Nordic Hydrology, 15, 1984, 307-318

A Mathematical Modelling System for Flood Forecasting

Paper presented at the Nordic Hydrological Conference
(Nyborg, Denmark, August – 1984)

T. Jønch-Clausen and J. Chr. Refsgaard

Danish Hydraulic Institute, Hørsholm, Denmark

In this paper comprehensive simulation models are presented which can forecast the streamflow in real time at various points in river systems and provide a tool for identifying improvements of the reservoir operations during flood situations while taking into consideration the conditions downstream. The mathematical modelling has involved rainfall-runoff predictions as well as flood routing. The application of the modelling system to a part of the 22,000 square kilometres Damodar River Catchment located in Bihar and West Bengal in India, is described.

Introduction

The consequences of rainfall flood events in terms of lost lives and property have become increasingly serious due to the increase in human habitation and activity along the rivers. Simple statistical models have for decades served as important flood forecasting tools. The recent years' progress within hydrology and river hydraulics has now made it feasible to perform flood forecasting by means of more advanced and comprehensive mathematical models. This paper presents the NAM-S11 mathematical modelling system for real time flood forecasting. It consists of four main elements: A hydrological rainfall-runoff model (NAM), a hydrodynamic model (System 11) for river routing and reservoir simulation, an updating procedure (linear "noise model") for use in real time operation, and a data management package for data processing. The modelling system has been applied to a part of the 22,000 km^2 Damodar River Catchment located in Bihar and West Bengal in India. The results of the model simulations in flood periods are presented and the application of the modelling system in real time forecasting is illustrated and discussed.

The Nam-S11 modelling system has been developed in a cooperation between Danish Hydraulic Institute (DHI) and the Central Water Commission of India (CWC), financed jointly by the Danish International Development Agency (DANIDA) and the Government of India. A comprehensive training programme has been an important part of this cooperation, and the modelling system is now transferred to computers in India where it is being operated by CWC engineers.

The Modelling System, Nam-S11

In the following the components of the NAM-S11 modelling system are briefly described.

The Rainfall-Runoff Model, NAM

NAM is a deterministic rainfall-runoff model of the lumped conceptual type. NAM is an abbreviation of the Danish: "Nedbør-Afstrømnings-Model", meaning precipitation-runoff-model. This model was originally developed by the Hydrologic Section of the Institute of Hydrodynamics and Hydraulic Engineering at the Technical University of Denmark (Nielsen and Hansen 1973). The NAM model has been further developed and extensively applied by DHI (Jønch-Clausen and Refsgaard 1982).

NAM simulates the rainfall-runoff process in rural catchments. It operates by accounting continuously for the moisture content in five different and mutually interrelated storages representing physical elements in the catchment (see Fig. 1).

The data input requirements are precipitation, potential evapotranspiration and (only if snow occurs) temperature data. The sampling interval of the input data can be given arbitrarily. Thus, typically, for flood modelling six-hourly or three-hourly rainfall data would be appropriate, while daily rainfall data would be sufficient for most other purposes.

For the purpose of flood forecasting a hydrological model of the NAM-type and -complexity is believed to be appropriate. It has been documented both by Kitandinis and Bras (1978) and by Jørgensen (1981), that conceptual models are superior to black box models (as e.g. the ARIMA type of models) for flood forecasting. A more complex conceptual model will probably not yield better streamflow simulations because the main uncertainty in the rainfall-runoff modelling of the flood situations usually pertains to the assessment of the rainfall input.

The NAM model is a well proven engineering tool which has been applied successfully to more than 50 catchments in different climatic regions throughout

