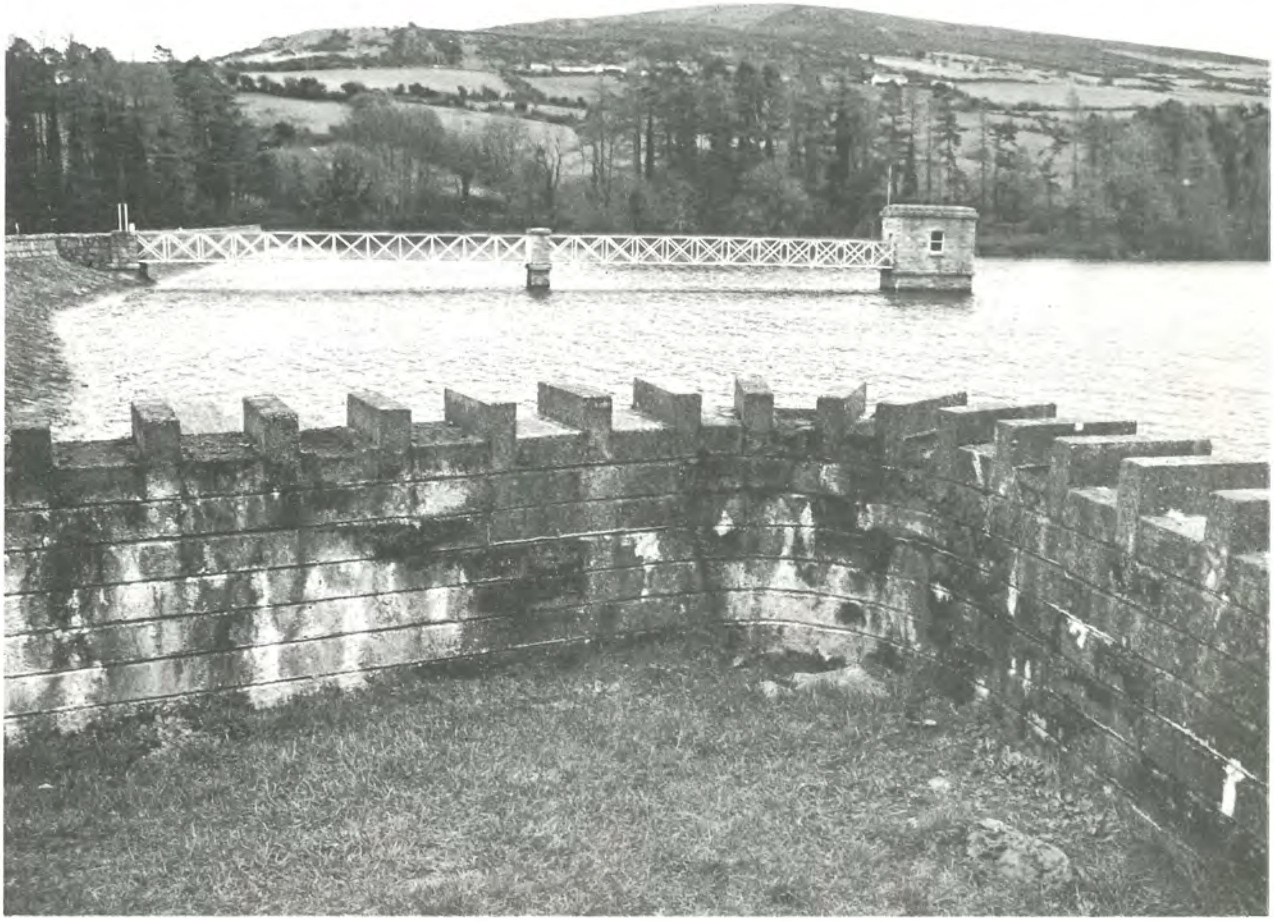
No. 14, 1998

SMHI

Reports Hydrology



The TELFLOOD project
Rainfall – Runoff Modelling and Forecasting

Bengt Carlsson and Sten Bergström

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Cover photo: The Dodder Reservoir, January 1998. Photo Bengt Carlsson.

CA-Tryck AB Norrköping 1998

Report Summary / Rapportsammanfattning

Issuing Agency/Utgivare	Report number/Publikation
Swedish Meteorological and Hydrological Institute SE-601 76 NORRKÖPING Sweden	RH No. 14
	Report date/Utgivningsdatum May 1998

Author (s)/Författare

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Title (and Subtitle)

The TELFLOOD project. Rainfall-Runoff Modelling and Forecasting

Abstract/Sammandrag

The aim of the TELFLOOD project is to improve methods for hydrological forecasting in steep catchments. The hydrological modelling task of SMHI has been to improve the HBV model and to develop and test routines for model updating and forecasting.

A new response routine, based on the variable contributing area concept, has been developed and proved to be successful in several experimental basins in Sweden, Italy and Ireland. The technique uses the contributing area in a way that is consistent with the procedure for soil moisture accounting and does not require further free parameters. Model improvements are significant to the standard HBV-96 version, in particular as concerns minor floods after dry periods.

A new updating routine, based on state corrections of the storages of the HBV model, was developed and tested. For some events it proved to be more efficient than the standard method based on input corrections.

Key words/sök-, nyckelord

hydrological modelling, hydrological forecasting

Supplementary notes/Tillägg	Number of pages/Antal sidor	Language/Språk
	28	English

ISSN and title/ISSN och titel
0283-1104 SMHI Reports Hydrology

Report available from/Rapporten kan köpas från:
SMHI
SE-601 76 NORRKÖPING
Sweden

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1. Introduction

The purpose of the TELFLOOD project is to develop methods for flood forecasting. Participating institutions are the Centre for Water Resources Research in Dublin Ireland (CWRR), the Irish Meteorological Service (IMS), the Swedish Meteorological and Hydrological institute (SMHI) and Dipartimento di Ingegneria della Strutture, dei Transporti, dell'Acqua, del Rilevamento e del Terratorio, University of Bologna, Italy (DISTART).

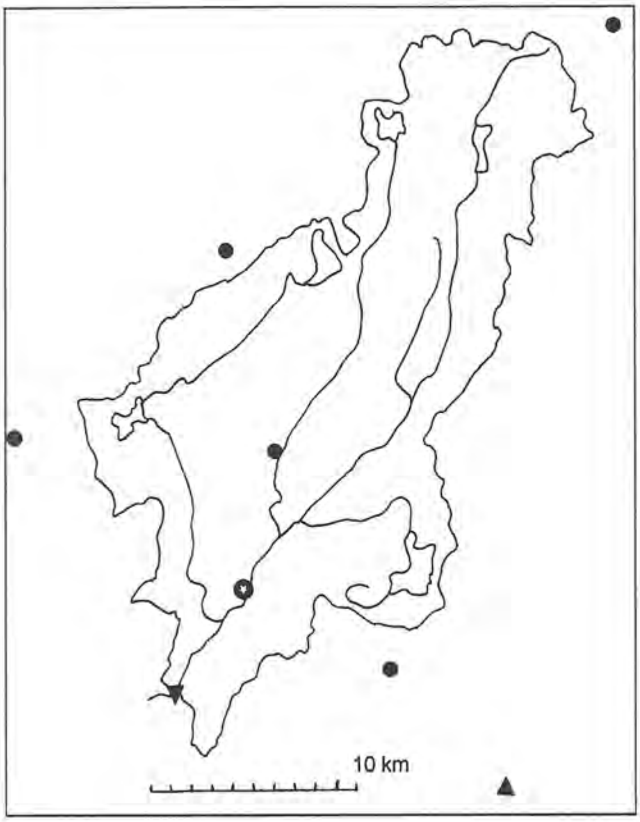
The project focuses on steep mountainous areas and other catchments with quick response. Special attention is also given to snow melt conditions in the Swedish mountains. Two of the Swedish basins were chosen because of their significance for hydropower production.

The heart of a hydrological forecasting procedure is the hydrological model or models, if an explicit routing model is included in the system. The better the simulation is the better will the forecasts become. The hydrological task at SMHI was to modify and improve the capacity of the HBV model to transform meteorological forecasts into forecasts of runoff. The hydrological model shall be able to produce both long term forecasts and forecasts shorter than 24 hours. Simulated runoff data from the Swedish HBV model were also delivered to the Irish CWRR for analysis and comparisons with simulations with other runoff models.

Fig. 2.1 *The TELFLOOD project experimental catchments in Ireland, Italy and Sweden.*

2. The experimental basins

The primary experimental basins were Pepparforsen in Sweden, Dodder in Ireland and Reno in Italy, all chosen to represent different kinds of catchments. These basins were later supplemented with some additional Swedish catchments, Tånemölla, Gävunda and Höljes (Figure 2.1.).



- ● Climate station with data every 24 h.
- ▲ Synoptic station with data every 12 h.
- ✪ Automatic meteorological station (not in use).
- ▼ Automatic discharge station.

Fig. 2.2 *The Pepparforsen catchment.*

Pepparforsen is a small unregulated lowland basin in southern Sweden almost without lakes (Figure 2.2.). The total area of the catchment is 380 km^2, divided into 2.5% lake, 73.5% forest and 24% open land. The response to rain is fast. There are seven nearby meteorological stations, one of which is a synoptic station which deliver data once every six hours. There was no division into subbasins in the model, but the area was divided in 5 elevation zones, from 72 to 211 m.a.s.l. The average elevation is 143 m.a.s.l. The Pepparforsen basin was chosen as suitable for development and test of the forecasting routines in the HBV model.

The total area of the Tånemölla catchment, also in southern Sweden, is 102 km^2 and it consists almost entirely of open land. There are five meteorological stations, which were used in the simulations. The basin was divided into two subbasins, of which the smallest near the outlet has a very fast response as it preferably consists of urban areas. The average elevation is less than 100 m.a.s.l. The Tånemölla basin was chosen as suitable for tests of the new response-routine in the HBV model described in Chapter 3.

More than 90% of the Höljes catchment is situated in Norway. The total area of 6 002 km^2 was divided into 7 subbasins, one of which is dominated by the great lake Femunden. The surface of Femunden is 203 km^2. The western part of the catchment is mountainous and the average elevation here is around 800 m.a.s.l. Data from some 20 Swedish and Norwegian climate station were used for the simulations.

The Gävunda catchment is a subbasin to one of the largest rivers in Sweden, river Dalälven. Dalälven is regulated and so is the Gävunda catchment. The simulations are thus made on reconstructed natural discharge at the outlet. The total area of Gävunda is 2 073 km^2. It is divided into three modelled subbasins and the number of climate stations used is around 15. The average elevation is some 400 m.a.s.l. and lake percent is 7%. The Höljes and Gävunda basins were chosen to test the new model routines under snow conditions.

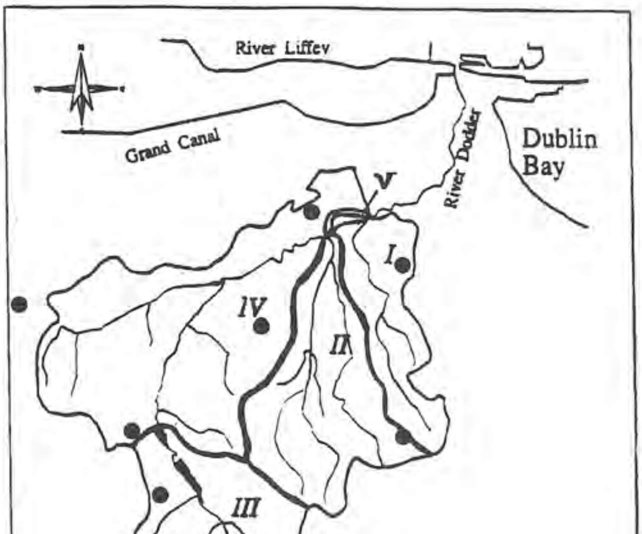


Fig. 2.3 *The Dodder catchment with precipitation stations.*

The Dodder catchment (Figure 2.3) is situated just south of Dublin in Ireland. The total area is 113 km^2 and it is all considered as open land in the modelling work. In its upper part there are two more than 100 years old reservoirs for water supply for the Dublin area. The elevation of the total catchment ranges from about 750 m.a.s.l. to near sea level. For the modelling work the area has been divided into five parts. Number five is a small area used sum up the runoff from the other subbasins to the outlet.

