OPERATIONAL HYDROLOGICAL FORECASTING BY CONCEPTUAL MODELS

by S Bergström, M Persson and B Sundqivst

HYDROLOGISKA BYRÅN

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SVERIGES METEOROLOGISKA OCH HYDROLOGISKA INSTITUT
HYDROLOGISKA BYRÅN

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1. Background

The economic consequences of the fluctuations of discharge in the Swedish rivers are substantial. Around 60 % of the total demand of electric energy is satisfied by hydroelectric power. The power plants are relying upon the proper operation of reservoirs and thus hydrologic forecasts become important.

Flooding is a problem, which is not immediately associated to Sweden, but intense springfloods like the one in 1977, can cause heavy damage and costs for the society and the public. Therefore forecasts of floods are of interest, particularly in rivers, where the damping effect of lakes is small.

During extremely dry summers, like the one in 1976, forecasts can be of interest for the planning of local water supply in certain areas.

Since 1972 the Swedish Meteorological and Hydrological Institute (SMHI) has been engaged in the development of a conceptual runoff model suitable for operational forecasting and other applications under Scandinavian conditions.

The model is now in operation in ten catchments in Sweden, and forecasts are issued regularly every spring and on some occasions in autumn and winter.

The work is being financed almost entirely by contracts with river regulation companies and local authorities in the river basins concerned. The SMHI has, at present, no public hydrologic forecasting service.

2. Model structure and calibration

Due to limitations in the available database a very simple model structure had to be accepted. By the end of 1975 a model was developed and applied experimentally to eleven catchments in Sweden and Norway with results which justified to proceed towards its operational use.

The model was named the "HBV-model" from the section of the SMHI where it was developed. A general outline of the model structure is shown in fig. 1. More detailed presentations have been made by, for example, Bergström and Forsman (1973) and Bergström (1976).

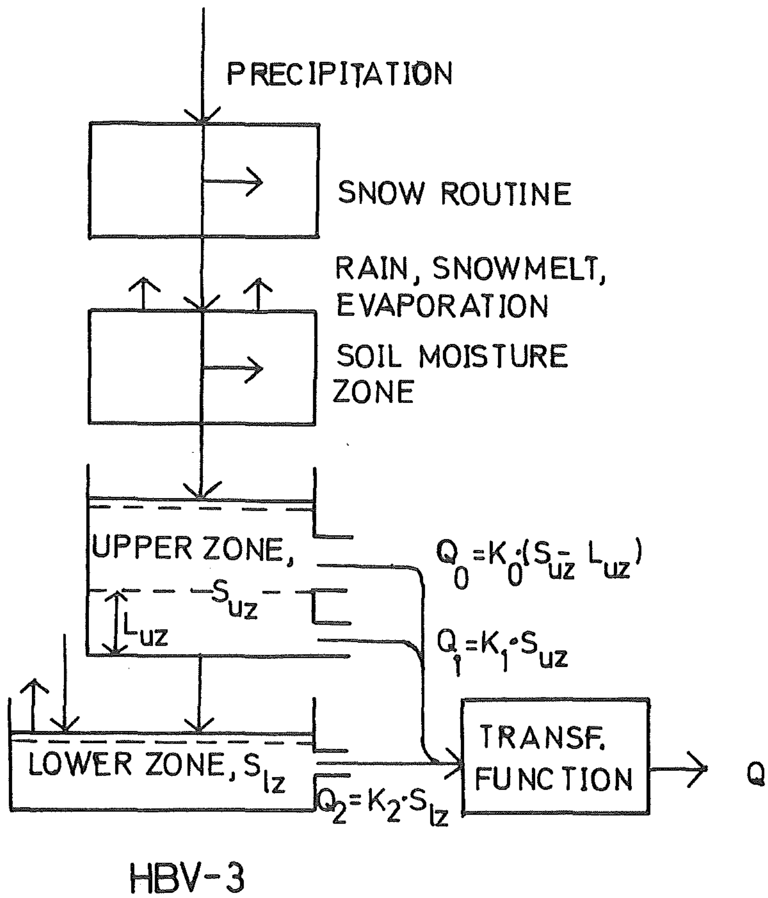

Fig. 1. The structure of the HBV-model.

The structure of the model can be separated into three main components.

1) A snow accumulation and ablation routine based on a degree day approach and individual computations in ten elevation zones.

2) A soil moisture accounting routine based on values of potential evaporation which are reduced to actual ones according to the present soil moisture state. The present soil moisture state is also a determining factor for the response of the model to input in the form of snowmelt or rain.

3) A response function with three near-linear components and a schematic time-area transformation.

The model is run on a daily basis with daily mean air temperatures, daily totals of precipitation and monthly standard values of potential evaporation computed for a 30-year normal period.

The HBV-model is indeed a very simple conceptual runoff model. Its complexity has been restricted by help of detailed studies of the sensitivity of the model to changes in its empirical coefficients. Therefore the model is also comparably easy to understand and handle and requires only small computer facilities.

The model has 13 empirical coefficients (parameters) which have to be estimated during its calibration. Many of these parameters have, however, proved to vary very little from catchment to catchment, a fact which simplifies the calibration procedure markedly.

The calibration procedure is based on subjective visual inspection of plotted hydrographs and by support of a sum of squares criterion of fit. Normally less than 20 test runs are needed if the model is calibrated by an experienced hydrologist.

3. Applications for operational forecasting

In the spring of 1978 the HBV-model was in operation for forecasts in 10 catchments in Sweden. Catchment size, number of climate stations and main purpose of the forecasts are shown in table 1 and the location of the catchments can be found in fig. 2. An example of the performance of the model is shown in fig. 3.