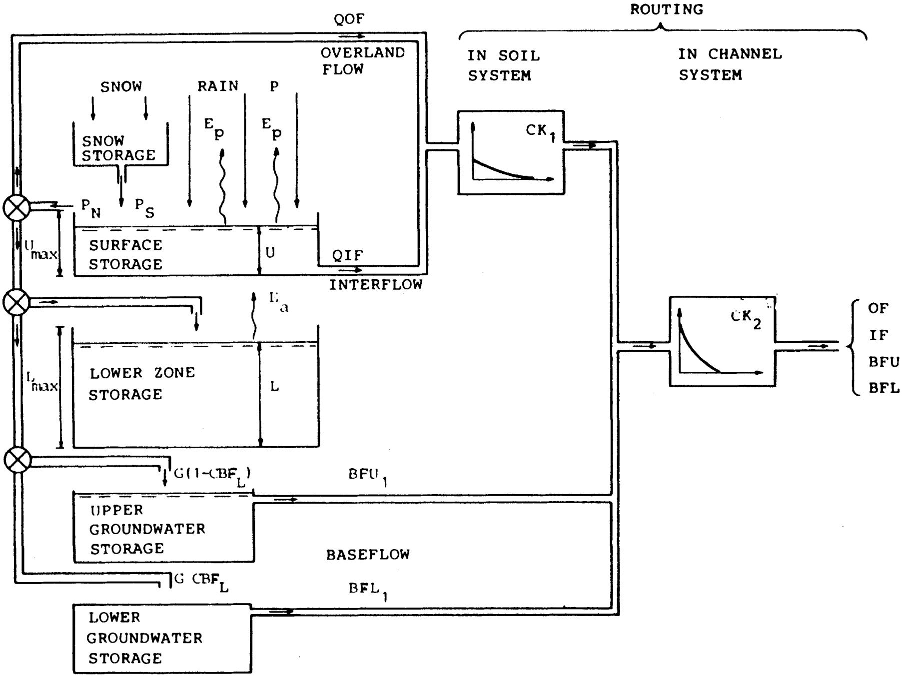

Fig. 1. Structure of the Nam rainfall-runoff model.

the World. Hence, in addition to numerous applications in Denmark, it has been applied for water supply studies in Borneo, Tanzania and Sri Lanka, irrigation and flood control studies in Thailand, flood forecasting and flood control studies in India, and for hydropower studies in Greenland and Tanzania.

The Hydrodynamic River Model, System 11

System 11 is a general mathematical modelling system for the simulation of flows and water levels in rivers, reservoirs, estuaries and canal systems.

In its most advanced form, System 11 is based upon numerical solution of the general one-dimensional 'Saint Venant' equations (conservation of mass and momentum)

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q$$

$$\frac{\partial}{\partial x}\left(\alpha \frac{Q^2}{A}\right) + \frac{\partial Q}{\partial t} + gA\frac{\partial \xi}{\partial x} + \frac{gQ|Q|}{M^2 A R_*^{4/3}} = gAI_o$$

Kinematic wave

Diffusive wave

Dynamic wave

where

A - flow area (m^2)
M - Manning's roughness coefficient ($m^{1/3}s^{-1}$)
g - acceleration of gravity (ms^{-2})
ξ - water depth (m)
Q - discharge (m^3s^{-1})
R_* - resistance radius (m)
α - momentum distribution coefficient
I_0 - slope of river bed
x - horizontal coordinate (m).

The equations are solved as time-centered, implicit difference equations in a grid, the prints of which can be set as required. For details regarding the numerical scheme references are made to Abbott (1979) and Cunge et. al. (1980) while the model is described more thoroughly in "System 11, a Short Description", DHI, 1984.

System 11 is very flexible. Thus, in order to save computer time it has the options of using the diffusive or the kinematic wave approximation if the fully dynamic wave description is not required. Several types of hydraulic structures can be described with System 11, for example, reservoirs, dams, weirs and other types of flow regulators. For the flow description over weirs or embankments automatic switching is performed between subcritical and supercritical flow conditions.

By virture of its general formulation, System 11 allows for description of (pseudo) two-dimensional flows over wide flood plains as illustrated in Fig. 2.

System 11 was developed in the early 1970's by DHI and was later adopted by the International Institute for Hydraulic and Environmental Engineering in Delft, the Netherlands and the U.S. Corps of Engineers, Waterways Experiment Station. Among the river systems and estuaries to which it has been applied are the Elbe River in West Germany, the Gambia River in West Africa, the Limfiord in Denmark, the Damodar River in India, the Nam Kam River in Thailand, and the Danube in Austria.

The Updating Procedure for Real Time Forecasting

A classical problem in real time operation of hydrological models is that the simulated runoff generally deviates from the measured runoff at the time of forecast. In order to obtain optimal benefit of the real time runoff measurements in the forecasts, some sort of updating of the hydrological model is required before the forecast is made.