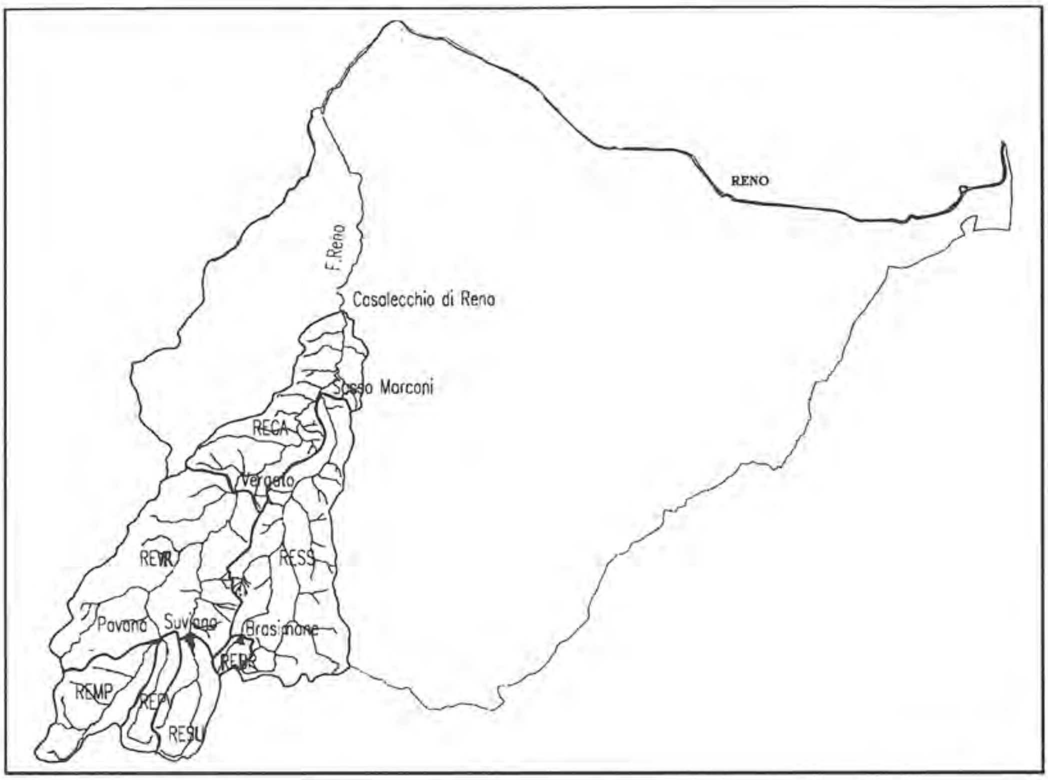


Fig. 2.4 *The Reno catchment at Casalecchio.*

During past centuries there has been a number of disastrous events in the Reno river in northern Italy. The mouth of the Reno is in the Adriatic sea (Figure 2.4.). A subbasin at Casalecchio of upper Reno was chosen as an experimental catchment in the TELFLOOD project. At Casalecchio the area is 1 051 km^2. The southern part of the Casalecchio basin is very steep and it reaches an elevation of over 2 000 m in the Apennines (AFORISM, 1996). Reno at Casalecchio, with 7 subbasins, was simulated with help of 26 precipitation stations and 10 temperature stations.

3. The model and the model modifications

3.1 The HBV model

The runoff-model used is the Swedish HBV model. It was originally developed in the 1970s by the Swedish Meteorological and Hydrological institute (SMHI) and has been improved and upgraded many times over the years (Bergström and Forsman, 1973; Bergström and Lindström, 1992; Bergström 1992, 1995; Gardelin and Lindström, 1996). The latest version, HBV-96, was used in the project (Lindström et. al. 1997). A schematic outline of HBV-96 can be found in Figure 3.1. It can be classified as a semi-distributed conceptual model and uses subbasins as primary hydrological units. Within these an area-elevation distribution and a crude classification of land use – forest, open and lake – is made. The model has seem proved to be a very useful tool both in practice -hydropower, water resources and so on- as well as in research applications. It has been applied in some 40 countries world-wide.

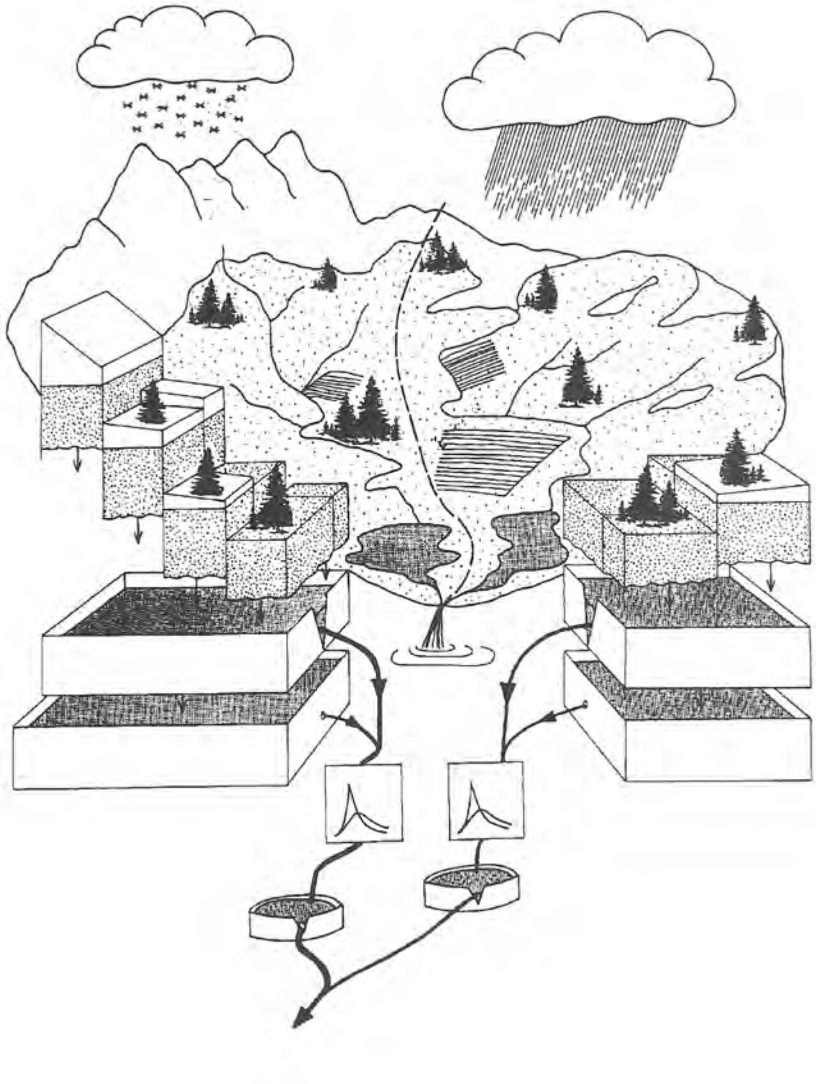


Fig. 3.1 *Principle structure of the HBV-96 runoff model.*

Input data are precipitation, temperature and potential evapotranspiration. Normally, monthly standard values of potential evapotranspiration are sufficient, but daily values can also be used as input or even calculated within the model from air temperatures (Lindström et. al. 1994). The model has a number of free parameters, values of which are found by calibration. There are also parameters describing the geographical characteristics of the basin.

3.2 A new approach to catchment response in the HBV model

When developing the HBV model in the early 1970s the statistically distributed model was the only practical approach to the problem of soil moisture accounting in an operational runoff model in basins with as poor data coverage as in northern Sweden. It was shown that the dynamics and basinwide variability of the soil could be satisfactorily described by a few simple equations representing how the ground responds to snowmelt and rain, and how evapotranspiration is reduced as the soil dries out, Figure 3.2 (Bergström and Forsman, 1973). A very similar approach is the cumulative distribution function later used for soil moisture simulation in the ARNO rainfall-runoff model (Todini, 1995). The approach has also found its way into climate modelling (Dümenil and Todini, 1992).

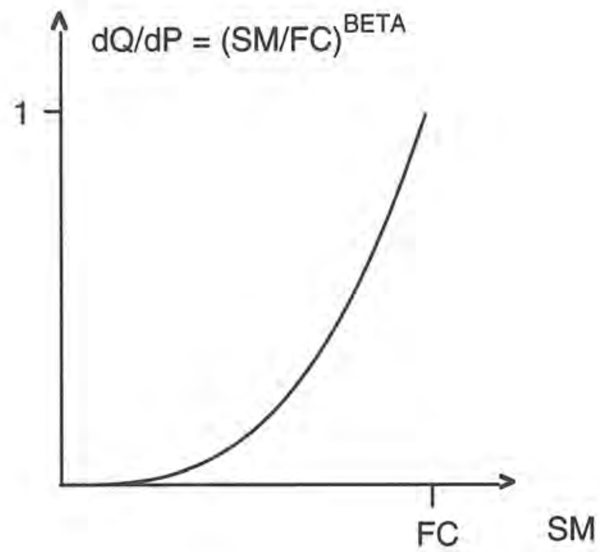


Fig. 3.2 *The runoff generation response (dQ) to increments of rain or snowmelt (dP) used in the HBV model since its introduction. SM is a variable representing the total soil moisture storage in the model, FC and BETA are empirical parameters.*

Initially the approach emanates from the oversimplified bucket theory with the very important additional condition that the water holding capacity of the soil in the basin has a statistical distribution. FC corresponds to the maximum basinwide water holding capacity of the soil and BETA describes how the runoff coefficient increases as this limit is approached. BETA is thus more an index of heterogeneity than of soil properties in the basin. Changes to this single parameter represent a great variety of conditions. A BETA-value of zero implies that the basin is entirely lacking in water-holding capacity in the soil, whereas a high BETA-value indicates such homogeneous conditions that the whole basin may be regarded as buckets that overflow simultaneously when their field capacity is reached.

Today a number of HBV model versions have been developed, but the parameterisation of soil moisture dynamics is still the same in the latest version, HBV-96, 25 years after the introduction of the model. Unfortunately the rest of the model is not consistent with theory behind this statistically distributed soil moisture accounting procedure.

3.3 A critical view of the response function of the HBV model

Everyone experienced with the HBV model has sometimes met the frustration when trying to calibrate its response function. There seems to be some built-in rigidity which makes it difficult to match flood peaks in summer and winter with the same parameter settings. Normally the recession is less steep when the catchment is wet than after a peak in summer. This results in a compromise in calibration and often in poor model performance during low flows, as these have little weight in the normally used R^2 criterion of fit.

The problem was discussed in detail by Bergström and Lindström (1992) who proposed a solution, based on recharge and discharge areas, which behave differently during wet and dry ground conditions. The results were promising, but unfortunately the method resulted in overparameterisation problems and severe interaction between previously independent model parameters. The basic idea, however, was brought up within the TELFLOOD project, with a more parameter-efficient approach.

The main point is that runoff during wet conditions is generated from more or less the whole catchment, while only a smaller fraction of the catchment and its corresponding aquifers are active during a dry spell. This fraction is normally situated in lower parts adjacent to the streams. Thus the active superficial aquifers, represented by **UZ** in the HBV model, are much smaller at peaks which occur during a dry period, and will be emptied faster if the outflow is the same as the one during wet conditions. This leads to faster recession when the catchment is dry.

If we look at the response function of a standard HBV model (Figure 3.3) we can see that it is too rigid to be able to describe seasonal dynamics in runoff response. First we have the drainage of the upper zone, $\mathbf{Q_{uz}}$, which is increasing non-linearly but without any seasonal changes in the recession coefficients. Then we have the percolation from the upper zone to the lower zone, representing percolation into deeper aquifers, which is kept constant by the parameter **PERC** as long as water is available in the upper zone, no matter how wet or dry the catchment is. If we accept the distribution approach in the soil we should be consistent and apply it to these two components of the response function as well.

