises between these two extreme standpoints, and so is the HBV-model. It is built up on a framework justified by physical considerations but parts of the model have more the character of a black box approach as it includes parameters which have to be calibrated through the analysis of input and output.

When developing the HBV-model, it was immediately realized that a detailed description of all components of the hydrological cycle would lead to a model of a complexity that cannot be justified by the objective to simulate runoff. Therefore it was decided to concentrate on the most significant parts of the runoff generating processes. In order to find these significant parts, work has been carried out according to a scheme which can be summarized in the following six points (Bergström 1974):

1. Assume a very simple model based on field measurements and intuition.
2. Test the model against recorded data.
3. Modify the model and test it again, make sure that the modifications are improving the model.
4. Study the stability and interactions of the parameters.
5. Test the model in catchments of different size, character and geographic location.
6. Carry out field investigations of the processes which are particularly important for the model structure.

Emphasis is put on the restriction of the number of free parameters. Therefore each parameter has to be used as efficiently as possible, meaning that a large spectrum of possibilities has to be covered by alternative values of one parameter.

The method has a lot in common with the ideas presented by Nash and Sutcliffe (1970). They suggested that one should start with a simple model and then elaborate it further, always with a glance at the efficiency of the model and the stability of its parameters. Other authors supporting this approach are von Bertalanffy (1968, page 187), who stated that "oversimplifications progressively corrected in subsequent development are the most potent or indeed the only means towards conceptual mastery of nature", and Kalinin (1971, page 244), who wrote that "when a problem goes beyond a certain boundry of mathematical complexity, a simpler apparatus is used in its solution". Fiering (1975), finally, strongly emphazises the need for more understanding of the physical laws before more complex models are developed. On the question of free parameters. Ibbit (1974) stated that "The economics of model operation necessitate that fitting problems be minimized and this implies that the number of parameters should be as low as possible".

4. TEST CATCHMENTS

The model has so far been run by the SMHI during 96 years or seasons in 11 catchments as presented in table 4.1 and fig. 4.1. The catchments cover a large spectrum of physiographic settings and geographical locations. The soil is mostly morain or of a pervious type. It remains an interesting future task to model a catchment dominated by clay.

Some of the catchments in table 4.1 are subbasins to Representative Basins established within the framework of the International Hydrological Decade. Lilla Tivsjön is a part of the Kassjöån basin, Nolsjön a part of Velen and Solmyren a part of the Lappträsket basin. The Filefjell basin is one of three Norwegian Representative Basins. Apart from being used as test catchments the Representative Basins have been valuable sources of information when developing the model structure, as they have improved our general understanding of the hydrological processes. Characteristics of all Nordic Representative Basins are presented by Falkenmark (1972).

The applications of the model to the Kultsjön, Malgomaj and Ströms Vattudal catchments were made for the river regulation company of the river Ångermanälven (Ångermanälvens Vattenregleringsföretag). These catchments will be subjects to operational forecasts starting in the spring of 1976.

The application to the Steinslandsvatn catchment was made at the Norwegian Water Resources and Electricity Board and was about to be finished when this was written. Worth mentioning is also a modification of the HBV-model made by Houmøller (1976) and applied to the 46.6 km^2 large Giber å basin outside Aarhus in Denmark.

The results from the different catchments will be incorporated in the following discussion on the methodology and the model structure. A more systematic presentation of the results is made in chapter 8 and in appendix 1. For more details concerning catchment characteristics and applications, the reader is referred to the references to table 4.1.

Table 4.1 Test catchments for the HBV-model

Catchment	Area (km^2)	Altitude range (m)	Lakes (%)	Predominant vegetation cover below timberline	Swamp (%)	Area above timberline (%)
L. Tivsjön 1) 2) 3)	12.7	200	2.7	Coniferous forest	8.0	0
Nolsjön 1) 2) 3)	18.2	55	1.5	"	14.2	0
Stabby 2) 3) 4)	6.4	37	0	"	2.3	0
Stormyra 2) 3)	4.0	67	0	"	1.6	0
Solmyren 3)	27.5	130	0.5	"	33.1	0
Gimdalsbyn 5)	2178	300	13	"	4	0
Kultsjön 7)	1109	1040	6	"	6	51
Malgomaj 7)	1862	1240	8	"	18	7
Malgomaj + Kultsjön 7)	2971	1240	7	"	14	23
Ströms Vattudal 6) 7)	3851	1015	10	"	5	13
Filefjell 8)	154	900	8.8	Deciduous forest	3.7	86
Steinslandsvatn	216	1115	6	"	2	88

1) Bergström (1972 A)

2) Bergström (1973)

3) Bergström and Forsman (1973)

4) Bergström (1972 B)

5) Bergström (1975)

6) Bergström and Jönsson (1975)

7) Bergström and Jönsson (1976 A)

8) Bergström and Jönsson (1976 B)

Fig. 4.1. Test catchments for the applications of the HBV-model.

5. METHODOLOGY

In this chapter some of the most important mathematical tools and methods used when developing the HBV-model will be discussed. Emphasis will be put on the points which have given rise to the most vivid discussions among modellers in the Scandinavian countries. An attempt will also be made to reflect reevaluations of some of the methods in the light of experience from the applications of the model.

5.1. Verification criteria

A verification criterion is a rule after which the performance of the model is judged. As this work is aimed towards the development of runoff models, this criterion is based on the agreement between a computed and a recorded hydrograph.

Several types of criteria can be found in the litterature, ranging from single values of goodness of fit to scatter diagrams and comparisons between computed and recorded flow duration curves (see for example WMO, 1975 B). As a matter of fact we have almost endless possibilities of describing the agreement between two graphs. The problem is to find the criterion that is most in agreement with our intentions regarding the model. The choice of criterion is an extremely critical point as it effects the optimum parameter values and thus the performance of the calibrated model.

In the following four sections some criterions used in the applications of the HBV-model will be discussed. They are all giving some representation of the agreement between the observed and the computed hydrographs, but as they all have their drawbacks and limitations, a rigorous visual inspection of the hydrographs is still indispensable when analysing the performance of the model.

5.1.1. Numerical criteria

A numerical criterion gives the agreement between the computed and the recorded hydrographs expressed as one single value. One of the most simple and most popular criteria is the sum of squares of the residuals, expressed as:

$$F^2 = \sum_{t=0}^{\tau} (Q_r(t) - Q_c(t))^2 \qquad (5.1)$$

where $Q_r(t)$ = observed discharge at time, t;
$Q_c(t)$ = computed " " " ";
τ = total period of time.

If the initial variance is expressed as:

$$F_o^2 = \sum_{t=0}^{\tau} (Q_r(t) - \overline{Q}_r)^2 \qquad (5.2)$$

where $\overline{Q}_r$ = arithmetic mean of the observed hydrograph over the time τ,

the proportion of the initial variance accounted for by the model can be expressed as:

$$R^2 = \frac{F_o^2 - F^2}{F_o^2} \qquad (5.3)$$

This criterion was defined by Nash and Sutcliffe (1970) as the efficiency of the model. The same criterion was proposed by Ibbit (1974).

R^2 and F^2 are essentially the same criterion. They will yield the same general shape of the error function and the same optimum parameter values. The advantage of the R^2-criterion is its character of a relative measure, facilitating comparisons between models. The value of R^2 will range from minus infinity to plus one, where plus one is representing a complete agreement between the two hydrographs.

The application of the HBV-model with the R^2-criterion has thrown some doubt on its representativeness when comparing models tested in different catchments or during different periods of time. If the initial variance is low as in fig. 5.1, small errors will cause low R^2-values, while at high initial variance the situation is the opposite, as seen in fig. 5.2.

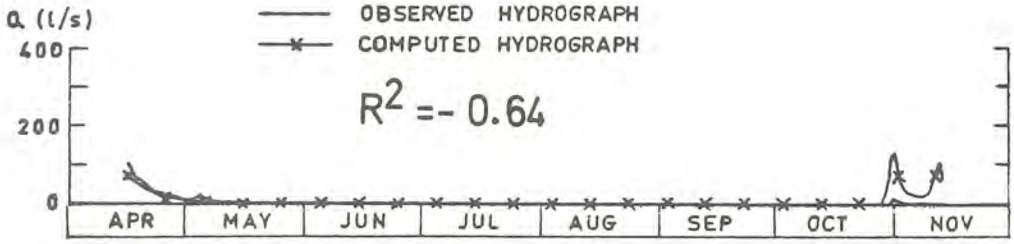


Fig. 5.1. Low R^2-value as a result of low initial variance (Stabby, 1959).

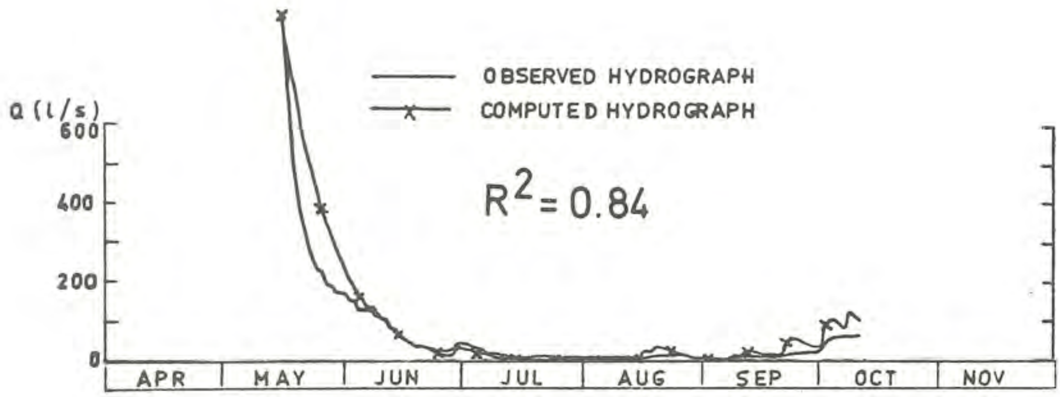


Fig. 5.2. High R^2-value as a result of high initial variance (L. Tivsjön, 1968).

In spite of these uncertainties the R^2-value has generally been a good indication of the overall fit of the model as long as the comparison is restricted to identical periods of time and to one catchment. This means that the best fit according to visual inspection and the R^2-value mostly coincide. Occasionally, as shown by Bergström and Jönsson (1976 B), the R^2-criterion can be misleading especially at values near optimum. This is due to the fact that the residuals are of different origin during different seasons. Large deviations due to input errors, for example during snowmelt, can mask small errors in another sequence of the hydrograph.

When applying the HBV-model to the reservoirs in the river Ångermanälven, the R^2-values fairly well reflected the general conclusions concerning the performance of the model according to visual inspection. The problem with variability of the initial variance was overcome by the long periods used for calibration and test (see table 8.2).

Bergström (1973) investigated some modified forms of (5.1) in the Stormyra basin according to:

$$F_{abs} = \sum_{t=0}^{\tau} |Q_r(t) - Q_c(t)| \quad (5.4)$$

$$F_{diff} = \sum_{t=0}^{\tau} |(Q_r(t) - Q_r(t-1)) - (Q_c(t) - Q_c(t-1))| \quad (5.5)$$

$$F^2_{mv} = \frac{1}{9} \sum_{t=0}^{\tau} (\sum_{i=0}^{2} Q_r(t+i) - \sum_{i=0}^{2} Q_c(t+i))^2 \quad (5.6)$$

Two parameters in the soil moisture zone of the HBV-model, β and L_p (see chapter 7.2.2), were fitted for snowfree periods with the different criteria. As can be seen from table 5.1 the choice of criterion strongly effected the optimum parameter values.

Table 5.1. Optimum parameters in the Stormyra basin with different numerical verification criteria. Fc = 50 (see chapter 7.2.2.)

	F_{abs}		F_{diff}		F^2_{mv}		F^2	
	β	L_p/Fc	β	L_p/Fc	β	L_p/Fc	β	L_p/Fc
1963	8.0	0.8	2.0	0.2	4.0	0.6	4.0	0.6
1964	2.0	0.2	8.0	0.2	4.0	0.2	4.0	0.2
1965	8.0	1.0	16.0	0.4	4.0	1.0	4.0	1.0
1966	4.0	0.4	16.0	0.6	8.0	0.6	8.0	0.6
1967	4.0	1.2	16.0	0.4	32.0	1.2	32.0	1.2
1968	4.0	0.8	4.0	0.2	4.0	1.0	4.0	1.0
1969	8.0	1.0	8.0	0.8	4.0	1.0	4.0	1.0
Average	5.43	0.77	10.00	0.40	8.57	0.80	8.57	0.80

The average parameter values in table 5.1 are computed for this comparison only. When fitting a model for more than one season, optimum parameters should be sought from the joint error function and not as a mean of the optimum parameters for each individual period.

5.1.2. The accumulated difference

A graph showing the accumulated difference between the observed and computed hydrographs has been a valuable help when analysing the results of the model.

$$a_t = \sum_{i=0}^{t} (Q_c(i) - Q_r(i)) \qquad (5.7)$$

where a_t = accumulated difference at time t,
$Q_c(i)$ = computed discharge at time i,
$Q_r(i)$ = observed discharge at time i.

If a_t is plotted along the time axis of the runoff, it is a convenient way of keeping track of errors in the simulated volumes over long periods of time. The usefulness of the accumulated difference was recognized by WMO (1975 B) when recommending its use as an alternative to double mass plots of computed and recorded discharges.

5.1.3. Scatter diagrams of peak flows

If the modelling of high flows is of particular interest, plottings of recorded peak discharge against computed peak discharge can be studied. Regarding scatter diagrams the problem with visual inspection of a graphical representation remains, but it can be overcome, if some numerical criterion of goodness of fit is adopted. WMO (1975 B) applied the method to maximum monthly flows, but in the work on the HBV-model each peak has been studied separately, neglecting minor timing errors. Scatter diagrams have not been plotted regularly for all catchments. A few examples will be given in chapter 8.1.2.

5.1.4. Flow duration curves

In the recommendations on verification criteria the WMO (1975 B) emphasizes the use of flow duration curves as they convey a maximum of information. Such curves were computed when applying the HBV-model to four catchments, as will be shown in chapter 8.1.3.

With flow duration curves, as with scatter diagrams, the analysis of a graphical representation remains a problem. In this case the curve represents the accumulated relative frequency of discharge. Because of the relatively few events with high flows, the curve must be interpreted carefully. The applications of the HBV-model indicate that the low flows easily can be overemphasized. Therefore a combination of scatter diagrams of maximum flows and flow duration curves is preferable if a representation of flow statistics is sought.

5.2. Split sample test

The test of a model must be carried out in two steps, if there are free parameters to optimize.

1. Calibration of the model. The free parameters are adjusted until an acceptable agreement between the observed and the computed hydrographs is obtained.
2. Test on independent data. The calibrated model is run for a period that was not used for calibration and thus did not effect the final values of the free parameters.

It is often argued that this procedure is a waste of information, and that as long a record as possible should be used to derive parameter values. This is certainly a valid point, but without the test on independent data our knowledge of the behaviour of the model is very limited. We only know that the given model successfully manages to interpolate a curve between a series of points. This can be achieved with several mathematical expressions, provided the number of constants (free parameters) is sufficient. The performance of the model is thus better reflected by the independent test period.

The distinction between fitting and calibration is particularly important when testing snowmelt models, because of the few events available for parameter estimation every year. This was exemplified clearly when applying the HBV-model to the Torpshammar catchment (4 230 km^2). The model was first calibrated to a close fit as shown in fig. 5.3. The independent period in fig. 5.4 revealed, however, that the calibration period had been too short to obtain proper parameter values. The close agreement in fig. 5.3 had little to do with modelling because of the large number of parameters and the few degrees of freedom for each estimate (i.e. few hydrological events).

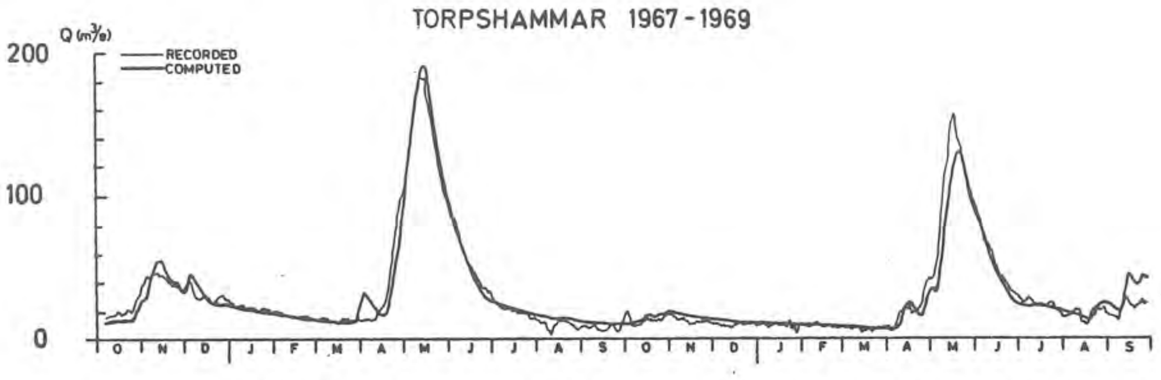


Fig. 5.3. Calibration period in the Torpshammar basin (1967-69). $R^2 = 0.95$.

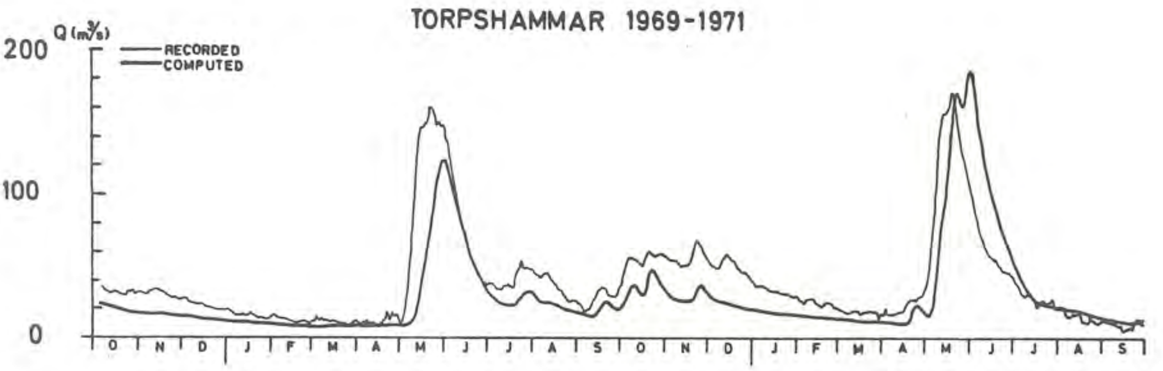


Fig. 5.4. Independent test period in the Torpshammar basin (1969-71). $R^2 = 0.50$.

If fig. 5.3 and 5.4 are analysed closer, it is evident that the climatic variability is one of the main sources of the unstable parameter values. In order to get a longer record the work in the Torpshammar catchment was abandoned and interest was concentrated to its upper half, the Gimdalsbyn catchment. A four year period was fitted, as shown in fig. 5.5. The independent test period still caused problems, as can be seen in fig. 5.6, due to the fact that some of the springfloods were of much higher order of magnitude than those used for calibration.

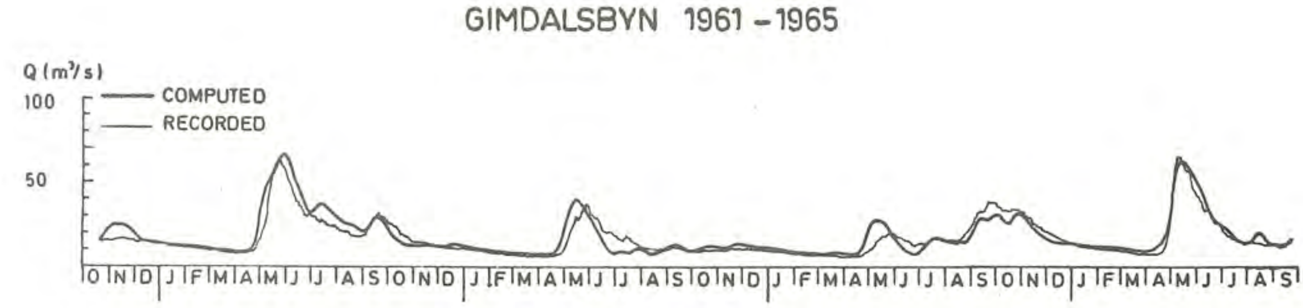


Fig. 5.5. Calibration period in the Gimdalsbyn catchment. $R^2 = 0.83$.

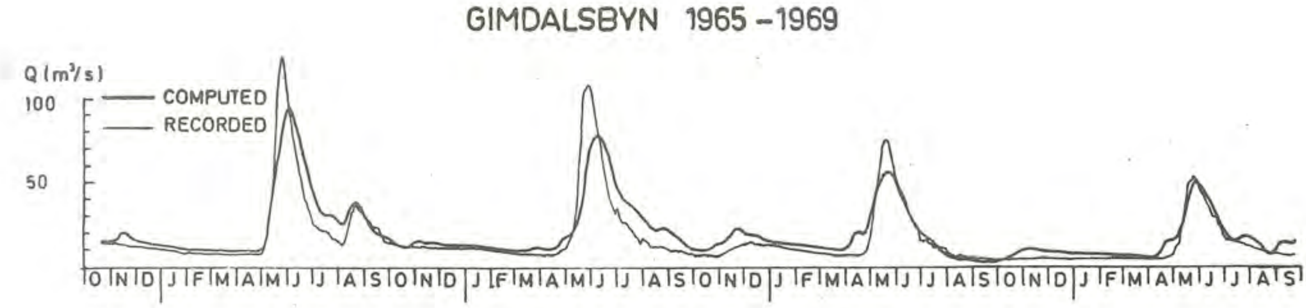


Fig. 5.6 Independent test period in the Gimdalsbyn catchment. $R^2 = 0.81$.

The recalibration of the model for the entire eight year period was not successful until the model structure had been modified (Bergström, 1975). An independent test for another four year period gave results comparable to those during calibration, and the model was accepted (see appendix 1, fig. A 16). The results from this procedure, presented as R^2-values, are given in table 5.2.

Table 5.2. R^2-values in Gimdalsbyn. Independent test periods underlined.

	Original model	Modified model
1961 - 1965	0.83	0.86
1965 - 1969	<u>0.81</u>	0.91
1969 - 1973		<u>0.86</u>

It must be stressed, however, that although the test period behaved fairly well with the modified model, the performance when simulating even larger or smaller events is still uncertain.

The more free parameters in the model, the more the problem with proper parameter values will become pronounced. Kuchment (1972) exemplified this when analysing models with a different number of free parameters (table 5.3). The results showed that an increasing number of parameters always improved the fit of the calibration period, while the independent period attained the best agreement with only a few parameters.

Table 5.3. The effect on the sum of squares criterion when gradually increasing the complexity of the model (Kuchment, 1972).

Year	Number of parameters			
	3	4	6	10
	Optimization			
1959 a	23.7	17.4	13.6	13.2
1960 b	15.9	10.6	9.0	6.6
1965 b	41.1	38.7	36.6	26.6
1964 a	7.1	5.8	9.0	2.5
1965 a	54.6	52.4	34.7	28.8
Σ	142.4	124.9	102.1	77.7
	(Independent data) Control			
1962 a	43.7	49.2	48.3	42.1
1962 b	50.9	41.3	68.4	57.2
1959 b	99.6	82.0	92.9	109.6
1964 b	44.8	32.1	19.6	32.0
1960 a	30.4	23.3	30.6	26.9
Σ	269.4	227.9	259.8	267.8
Σ tot.	411.8	352.8	361.9	345.5

Split-sample testing has been accepted by most modellers, but unfortunately work still appears which only shows the fitted period. Dawdy, Lichty and Bergmann (1972) support the split-sample theory when stating: "Accuracy should be measured in terms of prediction, rather than in terms of fitting. Accuracy of fitting indicates only how well the model can reproduce a set of data from adjusted model parameters. Accuracy of prediction indicates how well the model can reproduce a set of data that was not used to derive the parameter values. Therefore, prediction involves an independent test of accuracy of the model." In the WMO project on "Intercomparison of Conceptual Models Used in Operational Forecasting" (WMO, 1975 B) split-sample testing was considered the best way of comparing the performance of the participating models.

The optimal length of the calibration period is a delicate question which has to be considered when fitting the model. The period must include sufficient information, in terms of hydrological events, for the estimation of the parameters that are valid under all conditions in the basin. A successful independent period is no guarantee for proper parameter values, if both the calibration and the test periods are unrepresentative of the hydrological regime. With a conceptual model the hydrologist is, however, in a better position than without any model at all, as an extreme event will mostly give an extreme response even if the exact behaviour is represented poorly. Fig. 5.7 is an example where the highest peak during the independent test period (2 193 l/s) was more than four times as large as the maximum flow during calibration (498 l/s). The model underestimated the peak (1 680 l/s) but overestimated the total volumes. In general can be said that the model performed well taking into consideration the relatively small peaks during the calibration period.

The number of years or seasons used when calibrating and testing the HBV-model in different catchments are summarized in table 5.4, which clearly reflects the need for long periods when working with snowmelt models.

Table 5.4. Years or seasons in the calibration and test periods.

	Calibration	Test	Snowroutine
Lilla Tivsjön	1	2	no
Nolsjön	2	3	no
Stabby	3	6	no
Stormyra	4	3	no
Solmyren	1	2	no
Gimdalsbyn	8	4	yes
Kultsjön	8	5	yes
Malgomaj	8	4	yes
Malgomaj + Kultsjön	8	4	yes
Ströms Vattudal	8	5	yes
Filefjell	4	3	yes

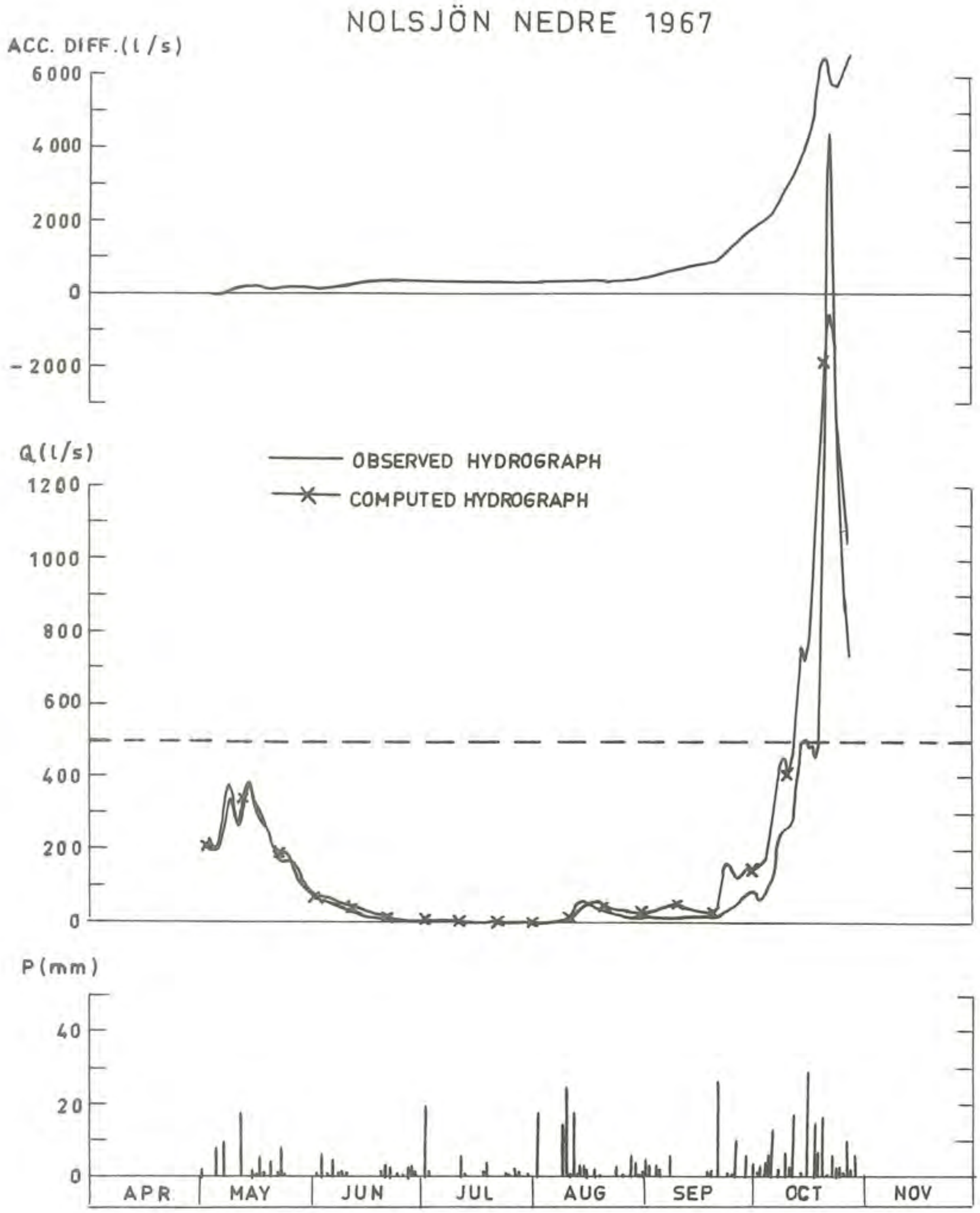


Fig. 5.7. Independent test period in the Nolsjön basin. (The highest level during calibration is indicated by a broken line.)

5.3. Mappings of the error function

Mappings of the error function have proved very useful when developing the HBV-model. The principle is to evaluate the verification criterion in a grid, defined by different parameter values. The topography of the response surface is visualized through isolines and subject to analysis. The method was suggested by Nash and Sutcliffe (1970) and exemplified by O'Connell, Nash and Farrell (1970) and by Mandeville, O'Connell, Sutcliffe and Nash (1970) in a series of papers on conceptual models. Further examples were given by Plinston (1972) and Dickinson and Douglas (1972).

The method has been used when calibrating the HBV-model under snowfree conditions (Bergström, 1972 B) as all but two parameters could be estimated from the map, from analysis of the hydrographs or by consideration of the characteristics of the catchment. A more important application, however, is the investigation of the general behaviour of the model as regards sensitivity to its parameters or their interdependence.

When applying a model to a new catchment a general knowledge of the error function topography simplifies the estimation of parameter values. If the stationery point is situated on a large plateau as in fig. 5.8.A, we can expect to reach a good fit without much adjustment, as the model is rather tolerant to deviations from optimum parameter values. If the optimum is well defined by steep slopes as in fig. 5.8.B, large deviations from optimum parameters cannot be accepted. If, finally, the response surface has the shape of a long flat valley, as in fig, 5.8.C, we can concentrate our adjustments to one parameter keeping the other at a reasonable value.

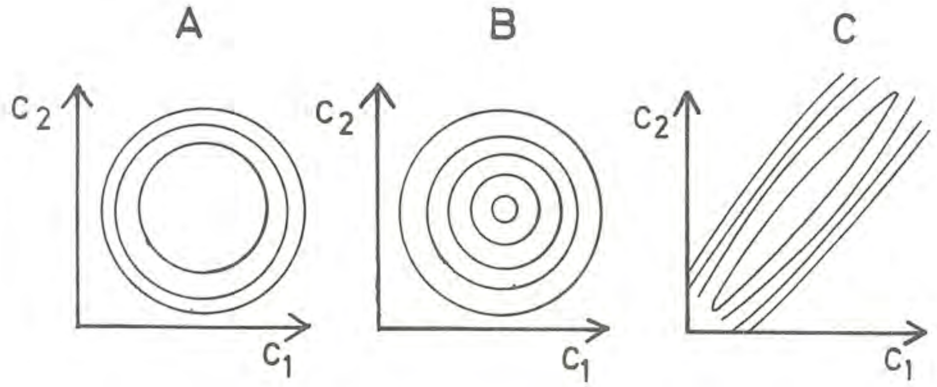


Fig. 5.8. Some alternative shapes of the response surface of the error function. C_1 and C_2 are free parameters.

Fig. 5.8.C. represents a situation that is often encountered. If sensitivity analyses are carried out with all but one parameter constant, the result will be a false impression of sensitivity to both parameters C_1 and C_2 as the analyses represent diagonal cuttings through the valley.

If the shape of the error function is of type C, it can be worth considering simplifications of the model by the exclusion of one parameter.

Examples of this application will be given in chapter 7.

It is important to realize a few points when interpreting the topography of the error function.

1. The error function topography is only showing the response of the verification criterion and is only valid as long as this criterion is properly describing the performance of the model.
2. Only a few parameters can be studied simultaneously. The conclusions are therefore valid for this particular set of parameters only. Consequently it is important to choose parameters that are likely to interact or show some other interesting qualities.
3. It is important not to judge the relative importance of the parameters from the density of the isolines only. The structure of the model must be considered as well in order to draw the correct conclusions. An important parameter controlling the level of baseflow, for example, will effect the sum of squares error much less than will a parameter for the timing of high peaks.

Examples of mappings in three dimensions (two parameters) and four dimensions (three parameters) will be given in the discussion of the model structure in chapter 7. In all applications F^2, according to eq. 5.1, will be used as verification criterion. Systematic error function studies by the HBV-model can be found in the work by Bergström and Forsman (1973), Bergström (1975) and Bergström and Jönsson (1976 B). Some guidance to the interpretation of the response surfaces in this text is given in appendix 2.

5.4. Automatic calibration

The need for rapid estimates of parameters in complex mathematical expressions has led to the development of a large number of algorithms for automatic optimization, or minimization, of an objective function. Hydrological modelling is a field, where these methods are often applied for calibration purposes.

One of the most popular "hill climbing" techniques was developed by Rosenbrock (1960). The search for a minimum (or maximum) of the objective function is made in a very efficient way by means of a transformation of the coordinate axes defined by the parameters in question. The procedure is illustrated schematically in three dimensions (two parameters) in fig. 5.9.

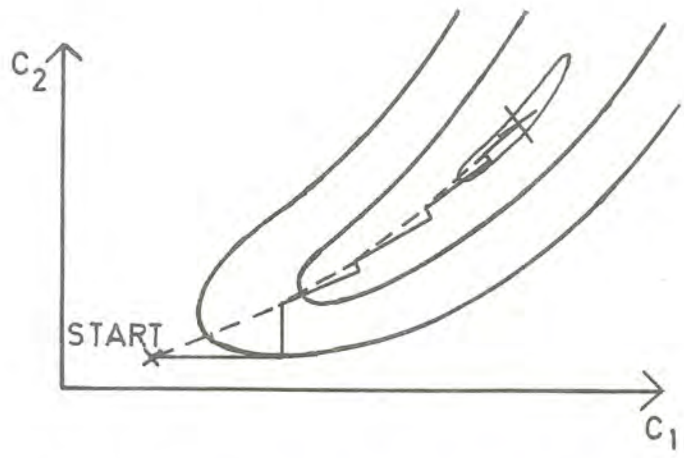


Fig. 5.9. The search technique developed by Rosenbrock (1960) with C_1 and C_2 as free parameters.

Ibbitt and O'Donnell (1971) found this method very efficient in a comparative test of different optimization procedures.

The Rosenbrock method was adopted in the work on the HBV-model when the introduction of a snowmelt routine increased the number of free parameters. It proved to be able to fit the model rapidly but there were many restrictions on its use which gave rise to more scepticism than enthusiasm.

1. The use of automatic methods demands a verification criterion which is objectively giving the best fit expressed as one single value. This problem was discussed further in chapter 5.1.
2. The lack of information about the error function topography was soon felt very unsatisfactory. The optimization through visual inspection and successive trials gives a much better feeling for the sensitivity of the model to its parameters. This is particularly important when developing a model.
3. Restrictions must be put on the parameters to prevent their values from violating the concepts behind the model structure. With these restrictions the restricting values will not infrequently be found as optimum values.
4. The optimization procedure might end up in a local instead of an absolute optimum, a problem which increases with the number of free parameters.

5. The calibration of snow melt models requires long calibration periods especially in highly damped catchments. Due to the limited size and capacity of the SAAB D22 computer used in the work on the Rosenbrock method the calibration period had to be split into parts. The computer time needed for each calibration was still considerable, and we had introduced a new problem, trying to average the optimum parameters from the different calibration periods.

The existenceof local stationary points far from the absolute optimum was exemplified when applying the Rosenbrock method to the Gimdalsbyn basin. The snowmelt parameters were given such poor initial estimates that the springfloods were completely out of phase. The automatic method, instead of adjusting this, simply gave the parameters such values that the springfloods were suppressed.

Generally it can be said that the confidence in automatic computer based procedures for calibration without any human interaction has decreased during the work on the HBV-model. This is in agreement with experience elsewhere. Burnash, Ferral and McGuire (1973) suggest the use of a man-machine interaction technique with initial manual calibration and possibility for a final "polishing" of the parameters with an automatic algorithm.

WMO (1975 B) in the report from the project on "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting" makes the following statement: "As far as possible, a combination of manual and automatic procedures should be used in model calibration."

Sugawara, Ozaki, Watanabe and Katsuyama (1974) state that the calibration of a model "somewhat resembles the driving of a motor car on the street. It is very difficult and probably impossible to make an automatic machine that can drive a car on the street, but many men can drive easily".

5.5. Subjective calibration

"In hydrologic research, there is no excuse for avoidable subjectivity. Nevertheless, the hydrologic literature is full of models justified by a single illustration which shows that the predicted output closely resembles the actual output. Such 'optimization by eye' is incapable of being integrated into a general body of scientific knowledge and is unworthy of the name of scientific hydrology."

The above statement was made by Dooge (1973, page 150). Theoretically it is a valid statement, practically, however, it is not easy to comply. The problem is that if we use an "objective" verification criterion, we conceal instead of avoid subjectivity. The choice of criterion is a subjective procedure in itself. Furthermore, the risk is that we blindly believe in the criterion without any glance at the hydrograph computed by the model and without sufficient knowledge of the representativeness of the criterion of fit.

Visual inspection of the computed and observed hydrographs has regained confidence and is now used in combination with the graph of the accumulated difference when calibrating the HBV-model. The R^2-value (eq. 5.3) is computed as a complement. A multicolor plotter simplifies the analysis considerably as not only the hydrographs but also the input variables and the conditions in the different components of the model can be visualized simultaneously. Examples of plottings are shown in appendix 1 (fig. A 17- A 21). The time scale is often expanded compared to these figures in order to increase the resolution.

The calibration is generally carried out in four steps with some interaction between them.

1. The confined parameters are determined from the map and from other information about the catchment.
2. First estimates are given to the free parameters. These can be based on experience from other catchments or analysis of the hydrograph. An initial test run is made.
3. Parameters, which mainly effect the volumes, are adjusted after inspection of the accumulated difference.
4. The remaining free parameters are adjusted after visual comparison between the computed and observed hydrographs.

Point 3 and 4 are repeated after each test run until an acceptable agreement is obtained between the computed and observed hydrographs. What is "acceptable" will not be determined until several unsuccessful attempts to adjust the model further have been made. A detailed discussion of this procedure together with a complete example from the Ströms Vattudal catchment was given by Bergström and Jönsson (1975).

The number of runs, needed to calibrate the model with this trial and error technique, and the degree of modification of the structure when applying the model to different catchments are shown in table 5.5.

Table 5.5. Number of runs and degree of modification when calibrating the HBV-model.

Catchment	Degree of modification	No. of runs
Gimdalsbyn	moderate	33
Kultsjön	"	38
Ströms Vattudal	no	18
Malgomaj	no	16
Filefjell	low	9

As the catchments are presented in the order in which they were tested, table 5.5 reveals that the experience of the hydrologist is a factor strongly effecting the efforts needed for the calibration of hydrological models.

