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Validation and Intercomparison of Different Updating Procedures for Real-Time Forecasting

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The paper presents a classification and a review of the updating procedures currently used in real-time flood forecasting modelling. On the basis of results from the WMO project 'Simulated Real-Time Intercomparion of Hydrological Models', comprising more than 10 commonly used hydrological models and a variety of different updating procedures, an analysis of the relative importance of updating procedures and hydrological simulation models is provided. In particular, an intercomparison is made beteween two models (NAMS11/MIKE11 and NAMKAL) consisting of the same hydrological model (NAM conceptual rainfall-runoff) but containing different routing modules (linear reservoirs *versus* hydraulic routing) and different updating procedures (error prediction *versus* state variable updating based on an extended Kalman filter). A main conclusion is that updating procedures significantly improve the performances of hydrological models for short-range forecasting. Furthermore, there are no clear conclusions regarding which type of updating procedure performs the better. However. intercomparison of the NAMS11 and NAMKAL models indicates that the extended Kalman filter is marginally better than an error prediction model in cases where the basic hydrological model simulation is good. Finally, it is concluded that the basic simulation is very essential for accurate forecasts, and that the better the basic simulations are the better the updating routines in general function. This puts emphasis on the importance of thoroughly calibrating and validating the hydrological simulation models before applying them together with updating routines in operational real-time forecasting.

Introduction

Economic losses from natural disasters increased three-fold between the 1960s and the 1980s (ICWE 1992), while floods and droughts kill more people and cause more damage than any other natural disasters (Rodda 1995). Thus, in spite of a continuous and ongoing construction of flood control structures such as reservoirs and dikes the flood damages in many countries have continued to increase. Hence the demands for systems capable of forecasting reservoir inflows and water levels in rivers and on flood plains have increased significantly.

With the emergence in recent years of new, reliable and cost-effective automatic data acquisition and transmission systems a key constraint for widespread operational use of hydrological models in real-time flood forecasting has been removed. Hydrological models are already today operationally used in many flood forecasting projects. However, it is the author's experience from monitoring of international tenders in this field that the number of integrated flood forecasting projects under planning and implementation in these years is significantly higher than it was a few years ago.

At the heart of any modern flood forecasting system is a model which takes information on the past and current states of the river basin, and the inputs to it, and forecasts discharge rates and/or water levels for a certain period into the future. The key elements of such a model are:

a) a hydrological (rainfall-runoff) model;
b) a river routing model; and
c) an updating procedure.

For specific applications other additional elements may be important such as a snow model for areas where snow plays a dominant role. Furthermore, comprehensive data processing programs are of crucial importance for operational use of flood forecasting models.

Hydrological models may be classified according to the description of the physical processes as black box, conceptual and physically-based, and according to the spatial description of catchment processes as lumped and distributed (Wood and O'Connell 1985; Nemec 1994; Refsgaard 1996 and others). In this respect three typical model types are the lumped black box, the lumped conceptual and the distributed physically-based. Typical examples of a black box, a conceptual and a distributed physically-based code are CLS (Todini and Wallis 1977), Sacramento (Burnash 1995) and MIKE SHE (Refsgaard and Storm 1995), respectively. For flood forecasting mainly black box and conceptual models are being used today.

River routing models may be classified as either lumped or distributed (Fread 1992). In lumped flow routing or hydrological routing, the flow is computed as a function of time at one location along the watercourse (in practice often as a multireach approach). In distributed flow routing or hydraulic routing the flows and water levels are computed as a function of time simultaneously at several cross sections along the watercourse. Hydraulic routing models are based on the St. Venant hydrodynamic equations and can generally account for backwater effects and hydraulic control structures. Hydrological routing models, on the other hand, are based on more simplified equations and require less input data. For small river systems hydrological routing is most frequently used, while hydraulic routing is required for rivers affected by backwater and spilling to flood plains as well as for accurate forecasting of water levels in river systems where the stage-discharge relationship shows hysteresis effects.

Hydrological models and river routing models are being used comprehensively for planning purposes in an off-line mode. For such applications the models will typically be calibrated so that the deviation between simulated and recorded flows are minimized. However, when used for short-term forecasting such as flood forecasting it is necessary also to take these deviations directly into account through some kind of feedback mechanism, referred to as data assimilation or updating. A classification of updating procedures based on WMO (1992) is given below.

The aim of the present paper is to focus on the requirements of updating procedures for flood forecasting and to review the performance of different updating procedures in a validation test conducted by WMO. By comparing the performances of different simulation (hydrological plus river routing) model types and different types of updating procedures the following question is addressed: What is more important, the simulation model or the updating procedure ?

The paper is structured as follows: The next section provides definitions of a terminology and a classification and gives a brief review of updating procedures currently used for flood forecasting purposes. The following section gives a brief summary of the results of WMO's project 'Simulated Real-time Intercomparison of Hydrological Models' with a focus on the importance of updating procedures. Subsequently, more detailed results and analyses are presented with respect to two of the models (NAMS11 and NAMKAL) for which the author was responsible during the WMO intercomparison project. These two models were hydrologically very similar, but had different updating procedures. Finally, the last section comprises a general discussion and conclusions.

Terminology, Classification and Review of Updating Procedures

The combined hydrological and river routing model may be referred to as the simulation model or the *process model*. The process model utilizes input variables that are either measured or estimated (*e.g.* areal precipitation, air temperature, potential evapotranspiration). A process model can be considered as composed of a set of equations that contain state variables and parameters. The two quantities are distinguished by the fact that parameters remain constant while the state variables vary in time. The process model output is observable and is generally discharge or water level. The transformation from input to output by the process model is called *simulation* (WMO 1992).

Process models that operate in real-time may take into consideration the measured discharge/water level at the time of preparing the forecast. This feedback process of assimilating the measured data into the forecasting procedure is referred to as *updating*. It should be noticed that in other disciplines such as oceanography and meteorology, and also by some authors in hydrology, the same process is denoted *data assimilation* (Heemink and Kloosterhuis 1990; Ottle and Vidal-Madjar 1994).