Table 1. Operational applications of the HBV-model in 1978

River	Catchment	Size (km^2)	Number of precipitation stations	Number of temperature stations	Main purpose
St. Luleälv	Porjus	2 863	4	2	regulation for power production
Ångermanälven	Kultsjön	1 109	3	1	
"	Malgomaj	1 862	3	1	
"	Ströms Vattudal	3 851	4	2	"
Ljusnan	Svegsjön	5 860	5	5	"
Dalälven	Trängslet	4 483	5	3	"
"	Stadarforsen	4 136	5	2	flood forecasting
Svartån	Karlslund	1 284	7	4	"
Emån	Blankaström	3 700	6	5	"
Tidan	Moholm	1 172	6	4	"

3.1. Data collection and processing

When operating the HBV-model we are relying upon the ordinary network of meteorological stations in Sweden. The data from the major part of this network is reported to the SMHI on a monthly basis. Therefore special arrangements have been made for the hydrological forecasting project which means that data are collected by telephone whenever needed. So far no automatic data collection and processing system is in operation, but work is in progress to minimize the amount of human interaction as far as possible. It is strongly felt that data collection

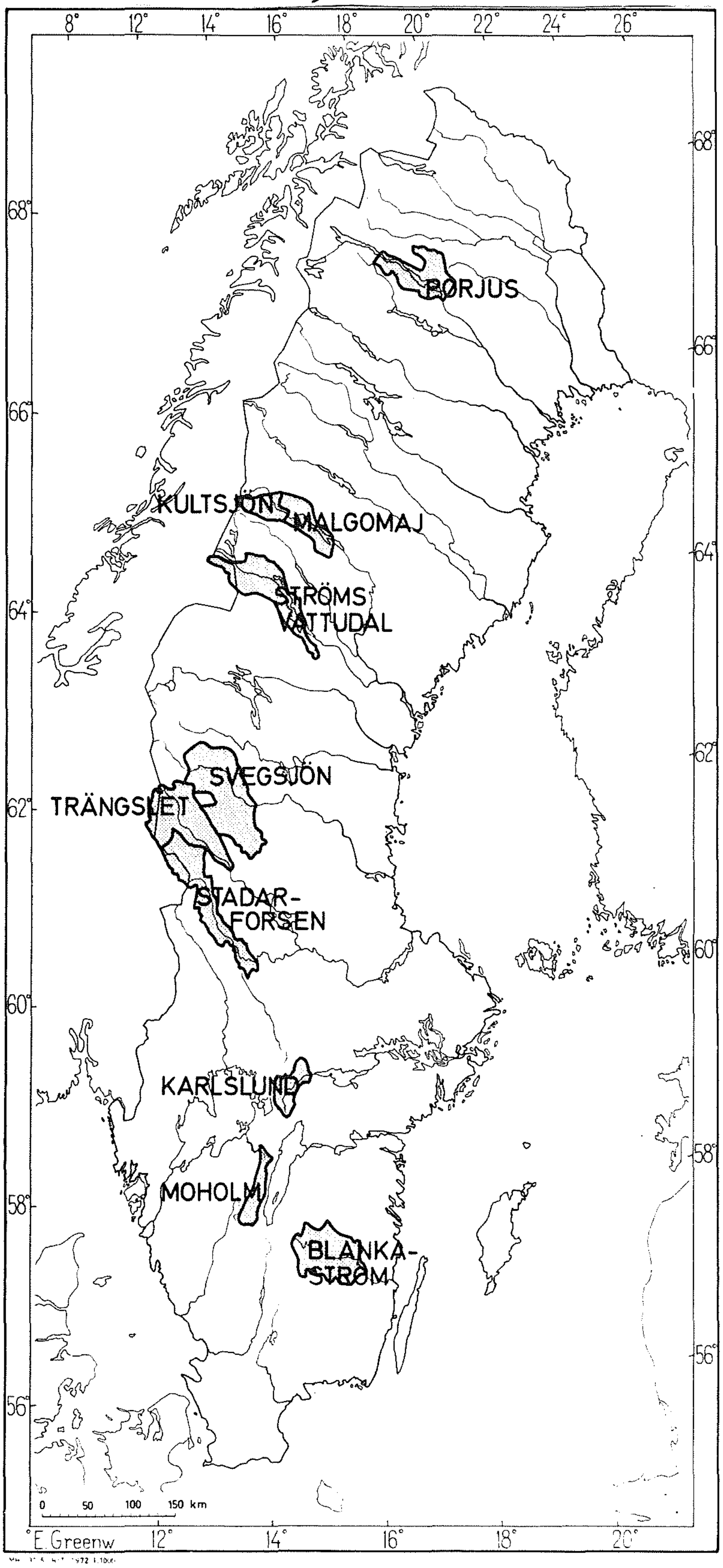

Fig. 2. Location of operational applications of the HBV-model in Sweden.

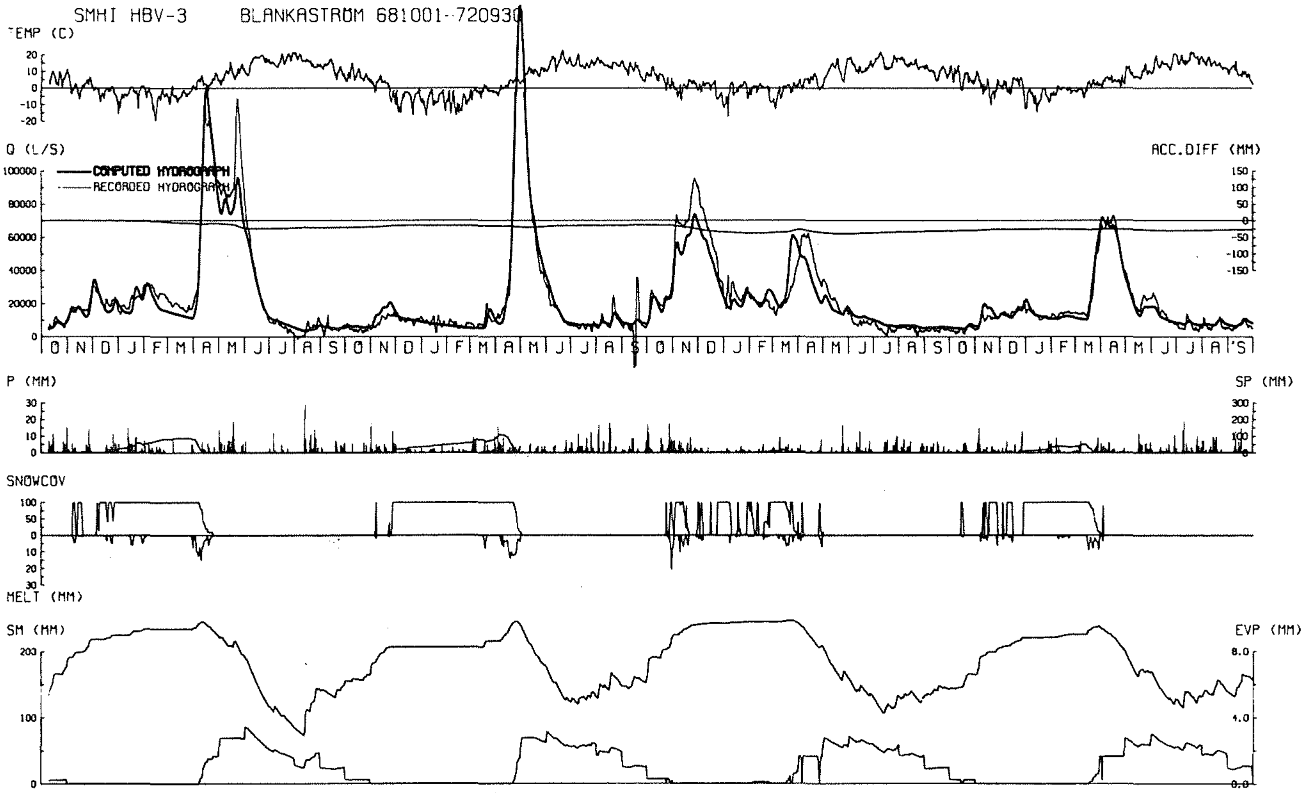

Fig. 3. Example of the performance of the HBV-model in Blanka-ström.

