REVIEW OF METHODOLOGIES AND SOFTWARE FOR FLOOD FORECASTING

NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAVAN
ROORKEE - 247 667, (UP) INDIA

1990 — 91

PREFACE

In recent years, there has been considerable increase in emphasis on non-structural measures of flood control and flood management. Flood forecasting plays a significant role not only for flood management and flood damage reduction but also for operation of multipurpose reservoirs. Significant improvements and corresponding benefits can be achieved if reliable forecasts are available with sufficient lead time. Models have been developed for real time flood forecasting involving different levels of complexities and data requirements.

This report presents a critical review of some available real time forecasting models with emphasis on application of conceptual models. The attempts made in India in this area have also been reviewed.

This report entitled: 'Review of Methodologies and Software for Flood Forecasting', is part of the work programme of Flood Studies Division of the Institute. The report has been prepared by Dr. S K Jain, Sc.'E' in interaction with Dr. S M Seth, Sc.'F' & Technical Coordinator.

Satish Chandra
(Satish Chandra)
Director

ABSTRACT

Flood forecasting is required for a number of purposes, e.g., flood control, flood damage reduction, and reservoir operation. Significant improvements in operation of water resources systems can be achieved if reliable forecasts are available with sufficient lead time.

The models which are used for real time flood forecasting can be classified in three categories - black box models, conceptual models, and physically based models. The first category includes models which are mostly based on Unit hydrograph theory. The physically based models are still in production stage and the computational requirements vis-a-vis facilities available at a typical installation make them unsuitable for real time application, at least for next several years. The conceptual models provide a framework which is theoretically more sound than the black box models. Further the fact that a basin is not a random assembly of different parts but a geomorphological system whose parts are related to each other by a long common history, encourages the hope that simplified concepts may be found adequate to describe the operation of the basin in converting rainfall to runoff.

This present report critically reviews the available real time forecasting models. Special emphasis is placed on application of conceptual models like NWSRFS, HBV model and NAM model. The attempts made in India in this area have also been reviewed.

***

REVIEW OF METHODOLOGIES AND SOFTWARE FOR FLOOD FORECASTING

CONTENTS

Page No

CHAPTER 1

1.0 INTRODUCTION

India is traversed by a large number of rivers, the major ones being the Brahmaputra, Ganga, Narmada, Mahanadi, Godaveri, Krishna etc. Most of the Indian rivers derive their supplies from the monsoons which occur during the months of June to October. During these months all these rivers swell over their banks and inundate large area of their flood plains. These high and abnormal floods cause heavy damage to the crops and nearby buildings, in addition to the disruption of the rail and road traffic. But the most severe damage due to these floods is that of the loss of life of the human beings.

The Rashtriya Barh Ayog estimated that 40 million ha area in the country is prone to floods. Till 1985 reasonable degree of protection has been provided to an area of 13 million ha. The value of flood losses from 1953 to 1980 has been estimated to be Rs. 9154 crores. On an average, property worth Rs. 327 crores is damaged due to floods annually. However, Subramanya(1984) gives a figure of Rs. 1000 crores as the annual flood damage in the country. There are about 12500 km of levees and 25600 km drainage channels affording protection from floods. About 60 to 80% of flood damages occur in the states of UP, Bihar, West Bengal, Assam and Orissa.

Various flood control and flood protection works such as dams, detention basins, river diversions, channel improvements, and embankments offer means of reducing the damage caused by flooding. All these protection works are designed and constructed to offer protection against a particular high flood of certain frequency, known as design flood. In some situations the economic factors make the control of design floods impractical or unjustifiable. Since, there is always the possibility of occurrence of a flood higher than the design flood, an absolute or permanent immunity from flood damage is not physically attainable by the flood protection measures. Hence it is necessary to take immediate steps to reduce the damage from unusual floods to the minimum by making appropriate preparations for it. This can best be achieved by a system of flood forecasting and flood warning.

The term 'hydrological forecast' refers to the prior estimate of the future state of hydrological phenomenon based on the knowledge of their underlying physical laws and the modifying effects of specific geographical conditions. WMO(1974) defines flood forecasting as "the prediction of stage, discharge, time of occurrence, and duration of a flood -- especially of peak discharge at a specified point on a stream -- resulting from precipitation and/or snowmelt". CWC(1980) defines flood forecasting as "the process of estimating the future stage or flows and its time sequence at selected points along the river during the floods". Flood forecasts are prediction of (i) the crest and its time of occurrence, and (ii) the stage expected at various points of time during the period of rising and falling stages of river above a specified water level called the warning level.

A forecast is not an exact prognosis, it inevitably contains an element of uncertainty which is usually quantified in terms of mathematical probability. Nevertheless, contemporary hydrology can forecast the values and dates of occurrence of many elements of the hydrological regimes of rivers, lakes and reservoirs with a sufficiently high degree of accuracy. Consequently, hydrological forecasts have become an indispensable factor in economic development. There is also a demand for hydrological forecasts for ensuring more rational runoff regulation and more efficient management of water power, inland, navigation, irrigation and water supply. Each of the above-mentioned branches of the economy has its own special needs for hydrological forecasts. These forecasts are also of great importance in flood protection since floods cause immense damage by the devastation of towns and villages, destruction of buildings, crops and livestock, and loss of human life. Early warning of high water levels make it possible to take measures to strengthen embankments, and evacuate the population and their property from the flooded area.