The updating procedures may be classified depending on the variables modified during the feedback process. In WMO (1992) four different methodologies, as illustrated in Fig. 1, have been defined. The four methodologies can be characterized as follows:

a) *Updating of input variables* – Updating of input variables, typically precipitation and air temperature, is the classical method justified by the fact that input uncertainties may often be the dominant error source in operational forecasting. This method is often based on manual iterative procedures and carried out by experienced modellers (*e.g.* Bergström *et al.* 1978), but automatic procedures have also been developed, *e.g.* the Computer Hydrograph Adjustment Technique (CHAT) (Sittner and Krouse 1979). It may be noted that updating of input variables results in changing (updating) state variables. For the manual procedures, a serious drawback is that making feedback of errors to the inputs at an appropriate time in the past may be problematic.

b) *Updating of state variables* – Adjustments of state variables such as the snowpack's water equivalent and the water contents of the model conceptual reservoirs simulating water storage at the surface, in the root zone, in the groundwater system and in the river system can be done in different ways. Examples of simple methodologies are found in the UBC (Quick 1995) and the SRM (Rango 1995) which enable updating of snowcover by simply substituting simulated snow cover variables by observed data from snow courses or satellites. The theoretically most comprehensive methodology is based on the Kalman filtering theory (Gelb 1974; Ahsan and O'Connor 1994). It is well proven for linear systems, but can with some modifications (extended Kalman filter) also provide an approximate solution for non-linear hydrological and hydraulic systems. Kalman filters can be integrated either with purely statistical transfer function models such as ARIMA (Box and Jenkins 1970) or with hydrological lumped conceptual models. Examples of the last type are extended Kalman filter applications to the Sacramento (Kitanidis and Bras 1978; Georgakakos *et al.* 1988) and the NAM (Refsgaard *et al.* 1983).

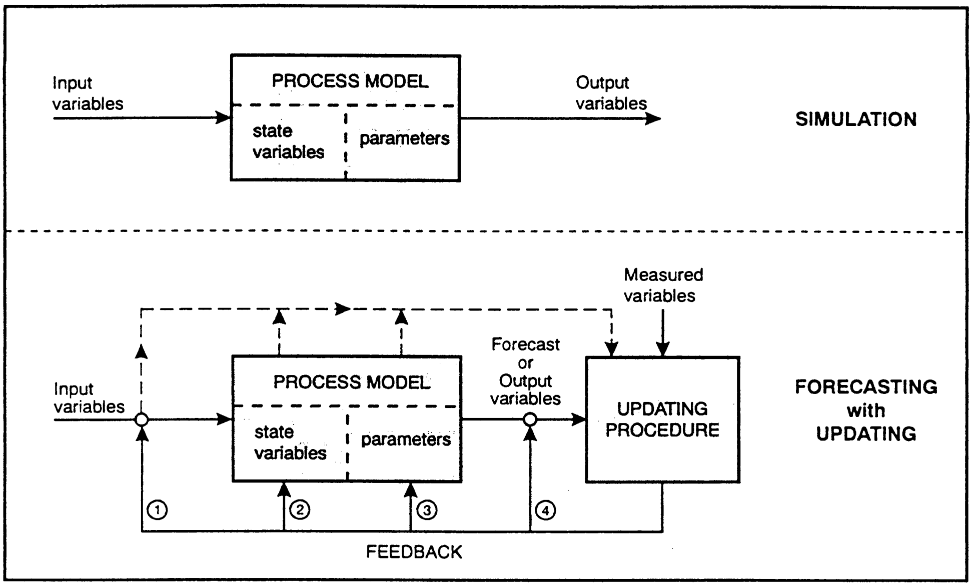

Fig. 1. Schematic diagrams of simulation and forecasting with emphasis on the four different updating methodologies (modified after WMO 1992).

c) *Updating of model parameters* – Whether adaptation of model parameters, originally assessed through calibration using historical data, on the basis of relatively few data during the updating period, is justified, is a matter of debate. In this context the author agrees with the views expressed by Kachroo (1992): "It is intuitively difficult to accept that the operation of any hydrological system can change significantly over such a short interval of time as the observation interval. Therefore, recalibrating the model at every time step has no real advantages, other than perhaps some computational attraction and that only when applied to simple forecasting models of the system analysis type. For a complex conceptual model, adaptive calibration is extremely difficult because of a large number of parameters involved". In practice the use of this method is mostly confined to statistical black box models where it may be argued that no clear distinction exists between state variables and model parameters. Typical parameters to be updated are the runoff coefficient and parameters describing the hydrograph routing. An example in this respect is updating of the runoff coefficient in SRM (Rango 1995).

d) *Updating of output variables (error prediction)* – The deviations between the simulation mode forecasts and the observed river flows, *i.e.* the model errors, are usually found to be serially correlated, giving rise to the possibility of forecasting the future values of these errors by means of time series models such as an autoregressive moving average (ARMA) model (Box and Jenkins 1970). The simulation mode forecasts, obtained by the process model, can then be improved by adding the error forecasts from the ARMA error model. This method, which is often referred to as error prediction, was the most widely used among the models participating in WMO's intercomparison project on simulated real-time forecasting (WMO 1992), and it is according to Ahsan and O'Connor (1994) "by far the most popular among hydrologists". Some of the earlier examples of error prediction include Jamieson *et al.* (1972), Lundberg (1982) and Szöllözi-Nagy *et al.* (1983).

The WMO Intercomparison Project

Test Catchments and Models

WMO has executed a project on *Simulated Real-time Intercomparison of Hydrological Models*. By focusing on the performance of updating procedures and short-range forecasting, the project was a natural follow up of two previous WMO intercomparison projects on hydrological simulation models (WMO 1975) and on snowmelt models (WMO 1986). The project background and implementation is described in WMO (1988).