Traditionally, updating is being performed by subjective manual methods. However, when applying a computer based flood forecasting system like the NAM-S11 a computerized updating procedure is a prerequisite for making the

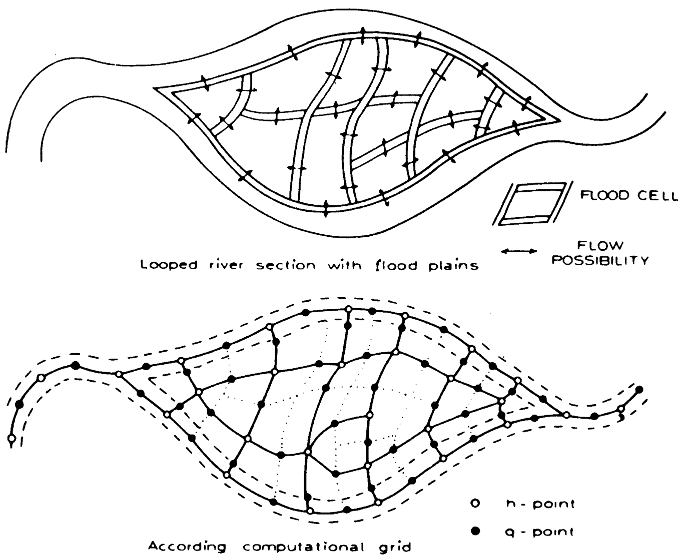

Fig. 2. Pseudo 2-dimensional simulation of flood plains, discretized by flood cells between the two river branches.

system work efficiently. Therefore, the updating procedure used here is a computerized technique. It is based on a socalled "noise-model" simulating the deviations between measured and simulated runoff through a linear autoregressive model. The simulated deviation ("noise") is used to adjust the streamflows simulated by NAM, prior to the routing by System 11.

Extensive research and investigations of current practices, e.g. in the U.S.A., have formed the basis for adopting the simple, yet very efficient linear autoregressive model approach to updating. The functioning of the updating procedure is illustrated in Fig. 3.

The Data Mangement Programs

An integral element of the NAM-S11 modelling system is a package of thoroughly documented data management programs. The importance of this package can hardly be overstressed. In a real-time forecast situation a fast, flexible and reliable data manipulation capability is an absolute requirement, without which even the most advanced simulation model is of no use.

The data management package consists of a number of small programs for readily checking and transforming the real-time data into formats directly applicable by the mathematical model. For instance, the weights assigned to the rainfall stations in the mean areal rainfall calculations are adjusted automatically when some of the stations fail to record (or report) data.

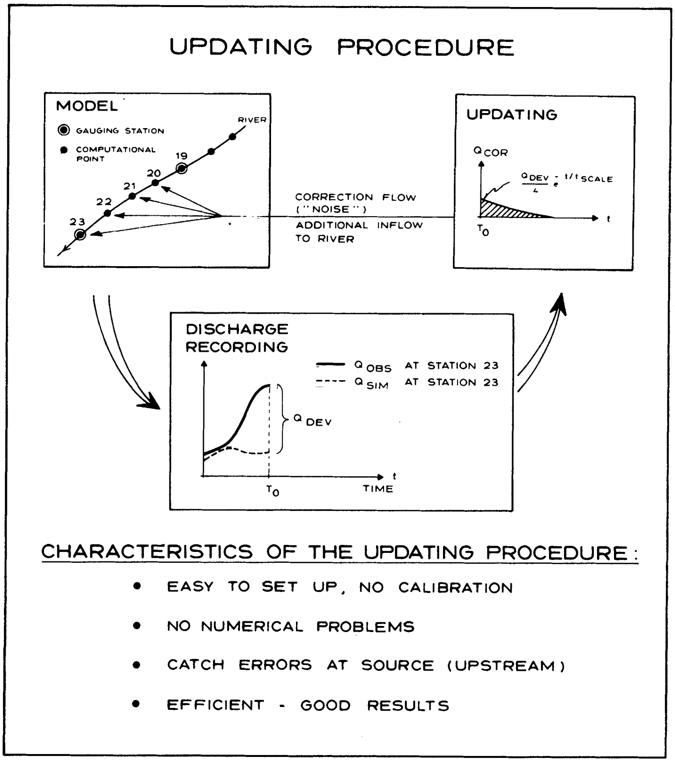

Fig. 3.
Principle of real-time updating procedure.