1.1 NEED FOR FLOOD FORECASTING

Warning of the approaching flood gives sufficient time to the authorities:

(i) To evacuate the affected people and livestock to safer places,

(ii) To make an intense patrolling of the flood protection works such as embankments so as to save them from breaches and failure.

(iii) To take better decisions regarding regulation of floods through the barrages and reservoirs so that the safety of these structures can be taken care of and greater protection can be provided to the downstream areas.

(iv) To operate the city drains (outfalling into the river) to prevent backflow and flooding of the areas drained by them.

1.2 CLASSIFICATION OF HYDROLOGICAL FORECASTS

WMO(1975) lists four main characteristics of hydrological forecasts which can also be used for their classification :

(a) the forecast lead time,
(b) the phenomenon being forecast,
(c) the computational method used, and
(d) the purpose of forecast.

Based on the criteria (a), the forecasts are classified as Long-term (several months lead time), Medium-term (several weeks lead time), or Short-term (lead time not exceeding 10-15 days).

Based on the criteria (b), the forecasts are called as the forecasts of river stage and/or discharge, time distribution of flood or maximum water level of reservoir etc. Depending on the computational method used, the forecasting methods can be classified as statistical methods, flood routing methods, or methods based on rainfall runoff modelling.

With regard to the purpose, the hydrological forecasts can be classified as either general purpose forecasts or special purpose forecasts.

The term flash flood forecasting essentially refers to the forecast of floods in basins with short response time and is generally needed for smaller river basins (having area < 1200 sq km and time to peak < 6 hours).

The low flow forecast is of interest for water supply, irrigation, hydropower plant operation, pollution control and navigation. These forecasts are formulated round the year irrespective of the river conditions in respect of discharge.

The term 'real-time' is used to denote that mode of operation in which the control decisions for a finite future time horizon are taken based on the condition of the system at that instant of time when this decision is to be taken and the forecasts about the likely inputs over this time horizon. After a known time interval, a new set of data becomes available, and the forecasts are updated in light of these.

A successful application of the real-time forecasting procedure requires a good telemetry system through which data can be observed on-line. The term on-line implies that the data are collected, transmitted and fed to a model and the model's output is obtained and then used in one uninterrupted sequence of activities, Askew(1978).

1.3 UTILITY AND EVALUATION OF FORECASTS

Singh(1989) lists three criteria which must be satisfied in order for a forecast to be useful : accuracy, reliability, and timeliness. An accurate forecast forms the basis of specific flood warnings and can help the water manager take necessary measures to mitigate flood damage. Moreover, inaccurate forecasts can do more harm than good by false alarm or no alarm at all. How reliable a forecast is depends upon the instrumentation used for measurements and forecast methodology. It is necessary that the equipment used should be robust and backups/standbys are provided at crucial places. For the forecasts to be of any use, timeliness is of utmost importance. The forecast lead time determines the efficiency of a flood warning system. The recent advancements in technology and automation permit significant improvements in forecast lead times.

The evaluation of the utility and effectiveness of the hydrological forecasts is an essential part of any forecasting system. It is necessary to evaluate the forecasts for possible revision of the procedures, methodologies and the setup.

The method used in forecasting any hydrological phenomena can be regarded as effective and its practical use justified only when the forecast errors of a given probability is less than the equally probable deviation of the forecast variable from its mean, WMO(1975). If this error is greater, then there is no advantage in making the forecast over the use of long-term means of the corresponding means. It is therefore imperative that the statistical method for determining the effectiveness of the forecasting methods should be based on comparisons of the forecast errors with deviations of the forecast variable form its mean value.

A number of criteria are available for evaluation of the hydrological forecasts. Some of these are given below.

The coefficient of determination of a forecast variable is defined as :

$$d_y = 1 - s^2 / \sigma^2 y \qquad (1.1)$$

where, s is the standard deviation of the forecast and σy is the standard deviation of the forecast variable. This coefficient is fully reliable when both the deviations $(y-\overline{y})$ and the forecast errors $(y_f - y)$ have Gaussian distribution.

The standard error of forecast is defined as :

$$S = \sqrt{S(y_f - y)^2} \;/\; (n-m) \qquad (1.2)$$

where, y is the observed value of the variable, y_f is the forecast value, n is the number of observations, and m is the number of degrees of freedom in the relationship employed in the forecast method.

For short term forecasts of discharges and stages, when the observed values at the time when the forecast is prepared excludes the possibilities of lower values (during the period of rising water) or higher values (during recession periods), forecasting errors should be compared with variations in the changes of the discharge or stage during the period covered by the forecast. In this case, the following statistical parameter can be used :

$$d_{\Delta} = 1 - S^2 / \sigma_{\Delta}^2 \qquad (1.3)$$

where, σ_{Δ} is the standard deviation of the forecast variable change from its mean change during the forecast period. The reliability of a forecasting method depends on the coefficient d_y and 'd_{Δ}'. The closer these coefficients are to unity, the greater will be the accuracy and reliability of the method.