TEMP	=	air temperature (°C)
Q	=	discharge (l/s)
ACC.DIFF.	=	accumulated difference between computed and observed discharge (mm)
P	=	areal precipitation (mm)
SP	=	computed areal snowpack (mm water equiv.)
SNOWCOV	=	computed snowcovered area (%)
MELT	=	computed snowmelt (mm)
SM	=	computed soil moisture state (mm)
EVP	=	computed actual evaporation (mm)

and processing problems can easily limit the capacity of a forecasting service and the development of efficient systems is therefore of outmost importance.

3.2. Updating the model

Updating the model means running the model with the latest meteorological and hydrological data and preparing it for a forecast.

If the computed discharge values are deviating from the recorded ones on the day of the forecast, the persistence of the errors will disturb the forecast. This is also the case, if the model during a snowmelt period, has missed one snowmelt occasion and thus is entering another with a biased snow budget.

In order to avoid these sources of errors the model is adjusted to the latest discharge values before a forecast is issued. This can, of course, be made in many different ways. We have chosen to adjust input data during the updating period until a close agreement between the observed and the computed hydrograph is obtained. During snowmelt periods the updating is generally based on temperature corrections, but sometimes the latest precipitation values can be subjects to adjustment. This method has the advantage of being easy to handle and to understand and is also taking into account the adjustments in all the different storages of the model simultaneously.

The updating procedure has so far been run manually with subjective decisions of which meteorological variable to adjust. This part of the forecasting procedure requires a high degree of hydrological judgement and experience and is therefore difficult to handle by an automatic algorithm.

An example of a proper updating is shown in fig. 4.

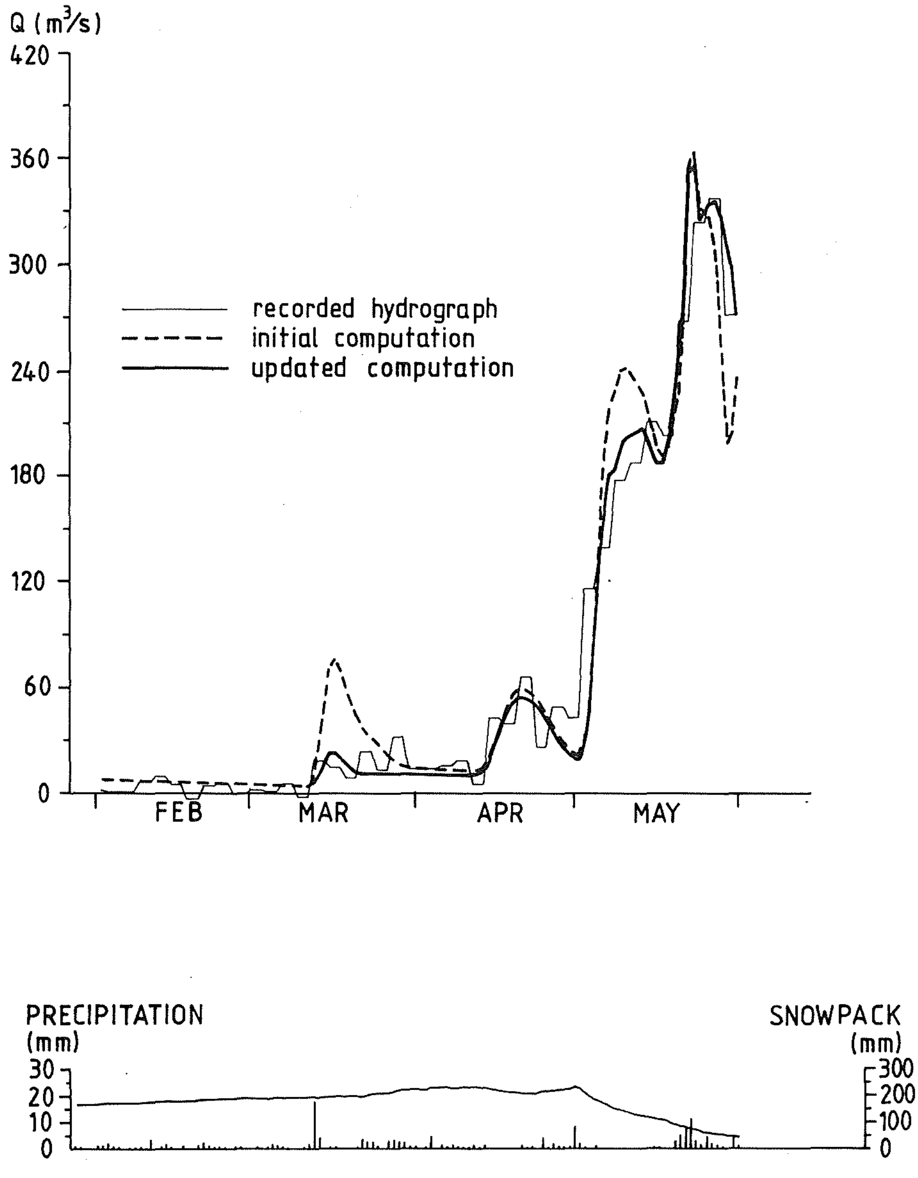

Fig. 4. Example of the effect of the updating routine during a snowmelt season (Ströms Vattudal, 1972).

3.3. Forecasting procedures

The forecasts are of three main types:

1) Short range forecasts
These are mainly based on meteorological forecasts over five days but are sometimes supplemented by alternative simulations with different weather conditions.

2) Forecasts of remaining springflood volumes
These are based on alternative simulations with historical recorded climate series starting from the actual snow, soil and runoff conditions as computed up to date by the model.

3) Estimation of risks for high floods
Alternative simulations as described under 2) are made and the simulated peaks are studied to estimate the risk for flooding. Sometimes these simulations of peaks are based on the conditions in the model at the end of a short range forecast.