Data from three catchments with significantly different hydrological characteristics were used for the tests. Some key features of the three test catchments are summarized in Table 1. The differences in forecast lead times shown in Table 1 also reflect differences in catchment response time. The Orgeval catchment is a small and fast responding catchment. Hence for modelling of flood hydrographs the rainfall-runoff generation mechanism has higher importance than the river routing process. The Bird Creek catchment is a medium size catchment with a comparatively much slower response, so that a good description of the river routing process becomes im-

Table 1 – Key features of test catchments

	Catchment		
Feature	Orgeval	Bird Creek	Illecillewaet
Country	France	United States	Canada
Catchment area	104 km^2	2,344 km^2	1,100 km^2
Calibration period	6 years	8 years	13 years
Data interval(s)	1 hours	1 d; 6 h	1 days
Forecast lead time(s)	9 hours	4 d; 96 h	20 days
Forecasts prepared	Every 3 hours	Every day	Every 5 days
Predominant type	Rainfall	Rainfall	Snowmelt

Table 2 – Models participating in the WMO workshop in Vancouver 1987

Model Name	Organization	Model Hydrological	Type Updating	Events forecasted		
				Orgeval	Bird Creek	Illecillewaet
UBC	University of British Colombia, Canada	Conceptual	State variables Error prediction	4		3
CEQUEAU	Universitê du Quebec, Canada	Conceptual	Input variables Error prediction	4	4	2
ERM	Hydro Consult & Water Research Institute, Bratislava, Czecho-Slovakia	Black box	State variables Model parameters Error prediction			3
GAPI	VITUKI, Hungary	Black box	Model parameters Error prediction	4	4	
SMAR	University College, Galway, Ireland	Conceptual	Error prediction	4	4	
CLS	University of Bologna, Italy	Black box	State variables	4	4	
VIDRA	Institute of Meteorology and Hydrology, Romania	Black box	Error prediction			
HBV	Swedish Meteorological and Hydrological Institute	Conceptual	Input variables	4	4	3
SRM	U.S. Department of Agriculture & Federal Institute for Snow and Avalanche Research, Switzerland	Black box	State variables Model parameters Error prediction			1
TANK	National Research Centre for Disaster Prevention, Japan	Black box	Input variables	3	3	2
SSARR	US Army Corps of Engineers, Portland	Conceptual	Input variables	4	4	3
HFS	US National Weather Service, Maryland	Conceptual	State variables	4	4	
NAMS11	Danish Hydraulic Institute	Conceptual	Error prediction	4	4	
NAMKAL	Danish Hydraulic Institute	Conceptual	State variables	4	4	

portant for flood forecasting. The Illecillewaet catchment is, in contrast to the two others, dominated by snowmelt runoff. Details on the catchment characteristics and the specific hydrographs are given in WMO (1988, 1992).

14 models from 15 different organisations participated in the intercomparison: Table 2 provides an overview. It is noted that many of the internationally most widely

used models featured in the workshop. In this context it may be noticed that the HFS is based on the Sacramento with an extended Kalman filtering approach for updating, and that the NAMS11 was a predecessor of the MIKE11. It is furthermore noticed that all four methodologies of updating procedure are represented. For black box type models examples of all four updating methods are found, and often more than one method is used. For conceptual type models updating of input variables are done for three models (CEQUEAU, HBV, SSARR), updating of state variables are done for three models (Kalman filtering for HFS and NAM, and simple snow cover correction for UBC), and finally error prediction are carried out for four models (UBC, CEQUEAU, SMAR, NAMS11).

Most of the models were applied to one or two of the three test catchments during the workshop (see Table 2). Thus, seven models featured exclusively for the two non-snow catchments, while two models featured only in the third snowmelt dominated catchment, and only four models featured in the tests for all three catchments. As the author was running two models which featured only in the two non-snow catchments, Orgeval and Bird Creek, only results from these catchments will be shown and discussed in the following.

As indicated in Table 2 the Bird Creek data were made available both on a six-hourly and on a daily basis, and the modellers were given the choice to make Bird Creek forecasts on a six hourly and/or daily basis. All of the modellers who made forecasts for Bird Creek prepared six-hourly forecasts, while approximately half of them in addition prepared daily forecasts. In the following only the six-hourly forecasts for Bird Creek are considered.

The Vancouver Workshop 1987

The blind tests were made during a workshop held in Vancouver during the period July 30-August 8 1987. Historical data for several years were made available beforehand, so that the modellers could calibrate their models before the workshop. Furthermore, two warm up events were provided to each participant before the workshop. During the workshop 'real-time' forecasts were then carried out with discharge data available up to the 'present time' and rainfall data available also for the forecast period. Four peak events were forecasted with seven forecasts (at consecutive times) for each event, as illustrated for NAMS11 and NAMKAL in Figs. 2 and 3. It should be emphasized that these four tests were made as blind tests where the participants had no prior knowledge of the actual discharge values during the forecast period.

Assessment of General Results

After the workshop a large number of numerical evaluation criteria have been calculated and intercomparisons between the performance of the individual models have been made. These results have been published in WMO (1992). The aim of the WMO project was not to make an official ranking of the models, and phrasing of the