6. DATA BASE

The complexity of a model is limited by our knowledge of the physical processes and the quality and quantity of available data. If the model is to be used for forecasts, the possibilitiy to forecast a certain variable can also be a limiting factor.

When calibrating a model the need for long, homogeneous series will exclude all instrumentation that does not have the status of a permanent station. Detailed studies of short duration can be used to back up the model structure but will not be of much help for operational purposes.

The main input and output variables in this work are precipitation, temperature, potential evaporation and discharge. Other meteorological variables have been used in some special investigations in attempts to improve the model. The number of precipitation and temperature stations used in each basin is shown in table 6.1. In the Swedish catchments data were provided by the SMHI, while for the Filefjell and Steinslandsvatn catchments data from the Norwegian Water Resources and Electricity Board were used.

Table 6.1. The number of temperature and precipitation stations in the applications of the HBV-model.

Catchment	Area (km^2)	Precipitation	Temperature
L. Tivsjön	12.7	1	-
Nolsjön	18.2	1	-
Stormyra	6.4	1	-
Stabby	4.0	1	-
Solmyren	27.5	1	-
Gimdalsbyn	2178	3	1
Kultsjön	1109	3	1
Malgomaj	1862	3	1
Malgomaj + Kultsjön	2971	5	2
Ströms Vattudal	3851	4	2
Filefjell	154	4	1
Steinslandsvatn	216	1	1

6.1. Precipitation

Daily totals from standard gauges were used in all test catchments. Areal means were computed by Thiessen polygons in the Gimdalsbyn catchment, while the topography and representativeness of each gauge were considered in the other catchments.

Changes in precipitation due to elevation differences were accounted for by a parameter, P_{lapse}, in all large catchments (> 100 km^2) with the exception of Gimdalsbyn, where the altitude range is moderate. This will be discussed further in chapter 7.1.10. In the other catchments uncorrected precipitation values were used for the snowfree periods. A snowfall correction factor, C_{sf}, was used in the snow accumulation procedure as will be discussed in chapter 7.1.2.

6.2. Temperatures

Temperatures measured in standard thermometer shelters 1.5 - 2.0 m above the ground were used in all the catchments. Daily means are generally computed, from three daily readings and maximum and minimum observations, by empirical coefficients derived at the SMHI (SMHI, 1966). In case data were missing, means of daily maximum and minimum temperatures have been used. In most catchments only one station was available. If two stations were at hand their artihmetic means are representing the areal temperature.

The temperature values are subjects to two correction factors. One is a threshold value, T_o, which can be said to correct for poor representativeness of the station, as will be discussed in chapters 7.1.1 and 7.1.4. The other is a lapse rate, T_{lapse}, accounting for the temperature gradient in catchments with considerable elevation range. T_{lapse} is discussed further in chapter 7.1.10.

6.3. Potential evaporation

Different ways of computing the potential evaporation have been used in the different catchments, depending mainly on the available data. Wallén (1966) computed long term means of the potential evaporation with Penman's formula att different locations in Sweden. These monthly values have been used with a correction for monthly mean temperatures in L. Tivsjön and Nolsjön. The same values were used without any temperature correction in Stormyra, Stabby, Kultsjön, Malgomaj and Ströms Vattudal. Monthly totals of the potential evaporation were computed by Penman's formula, specifically for the catchments of Solmyren (Persson, 1972), Gimdalsbyn and Filefjell.

Different values of the potential evaporation were tested when applying the model to the Stormyra basin outside Stockholm (Bergström, 1973). The conclusion from this investigation was that the results with daily values computed by Penman's formula are slightly better than those with monthly averages and still better than those with the values computed by Wallén. The choice between these methods had some effect on the optimum parameter values in the soil moisture zone.

When using mean monthly values of potential evaporation, a subjective interpolation was carried out in the smaller basins to avoid unwanted effects due to discontinuities in the histogram formed seasonal curve. As can be seen in the graphical representation of evaporation in appendix 1, fig. A 17 - A 21, this technique has not been used in the Kultsjön, Malgomaj, Ströms Vattudal or Filefjell catchments. In Kultsjön comparative test runs were made with a smoothed evaporation curve according to fig. 6.1.

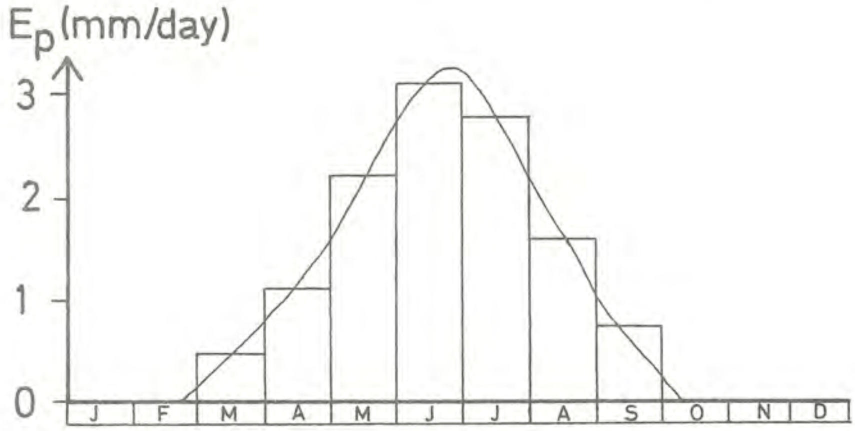


Fig. 6.1. The smoothed curve for potential evaporation in the Kultsjön catchment.

The effect on the discharge, when using the smoothed curve instead of the histogram, was not detectable by eye in the computed hydrograph. The results expressed as R^2-values are shown in table 6.2.

Table 6.2. The effect, expressed as R^2-values, of a smoothed curve of potential evaporation in the Kultsjön catchment.

	Histogram	Smoothed
1962 - 1966	0.7977	0.7975
1970 - 1974	0.8402	0.8399

The results are interesting, as they show that random errors in the computations of potential evaporation are of minor importance as long as the volumes are correct. This conclusion was supported by Parmele (1972) when studying the effect of errors in potential evaporation on the output from hydrological models.

6.4. Runoff

Runoff has been measured by means of discharge weirs in the small basins including Filefjell. In Gimdalsbyn observations of lake levels were transformed to outflow by a stage-discharge relation for the outlet of lake Idsjön. In Kultsjön, Malgomaj and Ströms Vattudal the model was used to simulate the local inflow to reservoirs which are parts of a rather complex system of hydroelectric power stations. Therefore the recorded hydrograph had to be computed according to:

$$Q_{loc} = Q_{tot} + \Delta S_r - Q_{in}, \tag{6.1}$$

where

Q_{loc} = local inflow to the reservoir,
Q_{tot} = total outflow as reported by the regulation company,
Q_{in} = inflow from an above situated reservoir as reported by the regulation company,
ΔS_r = change in storage in the reservoir from observations of its level.

As all terms in eq. 6.1 are subjects to errors, the resulting hydrograph is rather uncertain. Particularly critical are the observations of the level of the lake, or reservoir, as one reading will effect the storage component, ΔS_r, of two consecutive days. These uncertainties are causing fluctuations in the hydrograph as can be seen in appendix 1 (fig. A17 - A 20). In Ströms Vattudal the runoff values were averaged for three days in an attempt to overcome the problem, but when working on the other catchments the use of a multicolor plotter made it possible to analyse the hydrographs in spite of the fluctuations.

6.5. Consequences of errors in data

The errors in the data will effect the modelling procedure differently depending on their type and origin.

Systematic errors may be caused by poor measurements, poor representativeness of a station, or by uncertainties in the computations when estimating a variable. They can, to some degree, be accounted for by the free parameters when calibrating the model. These implicit corrections will effect the optimum parameters and thus complicate the generalizations of these.

Random errors may have the same origin as systematic errors. They cannot, however, be accounted for implicitly by the model. They will therefore effect the performance of reconstruction. Random, uncorrelated, errors in the input variables will cause persistance in the residuals between the computed and the observed hydrographs due to the different storages in the model structure. In operational hydrological forecasting these persistent errors can be eliminated by means of an updating procedure, as will be discussed in chapter 8.2.1.

Inhomogeneities in a data series is a type of systematic errors, which may be caused by, for example, a changed location of a meteorological station or a new method for the estimation of runoff during the period subject to analysis. Due to the implicit corrections by the free parameters inhomogeneities will cause unstable parameter values. Bergström and Jönsson (1975) showed an example, where a slight modification of the procedure for the computation of local inflow to the Ströms Vattudal reservoir was detected when calibrating the HBV-model.

7. THE MODEL STRUCTURE

The simulation of runoff by the HBV-model is made in three steps.

1. Snow accumulation and ablation.
2. Soil moisture accounting.
3. Generation of runoff and transformation of the hydrograph.

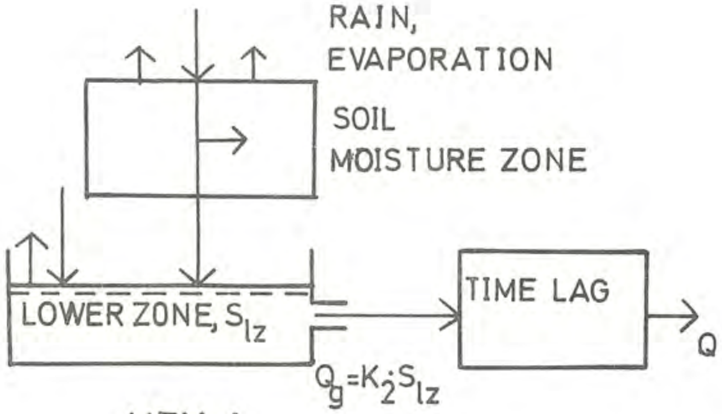
The basic philosophy has been to regard these steps as relatively independent. First of all snow accumulation and melt is considered. Meltwater and rainfall is then fed into a soil moisture accounting routine, which is the most essential part for the determination of runoff volumes. Finally the volumes are given an appropriate shape in the response function including routing of the water through a series of reservoirs and damping of the hydrograph by means of a transformation function.

A survey of the most important structures, which have been attempted, is shown in fig. 7.1. As the intention is to illustrate only the general linkage of components, the subroutines are described more in detail in the following chapters. Either these subroutines can be lumped or they can account for the statistical or geographical distribution of characteristics of the catchment.

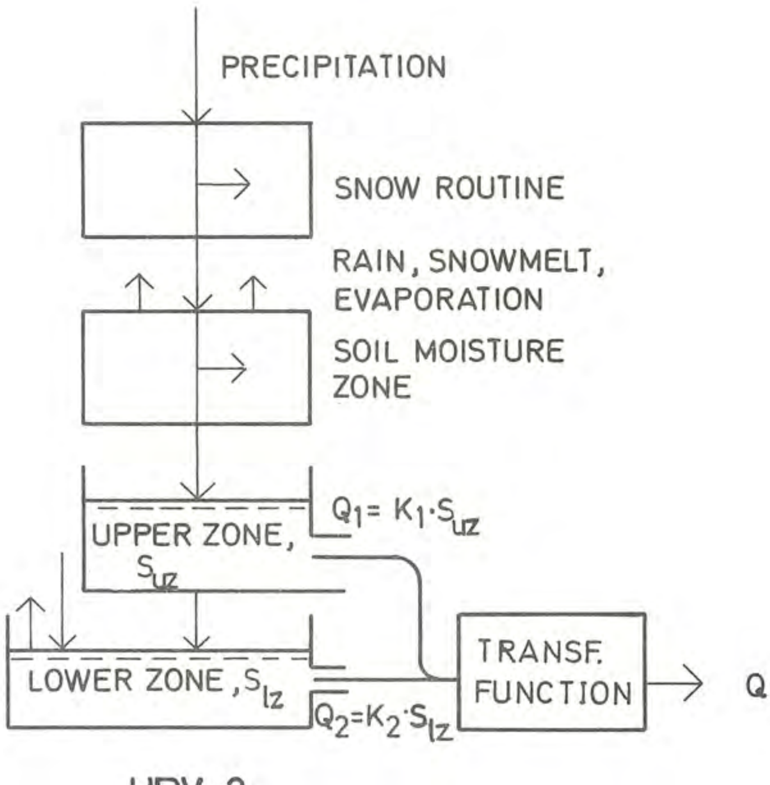
Although the models in fig. 7.1 look different, they are all developments from the first very simple HBV-1 structure and will also degenerate to this version with appropriate parameter settings. A list of parameters in the HBV-3 version is given in table 7.1. Each parameter is subject to a more detailed description in the chapter referred to in the table. The symbols used in table 7.1 can be criticized for not being a very consequent system of notation. The author is aware of this but has tried not to diverge too much from symbols used in other publications on the HBV-model. Table 7.2 shows where the different models have been applied so far. "Snowroutine" in the column of comments, means that a snowroutine has been incorporated and that the model has been run throughout the year. "Distributed snowroutine" indicates that a distribution of this snowroutine according to the area-elevation curve was made.

Table 7.1 Parameters in the HBV-3 model.

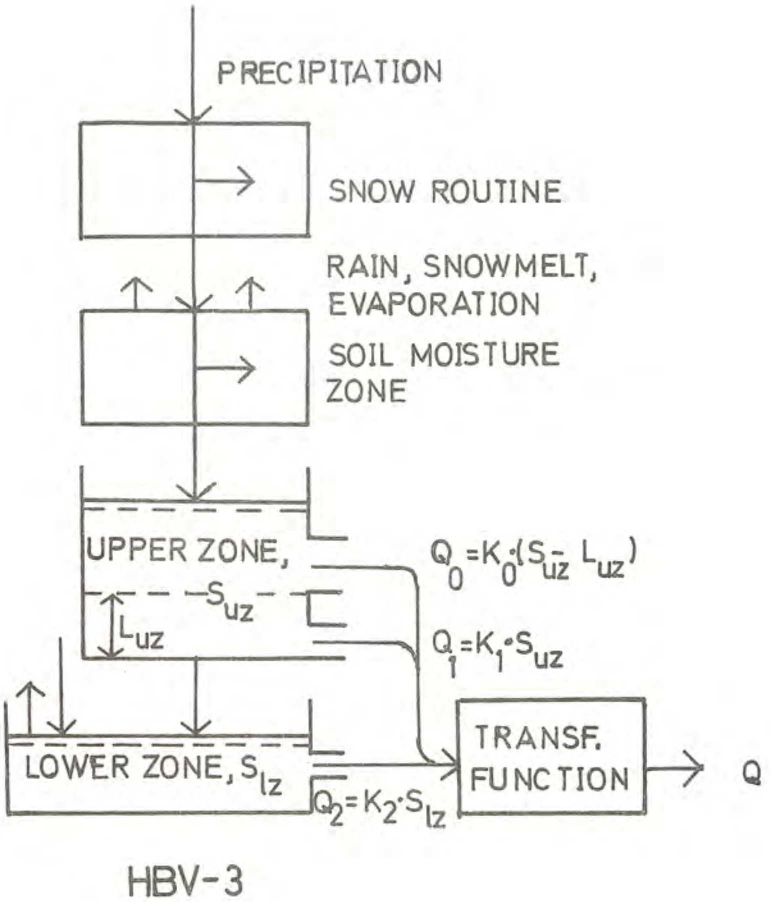
Corrections on input variables		Chapter
P_{corr}	= correction factor on rainfall	7.1.10
P_{lapse}	= precipitation-elevation correction	7.1.10
T_{lapse}	= temperature-elevation correction	7.1.10
T_o	= general temperature correction	7.1.1, 7.1.4
Parameters in the snowroutine		
C_{sf}	= snow fall correction factor	7.1.2
C_o	= degree-day melt factor	7.1.4
C_{wh}	= water holding capacity	7.1.6
S_b	= bottom storage under snowpack	7.1.6
Parameters in the soil moisture routine		
Fc	= maximum soil moisture storage	7.2.2
L_p	= limit for potential evaporation	7.2.2
β	= empirical coefficient	7.2.2
Parameters in the response function		
K_o	= storage discharge constant in the upper zone	7.3.2
K_1	= " " " " " " "	7.3.2
K_2	= " " " " " lower "	7.3.3
L_{uz}	= limit for slow drainage in the upper zone	7.3.2
C_{perc}	= percolation capacity into the lower zone	7.3.3
P_w	= part of the lower zone representing lakes and other wet areas	7.3.3
B_{max}	= maximum base in the transformation function	7.3.4
C_{route}	= parameter relating the base in the transformation function to the generated flow	7.3.4


RAIN,
EVAPORATION
SOIL
MOISTURE ZONE
LOWER ZONE, S_{lz}
$Q_g = K_2 \cdot S_{lz}$
TIME LAG
Q

HBV-1


PRECIPITATION
SNOW ROUTINE
RAIN, SNOWMELT,
EVAPORATION
SOIL MOISTURE
ZONE
UPPER ZONE,
S_{uz}
$Q_1 = K_1 \cdot S_{uz}$
LOWER ZONE, S_{lz}
$Q_2 = K_2 \cdot S_{lz}$
TRANSF.
FUNCTION
Q

HBV-2



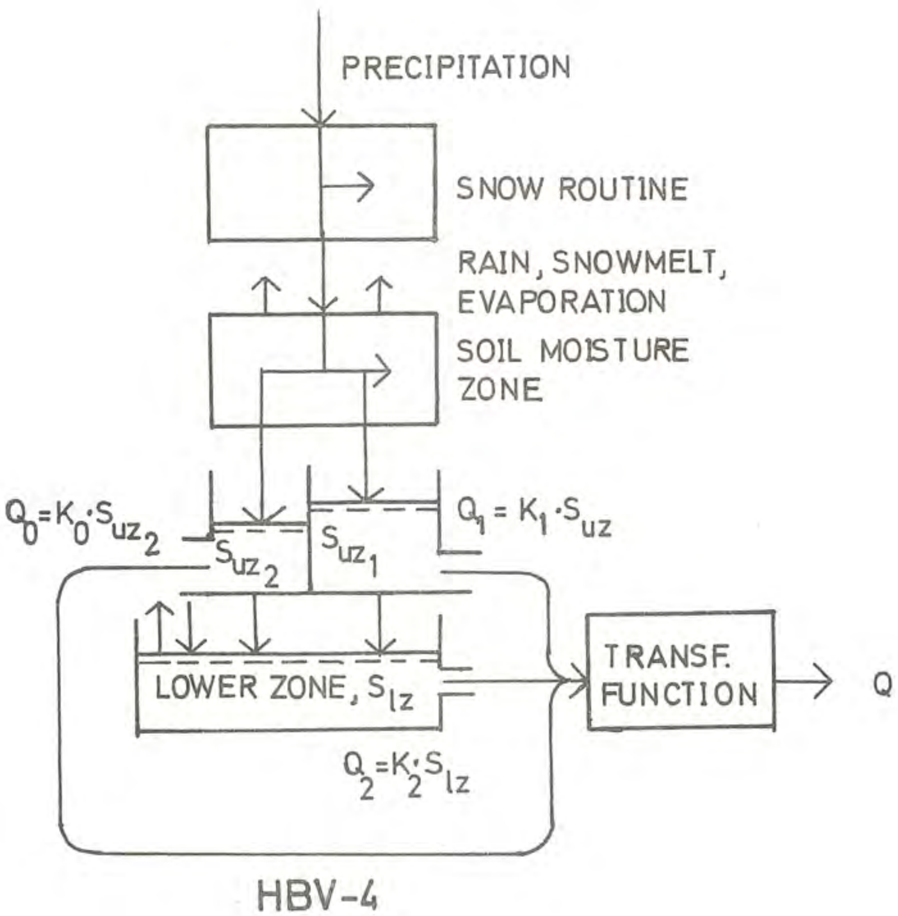


Fig. 7.1. Schematic representation of different versions of the HBV-model.

Table 7.2. Model structures in the different catchments.

Catchment	Model	Comments	
L. Tivsjön	HBV-1		
Nolsjön	HBV-2		
Stabby	HBV-2		
Stormyra	HBV-2		
Solmyren	HBV-2		
Gimdalsbyn	HBV-2	Snowroutine	
Kultsjön	HBV-2	Distributed	snowroutine
Ströms Vattudal	HBV-2	"	"
Malgomaj	HBV-2	"	"
Filefjell	HBV-3	"	"
Steindalsvatn	HBV-3	"	"

The soil moisture accounting procedures are essentially the same in all versions of the model. The subsequent increase in the number of runoff components is justified by experience from the different catchments. Two components have generally been sufficient in the Swedish catchments, but when applying the model to the Filefjell alpine basin three components were detected. Two ways of modelling this were attempted, represented by the HBV-3 and HBV-4 models. HBV-3 was considered superior both according to visual inspection and in terms of the R^2-criterion of fit. This comparison was discussed in detail by Bergström and Jönsson (1976 B).

All versions of the HBV-model are lacking components for direct surface runoff, as the water is controlled by the conditions in the soil moisture zone before any runoff can be generated. The position of the upper zone below the soil moisture zone is more an indication of the order in which computations are carried out than an attempt to describe the natural system. It would probably be more correct to integrate the soil moisture zone and the upper zone, as the upper zone represents the superficial drainage which might occur within the topmost layers of the soil. For computational reasons it is, however, convenient to make this separation into two storages, each one with its own budget.

The soil moisture zone as a buffer controlling the total volumes has been verified by a lot of applications of the model. Fig. 7.2 shows an example where a surface runoff component on top of the soil moisture zone would certainly yield poor results. After a long dry summer 46 mm of precipitation in August did not cause any runoff, which was modelled well by the HBV-2 model.

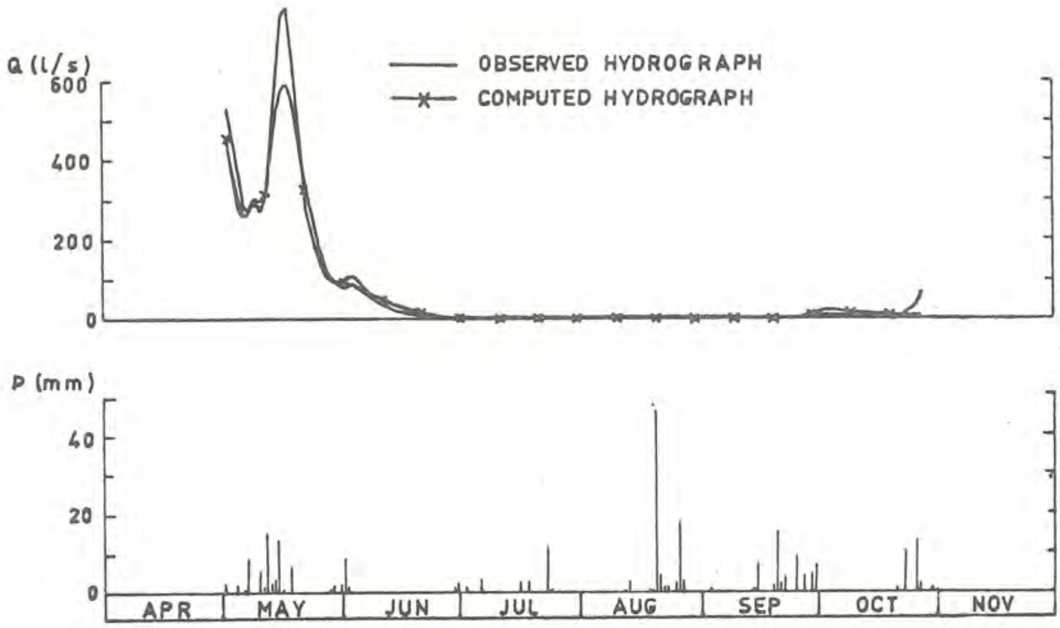


Fig. 7.2. Simulation of the response to a rainstorm after a long dry spell. Nolsjön (1969).

One explanation of the good performance of this model, without a direct surface flow component, might be the highly pervious soils in the test catchments and the fact that rainfall intensities are mostly moderate. One must, however, bear in mind that the soil moisture zone is accounting for all losses, including interception in vegetation, and thus it is more an index of the total wetness of the catchment than a detailed description of the conditions in the soil. Therefore detailed explanations can be questionable.

The capability of the model to reconstruct a given hydrograph is the rule, by which its performance is judged. The fact that a model is doing this properly must not, however, lead us to the conclusion that all components in the model are in agreement with the real hydrological system. Axelsson (1975) showed that he could obtain almost identical results, as with the HBV-2 model when applying a model with two parallell soil moisture zones and two parallell reservoirs to the Stormyra basin. To take the capability of reconstruction as an evidence of physical relevance would thus lead to two contradictory statements. This phenomenum was recognized by Amorocho and Hart (1964) as the problem of nonuniqueness of the processes of synthesis.

7.1. Snow accumulation and ablation

One glance at an annual hydrograph is sufficient to realize the significance of snow accumulation and melt for formation of runoff in Sweden (see for example fig. 5.3). To model these processes means that a few central problems must be considered.

1. Determination of the form of precipitation.
2. Corrections for the aerodynamic effect around the precipitation gauges and poor representativeness of the meteorological stations.
3. Determination of evaporation losses.
4. Computation of snowmelt.
5. Estimation of retention and refreezing of liquid water in the snowpack.
6. Correction of precipitation and temperature according to the altitude differences in the catchment.

A physically correct way to approach the snow modelling problem would be from the total heat budget of the snowpack, as discussed by,for example, U.S. Corps of Engineers (1956) and (1960), Forsman (1963) and Kuz'min (1972). The general equation would be of the form:

$$W_{sw} + W_{lw} + W_c + W_l + W_g + W_p + W_t + W_m = 0 \qquad (7.1)$$

where:

W_{sw} = absorbed short wave radiation,
W_{lw} = net long wave radiation,
W_c = convective heat flux,
W_l = latent heat flux (condensation and evaporation),
W_g = heat flux from the ground,
W_p = contribution of heat from precipitation,
W_t = change in the energy content of the snowpack.
W_m = heat equivalent of the snowmelt.

Among the variables necessary for a complete heat budget computation according to eq. 7.1 can be mentioned:

total solar radiation,
albedo,
longwave radiation balance (effective radiation),

air temperature,
air humidity,
wind speed,
temperature gradients in the soil and in the snow,
precipitation.

In addition to these variables some physical parameters governing heat exchange with the atmosphere, heat transfer within the snowpack, liquid water content in the snow and drainage of the snowpack, would have to be estimated.

Considering the data that are generally available in a catchment detailed heat budget computations, such as eq. 7.1, are hardly warranted. The great inhomogenities in the areal distribution of the snow cover is complicating the picture furter. Rather crude index methods are therefore often preferred in operational models.

When developing the snowroutine for the HBV-model recordings of air temperature and precipitation have been the main input variables. The air temperature is used as an index and is thus not only representing the convective component in eq. 7.1, but also other effects such as radiation and condensation. The routine was initially developed for the Gimdalsbyn catchment (Bergström, 1975) but has since then been modified in the light of experience from other applications. This will be discussed in the remaining part of chapter 7.1, in which some alternative methods and special investigations will be presented as well.

7.1.1. The form of precipitation

The problem with determination of the form of precipitation is usually solved in a rather simple manner. The air temperature is accepted as a determining factor meaning that snow accumulation starts as soon as the temperature is lower than a certain threshold value, T_o. This method has been used by the U.S. Corps of Engineers (1956) and Anderson (1973) among others. According to an investigation made by the U.S. Corps of Engineers, the T_o-value may vary between $- 1.7\ ^oC$ and $+ 4.4\ ^oC$ when studying hourly values. An investigation of daily values made at the Lilla Tivsjön climate station in Sweden is shown in fig. 7.3 (Bergström, 1975).

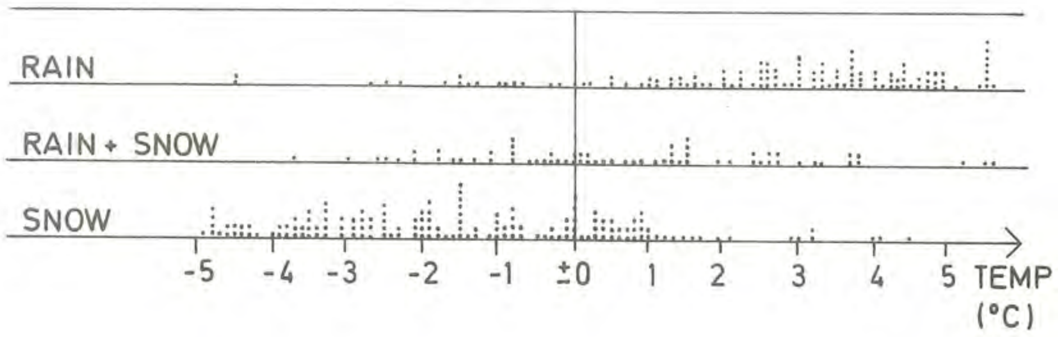


Fig. 7.3. The observer's note on the form of precipitation related to mean daily temperatures. Each point represents one day with precipitation.

The variability of T_o indicated by these investigations is of courşe inherent in the crudeness of the method. The risk for erroneous floods when using the T_o as a threshold value, is greatest when there is no snow on the ground or if the snowpack is ripe, i.e. filled with liquid water to its water holding capacity. Liquid precipitation on dry snow seldom effects runoff, as the water mostly will be retained in the snowpack and refreeze later on.

So far the method with a threshold value, T_o, has been used in all the applications of the HBV-model. The same parameter is used as a general correction for representativeness of the temperature station in the snowmelt routine. Examples of parameter values are given in chapter 7.1.4.

When the precipitation reaches the ground, the temperature of the soil determines whether it will remain in its original form, freeze or melt. Computations of the soil temperature can easily be very complicated, but a simple heat budget might help to improve the snow accumulation routine when the ground is snow-free. This has not been attempted in the HBV-model. The effect of frozen ground is discussed further in chapter 7.1.8.

7.1.2. Snow fall and evaporation corrections

To estimate the areal totals of snowfall is more difficult than to estimate rainfall. The catch of the standard gauge is often strongly reduced due to the aero-dynamic effect, especially at high windspeeds. The variability of snow accumulation over the catchment is also great, making the representativeness of the gauge a critical factor.

The effect of the density of the forest cover on snow accumulation was investigated in Finland by Seppänen (1961) and in Sweden by Waldenström (1975). The results show an increasing accumulation with decreasing density of the forest. Similar results were reported by Dietrich and Meiman (1974) when studying the effect of cuttings in a forest. One explanation may be that the interception of snow in the trees, which is subject to stronger exposure to wind and heat exchange with the atmosphere, will increase evaporation losses.

The above uncertainties cause systematic errors in the areal precipitation, as recorded by the precipitation gauges. This is corrected in the HBV-model by an empirical coefficient, C_{sf}, the snow fall correction factor.

Evaporation and condensation on the snow surface can be calculated according to a formula of the form (Nyberg, 1965):

$$E_a = (C_{e1} + C_{e2} \cdot u)\,(e_a - e_s) \cdot \tau, \qquad (7.2)$$

where:

E_a = actual evaporation from snow,
u = wind velocity,
e_a = vapor pressure in the atmosphere,
e_s = surface vapor pressure,
C_{e1} and C_{e2} = empirical coefficients,
τ = time period.

The introduction of this formula will, however, require input variables, representative values of which are not generally at hand in Swedish catchments.

Lemmelä and Kuusisto (1973) measured the net evaporation during six melt periods in Finland and reported a total value ranging from - 0.2 to + 9.4 mm/season. Nyberg (1965) arrived at a total amount of evaporation of 25 mm during two months in spring in the extreme north of Sweden. Gray (1973) discussed many aspects on evaporation from a snowpack and referred to investigations, which showed that the amount of evaporation in winter is negligible in northern latitudes (where chinooks do not prevail).

When developing the snow routine for the HBV-model it was found important to keep down the demand on input data. Therefore the variability of snow evaporation was neglected in the first approach, and the average loss was included in the snow fall correction factor, C_{sf}.

The snow fall correction factor is thus playing a very important role in the model. As this parameter is mainly effecting the total volumes, it is easy to get a good estimate after just a few test runs. The best way is to study the behaviour of the accumulated difference between the computed and the recorded springfloods and to adjust C_{sf} until all systematic errors are eliminated. Typical values of C_{sf} are given in table 7.3.

Table 7.3. Snow fall correction values, C_{sf}.

Gimdalsbyn	0.80
Kultsjön	1.23
Malgomaj	1.05
Ströms Vattudal	1.12
Filefjell	1.70

As the value of C_{sf} is both depending on the choice of precipitation stations and their respective representativeness and accounting for evaporation from snow, its great variability is not surprising. Values lower than one, as in Gimdalsbyn, are possible for the same reason. The C_{sf}-value interacts strongly with the assumed value of the altitude lapse rate of precipitation, as will be discussed in section 7.1.10.

The fact that C_{sf} is one of the most critical parameters in the model was confirmed when applying the HBV-model to the Filefjell basin without any previous calibration (Bergström and Jönsson, 1976 B). The difficulty to relate this parameter to catchment characteristics is one of the main obstacles on the road towards the application of the HBV-model to ungauged catchments. It is evident that an increased density of the precipitation network would help to stabilize the C_{sf}-values.

7.1.3. Wind corrections on snow accumulation

An attempt was made to correct the computed snow accumulation for wind velocity when applying the model to the Malgomaj catchment (Bergström and Jönsson, 1976 A). Three daily readings of wind velocity were available at Stensele, 50 km from the divide. The correction was made according to the following equation:

$$\Delta S_s = P \cdot (C_{u1} + C_{u2} \cdot u), \qquad (7.3)$$

where:

ΔS_s = snow accumulation (mm water equivalent),
P = recorded precipitation (mm),
C_{u1} and C_{u2} = empirical coefficients,
u = wind velocity (m/sec.)

A few combinations of C_{u1} and C_{u2} were tested in order to study their effects on the variability of volume errors over four years. Table 7.4 is showing the volume errors in mm evaluated from the graphical representation of the accumulated difference for different springfloods without wind correction, with correction for average windspeed and with correction for maximum windspeed among the three readings.

Table 7.4. The effect of wind corrections on the volume errors in mm during springfloods in the Malgomaj catchment.

	1967	1968	1969	1970
Without correction	- 60	- 20	0	0
Average wind velocity	- 60	- 30	0	- 10
Maximum wind velocity	- 50	- 20	0	- 5

The results in table 7.4 are based on a C_{u1}-value of 0.1 corresponding to a 10 % increase in accumulation per m/s windspeed. C_{u1} was adjusted to get comparable total volumes over the entire period as the investigation was made not in order to reduce the total volume error but its variability. The results show that no substantial change in the variation of the volume errors could be obtained by equation 7.3.

According to Larson and Peck (1974) a ten percent correction per m/s wind velocity is a reasonable figure for an unshielded gauge. Their investigation showed that wind corrections in the accumulation routine improved the performance of the hydrologic model of the National Weather Service Forecast System. It is realistic to believe that the lack of improvement when trying to account for wind speed in the HBV-model is mainly due to poor representativeness of the wind velocity data.

7.1.4. Temperature index methods for snowmelt computations

The simplest way to compute snowmelt from temperatures is undoubtedly the degree-day method according to:

$$M = C_o \cdot (T - T_o) \qquad (7.4)$$

where:

M = snowmelt (mm/day),
C_o = degree-day factor (mm/$^oC \cdot$ day),
T = surface air temperature (^oC),
T_o = threshold value of the temperature (^oC).

The method has been widely applied in more or less modified form all around the world. Kuz'min (1972) refers to this method as "the simplest and most accurate of all examined methods". Other references are for example: U.S. Corps of Engineers (1956) and (1960), Sugawara, Ozaki, Katsuyama and Watanabe (1975) and Popov (1968) (in forests). A modified form was presented by Martinec (1975). Quick and Pipes (1975) and Anderson (1973) are using the method under certain meteorological conditions.

This type of index methods has the advantage of being simple and easy to handle. On the other hand it is difficult to generalize its parameters as they are empirical and cannot be estimated through physical considerations. Therefore the degree-day factor and the threshold temperature have to be determined specifically for each catchment.

Bergström (1975) showed examples indicating that the degree-day factor would increase with proceeding melt and introduced the following equation:

$$M = C_o \ (1 + C_{eff} \ \Sigma M) \ (T - T_o), \qquad (7.5)$$

where:

C_{eff} = a coefficient accounting for the ripeness of the melting snow.

Martinec (1975) obtained a similar effect when relating C_o to the density of the snowpack, as the density is correlated to the ripeness of snow. Anderson (1973) introduced a seasonal variation in the degree-day factor, which results in an increasing C_o-value during melt periods in spring.

The introduction of C_{eff} in eq. 7.5 complicated the snowroutine considerably.

It was necessary to keep track of the accumulated melt, ΣM, of all underlying layers when fresh snow was falling on snow that had already started to melt. Snowmelt was assumed to occur at the top of the topmost layer and two consequtive layers were consolidated to one as soon as they reached the same value of ΣM as shown schematically in fig. 7.4.

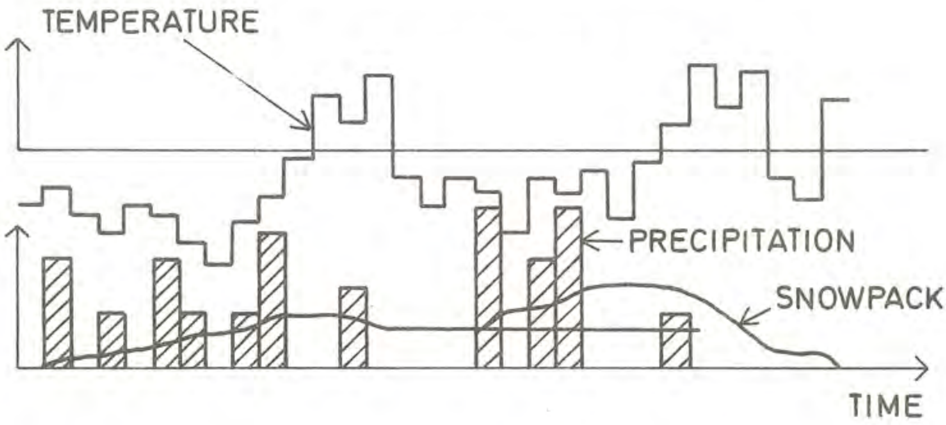


Fig. 7.4. The build-up and consolidation of the layers in the snowroutine according to eq. 7.5.

The error function response around the optimum C_{eff}-values were studied in the Gimdalsbyn catchment (Bergström, 1975) and in the Filefjell catchment (Bergström and Jönsson, 1976 B). The study in Filefjell is shown in fig. 7.5. It is a good example of how mappings of the error function can reveal an insignificant parameter. The optimum C_{eff}-values did not deviate from zero at any T_o-level. This result confirmed the investigations of C_{eff} in Gimdalsbyn and was also supported by visual inspections of the hydrographs when attempting non-zero-values of C_{eff}. The conclusion is thus that although the introduction of C_{eff} is justified by field measurements, its effect cannot be observed in the discharge at the outlet of the catchment. The result is important, as it simplifies the model considerably with positive consequences for both programming efforts and needed computer time.