1.4 SCOPE OF THE PRESENT REPORT

The present report is concerned with the methods used for forecasting of floods generated due to rainfall only. The floods which are generated due to snowmelt or dam failures etc. are not considered in this report.

Various methods used for forecasting this type of floods are reviewed. The evolution of flood forecasting services in India along with application has also been reviewed in this report.

2.0 STATISTICAL METHODS OF FLOOD FORECASTING

These methods make use of the statistical techniques for formulation of flood forecasts. The methods developed can be used in the form of graphical relations or mathematical equations. A large number of data covering a wide range of conditions are analyzed to derive the relationships which use gauge to gauge relationship with or without additional parameter and rainfall peak-stage relationship.

2.1 DATA REQUIREMENTS AND DATA COLLECTION

A large number of hydrological and hydrometeorological data are required for development of a river forecasting model and for operational forecast formulation. At the development stage of a flood forecasting model, all the available historical data can be utilized for identification of the various parameters whereas at the time of actual forecast formulation, only limited number of data may be available in time. Correct observation, systematic collection and proper processing of these data are essential.

Basically gauge/discharge and rainfall data are required for flood forecasting purposes. The number of reporting stations depends upon hydrologic needs and availability of observers and communications. The rainfall records should be adequate to provide reasonable estimates of the average precipitation over the area under study. The density of raingauge station required varies with basin topography and meteorological factors.

Apart from these informations about interception, evapotranspiration, inter- flow, infiltration, ground water and percolation are used as inputs to several conceptual models which are in operational use in many advanced countries. Although these data are not used at present for operational purposes in India, they are being used for development of a better flood forecasting models. The use of such data will definitely improve the model efficiency and hence there is imperative need for setting up proper hydrometeorological stations in selected river basins where evaporation, temperature, sunshine duration, humidity, wind velocity and soil moisture etc. could be observed in systematic manner and used for flood forecasting.

2.1.1 Frequency of Data Observation

The frequency of report from various hydrological and hydrometeorological stations depends upon basin characteristics.

In large basins where precipitation is not directly used in forecast formulation daily report of rainfall may be adequate in normal circumstances but hourly observations are necessary with the help of SRRG in order that the observed data are used for model development and also for issue of advisory forecasts in heavy and prolonged storms. But forecasts for small basins with rapid concentration time may require reports at interval of one hour or even less during heavy storms. For example for slow rising rivers like Brahmaputra in its lower reaches where the maximum rise in water level is of the order of about 30 cms in 24 hours, rainfall data at 12 hrs or 24 hrs interval for upper catchment may be adequate. On the other hand in flashy rivers like Teesta whose concentration time is small and variation of rainfall intensity is quite considerable, it will be necessary to use 3 hourly or even hourly rainfall data from adequate number of SRRGs. The use of daily rainfall data collected through ordinary raingauges is normally limited to initial water balance studies. For all practical purposes of flood forecasting, rainfall data collected through stations reporting (multi) hourly rainfall data are only used. In respect of river-gauge, hourly observations at all sites are desirable. Also, there should be fool-proof arrangement for recording the peak of the floods. The frequency of transmission of river-stage will depend upon the exigencies of the situation. Normally the hourly observed data are transmitted to control room/flood forecasting centres twice or thrice a day, but when the rivers are above danger level, the frequency needs to be increased to meet the specific requirements.

2.2 FORECASTING METHODS BASED ON STATISTICAL APPROACH

The methods based on statistical approach make use of the statistical techniques to analyze the historical data with an objective to develop methods for the formulation of flood forecasts. The methods thus developed can be presented either in the form of graphical relations or mathematical equations. A large number of data, covering a wide range of conditions are analyzed to derive the relationship which, inter-alia, includes gauge-to-gauge relationship with or without additional parameter and rainfall peak stage relationship.

These methods are most commonly used in India as well as other countries of the world. These are discussed in brief in the subsequent sections.

2.3 CORRELATION BETWEEN UPSTREAM AND DOWNSTREAM GAUGES/DISCHARGES

In the techniques of gauge/discharge correlation the various variables which affect the stage at the forecasting point are :

a) Stage and discharge of the base station,
b) Stage and discharge of the forecasting station,
c) Change in stage and discharge of the base station,
d) Travel time at various stages,
e) The rainfall (amount, intensity and duration) in the intercepting catchment,
f) Topography, nature of vegetation, type of soil, land use, density of population, depth of groundwater table, soil moisture efficiency etc. of the intercepted catchment.
g) The atmospheric and climatic conditions, and
h) Stage and discharge of any important tributary joining the main stream between the base station and the forecasting station.

The factors (a) to (d) are basic parameters used in developing the correlation curves. The factor (e) and (f) are taken into account by introducing the rainfall and Antecedent Precipitation Index (API). The factor (g) is a minor one and can be considered by introducing an additional parameter as week number of year. However, it is not very important for Indian rivers as most of the floods occur during monsoon period only.

The factor (h) is very important and can be neglected if the contribution of the tributary is very small.

One of the most simple and very useful graphical relation is the Flood Profile Nomogram. This diagram indicates the peak stage at each station along the river for a storm. A number of such lines are drawn for various conditions of storms. The various line should be drawn in different inks and the specific meteorological conditions such as heavy concentrated rainfall or other conditions such as breach of embankment etc. should be mentioned. Although the diagram does not help in accurate forecast formulation forecast.