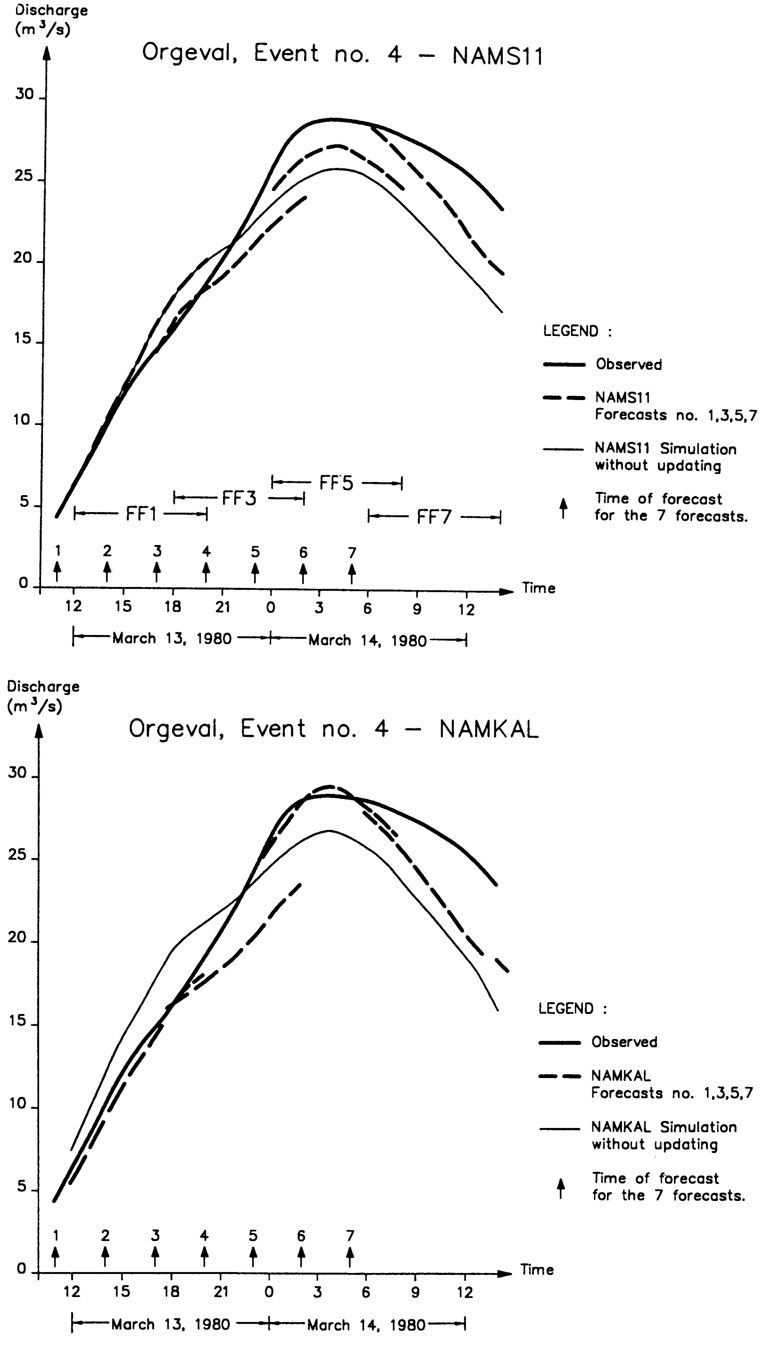

Fig. 2. Simulation and forecast results for the NAMS11 and the NAMKAL models for the Orgeval event No. 4.

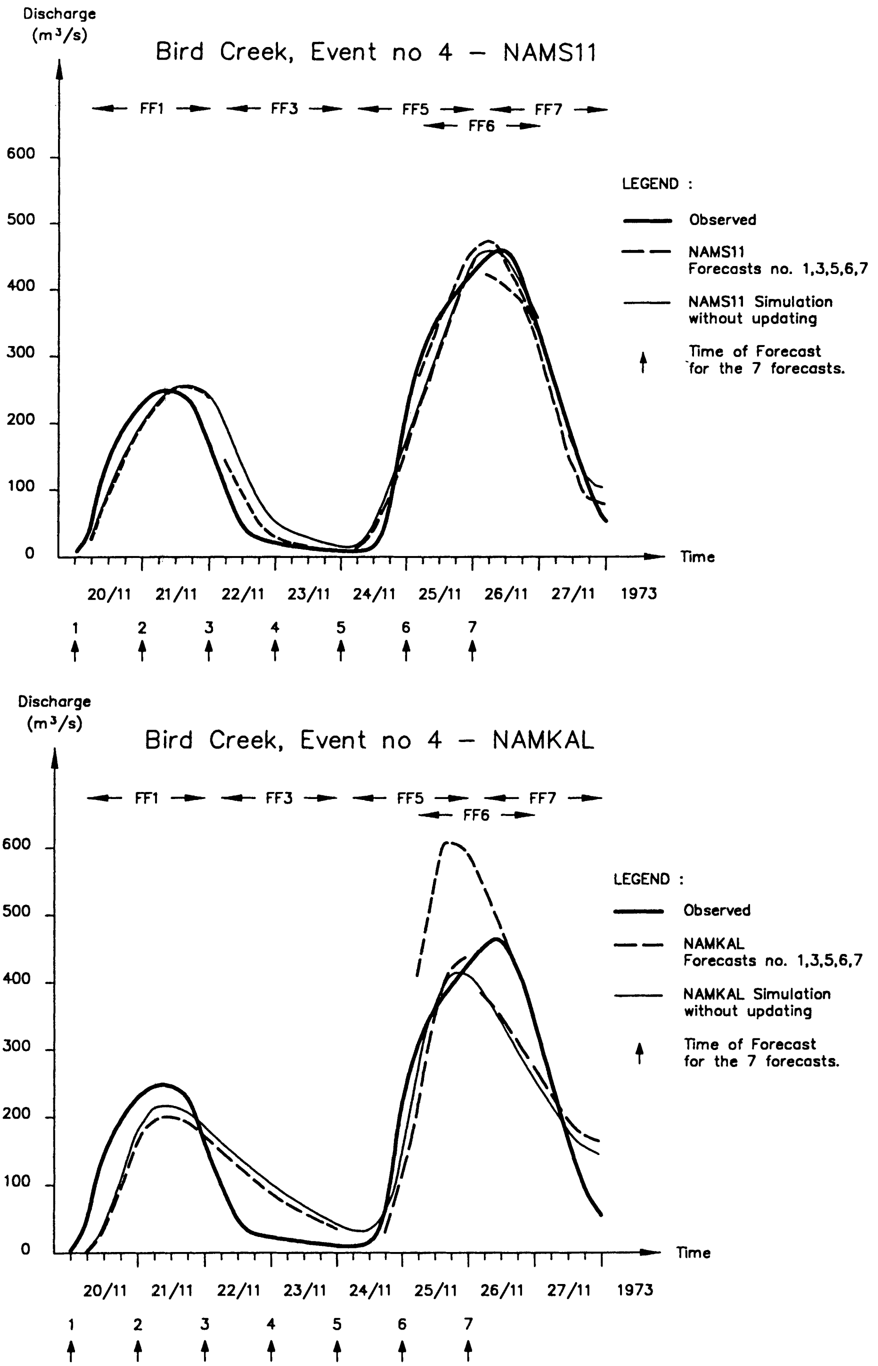

Fig. 3. Simulation and forecast results for the NAMS11 and the NAMKAL models for the Bird Creek event No. 4.