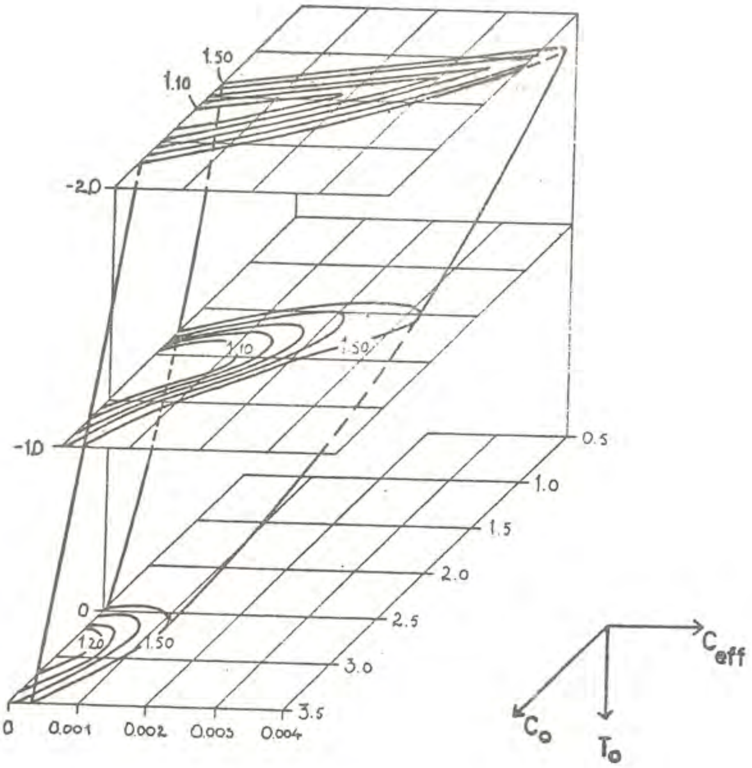


Fig. 7.5. The response of F^2 to C_o, T_o and C_{eff}. Filefjell (1967 - 1971).
(The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

The values of the snowmelt parameters in the different catchments are shown in table 7.5. C_{eff} was used as an active parameter when applying the model to the Gimdalsbyn catchment, but the fit was almost as good when $C_{eff} = 0$.

Table 7.5. Snowmelt parameters in the different catchments.

	C_o (mm/°C·day)	C_{eff} (mm^{-1})	T_o (°C)
Gimdalsbyn	1.25 1)	0.01	0
alternative	2.0 1)	0	0
Kultsjön	3.2	0	0.5
Malgomaj	2.5	0	1.0
Ströms Vattudal	2.5	0	1.0
Filefjell	2.5	0	- 1.0

1) Mean in a statistically distributed routine (chapter 7.1.9).

As can be seen in fig. 7.5, there is a strong interaction between T_o and C_o, which makes it difficult to draw any firm conclusions about the exact value of these parameters. One further complication is the areal-elevation distribution which will be discussed in chapter 7.1.10. In spite of this, C_o and T_o seem to be rather stable parameters, a fact which simplifies a reasonable first estimate in a new catchment.

As a comparison the U.S. Corps of Engineers (1960) suggests $C_o = 2.25$ (mm/°C · day) and $T_o = 0$ °C in forests and $C_o = 2.7$ (mm/°C · day) and $T_o = -4.4$ °C in open fields. The following figures were given by the WMO (1975 A) as a first approximation in practical calculations:

	C_o (mm/°C · day)
Dense coniferous forest (crown density 0.8 - 1.0):	1.4 - 1.5
Coniferous forest of average density (crown density 0.6 - 0.7) and dense mixed forest:	1.7 - 1.8
Low density coniferous and deciduous forest (average crown density):	3 - 4

The WMO points out that the figures are less accurate for open country than for forests due to increasing relative effect of radiation and wind velocity. It can also be worth mentioning that the degree-day factor is most likely to be dependent on the latitude and aspect of the catchments and the day of the year.

7.1.5. Alternative meltfunctions

Some alternative meltfunctions have also been tested or at least considered in the HBV-model. In the Malgomaj catchment the wind velocity was included (Bergström and Jönsson, 1976 A) according to:

$$M = (C_{m1} + C_{m2} \cdot \overline{u}) \cdot (T - T_o), \qquad (7.6)$$

where:

C_{m1} = empirical coefficient,
C_{m2} = empirical coefficient,
$\overline{u}$ = average wind velocity (m/s).

Data on windspeed were available at Stensele about 50 km from the divide as three readings per day. The new model was calibrated for the years 1962 - 1966, and 1966 - 1970 were used as an independent test period. The parameter values were $C_{m1} = 1.5$, $C_{m2} = 0.55$. The results are compared to those by the original model in table 7.6.

Table 7.6. The effect of wind corrections on the melt function in the Malgomaj catchment.

Period	1962 - 1966	1966 - 1970
Without correction	0.7856	0.8316
With correction	0.7879	0.8473

Table 7.6 indicates a very small improvement, which was not altogether in agreement with the impression from visual inspection of the hydrographs. Due to this fact, together with the complications when introducing a new input variable, the modified form of the melt function was not adopted.

Some work on the introduction of short wave radiation into the snowmelt computations was initiated in the Gimdalsbyn catchment, but the results (never published) were questionable. Poor data and lack of information due to the damping in the basin made the interpretation of the results difficult. Studies of the effect of radiation and other meteorological variables on snowmelt would be more fruitful in a catchment with high quality data, a quicker response and less regular snowmelt seasons.

7.1.6. Water retention in the snowpack

When snowmelt starts. water is percolating through the snowpack. This is actually the most important mechanism for heat transfer from the snow surface (Kuz'min, 1972). Some of this water will be retained by capillary forces and thus detain water yield and discharge into the river. Some water may also accumulate under the snow in its lowest layer, further delaying runoff.

The water-holding capacity of a snowpack is a function of the aggregate structure of the snowpack itself. The capacity decreases with the melting process along with the metamorphoses of the snow. The figures found in the literature are highly variable. The U.S. Corps of Engineers (1960) recommends 2 - 5 % of the total snowpack during melt. Kuz'min (1972) suggests 35 - 55 % for freshly fallen snow decreasing to 5 - 15 % during active snowmelt. According to the WMO (1975 A) fine, crystalline drifting snow is capable of containing up to 40 % of liquid water, while large granular snow at the end of melting has a water-holding capacity of about 5 - 8 %.

In the HBV-model two ways to model water retention in the snowpack have been attempted. First a water holding capacity C_{wh} must be exceeded before the pack can yield any water. Then, in a few catchments, a bottom storage, S_b, was introduced under the snowpack. Values of C_{wh} and S_b from the catchments, where snowmelt has been modelled, are shown in table 7.7.

Table 7.7. Water retention parameters in the different catchments.

	C_{wh} (%)	S_b (mm)
Gimdalsbyn	5	10
Kultsjön	5	0
Malgomaj	10	0
Ströms Vattudal	5	0
Filefjell	5	10

The values in table 7.7 are rather arbitrary. Error function studies carried out by Bergström (1975) and Bergström and Jönsson (1976 B), fig. 7.6, show that the interaction is strong between the two parameters. The sensitivity of the F^2-criterion to these parameters is also low, which makes it difficult to draw anything but qualitative conclusions.

S_b / C_{wh}	0	10	20	30	40
0	1.2555	1.0962	1.0615	1.0151	0.9908
3	1.1115	1.0428	1.0097	0.9903	0.9952
5	1.0497	1.0157	0.9880	0.9963	1.0145
8	1.0246	1.0119	0.9992	1.0248	1.0548
10	1.0249	1.0246	1.0347	1.0704	1.1187

Fig. 7.6. The response of F^2 to S_b and C_{wh}. Filefjell (1967 - 1971). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

7.1.7. Refreezing of liquid water

A refreezing routine is necessary, if snowmelt is interrupted by the intrusion of cold air. In the HBV-model this is simulated by eq. 7.5, which will automatically yield negative melt rates at low temperatures. If so, the liquid water content is reduced and added to the snowpack, and in case $C_{eff} > 0$, the accumulated melt figure is reduced. The method is very crude, considering that melting and freezing are different processes, which occur at different levels in the snowpack, but it was adopted in order to avoid more free parameters. The amount of liquid water is also small, so that it will mostly refreeze entirely during a cold period. During a poorly defined melt period, however, with temperature fluctuations around freezing, a better procedure for the computation of refreezing might be a way of improving the performance of the model.

7.1.8. The effect of frozen ground

The effect of frozen ground on the runoff process was discussed by the WMO (1975 A). So far no such effect has been considered in the HBV-model. The areal variablility of the soil cover and the lack of knowledge of the impact of frozen ground are problems making an attempt to model this process but little tempting. The applications of the model so far have led to the rather intuitive conclusion that the effect of frozen ground is either accounted for by the existing free parameters, or it is of minor importance for the performance of the model.

7.1.9. Statistical distribution of the degree-day factor

The snowroutine discussed so far can be said to simulate the processes in one single point. It is obvious that the great areal inhomogeneities as regards snowpack and meteorological variables must be considered in one way or another. Most critical is the effect of partly snowcovered and partly bare ground in the basin. One way of modelling this could be to adopt an areal depletion curve relating snow covered area to the accumulated melt, as suggested by Anderson (1973) and the WMO (1975 A). This method is relatively simple but entails difficulties if fresh snow is falling on a snowcover which is already reduced by melting. A more convenient way is to divide the catchment into a number of zones and to distribute one or more of the parameters or variables over these zones in order to simulate different conditions in different parts of the catchment.

In fig. 7.7 it is shown how a rectangular distribution of C_o (or T) in the simple degree-day model (eq. 7.4) will effect the overall input from snowmelt to the soil, in case five different zones are used. A constant water-holding capacity is assumed together with a constant temperature above freezing. The part with highest C_o-value will start to melt quickly and consequently the snow will end soon, while the situation is the opposite at low C_o-values. As can be seen, the superposition of the different contributions gives a completely different input to the underlying parts of the model than would an entirely lumped procedure.

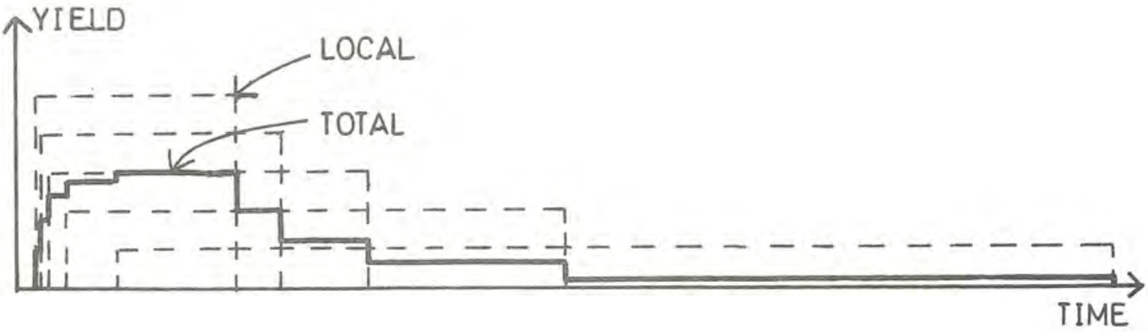


Fig. 7.7. The effect of a distribution of C_o or T in the expression $M = C_o\ (T - T_o)$ at constant water-holding capacity and constant temperature above freezing.

A rectangular distribution of the degree-day factor, C_o, was assumed when applying the HBV-model to the Gimdalsbyn catchment (Bergström 1975). C_o was ranging from $C_{o\ max}$ to $C_{o\ max} - C_{o\ int}$ in ten different zones. Both $C_{o\ max}$ and $C_{o\ int}$ were regarded as free parameters. Studies of the error function topography revealed, however, that this distribution had very little effect on the model performance (fig. 7.8). A minimum in the error function was obtained along a valley defined by the equation $2\ C_{o\ max} - C_{o\ int}$ = constant, which is identical to $(C_{o\ max} + C_{o\ min})/2$ = = constant (broken line in fig. 7.8). The distribution of C_o had little effect on the model as long as the average degree-day factor remained constant. Once again did error function studies help to keep down the complexity of the model as the assumptions of a variable degree-day factor did not have any positive effect on the model performance.

$C_{o\,int}$ \ $C_{o\,max}$	1.1	1.3	1.5	1.7	1.9
0.00	1.02	0.64	0.67	0.98	1.56
0.25	1.53	0.85	0.60	0.74	1.15
0.50	2.12	1.26	0.74	0.63	0.85
0.75	2.89	1.79	1.06	0.67	0.67
1.00	3.84	2.44	1.53	0.92	0.66

Fig. 7.8. The response of F^2 to $C_{o\,max}$ and $C_{o\,int}$. Gimdalsbyn (1961 - 1969). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^5$.)

7.1.10. Area-elevation distribution of the snowroutine.

When applying the model to a catchment of considerable elevation range, the altitude effect on air temperature and precipitation cannot be neglected. The usual way of accounting for the temperature gradient is to adopt the moist adiabatic lapse rate, T_{lapse}, - 0.6 °C/100 m. This method has been used by the U.S. Corps of Engineers (1960), Quick and Pipes (1975), Sugawara et.al. (1975) and Kuz'min (1972) among others. The method is a great simplification considering the complex meteorological conditions, such as frequent temperature inversions, but it is probably the most practical way of extrapolation in catchments where all temperature stations are situated in the lower parts.

A lapse rate of - 0.5 °C/100 m was used in the Kultsjön, Malgomaj and Ströms Vattudal catchments and - 0.6 °C/100 m was used when applying the model to Filefjell. The catchments were subdivided into ten elevation zones of equal size, and the temperature was adjusted according to equation 7.7 before entering the snowroutine.

$$T_i = T + T_{lapse} \cdot \Delta H_i, \tag{7.7}$$

where:

T_i = temperature in the i:th zone (°C),
T = recorded temperature (°C),
ΔH_i = mean altitude difference between the temperature stations and the mean elevation in the i:th zone (100 m).
T_{lapse} = elevation lapse rate of temperature (°C/100 m).

T_{lapse} has been used as a confined parameter in all catchments. An error function study carried out in Filefjell (Bergström and Jönsson, 1976 B) is shown in fig. 7.9. The interaction with T_o is not surprising, but it is interesting to note that both parameters are significantly deviating from zero. Contrary to the statistical distribution discussed in chapter 7.1.9 this routine is improving the performance of the model.

T_o / T_{lapse}	0	-0.5	-1.0	-1.5	-2.0	-2.5	-3.0
-0.00	2.4387	3.2802	4.7241	7.0543	9.2334	.	.
-0.30	1.3079	1.4641	1.9773	2.8460	4.2630	.	.
-0.60	1.4029	1.0011	0.9748	1.2362	1.7852	2.6464	3.9447
-0.90	2.5742	1.7550	1.2094	0.8946	0.9055	1.2149	1.7196
-1.20	3.8130	2.9987	2.3162	1.6205	1.1468	0.9544	1.0139

Fig. 7.9. The response of F^2 to T_{lapse} and T_o. Filefjell (1967 - 1971). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

It is, however, dangerous to draw anything but qualitative conclusions concerning the correct value of T_{lapse} from fig. 7.9. The exact position of the minimum is strongly effected by our basic assumptions, erroneous data and estimates of other parameters.

The correction of precipitation with altitude is even more difficult than are temperature corrections. Observations of the total catch at precipitation stations at different altitudes are normally the only source of information available. Wallén (1951) investigated a number of stations in Sweden in this respect. His results have been the basis of the precipitation lapse rates, P_{lapse}, in the Swedish catchments when applying the HBV-model. Recommendations from the Norwegian Water Resources and Electricity Board were used in the Filefjell basin. P_{lapse} has been used as a confined parameter in all applications of the model.

The corrections of precipitation are made from the average altitude of the precipitation stations to the mean altitude in each elevation zone. During the snow free period the snow routine is inactive and precipitation was multiplied by a factor, P_{corr}, instead of being processed by the snow routine in all elevation zones. P_{corr} was identical to the average elevation corrections in the ten elevation zones, $\overline{P}_{lapse}$, in the Kultsjön and Filefjell catchments. It deviated from $\overline{P}_{lapse}$ in Malgomaj and Ströms Vattudal. It would have been better to be more consequent in the asessment of P_{corr} as it is a parameter which interacts with the parameters in the soil moisture zone and thus complicates the generalizations of these. In future work P_{corr} will therefore be treated as a confined parameter with a value equal to $\overline{P}_{lapse}$. Values of P_{lapse}, $\overline{P}_{lapse}$ and P_{corr} are presented in table 7.8.

Table 7.8. Precipitation correction parameters.

	P_{lapse} (%/100 m)	$\overline{P}_{lapse}$	P_{corr}
Kultsjön	18	1.33	1.33
Malgomaj	15	0.95	1.0
Ströms Vattudal	16	1.16	1.0
Filefjell	12	1.4	1.4

Investigations by Bergström and Jönsson (1976 B) (fig.7.10) show that the interaction is strong between the precipitation-elevation correction factor, P_{lapse}, and the snow fall correction factor, C_{sf}, as these two parameters are effecting the total snowpack in the catchment. As mentioned earlier it is wise, under these circumstances, to set a reasonable approximation on one of the parameters, in this case P_{lapse}, and concentrate on the other, C_{sf}, when calibrating the model.

It is realistic to believe that the potential evaporation has a negative lapse rate with elevation due to the decreasing vapor pressure deficit. So far, however, no distribution of the values of potential evaporation according to the area-elevation curve has been attempted in the applications of the HBV-model.

C_{sf}	1.3	1.5	1.7	1.9	2.1
P_{lapse}					
4	2.5785	1.9933	1.5108	1.1933	1.0731
8	1.9832	1.4535	1.1174	1.0079	1.0727
12	1.5082	1.1291	0.9748	1.0691	1.3412
16	1.1882	0.9822	1.0522	1.3288	1.8761
20	1.0244	1.0267	1.2709	1.8419	2.6675

Fig. 7.10. The response of F^2 to C_{sf} and P_{lapse}. Filefjell (1967 - 1971). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

The areal distribution of the snow routine entails difficulties in the underlying routines as they will be subjects to a distributed input instead of a lumped one. Attempts to account for this by a distributed soil moisture zone will be presented in chapter 7.2.4.

7.2. The soil moisture zone

The conditions in the soil moisture zone are acting as a controlling agent in the formation of runoff, as exemplified in chapter 7, fig. 7.1. Consequently the soil moisture accounting part of the model is where the main contribution to runoff from precipitation and snowmelt is determined. The part of the lower zone, which represents lakes and rivers, can also contribute directly, but this area is mostly small compared to the total catchment.

As mentioned in the introductory discussion of chapter 7, interception of precipitation in the vegetation will be accounted for implicitly in the soil moisture routine if not modelled separately. Interception is of course related to the vegetation cover, which is a function of the time of the year. If we further consider the very complex laws governing water retention and transport in a heterogenous soil column, it is evident that the striving for a physically correct representation of the processes in the soil moisture zone will lead to very complex models. The picture is further complicated by the great areal variability of the vegetation cover and soil characteristics.

As the objective is to keep the HBV-model as simple as possible, the soil moisture accounting procedure is developed from greatly simplified assumptions according to the strategy lined out in chapter 3. The routine is based on physical considerations but is adjusted specifically to each catchment by empirical coefficients, i.e. free parameters.

7.2.1. A simple reservoir approach

One of the most simple representations of the processes in the soil is to regard the soil moisture zone as a reservoir, which has to be filled to a certain level, or capacity, Fc, before any water can pass through (fig. 7.11).

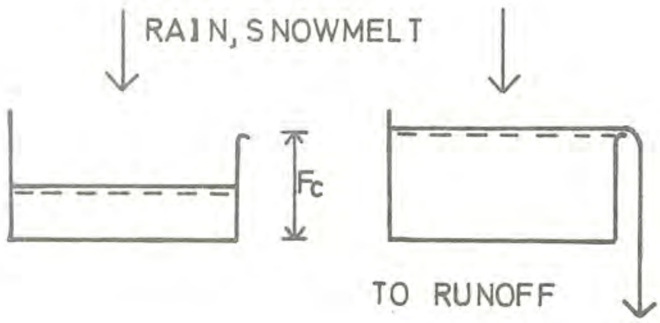


Fig. 7.11. A simple soil moisture accounting procedure.

The parameter Fc can be said to represent the maximum available water in the soil moisture zone, expressed as the difference between field capacity and wilting point. Due to the greatly simplified approach and unavoidable implicit corrections one must, however, be careful not to abuse Fc when relating parameter values to catchment characteristics.

The procedure in fig. 7.11 has some physical relevance but it is incapable of handling the great areal variability of the soil cover in most catchments Therefore its response will be too abrupt as soon as the soil moisture storage is filled to Fc. If the catchment area is divided into a number of zones in the model, and a distribution of Fc is assumed, a contributing area approach is obtained , where each individual zone with the area Z_i will contribute to runoff as soon as its soil moisture storage is filled to its capacity, Fc_i. The response of this routine will be much less abrupt, as illustrated in fig. 7.12.

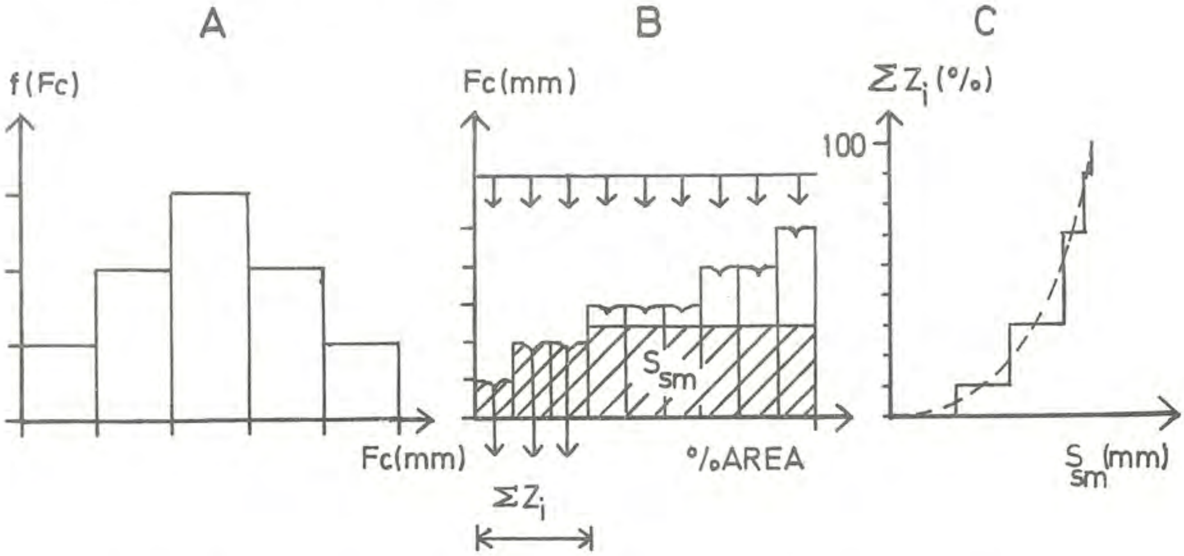


Fig. 7.12. Distribution of the simple reservoir soil moisture routine.

A: The distribution of Fc.

B: Schematic representation of contributing areas and soil moisture conditions.

C: Contributing area, ΣZ_i, as a function of the soil moisture storage, S_{sm}.

Fig. 7.12 shows an idealized progression from initially dry conditions. The modelling of evaporation from each zone will complicate the picture so that no unambiguous curve, which relates the contributing area to soil moisture conditions, will exist.

Axelsson (1975) and Becker (1975) showed examples of some modified forms of the above approach. It is also the basis of the two soil moisture accounting procedures which have been tested in the HBV-model, as will be discussed in the remaining part of chapter 7.2.

7.2.2. Soil moisture accounting in the HBV-model

The contributing area concept in fig. 7.12 has been adopted in the soil moisture accounting procedure of the HBV-model. Due to a lumped evaporation routine, the total soil moisture procedure is of a quasi-distributed rather than distributed character.

The soil is assumed to react upon rainfall or snowmelt, ΔP, in a fashion shown in fig. 7.3, which is in analogy with fig. 7.12.C.

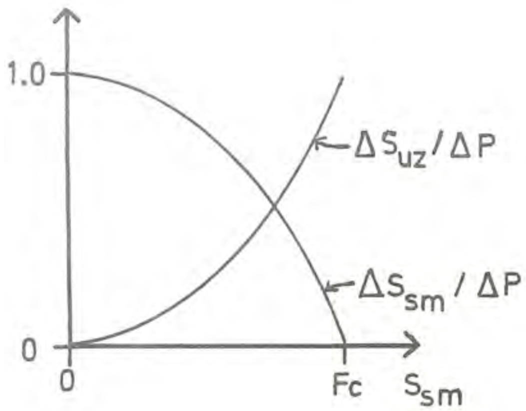


Fig. 7.13. The contributions from rainfall or snowmelt, P , to the soil moisture zone, S_{sm}, and the upper zone, S_{uz}.

Mathematically the procedure can be expressed as:

$$\frac{\Delta S_{uz}}{\Delta P} = \left(\frac{S_{sm}}{Fc}\right)^{\beta} \qquad (7.8)$$

$$\frac{\Delta S_{sm}}{\Delta P} = 1 - \left(\frac{S_{sm}}{Fc}\right)^{\beta} \qquad (7.9)$$

where:

- P = precipitation or snowmelt,
- S_{uz} = storage in the upper zone,
- S_{sm} = actual computed soil moisture storage,
- Fc = maximum soil moisture storage in the model,
- β = empirical coefficient.

The amount ΔS_{uz} will pass through the soil moisture zone and eventually contribute to runoff or evaporation from the lower zone. ΔS_{sm} will contribute to the soil moisture storage with evaporation as the only exit from the system. β is a free parameter which gives the curves in fig. 7.13 their shapes. At β-values of plus infinity the routine will degenerate to the simple reservoir type in fig. 7.11, while if β equals zero there will be no active soil moisture storage at all. The routine is thus very economic in terms of free parameters, as a large spectrum of possibilities can be covered when changing β and Fc.

Potential evaporation is reduced to actual values according to the simple function of the total computed soil moisture conditions in fig. 7.14.

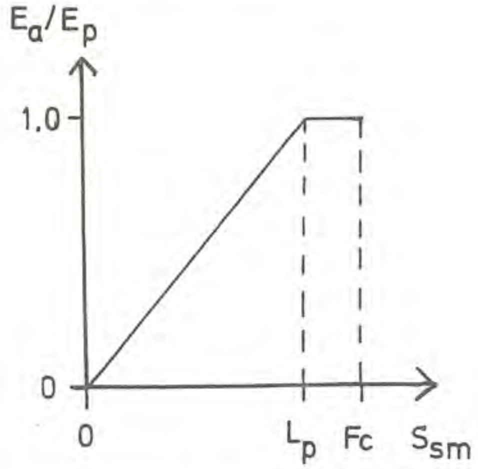


Fig. 7.14. Reduction of potential evaporation, E_p, to actual, E_a.

This can be expressed as:

$$E_a = E_p \qquad \text{if} \qquad S_{sm} \geq L_p$$

$$E_a = E_p \cdot \frac{S_{sm}}{L_p} \qquad \text{if} \qquad S_{sm} < L_p \tag{7.10}$$

where:

E_p = potential evaporation,
E_a = actual evaporation,
S_{sm} = actual computed soil moisture storage,
L_p = limit for potential evaporation.

Due to its simplicity this method for reduction of potential evaporation has been very popular in hydrological modelling. It was used by Porter and McMahon (1971), Girard, Fortin and Charbonneau (1971) and Dickinson and Douglas (1972) to mention a few authors.

The parameter L_p is sometimes said to represent the root zone constant, above which evaporation will occur at potential rate from a soil profile. If the distributed approach is adopted, it is, however, more realistic to interpret L_p as the general moisture conditions above which the entire catchment has the opportunity to evaporate at potential rate. A general decrease of evaporation with decreasing soil moisture storage is a realistic assumption, anyhow. Kristensen and Jensen (1975) elaborated this a bit further when accounting for the intensity of the potential evaporation by different shapes of the curve in fig. 7.14. This modification cannot be considered in the HBV-model, unless better evaporation data are obtained.

The above soil moisture routine has been used in all test catchments. The parameter values are shown in table 7.9. The procedure, when fitting the model has generally been to start with adjustments of β, with L_p equal to Fc and with Fc at values regarded as reasonable from considerations of the soil and vegetation cover in the catchment. Thereafter L_p has been adjusted and finally, if found necessary, different values of Fc have been tested. This procedure is reflected in the rather regular Fc-and L_p- values in table 7.9.

Table 7.9. Parameter values in the soil moisture zone.

	Fc	L_p/Fc	β
Lilla Tivsjön	100	0.7	3.4
Nolsjön	200	0.8	8.0
Stabby	100	1.0	7.0
Stormyra	50	0.8	4.0
Solmyren	100	1.0	2.25
Gimdalsbyn	200	1.0	1.80
Kultsjön	150	1.0	3.0
Malgomaj	150	1.0	2.0
Ströms Vattudal	150	1.0	1.0
Filefjell	150	1.0	2.0

When analysing the values of the soil moisture parameters, it is important to bear in mind the possible effects of erroneous input data, the interactions with the precipitation correction factor, P_{corr} (see chapter 7.1.10) and other implicit corrections. It is also important to remember the role played by β as an exponent in eq. 7.8 and 7.9, making the model little sensitive to changes in β at high β-values. When analysing the error function the latter problem is overcome with a log transformation of the β-axis.

A general conclusion is that the model can be fitted quite well with a rather crude approximation of Fc and with L_p/Fc equal to one. The fact that all β-values lie between one and eight and thus give a concave shape of the $\Delta S_{uz}/\Delta P$ -curve (fig. 7.13) is supporting the hypothesis lined out in fig. 7.12.

The error function topography of the soil moisture parameters was studied by Bergström and Forsman (1973), Bergström (1975) and Bergström and Jönsson (1976 B). Two of these studies are shown in fig. 7.15 and 7.16.

β \ Fc	50	100	150	200	250
0.5	3.48	2.95	2.63	2.34	2.33
1.0	2.45	1.83	1.38	1.12	1.20
2.0	2.04	1.53	1.06	0.77	0.96
4.0	1.97	1.72	1.34	1.08	1.32
8.0	1.99	1.98	1.76	1.59	1.90

Fig. 7.15. The response of F^2 to Fc and β with L_p/Fc at a constant value. Gimdalsbyn (1961 - 1969). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^5$.)

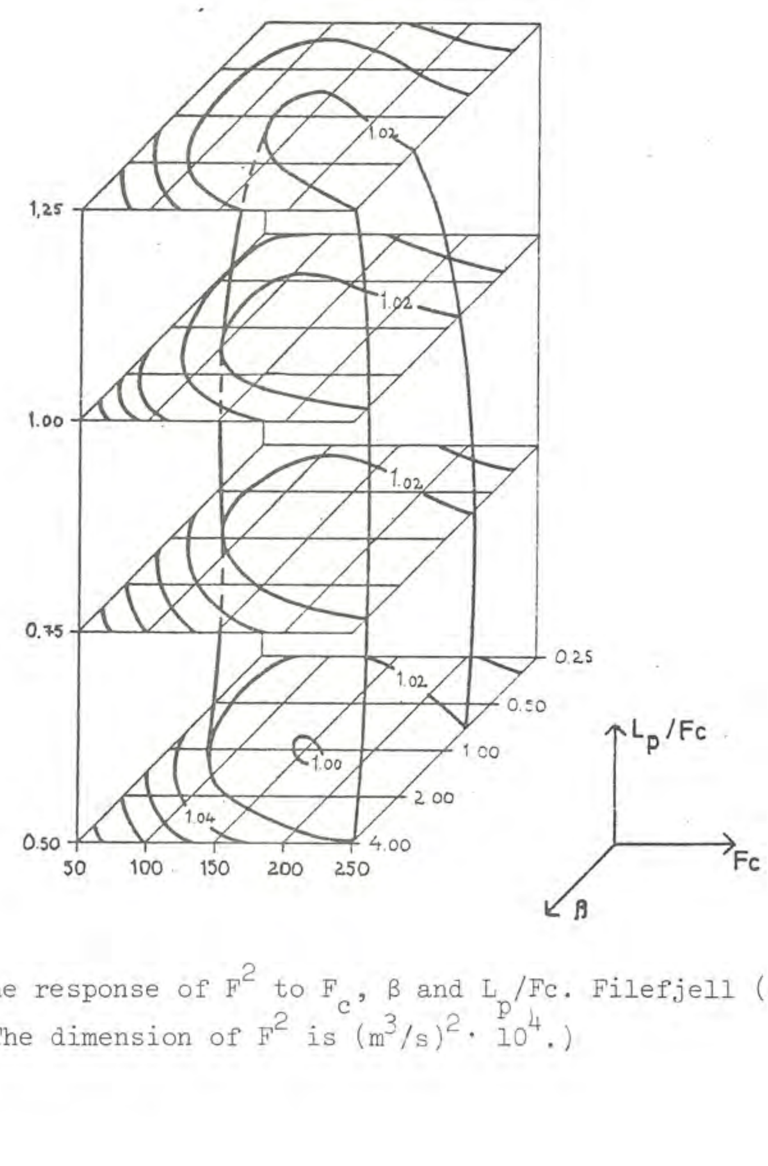


Fig. 7.16. The response of F^2 to F_c, β and L_p/Fc. Filefjell (1967 - 1971). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

All studies of the error function have confirmed that the simple reservoir routine in fig. 7.11 is too rigid a representation of the soil moisture zone, as β has a well defined optimum value.

In order further to investigate the role played by the soil moisture zone, the active and relative active soil moisture storages have been computed in a few test catchments according to:

$$S_{act} = Fc - S_{sm_{min}} \qquad (7.11)$$

$$s_{act} = \frac{S_{act}}{Fc} \qquad (7.12)$$

where:

S_{act} = active soil moisture storage (mm),
s_{act} = relative active soil moisture storage,
$S_{sm_{min}}$ = minimum soil moisture storage during the period (mm).

S_{act} and s_{act} are thus measures of the maximum reduction of the soil moisture storage, S_{sm}, during a specific period. A small value of s_{sm} indicates that only a fraction of the storage is playing an active role, which will have consequences for the sensitivity of the model to the parameters in the soil moisture zone. Values of S_{act} and s_{act} are presented in table 7.10.

Table 7.10. Active, S_{act}, and relative active, s_{act}, soil moisture storage in the HBV-model.

	Area above timberline (%)	S_{act} (mm)	s_{act}	Fc (mm)	Number of years
Gimdalsbyn	0	154	0.77	200	12
Malgomaj	7	86	0.57	150	12
Ströms Vattudal	13	90	0.60	150	13
Kultsjön	51	71	0.47	150	13
Filefjell	86	50	0.33	150	7

Considering the climatological impact it is not surprising that the active soil moisture storage is decreasing with increasing area above timberline. In the Filefjell alpine basin only one third of the assumed available water is exchanged. This is reflected by a low sensitivity of the model to changes in the parameters L_p, Fc and β in the soil moisture zone (fig. 7.16).

From the results in table 7.10 it is obvious that one must be very careful when relating Fc-values to physical characteristics. When designing the model, Fc was meant to represent the maximum available water content of the soil, i.e. the difference between field capacity and wilting point. If just a part of the soil moisture storage is active, it is, however, difficult to draw any conclusions concerning the relevance of a chosen Fc-value.

7.2.3. An alternative soil moisture routine

The routine discussed in the previous chapter was based on a contributing area concept with a lumped evaporation procedure. A more logical routine treating evaporation separately in a number of zones with varying values of the maximum soil moisture storage, Fc, was tested in the Stabby catchment. The catchment was divided into ten zones with a distribution of Fc according to fig. 7.17. Each zone was then modelled according to the simple storage concept lined out in chapter 7.2.1, fig. 7.11.

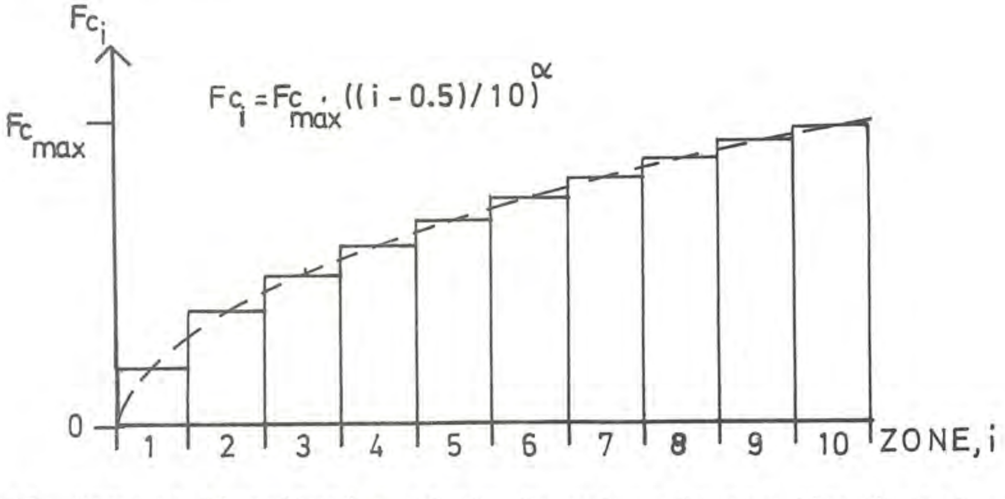


Fig. 7.17. Assumed distribution of the Fc-values in the distributed soil moisture routine.

Actual evaporation from each zone, E_{a_i}, was computed separately in analogy with fig. 7.14, as shown in fig. 7.18. Identical values of the difference $Fc_i - L_{p_i}$ were assumed in all zones.

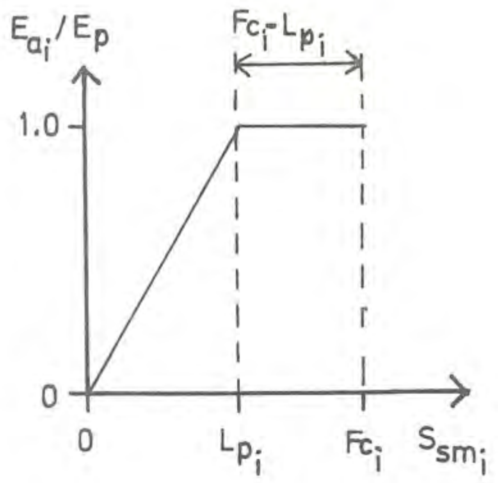


Fig. 7.18. Evaporation from the different zones in the distributed soil moisture routine.

If the value of $Fc_i - L_{p_i}$ exceeded Fc_i in any zone, the soil moisture storage was subject to unreduced evaporation until emptied.

The above routine was compared to the one described in chapter 7.2.2. for the snowfree periods of 1959, 1960 and 1961. It was calibrated through mappings of the F^2-surface with different values of α, $Fc_i - L_{p_i}$ and Fc_{max}. Fitted values were α = 0.4, $Fc_i - L_{p_i}$ = 0 and Fc_{max} = 150 mm. The response surface at this Fc_{max}-value is shown in fig. 7.19.

α $(Fc_i - L_{p_i})$	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8
-20.0	736.	756.	803.	897.	1026.	1185.	1372.	1566.
-15.0	691.	694.	720.	787.	1331.	1023.	1183.	1355.
-10.0	689.	664.	664.	705.	780.	884.	1015.	1160.
- 5.0	709.	667.	643.	655.	705.	778.	878.	852.
0	745.	685.	648.	641.	664.	713.	782.	868.
5.0	829.	744.	693.	669.	672.	699.	745.	804.
10.0	947.	838.	767.	729.	713.	719.	746.	784.
15.0	1128.	983.	889.	828.	793.	778.	778.	799.

Fig. 7.19. The response of F^2 to α and the difference $Fc_i - L_{p_i}$ at Fc_{max} = 150 mm. Stabby (1959 - 1961). (The dimension of F^2 is $(1/s)^2 \cdot 10^{3}$)

The results expressed as R^2- and F^2-values are shown in table 7.11. Due to the low initial variance the R^2-value is a misleading criterion of fit for the period 1959 as shown in fig. 5.1. The total error expressed as F^2 is therefore the most appropriate base for comparison in this investigation.

Table 7.11. Comparison between the distributed and the original soil moisture routines. (Stabby 1959 - 1961).

	R^2			Total F^2 $(l/s)^2$
	1959	1960	1961	
Distributed routine	0.47	0.92	0.54	$64 \cdot 10^4$
Original routine	- 0.64	0.93	0.80	$40 \cdot 10^4$

Although it was possible to fit both models well to each year individually, the total error was larger by the distributed model when making a simultaneous calibration of all three years. The conclusion is therefore that the distributed model is inferior to the one adopted in the HBV-model.