The various type of graphs which are used in forecast formulation can be classified as:

i) Direct correlation between gauges or discharge of U/S and D/S station.

ii) Correlation between gauges or discharges at U/S and D/S stations with additional parameters.

Some of the correlation diagrams which are commonly used are discussed here.

2.4 DIRECT CORRELATION BETWEEN GAUGE AND DISCHARGE AT D/S

In such graph basically, only gauge and discharge data at forecasting stations and the base stations are utilized in different forms. The following type of correlations are generally used.

A) Gauge-to-gauge Correlation

The simplest of all is the correlations between the N^{th} hours stage of base station and (N+T)th hour stage of forecasting stations, where T is the travel time of flood wave between the base station and the forecasting station.

This type of graph can be developed and used for a reach of the river where there is no major tributary with considerable discharge, catchment between the two station is small so that the effect of rain is negligible and the travel time from base station to the forecasting station is fairly constant for various stages.

However, in most of the cases the travel time is not constant and varies with water level. Apart from this such relations give considerable errors under different conditions. These relations can be improved if the following aspects are taken into account.

i) The variation in travel time- This can be taken into account by appropriately drawing a travel time-curve (U/S stage Vs. travel time).

ii) Varying conditions during rising and falling stages of the flood. It is always desirable to draw separate curves for rising and falling conditions.

iii) Antecedent Moisture conditions of the stream- It is observed that during the first few storms the actual observed water level is generally lower than the forecast level. This is mainly due to the fact that during dry soil conditions, there is more infiltration and hence lesser runoff in the stream. This can be roughly account for by drawing two different sets of curve, one for the initial flood waves and the other for remaining flood waves.

iv) Downstream Boundary conditions- This is also a very important factor, especially for forecasting in the lower reaches of the river which falls in the sea or a lake. When the outfall channel is in high stage or there is high tide in the sea, it will definitely have back water effect and the water level in the falling stream will be different than that in normal conditions. Hence it is always desirable to take into account the tidal effect or the water level of outfall channel. The data from the tidal gauge in conjunction with the annual tidal table will be very useful in determining the tidal influence and back water effect on the lower reaches of the river.

v) Characteristic of flood Wave- Generally the forecast at D/S stations are quite reliable when the storm results in formation of hydrograph with a single peak. But when one flood wave is immediately followed by another, there is considerable effect in the water level at downstream station in different conditions. For example when a smaller flood wave is followed by a comparatively larger flood wave with high peak, the two flood waves may overlap resulting in slight increase in the level at D/S station than that in normal case. On the contrary, if a larger flood wave is followed by a smaller flood wave, the smaller flood wave may not have any effect by the time it reaches the D/S station. This is very important aspect and can be taken care of, to some extent, by using the modified routing equations.

Various other correlation diagrams which taken into account the above discussed and some other factors are described in brief in the subsequent paragraphs.

B) Direct correlation between peaks at forecasting station and base station:

The gauge (peak) at the base station and the gauge (peak) at the forecasting station for the various intensities of flood are plotted. The travel time at various intensities of flood is also plotted corresponding to peak. Such graphs have been successfully used for river Subernarekha in Orissa where warning time available is about 24-30 hrs.

C) Correlation between the change in stage of the base station and change in the stage of forecasting stations during T hours (T= Time of travel of flood wave between the base station and forecasting site).

Such a method obviates errors, to some extent, due to aggradation or degradation in the river section, depending upon flows. This correlation has been found more suited to large rivers with more uniform change in levels and discharges between the base stations and the forecasting stations. A multi-tributary model for river Brahmaputra has been developed using the change in stage at the forecasting station and three different base stations on various tributaries.

D) Correlation between the N th hour and (N+T)th hour stage of the forecasting station with change in stage at the base station during past "T" hours as variable. Different sets of graphs are drawn for rising and falling conditions of the river.

Such graphs are used for forecasting river stage at a number of sites. If there is larger fluctuation in the stage of the base stations, the parameter of average gauge within past "T" hrs at the base stations is introduced in the 1st quadrant instead of change in stage of the base station. In the 2nd quadrant N_{th} hour stage of the base station is also leveled to account for the intensity of flood. This has been found suitable when the base station is D/S of a control structure on the river, through which the flows are released with wide fluctuations.

E) In rivers having wide fluctuation in U/S stage and relatively much less reduced fluctuations in lower reaches due to large scale inundation/valley storage in between the two points, tendency effect is considered. This is done by correlating Nth and (N+T)th hour stage of the forecasting site in past "T" hours as variable in the 1st quadrant. The average gauge of the base station is considered as a variable in the 2nd quadrant. This type of graphs have proved quite useful in Bagmati and Adhwara group of rivers in Ganga Basin.

2.5 CORRELATION BETWEEN GAUGES AT UPSTREAM & DOWNSTREAM WITH ADDITIONAL PARAMETERS

When the direct gauge to gauge correlation are not successful because of appreciable contribution due to rainfall in the inreach catchment, intermediate tributaries or the varying soil moisture condition etc., the introduction of additional parameters like discharge of the tributary, average rainfall over the intercepting catchment, and API, becomes necessary for better results.