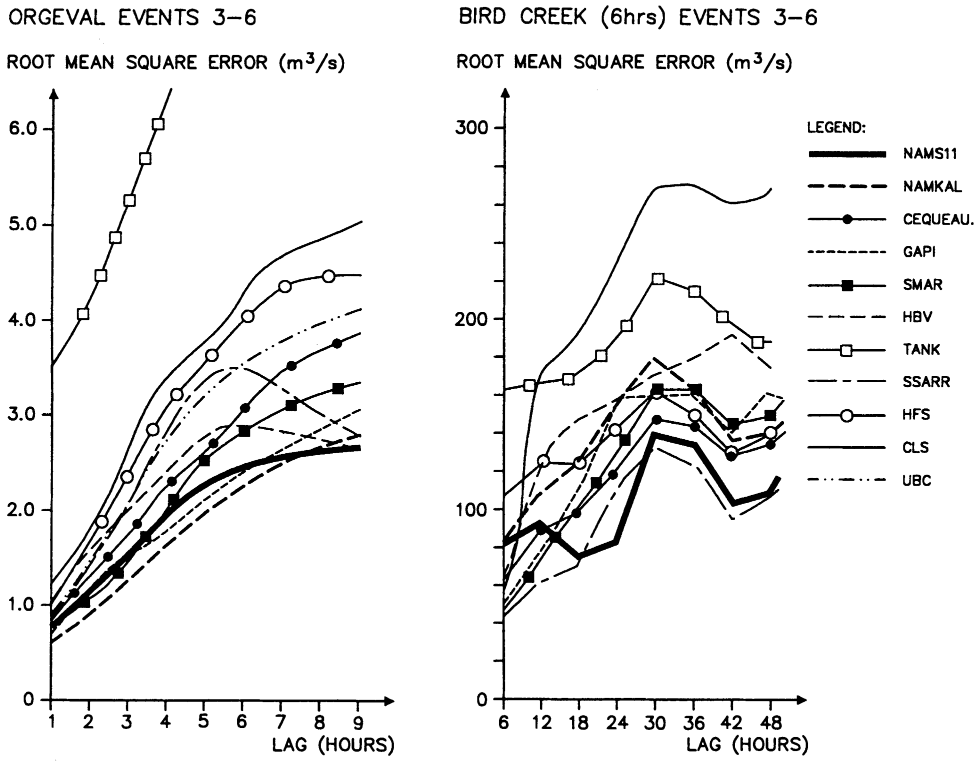

Fig. 4. Root Mean Square Errors (RMSE) as a function of forecast lead time for all models participating in the Orgeval and Bird Creek catchments. The RMSE values are averaged over the four forecasted flood events with blind tests (events 3-6).

comments on the results as given in the final report required consensus among all participants. As a consequence the conclusions drawn in WMO (1992) are somewhat 'cautious' and do not contain significant analysis of the performance of different types of updating procedure. Hence the following are the author's own assessment of the general results.

A generally accepted numerical criteria of interest is the root mean square of the errors between observed and forecasted values, RMSE. The RMSE calculated over all the four flood events (each with seven forecasts) forecasted during the workshop are shown in Fig. 4 for the Orgeval and Bird Creek catchments. Here the forecast accuracy, expressed in terms of RMSE, is shown as a function of forecast lead time.

As can be seen from Fig. 4 the intercomparison test turned out to be a very close 'race' with at least one third of the models performing almost equally well. Depending on the selected criteria for comparison (which catchment, priority to short, medium or long lead times, etc) several of these will be able to claim to be the 'best model'.

The forecast accuracies obtained by the models can be attributed partly to the accuracy of the basic simulations (without updating) and partly to the efficiency of the updating routines for the various models. It may be difficult to generally distinguish between the two factors; however the following findings appear from the Orgeval and Bird Creek results:

- All four types of updating procedure are represented both among the models with the best performance and among the models with the poorest performance. This indicates that the selection of a specific updating methodology is only one out of several important factors, when deciding about the adequate modelling approach.
- For Orgeval the RMSE generally increases with lead time. This indicates the positive impact of the updating routines. The exception to this are two models (HBV, SSARR) where the RMSE curves do not show a monotonic trend implying that the updating procedure is not functioning optimally. It may be noted that the updating procedures for these two models are based on correction of input variables and are carried out using a manual iterative procedure.
- For Bird Creek the RMSE generally increases with lead time up to about 30 hours, implying that the positive effects of the updating is confined to such a period. An exception to this monotonic curve is the NAMS11, which is analyzed further below.
- Thus for both the Orgeval and Bird Creek catchments the RMSE is generally significantly smaller for short lead times than for long lead times. This shows that updating procedures significantly improve the performance of hydrological models for short-range forecasting.
- In many cases the models with best performance for short lead times were also those with the best results for the long lead times (the RMSE curves for the different models do not often cross each other). This indicates that the goodness of the basic simulation (by the process model) is crucial to forecast accuracy, in particular for large lead times but also to some extent for short lead times.

Validation and Intercomparison of NAMS11 and NAMKAL

Outline of NAMS11 and NAMKAL Models

DHI was represented at the Vancouver workshop with two different models: NAMS11 and NAMKAL.

NAMS11 comprises the following elements:

- The NAM rainfall-runoff model.
- DHI's general river modelling system (System 11), which is based on numerical solution of the St. Venant hydrodynamic equations for one-dimensional flow.
- An updating routine based on the error prediction technique. The updating rou-

tine considers the error between the NAM+System11 model simulated and the observed discharge values in past time up to the time of forecast and predicts (by a first order autoregressive model) how this error will behave after the time of forecast. The predicted error (in discharge) is then added as lateral inflow/outflow to the System11.

Basically, the NAMS11 is hydrologically/hydrodynamically identical to its newer version *MIKE 11*. For several years now the NAMS11/MIKE 11 has been applied operationally in a large number of countries under a variety of hydrological regimes. Descriptions of the modelling system and examples of its applications are given in Jønch-Clausen and Refsgaard (1984), Refsgaard *et al.* (1988) and Havnø *et al.* (1995).

The *NAMKAL* is the NAM model reformulated in state space form and built into an extended Kalman filtering algorithm for updating. Thus it comprises the following elements:

- The NAM rainfall-runoff model (basically identical to the above) formulated in state space form. Thus the water contents in the upper zone storage, the lower zone storage, the groundwater storage and the two 'linear' routing reservoirs are state variables subject to updating.
- No explicit river routing component. Instead the two 'linear reservoirs' in the NAM routing have been utilized.
- Updating by use of the Kalman filter, *i.e.* a feedback from deviations between simulated and observed discharges to the state variables.

The NAMKAL was originally developed at the Technical University of Denmark in 1981 and has so far only been applied to research projects (Refsgaard *et al.* 1983; Storm *et al.* 1988).