The sensitivity of the distributed model to the resolution in the subdivision was also tested. The model was run with a subdivision of 2, 4, 6 ... to 20 zones. There was very little difference from 6 and higher numbers of zones.

7.2.4. Distribution according to the area-elevation curve

When distributing the snow routine according to the area elevation curve, as discussed in section 7.1.10, not only the snowpack but all underlying components of the model are effected, as snowmelt is simulated differently in the different zones of the catchment. A critical part in this respect is the soil moisture zone. In the HBV-2 and HBV-3 models discussed so far this problem was ignored, and all the snowmelt was fed into one common soil moisture zone. This is, of course, a questionable point, and therefore a distributed soil moisture zone was tested in the sense that separate soil moisture accountings, based on the procedure in chapter 7.2.2, were carried out in each elevation zone (Bergström and Jönsson 1976 A). The investigation was carried out in the Kultsjön catchment (1962 - 1974).

The problem with such a differentiation is that the number of free parameters will multiply by the number of elevation zones, making it difficult to obtain stable parameter estimates. In order to avoid this problem, β and L_p/Fc were regarded as invariable with the altitude while Fc was subject to a rectangular distribution according to fig. 7.10.

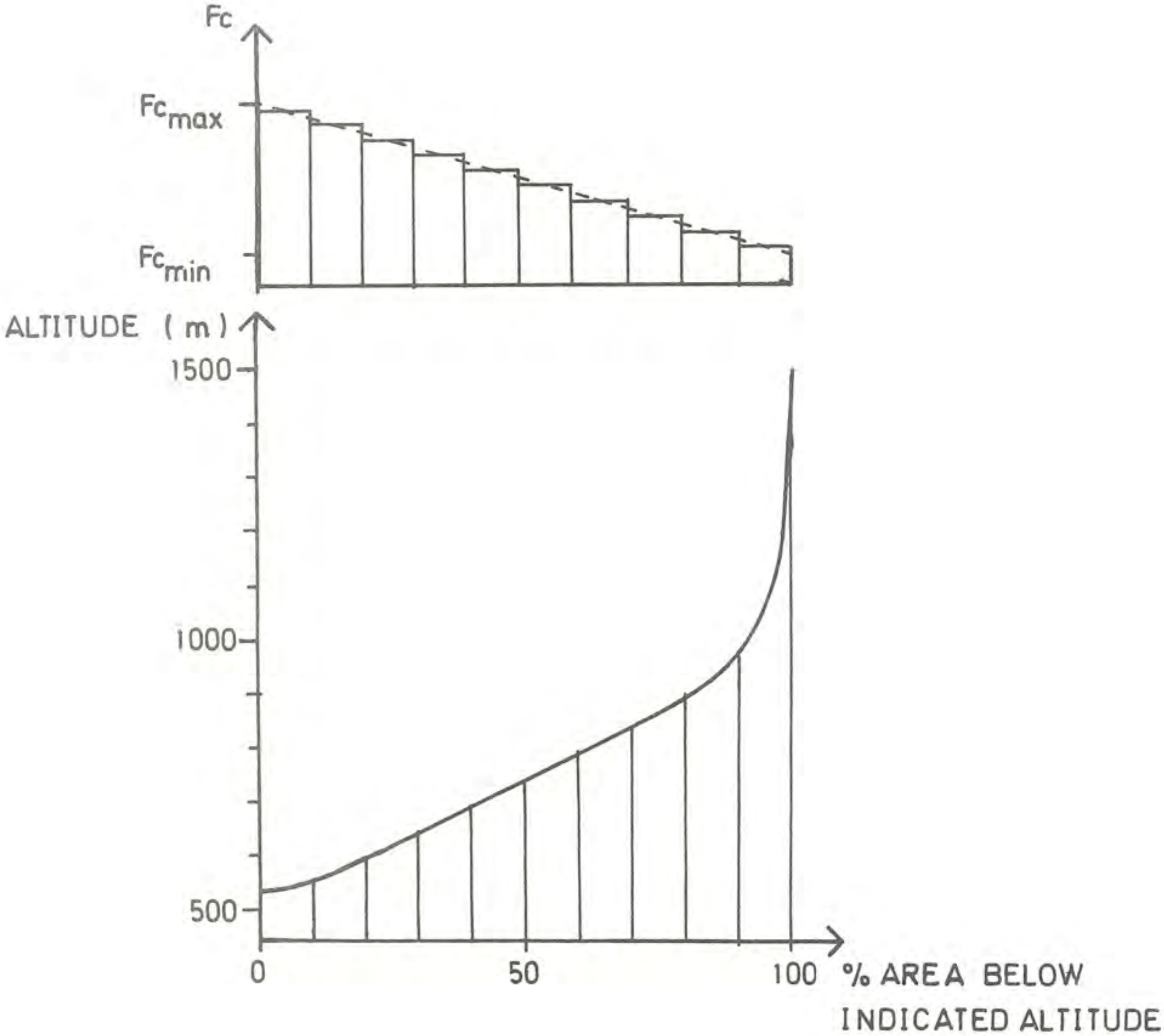


Fig. 7.20. Distribution of the soil moisture zone according to the area-elevation curve in the Kultsjön catchment.

The model was run both with invariable Fc-values and with a distribution ranging from 25 mm to 275 mm. The results are summarized in table 7.12.

Table 7.12. Results with a lumped soil moisture routine and one distributed according to the area-elevation curve. Kultsjön (1962 - 1974).

	R^2		
	1962 - 1966	1966 - 1970	1970 - 1974
Lumped			
Fc = 150 mm	0.7977	0.8712	0.8402
Distributed			
Fc_{max} = 150 mm Fc_{min} = 150 mm	0.7931	0.8731	0.8512
Distributed			
Fc_{max} = 275 mm Fc_{min} = 25 mm	0.7902	0.8753	0.8495

It is evident from table 7.12 that the differences in performance between the lumped and the distributed models are quite small, and that a lumped model is sufficient in the Kultsjön catchment. This conclusion was supported by visual inspection of the hydrographs.

7.3. The response function of the HBV-model

The response function is the part of the model which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part p_w which represents lakes, rivers and other wet areas.

The HBV-model has a nonlinear response function, but some of its components are of a linear, or at least, quasi-linear character. It is sometimes argued that a linear response function should be more convenient because of the existence of analytical solutions. The estimation of the parameters in the nonlinear function described below is, however, no great problem. Therefore it seems wise not to compromise in the sense that a physical behaviour, which we know is nonlinear, is forced into a linear framework.

The most successful versions of the HBV-model have a response function which can be illustrated, in a general form, as in fig. 7.21.

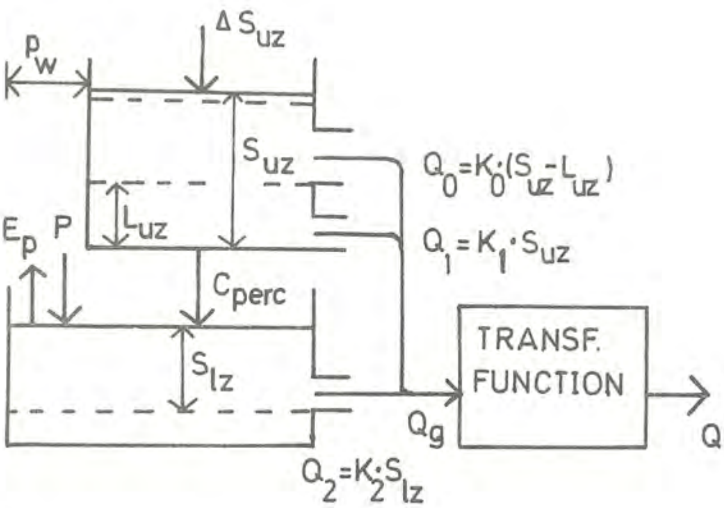


Fig. 7.21. The response function of the HBV-model.

Excess water enters the upper zone. It leaves as runoff through its two outlets or percolates, at a constant rate, C_{perc}, down to the lower zone, from which it can either evaporate or drain. At last a transformation function is activated to give a proper shape of the hydrograph which is generated by the two reservoirs. Fig. 7.21 is actually showing the HBV-3 version, but with proper parameter settings HBV-1 and HBV-2 can be obtained.

The linkage between the upper zone and the lower zones has been supported by a work by Waldenström and Andersson (1973). Special high-frequency measurements of soil moisture and ground water in the Kassjöån Representative Basin, of which Lilla Tivsjön is a part, showed that recharge of groundwater continues for some time after the termination of rainfall and replenishment of the soil moisture deficit. In the model recharge of the lower zone will continue until the upper zone is empty.

It is tempting to attribute the different runoff components in the response function to the three components often discussed in the handbooks: overland flow, interflow and groundwater flow. (See for example: Gray, 1973.) It must be stressed once again, however, that the fact that the model yields reasonable discharge values, is no confirmation of the physical relevance of the model. It might be possible to achieve similar results with other structures.

7.3.1. The single linear reservoir

The corner-stone on the response function is the single linear reservoir shown in fig. 7.22.

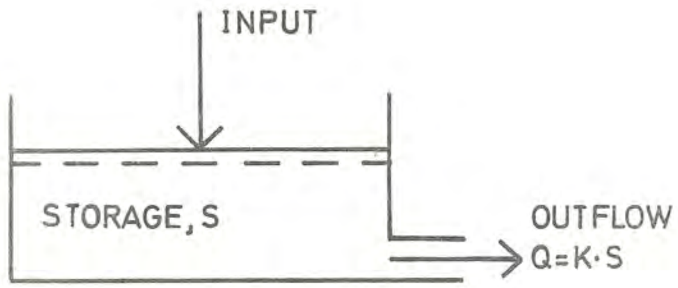


Fig. 7.22. The single linear reservoir.

Its differential equation during a dry period (no input) can be expressed as:

$$\frac{d\ S(t)}{d\ t} = -\ K \cdot S(t), \qquad (7.13)$$

where:

S(t) = storage at time t,

K = storage discharge constant (recession coefficient).

Eq. 7.13 has the general solution:

$$S(t) = S(t_o) \cdot e^{-K\cdot(t-t_o)} \qquad (7.14)$$

if we introduce the discharge $Q(t) = \frac{-d\ S(t)}{d\ t}$ into eq. 7.13

$$S(t) = \frac{-1}{K} \cdot \frac{d\ S(t)}{d\ t} = \frac{1}{K}\ Q(t)$$

and substitute S(t) in eq. 7.14, we obtain

$$Q(t) = Q(t_o)\ e^{-K\cdot(t-t_o)} \qquad (7.15)$$

During a dry period the single linear reservoir will show an exponential decay which is a quality often detected when analysing hydrographs.

Instead of the storage discharge constant K with the dimension (time^{-1}) the invers, 1/K, with the dimension (time) is sometimes used.

Another possibility is to use the relation:

$$r = \frac{Q\ (t+1)}{Q(t)}\ , \qquad (7.16)$$

which can be related to K, if one time step is used in eq. 7.15:

$$Q\ (t_o + 1) = Q(t_o) \cdot e^{-K \cdot 1}$$

or:

$$\ln \frac{Q(t_o)}{Q(t_o+1)} = K = \ln \frac{1}{r} \qquad (7.17)$$

In this work K will be used as the characteristic parameter of a reservoir. In some of the investigations of the HBV-model, a K-value, which is directly relating storage in mm to discharge in l/s, is used. This value is, however, not independent of catchment size, which complicates comparisons and generalizations.

The single linear reservoir will be distorted when linked together to form the response function. A linear character can, under certain conditions, still be assumed, which will help in the calibration of the model or at least in finding first estimates of some parameters. If ln Q is plotted against time during a dry spell, the gradients of the hydrograph at different magnitudes of discharge are good first estimates of the different recession coefficients, K_o, K_1 and K_2 in fig. 7.21.

The single linear reservoir is only one of many possible ways of modelling a storage discharge process in nature. Roche (1970) shows examples of other reservoirs with different physical interpretations. He points out that the single linear reservoir can be visualized as a container with a porous outlet, thus obtaining eq. 7.13 from Darcy's law.

7.3.2. The upper zone

A very general interpretation of the configuration of the upper zone in fig. 7.21 could be expressed as follows: If yield from the soil exceeds a certain percolation capacity, the water will start to drain through more superficial channels and thus reach the rivers and streams with a higher drainage coefficient, K_1. At a storage in the upper zone exceeding L_{uz}, these channels are filled to their capacity, and even more rapid drainage according to K_o will start. This explanation is somewhat vague, but the interpretation is not a determining factor for the model as long as we are working with a lumped approach, a fact that was discussed by Bergström and Jönsson (1976 B).

The introduction of K_o in the HBV-3 version of the model is, of course, disturbing the linearity of the upper zone considerably. Even if K_o is zero, that is if we study the HBV-2 version, the upper zone will be a distorted linear reservoir due to the parameter C_{perc}. Its differential equation during a dry period will be of the form:

$$\frac{d\ S_{uz}(t)}{d\ t} = -K_1 \cdot S_{uz}(t) - C_{perc}, \quad \text{if } S_{uz}(t) > 0, \tag{7.18}$$

where:

$S_{uz}(t)$ = storage in the upper zone at time t,
K_1 = storage discharge constant,
C_{perc} = percolation rate to the lower zone.

A general solution to 7.18 is:

$$S_{uz}(t) = -\frac{C_{perc}}{K_1} + \left(\frac{C_{perc}}{K_1} + S_{uz}(t_o)\right) e^{-K_1 \cdot (t-t_o)} \tag{7.19}$$

The smaller C_{perc} is, compared to K, the more the response of the upper zone will approach that of the single linear reservoir discussed in section 7.3.1. The response is shown graphically in fig. 7.23.

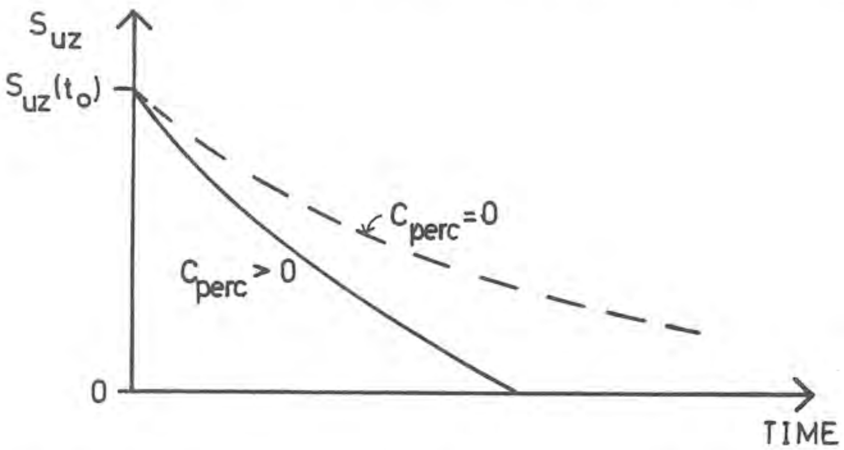


Fig. 7.23. The response of S_{uz} during a dry spell, if K_o = 0.

The response of the model to the parameters of the upper zone have been studied by Bergström and Forsman (1973) and Bergström and Jönsson (1976 B). The result from a study of K_o, K_1 and L_{uz} in the Filefjell basin is shown in fig. 7.24.

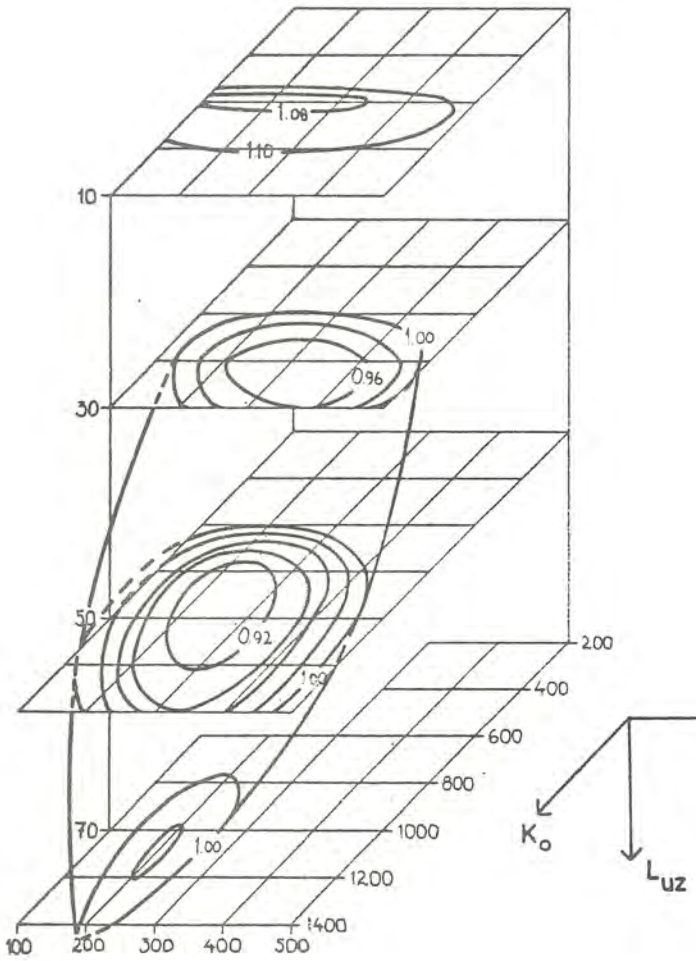


Fig. 7.24. The response of F^2 to K_o, K_1 and L_{uz}. Filefjell (1967 - 1971). (The K-values are relating storage in mm to discharge in l/s. The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

It is interesting to note the increasing importance of K_1 with increasing L_{uz}-values reflected by the switch in the main axis of the ellipse formed by the isolines. The explanation to this is that at high L_{uz}-values the HBV-3 model will degenerate to HBV-2 with K_o as an inactive parameter, while at low L_{uz}-values the effect of K_o is more pronounced. Fig. 7.23 is also a good indication of the significant improvement of the model when introducing a third runoff coefficient in the Filefjell basin, as the optimum K_o-value is situated far from zero.

7.3.3. The lower zone

The lower zone can be said to represent the total groundwater storage of the catchment. C_{perc} is thus a parameter governing groundwater recharge. The interpretation of this zone is somewhat easier than that of the upper zone. The fact that one slow and at least one quick runoff component have been detected in all investigated catchments, no matter if they are homogenous or heterogenous, is supporting the theory that the slow component is caused by a lower reservoir and not a parallell one. It is true that a model with one runoff component, HBV-1, was used in the Lilla Tivsjön catchment, but later work (Bergström, 1973) showed that the HBV-2 version is preferable, if higher flows are to be modelled in the catchment.

If we assume that no part of the lower zone is subject to direct precipitation or evaporation, the reservoir will be linear and have a response according to:

$$\frac{d\,S_{lz}(t)}{dt} = -\,K_2 \cdot S_{lz}\,(t) + C_{perc} \quad \text{if} \quad S_{uz}(t)>0$$

$$\frac{d\,S_{lz}(t)}{dt} = -\,K_2 \cdot S_{lz}\,(t) \quad \text{if} \quad S_{uz}(t) = 0, \qquad (7.20)$$

where:

$S_{lz}(t)$ = storage in the lower zone at time t,
$S_{uz}(t)$ = storage in the upper zone at time t,
K_2 = storage discharge constant for the lower zone,
C_{perc} = percolation rate from the upper zone.

The solution to 7.20 is:

$$S_{lz}(t) = \frac{C_{perc}}{K_2} - \left(\frac{C_{perc}}{K_2} - S_{lz}(t_o)\right) e^{-K_2\cdot(t-t_o)}, \text{ if} \quad S_{uz}(t)>0$$

$$S_{lz}(t) = S_{lz}(t_o) \cdot e^{-K_2\cdot(t-t_o)}, \text{if} \quad S_{uz}(t) = 0. \qquad (7.21)$$

The response of S_{lz} is visualized in fig. 7.25.

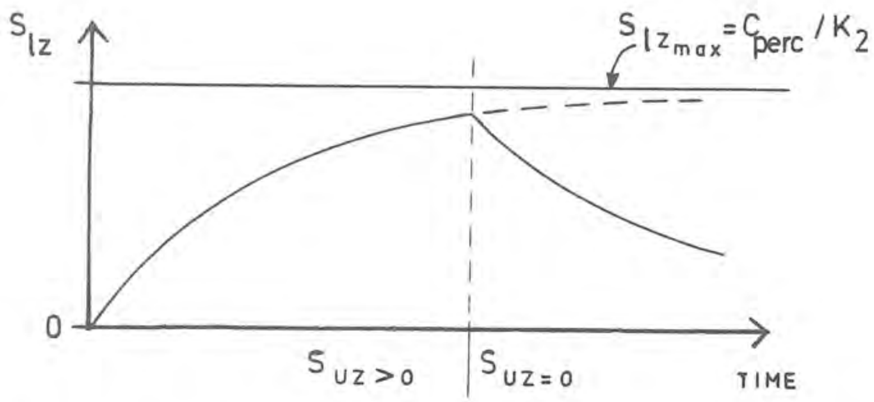


Fig. 7.25. The response of the lower zone to input from the upper zone.

If S_{uz}>0, S_{lz} is raising and is asymptotically approaching the value C_{perc}/K_2. As soon as the upper zone is empty, i.e. $S_{uz} = 0$, the lower zone will decline exponentially towards zero.

The introduction of a part, p_w, representing lakes, rivers and other wet areas, somewhat complicates the picture on the input side. Recharge from the upper zone will occur parallell to direct precipitation and evaporation on the part, p_w. The effect of precipitation will be present throughout the year as the pressure of the snowpack on the ice will have the same effect as direct rainfall on a water surface. Evaporation from the part, p_w, is assumed to occur at potential rate, as soon as the ice has disappeared from the lakes. The same values of potential evaporation as from land are used in combination with a standard date for icefree conditions. (See chapter 7.3.5.) The lower zone has a dead storage which is allowing runoff to cease completely due to evaporation from lakes in dry summers.

One attempt was made to model the lakes as a separate reservoir, through which the response of both the upper and the lower zones were routed. The estimation of the storage discharge curve of this reservoir caused problems, as it interacted with K_2 and K_1. The work was abandoned but it is strongly felt that the routing through lakes and improvement of the lake evaporation routine is still a point where the model could be improved.

A mapping of the response surface with K_2 and C_{perc} as free parameters was made when applying the model to the Filefjell catchment (Bergström and Jönsson, 1976 B), (fig. 7.26). The optimum parameter values in the

F^2-sense of the term did not coincide with judgements from visual inspection of the two hydrographs. The F^2-criterion showed low sensitivity to changes in K_2 and C_{perc}, which is not surprising as they are mainly effecting the low flow recessions with small but persistant residuals. The contribution to a sum of squares criterion is therefore rather small compared to timing errors of flood peaks for example.

K_2 / C_{perc}	10	50	90	130	170	210	250	290
0	1.0369	1.0291	1.0430	1.0595	1.0769	.	.	.
1	1.0304	0.9524	0.9632	0.9855	1.0097	.	.	.
2	1.1328	0.9436	0.9289	0.9440	0.9666	.	.	.
3	1.3171	0.9817	0.9232	0.9211	0.9362	0.9576	0.9811	1.0049
4	1.5355	1.0396	0.9264	0.9026	0.9085	0.9264	0.9495	0.9745
5	.	.	.	0.9058	0.8995	0.9121	0.9336	0.9590
6	.	.	.	0.9321	0.9115	0.9177	0.9367	0.9618
7	.	.	.	0.9695	0.9335	0.9323	0.9479	0.9717

Fig. 7.26. The response of F^2 to C_{perc} and K_2. Filefjell (1967 - 1971). (K_2 is relating storage in mm to discharge in l/s. The dimension of F^2 is $(m^2/s)^2 \cdot 10^4$.)

7.3.4. The transformation function

The transformation function is sometimes named the time-area transformation function, but difficulties in the physical interpretation of the recession coefficients, as will be discussed in the following chapter, have led to some sceptisism as regards the latter name.

The effect of the transformation function on the hydrograph is illustrated in fig. 7.27, where Q_g represents generated runoff from the upper and the lower zones in fig. 7.21.

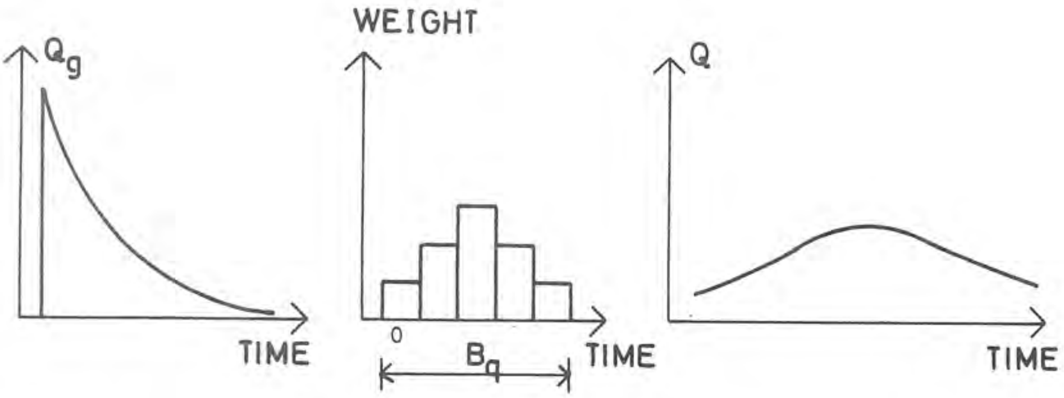


Fig. 7.27. The effect of the transformation function on the generated hydrograph.

Q_g is distributed on consequtive days according to a triangular function, with the base B_q. B_q is a variable, which depends on the magnitude of Q_g according to:

$$B_q = B_{max} - C_{route} \cdot Q_g, \quad \text{if } (B_{max} - C_{route} \cdot Q_g) \geq 1,$$
$$B_q = 1, \quad \text{if } (B_{max} - C_{route} \cdot Q_g) < 1, \quad (7.22)$$

where:

B_q = base in the triangular function (days),
B_{max} = maximum base at low flows (days),
C_{route} = free parameter $(days/(m^3/s))$,
Q_g = generated runoff from the upper and the lower zones (m^3/s),
TIME = 0 is the day on which runoff was generated.

Thus a variable transformation function is obtained, which, to some degree, may account for the variations of time-of-travel with magnitude of runoff. Eq. 7.22 was introduced when the model was applied to the Gimdalsbyn catchment, a strongly damped forested basin with a high percentage of lakes (Bergström, 1975). The F^2-surface at different values of B_{max} and C_{route} is shown in fig. 7.28.

C_{route}	0.32	0.29	0.26	0.23	0.20	0.17	0.14	0.11	0.08	0.05	0.02	0.00
B_{max}												
10	.	.	.	.	.	.	.	.	.	.	1.10	0.98
20	.	.	.	.	.	.	.	0.89	0.73	0.73	0.85	0.95
30	.	.	.	.	0.92	0.71	0.67	0.74	0.92	.	.	.
40	1.08	0.81	0.71	0.74	0.87	1.09	1.36	.	.	.	.	.
50	0.93	1.12	1.36	1.64	1.96	.	.	.	.	.	.	.

Fig. 7.28. The response of F^2 to B_{max} and C_{route}. Gimdalsbyn (1961 - 1969). (The dimension of F^2 is $(m^3/s)^2 \cdot 10^5$.)

A non-variable transformation function is obtained, if $C_{route} = 0$. As can be seen from fig. 7.28, the introduction of C_{route} improved the model significantly in the Gimdalsbyn catchment. In some basins with a quicker response C_{route} has not been used.

From the work on the Filefjell catchment (Bergström and Jönsson, 1976 B) response surfaces of K_o and K_1 at different B_q-values and with $C_{route} = 0$ are shown in fig. 7.29. Although there is some interaction between K_o and B_q the latter has a very distinct optimum at $B_q = 2.0$.

It is sometimes argued that a more physically based time-area transformation function according to Chezy's formula or similar would be preferable. One must, however, bear in mind that for proper use of Chezy's formula not only the basin slope but also the wet perimeter is needed. Otherwise the formula will not account for the relation between time of concentration and magnitude of discharge.

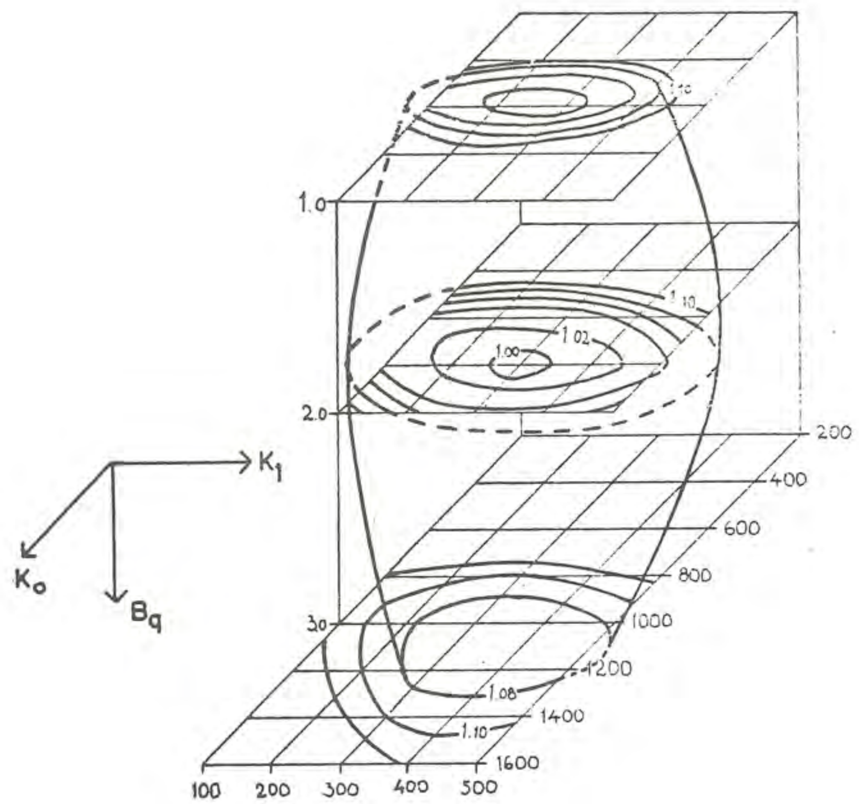


Fig. 7.29. The response of F^2 to K_o, K_1 and B_q with C_{route} = 0. Filefjell (1967 - 1971). (The K-values are relating storage in mm to discharge in l/s. The dimension of F^2 is $(m^3/s)^2 \cdot 10^4$.)

It can be discussed, whether the same transformation function should be applied to all runoff components. But as long as the physical interpretation of these components is unclear and the results are satisfactory, there is little reason to introduce more complexity than necessary for the purpose of the model. There is a possibility, however, that a more complex damping function, based on the laws of fluid dynamics, might simplify the generalization of parameters and thus be a better approach to the problem of ungauged catchments.

The technique to damp out the response of one more or less linear reservoir by a triangular weighing function can sometimes be seen used in the opposite way. Dawdy et. al. (1972), for example, obtained the hydrograph by the routing of the time-area histogram through a linear reservoir. By definition the response is identical with the damping of a generated hydrograph, as long as the reservoir is linear. In the stanford IV model (Crawford and Linsley, 1966) a method that resembles the one used in the HBV-model is described. The authors refer to the method as the "channel time-delay histogram".

7.3.5. Parameter values of the response function

The recession coefficients in the response function are given first estimate from plottings of the logarithms of discharge against time during a dry period (see chapter 7.3.1). This method, referred to as recession analysis, is commonly used when identifying parameters in an exponential response function (see, for example, Burnash et. al., 1973, or Sugawara et. al., 1974). Applications to the HBV-model were shown by Bergström (1972 B), Bergström and Jönsson (1975) and Bergström and Jönsson (1976 B). When applying recession analysis to the HBV-model a few points should be stressed.

1. Due to the linkage between the upper zone and the lower zone, the linearity of the upper zone will be distorted and the recession analysis will yield only approximate K_o- and K_1-values.

2. The coefficient of the lower zone, K_2, will be distorted by evaporation. Therefore it is advisable to carry out the analysis during a winter recession.

3. The variable transformation function is another factor which introduces uncertainties into the estimates of the recession coefficients.

Due to the above uncertainties recession analysis must be carried out as a first step only and always in combination with visual inspection of the hydrographs. Poor estimates of the coefficients will immediately be revealed when comparing the computed and the observed recession limbs.

Analysis of the hydrograph can also be used to give a first estimate of C_{perc} as discussed by Bergström and Jönsson (1975), but the value must generally be adjusted after visual comparison between the computed and the observed hydrographs. The same goes for the parameter L_{uz} in the upper zone of the response function.

The part of the lower zone, p_w, representing lakes, rivers and outflow areas, is determined from the map as the lake percentage plus a correction for swamps and other wet areas. As the work on the applications of the model has been going on for several years, these corrections, being rather arbitrary, have unfortunately not been made according to a consequent rule. The differences are, however, small and of minor importance, as the model is rather insensitive to differences in p_w as shown by Bergström and Jönsson (1976 B). Evaporation from the wet parts is assumed to occur as soon as there are icefree conditions in the lakes. Long term observations by Moberg (1967) of ice conditions have been used to determine standard dates for each catchment in Sweden, while surface water temperature recordings were used in the Filefjell catchment.

The remaining parameters in the response function, C_{route} and B_{max}, are found by visual inspection of the hydrographs and the accumulated difference-curve.

In table 7.13 the parameters in the response function are shown together with some characteristics of the catchments.

Table 7.13. Response function parameters and catchment characteristics.

Catchment	Size km^2	Area above timber-line (%)	p_w (%)	L_{uz} (mm)	K_0 (day^{-1})	K_1 (day^{-1})	K_2 (day^{-1})	C_{perc} (mm/day)	B_{max} day	C_{route} (days/(m^3/s))
Lilla Tivsjön	12.7	0	4.6	-	-	-	0.079	-	-1)	0
Nolsjön	18.2	0	2.0	-	-	0.194	0.071	0.5	4	0
Stabby	6.4	0	0.5	-	-	0.360	0.137	0.9	2	0
Stormyra	4.0	0	3.0	-	-	0.422	0.126	0.8	2	0
Solmyren	27.5	0	10.0	-	-	0.063 2)	0.019 2)	0.5	3	0
Gimdalsbyn	2178	0	15.0	-	-	0.033	0.014	0.6	40	0.23
Kultsjön	1109	51	7.0	-	-	0.335	0.0234	1.3	2	0.0103
Malgomaj	1862	7	12.0	-	-	0.299	0.0399	0.6	2	0
Ströms Vattudal	3851	13	10.0	-	-	0.130	0.0336	0.4	5	0.007
Filefjell	154	86	10.0	20	0.394	0.126	0.0281	0.6	2	0

1) A time lag of one day was used instead of damping in the HBV-1 model.
2) Poor estimate due to poor performance of the model.

When analysing table 7.13 some relation between catchment size and K_1 can be observed for the small catchments, while for the larger ones it is more difficult to recognize any pattern. K_2 shows some relation to the catchment size for the whole sample. When relating parameters to the wet area, p_w, it is important to note that net inflow, according to eq. 6.1, was modelled in the Kultsjön, Malgomaj and Ströms Vattudal catchments, which means that p_w must be reduced to a rather small figure, as the reservoir is representing the major part of the lakes. The only conclusion as concerns lakes is therefore their drastic effect on the recession coefficients, B_{max} and C_{route} in the Gimdalsbyn catchment.

C_{perc} is a parameter which is surprisingly stable in all catchments. It is also the experience that C_{perc} causes a minimum of trouble when fitting the model. Due to its small variability it is hard to relate the parameter to any of the catchment characteristics presented in table 7.13 or 4.1.

The distinction in fig. 7.21 between generation of runoff and transformation of the hydrograph with a time-area concept was given a critical discussion by Bergström and Jönsson (1976 B). The main point was that if the concept was true, the recession coefficients would be independent of the catchment size, as all areal effects would be handled by the time-area function. The pattern in table 7.13 is rather irregular, but there seems to be some increase of the coefficients with very small basins, a result supported by a work by Persson (1976). Instead of firmly sticking to the time-area concept, it might therefore be less hazardous to regard the response function as a wholeness which accounts for the whole conglomerate of runoff processes on the ground, in the ground, and down through the system of streams, rivers and lakes without any specification of each individual process.

7.4. Computational details

All the computations in the model are carried out on a daily basis. Daily totals of precipitation or snowmelt are fed into the soil moisture zone, and daily totals of discharge are leaving the transformation function.

In the computor program amounts of water are processed through the different procedures in the same order as they are shown in fig. 7.1. In the soil moisture zone the separation between contributions to runoff and soil moisture storage shown in fig. 7.13 caused problems due to the nonlinear character of the function. Therefore precipitation and snowmelt are fed into this routine mm by mm with subsequent adjustments of the soil moisture state.

In the evaporation routine actual evaporation is estimated from the arithmetic mean of the computed soil moisture conditions before and after the processing of rain or snowmelt. Actual evaporation is further reduced in proportion to the number of elevation zones with snowcover, so that evaporation will cease completely, if the entire catchment is modelled as snowcovered.

In the upper zone C_{perc} is satisfied before any runoff is computed, and in the lower zone the contribution from the upper zone, precipitation and evaporation are accounted for before the outflow is computed. Of course it can be argued that recharge and outflow of the lower zone should be more integrated, but, due to the slow response of this zone, the long term effects of recharge and evaporation are more important than are their time of occurrance during one day.

When distributing the model according to the area-elevation curve of the catchment, the position of the lakes is important for the computed volumes due to the precipitation lapse parameter, P_{lapse}. So far the lakes have been treated as if they were situated in the lowest parts of all the catchments.

During the work on the variable transformation function it was found necessary not to restrict B_q to integer values, as, particularly at low B_q-values, the switch from one B_q-value to another caused discontinuities in the computed hydrograph. B_q is therefore allowed to vary continuously according to eq. 7.22, and the histogram in the damping function is computed as the area below a triangle for each specific day, as seen in fig. 7.30.

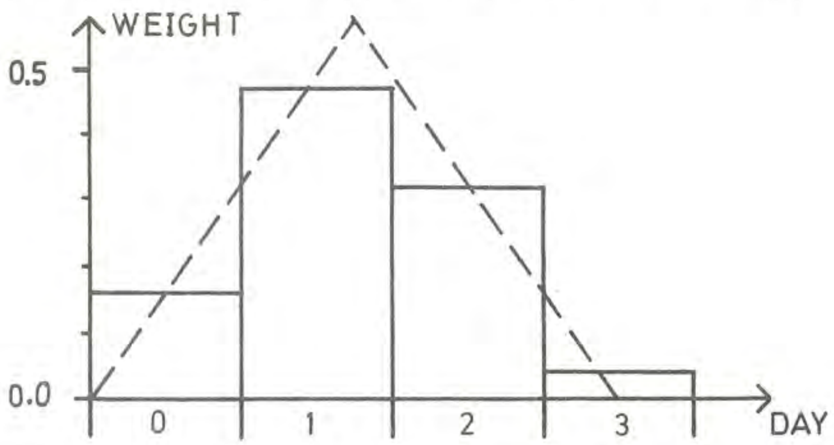


Fig. 7.30. The transformation function at B_q = 3.5.

When applying the variable transformation function, great care must be taken not to violate the principle of conservation of matter. The best way was found to be to spread out the generated runoff, Q_g, on the subsequent days according to the weights in fig. 7.30 and sum up all contributions for each day separately.