3.4 A new response routine

One possible key to the solution of the problems of the traditional response routine lies in a more consistent use of the expression for areal wetness illustrated in Figure 3.2.

$$\mathbf{(SM/FC)^{BETA}}$$

This expression represents the contributing area, or the non-dormant part of the catchment and is governing catchment response in the soil moisture accounting routine of the model. It should be used more consistently through the model. In practise this means that deep percolation, represented by **PERC** (Figure 3.3), should be replaced by

$$\mathbf{PERC = C \cdot (SM/FC)^{BETA}} \qquad (1)$$

where C is the empirical coefficient to be calibrated. The rationale is that only the wet fraction of the catchment is active and thus participate in the filling of deeper aquifers under dry conditions. Percolation will thus be smaller.

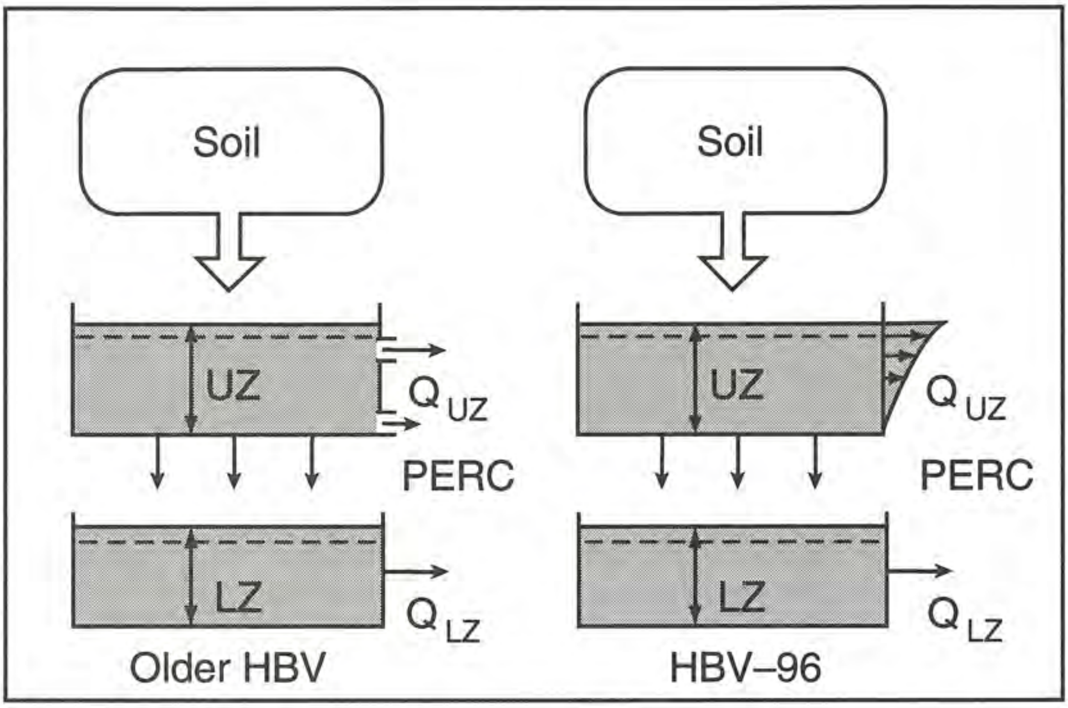


Fig. 3.3 *Schematic of the response routine of an older HBV model and the recent HBV-96 model version*

The analysis of the effects of the contributing-area concept on the recession coefficients is more complex. A recession coefficient represents the percentage of a modelled reservoir or storage that is emptied during one model time-step. In the upper zone of older HBV model versions this is modelled in a non-linear way by help of two recession coefficient and one threshold value and in the latest HBV-96 model the non-linearity is expressed by one recession coefficient, **K**, and the exponent **(ALFA+1)** according to:

$$Q_{uz} = K \cdot UZ^{(ALFA+1)} \qquad (2)$$

Where Q_{uz} represents generated runoff from the upper zone of the model.

If we assume that only the fraction $(SM/FC)^{BETA}$ of the basin is active during a dry spell, we have to assume that the upper zone only has the corresponding horizontal extension. This means that the runoff is generated from a smaller area of active aquifers than during a wetter period. Therefore the storage in these aquifers, as represented by the upper zone, **UZ**, in the model, has to be replaced by $UZ/(SM/FC)^{BETA}$ if we want to maintain the volume of water stored in the catchment. If we replace **UZ** in eq. 2 with this expression runoff generation from this new reduced upper zone of the model will be expressed as:

$$Q_{uz}=K \cdot (UZ/(SM/FC)^{BETA})^{(ALFA+1)} \qquad (3)$$

The effect is rather dramatic. If the soil is dried out to half of its field capacity and we assume normal values of ALFA (1.0) and BETA (2.0) the recession from the upper zone will be as much as 16 times as rapid. It is however limited by the fact that it can never exceed a value of 1. Deep percolation will also be subject to a rather drastic change under the above conditions (BETA=2, SM/FC=0.5). **PERC** will be reduced to 25% of its value and the time available for deep percolation will be reduced due to the increased recession from the upper zone. Together this means considerably lower modelled percolation and thus also lower modelled base flow during dry spells. Equally important is that the low value of **PERC** will trigger modelled peaks, even at moderate amounts of effective precipitation. This is in accordance with experience in many catchments, as mentioned above. The overall behaviour of the proposed new routine is schematically described in Figure 3.4.

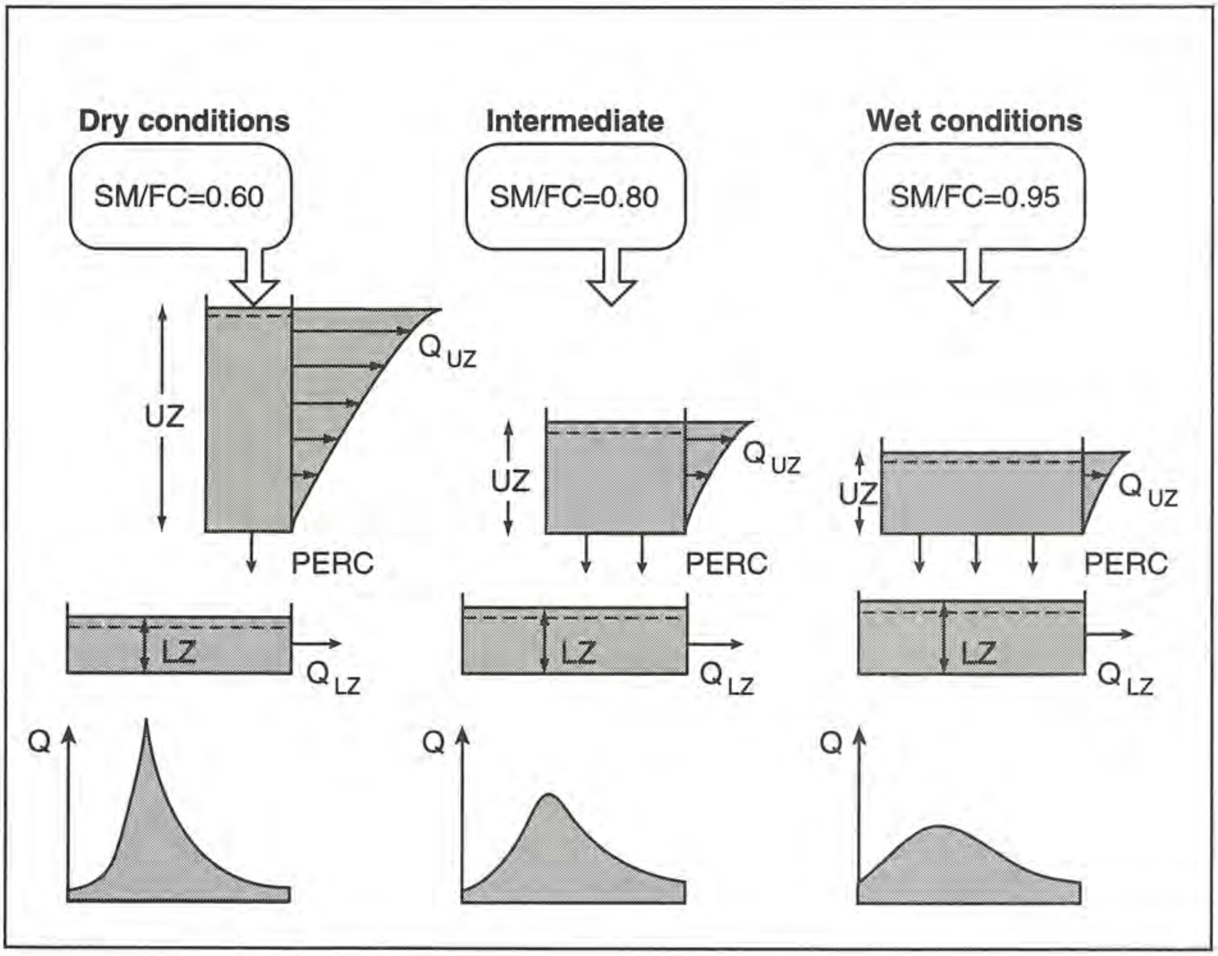


Fig. 3.4 *Principle behaviour of the tested new response routine for the HBV model. The input from the soil is assumed to be identical in this example.*

3.5 Test of the new routine

Test of the new routine is still in progress but the results look so far encouraging. The new model routine has been tested in the catchments in Sweden, Italy and Ireland (Table 3.1). The catchments are described in Chapter 2.

The most simple way to find out weather the new routine gives a better simulation than the other is just to inspect the simulated graphs. Generally also the criterion R^2 is used. The difficulty is that this criterion gives relatively little guidance with respect to the low flow periods, which are the most interesting ones for this model modification. Nevertheless R^2 values are shown in Table 3.2. For the Dodder catchment the whole available period was used for calibration.

Table 3.1 *Catchments involved in the TELFLOOD project and modelled periods for test of the new response routine of the HBV model.*

Catchment	Calibration period	Validation period
Gävunda, 2 073 km^2, Dalälven, Central Sweden	1990-93	1994-96
Höljes, 6 002 km^2, Klarälven, Central Sweden	1990-93	1994-96
Tånemölla, 102 km^2, Southern Sweden.	1980-90	1991-96.
Pepparforsen, 380 km^2, South-western Sweden.	1980-90	1991-96.
Reno, 1053 km^2, Northern Italy.	1990-93	1994-95.
Dodder, 113 km^2, Eastern Ireland.	1992-95.	No validation.

Figure 3.5 - 3.6 show the differences in general behaviour, exemplified for the TELFLOOD experiment catchments Tånemölla and Reno. The graphs look similar for all catchments. They all show pronounced improvements of low flow simulations and also of some peaks like in the catchments Dodder and Reno (Figures 3.7 and 3.8.). Special attention should be given to the simulation of the Gävunda catchment (Figure 3.9.). For the hydrological year 1995-96 the old model failed to simulate the natural runoff during the winter. Here, and also in Figure 3.10, we have examples of how the new routine is able to improve the results also during wintertime. The reason for this is that recharge to deep groundwater is reduced in fall and thus the winter base flow will be lower.

The general effect of the new procedure can be summarised in the duration curve and scatter diagram as illustrated is for the Dodder basin in figure 3.11. The new routine decrease the flow at low flows and increase the flow at higher flows.