Application to the Damodar River, India

The NAM-S11 modelling system has been applied to the 22,000 km^2 Damodar River Basin in the north-eastern part of India in the states of Bihar and West Bengal (Fig. 4). The low-lying alluvial flats along the lower reaches are subject to frequent inundations causing serious damages. Five multi-purpose dams have

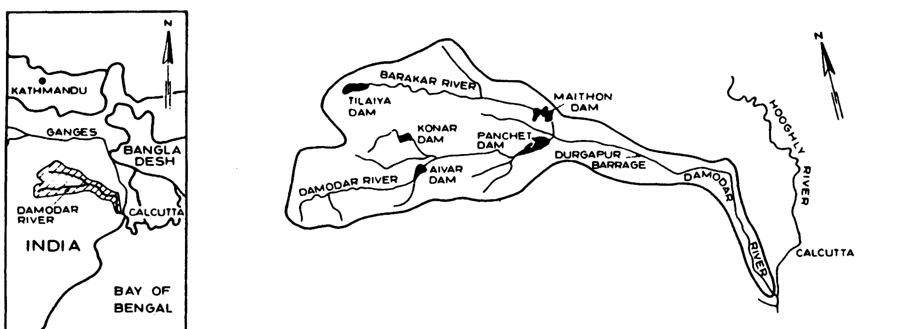

Fig. 4. The Damodar River Catchment.

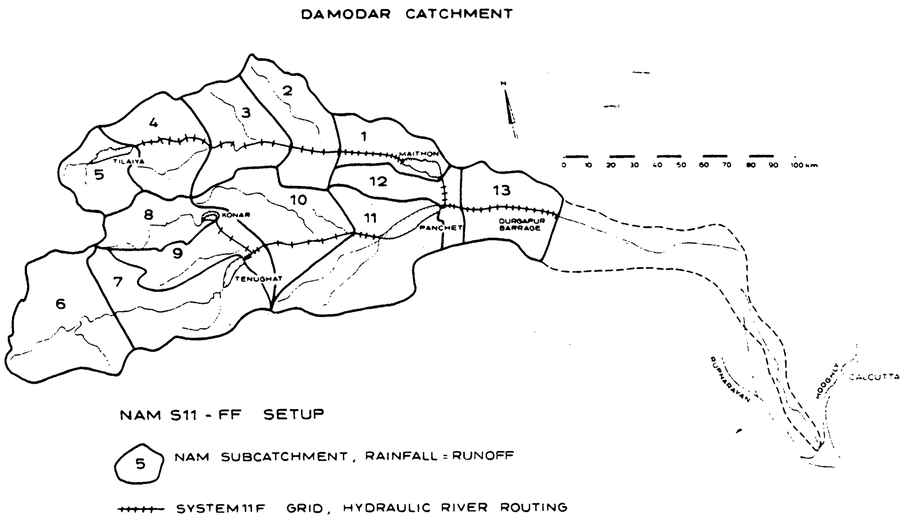

Fig. 5. NAM-S11 set-up on the upper Damodar catchment.

been constructed in the upper catchment – primarily with a view to controlling floods.

The application has had the following three main objectives:

- Focus project for the training of Indian engineers in the use of the modelling system, for
- Flood forecasting, i.e. forecasting of flows at different locations on the system for various reservoir operation strategies, and
- Flood control, i.e. analysis of the effect on flooding patterns of various structural flood control measures.

The application of the NAM-S11 System for flood forecasting in the upper Damodar River basin is briefly described in the following.

Model Set-up

The model set-up for the catchment upstream of Durgapur Barrage is presented in Fig. 5. The total catchment of 19,550 km^2 has been divided into 13 subcatchments with separate rainfall and evaporation input in the rainfall-runoff (NAM) modelling. Hydraulic river routing (System 11) has been performed from Tilaiya, Konar and Tenughat reservoirs down to Durgapur Barrage using a total of 84 grid points to model the 470 km long river reaches. A longitudinal profile of the System 11 grid on the Barakar River is shown in Fig. 6. The outflows from the NAM model are taken as inflow to the System 11.