When starting a simulation some assuptions concerning the initial conditions of the different storages of the model must be made. In those catchments, where only snowfree conditions were modelled, the soil moisture storage was assumed to be filled to its capacity, Fc, as the simulations started just after the termination of the snowmelt period. In the other catchments simulations started in the autumn and the soil moisture storage was generally reduced to two thirds of Fc. This assumption may have some effect on the snowmelt volumes the following spring, a fact that is worth considering when analysing the results. Initial values of the upper and lower zones can be found quite easily from the recession coefficients and some realistic assumptions about the contributions from each zone. Erroneous initial values in these zones will be detected after the first run and can thus be corrected. If the calibration and test are made in chronological order, and throughout the year, the above problems are limited to the first year of the calibration period, as for all the consecutive periods the conditions can be transferred from the preceeding period.

The work on the HBV-model was carried out on a SAAB D 22 computer until June 1975, when this was replaced by a SAAB D 23. If organized in the above way with computations on a daily basis, the simulation of one year (365 days) requires approximately 16 seconds in the SAAB D 23. The model, however, is not larger than that it can be programmed on a modern desk calculator, which simplifies the access but increases the time for each computation.

8. APPLICATIONS

The model has so far been applied to a variety of catchments in Sweden and Norway as described in chapter 4. The main purpose has been to test the capability of the model to reconstruct a given hydrograph after calibration and to verify its performance as a forecasting tool. The simulation of discharge without any calibration, i.e. the application of the model to ungauged catchments was touched upon when testing the model in the Filefjell basin (Bergström and Jönsson, 1976 B). The results looked promising but more experience will be needed before this can be made on a routine basis.

8.1. Reconstruction of the hydrograph

In appendix 1 a sample of simulated hydrographs is shown together with recorded discharge. The time periods used in the applications to Gimdalsbyn, Kultsjön, Malgomaj and Ströms Vattudal are beginning on the first of October and ending on the 30th of September in order to avoid carry over effects due to snow storage. For the same reason the simulations in Filefjell start on the first of September. Among all test catchments Solmyren stands out as difficult to model (fig. A 13) having poor representation of the recession limbs. The response function of the HBV-2 model is evidently too simple for this complex hydrograph. A study of the hydrological conditions of the different subcatchments in Solmyren carried out by Häggström, Jansson, Runesson and Simonides (1972) showed that the runoff characteristics are highly variable, which results in a hydrograph with several runoff components.

In some of the small catchments, the model tends to overestimate the runoff in autumn (for example fig. A 4 , A 5 and A 9), a problem which might be caused by the crude soil moisture accounting procedure, but evaporation data as a source of error cannot be neglected.

The independent test period in the Gimdalsbyn catchment (fig. A 16) shows a flood in summer, which is poorly modelled. No explanation for this has been found but poor parameter estimates cannot be excluded, as no counterpart to this flood occurred in any of the summer periods used for calibration.

The plottings from Kultsjön, Malgomaj, Ströms Vattudal and Filefjell are showing the conditions in the different parts of the model during the simulation as graphs of snowpack, snowcovered area, yield from the snow routine, soil moisture storage and evaporation (fig. A17 - A 21). In the three catchments of Kultsjön, Malgomaj and Ströms Vattudal the model was applied for operational purposes. Therefore a rather low density of meteorological stations and poor runoff data had to be accepted. Particularly the Malgomaj catchment is poorly covered (Bergström and Jönsson 1976 A), which is reflected in the performance of the model (fig. A 18).

The question of how large catchments we can model with one model structure is of vital importance if our aim is to develop a model which is easy to handle and simple to calibrate. The application of the HBV-2 version to the Kultsjön and Malgomaj catchments created the opportunity to study this problem (Bergström and Jönsson, 1976 A). The model was therefore re-calibrated for the entire catchment area as one model with identical meteorological stations as when calibrating the two catchments separately. It was found that the HBV-3 version gave the best results, as a third runoff component was detected. The results, compared to those obtained after the calibration and the test of each catchment separately, are shown in table 8.1.

Table 8.1. Comparisons between the application of one model and two models to the Kultsjön and Malgomaj catchments. Independent test periods underlined.

	R^2		
	1962 - 1966	1966 - 1970	1970 - 1974
One model	0.8184	0.8701	<u>0.8648</u>
Two models	0.8436	0.8796	<u>0.8834</u>

The results in terms of R^2-values in table 8.1 are in agreement with the impressions from visual inspection of the hydrographs. They are interesting as they show that we can extract more information and thus obtain a better model if we have the possibility to split the catchment into sub-catchments. The independent test period for the separated application is shown in appendix 1, fig. A 19.

8.1.1. R^2-values

A summary of the results in all test catchments expressed as R^2-values according to eq. 5.3 is shown in table 8.2.As discussed in chapter 5.1.1, this can be a misleading criterion of fit, especially if the period is short and the climatic variability is high. This is the situation in some of the small catchments, resulting in highly variable and sometimes discouraging R^2-values (for example Stabby 1959 and 1963, Stormyra 1964).

Table 8.2. Results from the test catchments, expressed as R^2-values.

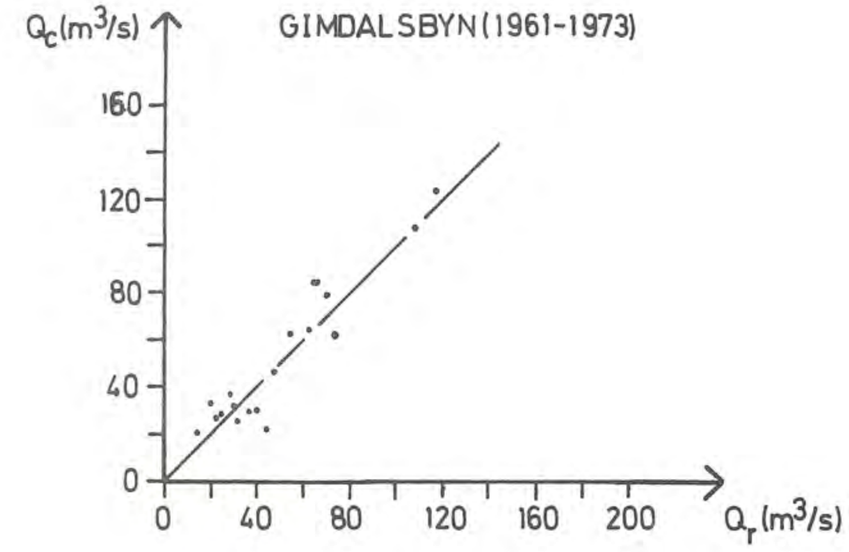
Catchment	Period	Calibration	Test	R^2
Lilla Tivsjön	1969	x		0.98
	1968		x	0.84
	1967		x	0.97
Nolsjön	1971	x		0.81
	1970	x		0.91
	1969		x	0.97
	1968		x	0.90
	1967		x	0.88
Stabby	1959	x		- 0.64
	1960	x		0.93
	1961	x		0.80
	1962		x	0.76
	1963		x	- 0.90
	1964		x	0.84
	1965		x	0.93
	1966		x	0.64
	1967		x	0.62
Stormyra	1963	x		0.87
	1964	x		- 0.24
	1965	x		0.77
	1966	x		0.63
	1967		x	0.61
	1968		x	0.10
	1969		x	0.42
Solmyren	1971	x		0.91
	1970		x	0.80
	1969		x	0.73

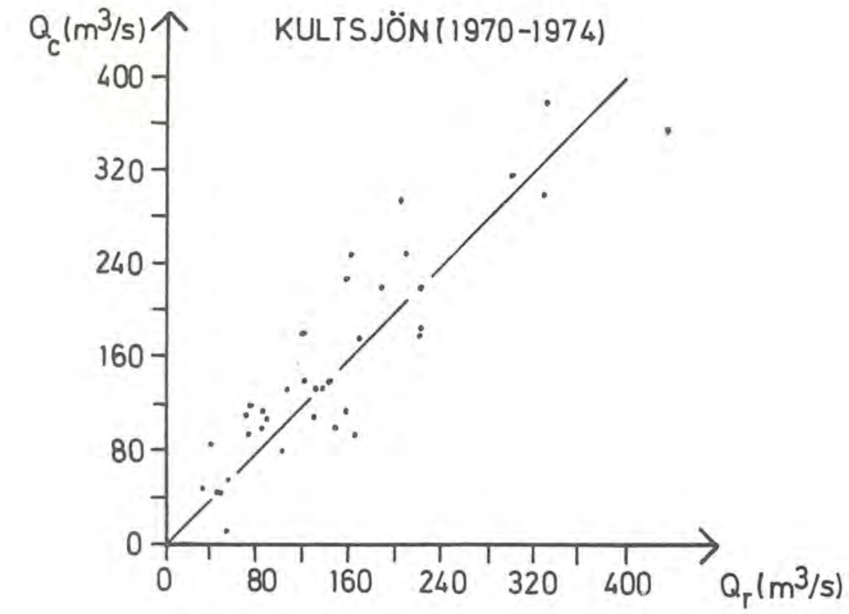
Catchment	Period	Calibration	Test	R^2
Gimdalsbyn	1961-65	x		0.86
	1965-69	x		0.91
	1969-73		x	0.86
Kultsjön	1962-66	x		0.80
	1966-70	x		0.87
	1970-74		x	0.84
	1974-75		x	0.89
Malgomaj	1962-66	x		0.79
	1966-70	x		0.83
	1970-74		x	0.79
Kultsjön + Malgomaj	1962-66	x		0.84
	1966-70	x		0.88
	1970-74		x	0.88
Ströms Vattudal	1962-66	x		0.84
	1966-70	x		0.88
	1970-74		x	0.88
Ströms Vattudal	1962-66	x		0.84
	1966-70	x		0.90
	1970-74		x	0.83
	1974-75		x	0.91
Filefjell	1967-71	x		0.88
	1971-74		x	0.86

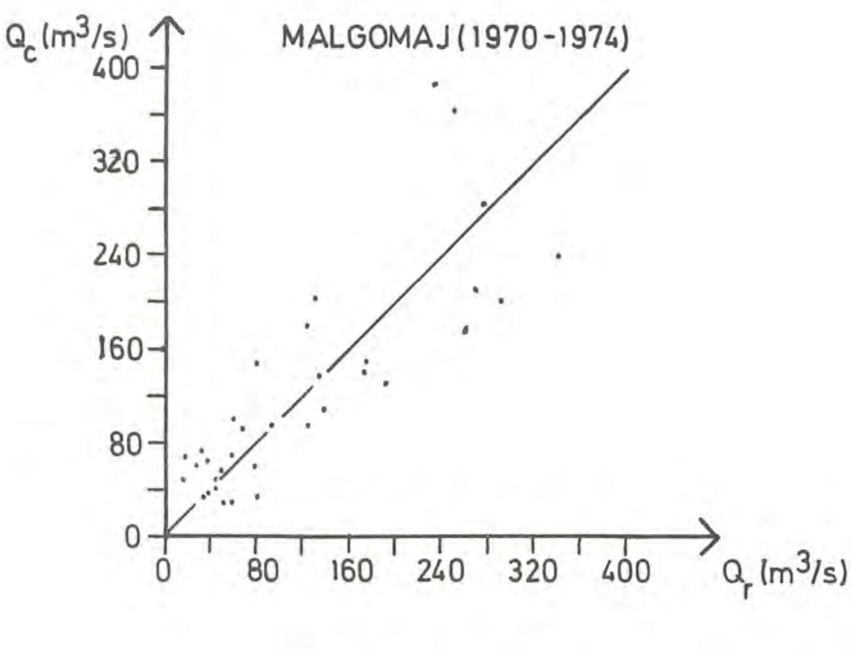
8.1.2. Scatter diagrams of peak flows

A scatter diagram of peak flows is a plotting of computed peak flows against observed peak flows as described in chapter 5.1.3. Such diagrams have been constructed for independent test periods in the Kultsjön, Malgomaj, Ströms Vattudal and Filefjell catchments. In Gimdalsbyn the total period for calibration and test of the model was used in order to increase the sample size.

Only fairly distinct peaks have been analysed, and minor timing errors between the computed and observed discharges have been ignored. The results are presented in fig. 8.1.


GIMDALSBYN (1961-1973)
$Q_c (m^3/s)$
0
40
80
120
160
0
40
80
120
160
200
$Q_r (m^3/s)$


KULTSJÖN (1970-1974)
$Q_c (m^3/s)$
0
80
160
240
320
400
0
80
160
240
320
400
$Q_r (m^3/s)$


MALGOMAJ (1970-1974)
$Q_c (m^3/s)$
0
80
160
240
320
400
0
80
160
240
320
400
$Q_r (m^3/s)$

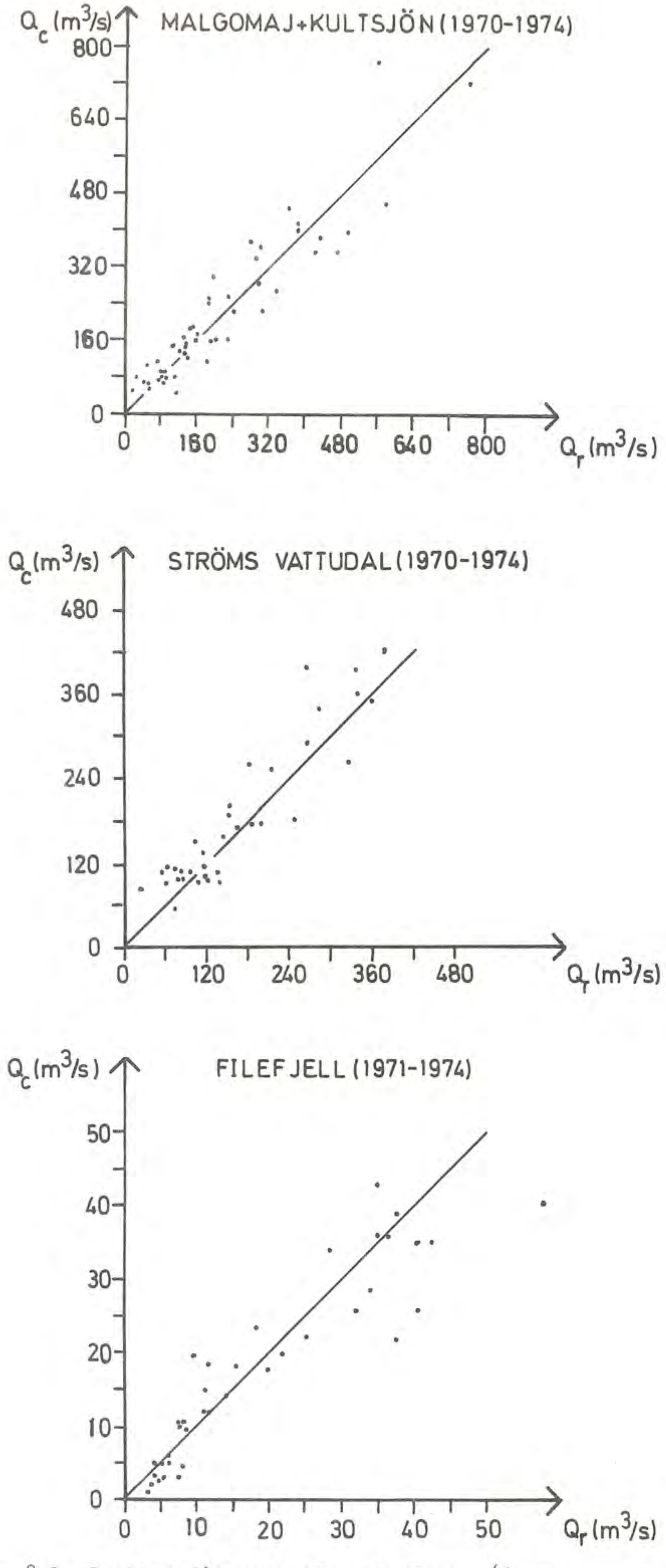


Fig. 8.1. Scatter diagrams of peak flows. (Q_c = computed discharge, Q_r = observed discharge.)

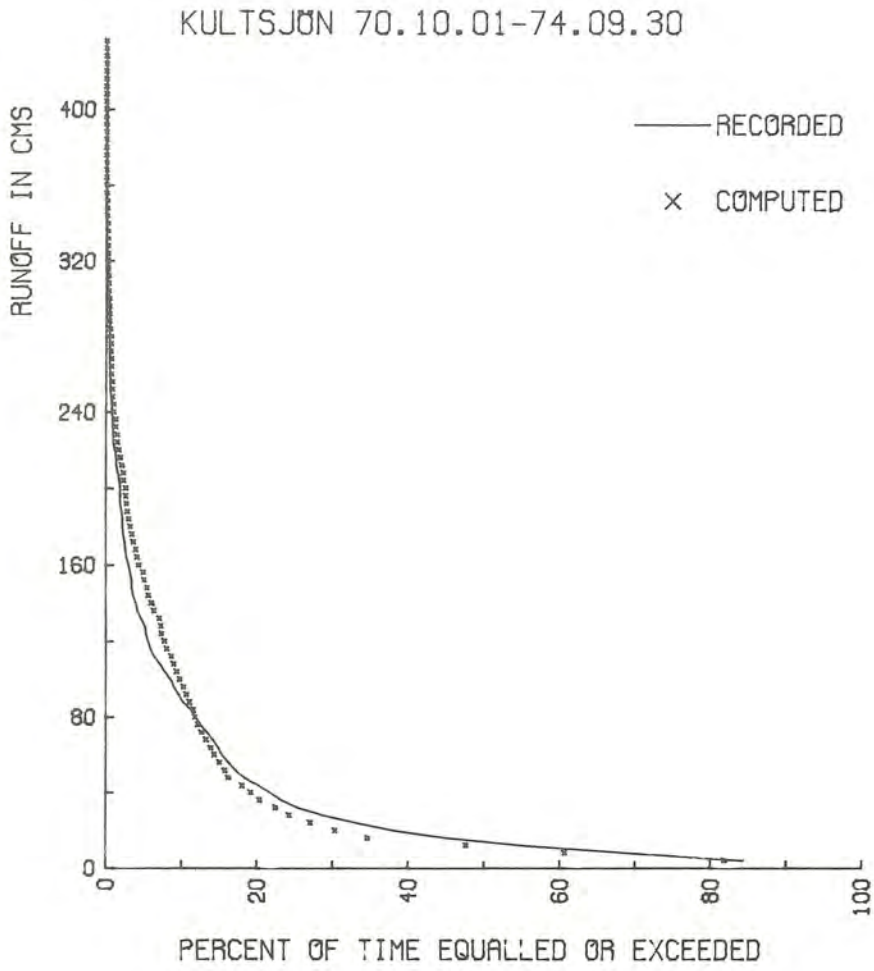
Two catchments, Malgomaj and Filefjell, are standing out as difficult to model as far as flood peaks are concerned. In the Filefjell catchment the model underestimates high peaks while in Malgomaj the bias is less pronounced.

8.1.3. Flow duration curves

A flow duration curve is a graphical representation of the cumulative relative frequency of runoff. Such curves have been established and compared for the computed and observed hydrographs in the Kultsjön, Malgomaj, Ströms Vattudal and Filefjell catchments. Only independent test periods have been analysed. They are shown in fig. 8.2.

It is interesting to analyse the flow duration curves, the scatter diagrams and the plotted hydrographs simultaneously. The agreement between the flow duration curves look very good for Malgomaj and Ströms Vattudal, which, particularly for Malgomaj, is in conflict with the conclusion when analysing the scatter diagrams. It is obvious that the analysis of flow duration curves requires careful attention, if conclusions concerning high flows are to be drawn. A combination of flow duration curves and scatter diagrams of peak flows is preferable. A further observation is that all graphs show a slight bias on the low side at low flows, which is worth attention in future applications.

Neither scatter diagrams nor flow duration curves have been used when calibrating the model. In future work they will, however, be incorporated in the calibration process, as they have proved to give valuable additional information about the performance of the model and as they are very easy to analyse.



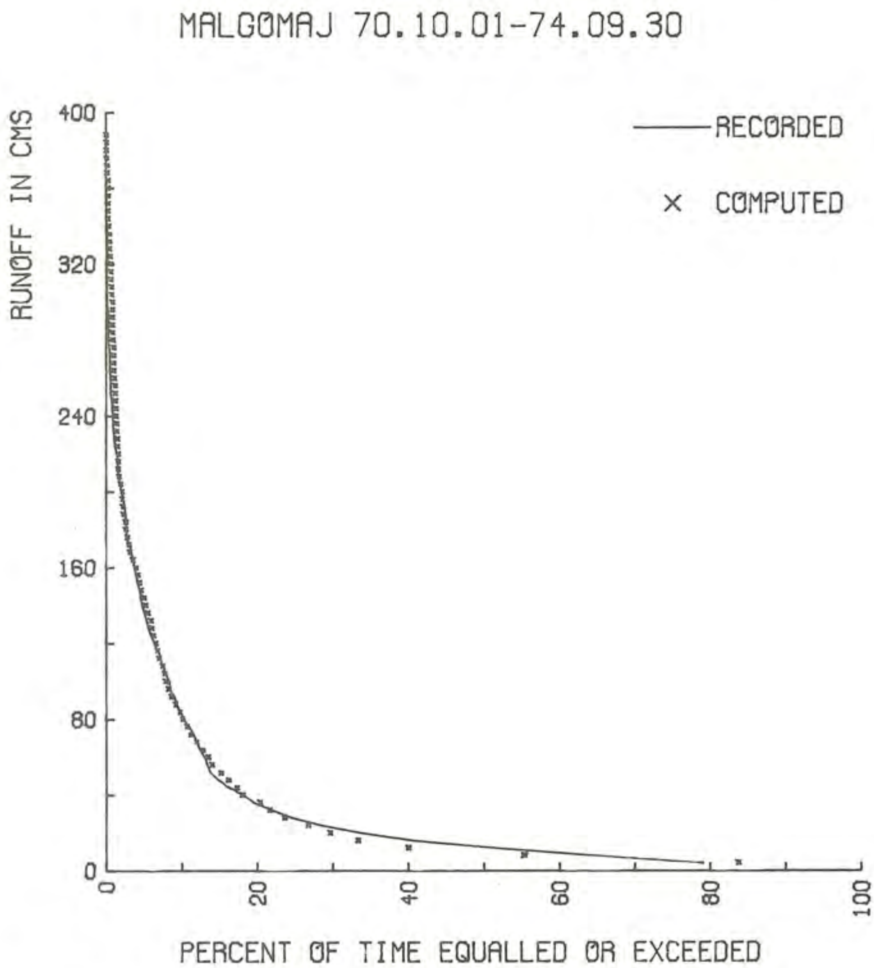
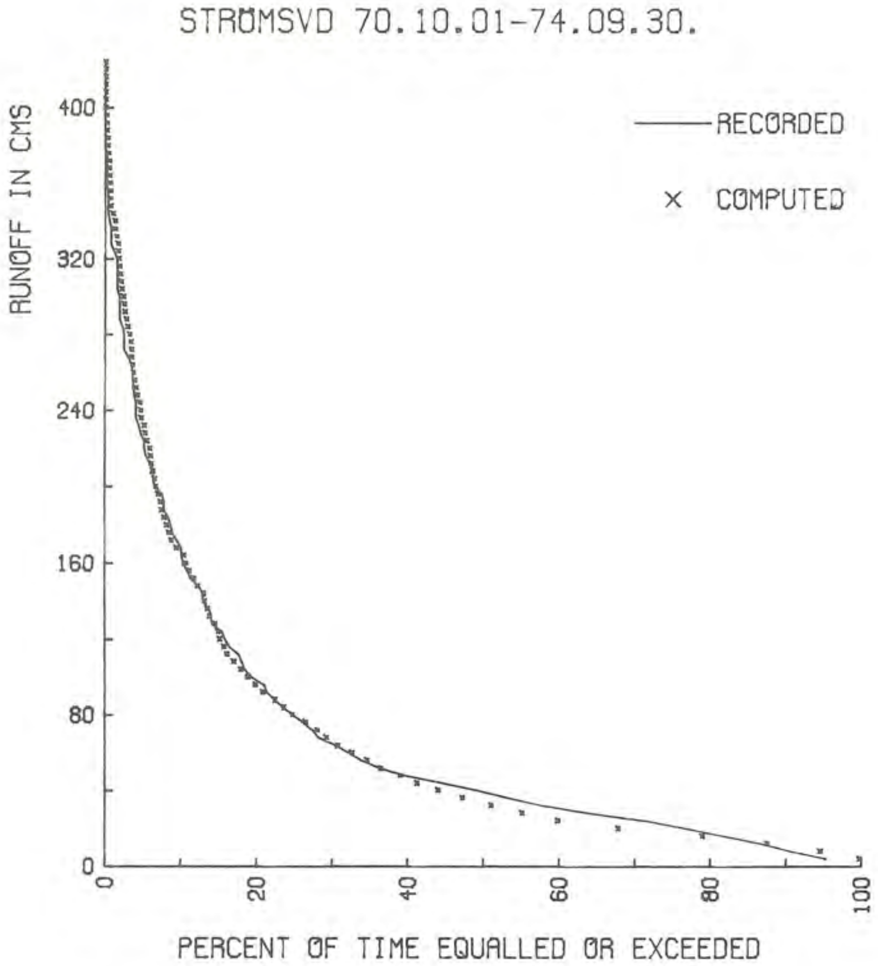


Fig. 8.2. Flow duration curves. (CMS = m^3/s.) (Continued)



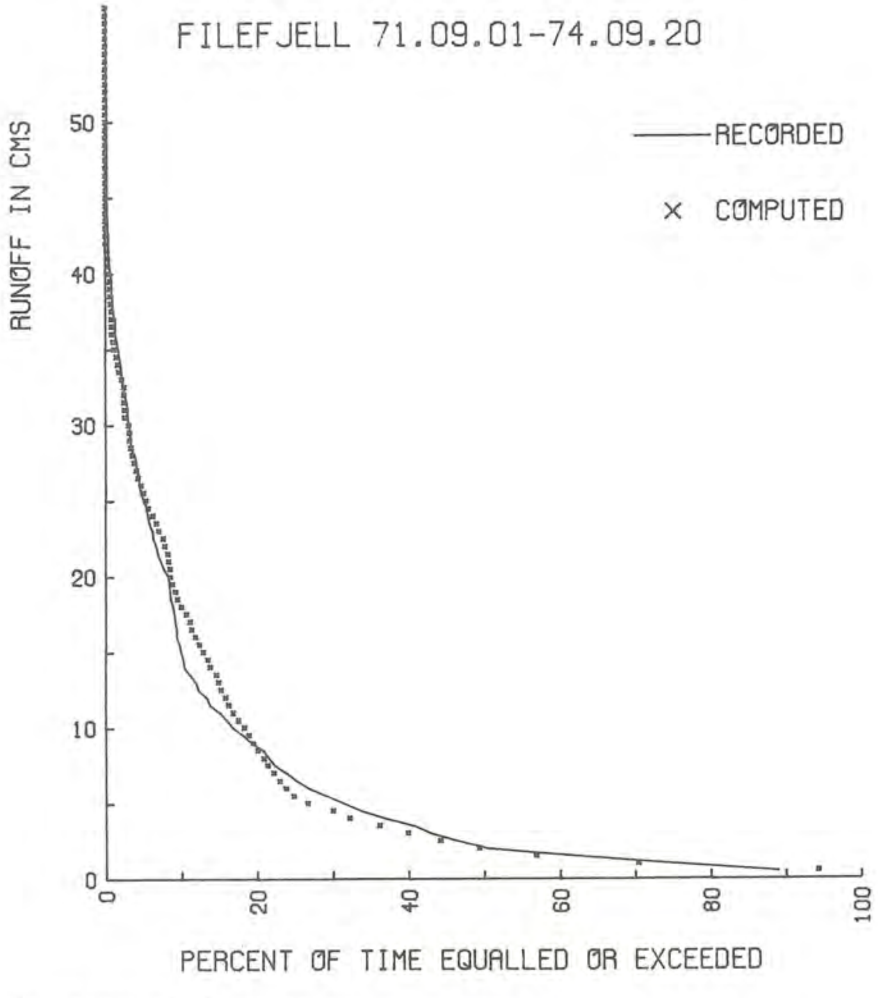


Fig. 8.2. (Continued) Flow duration curves.

8.2. Hydrological forecasting

Hydrological forecasting means the utilization of hydrological and meteorological information for the prediction of future discharge of a river. One way of doing this is by means of a conceptual runoff model, historical climate series and a weather forecast as indicated in fig. 8.3.

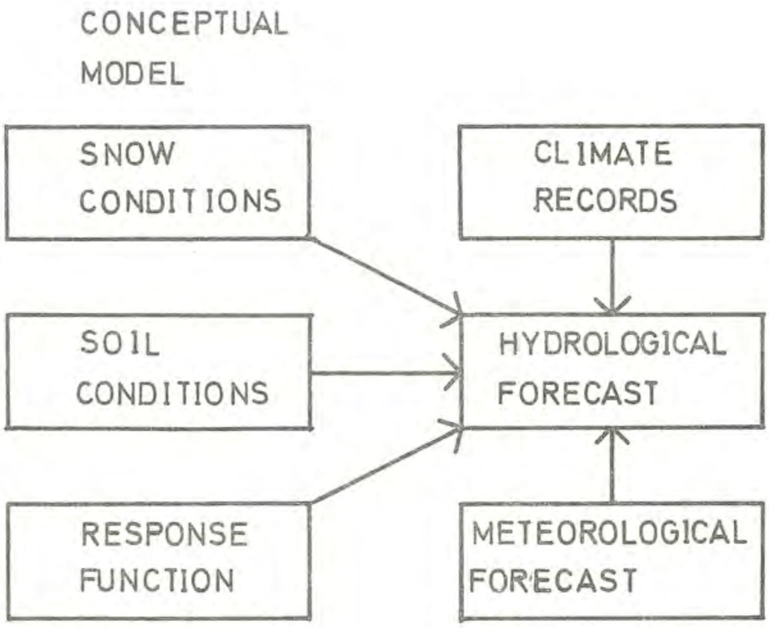


Fig. 8.3. The main factors in a hydrological forecast.

The conceptual model is accounting for the memories and dynamics of the hydrological system and is thus restricting the possible effects of future meteorological conditions. The historical meteorological series can be used for long or short range forecasts by the simulation of possible alternative outcomes. Weather forecasts can be used for short range hydrological forecasts, i.e. in Sweden five days or less, or for the simulation of the first days of a long range forecast.

The relative importance of each factor in fig. 8.3 is highly variable from catchment to cathment and from season to season. If a catchment has a damped response, such as in the Gimdalsbyn catchment, the potential for a successful forecast is good, as visualized in fig. 8.4. which gives the results by the HBV-model run with four different climate series starting from identical initial conditions.

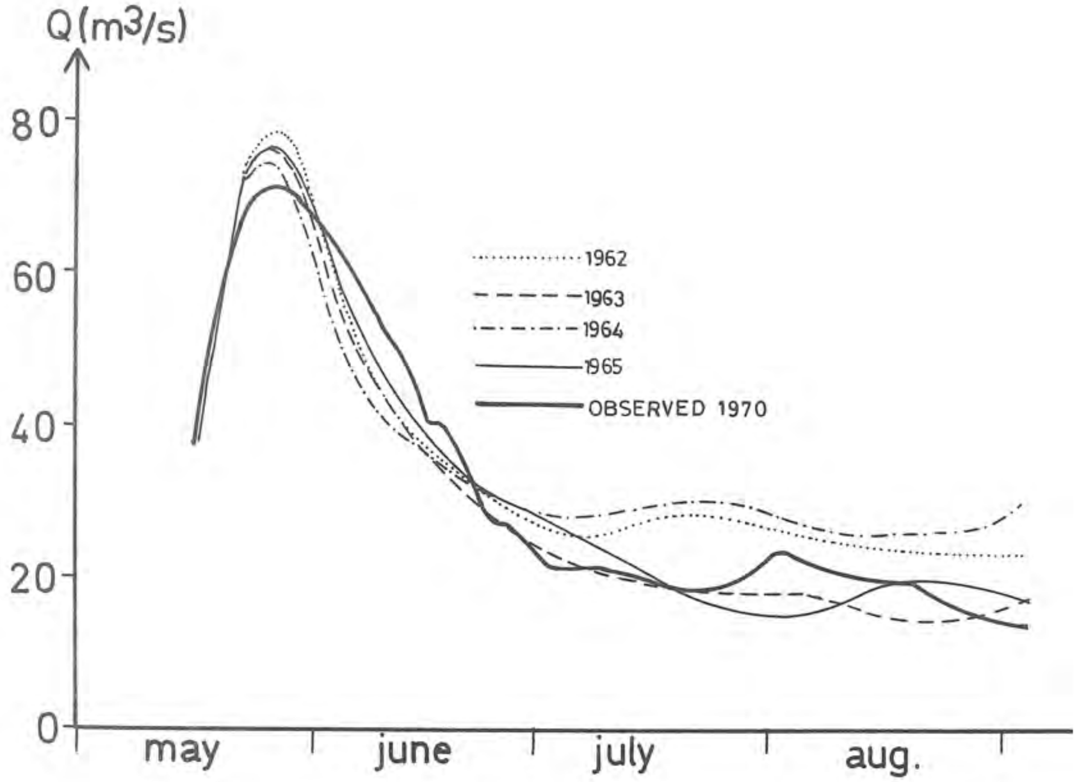


Fig. 8.4. Hydrograph response to different meteorological conditions in a damped catchment. Gimdalsbyn (1970).

The dynamics of the response function was the dominating factor, and therefore the different meteorological conditions had little effect on the hydrograph until the springflood had passed.

The opposite situation, in the Ströms Vattudal catchment, is illustrated in fig. 8.5. The same procedure as above was repeated, but the meteorological conditions strongly effected the shape of the springflood. In the latter case the importance of the meteorological forecast is obvious, but the accumulated snowpack is still a limiting factor.

Fig. 8.4 is an indication of the importance of correct initial conditions in the different components of the model as they may have a dominating influence on the future computed hydrograph. Therefore, before going any further into forecasting procedures, the problem of adjustments of these conditions will be discussed.

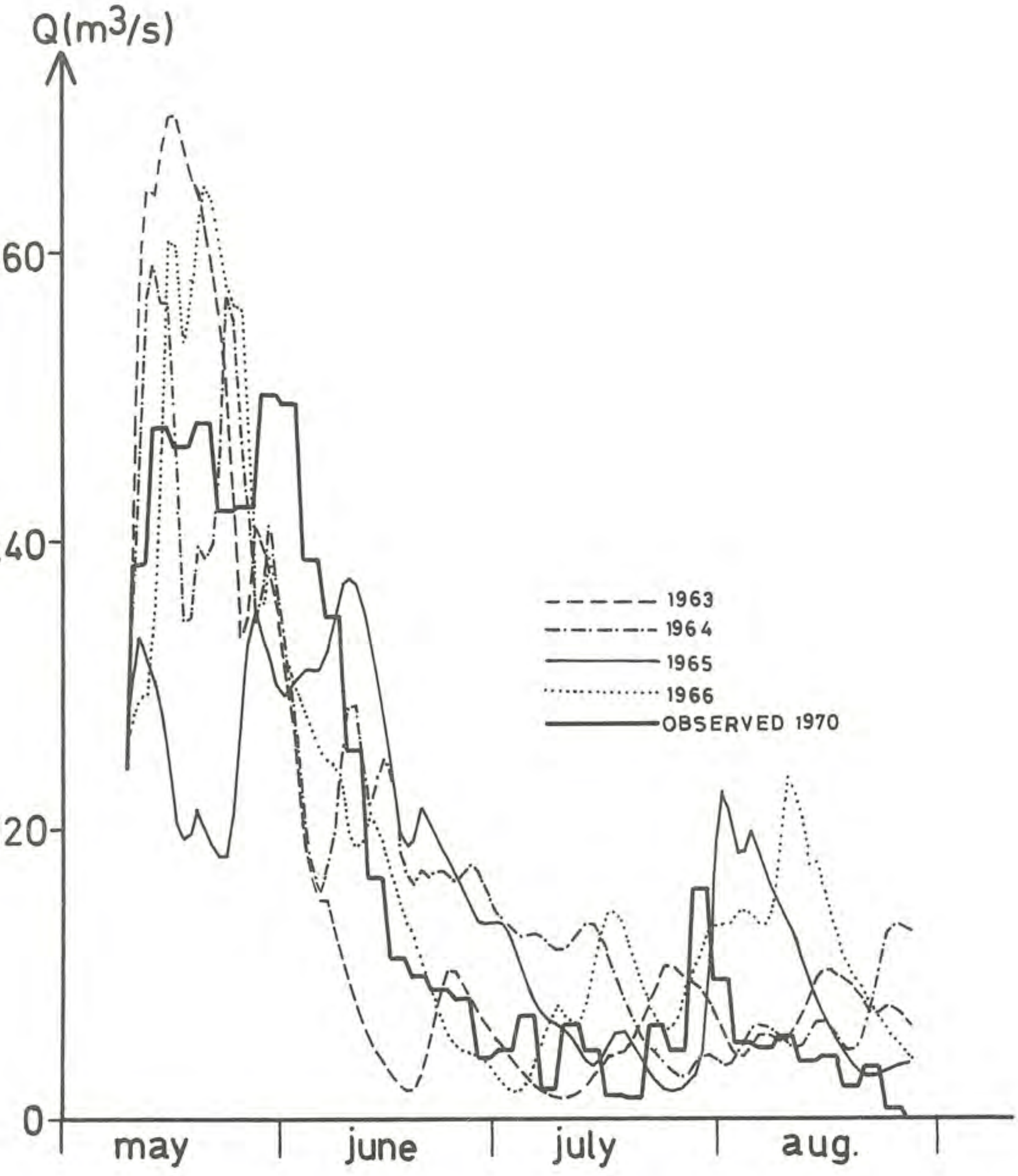


Fig. 8.5. Hydrograph response to different meteorological conditions in a weakly damped catchment (Ströms Vattudal, 1970).

8.2.1. Updating

If the forecast is initiated with erroneous discharge values, that is with improper state in the response function, the persistance will cause systematic errors in the forecast for a period of time which is depending on the characteristics of the hydrograph. If the snowmelt routine has overestimated the melt for a part of the snowmelt season, the remaining period is likely to be underestimated as the snow budget is biased. Furthermore, if the model has overestimated a rainflood because of poor precipitation data, the next flood is likely to be overestimated, too, due to improper conditions in the soil moisture zone. The updating routine is a means by which erroneous model conditions are corrected in order to avoid errors of the above type. One can say that knowledge of the observed discharge is used to adjust the memories of the conceptual model (fig. 8.3) in order to improve its future performance.

When updating the model the possibilities to adjust the free parameters in the model are small, as these have been found through calibration over a long period and shall be regarded as time-invariant for each specific catchment. The adjustment of the conditions in the response function is a more tempting possibility, as we can figure out, fairly well, the corrections needed by looking at the recession coefficients. The method has its drawback, however, in the fact that the deviation might be caused by errors in precipitation or in the snowmelt routine thus effecting the snowpack and the soil moisture storage as well.

The simplest and safest way is to assume that all the errors originate from the input, precipitation, temperature or evaporation. Automatic methods to correct these have been sought when working on the HBV-model, but again a quasi-automatic method with visual inspection as an important source of information has been considered the best way to solve the problem. Simultaneous inspections of the hydrographs, the records of temperature and precipitation together with computed snowpack are used in the search for the cause of the deviation and the period during which to correct the data. Once this is determined, the model is repeatedly restarted from a given date with an automatic routine adjusting the data in small steps until an acceptable agreement is obtained. If the initial discharge value is the main problem, the deviation on this single day can be used as criterion of fit. If, for example, during a snowmelt period, we want to delete an erroneous peak in order to correct the snowpack, the R^2-value can be used in the search for the best corrections.

An example of updating in the Gimdalsbyn catchment is shown in fig. 8.6. The springflood was overestimated, which was corrected by reduction of the precipitation for some period during snow accumulation. The timing of the flood was finally corrected slightly by adjustments of the temperature values.