Table 3.2 *Results, expressed as R^2, for the proposed structure as compared to HBV-96. All results, except for Tånemölla, are achieved by automatic calibration.*

Calibration:	HBV-96	New model	Validation: HBV-96	New model
Tånemölla	0.886	0.856	0.876	0.879
Pepparforsen				
12 h	0.942	0.947	0.936	0.921
24 h	0.924	0.926	0.918	0.913
Höljes	0.904	0.902	0.959	0.964
Gävunda	0.888	0.880	0.886	0.869
Reno	0.862	0.864	0.670	0.734
Dodder	0.843	0.854	-	-

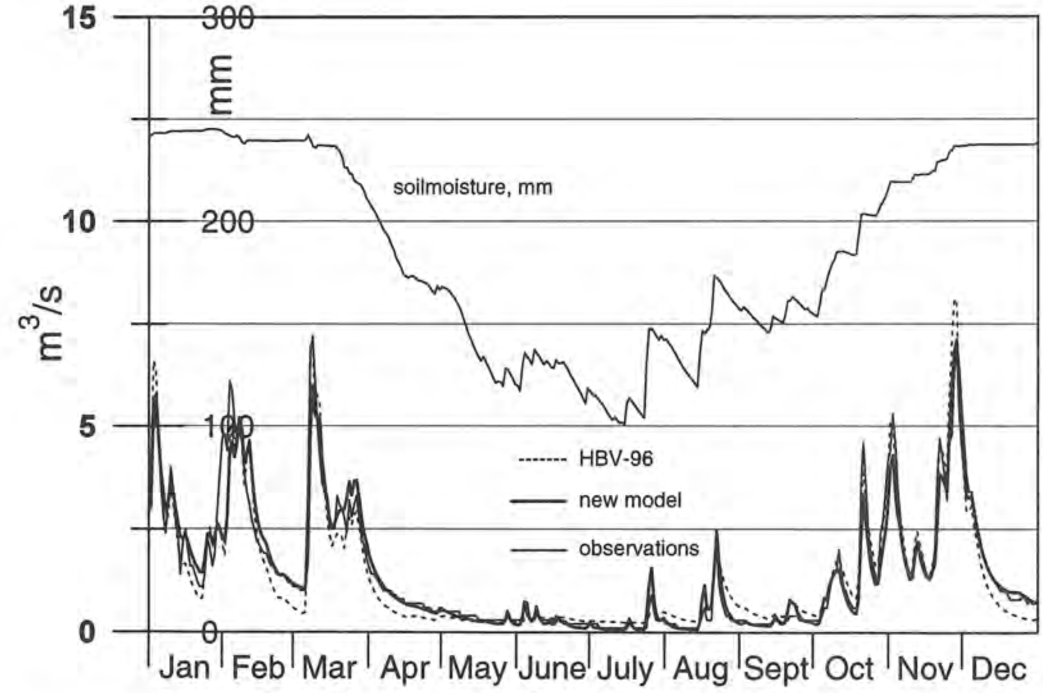


Fig. 3.5 *Differences in general behaviour between HBV-96 and the new model exemplified by the simulation for the Tånemölla catchment during a relatively dry period in 1981.*

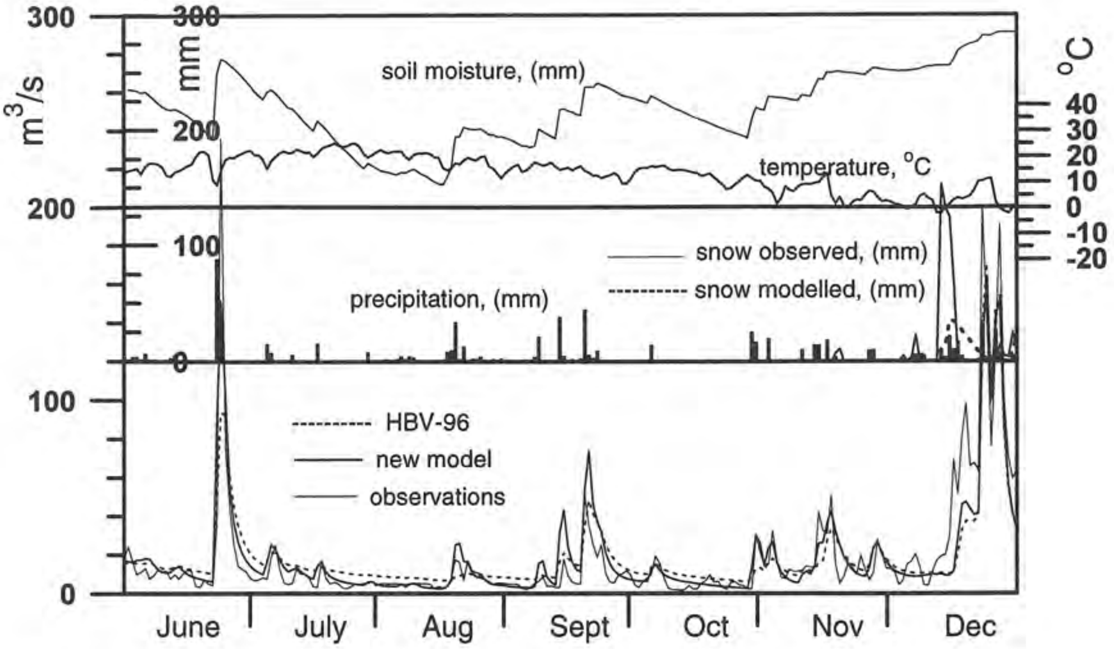


Fig. 3.6 *Differences in general behaviour between HBV-96 and the new model in the Reno catchment at Casalecchio 1995.*

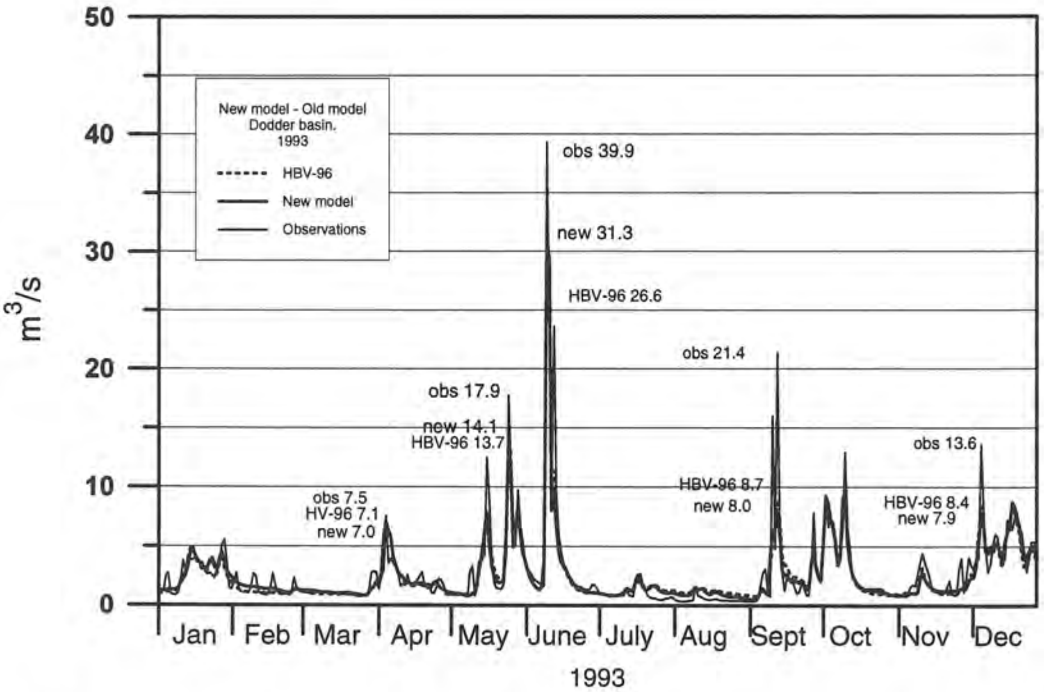


Fig. 3.7 *Differences in general behaviour between HBV-96 and the new model in the Dodder catchment 1993. Also at high flows the new model routine gives a better result.*

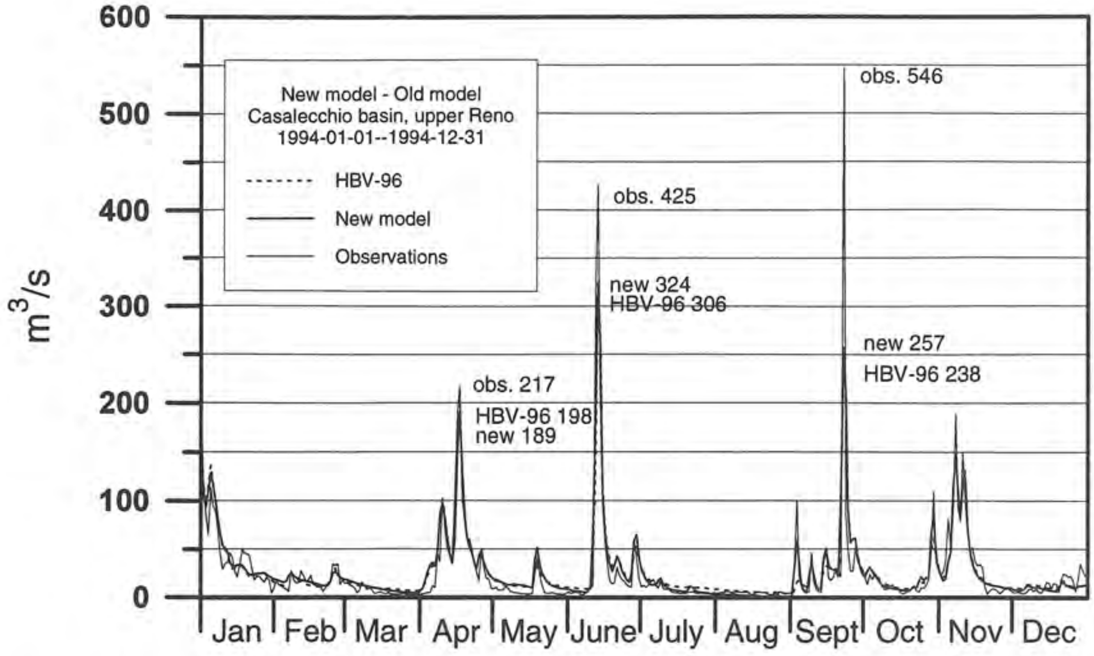


Fig. 3.8 *Differences in general behaviour between HBV-96 and the new model in the Reno. catchment 1994. Also at high flows the new model routine gives a better result*

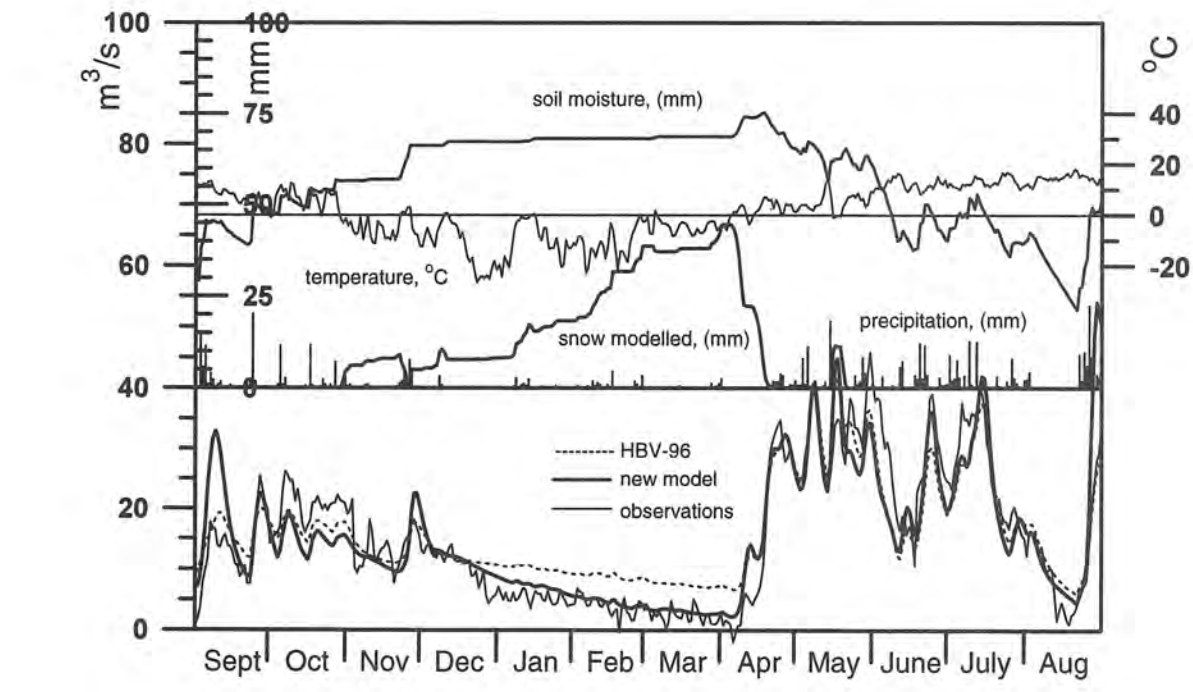


Fig. 3.9 *Differences in general behaviour between HBV-96 and the new model in the Swedish basin Gävunda. This example shows the improvements during the winter 1995-96.*