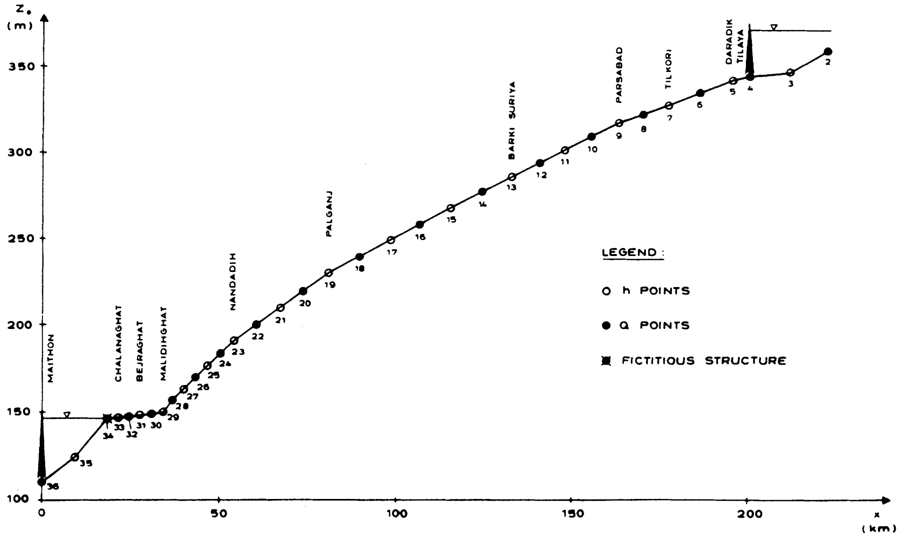

Fig. 6. Longitudinal profile and the System 11 computational grid for the Barakar River.

The time step in the NAM calculations has been chosen as six hours - corresponding to the time intervals in the collected rainfall data. The time step in System 11 has been chosen as 0.5 hours in the dynamic wave version, 1.5 hours in the simpler diffusive wave version and 6 hours in the kinematic wave version. In the kinematic wave version, the grid is coarser than in the set-up shown in Fig. 6.

Model Calibration and Verification

The NAM-S11 system has been calibrated on 1978-80 data and tested (verified) on data from the period 1971-77. The model performances in the calibration period and in the test period were found to be of the same quality. Generally, the simulation results can be characterized as very good. As an example of a calibration result the simulated and the recorded inflows to Maithon Reservoir during the 1980 monsoon season are shown in Fig. 7.

Importance of the Updating Procedure

The only flood in the ten-year period 1971-80 which initially has not been simulated satisfactorily is the flood of September 26-27, 1978. Detailed analyses of the rainfall and discharge data have indicated that the initial poor fit is probably due to uncertainties in the rainfall input data.

Therefore, in order to test the updating capabilities of the system, the updating procedure has been applied to the flood event of September 26-27, 1978. The result is shown in Fig. 8. Compared to the initial simulation (without updating),

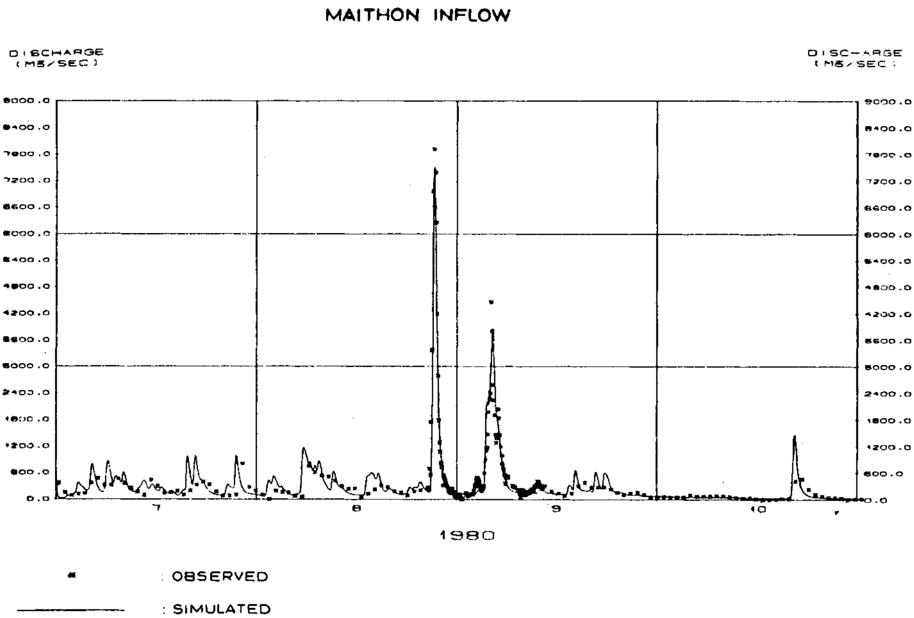

Fig. 7. Simulated and observed inflow to Maithon Reservoir during the 1980 monsoon season.

the peak value has increased from 8,200 m^3/s to 10,800 m^3/s, which must be compared to the recorded peak of 12,300 m^3/s. It should be noticed that the updating has been performed for every three hours of simulation only, corresponding to the time interval between the collected discharge data. As hourly discharge data availability is expected in real time forecast situations, the updating procedure is expected to yield an even more accurate fit than the one shown in Fig. 8.