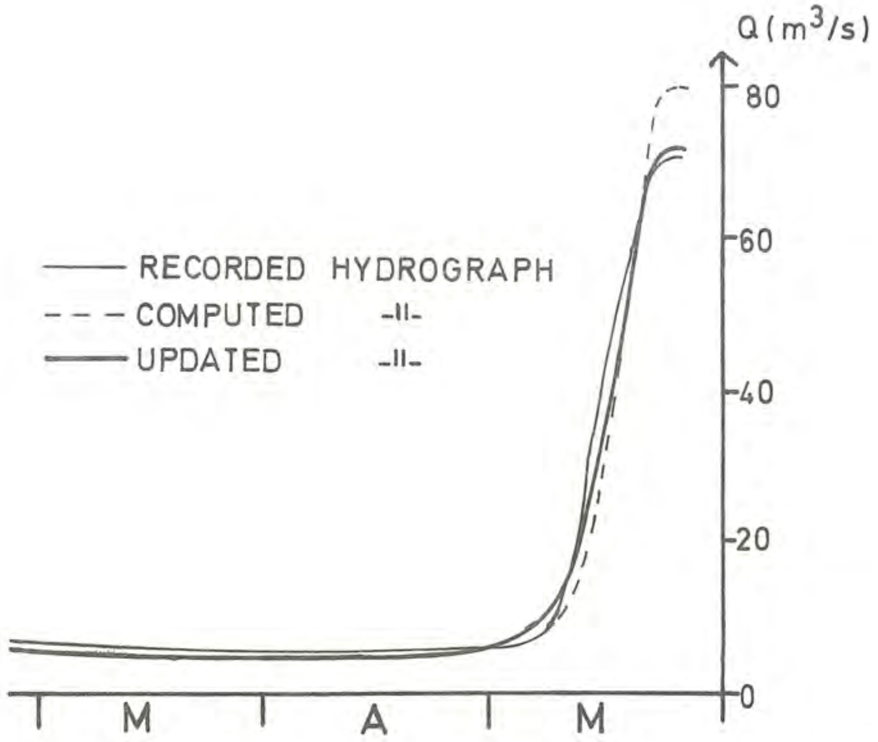
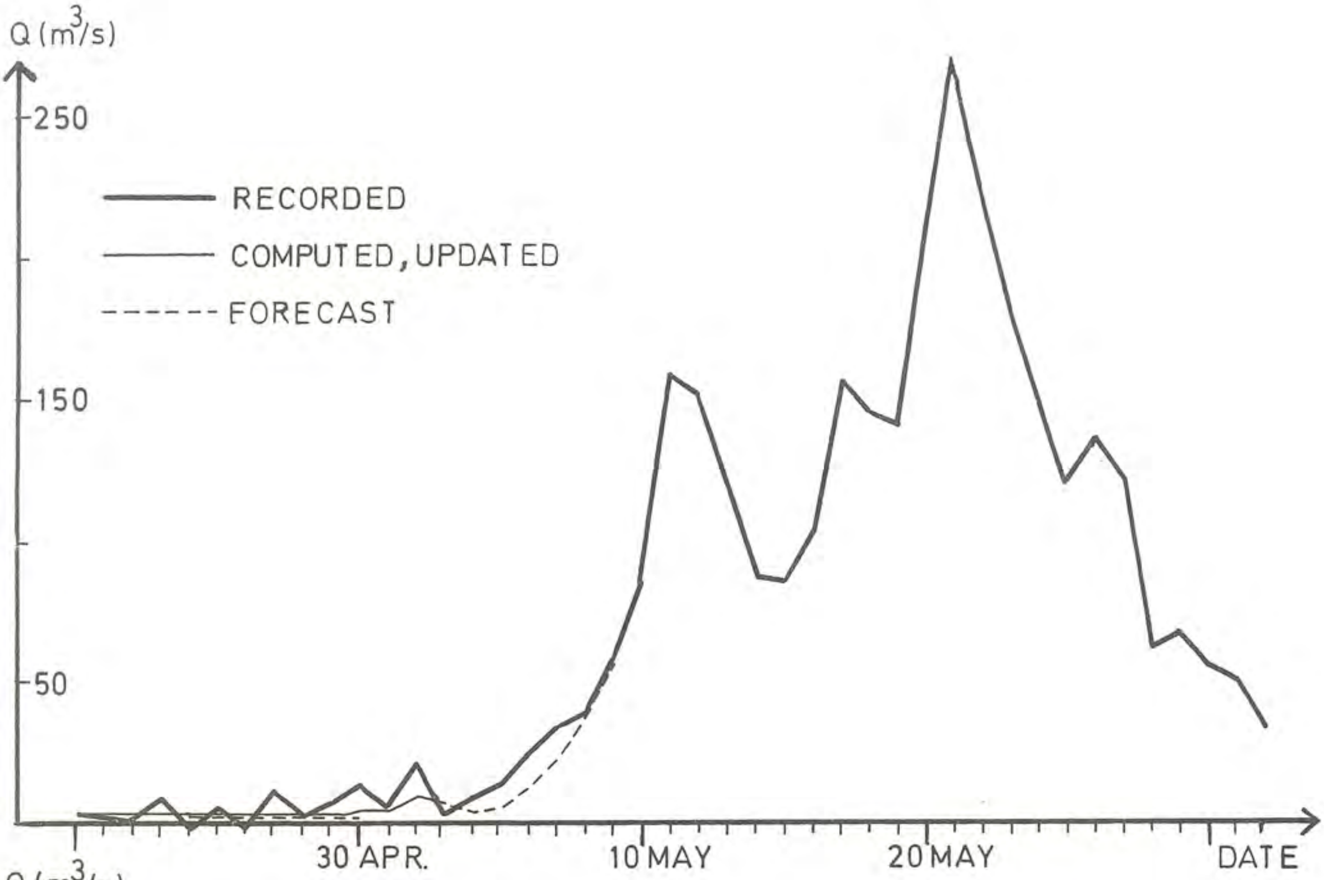


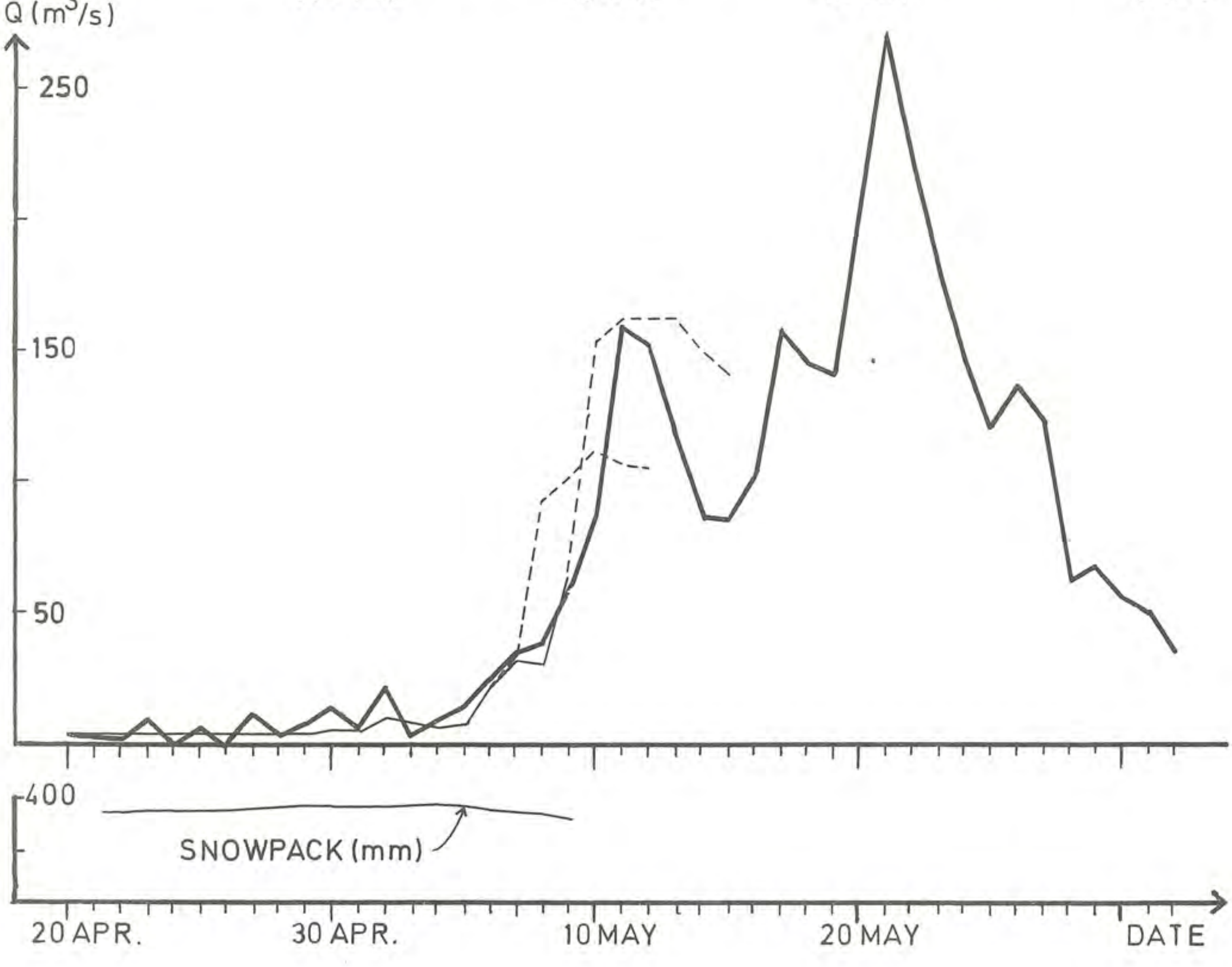
Fig. 8.6. Example of updating (Gimdalsbyn, 1970).

8.2.2. Short range forecasting

Short range forecasts were carried out with the HBV-model as a case study in the Kultsjön catchment (Bergström and Jönsson, 1976 A). Input to the model were forecasted temperature and precipitation values obtained from a barotropic meteorological model at the SMHI. This model delivers forecasts of five days' duration for a number of meteorological stations in Sweden. Unfortunately the network is not very dense, and the coverage of Kultsjön is rather poor. The case study was based on meteorological forecasts in Storlien about 250 km from the Kultsjön catchment. The temperatur values were corrected by a long term relation between Storlien and Klimpfjäll, the temperature station in the Kultsjön catchment. No such correction was carried out for the precipitation values, but this would have been more appropriate, as the average catch in Storlien is higher than that of the stations used in the application to the Kultsjön catchment.

The springflood in 1975 and an extreme flood in September the same year were subjects to the investigation. The results from sequences of forecasts


Q (m³/s)
250
150
50
RECORDED
COMPUTED, UPDATED
FORECAST
30 APR.
10 MAY
20 MAY
DATE


Q (m³/s)
250
150
50
400
SNOWPACK (mm)
20 APR.
30 APR.
10 MAY
20 MAY
DATE

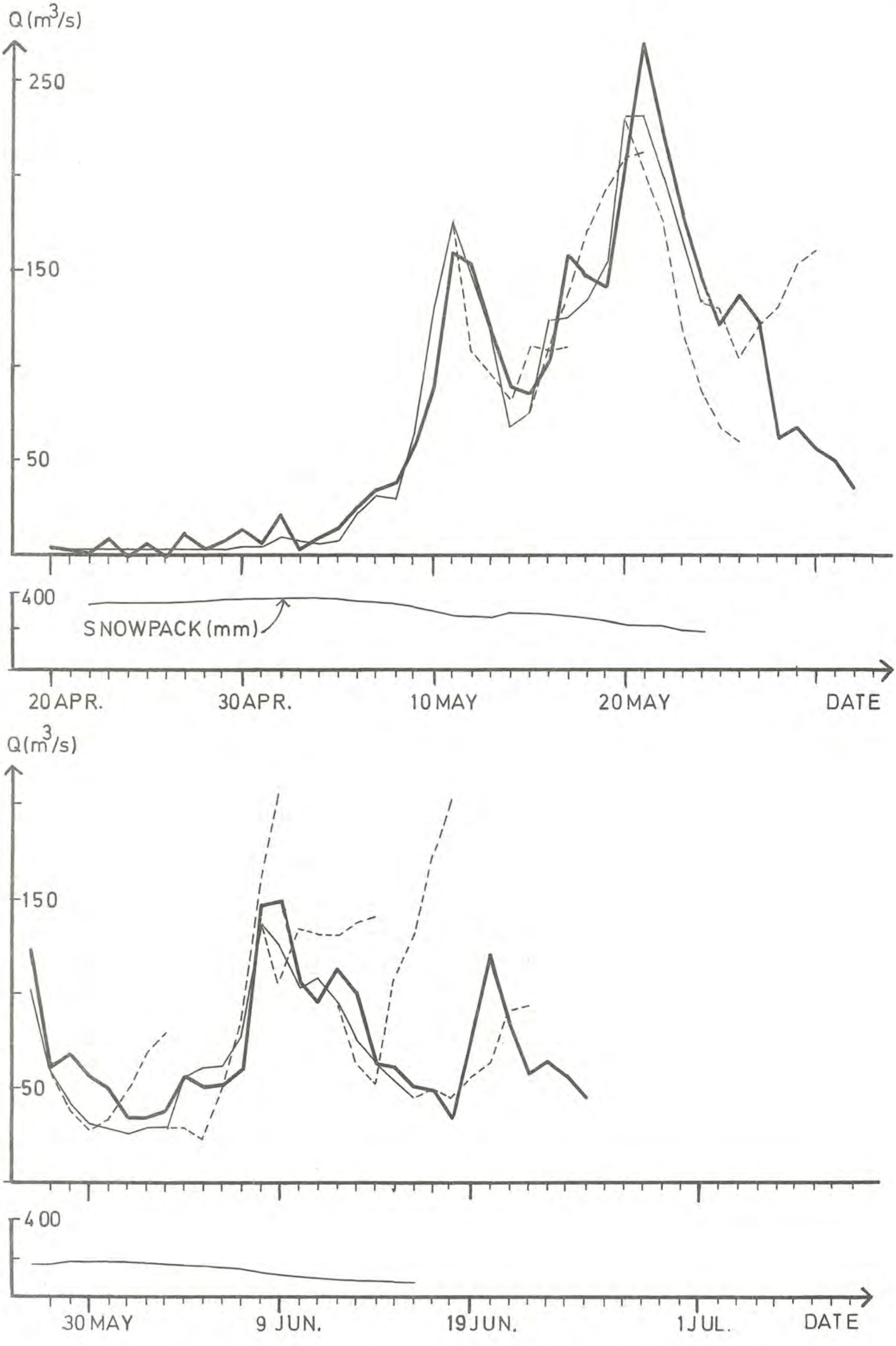


Fig. 8.7. Short range forecasts of inflow to the Kultsjön reservoir in the spring of 1975. (Computed snowpack in water equivalents.)

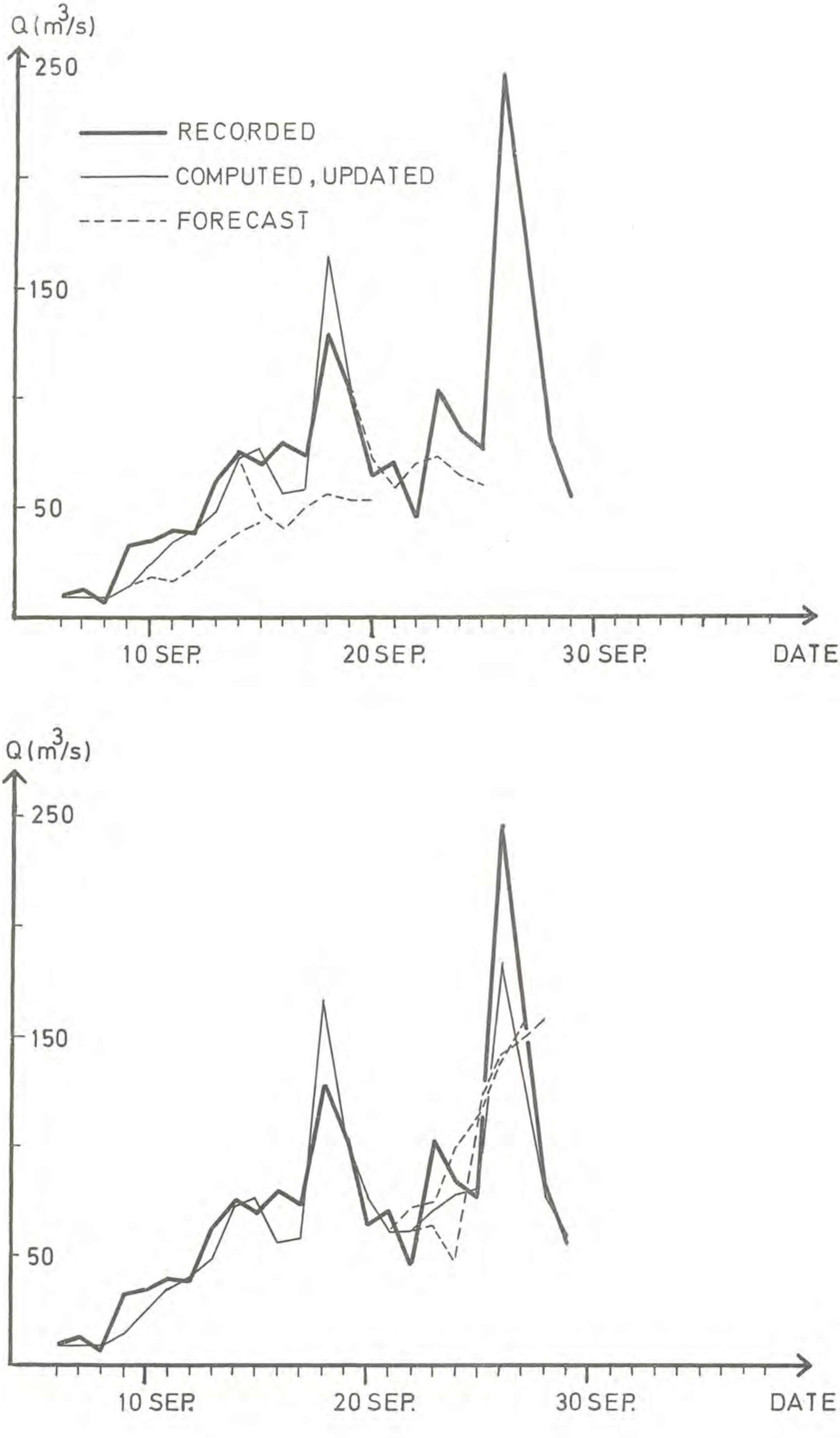


Fig. 8.8. Short range forecasts of inflow to the Kultsjön reservoir in September 1975.

are presented in fig. 8.7 and 8.8. The springflood was predicted fairly well as long as snowmelt was dominating, while uncertain precipitation forecasts caused problems for both periods. The long distance to the meteorological station, on which the forecasts were based, makes the precipitation values very uncertain. In these applications they would hardly be any better with a correction factor, accounting for the systematic deviations in catch. The temperature has a much more favourable spatial correlation pattern and is thus easier to forecast. When analysing the results it must be born in mind that the Kultsjön catchment is an extreme one because of its quick response. Therefore the forecasts are very susceptible to the meteorological input and the support by the dynamics of the response function is small.

More experience with short range forecasting will be gained in the future, as the model will be used operationally for this purpose, beginning in the spring of 1976. Particularly the calibration of the meteorological forecasting procedures to appropriate meteorological stations have to be considered.

8.2.3. Long range forecasting

Long range forecasting can be carried out along the lines touched upon in fig. 8.4 and 8.5. If the model is updated and run with alternative climate series, an array of outcomes can be obtained for further analysis. This method was applied by Danielsson and Wretborn (1975) and was used in the first tentative long range forecasts by the HBV-model in 1975 (Bergström and Jönsson, 1976 A). In the winter of 1976 the method was taken into operation for the prediction of springflood volumes in the Ströms Vattudal and Kultsjön catchments.

An example of a long range forecast, issued on the 1st of March and stretching to the 31st of July, is shown in fig. 8.9. Meteorological data from the corresponding period of the years 1962 - 1975 were used. The extreme low curve is a simulation with temperatures according to the year 1975 and with zero precipitation in order to arrive at a lower boundry.

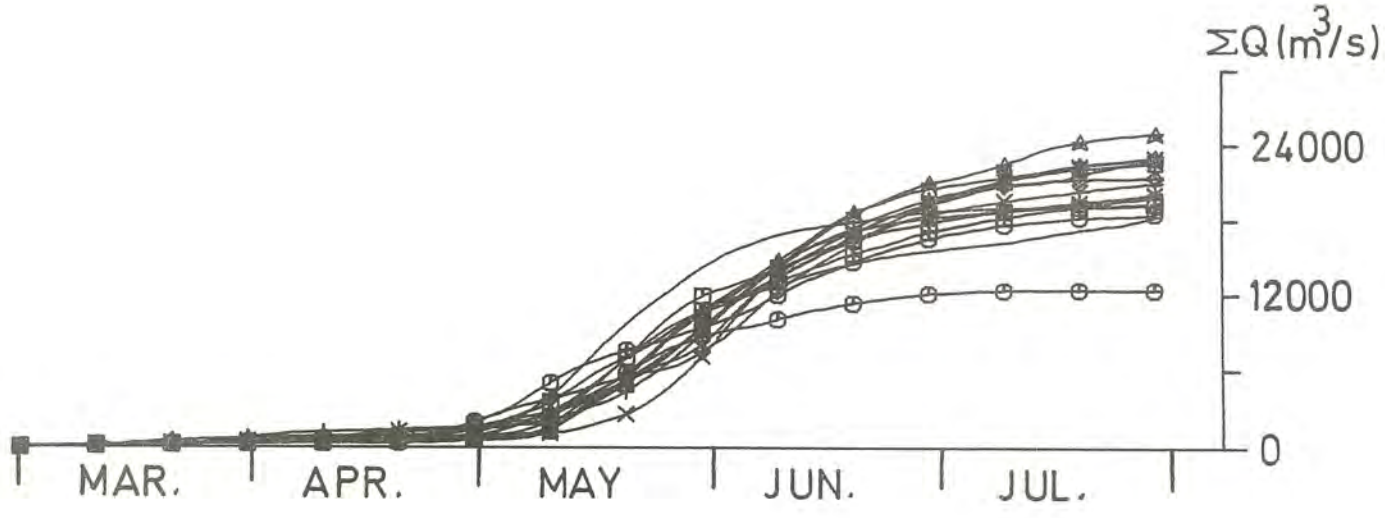


Fig. 8.9. Long range forecast of inflow to the Ströms Vattudal reservoir in 1976.

A forecast of the above type can be of good help when operating a reservoir, but the outer limits must be treated with care. If, for a moment, we neglect the effect of poor model performance and erroneous data for the forecasted period, two principle sources of uncertainty have to be considered in the forecast. One is the climatic variability, which is well reflected in the distributions of outcomes from the simulations. Another effect is the one of biased initial conditions in the model, which cannot be detected by analysis of the outcomes. If, for example, the snowpack is overestimated in the model on the date when the forecast is issued, all the simulations will suffer from this. The establishment of confidence limits on the outcome is not an easy task and has not been attempted except for the determination of upper and lower extremes, based on the sample of simulated volumes.

An investigation of the reliability of the above long range forecasting procedure in the Ströms Vattudal catchment is shown in table 8.3. Data from 1962 to 1974, excluding the year subject to forecasting, were used for the establishment of the average and extreme outcomes over different periods. From the table can be seen that the observed outcomes are exceeding the high extremes for all periods in 1972 and are falling below the low extreme for one period in 1974. The poor results in 1972 are easier understood, if fig. A 20 in appendix 1 is studied. The wet period in July is somewhat extreme and had no counterpart during the same periods of the other years. This wet period has been included in the forecasts for the other years and also in the forecast in 1976 (fig. 8.9).

Table 8.3. Results from forecasts with the HBV-model in Ströms Vattudal, based on eleven years of meteorological data.

Period	HBV-2 $\Sigma Q(m^3/s)$ high	HBV-2 $\Sigma Q(m^3/s)$ mean	HBV-2 $\Sigma Q(m^3/s)$ low	Observed outcome $\Sigma Q(m^3/s)$
1971				
1.2. - 31.7.	15 800	12 960	10 250	15 570
1.3. - 31.7.	17 620	14 210	11 580	14 860
1.4. - 31.7.	16 560	13 640	10 770	14 540
1.5. - 31.7.	16 280	13 410	11 320	14 030
16.5. - 31.7.	14 290	10 650	8 330	11 130
1.6. - 31.7.	9.690	7.020	5 640	6 680
1972				
1.2. - 31.7.	17 450	14 470	11 740	18 530
1.3. - 31.7.	15 370	13 110	10 630	18 450
1.4. - 31.7.	15 560	13 240	10 490	18 070
1.5. - 31.7.	13 870	12 460	10 550	17 110
16.5. - 31.7.	11 030	9 490	7 390	17 810
1.6. - 31.7.	7 800	6 110	4 880	10 420
1973				
1.2. - 31.7.	15 470	12 480	9 780	15 400
1.3. - 31.7.	16 340	12 960	10 380	14 650
1.4. - 31.7.	14 600	11 540	8 710	13 680
1.5. - 31.7.	14 420	12 060	9 450	12 460
16.5. - 31.7.	14 900	11 270	9 000	11 050
1.6. - 31.7.	10 360	7 780	6 280	7 150
1974				
1.2. - 31.7.	20 630	17 920	14 630	14 980
1.3. - 31.7.	21 200	17 990	15 120	14 490
1.4. - 31.7.	18 610	15 810	12 690	14 260
1.5. - 31.7.	14 740	12 080	9 940	11 750
16.5. - 31.7.	12 600	9 040	6 740	9 420
1.6. - 31.7.	6 770	4 240	2 990	6 140

A very tempting approach to long range hydrological forecasting is the use of stochastic models for the generation of meteorological data to the model. Stochastic generation of temperature and precipitation is, however, a complex problem due to the involved correlation pattern between the two variables, and no such method is, according to the author's knowledge, at present in operational use.

8.2.4. Operational systems

In the spring of 1976 the HBV-model was entering an operational phase. A system for direct on-line operation of the model for the reservoirs in Kultsjön, Malgomaj and Ströms Vattudal was being developed by the Kraftdata AB in cooperation with the river regulation company (Ångermanälvens Vattenregleringsföretag) and the SMHI. Forecasts were also issued directly by the SMHI.

The rapid transmission and processing of field data is of vital importance in hydrological forecasting. This can actually be an argument for restrictions in the model on the demands of input data. So far the model is operated with manned meteorological stations, reporting the most recent data by telephone. In the future more emphasis has to be put on this problem, at least if automatic stations in remote areas are incorporated in the work, and if the number of forecasts per day is increasing.

Operational systems also require good access to computer and practical routines for updating and forecasting. Particularly the updating procedure requires a system with some built-in safety functions, as the observed field data will be manipulated. When running the model operationally it may be convenient to save data on the internal variables, i.e. the conditions in the model, at some intervals in order to be prepared for restarts in the updating procedure.

9. CONCLUSIONS

A very general but important conclusion from the work on conceptual runoff models at the SMHI is that the simulation of river flow from meteorological data can be made with surprisingly simple models. Detailed subroutines, which may be justified by field measurements, can often be greatly simplified, when incorporated into a runoff model, without any degeneration of the model performance.

The HBV-2 and HBV-3 versions of the HBV-model have proved to be capable of reconstruction of a hydrograph from data of precipitation, temperature and potential evaporation in several test catchments, if the parameters of the model are adjusted during a calibration period. Generalization of these parameters is a difficult problem due to interactions and implicit corrections. More experience is therefore needed before the HBV-model can be applied to ungauged catchments.

The model can also be used for hydrological forecasting. The performance of the model for this purpose is increased, if a reliable updating routine is incorporated for adjustments of the initial conditions of the model before performing the forecast. Meteorological forecasts and recorded climatic series can be used in short range and long range hydrological forecasts.

The model has not been used for predictions of the effects of future physical changes in a catchment. As long as the physical interpretation of some of the components of the structure is unclear, the only approach to this problem are empirical relations between parameters and catchment characteristics which requires a lot more experience of applications to catchments of different types.

Proper assessment of the parameters of the model is of outmost importance for its performance. A good model with a potential for close reconstruction of discharge will be of little value, if it is poorly calibrated. The many aspects on a good agreement between a computed hydrograph and an observed one make the use of automatic calibration and a single numerical verification criterion questionable. The calibration procedure is therefore still a rather subjective process.

The model has been used for operational hydrological forecasting since the spring of 1976. Future work will probably be concentrated both on the development of better forecasting procedures and more efficient systems for data collection, updating and forecasting. The model will also be applied to some other catchments for operational purposes. At present work is in progress on three catchments of the river Västerdalälven, the river Stora Luleälv and the river Ljusnan.

A P P E N D I X 1

PLOTTINGS OF COMPUTED AND RECORDED HYDROGRAPHS

LIST OF SYMBOLS

ACC. DIFF.	accumulated difference between the computed and the observed hydrographs.
EVP	computed actual evaporation.
MELT	yield from the snow routine (including rainfall when the ground is partly snowcovered).
P	recorded precipitation, areal means.
SM	computed soil moisture storage.
SNOWCOV	computed snow covered area.
SP	computed average snowpack.
TEMP	recorded temperature, areal means.
Q	computed and recorded discharge.

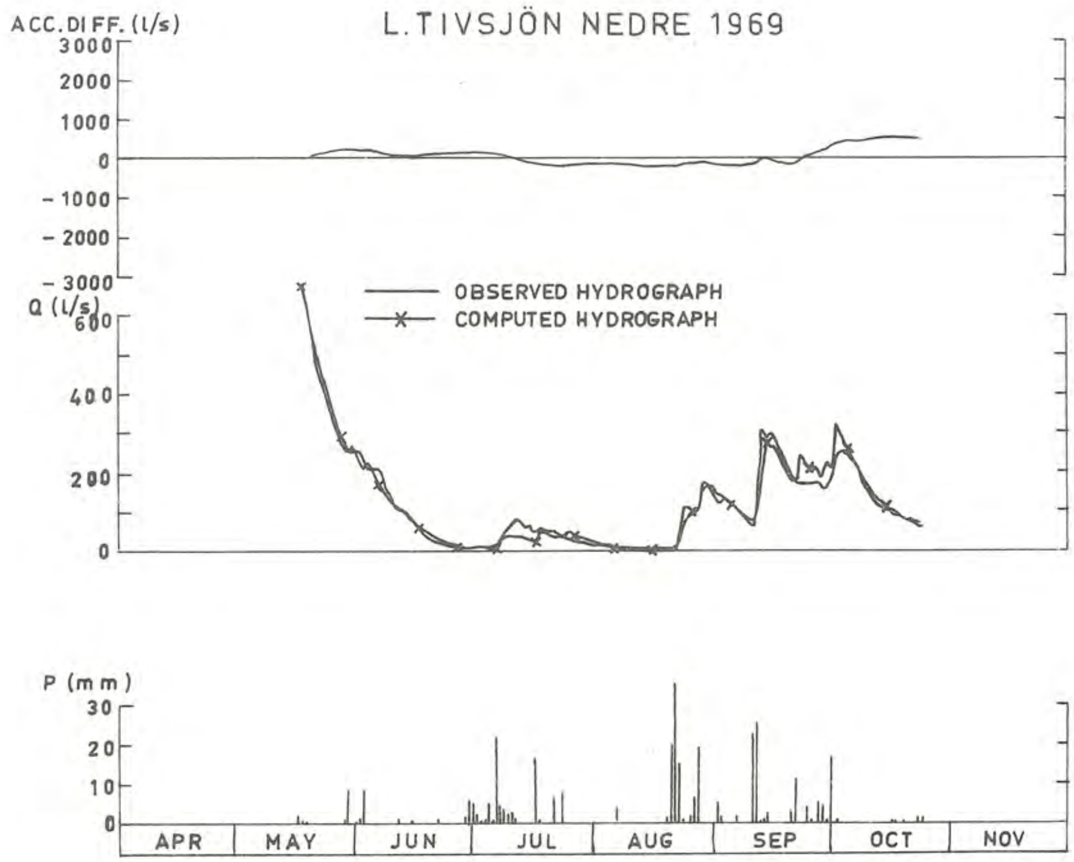


Fig. A 1. Fitted period in the Lilla Tivsjön catchment.

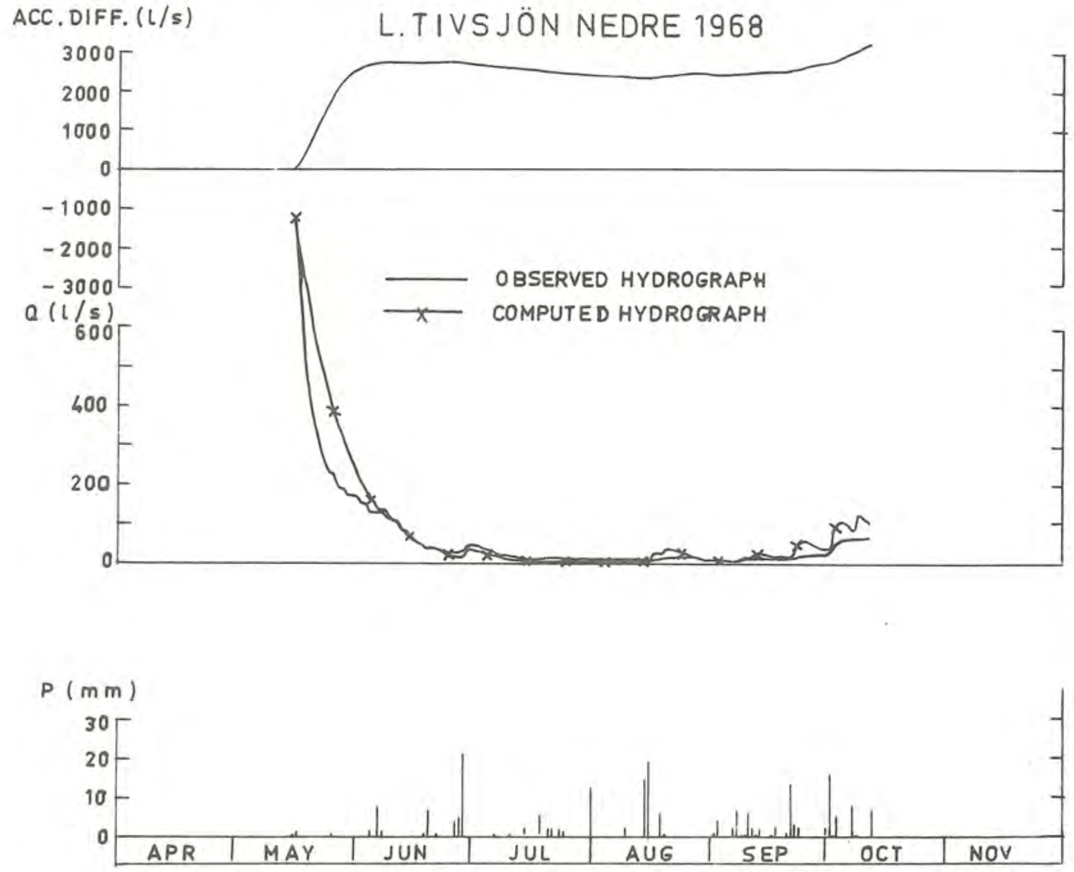


Fig. A 2. Test period in the Lilla Tivsjön catchment.

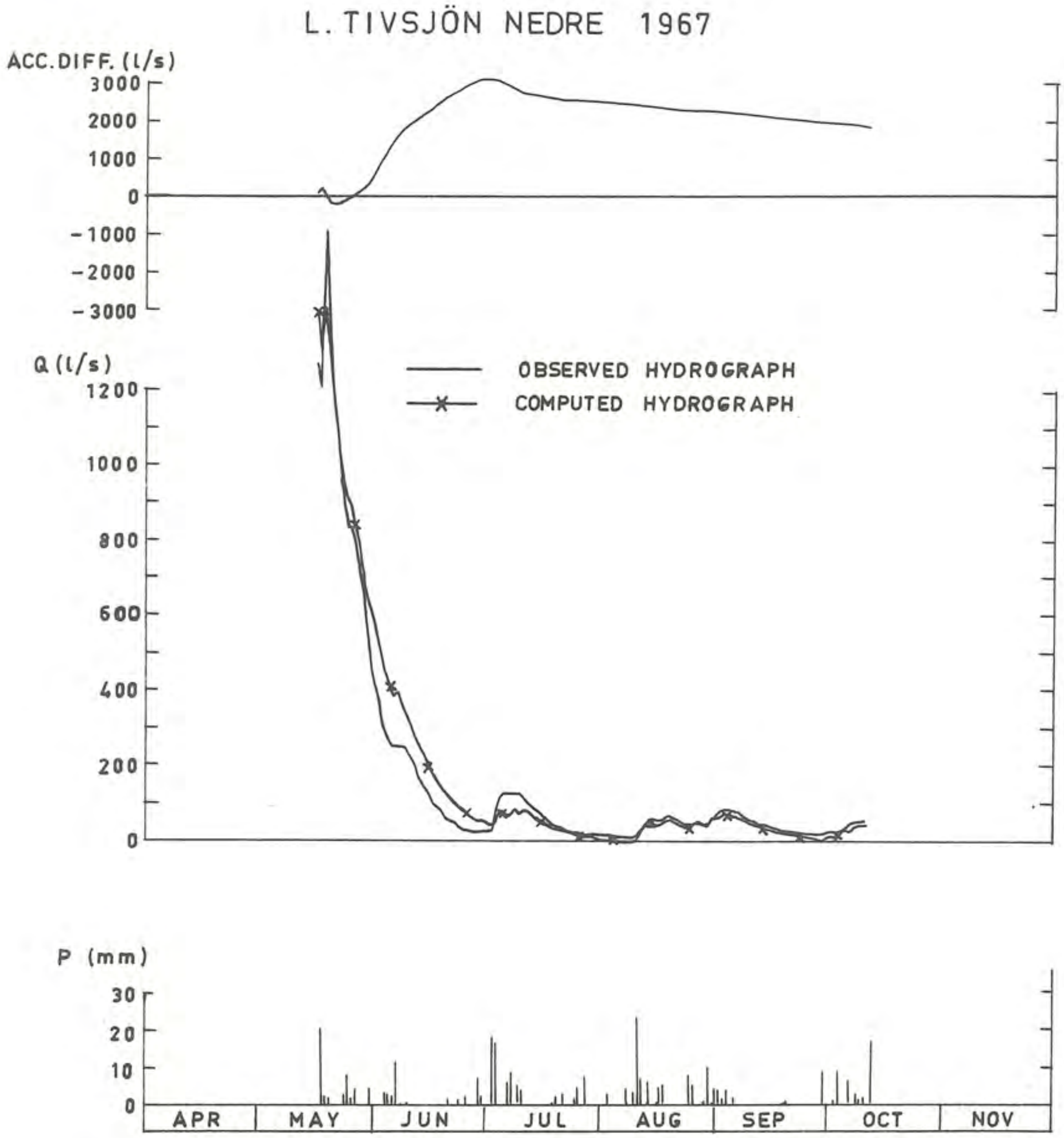


Fig. A 3. Test period in the Lilla Tivsjön catchment.