With the availability of more data and better data transmission facilities, the correlation diagrams are being developed with additional parameters.

Some of such diagrams which are at present under use are discussed below in brief.

(a) Correlation between the Nth hour, and (N+T)th hour gauge of the forecasting station with the change in the level of a tributary during past T1 hours and change in level of the base station during past T hour;

(b) Correlation between the Nth hour and (N+T)th hour gauge of the forecasting station with the following parameters:

(i) Rise/Fall at upstream base station,
(ii) Rainfall observed at the upstream base station.

When a number of tributaries affect the water level at the forecasting station, the change in the base station on the main river as well as base station on the tributary can be considered as additional parameters.

2.5.1 Multi Tributary Model

A discrete, linear, time invariant model has been used for operational flood forecast of river Brahmaputra at Dibrugarh. This model is based on the difference of the gauge reading at the forecasting station and the upstream base station in the tributary. The use of differences of gauge readings as input in the model takes care of the aggradation or degradation of the river bed of the tributary and the main river. The model in general is expressed as:

$$g_{(i+T),i} = A_1 , g_{i(i-T)} + \sum_{j=1}^{m} A_{2,j} \, h_{(i-Tj+T),(i+Tj)} + \sum_{j=1}^{m} A_{3,j} \, h_{(i-Tj),(i-Tj-T)} \quad \ldots.\ 2.1$$

where, m = number of tributary (= 3 in this case),
T = Forecasting time,
T_j = Lag time between the forecasting station ($T < T_j$) and jth tributary gauging site.

$h_{(i-Tj+T),\ (i-Tj)}$ = Difference in gauges at the upstream station on the tributary between (i-Tj+T) and (i-Tj)th instant.

$h_{(i-Tj),\ (i-Tj-T)}$ = Difference in gauges at the upstream station on the tributary between (i-Tj) and (i-Tj-T)th instant.

$g_{i,\ (i-T)}$ = Difference in gauge at ith and (i-T) the instant of time at the forecasting station.

= Difference in gauge at (i-T)th and ith instant

$g_{(i-T),i}$ of time at the forecasting station, i.e. the forecast value.

$A_{1,j}$, $A_{2,j}$, $A_{3,j}$ are the parameters which are to be found out.

The parameters $A_{1,j}$, $A_{2,j}$ and $A_{3,j}$ can be estimated by the method of least squares technique. In this case the forecast at Dibrugarh is formulated with the help of observed gauge data on three major upstream tributaries -- Dihang, Debang, and Lohit.

2.6 RAINFALL STAGE METHOD

The relationship for estimating the peak discharge or the peak stage with the help of rainfall data is of great operational significance in the sense that it enables one to find the expected peak discharge or stage which is one of the important requirements in flood warning. In its simplest form, it is the relation between the average rainfall over the catchment and the peak stage. This relation may be either a graphical of mathematical and can be very easily established by using the statistical technique. The results can be further improved by incorporating other parameters such as API. These relations have been used in many places with quite good result but the deficiency in this method is that the time of occurrence of the peak or the full shape of hydrograph can not be forecasted.

2.7 FLOOD FORECASTING USING ARMAX MODEL

The stochastic models take into account the stochastic nature of the data and the errors in progress. Stochastic models used in forecasting, e.g., Hipel (1977), Goel(1982), Chander et al (1980), Gosain and Chander (1984), consist of a deterministic part and error term. Such models can be expressed by an ARMA (p,q) model as in equation (2.2):

$$Y_t = \phi_1 Y_{t-1} + \dots\dots\dots + \phi_p Y_{t-p} + \theta_1 X_{t-1} + \theta_q X_{t-q} + \epsilon_t \qquad (2.2)$$

where, Y_t is the current state of variable (discharge/stage) which is assumed to depend on the past values of rainfall data X_{t-1}, X_{t-q}, runoff data Y_{t-1}, Y_{t-p} and an error term. The structure of this model, i.e. the order (p,q) of the model is identified by the autocorrelation and partial autocorrelation structure of the data and the parameters are estimated using the least squares technique. The forecast and the observed values of Y_t are compared and the residual errors are checked for correlation. A model is considered adequate if the residual errors are uncorrelated otherwise the order of the model is increased or an error model is incorporated in equation (2.2). The detailed procedure of identification and estimation is given by Hipel et al (1977).

Such models have limited data requirements and can be identified using an objective criteria. They have the capability of operation with interrupted data and have small computer requirements. Methods like recursive least squares can be used to update the parameters of such models thus taking into account the variability of the hydrological system. Chander et al (1980) and Goel (1982) have used models belonging to this family for forecasting stage differences on the tributaries and for forecasting stages using previous rainfall as the input.

2.8 REAL TIME FLOOD FORECASTING USING UNIT HYDROGRAPH MODELS

The unit hydrograph method has long been recognized as a useful tool for converting excess rainfall to direct surface runoff by linear transformation. The assumptions underlying this method and its limitations have been discussed in a number of text books.