Thus in situations with an initial discrepancy between simulated and recorded flows the deviations can be reduced (almost removed) using the updating procedure, hence obtaining a more accurate forecast from the more realistic initial conditions.

An illustration of the application of an updated model is shown in Fig. 9 which indicates how a range of forecasts can be obtained for various expected rainfall amounts during the next 24 hours.

Future Flood Forecasting Activities in India

The NAM-S11 modelling system is currently (May 1984) being operated by Indian engineers on a Hewlett Packard 1000 computer in Delhi, where it is being set up for flood forecasting on the Yamuna River, as well as for modelling of the effects

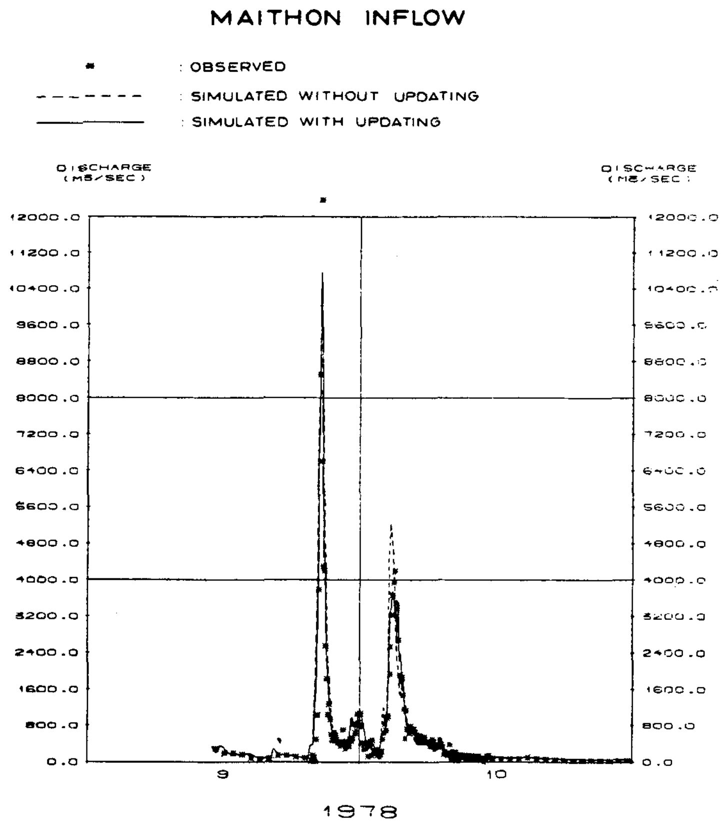

Fig. 8. Result of the updating procedure applied to the flood of September 1978.

.of alternative river training measures on the Delhi reach of the river (flood control). The objective of the transfer of know-how and computer models from DHI to CWC has been to enable CWC to set up and apply the NAM-S11 on catchments anywhere in India – for flood forecasting and for flood control –, and the Yamuna application is the first such independent effort from CWC to apply the system.

Furthermore, CWC and DHI plan to install NAM-S11 on an (already acquired) Indian manufactured computer in Maithon and test it real-time during the coming 1984 monsoon season (time permitting ...). Once installed at Maithon it is planned to utilize the NAM-S11 system to optimize reservoir operation for flood management in the basin. Initial analyses of alternative reservoir operation strategies in flood situations have concluded that flood peaks can be reduced significantly (up to 35% in 1978) by adopting a more flexible reservoir operation policy than the one currently in force.