An example of computer output from forecasts of the two latter types is shown in fig. 5 where each one of the plotted hydrographs represents a simulation based on the updated state of the model and a recorded climate series for one previous year. The simulations are thus providing us a distributed forecast which can be used for the estimation of probabilities. The last simulation is made with zero precipitation during the period in order to arrive at an absolute minimum forecast. This simulation is normally excluded from the statistical analysis of the simulations.

4. Results

In 1977 and 1978 forecasts have been issued by the HBV-model on altogether 133 occasions in the ten catchments shown in fig. 2. On most of these occasions both short range (type 1) and long range (type 2 and 3) forecast were produced, but some river regulation companies were merely interested in long range forecasting of volumes. On a few occasions only short range forecasts were issued. Below a few examples of forecast during 1977 and 1978 are compared to the outfall. More detailed analyses for some of the rivers can be found in VAST (1978) and Bergström (1977) and (1978).

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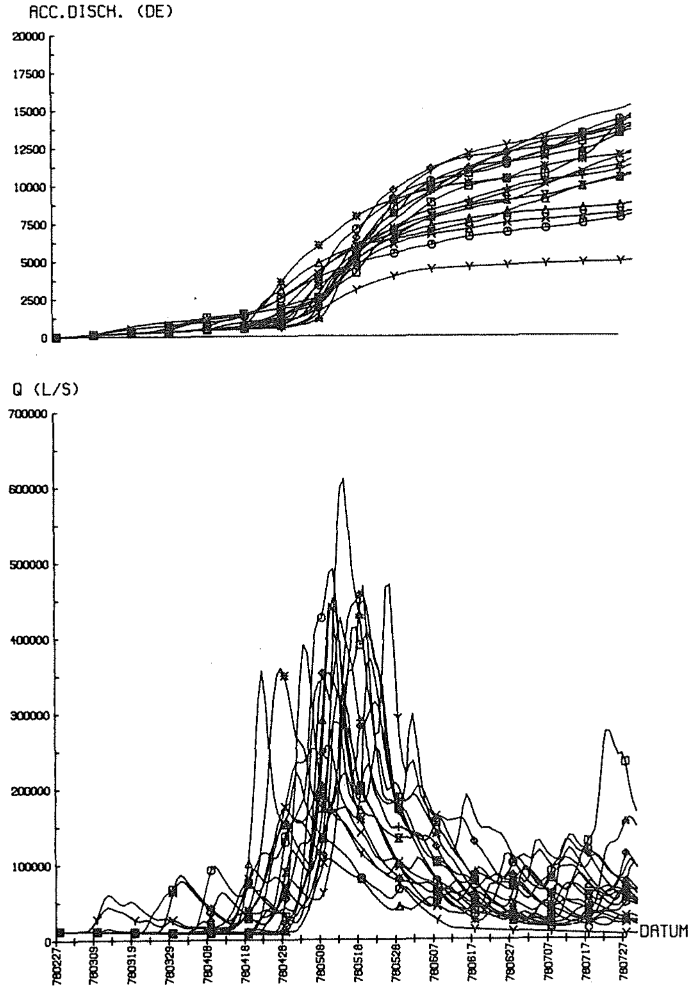

KLIMATSERIE AATAL		ACK. Q DE
1961		12160
1962		13570
1963		14490
1964		10700
1965		11620
1966		14340
1967		13760
1968		12020
1969		10610
1970		13860
1971		11220
1972		15200
1973		14600
1974		7970
1975		8720
1976		8190
1977		13990
1977	0-NDB	4930

KLIMATSERIE AATAL		FLODESTOPP M^3/S
1961		208
1962		413
1963		491
1964		356
1965		256
1966		458
1967		470
1968		360
1969		268
1970		611
1971		453
1972		353
1973		371
1974		159
1975		445
1976		328
1977		426
1977	0-NDB	202

Fig. 5. Example of long range forecasts of remaining inflow (ACC.DISCH.) and flood peaks (Q) by simulations with 17 climate series in Trängslet. The 18th simulation is based on the temperatures in 1977 and zero precipitation.

4.1. Porjus 1977

Fig. 6 is showing a summary of the forecasts of remaining local inflow to Porjus in 1977. The forecasted period is from the date of the forecast until the end of June. Each vertical line represents one forecast with its minimum, mean and maximum among the simulations (the simulation with zero precipitation is excluded).

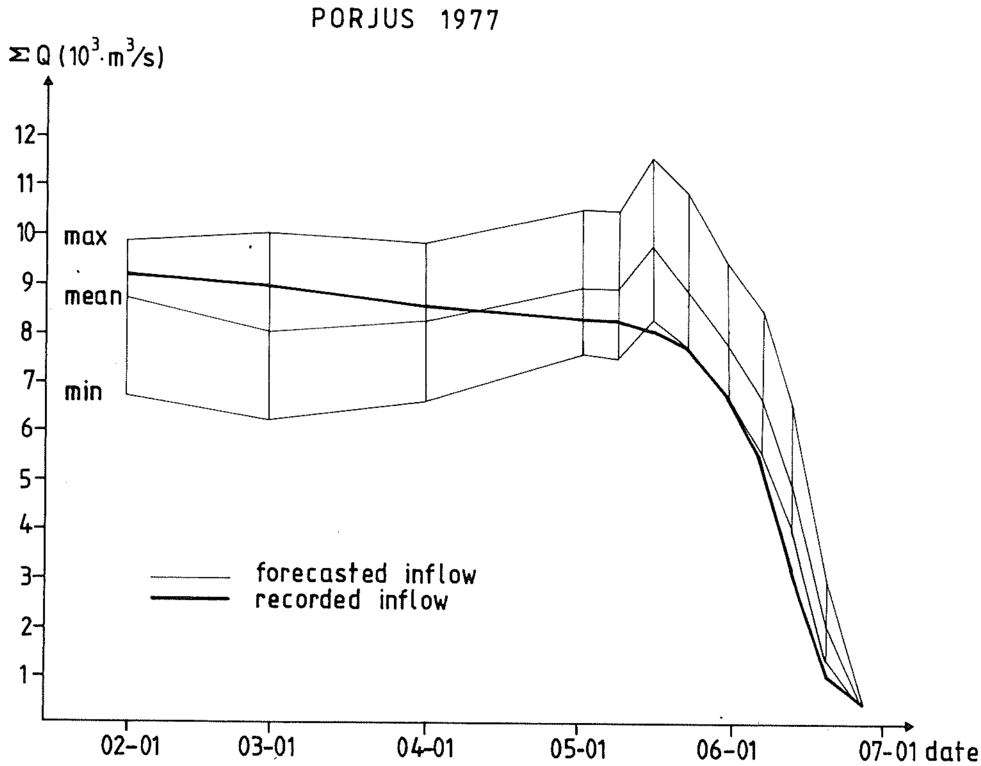

Fig. 6. Summary of the long range forecasts of the remaining inflow to Porjus from the date of the forecast until the end of June 1977, each forecast is based on 7 simulations.