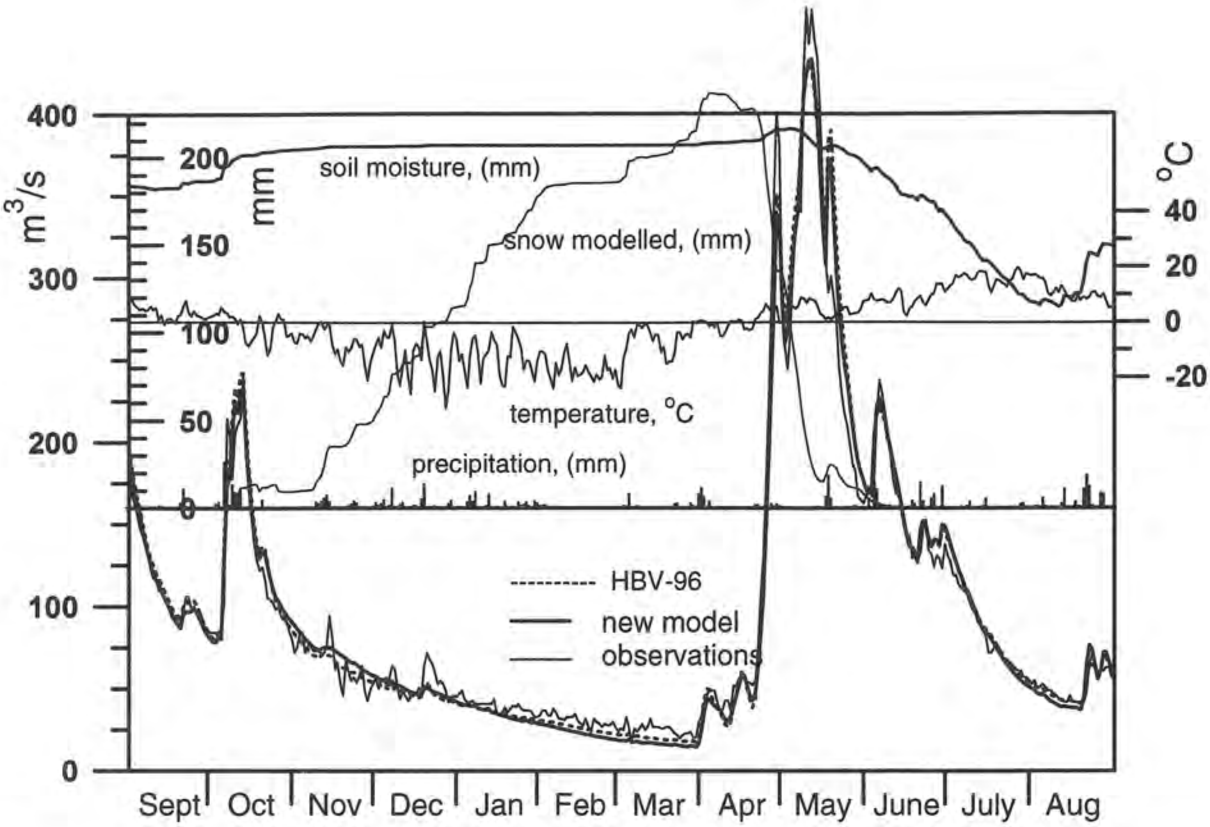
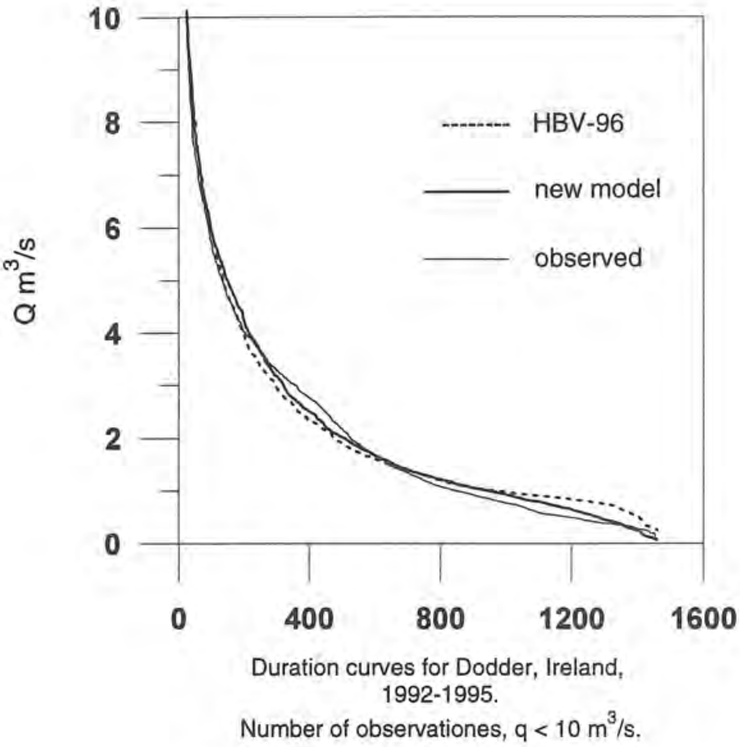


Fig. 3.10 *Differences in general behaviour between HBV-96 and the new model in the basin Höljes. The new simulation is slightly worse at high soil moisture content during the winter 1995-96, but it is still successful in modelling the flood at snowmelt.*

4. Runoff simulation and forecasting procedure

4.1 The forecasting procedure

A flood forecasting system uses information both from the past, historical data records, and from the future, i.e. meteorological forecasts. Output are forecasted discharge or water levels for one or several model time steps. In a review of the results from the WMO (1988) workshop in Vancouver 1987 Refsgaard (1997) gives an overview of the forecasting procedures used by the 14 participating models. The main conclusions is that a good basic simulation is essential for a good forecast and that the forecast is significantly improved by updating. Updating is a feedback process assimilating observed flow into the modelling procedure. In meteorology and oceanography the method is named data-assimilation. Updating can be made in at least four different ways: updating of input variables, state variables, output variables (error prediction) and model parameters (adaptive calibration).



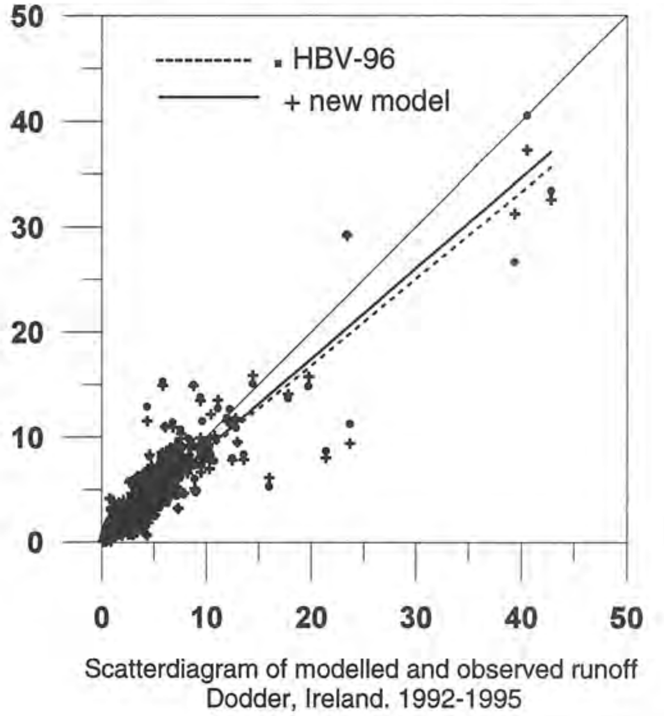


Fig. 3.11 *Differences in general behaviour between HBV-96 and the new model in the Dodder catchment. The new routine decrease the flow at lowest flows and increase the flows at higher flows.*

The present version of the HBV model, HBV-96, uses updating of input variables. Input data, precipitation and temperature, are changed until the simulated runoff is close to observed. This is made automatically for a chosen time period before the forecast. One consequence of this procedure is that internal state variables, for instance the water storage, will change and thus influence results many time steps ahead. It is, however, not possible to reduce water storage in the model if there is no precipitation or no snowmelt during a specific period. If the updating instead is based directly on a state variable, i. e. water equivalents of the snowpack, soil moisture or ground water storage, this type of error can be reduced in the next time step. Some experiments with updating of the state were carried out by the HBV model within the TELFLOOD project.

One additional possibility is to introduce what is called error prediction, which means updating of output variables. For instance can the deviations between the forecasted and the observed flow be added to the forecast as a time series (Box and Jenkins, 1970; Lundberg, 1982). This procedure will often give similar effect as the updating of the model states.

There is also the possibility of what Kachroo (1992) call adaptive calibration, which means that the model parameters are re-calibrated continuously for each step of observation and forecast. Intuitively the method is doubtful. It is in conflict with the strive for a long calibration period when establishing the original model parameters and can easily lead to simple curve-fitting. It is further unclear with which parameter values to proceed the simulation once the model has been updated.

4.2 Runoff simulations and forecasting experiments

The HBV model was first set up for the Pepparforsen catchment with the time steps of 24 h and 12 h. From the climate stations data were available only every 24 h which means that for the 12 h time step the data from the climate stations had to be proportioned according to the synoptic observations south of the area.

Figure 4.1 shows 24 h and 12 h simulations from the Pepparforsen catchment. Individual calibrations were made. Both can be considered as good simulations with R^2 values around 0.87. However, on some occasions the simulation failed, like in May 1996 when the runoff was greatly underestimated. May 1996 was thus taken as a test period for further development of the short range forecasting routines in the HBV model.

In Figures 4.2 and 4.3 consecutive 24 h and 12 h single time step forecasts are shown. That is, for every forecast the model is run to the time step just before the forecast and then a single time step forecast is done. For some time before the forecast the simulation is updated by changing the precipitation. This is made automatically.