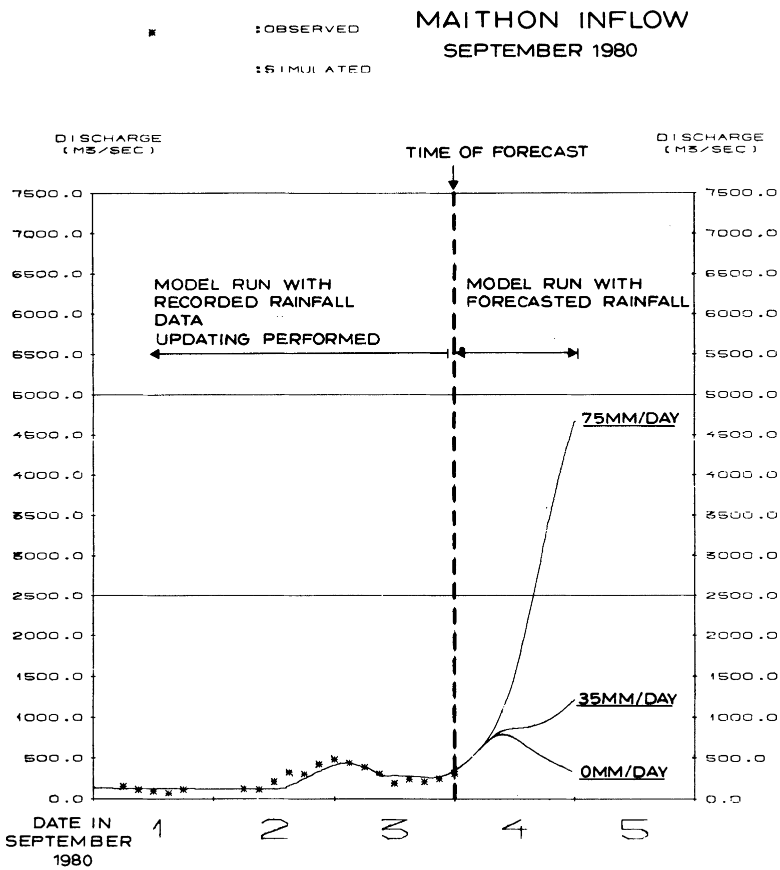

Fig. 9. Example of flood forecasting for September 4, 1980, using three alternative rainfall forecasts.

Conclusions

The NAM-S11 modelling system has been developed and applied to the Damodar River basin in India as the result of an Indo-Danish cooperation.

Indian engineers have undertaken a comprehensive training programme in Denmark and in India, and the NAM-S11 is now being operated successfully by these engineers on computers in India.

The results of the application of the NAM-S11 for flood forecasting in the Damodar River basin for the period 1971-80 have been encouraging. In most of the flood events the agreement between simulated and observed floods have been excellent, and the updating procedure has proved able to correct the simulated discharges efficiently, so that the model in all real time forecast situations will start the forecast of future discharges with a good fit between simulated and measured discharges at the time of forecast. The system has furthermore demonstrated its capability to optimize reservoir operation for flood management.

Installed on an Indian computer in Maithon the NAM-S11 system will now be tested real-time during flood events in the Damodar River basin. It is hoped that the system subsequently will be accepted for widespread application for flood forecasting in India – and elsewhere.

Acknowledgement

The NAM-S11 flood modelling system has been finally developed in a cooperation between Danish Hydraulic Institute and the Central Water Commission of India, financed jointly by the Danish International Development Agency (DANIDA) and by the Government of India.

References

Abbott, M.B. (1979) *Computational hydraulics,* Elements of the theory of free surface flows, Pitman.

Cunge, J.A., Holly, F.M., and Verwey, A. (1980) *Practical aspects of computational river hydraulics,* Pitman.

Jønch-Clausen, T., and Refsgaard, J.C. (1982) Tropical experiences with the NAM model, Nordic Hydrologic Conference, Norway.

Jørgensen, G.H. (1981) Forecast models, M.Sc. Thesis. ISVA, Technical University of Denmark (in Danish).

Kitandinis, P.K. and Bras, R.L. (1978) Real time forecasting of river flows, Technical Report 235, Ralph M. Parsons Laboratory for Water Resources and Hydrodynamics. MIT.

Nielsen, S.A., and Hansen, E. (1973) Numerical simulation of the rainfall-runoff process on a daily basis, *Nordic Hydrology, Vol. 4,* 171.

Received: 1 October, 1984

Address:
Danish Hydraulic Institute,
5 Agern Allé,
DK-2970 Hørsholm,
Denmark.