The earliest forecasts were the most accurate ones while a bias in the snow accumulation of the model caused an overestimation of the remaining inflow for the last ones.

It is important to note that a close agreement between the mean forecast and the outfall in fig. 6 not always indicates a good forecasting model. If, for example, the period following the forecast is exeptionally dry, the forecast shall be an overestimation if the model is good. The most efficient way of telling wheather the deviation from the forecast is caused by the model or by extreme weather conditions is to run the model with actual input data for the period in question. A poor model performance can then be revealed by comparisons between the recorded hydrograph and the computed one.

4.2. Svegsjön 1977

Fig. 7 is showing results of the short range forecasts of inflow to Lake Sveg (Svegsjön) during the spring of 1977. As can be seen, the model, supported by good meteorological forecasts, managed to predict the start of the springflood and also followed the development fairly well.

The long range forecasts of remaining spring flood volumes to Svegsjön are shown in fig. 8. As for Porjus the overestimation is caused by a bias in the snowbudget, which, however, was corrected by the updating routine before the last forecast was issued.

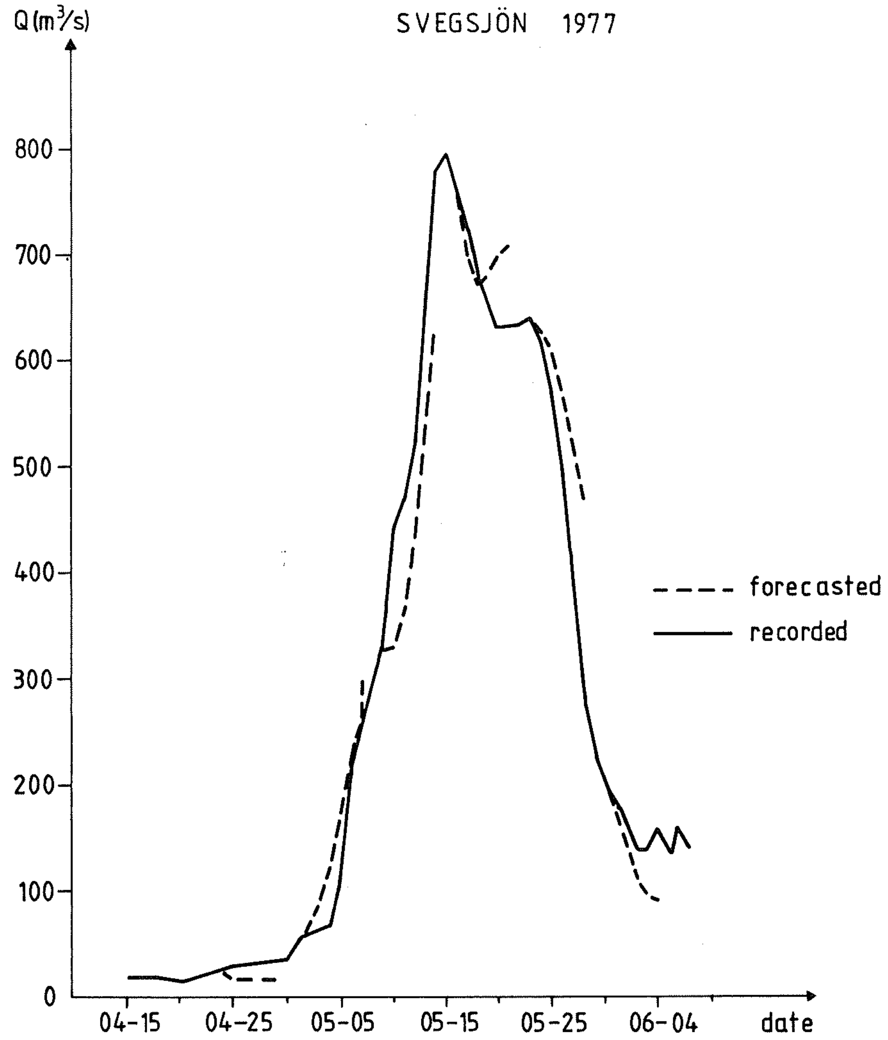

Fig. 7. Summary of the short range forecasts of the inflow to Svegsjön in 1977.

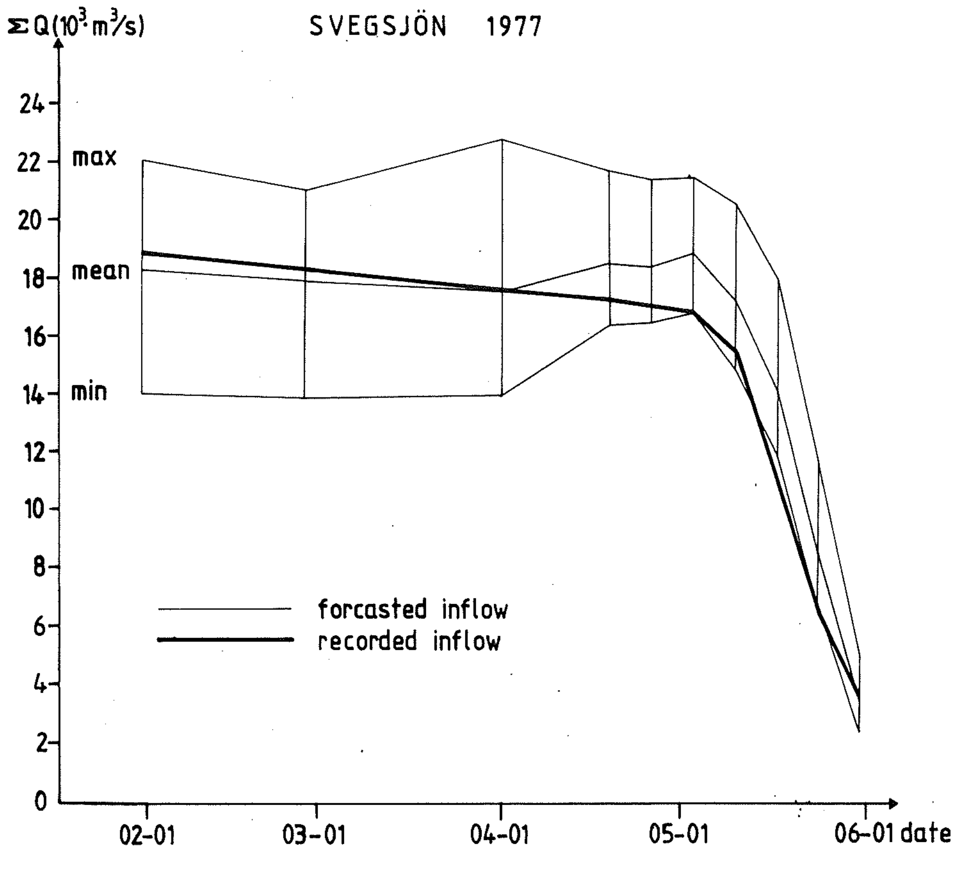

Fig. 8. Summary of the long range forecasts of inflow to Svegsjön in 1977, each forecast is based on 15 simulations.