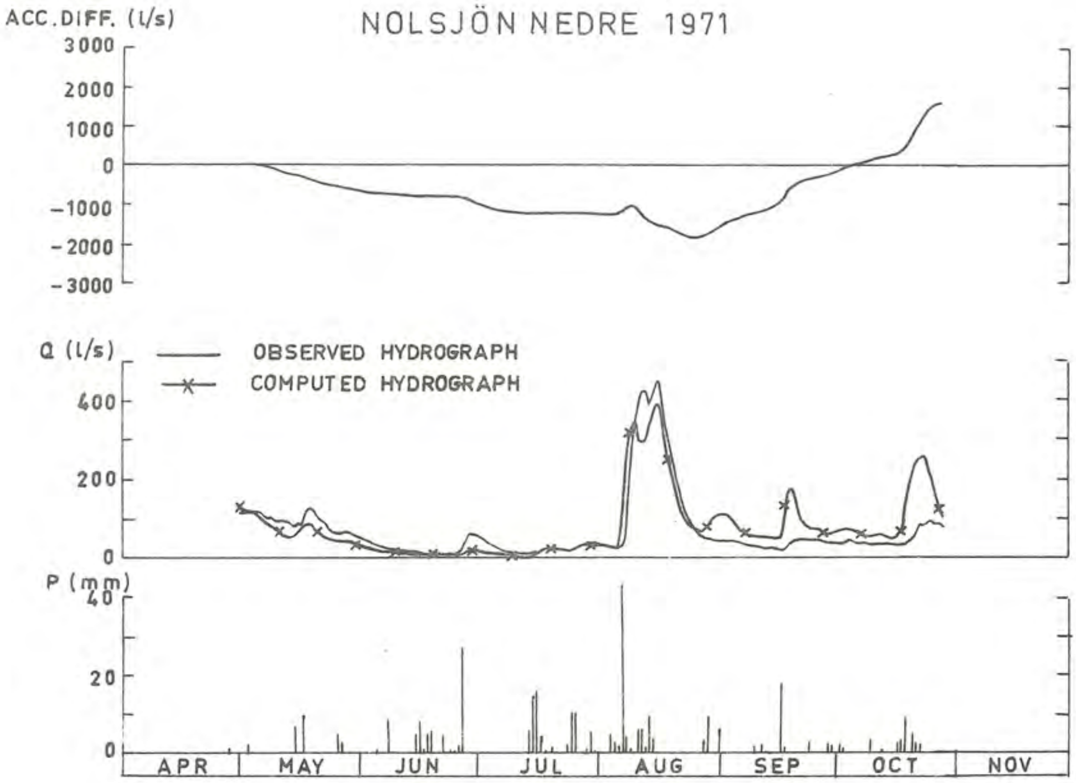


Fig. A 4. Fitted period in the Nolsjön catchment.

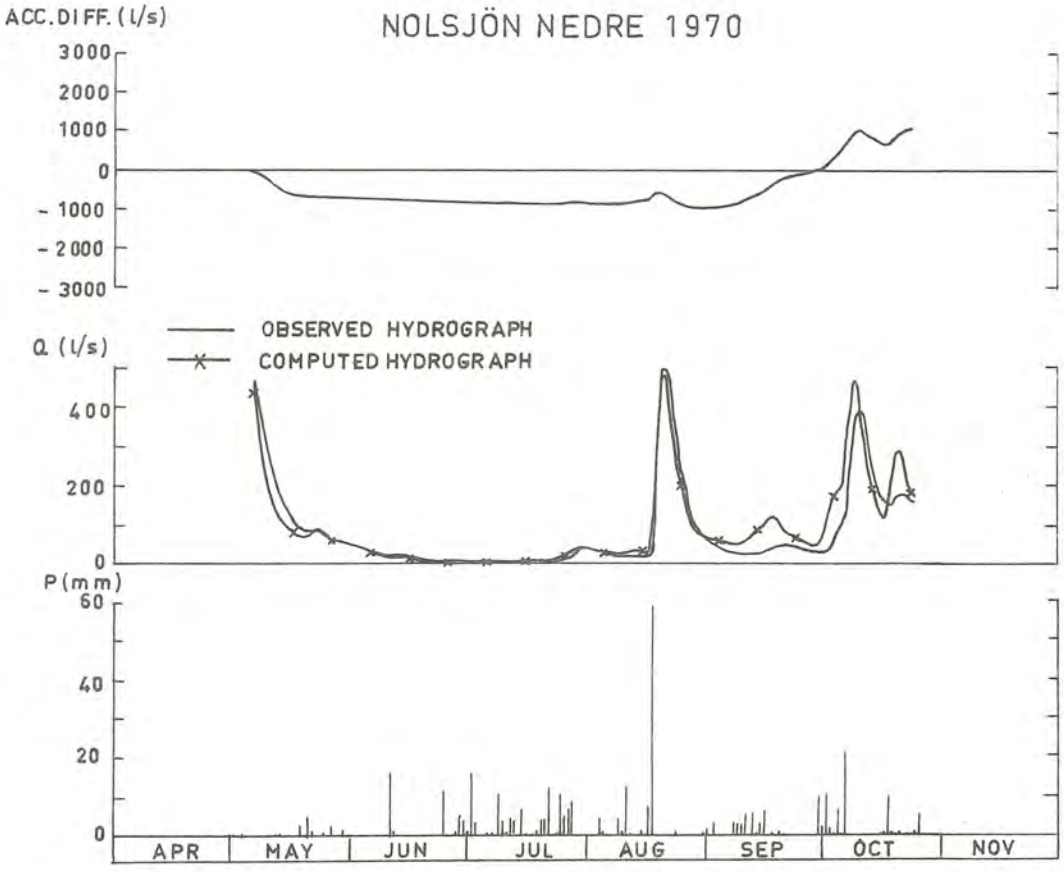


Fig. A 5. Fitted period in the Nolsjön catchment.

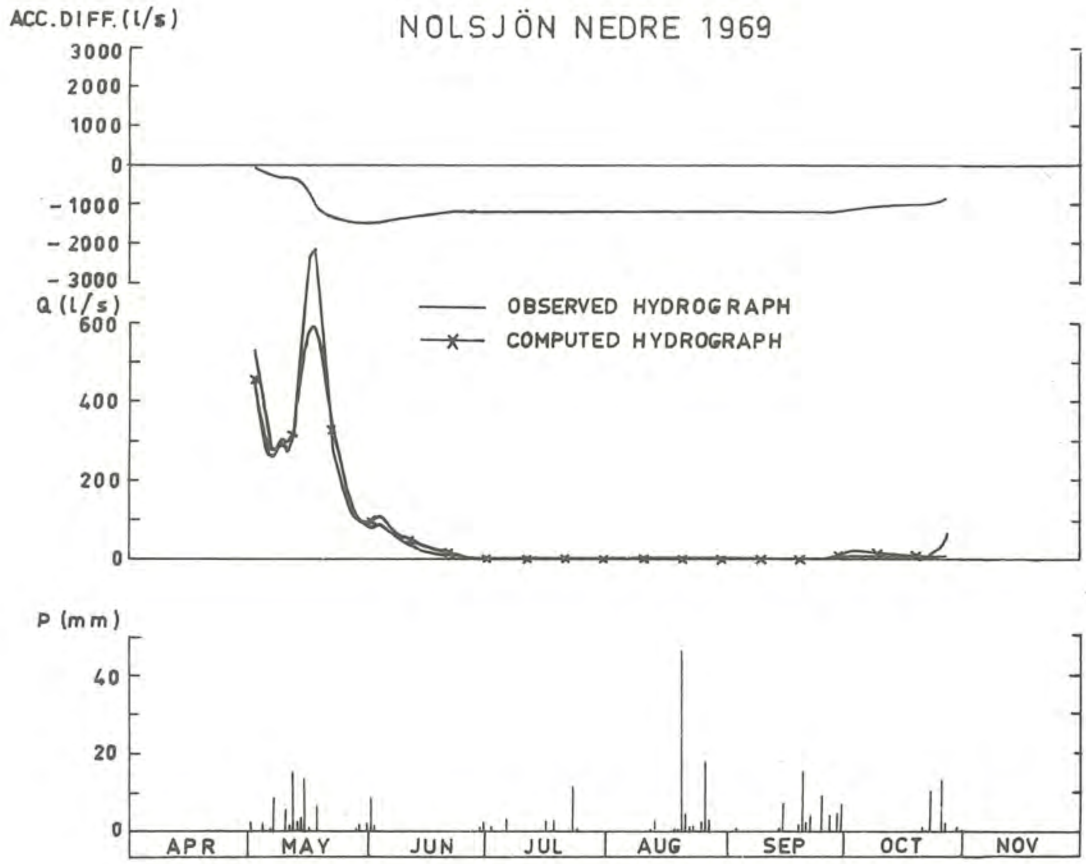


Fig. A 6. Test period in the Nolsjön catchment.

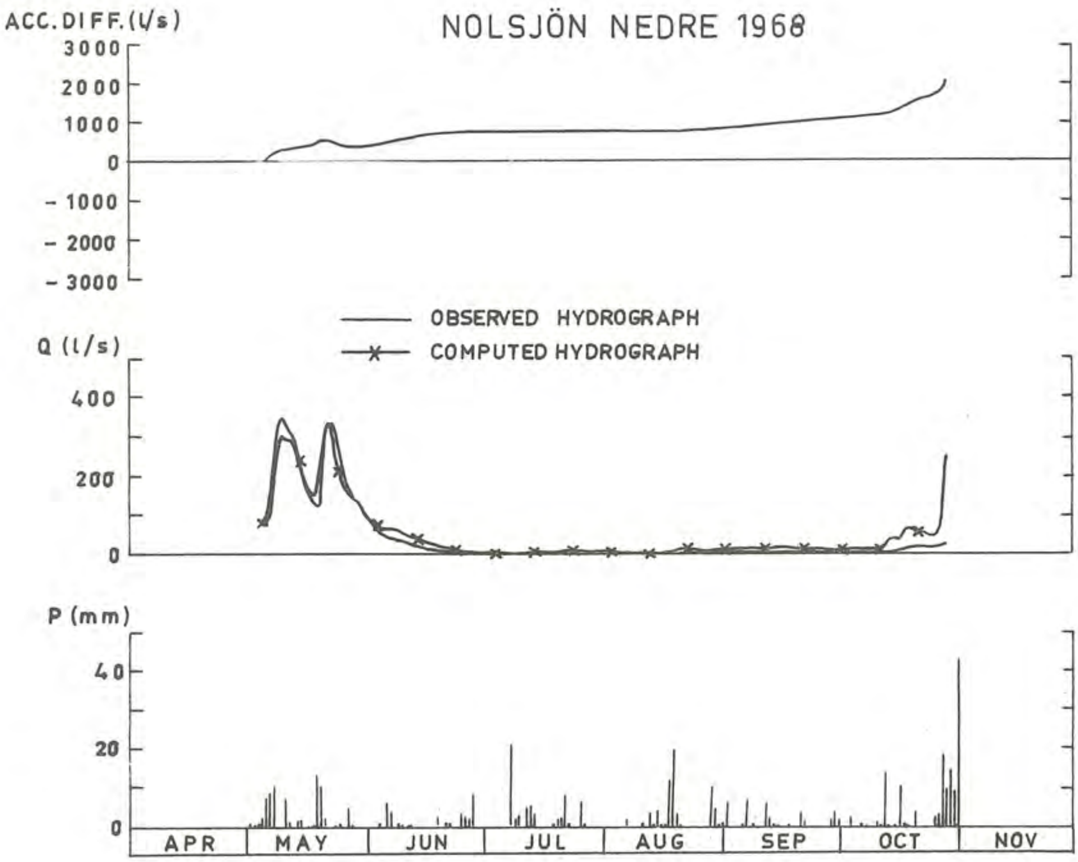


Fig. A 7. Test period in the Nolsjön catchment.

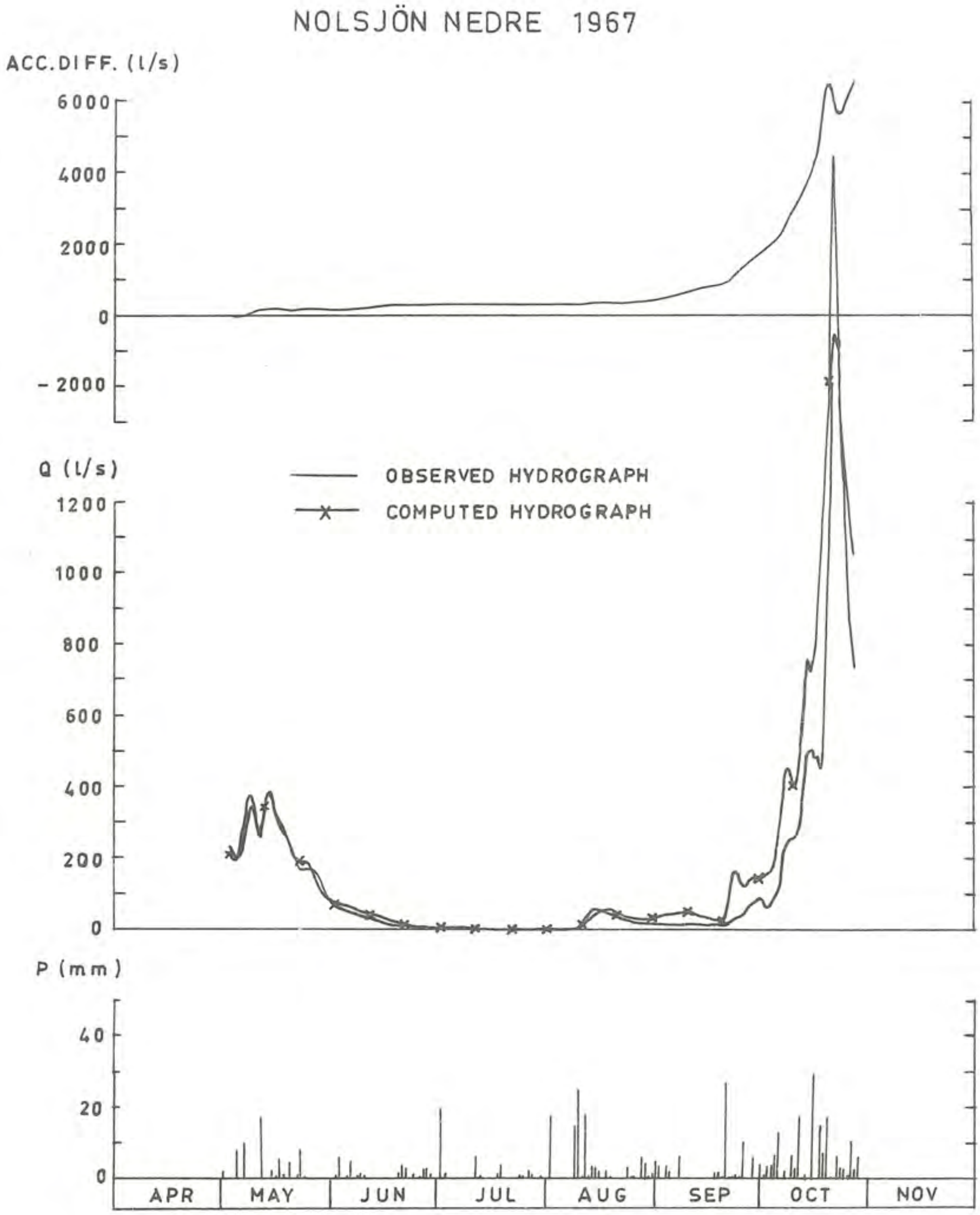


Fig. A 8. Test period in the Nolsjön catchment.

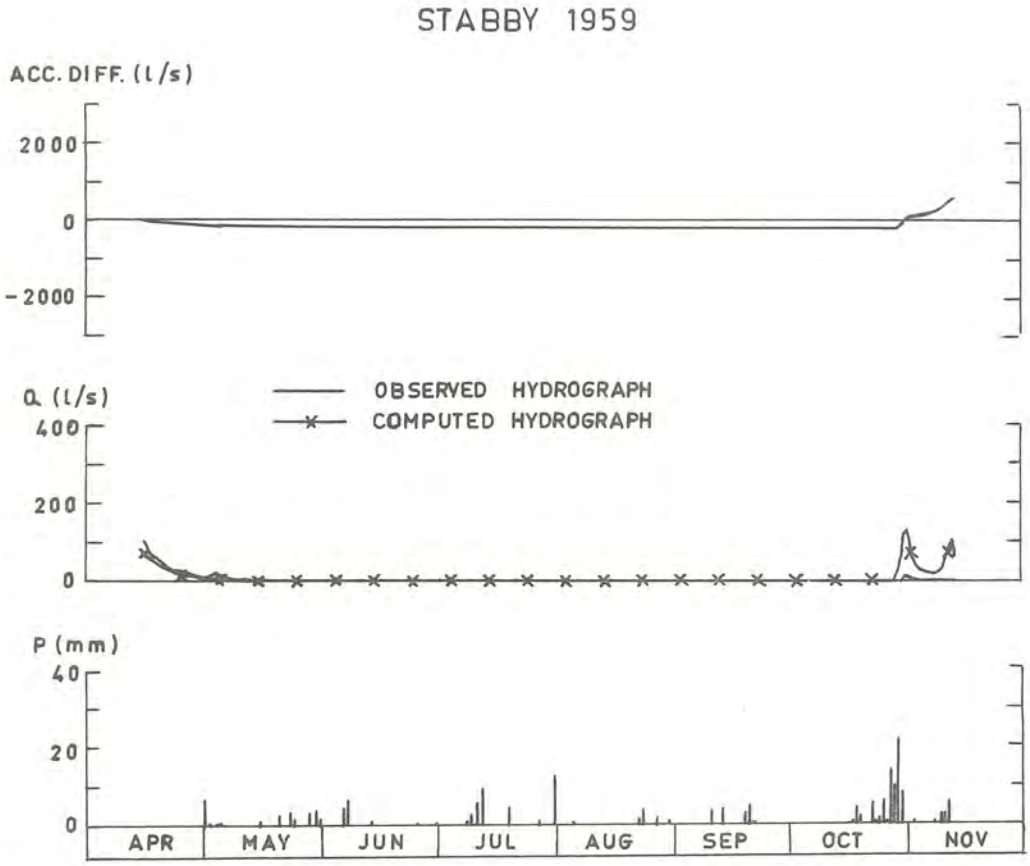


Fig. A 9. Fitted period in the Stabby catchment.

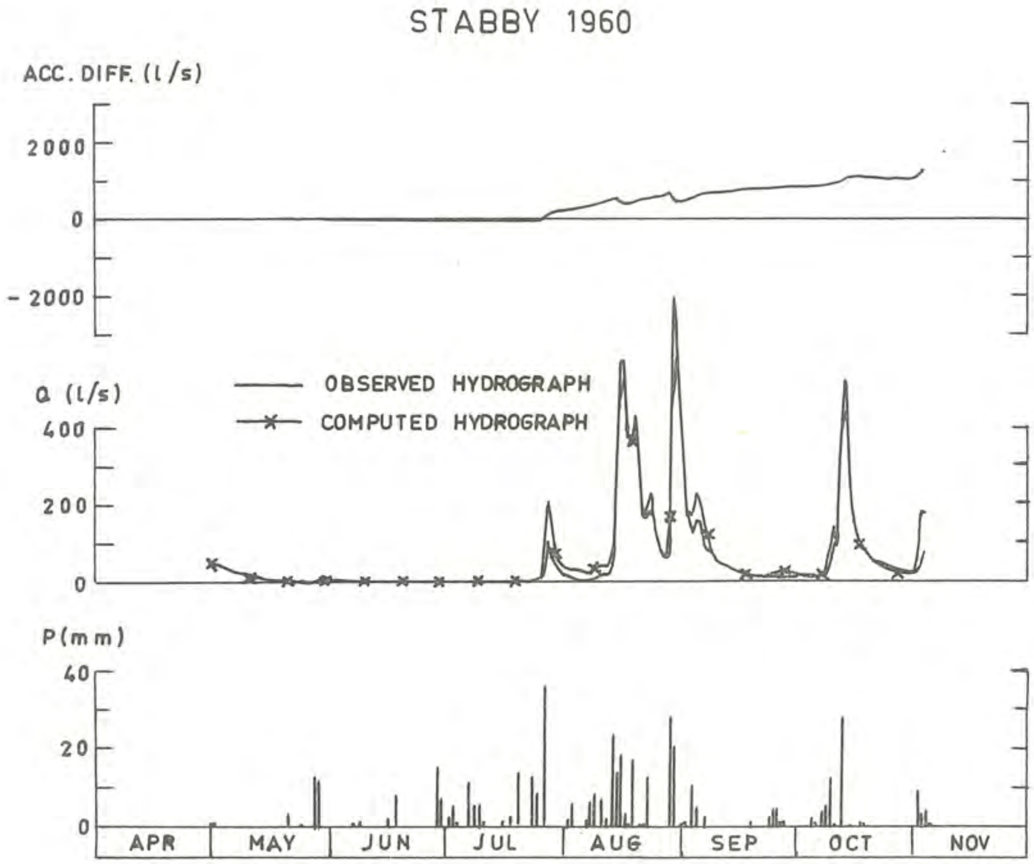


Fig. A 10. Fitted period in the Stabby catchment.

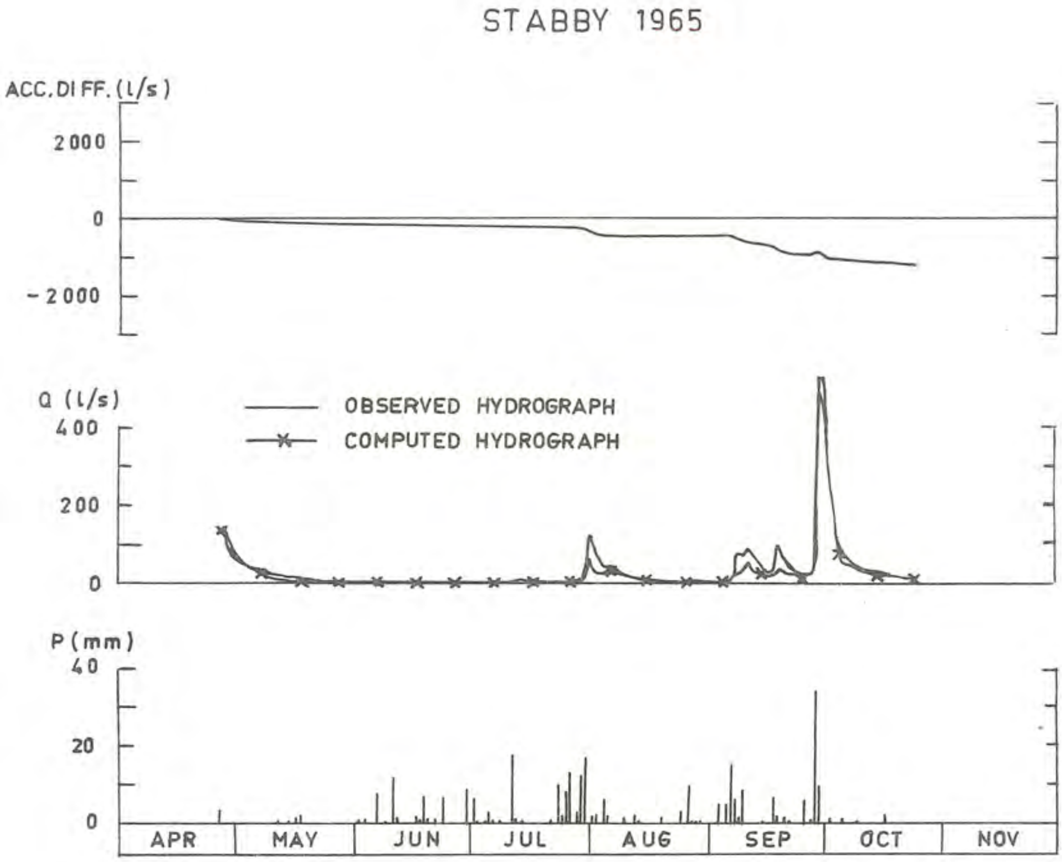


Fig. A 11. Test period in the Stabby catchment.

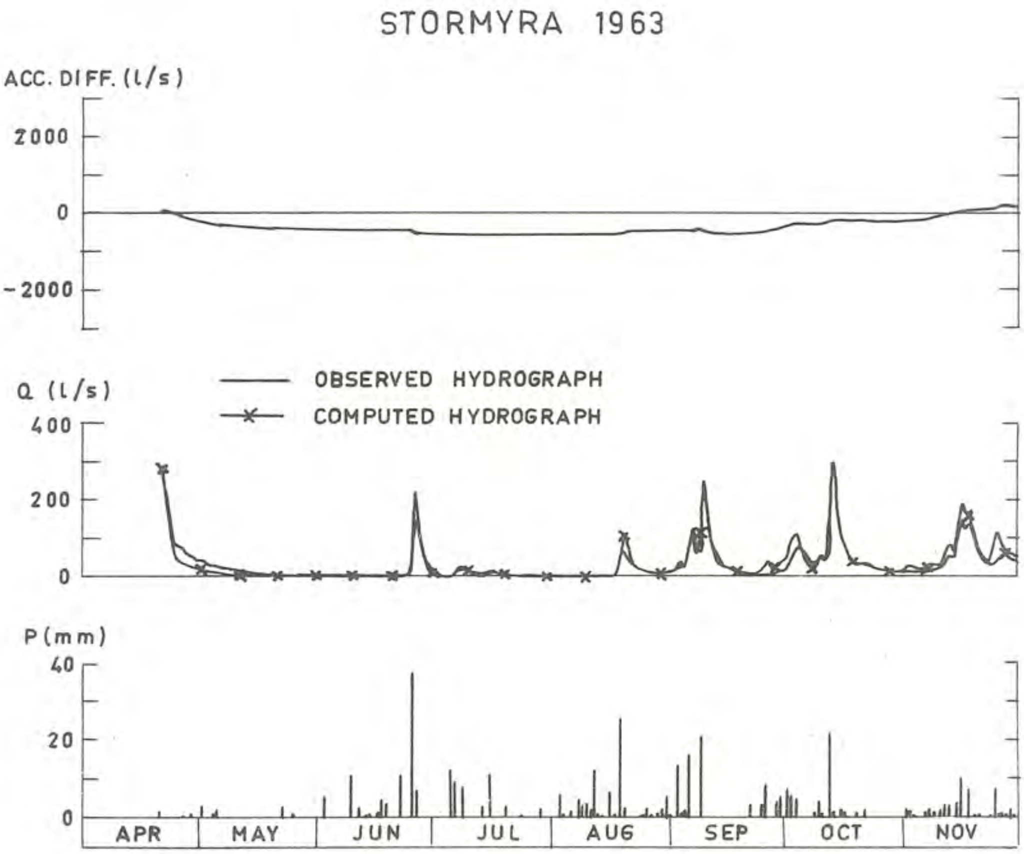


Fig. A 12. Fitted period in the Stormyra catchment.

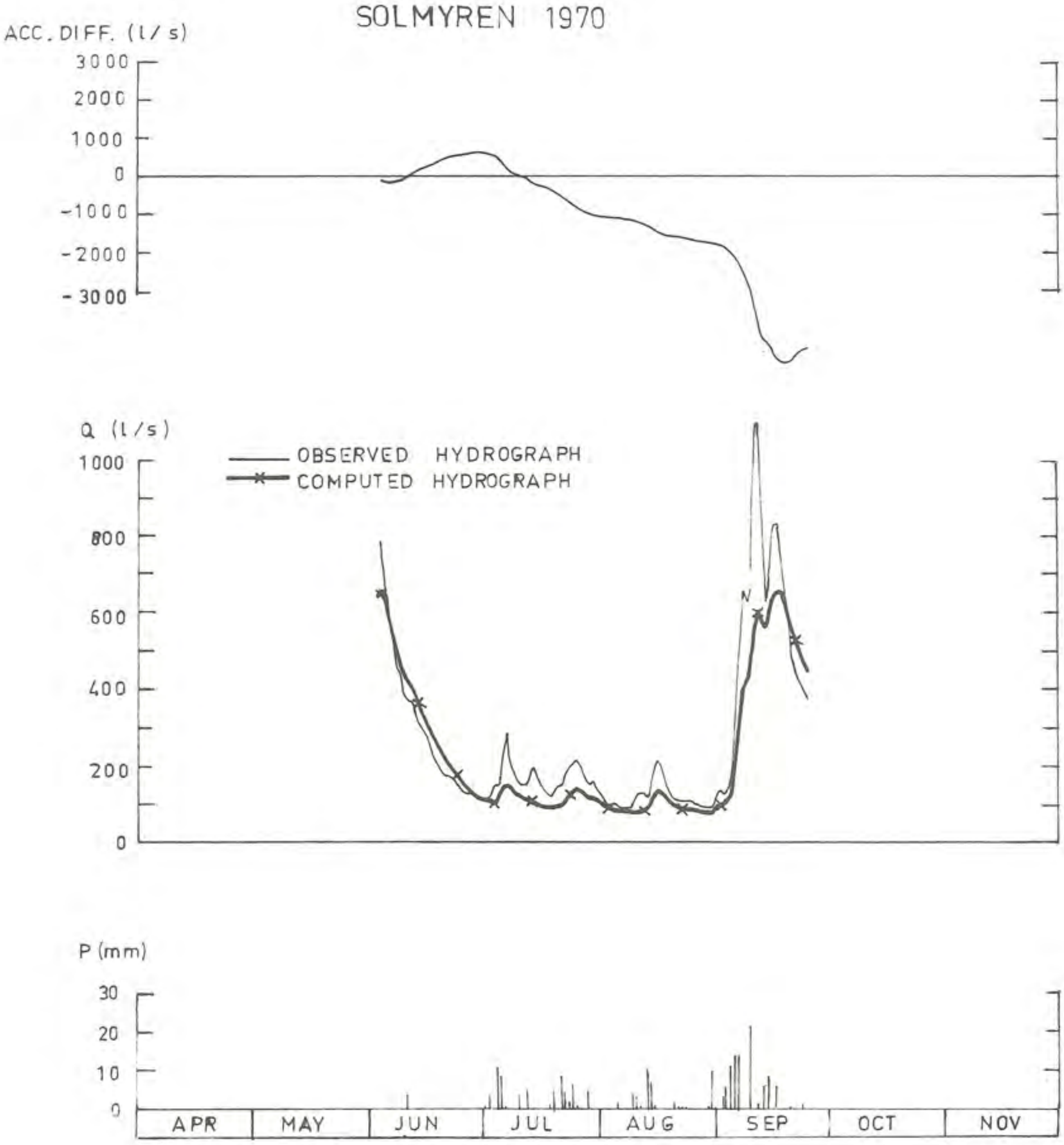


Fig. A 13. Test period in the Solmyren catchment.

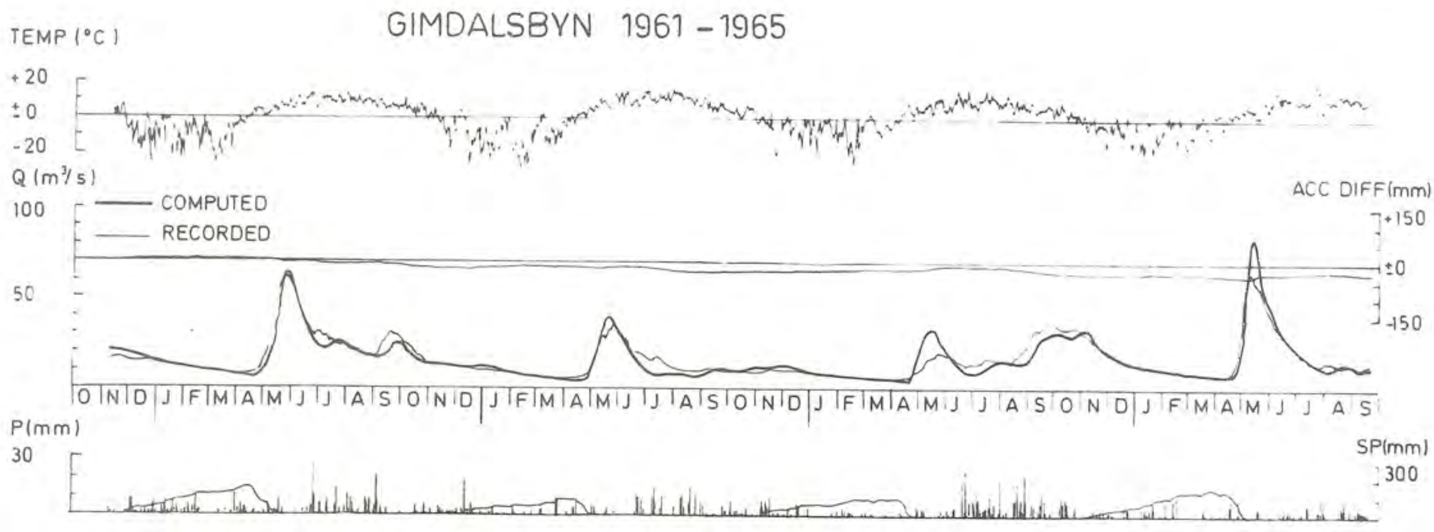


Fig. A 14. Fitted period in the Gimdalsbyn catchment.

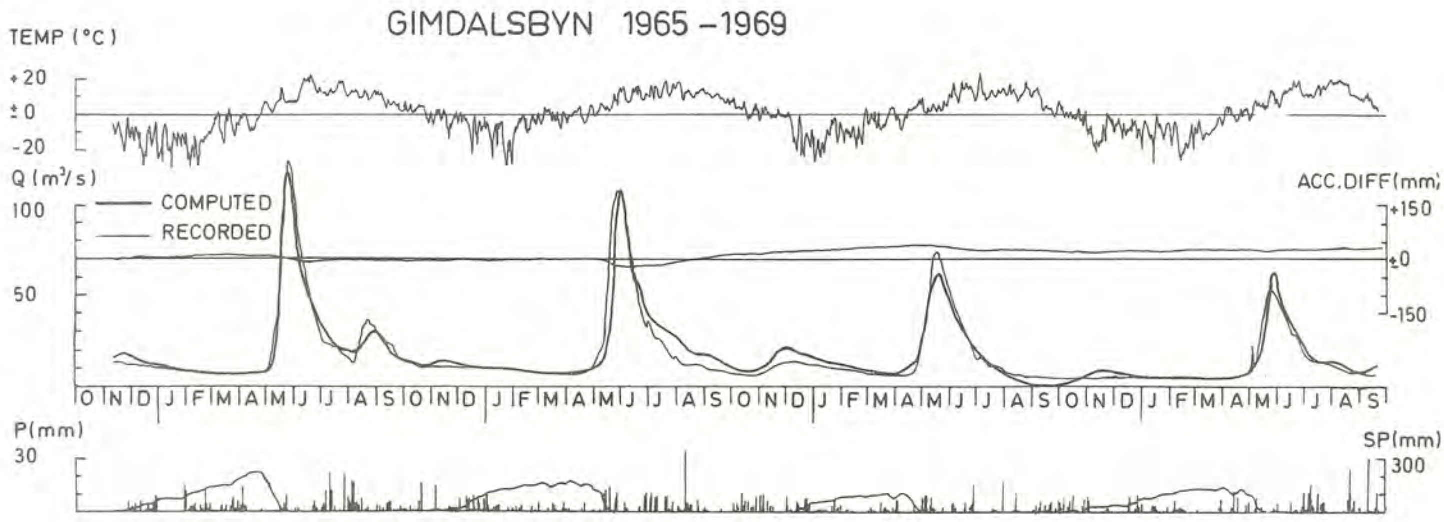


Fig. A 15. Fitted period in the Gimdalsbyn catchment.

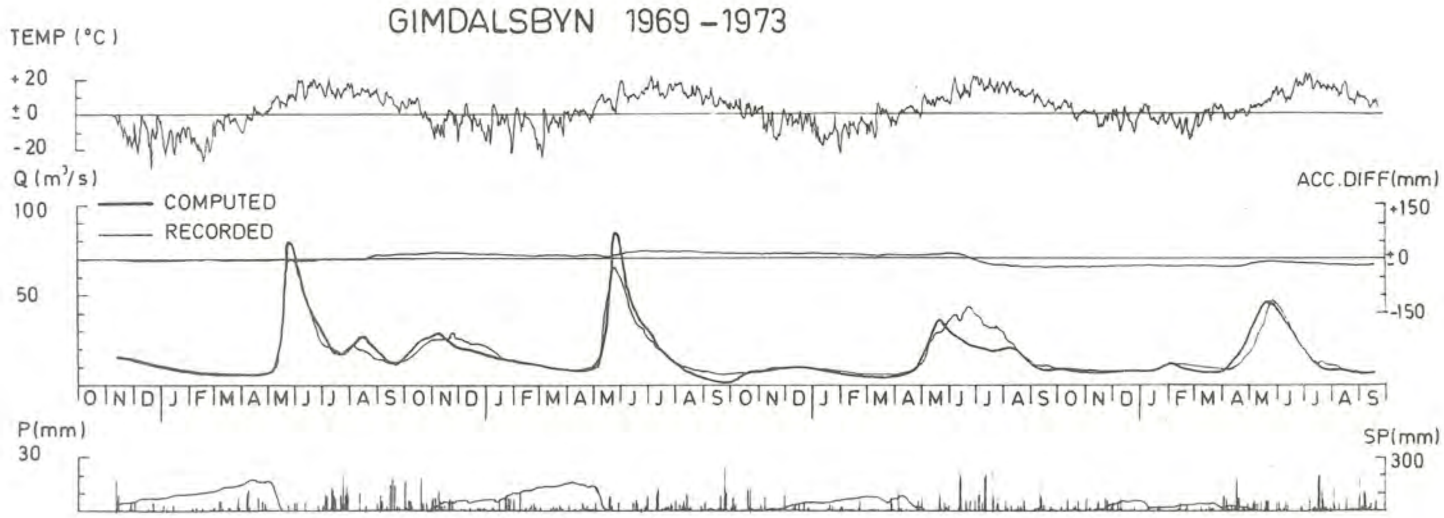
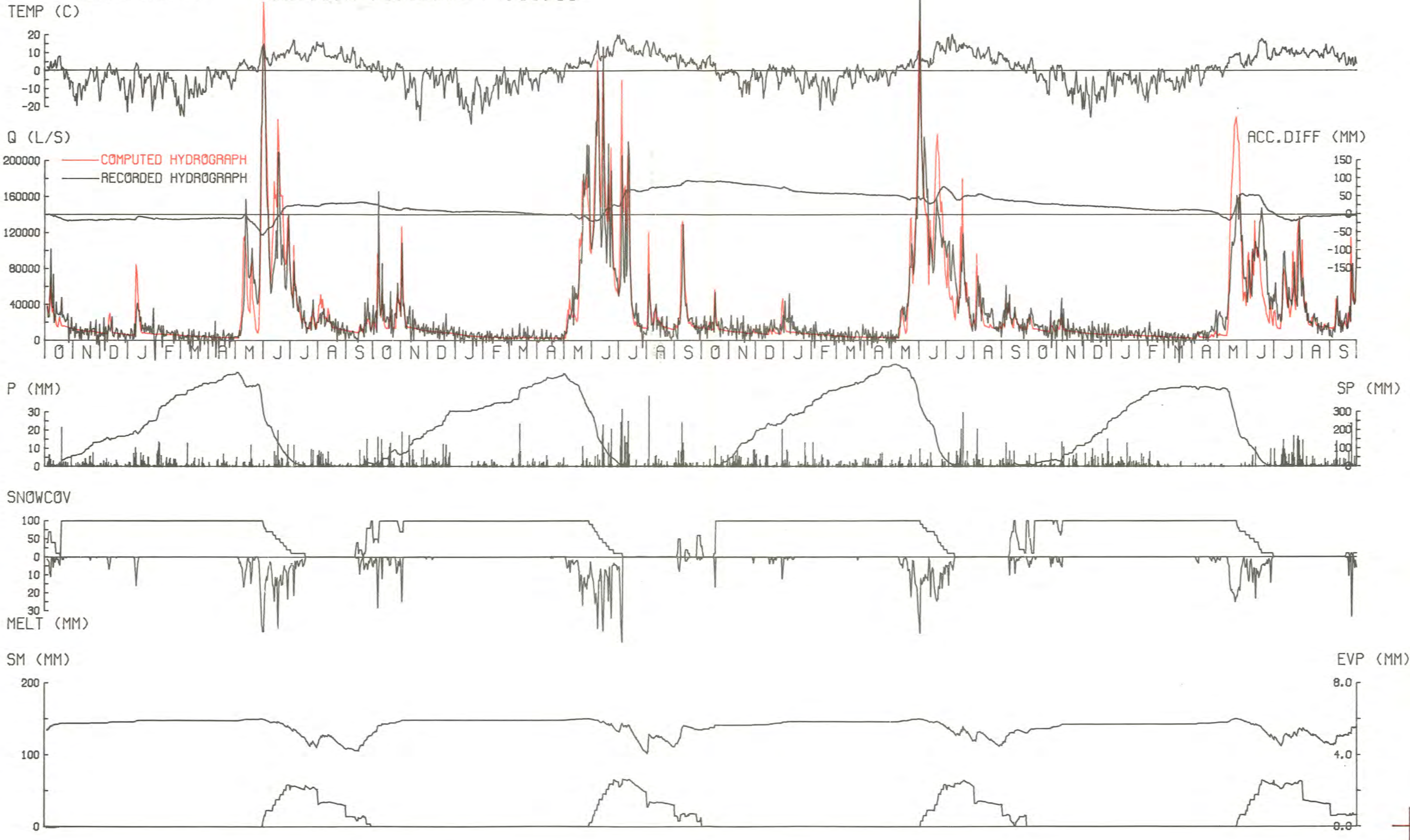


Fig. A 16. Test period in the Gimdalsbyn catchment.