Thus the NAMS11 and the NAMKAL contains the same rainfall-runoff model, and the same NAM parameter values were utilized except for the two routing constants, which in NAMKAL also had to account for the river routing. The NAMKAL is lacking a hydraulic river routing part, for which purpose it cannot be expected to give good results on larger catchments (Bird Creek) while the river routing is not expected to be of any significance in the small catchments (Orgeval). Finally, the updating techniques are fundamentally different.

Validation Results and Intercomparison of NAMS11 and NAMKAL

To illustrate the results produced during the Vancouver workshop results of a typical event for each of the two catchments are shown in Figs. 2 and 3. Furthermore, the summary results expressed in terms of root mean square errors (RMSE) as a function of forecast lead time and the RMSE for the simulation (without updating) are shown in Fig. 5.

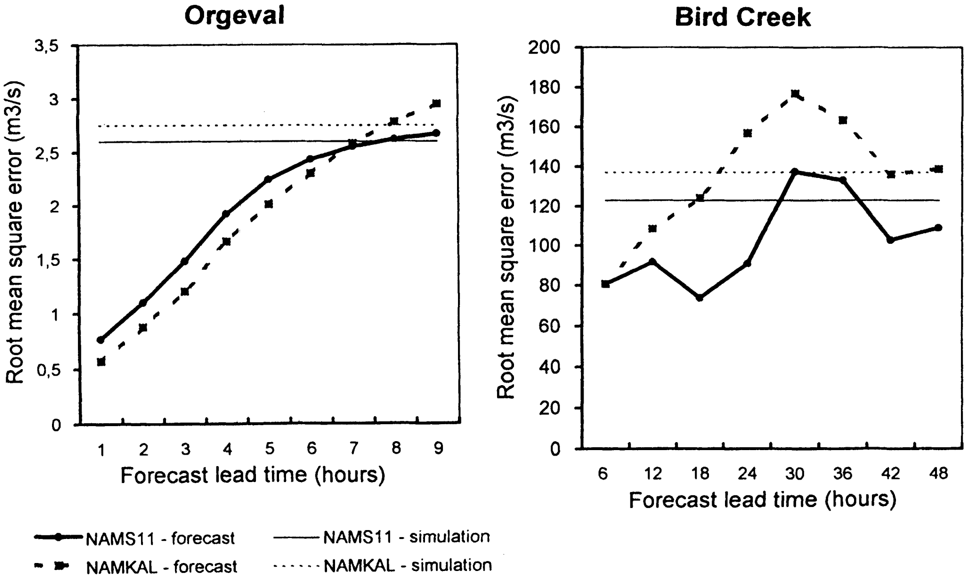

Fig. 5. Root Mean Square Errors (RMSE) as a function of forecast lead time for NAMS11 and NAMKAL at Orgeval and Bird Creek catchments. The RMSE values are averaged over the four forecasted flood events with blind tests (events 3-6).

Fig. 2 shows some of the NAMS11 and NAMKAL results for event No. 4 in Orgeval, while similar results are shown in Fig. 3 for event No. 4 in Bird Creek. Both figures show the observed discharges and the discharges which have been simulated without using the updating routines (*i.e.* without considering feedback from the observed values). Furthermore, the time of forecast (*i.e.* time up to which observed discharges are known) are indicated for the 7 forecasts issued for these events. Finally, the model forecasts Nos. 1, 3, 5 and 7 are shown for the Orgeval while the forecasts Nos. 1, 3, 5, 6, and 7 are shown for the Bird Creek.

In Figs. 2 and 3 the forecasts start at lead time 1, where the forecasts are seen in many cases to deviate from the observed values. For the NAMKAL the user has to provide input on measurement noise and system noise. The system noise is specified in terms of a standard error to the rainfall input. The standard error was kept constant in time, *i.e.* the system noise was in each time step proportional to the rainfall input. The measurement noise is given as a standard error on the measured discharge data. As no information was available on uncertainties of the observed discharge data and as the success criteria (RMSE) in the Vancouver workshop was calculated on the basis of assumed error free observed discharge data, the measurement noise in the NAMKAL was assumed to be zero. This forces the NAMKAL to fit the observed discharge data at the time of forecast, but does not necessarily guarantee an optimal performance. The state variables which were updated were water contents in soil moisture and river routing storages. Although the updatings in general intuitively appeared reasonable, it must be emphasized that it is difficult to assess the physical relevance of the state updating.

For Orgeval (Fig. 2) it appears that the simulations for the two models as expected are almost identical. The reason for this is that river routing is almost without importance and that the NAM parameter values are identical. Thus, the differences in the forecast results are due to the two different updating methods. Finally, it is noticed that the simulations agree reasonably with the observed hydrograph with respect to shape, timing and size of peak.

For Bird Creek (Fig. 3) it is obvious that the simulations for the two models as expected are significantly different. The NAMS11 simulation shows a quite good agreement with the observed hydrograph. The NAMKAL simulation shows generally a poor agreement with the observed hydrograph with respect to timing of peaks, shape of hydrograph (in particular recession) and size of peaks. The reason for this poor NAMKAL simulation is the lack of an adequate river routing capability; the two linear routing reservoirs are simply not able to reproduce the shape of the Bird Creek hydrograph, which is characterized by a 24-48 hours lapse time until the hydrograph suddenly starts rising and by a somewhat unusual shape (the rising and the receding sides of the hydrograph being equally steep). From the forecast results it appears that the updating has only marginal effect on the NAMS11 forecasts because the basic simulation already is quite good. On the other hand, the Kalman updating in NAMKAL is seen not to be able to make much improvement in the forecasts as compared to the basic simulations and in one case (forecast No. 6) actually causes a poor simulation of the peak size and time to become an even worse forecast.

From Fig. 5 it is seen that, for the Orgeval catchment, the RMSE generally increases as a function of lead time. Actually the RMSE approaches the RMSE value for the simulation without updating. This indicates the positive effect of the updating routines.