4.3. Stadarforsen 1977 and 1978

The estimations of risks for high floods in Stadarforsen in 1977 based on forecasts of type 3 (excluding the zero precipitation simulation) are summarized in fig. 9. As can be followed in the figure there was an increasing risk during the spring caused by abundant precipitation and late snowmelt. The highest peak lies within the 50 % limits for four of the five last forecasts. The second flood peak, which caused some damage in the river basin, was a result of a combination of intense rainfall and snowmelt, i.e. rather extreme conditions.

STADARFORSEN 1977

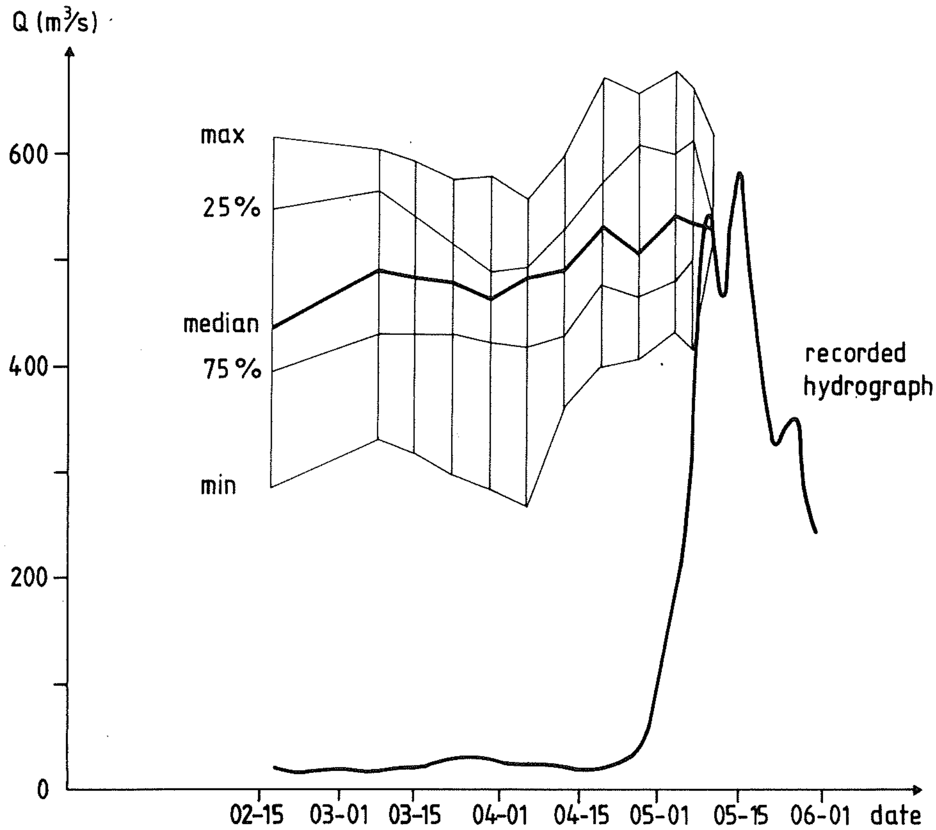

Fig. 9. Summary of the long range estimation of flood risks in Stadarforsen in 1977, each forecast is based on 16 simulations.

The short range forecasts in Stadarforsen 1977 are summarized in fig. 10. Fig. 11 and fig. 12 are showing the corresponding forecasts for 1978.

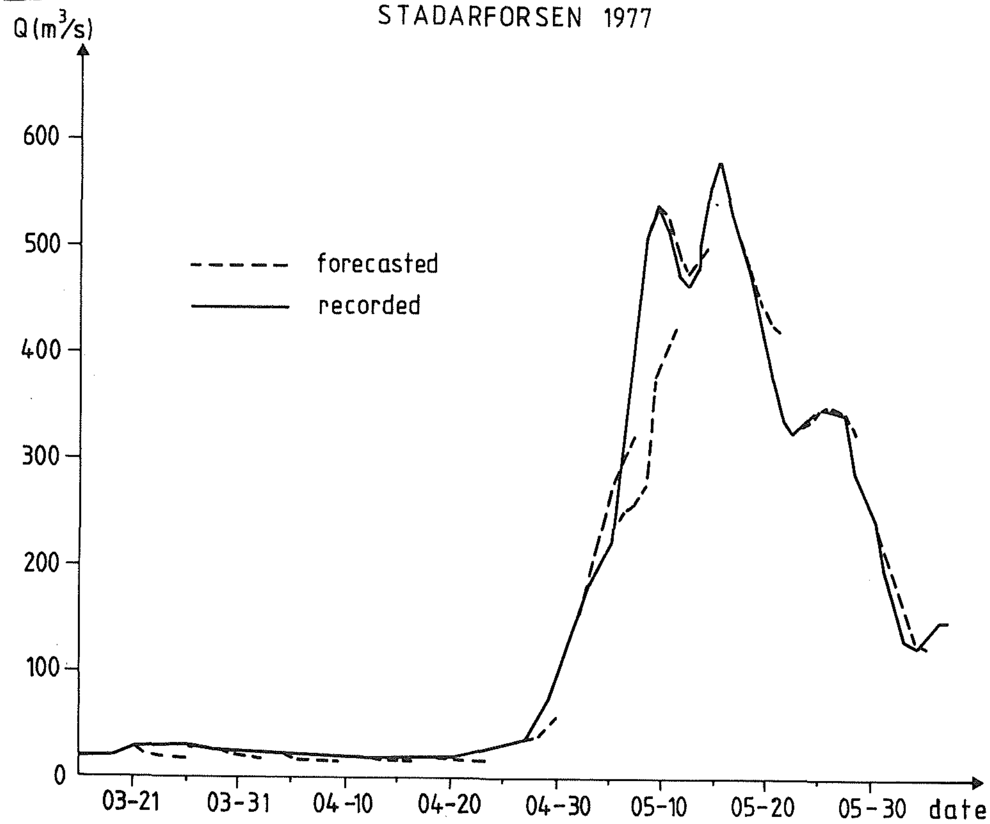

Fig. 10. Summary of the short range forecasts in Stadarforsen in 1977.