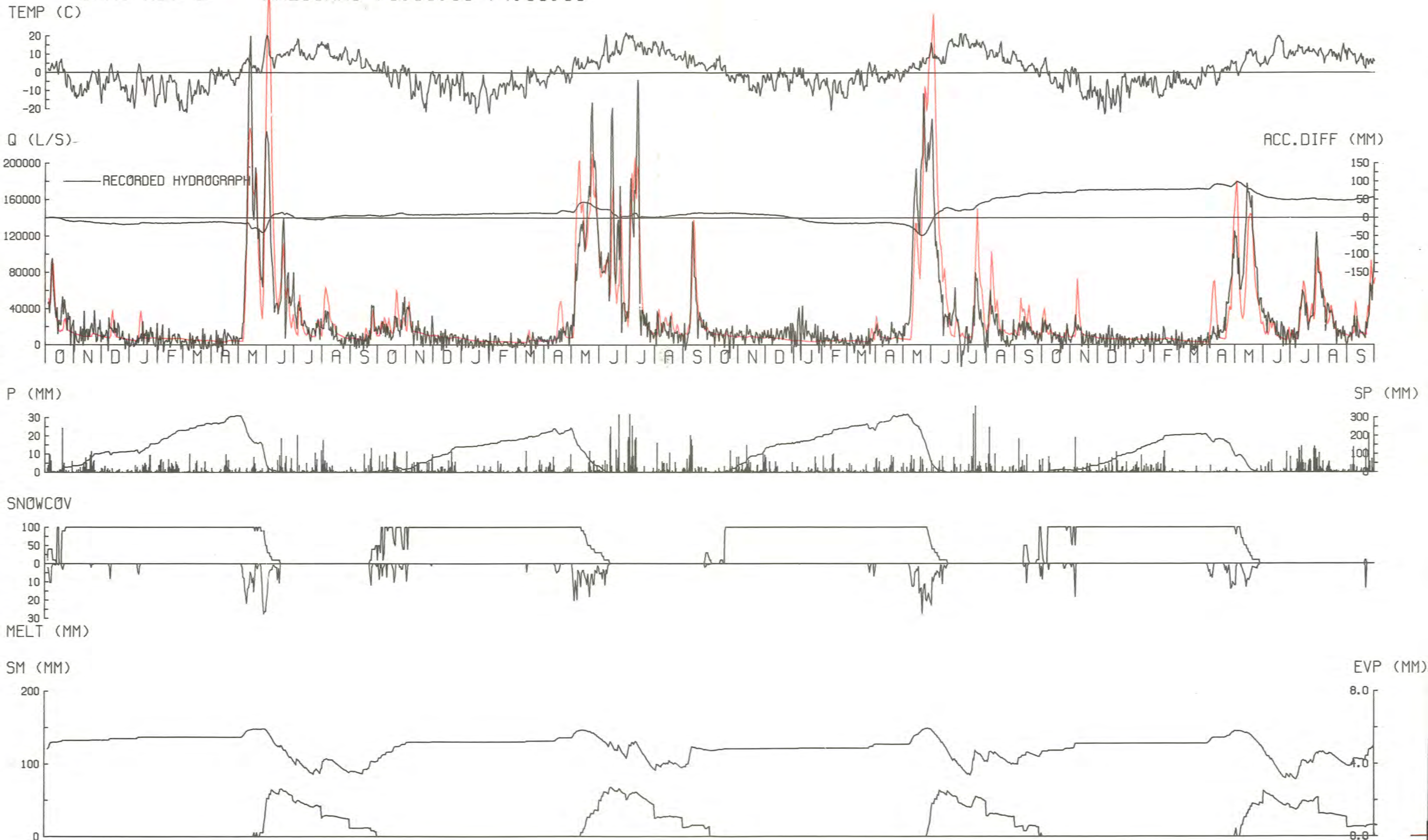
Figures in the following pages:

SMHI HBV-3 KULTSJÖN 70.10.01-74.09.30



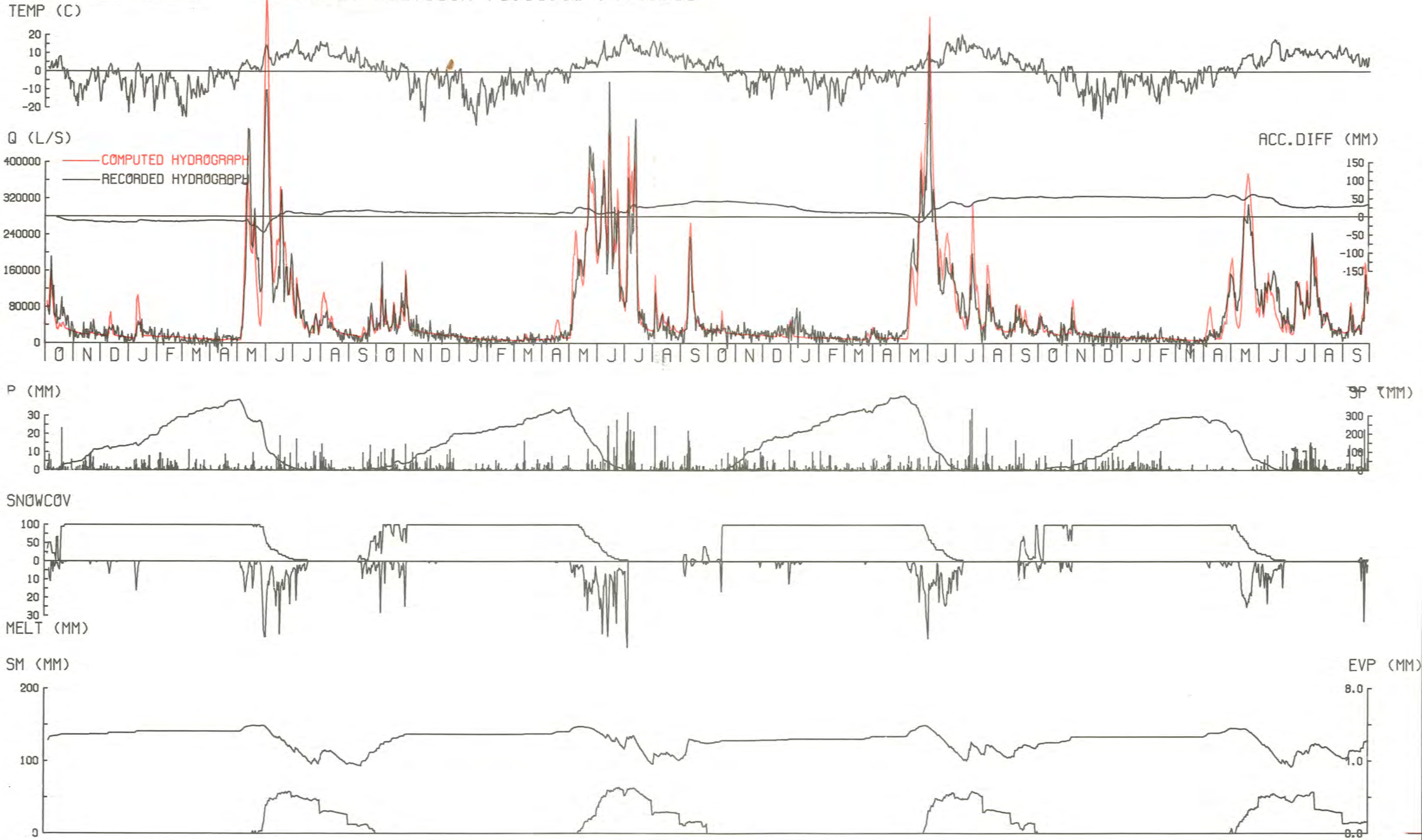
JOB 17 HBV3 HV*SB
DATE: 751125 TIME: 10.07 PROGRAM: HBV3

SMHI HBV-3 MALGØMAJ 70.10.01-74.09.30



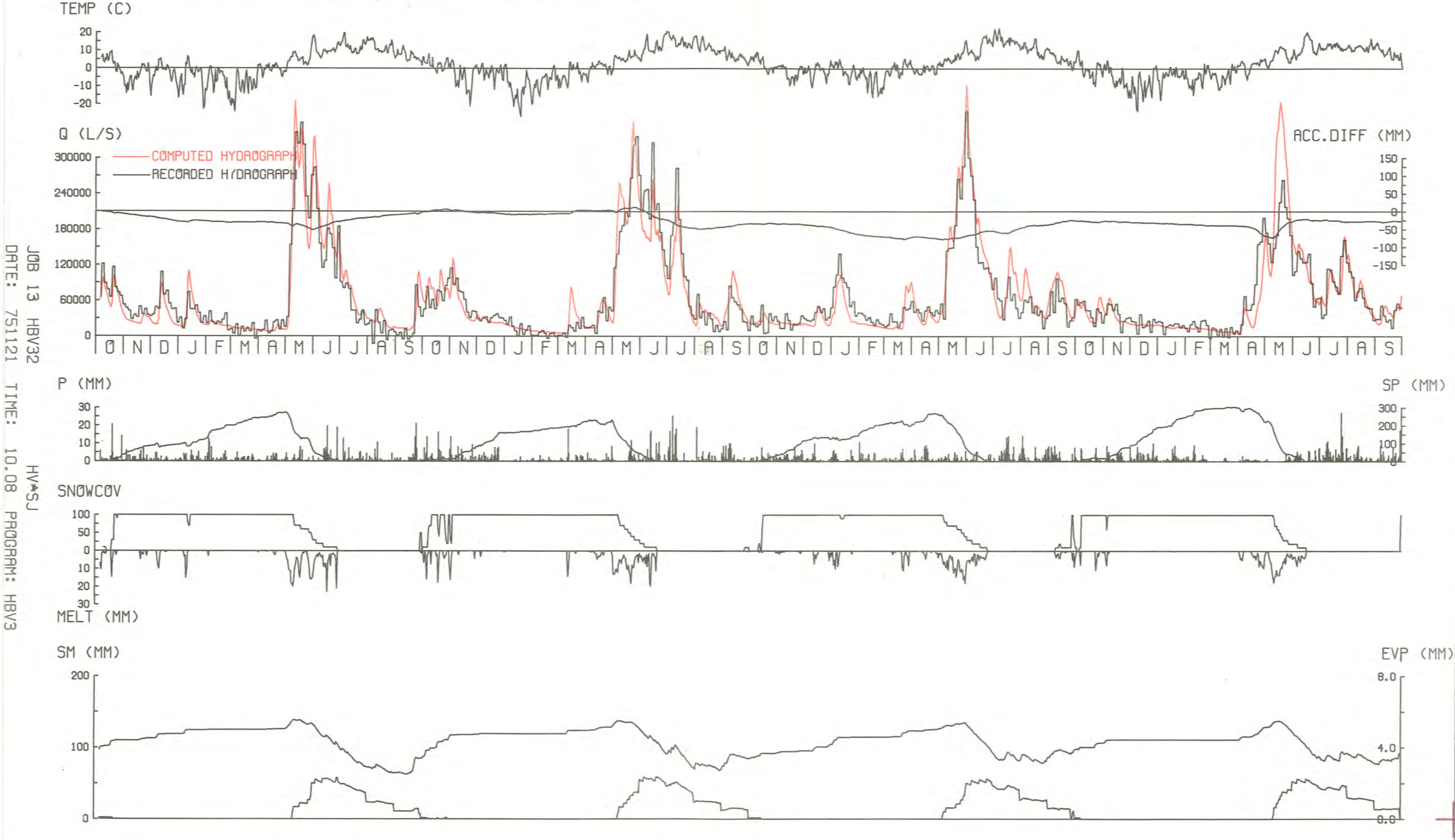
JOB 74 HBV32 HV*SJ
DATE: 751106 TIME: 13.21 PROGRAM: HBV3

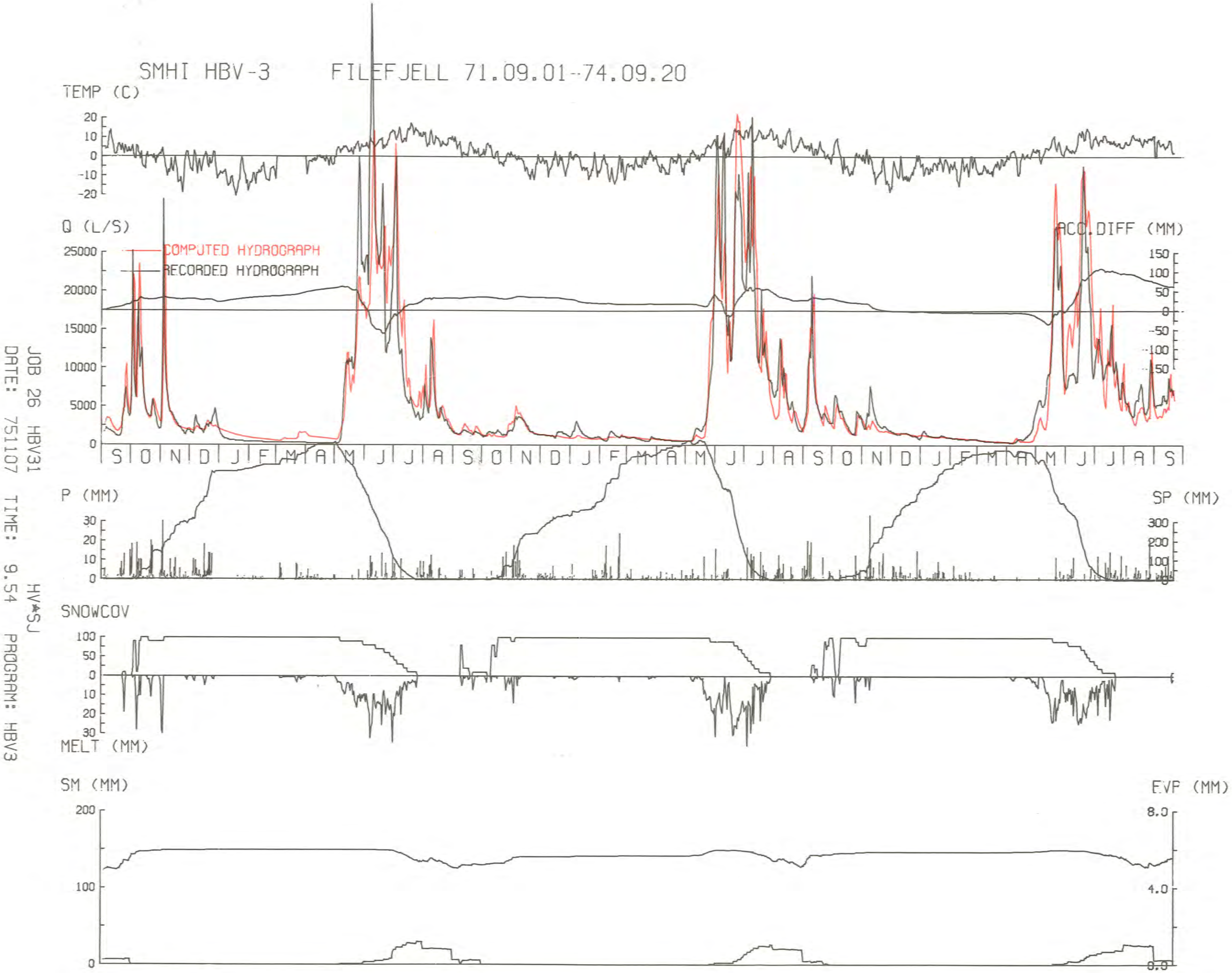
SMHI HBV-3 MALGOMAJ+KULTSJÖN 70.10.01-74.09.30



JØB 19 HBV32 HV*SB
DATE: 751121 TIME: 12.45 PRØGRAM: HBV32

SMHI HBV-3 STRÖMSVD 70.10.01-74.09.30.




SMHI HBV-3 FILEFJELL 71.09.01-74.09.20
TEMP (C)
Q (L/S)
COMPUTED HYDROGRAPH
RECORDED HYDROGRAPH
ACC.DIFF (MM)
S O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
P (MM)
SP (MM)
SNOWCOV
MELT (MM)
SM (MM)
EVP (MM)
JOB 26 HBV31 HV*SJ
DATE: 751107 TIME: 9.54 PROGRAM: HBV3

APPENDIX 2

SOME ASPECTS ON THE INTERPRETATION OF THE RESPONSE SURFACES

The main purpose of the studies of the response surfaces has been to trace interacting or insignificant parameters. For the determination of interacting parameters a qualitative analysis of the response surfaces is sufficient while the classification of a parameter as insignificant, or incative, requires some measure of the sensitivity of the model, or more correct, the F^2-criterion. When studying several parameters simultaneously in a catchment their relative importance will very soon be clear by the density of the isolines when drawing the maps of the F^2-topography, but without this possibility for internal comparisons the F^2-criterion might be difficult to interpret. Therefore some convenient transformations are presented below.

With F^2 as the sum of squares of the residuals between the computed and the recorded discharge the mean error, σ, can be expressed as:

$$\sigma = \sqrt{\frac{F^2}{n}}, \qquad \text{(A 1)}$$

where:

n = the number of values for the computation of F^2.

If a change of the parameters is causing a change, ΔF^2, of the sum of squares criterion, the corresponding change of the mean error, $\Delta\sigma$, will be:

$$\Delta\sigma = \sigma \cdot \left(\sqrt{\frac{F^2 + \Delta F^2}{F^2}} - 1\right) \qquad \text{(A 2)}$$

A convenient rule when analysing the response surfaces is that a 10 % change of F^2 results in a 4.88 % change of σ.

Values of n, σ and F^2 at fitted parameter values for the cathcments subjects to studies of the response surfaces are shown in table A 1.

Table A 1. Estimations of the mean errors at fitted parameter values.

Catchment	Period	F^2	n (days)	σ
Filefjell [1]	1967 - 1971	$1.0157 \cdot 10^4 (m^3/s)^2$	1458	$2.64\ m^3/s$
Gimdalsbyn [2]	1961 - 1969	$0.74 \cdot 10^5 (m^3/s)^2$	2826	$5.10\ m^3/s$
Stabby	1959, 1960, 1961	$64 \cdot 10^4 (l/s)^2$	635	10.07 l/s

1) In fig. 7.9 and 7.10 the value of F^2 is slightly lower due to a minor correction of the computer program when analysing the area-elevation lapse parameters.

2) Fig. 7.15 shows a study carried out before the calibration was completed. The optimum value of $F^2 = 0.77 \cdot 10^5 (m^3/s)^2$.

Another possibility, when analysing the response surfaces, is to transform the F^2-values to R^2-values according to eq. 5.3. Such a transformation, valid for the Filefjell catchment for the period 1967 - 1971 is shown in table A 2.

No such transformation has been carried out for the Gimdalsbyn or Stabby catchments, as it requires the joint total initial variance for the periods, a quantity which, unfortunately, was not evaluated when working on these catchments.

Table A 2. Transformations from F^2-values to R^2-values valid for the Filefjell catchment 1967 - 1971.

$F^2 \cdot 10^{-4}$	R^2
0.85	0.8978
0.90	0.8917
0.95	0.8857
1.00	0.8797
1.05	0.8737
1.10	0.8677
1.15	0.8617
1.20	0.8557

LIST OF REFERENCES

AMOROCHO, J. and HART, W.E., 1964 — "A Critique of Current Methods in Hydrological Systems Investigation". Transactions, American Geophysical Union, Vol. 45, No.2.

ANDERSON, E.A., 1973 — "National Weather Service River Forecast System - Snow Accumulation and Ablation Model". NOAA Technical Memorandum NWS HYDRO-17, Silver Spring, MD.

AXELSSON, C.L., 1975 — "Test av en geometriskt fördelad avrinningsmodell". Swedish Natural Science Research Council, Report No. 44, Stockholm.

BECKER, A., 1975 — "EGMO-Einzugsgebietsmodelle zur Abflussberechnung, -vorhersage und -simulation". Wasserwirtschaft-Wassertechnik, Vol. 25, No. 9.

BERGSTRÖM, S., 1972 A — "Utveckling och tillämpning av en digital avrinningsmodell". Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI, nr 22, Stockholm.

BERGSTRÖM, S. 1972 B — "The Application of a Simple Rainfall-Runoff Model to a Catchment with Incomplete Data Coverage". Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI, nr 26, Stockholm.

BERGSTRÖM, S. 1973 — "Utveckling och tillämpning av SMHI:s avrinningsmodell, HBV-2". Femte nordiske feltsymposium, Institutt for Vassbygging, NTH, Trondheim, pp 121 - 145.

BERGSTRÖM, S., 1974 — "Metodiken vid utveckling av matematiska avrinningsmodeller". Vannet i Norden, årg. 7, nr 2.

BERGSTRÖM, S., 1975 — "The Development of a Snow Routine for the HBV-2 Model". Nordic Hydrology, vol. 6, No. 2.

BERGSTRÖM, S. and FORSMAN, A., 1973 — "Development of a Conceptual Deterministic Rainfall-Runoff Model". Nordic Hydrology, vol. 4, No. 3.

BERGSTRÖM, S. and JÖNSSON, S. 1975 — "Calibrating and Testing a Reservoir Inflow Model - A Case Study". (Prepared for the International Symposium and

Workshops on the Application of Mathematical Models in Hydrology and Water Resources Systems, Bratislava.) SMHI-HBV, Memo. No. 157, Norrköping.

BERGSTRÖM, S. and JÖNSSON, S., 1976 A — "Tillämpning av HBV-2 modellen på regleringsmagasin i Ångermanälven". Sveriges Meteorologiska och Hydrologiska Institut, HB rapport nr 18, Norrköping.

BERGSTRÖM, S. and JÖNSSON, S., 1976 B — "The Application of the HBV Runoff Model to the Filefjell Research Basin". Sveriges Meteorologiska och Hydrologiska Institut, rapport nr RHO 5, Norrköping.

VON BERTALANFFY, L., 1968 — "General System Theory". Allen Lane, The Penguin Press, London.

BOBIŃSKI, E., PIWECKI, T. and ZELAZIŃSKI, J., 1975 — "The Mathematical Simulation Model for the Sola and Dunajec Rivers Real-Time Flow Forecasting". Contribution to the Symposium and Workshops on the Application of Mathematical Models in Hydrology and Water Resources Systems, Bratislava.

BURNASH, R.J.C., FERRAL, R.L. and MC GUIRE, R.A., 1973 — "A Generalized Streamflow Simulation System". U.S. Department of Commerce, National Weather Service and State of California, Department of Water Resources, Sacramento.

CLARKE, R.T., 1973 — "A Review of Some Mathematical Models Used in Hydrology, with Observation on Their Calibration and Use". Journal of Hydrology, No. 19.

CRAWFORD, N.H. and LINSLEY, R.K., 1956 — "Digital Simulation in Hydrology: Stanford Watershed Model IV". Department of Civil Engineering, Stanford University, Technical Report No. 39, Stanford.

DANIELSSON, O. and WRETBORN, G. 1975 — "Vattenkraft: Nu kan produktionen planeras bättre". Teknisk Tidskrift, årg. 105, nr 9.

DAWDY, D.R., LICHTY, R.W. and BERGMANN, J.M., 1972 — "A Rainfall-Runoff Simulation Model for Estimation of Flood Peaks for Small Drainage Basins". Geological Survey Professional Paper 506-B, Washington, D.C.

DICKINSON, W.T. and DOUGLAS, J.R., 1972 — "A Conceptual Runoff Model for the Cam Catchment". Institute of Hydrology, Report No. 17, Wallingford.

DIETRICH, T.L. and MEIMAN, J.R., 1974 — "Hydrologic Effects of Patch Cutting of Lodgepole Pine". Hydrology Papers, Colorado State University, No. 66, Fort Collins.

DOOGE, J.C.I., 1973 — "Linear Theory of Hydrologic Systems". Agricultural Research Service, U.S. Department of Agriculture, Technical Bulletin No. 1468, Washington, D.C.

FALKENMARK, M., (Editor) 1972 — "Representative Basins. Introductory Volume". Hydrological Data Norden, Oslo.

FIERING, M.B., 1975 — "Reservoir Planning and Operation". Lecture notes from the Institute on Application of Stochastic Methods to Water Resources Problems. Colorado State University, Fort Collins.

FORSMAN, A., 1963 — "Snösmältning och avrinning". Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI,nr 2, Stockholm.

GIRARD, G., FORTIN, J.P. and CHARBONNEAU, R., 1971 — "Un modèle hydrométeorologique simplifié et quelques applications régionales". Contribution to the International Symposium on Mathematical Models in Hydrology, Warsaw.

GRAY, D.M., (Editor) 1973 — "Handbook on the Principles of Hydrology". Water Information Center, Inc. New York.

GRIP, H., 1973 — "A Deterministic Parametric Water-Balance Model". Nordic Hydrology, vol. 4, No. 3.

HOUMØLLER, O., 1976 — "En hydrologisk geologisk undersøgelse af Giber å området". Rapport over specialprojekt udført ved Laboratoriet for Geofysik, Aarhus Universitet, Aarhus.

HÄGGSTRÖM, M., JANSSON, B.-O., RUNESSON, T. and SIMONIDES, A. 1972 — "Representativa området Lappträsket: Hydrologisk undersökning av Solmyren". Swedish Natural Science Research Council, Report No. 20, Stockholm.

IBBITT, R.P., 1974 — "Representative Data Sets for Comparative Testing of Mathematical Models for Representative and Experimental Basins". UNESCO SC. 74/WS/11.

IBBITT, R.P. and O'DONNELL, T., 1971 — "Fitting Methods for Conceptual Catchment Models". Journal of the Hydraulics Division, ASCE, vol. 97, No. HY 9.

KALININ, G.P., 1971 — "Global Hydrology". U.S. Department of Commerce, National Technical Information Service. Translated from Russian by the Israel Program for Scientific Translations, Jerusalem.

KRISTENSEN, K.J., and JENSEN, S.E., 1975 — "A Model for Estimating Actual Evapotranspiration from Potential Evapotranspiration". Nordic Hydrology, vol. 6, No. 3.

KUCHMENT, L.S., 1972 — "Matematicheskoe Modelirovanie Rechnogo Stoha" (Mathematical Modelling of River Runoff). Gidrometeoizdat, Leningrad.

KUZ'MIN, P.P., 1972 — "Melting of Snow Cover". U.S. Department of Commerce, National Technical Information Service. Translated from Russian by the Israel Program for Scientific Translations, Jerusalem.

LARSON, L.W., and PECK, E.L., 1974 — "Accuracy of Precipitation Measurements for Hydrologic Modelling". Water Resources Research, vol. 10, No. 4.

LEMMELÄ, R. and KUUSISTO, E., 1973 — "Evaporation-Condensation and Snowmelt Measurements in Finland". Nordic Hydrology, vol. 4, No. 4.

MANDEVILLE, A.N., O'CONNELL, P.E., SUTCLIFFE, J.V. and NASH, J.E., 1970 — "River Flow Forecasting Through Conceptual Models, Part III - The Ray Catchment at Grendon Underwood". Journal of Hydrology, No. 11.

MARTINEC, J., 1975 — "Snowmelt-Runoff Model for Stream Flow Forecasts". Nordic Hydrology, vol. 6, No. 6.

MOBERG, A., 1967 — "Svenska sjöars isläggnings- och islossningstidpunkter 1911/12 - 1960/61. Del I. Redovisning av observationsmaterial." Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI, nr 4, Stockholm.

NASH, J.E. and SUTCLIFFE, J.V., 1970 — "River Flow Forecasting Through Conceptual Models Part I - A Discussion of Principles". Journal of Hydrology, No. 10.

NIELSEN, S.A. and HANSEN, E., 1973 — "Numerical Simulation of the Rainfall-Runoff Process on a Daily Basis". Nordic Hydrology, vol. 4, No. 3.

NYBERG, A., 1965 — "A Study of the Evaporation and Condensation at a Snow Surface". Arkiv för Geofysik, band 4, nr 30.

NYBERG, G., 1972 — "En matematisk avrinningsmodell". Avdelningen för Hydrologi vid Institutionen för Naturgeografi, Uppsala Universitet, Uppsala.

O'CONNELL, P.E., NASH, J.E. and FARRELL, J.P., 1970 — "River Flow Forecasting Through Conceptual Models. Part III - The Brosna Catchment at Ferbane". Journal of Hydrology, No. 10.

PARMELE, L.H., 1972 — "Errors in Output of Hydrologic Models Due to Errors in Input Potential Evaporation". Water Resources Research, vol. 8, No. 2.

PERSSON, M., 1972 — "Hydrologiska undersökningar i Lappträskets representativa område. Rapport III: Avdunstning och vattenomsättning." Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI, nr 24, Stockholm.

PERSSON, M., 1976 — "Hydrologiska undersökningar i Lappträskets representativa område. Meddelande nr VII: Avrinningen och dess variationer inom området". Sveriges Meteorologiska och Hydrologiska Institut, HB rapport nr 13. Norrköping.

PLINSTON, D.T., 1972 — "Parameter Sensitivity and Interdependence in Hydrological Models". In: J.N.R. Jeffers (Editor) "Mathematical Models in Ecology". Blackwell, Oxford, pp. 237 - 247.

POPOV, E.G., 1968 — "Osnovy Gidrologicheskikh Prognozov" (The Basis for Hydrological Forecasts). Gidrometeoizdat, Leningrad.

PORTER, J.W. and MC MAHON, T.A., 1975 — "A Model for the Simulation of Streamflow Data from Climatic Records". Journal of Hydrology, No. 13.

QUICK, M.C. and PIPES, A., 1975 — "U.B.C. Watershed Model". Contribution to the Symposium and Workshops on the Application of Mathematical Models in Hydrology and Water Resources Systems, Bratislava.

ROCHE, M., 1971 — "Les divers types de Modèles déterministes". La Houille Blanche, vol. 26, No. 2.

ROSENBROCK, H.H., 1960 — "An Automatic Method for Finding the Greatest or Least Value of a Function". The Computer Journal, vol. 7, No. 3.

SCHERMERHORN, V.P., and KUEHL, D.W., 1968 — "Operational Streamflow Forecasting with the SSARR Model". Symp. Use of Analogue and Digital Computers in Hydrology, vol. 1, Tucson, Arizona, IASH, 80, pp 317 - 328.

SEPPÄNEN, M., 1961 — "On the Accumulation and Decreasing of Snow in a Pine Dominated Forest in Finland". Meddelanden från Hydrologiska byrån XX, Helsinki.

SMHI, 1966 — "Meteorological Observations in Sweden 1965". Sveriges Meteorologiska och Hydrologiska Institut, årsbok 47 (1965), del 2.2, Stockholm.

SUGAWARA, M., OZAKI, E., WATANABE, I. and KATSUYAMA, Y, 1974 — "Tank Model and Its Application to Bird Creek, Wollombi Brook, Bihin River, Kitsu River, Sanaga River and Nam Mune". Research Notes of the National Center for Disaster Prevention, No. 11, Tokyo.

SUGAWARA, M., OZAKI, E., WATANABE, I. and KATSUYAMA, Y., 1975 — "Runoff Analysis of Snowy Mountainous Regions in Japan". Research Notes of the National Center for Disaster Prevention, No. 17, Tokyo.

U.S. CORPS OF ENIGNEERS, 1956 — Snow Hydrology". U.S. Army, Corps of Engineers, North Pacific Division, Portland.

U.S. CORPS OF ENGINEERS, 1960 — "Runoff from Snowmelt". U.S. Army, Corps of Engineers, EM 1110-2-1406, Washington, D.C.

WALDENSTRÖM, A., 1975 — "Hydrologiska undersökningar i Kassjöåns representativa område. Meddelande nr IV. Snötaxering 1974 och vattenomsättning 1969-1973". Sveriges Meteorologiska och Hydrologiska Institut, HB rapport nr 8, Stockholm.

WALDENSTRÖM, A. och ANDERSSON, U.-M., 1973 — "Mark- och grundvattenstudier i Kassjöåns representativa område". Sveriges Meteorologiska och Hydrologiska Institut, notiser och preliminära rapporter, serie HYDROLOGI nr 29, Stockholm.

WALLÉN, C.C., 1951 — "Nederbörden i Sverige. Medelvärden 1901-1930". Meddelanden från Sveriges Meteorologiska och Hydrologiska Institut, serie A, nr 4, Stockholm.

WALLÉN, C.C., 1966 — "Global Solar Radiation and Potential Evapotranspiration in Sweden". Sveriges Meteorologiska och Hydrologiska Institut, meddelanden, serie B, nr 24, Stockholm.

WMO, 1975 A — "Hydrological Forecasting Practices". Operational Hydrologi, Report No. 6, WMO-No. 425, Geneva.

WMO, 1975 B — "Intercomparison of Conceptual Models Used in Operational Hydrological Forecasting". Operational Hydrology, Report No. 7, WMO-No. 429, Geneva.

Notiser och preliminära rapporter

Serie HYDROLOGI

Nr 1 Sundberg-Falkenmark, M
Om isbärighet.
Stockholm 1963

Nr 2 Forsman, A
Snösmältning och avrinning.
Stockholm 1963

Nr 3 Karström, U
Infrarödteknik i hydrologisk tillämpning:
Värmebilder som hjälpmedel i recipientundersökningar.
Stockholm 1966

Nr 4 Moberg, A
Svenska sjöars isläggnings- och islossningstidpunkter
1911/12 - 1960/61. Del 1. Redovisning av observationsmaterial.
Stockholm 1967.

Nr 5 Ehlin, U & Nyberg, L
Hydrografiska undersökningar i Nordmalingsfjärden.
Stockholm 1968

Nr 6 Milanov, T
Avkylningsproblem i recipienter vid utsläpp av kylvatten.
Stockholm 1969

Nr 7 Ehlin, U & Zachrisson, G
Spridningen i Vänerns nordvästra del av suspenderat materiel
från skredet i Norsälven i april 1969.
Stockholm 1969

Nr 8 Ehlert, K
Mälarens hydrologi och inverkan på denna av alternativa
vattenavledningar från Mälaren.
Stockholm 1970

Nr 9 Ehlin, U & Carlsson, B
Hydrologiska observationer i Vänern 1959 - 1968
jämte sammanfattande synpunkter.
Stockholm 1970

Nr 10 Ehlin, U & Carlsson, B
Hydrologiska observationer i Vänern 17 - 21 mars 1969.
Stockholm 1970

Nr 11 Milanov, T
Termisk spridning av kylvattenutsläpp från Karlshamnsverket.
Stockholm 1971

Nr 12 Persson, M
Hydrologiska undersökningar i Lappträskets representativa
område. Rapport I.
Stockholm 1971.

Nr 13 Persson, M
Hydrologiska undersökningar i Lappträskets representativa
område. Rapport II: Snömätningar med snörör och snökuddar.
Stockholm 1971.

Nr 14 Hedin, L
Hydrologiska undersökningar i Velens representativa område. Beskrivning av området, utförda mätningar samt preliminära resultat. Rapport I.
Stockholm 1971

Nr 15 Forsman, A & Milanov, T
Hydrologiska undersökningar i Velens representativa område. Markvattenstudier i Velenområdet. Rapport II.
Stockholm 1971

Nr 16 Hedin, L
Hydrologiska undersökningar i Kassjöåns representativa område. Nederbördens höjdberoende samt kortfattad beskrivning av området. Rapport I.
Stockholm 1971

Nr 17 Bergström, S & Ehlert, K
Stochastic Streamflow Synthesis in the Velen representative Basin.
Stockholm 1971

Nr 18 Bergström, S
Snösmältningen i Lappträskets representativa område som funktion av lufttemperaturen.
Stockholm 1971

Nr 19 Holmström, H
Test of two automatic water quality monitors under field conditions.
Stockholm 1972

Nr 20 Wennerberg, G
Yttemperaturkartering med strålningstermometer från flygplan över Vänern under 1971.
Stockholm 1971

Nr 21 Prych, A
A warm water effluent analyzed as a buoyant surface jet.
Stockholm 1972

Nr 22 Bergström, S
Utveckling och tillämpning av en digital avrinningsmodell.
Stockholm 1972

Nr 23 Melander, O
Beskrivning till jordartskarta över Lappträskets representativa område.
Stockholm 1972

Nr 24 Persson, M
Hydrologiska undersökningar i Lappträskets representativa område. Rapport III: Avdunstning och vattenomsättning.
Stockholm 1972

Nr 25 Häggström, M
Hydrologiska undersökningar i Velens representativa område. Rapport III: Undersökning av torrperioderna under IHD-åren fram t.o.m. 1971.
Stockholm 1972

Nr 26 Bergström, S
The application of a simple rainfall-runoff model to a catchment with incomplete data coverage.
Stockholm 1972

Nr 27 Wändahl, T & Bergstrand, E
Oceanografiska förhållanden i svenska kustvatten.
Stockholm 1973

Nr 28 Ehlin, U
Kylvattenutsläpp i sjöar och hav.
Stockholm 1973

Nr 29 Andersson, U-M & Waldenström, A
Mark- och grundvattenstudier i Kassjöåns representativa område.
Stockholm 1973

Nr 30 Milanov, T
Hydrologiska undersökningar i Kassjöåns representativa område.
Markvattenstudier i Kassjöåns område. Rapport II.
Stockholm 1973

SMHI Rapporter

HYDROLOGI OCH OCEANOGRAFI

Nr RHO 1	Weil, J G Verification of heated water jet numerical model. Stockholm 1974
Nr RHO 2	Svensson, J Calculation of poison concentrations from a hypothetical accident off the Swedish coast. Stockholm 1974
Nr RHO 3	Vasseur, B Temperaturförhållanden i svenska kustvatten. Stockholm 1975
Nr RHO 4	Svensson, J Beräkning av effektiv vattentransport genom Sunninge sund till Byfjorden. Stockholm 1975
Nr RHO 5	Bergström, S & Jönsson, S The application of the HBV-model to the Filefjell research basin. Norrköping 1976
Nr RHO 6	Wilmot, W A numerical model of the effects of reactor cooling water on fjordcirculation, I och II (bilaga till I). Norrköping 1976
Nr RHO 7	Bergström, S Development and application of a conceptual runoff model for Scandinavian catchments. Norrköping 1976