One of the important areas in hydrology pertains to the study of the transformation of the time distribution of rainfall on the catchment to the time distribution of runoff. This transformation is studied by first relating the volume of rainfall to the volume of direct surface runoff, thus determining the time distribution of rainfall excess (the component responsible for direct surface runoff on the catchment) and then transforming it to the time distribution of direct runoff through a discrete or continuous mathematical model. The first step decides the volume of the input to the catchment and, therefore, any error in its determination is directly transmitted through the second step to the time distribution of direct runoff. A number of watershed or conceptual models find this component for each time step through a number of stores representing various processes on the catchment. The parameters of these models including those in the functional relationship are determined from the historical record and their performance is tested by simulating some of the rainfall-runoff events which have not been used in the parameter estimation process. The models need to be run continuously so that the status of various stores is available at all times. One of the operational uses of these models is in the area of real time forecasting. In such a situation, these models are run by inputting the rainfall and forecasts are issued either assuming no rainfall beyond the time of forecast value of the rainfall in the future.

The infiltration part of these models and their context decide the volume of input. At the time of calculation, the catchment is also performing the transformation operation to produce the direct runoff at the gauging station. Since the model is simulating the action of the catchment it would be appropriate to make use of this information in finding out the contribution which the rainfall is going to make to the direct runoff of the catchment. However, the complexity of these models does not lend itself to this exercise during the event. Of late methods based on unit hydrograph approach have been formulated for real time forecasting which overcome the difficulties associated with complex hydrological models.

The Hydrologic Engineering Centre (HEC) of the U.S. Army Corps of Engineers, USA has developed a computer model, HEC-1F, for the purpose of real time forecasting. The HEC-1F model uses the unit hydrograph technique with constant loss rate to forecast the runoff. Forecast by the HEC-1F model is accomplished by re-estimating the unit hydrograph parameters and the loss rate parameter as additional rainfall runoff data are reported and using these updated parameters the future flows are estimated. The Snyder's synthetic unit hydrograph described by two parameters is used in this model. For estimation of the unit hydrograph and constant loss rate parameters, the model uses univariate search technique. HEC (1984) provides the complete details of the model. This model has been applied in a large number of Indian studies.

Several researchers have used Unit Hydrograph for Flood Forecasting. The following is based on Chander et al(1984). This model uses first appreciable rise in hydrograph and estimates the ø -index value for the flood event. This value is updated as more record becomes available. At each step the estimate of ø-index is used to determine the rainfall excess, which is turn is involved with the unit hydrograph of the catchment to forecast the resulting flood hydrograph. The rainfall 'T' (initial lag) hours prior to the rise in the hydrograph is considered to contribute to interception, depression storage and infiltration and is, therefore, not used in evaluating rainfall excess. Mathematically the runoff is computed using the following equation:

$$Q_{i+T} = \sum_{j=1}^{i\leq m} (P_{i-j+1} - F_i) U_j \qquad (2.3)$$

where

Q_i = direct runoff at time i,

P_i = precipitation at time i,

F_i = ø-index value at time i,

U_j = Unit hydrograph ordinates. Unit time of UH is considered to be equal to the discrete time D of the eq. (2.3),

m = number of unit hydrograph ordinates.

F_i at each step is computed and updated using eq (2.4) :

$$F_i = \frac{\sum_{j=1}^{i} \sum_{k=1}^{i} (P_{j-k+1} U_k - Q_{j+T}) \left(\sum_{k=1}^{i} U_k \right)}{\sum_{i=1}^{i} \left(\sum_{k=1}^{j} U_k \right)^2} \qquad (2.4)$$

The parameters of the model are the initial lag "T", D-hour unit hydrograph ordinates and the ϕ-index value.

The rainfall over a catchment does not produce an immediate response by way of measurable increase in runoff at the gauging site. In a flood producing rain the point of start of rising limb of the hydrograph indicates that the surface runoff has started contributing to the flow at the gauging site. This sudden rise is attributed to the occurrence of rainfall excess on the catchment because of rainfall intensities which are higher then the infiltration rate. Since the infiltration rate on the catchment is not known the best guess of the starting time of rainfall excess on the catchment is the time of occurrence of the inflection point of the rainfall mass curve immediately proceeding the inflection point of the flow mass curve. The time distance between these inflection points is termed as initial lag "T". The initial lag varies from storm to storm depending on its areal distribution. However, the value of this parameter is known at the time of forecast and therefore this variability does not pose any problem in formulating the forecast.

An average D-hour unit hydrograph thus obtained, is used in the forecasting model. The ϕ-index is an important parameter which needs to be determined to enable the computation of forecasts using Eq. (2.3). The parameter is computed using Eq. (2.4) when a sudden rise is experienced at the gauging site. The baseflow is assumed to be constant and is added to the computed forecast of direct runoff values to obtain the forecast of runoff. As rainfall and runoff progresses in time, Eq. (2.4) is used to update the value of ϕ-index and updated forecast is issued. In all forecast computation it is assumed that no rainfall occurs beyond the time of forecast and the latest value of ϕ-index is valid for all times prior to the time of forecast.