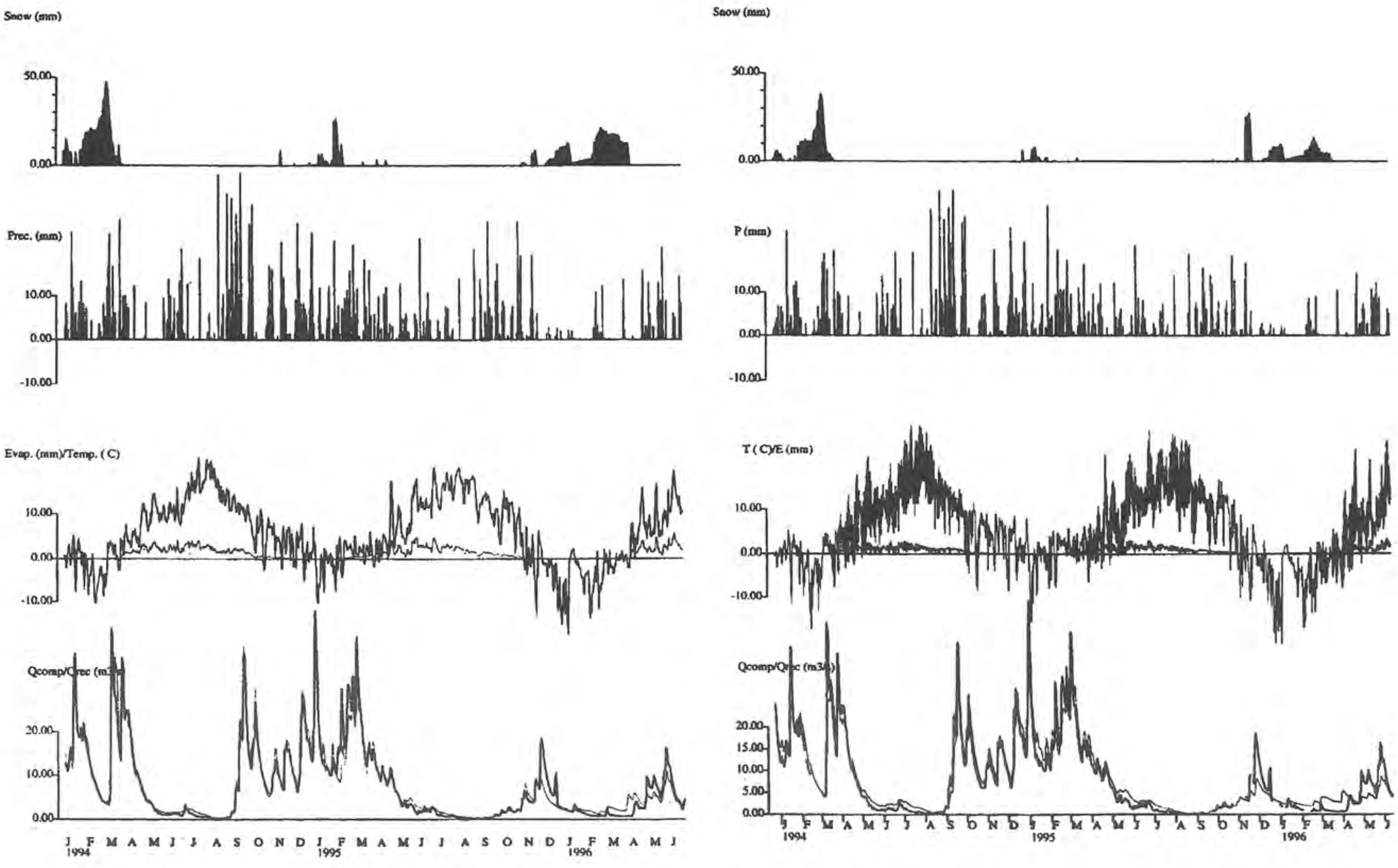


Fig. 4.1 *Behaviour of the simulation when turning from 24 h (left) to 12 h (right) time steps. Pepparforsen catchment 1994-96. Thin line: simulated runoff. Thick line: observed runoff.*

HIRLAM precipitation forecasts, climate station data and HIRLAM/MESAN data for the period 1996-05-20--24 were prepared and used in the forecasting tests. With MESAN (mesoscale analysis) is understood data prepared from both HIRLAM forecasts and observed data. (Häggmark et. al. 1997).

In Figure 4.2 the HBV model forecasting routines were tested with precipitation input from climate stations, HIRLAM 22 km precipitation forecasts and mesoscale analysis of HIRLAM data and synoptic stations, see Table 4.1. The totals for the period show a lower number for the HIRLAM-runoff forecasts, mainly due to the low precipitation forecasts on May 24 and 25 (Gollvik, 1997).

Table 4.1 *Precipitation input data used for testing forecasting routines in the HB -model.*

Time step 12 h	Met. stns.	HIRLAM 22 km	MESAN
1996-05-20 06 - 1996-05-20 18	1.3	0.7	2.1
1996-05-20 18 - 1996-05-21 06	6.7	5.7	5.7
1996-05-21 06 - 1996-05-21 18	8.1	8.2	10.6
1996-05-21 18 - 1996-05-22 06	0.5	1.6	0.5
1996-05-22 06 - 1996-05-22 18	3.7	1.3	2.4
1996-05-22 18 - 1996-05-23 06	0.6	0.01	0.3
1996-05-23 06 - 1996-05-23 18	0.3	3.6	0.04
1996-05-23 18 - 1996-05-24 06	1	1.2	1.1
1996-05-24 06 - 1996-05-24 18	8.8	3.7	8.5
1996-05-24 18 - 1996-05-25 06	11.2	1.8	9.5
Sum.	42.2	27.8	40.7

Time step 24 h	Met. stns.	HIRLAM 22 km	MESAN
1996-05-20 06 - 1996-05-21 06	8	6.3	7.9
1996-05-21 06 - 1996-05-22 06	8.6	9.7	11.1
1996-05-22 06 - 1996-05-23 06	4.3	1.3	2.7
1996-05-23 06 - 1996-05-24 06	1.3	4.8	1.2
1996-05-24 06 - 1996-05-25 06	20	5.5	18.1
Sum.	42.2	27.7	41

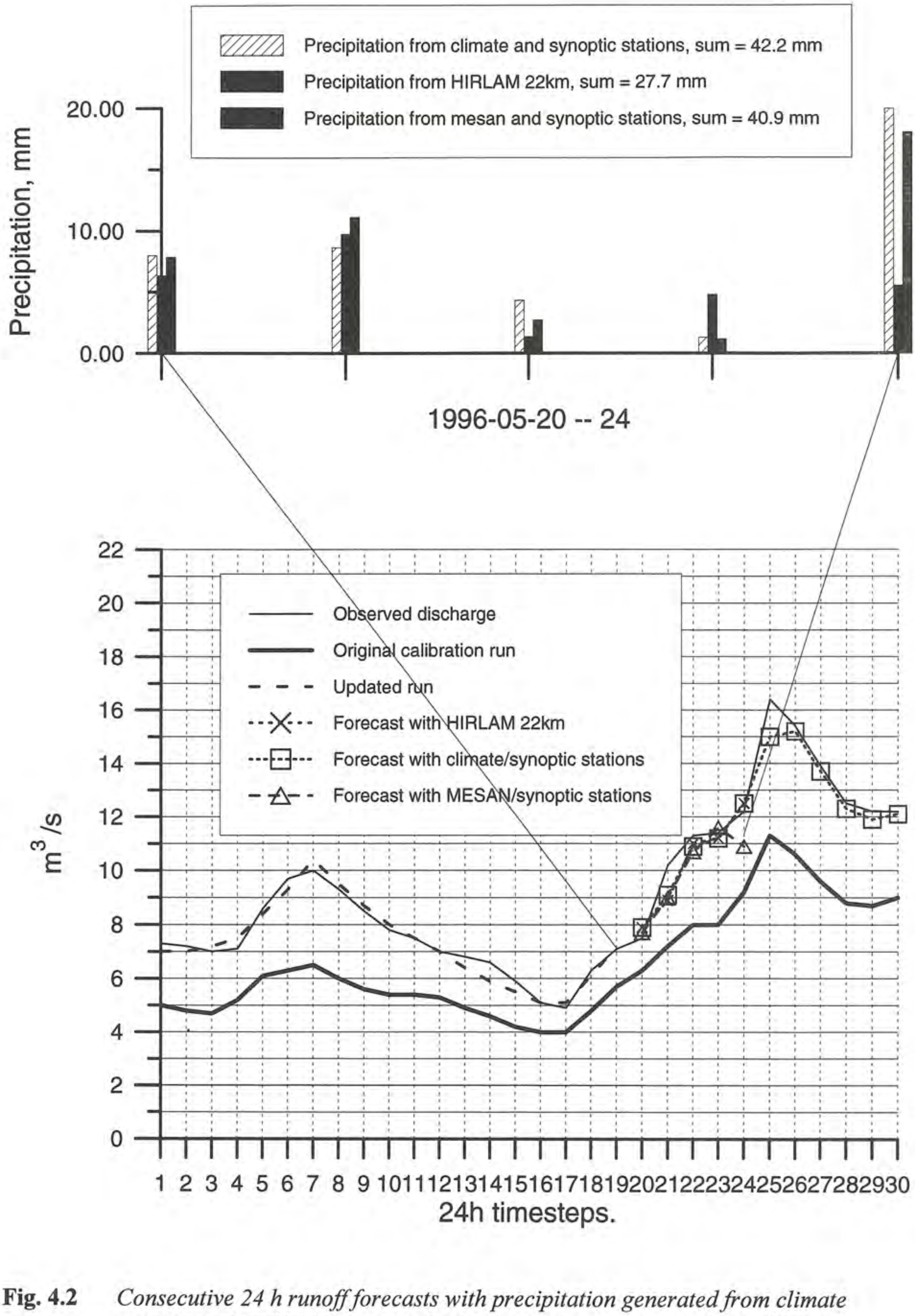


Fig. 4.2 *Consecutive 24 h runoff forecasts with precipitation generated from climate stations and HIRLAM forecasts in the Pepparforsen basin in May 1996.*

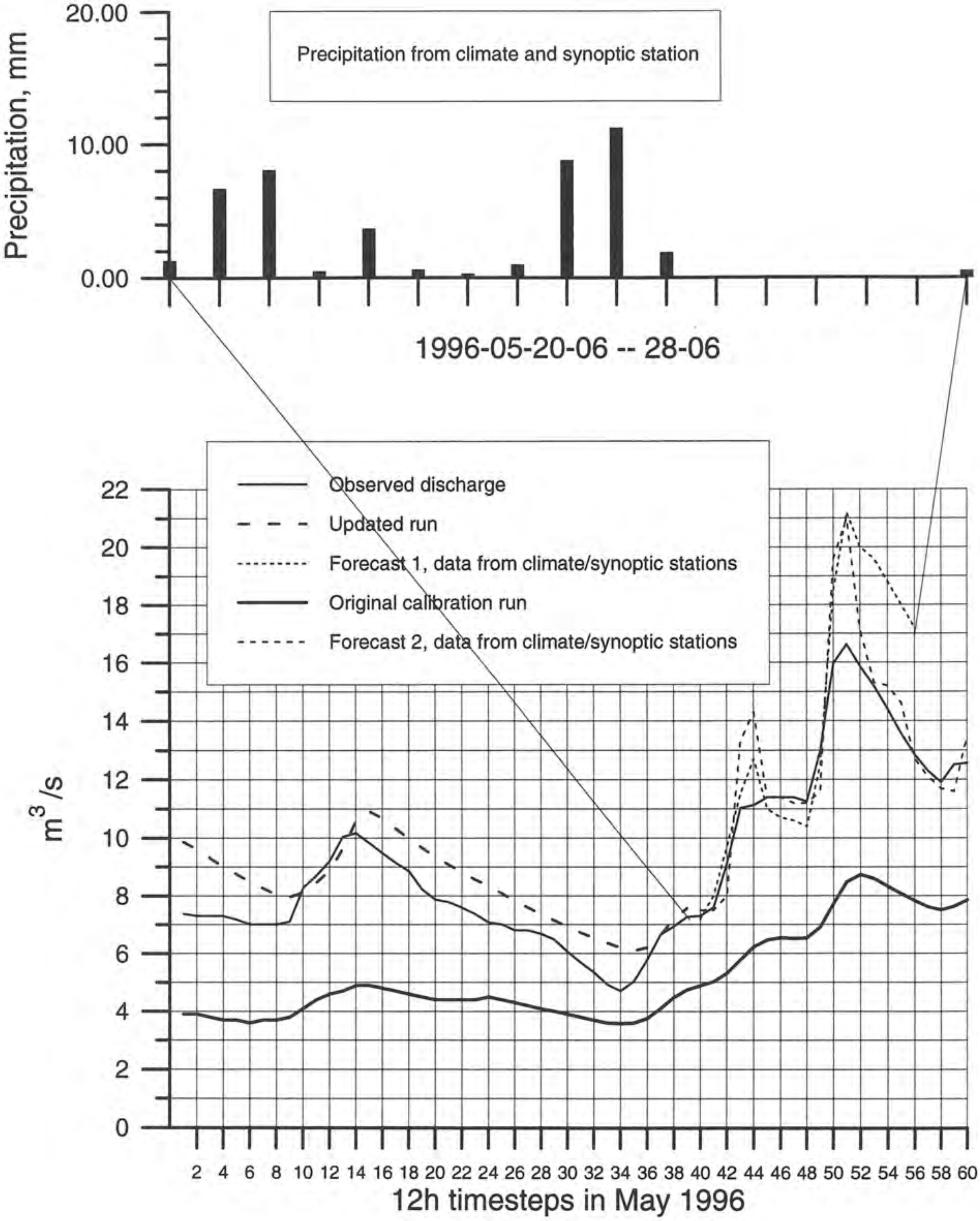


Fig. 4.3 *Consecutive 12 h runoff forecasts with precipitation generated from climate stations. Forecast 2 indicate a new forecasting routine. The Pepparforsen basin in May 1996.*

Besides the original HBV forecasting routine a new modified routine, based on updating of model state variables, was tested, Figure 4.3. The model is here run with the time step 12 h. The updated period shows a typical error that occurs, when updating of precipitation is used (Forecast No. 1). After filling up the response box, the storage empties too slowly, and the modelled runoff will continue to be to high until there is a new natural rise. If also the model state is updated (Forecast No. 2), the return to the observed runoff is immediately performed by the updating procedure during the next time step. In the forecast presented in Figure 4.3 the model state is updated only on the last time step.