The last nine ones of the long range estimations of flood risks in 1978 are based on the state in the model after a short range forecast over 5 days. This method helped to narrow the interval between the maximum and the minimum simulation.

The long range estimations of flood peaks in 1978 are interesting as they showed a rather high risk in April (in the order of 25 %) for a flood of the same order of magnitude as the one in 1977. The risk, however, decreased substantially as soon as the first flood started in May, and it was clear that the spring-flood would pass in two steps.

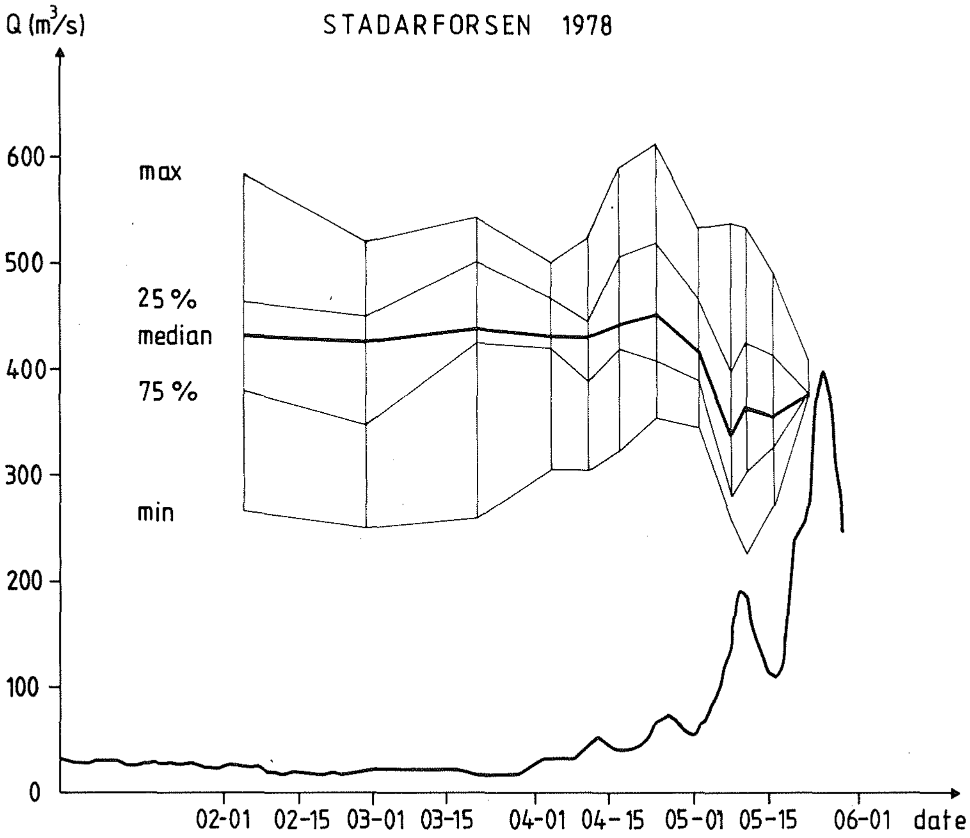

Fig. 11. Summary of the long range estimations of flood risks in Stadarforsen in 1978, each forecast is based on 17 simulations.

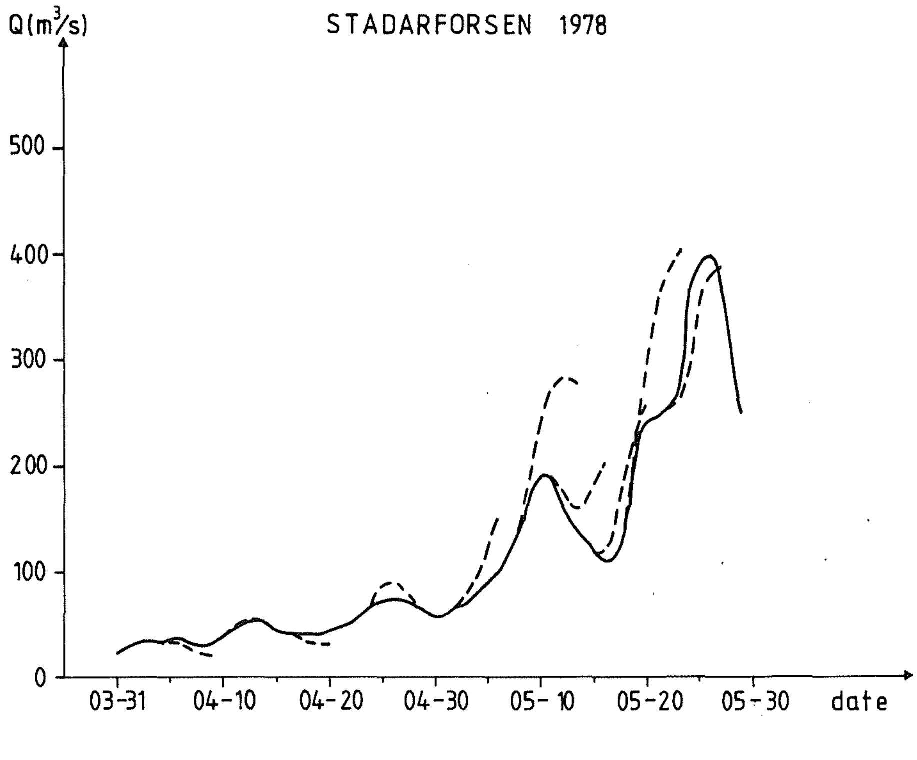

Fig. 12. Summary of the short range forecasts in Stadarforsen in 1978.

The short range forecasts in 1978 had a tendency to overestimate the meltrates. This problem has not been analysed in detail but cannot be blamed on the meteorological forecasts. This tendency did not show up during the 1977 forecasting period in Stadarforsen (fig. 10).

4.4. Moholm 1978

The three estimations of flood risks in Moholm (Tidan) in 1978 are shown in fig. 13 and a short range forecast of the culmination of the flood, based on two alternative simulations, is shown in fig. 14.