Real time forecasting is performed using Eq. (2.3) for the isolated events of the catchment. It is presumed that rainfall and runoff data at discrete time D are available to the forecaster through a telemetric system installed on the catchments. The steps involved in the computation are :

i) Compute the Theissen Weights to obtain average rainfall on the catchments.

ii) Derive an average D-hour unit hydrograph analyzing the observed rainfall-runoff data for various isolated events.

iii) The forecast formulation awaits the occurrence of the first rise in the hydrograph at the gauging site leading to the determination of Q_{i+T}. For example if hourly hydrograph values are (30,30,70....), then the base flow is taken as 30 and maintained at this value and Q_{i+T} is taken as 40. Determine the initial lag by plotting the rainfall and flow mass curves.

iv) Determine initial value of F using eq.(2.4) with known value of Q_{i+T},

v) Use the value of ø-index obtained from the previous step to compute rainfall excess for (T+1) time steps.

vi) Compute the forecasted values of direct surface runoff at various lead times or the whole resulting direct runoff hydrograph from Eq. (2.3) using the known rainfall excess and assuming no rainfall occurs beyond the time of forecast.

vii) Update the value of ø-index at each time step K using Eq. (2.3) and repeat step (v) and (vi) to formulate the forecast. In step (v) the rainfall excess is computed for (T+K) time steps.

****

CHAPTER 3

CONCEPTUAL MODELS FOR FLOOD FORECASTING

3.0 PHILOSOPHY OF CONCEPTUAL MODELS

A rainfall-runoff model is used to simulate the hydrologic response of a catchment to input rainfall. These models can be broadly divided in three categories : Black box models, Conceptual models, and Physically based models.

Black box models are based on transfer functions which relate inputs with outputs. These models, as the name suggests, generally do not have any physical basis. Some commonly used black box models include the unit hydrograph based approaches, regression analysis, and time series models. These models have been in use for a long time. The parameters of these models are obtained either by analytical solution or through numerical optimization. The success of these models can be attributed mainly to simple mathematics, minimal computational requirements and acceptable results. However, it is not advisable to use these models for the input data which falls outside the calibration range. This is because in such cases the implicit understanding of the physical system and assumptions made, such as of linearity, may not remain valid and the modeling relies only on the mathematical equations, Anderson and Burt(1985). Due to this serious drawback, the use of these models for extreme events should always be made with utmost caution.

The catchment is a complex system where various physical, chemical, and biological processes take place continuously and govern the movement of water. In practice it is not feasible to model all these processes. Some simplifications have to be made either in the representation of the system or in the processes involved or both. The most common simplification made is spatial lumping and replacement of various components of the hydrological cycle by conceptual storages. It amounts to saying that the catchment system and its inputs and responses can be represented using the dimensions of depth and time. The within catchment variations of inputs and parameters are ignored. Due to this spatial averaging, the lumped model concept tends to be considered adequate only for small homogeneous catchments, Blackie and Eeles(1985). However, in practice they have been applied to sufficiently big and heterogeneous catchments. The computational requirements of these models are moderately small vis-a-vis the computational speeds available at a typical computer installation nowadays.

The term 'Physically Based' is used to denote that class of models which tend to use the known physical laws of various processes to model the catchment response. These laws are expressed through partial differential equations which are solved using numerical methods. These models are distributed in nature since the partial differential equations generally involve space coordinates. A discretization of spatial and temporal coordinates is made and the solution is obtained at the node points of this discretized representation. This implies that these models can be used for forecasting the spatial as well temporal pattern of more than one hydrological variable. However, the input data and computational requirements are enormous. Due to this, the use of these models for real-time forecasting has not reached the 'production stage' so far, particularly for data availability situations prevalent in developing countries like India. The Systeme Hydrologique Europeen (SHE), the Institute of Hydrology Distributed Model (IHDM), and the USDA ARS small watershed model are the familiar models from this group. Some of them are briefly described by Beven(1985).

3.1 ADVANTAGES OF CONCEPTUAL MODELS

The main advantages of using a lumped catchment are the following :

a) The CPU time requirement of conceptual models are quite small and therefore these models can be used to give the forecast in a short time. The computational efficiency of these models results form the fact that these models make use of several storages to represent the movement of water through different elements of the catchment. The model is nothing but a logical procedure to regulate the inputs and withdrawals of water from these storages.

b) The requirement of other computer resources for these models are also very small and hence some of these can be used on micro computers as well.

c) In the flood forecasting studies, normally only one variable, i.e., discharge is of interest which is the major output from most of such models.

A considerable amount of research effort in the area of hydrology during the past two decades has been devoted towards development of computer based models of rainfall runoff process. These models are useful tools for three major applications - for research leading to improved understanding of rainfall runoff process, extension of discharge data and catchment yield estimation, and as an aid in short term management of water resources systems.

In the following, a few well known conceptual models which have been used for flood forecasting are being reviewed.

3.2 THE NAM MODEL

The "Nedbor Afstromnings Model" (NAM) model was developed in Denmark and is based on the approach proposed by Nielsen and Hansen (1973). It is a deterministic, conceptual lumped type model. Being a lumped model, the parameters and variables are assumed to represent the average values for the entire catchment. The structure of the NAM model is shown in Fig. 3.1.

The input precipitation can be either in form of snow or rainfall. In the model, the part of input precipitation which is intercepted by vegetation along with water trapped in surface depressions and the upper soil layer is represented by a conceptual surface storage. The amount of water in this storage at any time is denoted by U; the capacity of this storage is denoted by UMAX. The withdrawals from this storage take place through evapotranspiration which occurs at the potential rate and interflow.