From Fig. 5 it is furthermore seen that, for the Bird Creek catchment, the RMSE for NAMS11 shows approximately the same values for lead times 6, 12, 18 and 24 hours, after which the RMSE values increase to a level corresponding to the RMSE of the simulation. In contrary to the case of Orgeval, the NAMS11 RMSE curve does not display a monotonic trend. For example the RMSE for 18 hours lead time is smaller than RMSE for 6-12 hours lead time. An analysis of the results reveals that this 'abnormal' behaviour is due to the inability of the NAMS11 updating routine to effectively account for phase errors between observed and forecasted peaks. An example of this can be seen as forecast No. 7 in Fig. 3. Here the NAMS11 simulation at the time of forecast, just before the second peak, is higher than the observed value. Therefore the updating predicts this error (simulated – observed) to continue to be negative during the forecast period. As can be seen from the figure the deviation between simulated and observed hydrographs turned out to be caused by a minor phase difference, and the updating in this case actually proved to result in a poorer forecast as compared to the simulation without updating.

It was known from the warm up events that the NAMS11 updating procedure was not functioning well in the case of phase errors for the Bird Creek catchment. Therefore, during the tests at the Vancouver workshop the updating was often (manually) switched off, when the time of forecast was at the rising limb of the hydrograph. One likely reason for the main part of the phase errors in the Bird Creek simulations may be that the entire catchment is treated as one lumped catchment with mean catchment rainfall as the only input data, and hence rainfall events that are centred over the upstream or the downstream part of the catchment are (erroneously) routed similarly with the same time lag. This recognised phase error problem has, subsequently, resulted in the development of an improved updating routine capable of distinguishing between phase and amplitude errors (Rungø *et al.* 1991).

Discussion and Conclusions

The NAMS11 and the NAMKAL contain the same conceptual rainfall-runoff model but different river routing components and different updating components. As river routing is of negligible importance for the Orgeval but very important for the Bird Creek, the performances of the two models for the two catchments may be used to derive conclusions with regard to comparison of updating procedures and to the relative importance of a process model (in this case river routing) as compared to the updating procedure:

- For the Orgeval catchment the basic simulations are practically identical and the only significant difference is the updating procedure employed. An intercomparison between the two updating routines indicates that the performances are almost equally good, with the Kalman filter being marginally better than the error prediction model, especially for small lead times.
- For the Bird Creek, however, the river routing was crucial and the NAMKAL routing (based on two linear reservoirs) was not adequate. Thus, the accuracy of the basic simulation with the NAMS11 was better than that of the NAMKAL. The results of the forecasting were that the NAMS11 performed significantly better than the NAMKAL, illustrating that NAMKAL's more complex updating routine (extended Kalman filter) was not able to compensate for a poor basic simulation with physically unrealistic hydrographs.

These results indicate that an extended Kalman filter may be the better updating procedure in cases where the basic simulation by the process model is good, but it is no guarantee for good forecasts in cases where the process model provides a poor simulation. This finding is supported by Moore *et al.* (1993) who conclude that state updating is more reliable than error prediction where time delays (*i.e.* longer river channels) do not dominate.

The forecast accuracy depends on both the accuracy of the basic simulation achieved by the process model and on the efficiency of the updating routine. The importance of the updating procedure in reducing the root mean square error (RMSE) values for short lead times, as compared to simulation without updating, is very significant for all models. However, a good updating procedure is not sufficient for obtaining accurate forecasts. Thus, generally, the basic simulation is crucial to forecast accuracy and the updating routines function more optimally the better the basic simulation is.

It is noticed that one of the conceptual models (HFS, *i.e.* Sacramento) provides results which, particularly for longer lead times, are significantly poorer than comparable conceptual models such as NAM, SSARR, SMAR. This is not believed to be due to the model structure, but may very likely be explained by a possible non-optimal calibration of the Sacramento model.

The results revealed that the updating techniques in some cases did not function optimally. Thus, there is still scope for significant improvement. A common problem experienced by most (if not all ?) of the updating routines is the problem of distinguishing between phase and amplitude errors.

The most complex updating procedure assessed in this study is a state variable updating procedure based on the extended Kalman filter which was used by two models NAMKAL and HFS. A comparison between NAMKAL and NAMS11 on the Orgeval catchment indicates that the extended Kalman filter is only marginally better than a simple error prediction model. However, as noted by Ahsan and O'Connor (1994) all the capabilities of the Kalman filter are not actually utilized, because the objective of the forecasting, consciously or subconsciously, is to match the subsequently observed flows as closely as possible without considering the actual uncertainties on the measured flows. They foresee that hydrologists will make more use of Kalman filtering in the future in connection with assimilation of remote sensing data, which may well be corrupted by significant noise.

The author agrees with Ahsan and O'Connor (1994)'s indication that, most likely, updating of hydrological models by use of spatial remote sensing data (such as Entekhabi *et al.* 1994 and Ottlé and Vidal-Madjar 1994) may emerge as an equally important field of application of updating procedures. Furthermore, it appears obvious that the state variable updating procedures directly are the more suitable for incorporating remotely sensed spatial data on variables, such as snow cover, soil moisture and vegetation status, into hydrological models. These variables appear as internal, spatially correlated variables and not as final independent outputs, such as discharge at one location. However, for updating of spatial remote sensing data nonlinearities in measurement and system equations may put in question the optimality of the Kalman filter based methods and encourage exploration of alternative state space updating methods.

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References

Ahsan, M., and O'Connor, K.M. (1994) A reappraisal of the Kalman filtering technique, as applied in river flow forecasting, *Journal of Hydrology*, *Vol. 161*, pp. 197-226.

Bergström, S., Persson, M., and Sundquist, B. (1978) Operational hydrological forecasting by conceptual model. HB report 32, Swedish Meteorological and Hydrological Institute. Presented at the Nordic Hydrological Conference, Vemdalen, Sweden.

Box, G.E.P., and Jenkins, G.M. (1970) *Time series analysis, forecasting and control*, Holden-Bay Inc, San Francisco.

Burnash, R.J.C. (1995) The NWS river forecast system – catchment modelling, in: Singh, V.P. (Ed) Computer Models of Watershed Hydrology, Water Resources Publications, pp. 311-366.

Entekhabi, D., Nakamura, H., and Njoku, E.G. (1994) Solving the inverse problem for soil moisture and temperature profiles by sequential assimilation of multifrequency remotely sensed observations, *IEEA Trans. Geoscience and Remote Sensing*, *Vol. 32(2)*, pp. 438-448.

Fread, D.L. (1992) Flow routing, in Maidment, D.R. (Ed.): *Handbook of Hydrology*, McGraw-Hill, Chapter 10.