The 24 h forecasts in Figure 4.2 are acceptable. The highest peak in May is underestimated with only one cubic meter per second. When the precipitation input was split into 12 h periods, Figure 4.3, the highest peak was overestimated by about 5 m^3/s or 25%, both with the original routine and the new one. Although this is a difficult period the forecast should not deviate this much. For situations with a better original run the results are much better.

From the automatically calibrated graphs in Figure 4.1 and the R^2 values the modelling results could be judged as equal. However, if we look at the scatter diagrams in Figure 4.4 we can notice a difference between the two, i. e. the underestimation of the simulated higher runoff is more pronounced in the 12 h run. We can also notice that the 24 h data set is smoother than the 12 h set. This is due to the fact that splitting the data is not done in equal parts but in portions depending on the precipitation at the synoptic station and this procedure strengthens the tendency. In a forecast situation the higher values may exaggerate the updating corrections before a runoff peak with the result described earlier. A manual calibration can adjust for the errors introduced when splitting the data, Figure 4.4.

If we introduce updating of the model state on every 12 h time step in the new model version we obtain the result visualised in Figures 4.5 and 4.6. At first we have to draw attention to the fact that that both the simulation and the updating here is much better than in the previous runs with the HBV-96 model version. The results in Figure 4.5, which shows consecutive 24 h forecasts are quite comparable with the results in Figure 4.2 but here the accordance between the observed and forecasted data is even better. In Figure 4.6 the forecast lead time is three days and it covers the highest flow with the same good result.

With one exception, Tånemölla, all model calibrations in this report are made automatically. This means that no special emphasis is put on high flow situations. If we, with this in mind, examine high flow in river Reno in September 1994 and try to forecast the highest value measured during the simulated years, 546 m^3/s, it is not astonishing that the peak is underestimated, Figure 4.7. Some of the error can be overcome by a manual calibration with respect to high flows, but the result can also to some extent depend on errors in the precipitation data set as there is a considerable volume error on this occasion.

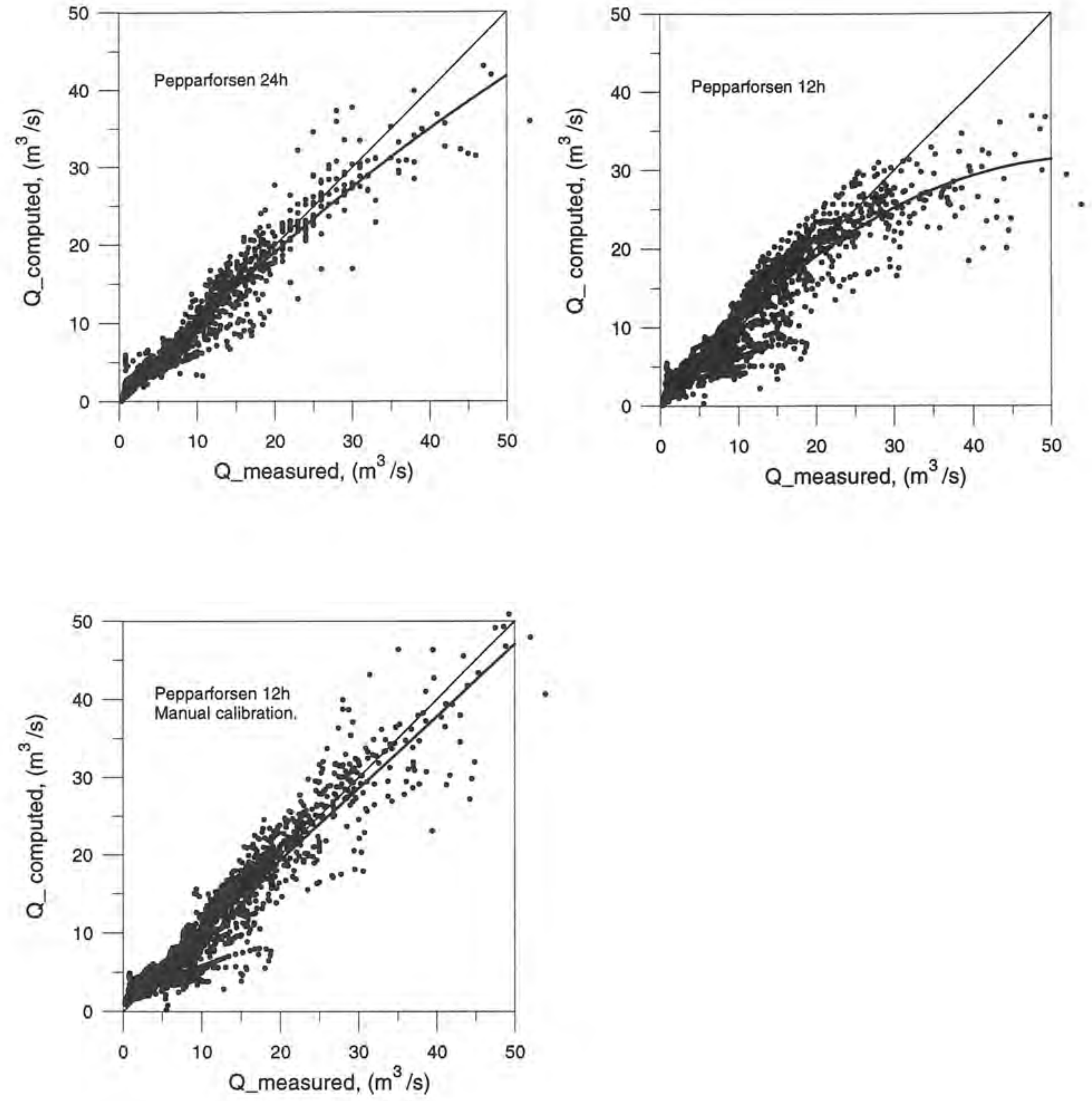
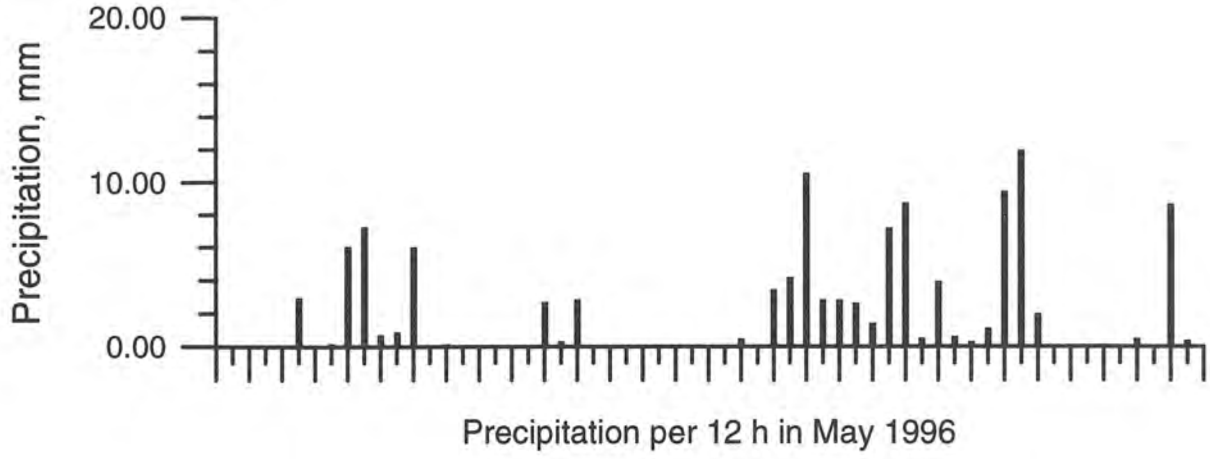


Fig. 4.4 *Scatter diagram showing the relationship between observed and computed runoff for 12 h and 24 h model time steps. The difference in shape is due to the splitting of precipitation in not equal parts in relation to the precipitation at a nearby synoptic station. The Pepparforsen basin 1980 - 1996.*



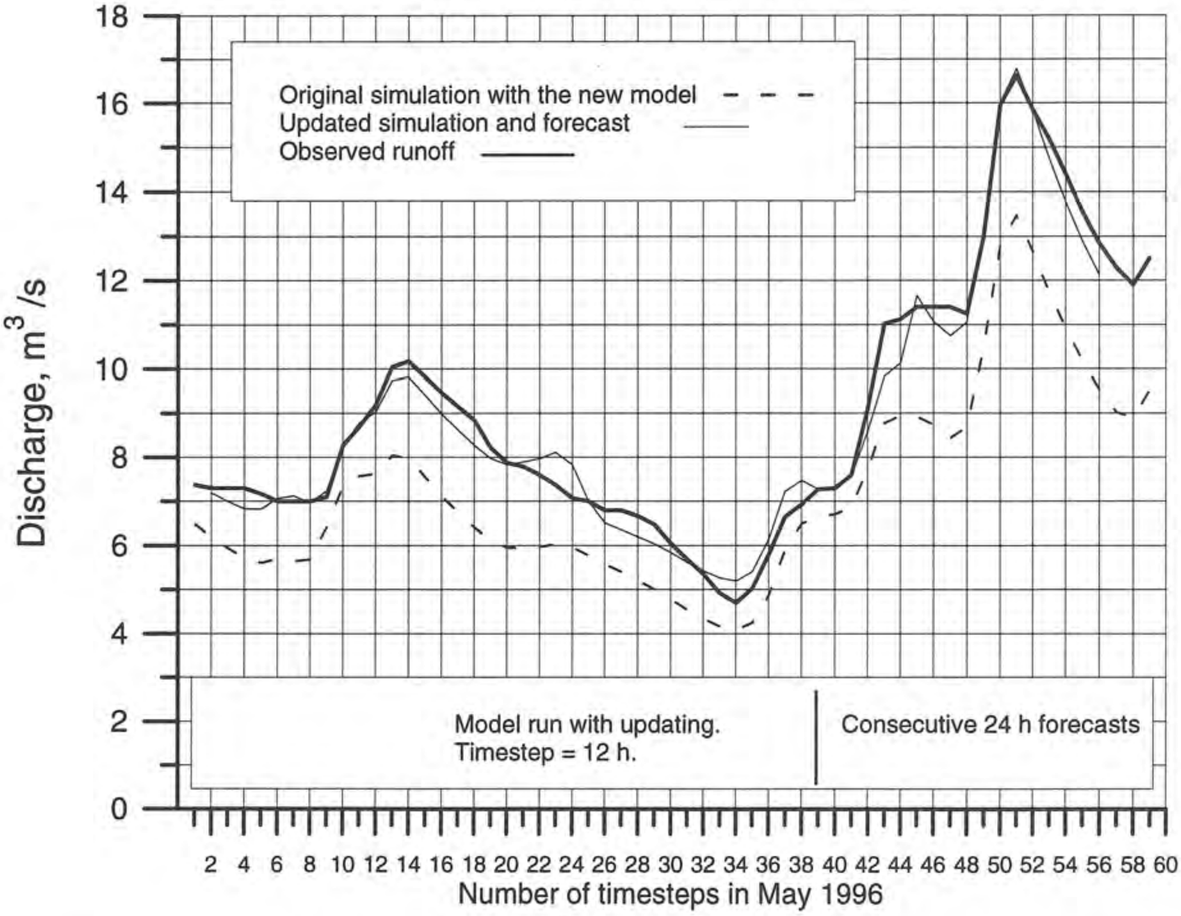
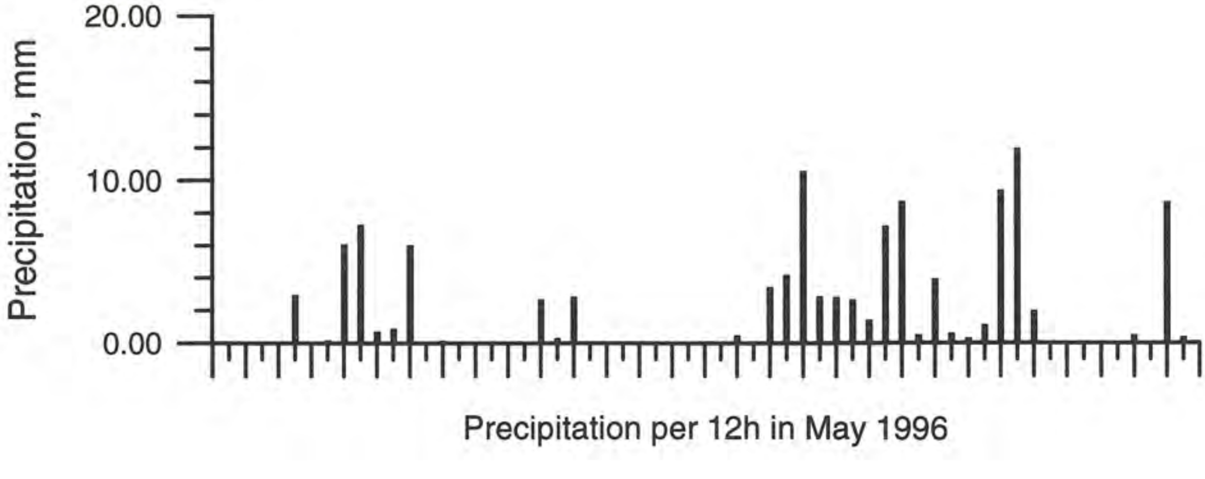