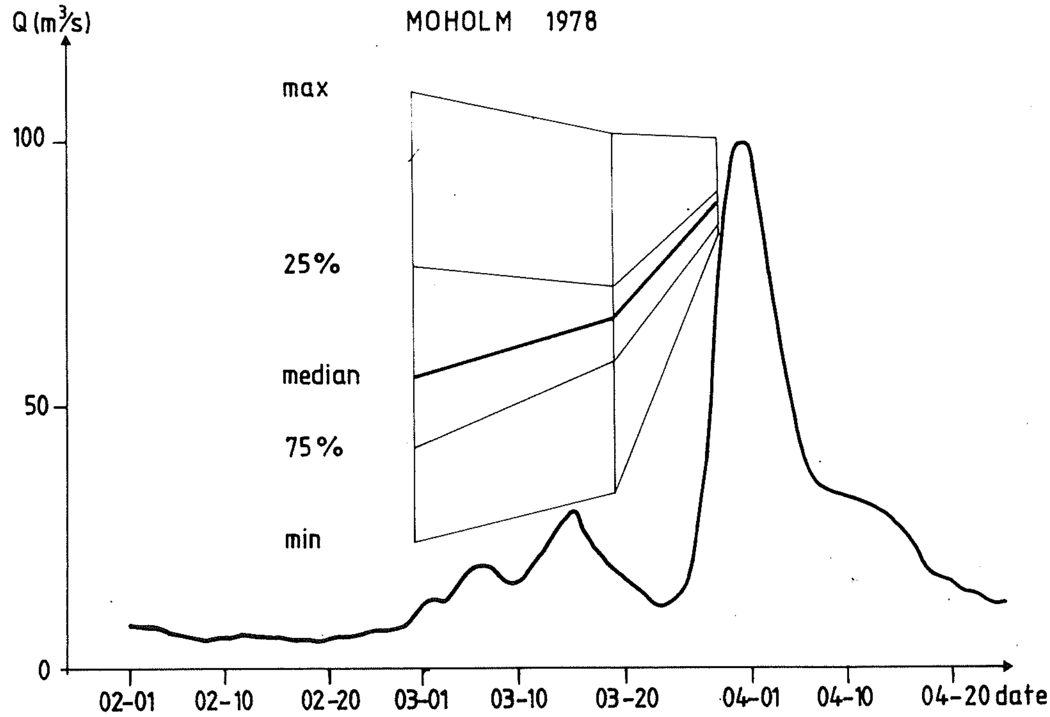

Fig. 13. Long range estimations of flood risks in Moholm in 1978, each forecast is based on 12 simulations.

The recorded flow was close to the upper extreme of the long range forecasts. This was due to extreme weather conditions. The short range forecast showed that the snow budget computations in the model were correct.

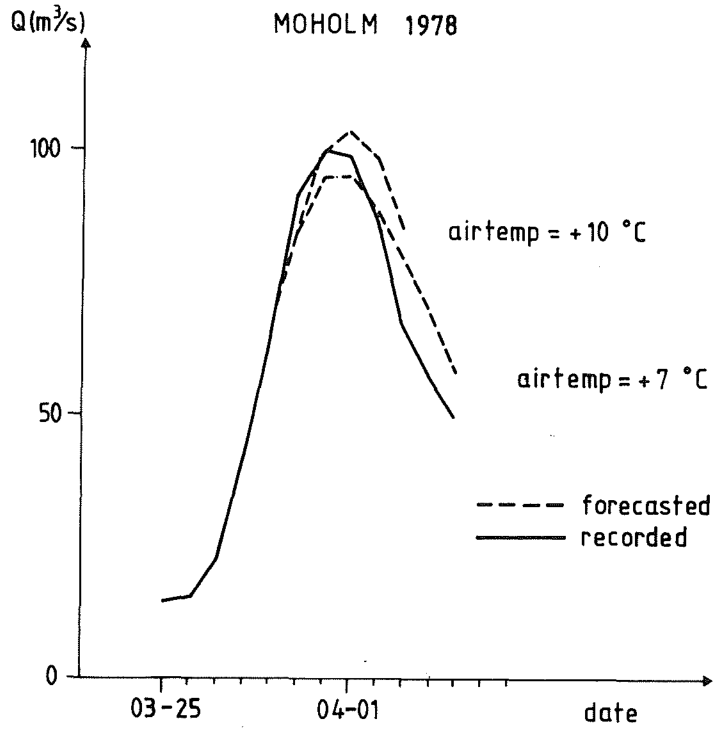

Fig. 14. Short range forecast in Moholm in 1978.

5. Computer and manpower requirements

The HBV-model is a comparatively small model and requires only moderate computer facilities. It was developed on a SAAB-D22 computer and has later been transferred to a SAAB-D23 and now a UNIVAC 1100-21 at the SMHI. A four years period of test run of the model on the UNIVAC-computer requires a CPU-time in the order of 80 sec.

The simple structure has made it possible to use a desk calculator for shorter computations. At the SMHI a Hewlett Packard 9821 with plotter has been used for the updating of the model provided the periods have not been longer than a few weeks.

At present the hydrologic forecasting system at the SMHI is being revised and in the future all computations and data handling will be made by the UNIVAC computer.

During the most intense forecasting periods in spring 2 - 3 hydrologists are engaged in forecasting. They are supported by one assistant who is collecting data by telephone.

6. Cost benefit

The cost of calibration of the HBV-model, when made on contract, is in the order of 60 000 Sw.crs. (13 000 U.S. dollars, 1978). The figure varies depending on the amount of data to be handled and on the complexity of the particular catchment. The costs for one forecast is also variable and depends on the number of meteorological stations, the length of the updating period and the type of forecast among others. A realistic figure is around 1 000 Sw.crs per forecast (220 U.S. dollars, 1978).

The costs for calibration and operation of the model are small compared to the value of the water which to-day is leaving the hydroelectric power plants through the spillways instead of through the turbines. It is, however, very complicated to estimate exactly how much the losses could be reduced by better hydrological forecasts. This question was discussed in Sweden by the VAST-group on hydrological models (VAST, 1978). A very tentative estimation made by the VAST-group for River Dalälven indicated that an average gain of 20 GWh/year might be a realistic figure in this particular river. The hydroelectric power production in Dalälven represents approximately 1/15 of the total Swedish hydroelectric power production.

This cost-benefit analysis is far from complete and can only serve as an example of potential benefit of reliable hydrological forecasts. The figures indicate, however, that the costs of model calibration and operation are small compared to the potential for increased hydroelectric power production.

A cost-benefit analysis for forecasts of high floods and flooding is even more difficult. It is, however, clear that the spring-flood in central Sweden in 1977 created damage for tens of millions of Sw. crs and that some of the private property destroyed could have been saved, if detailed forecasts were at hand in the critical rivers. Flood forecasting for the public is, however, not only a question of cost-benefit in its monetary sense. It has a psychological aspect as well which must not be neglected.

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