Gelb, A. (Ed.) (1974) *Applied optimal estimation*, MIT Press, Cambridge, Mass.

Georgakakos, K.P., Rajaram, H., and Li, S.G. (1988) On improved operational hydrologic forecasting of streamflows, IIHR Report No. 325, Department of Civil Engineering and Iowa Institute of Hydraulic Research, The University of Iowa.

Havnø, K., Madsen, M.N., and Dørge, J. (1995) MIKE 11 – a generalized river modelling package, in Singh, V.P. (Ed): Computer Models of Watershed Hydrology, Water Resources Publications, pp. 733-782.

Heemink, A.W., and Kloosterhuis, H. (1990) Data assimilation for non-linear tidal models, *Int.J. Num.Meth.Fluids*, *Vol. 11*, pp. 1097-1122.

ICWE (1992) The Dublin Statement and report of the conference, International Conference on Water and the Environment: Development issues for the 21st century. 26-31 January 1992, Dublin, Ireland.

Jamieson, D.G., Wilkinson, J.C., and Ibbitt, R.P. (1972) Hydrologic forecasting with sequential deterministic and stochastic stages, Proceedings from the International Symposium on Uncertainties in Hydrology and Water Resources Systems, Tucson, Arizona, Vol. 1, pp. 177-187.

Jønch-Clausen, T., and Refsgaard, T. (1984) A Mathematical Modelling System for Flood Forecasting, *Nordic Hydrology*, *Vol. 15*, pp. 307-318.

Kachroo, R.K. (1992) River flow forecasting. Part 1. A discussion of the principles, *Journal of Hydrology, Vol. 133*, pp. 1-15.

Kitanidis, P.K., and Bras, R.L. (1978) Real-time forecasting of river flows, Technical Report 235. Ralph M. Parson's Laboratory for Water Resources and Hydrodynamics, MIT, Cambridge, Mass.

Lundberg, A. (1982) Combination of a conceptual model and an autoregressive error model for improving short time forecasting, *Nordic Hydrology, Vol. 13*, pp. 233-246.

Moore, R.J., Austin, R., and Carrington, D.S. (1993) Evaluation of FRONTIERS and local radar rainfall forecasts for use in flood forecasting models, R&D Note 225, National Rivers Authority, UK.

Nemec, J. (1994) Distributed hydrological models in the perspective of forecasting operational real time hydrological systems (FORTHS), in: Rosso, R., Peano, A., Becchi, I, and Bemporad, G.A. (Eds.) Advances in distributed hydrology, Water Resources Publication, pp. 69-84.

Ottlé, C., and Vidal-Madjar, D. (1994) Assimilation of soil moisture inferred from infrared remote sensing in a hydrological model over the HAPEX-MOBILHY region, *Journal of Hydrology, Vol. 158*, pp. 241-264.

Rango, A. (1995) The snowmelt runoff model (SRM), in Singh, V.P. (Ed): Computer Models of Watershed Hydrology, Water Resources Publications, pp. 477-520.

Refsgaard, J.C., and Storm, B. (1995) MIKE SHE, in Singh, V.P. (Ed): Computer Models of Watershed Hydrology, Water Resources Publications, pp. 809-846.

Refsgaard, J.C., Rosbjerg, D., and Markussen, L.M. (1983) Application of Kalman filter to real-time operation and to uncertainty analyses in hydrological modelling, *IAHS Publication No 147*, pp. 273-282.

Refsgaard, J.C., Havnø, K., Ammentorp, H.C., and Verwey, A. (1988) Application of hydrological models for flood forecasting and flood control in India and Bangladesh, *Advances in Water Resources, Vol. 11*, pp. 101-105.

Refsgaard, J.C. (1996) Terminology, modelling protocol and classification of hydrological model codes, in Abbott, M.B., and Refsgaard, J.C. (Eds.): *Distributed Hydrological Modelling*, Kluwer Academic Publishers, pp. 17-39.

Rodda, J.C. (1995) Whither world water? *Water Resources Bulletin, Vol. 31(1)*, pp. 1-7.

Rungø, M., Refsgaard, J.C., and Havnø, K. (1991) The updating procedure in the MIKE 11 modelling system for real-time forecasting, in: Proceedings of the International Symposium on Hydrological Applications on Weather Radar, University of Salford, 14-17 August 1989, Ellis Horword, pp. 497-508.

Sittner, W.T., and Krouse, K.M. (1979) Improvement of hydrologic simulation by utilizing observed discharge as an indirect input, NOAA Technical Memorandum NWS HYDRO-38.

Storm, B., Jensen, K.H., and Refsgaard, J.C. (1988) Estimation of catchment rainfall uncertainty and its influence on runoff prediction, *Nordic Hydrology, Vol. 19*, pp. 77-88.

Szöllözi-Nagy, A., Bartha, P., and Harkayi, K. (1983) Microcomputer based operational hydrological forecasting system for river Danube, Technical Conference on Mitigation of Natural Hazards through Real-Time Data Collection Systems and Hydrological Forecasting, Sacramento, California.

Todini, E., and Wallis, J.R. (1975) Using CLS for daily or longer period rainfall-runoff modelling, in: *Mathematical Models for Surface Water Hydrology*, John Wiley & Sons.

WMO (1975) Intercomparison of conceptual models used in operational hydrological forecasting, WMO operational hydrology report no 7, WMO no 429, World Meteorological Organisation, Geneva.

WMO (1986) Intercomparison of models for snowmelt runoff, WMO operational hydrology report no 23, WMO no 646, World Meteorological Organisation, Geneva.

WMO (1988) Simulated real-time intercomparison of hydrological models, Report from WMO workshop in Vancouver, Canada, August 1987, WMO/TD no 255, World Meteorological Organisation, Geneva.

WMO (1992) Simulated real-time intercomparison of hydrological models, WMO operational hydrology report no 38, WMO no 779, World Meteorological Organisation, Geneva.

Wood, E.F., and O'Connell, P.E. (1985) Real-time forecasting, in Anderson, M.G., and Burt, T.P. (Eds.): *Hydrological Forecasting*, John Wiley & Sons, pp. 505-558.

Quick, M.C. (1995) The UBC watershed model, in Singh, V.P. (Ed): Computer Models of Watershed Hydrology, Water Resources Publications, pp. 233-280.

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