Fig. 4.5 *Consecutive 24 h runoff forecasts with precipitation generated from climate stations. This results should be compared with Figure 4.3. The Pepparforsen basin in May 1996.*



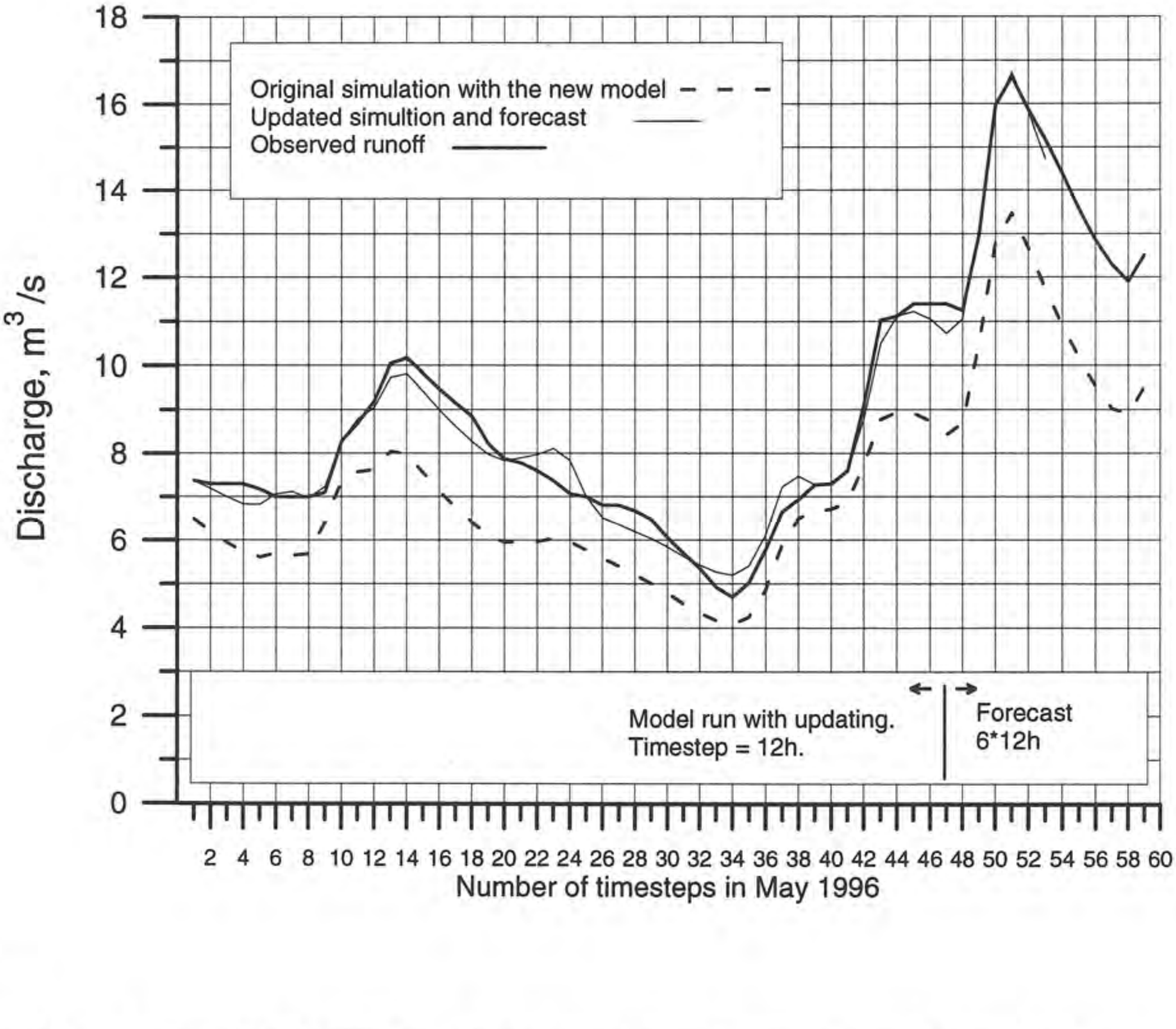


Fig. 4.6 *A three days forecast made with a new forecasting routine and the model time step 12 h. The Pepparforsen basin in May 1996.*

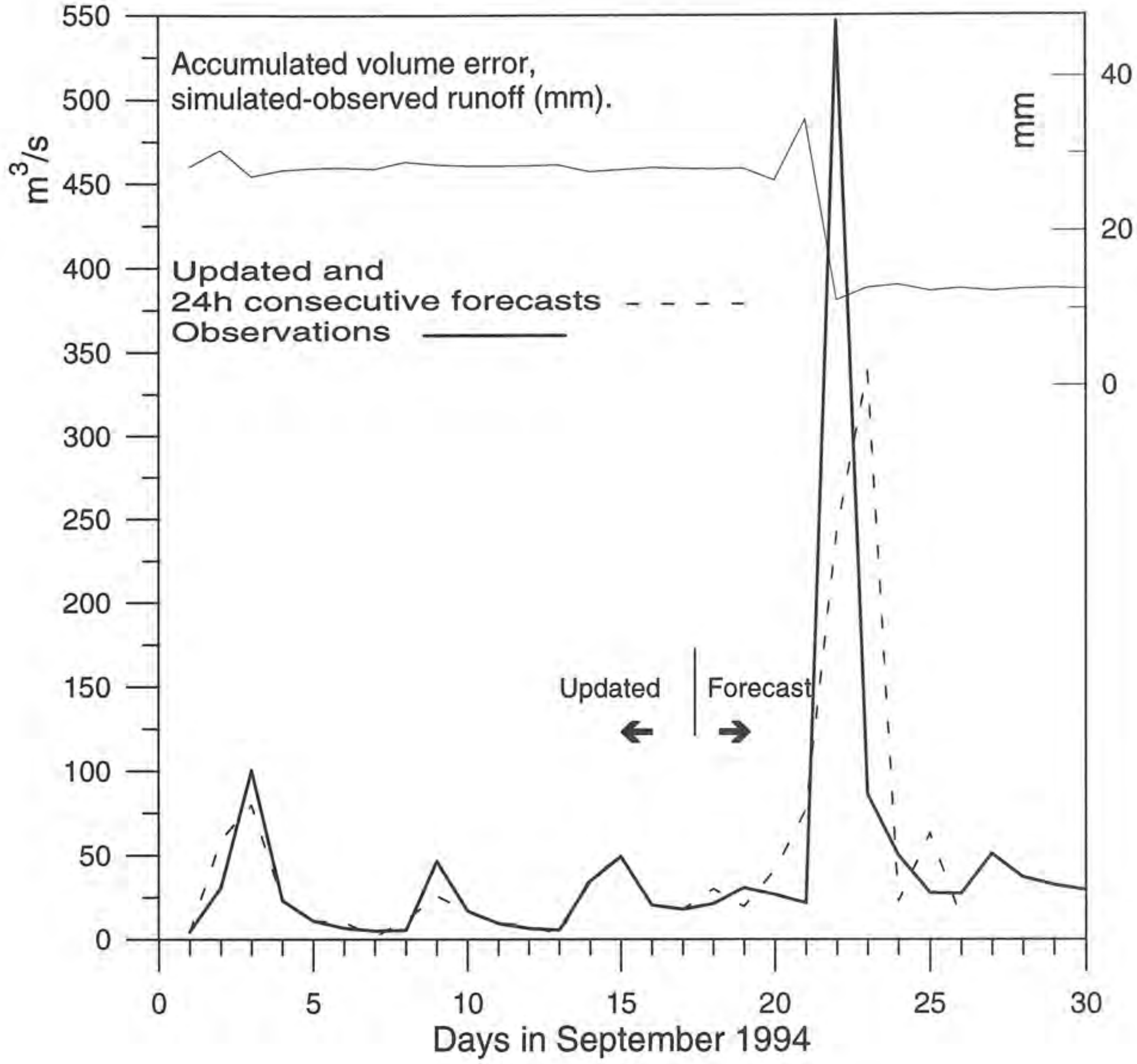


Fig. 4.7 *Consecutive 24 h runoff forecasts with precipitation generated from climate stations. This period, September 1994, includes the highest flow observed in the simulation of the Reno catchment.*

5. Discussion and conclusions

The proposed new response function for the HBV model is definitely more attractive from a scientific point of view as it more consistently handles the moisture dynamics and areal variability in a catchment. The improvements expressed as R^2 may look marginal, but they are considerable if low flow periods are analysed in more detail. This again addresses the problem of representing goodness-of-fit by single numerical criteria.

One advantage of the HBV model has always been its ease of calibration and use. One reason for this is that subroutines and parameters are relatively independent. The new routine introduces one complexity as the response function is now dependent on parameters of the soil moisture routine. This has to be considered during the calibration process. Although the new routine is seemingly more complex it does not introduce more empirical parameters. On the contrary there seems to be a possibility to reduce by one by avoiding the use of a parameter for capillary flux, which is introduced in some applications to adjust for the problems discussed above.

The precision of a runoff forecast is basically depending on the original calibration of the model. A bad simulation can, to some degree, be compensated by a good updating routine. The routine used in the HBV model, updating of observed precipitation and temperature, has shown some limitations at events with poor simulations.

When adding a new updating routine to the HBV model we choose between error prediction and updating the state and. Both Refsgaard (1997) and Moore et. al. (1993) have reported that updating the state is the most advisable method. Tests of this method has shown improvements also on difficult events. However, at very high flows the updating method needs improvements and here error prediction will be tested in the future. An additional problem that needs further improvements is how to handle the phase errors that can occur both at updating and forecasting.

Acknowledgements

This work was carried out within the TELFLOOD project with funds from the European Commission's Programme Environment and Climate (Contract No. ENV4-CT96-0257), Swedish Meteorological and Hydrological Institute, and the Swedish Association of River Regulation Enterprises (VASO).

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ISSN 0283-1104