The soil moisture in the root zone from which plants can draw water for transpiration is represented by a lower zone storage. The withdrawals from this storage take place by the process of evapotranspiration through the roots of the vegetation. The actual amount of this loss depends upon the relative moisture content of this storage. The relative moisture content of this storage also governs the amount of interflow, the proportion of water which flows as overland flow and the recharge to the ground water. L and LMAX denote the moisture content at a particular time and the capacity of this storage respectively.

In the NAM model, the ground water storage is divided in two storages - lower and upper. These storages act as linear reservoirs continuously draining to the river as baseflow. They differ only in terms of their time constants. A fraction of the ground water recharge G, CBFL*G goes to lower storage and (1-CBFL)*G goes to the upper storage. The parameter CBFL is a positive constant less than unity. The user has the option of activating only one ground water storage through the parameter CBFL. The time constant of the upper and lower ground water storages are denoted by CKBFU and CKBFL respectively.

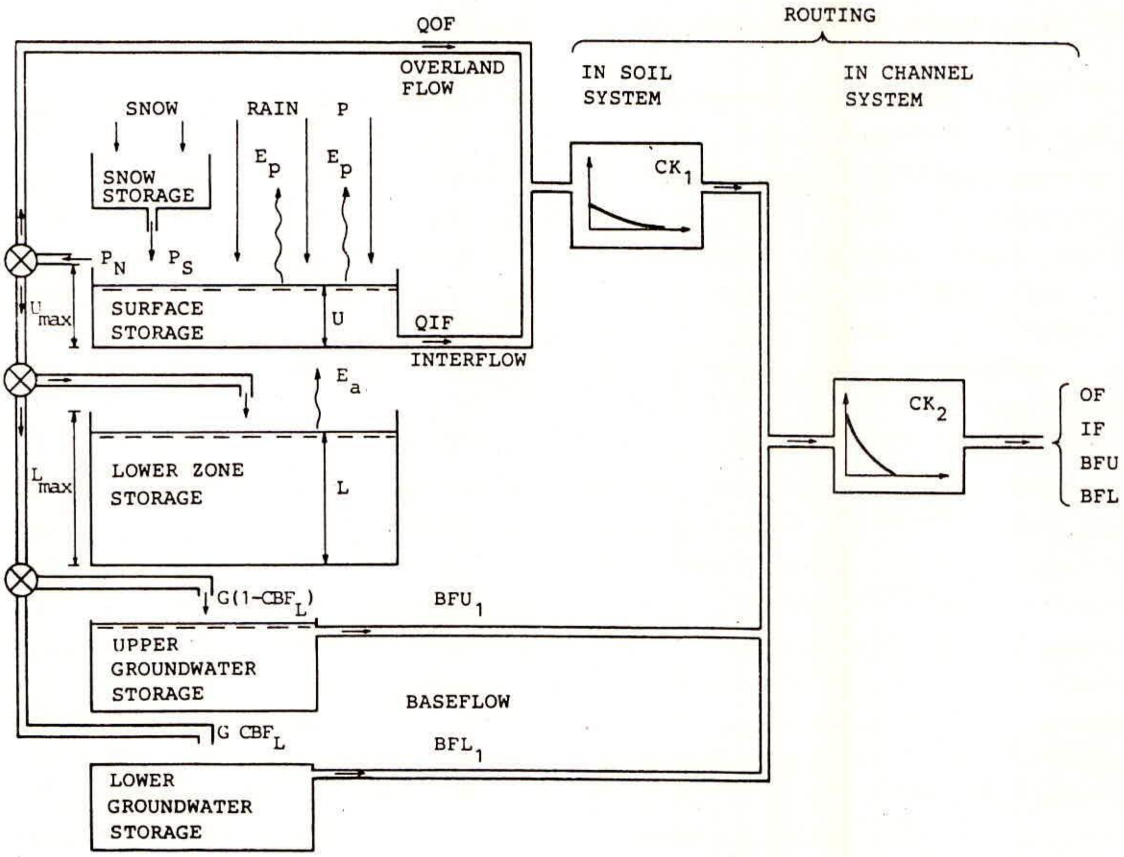

Fig.3.1 Structure of the NAM model, adopted from DHI (1982)

The interflow and overland flows are added and then routed through one linear reservoir. After this, the baseflow contribution is added with them and the combined flow is again routed through another linear reservoir to obtain the discharge hydrograph at the basin outlet.

The interflow contribution QIF which linearly varies which the relative moisture content of the lower zone storage can be calculated by

$$QIF = \begin{cases} CQIF * U * (L/LMAX - CLIF) / (1 - CLIF) & \text{for } L/LMAX > CLIF \\ 0 & \text{for } L/LMAX < CLIF \end{cases} \qquad (3.1)$$

where

CQIF = a positive drainage coefficient for interflow, having the dimension of Hour-1. This coefficient together with UMAX determines the amount of interflow contribution,

CLIF = a positive constant less than unity, representing threshold value for interflow.

Whenever the capacity of the surface storage is exceeded, water spills from it. A fraction of this spilled water PN contributes to the overland flow. The remaining water infiltrates and is divided between lower zone storage and ground water storage. The overland flow can be calculated by

$$QOF = \begin{cases} CQOF * PN * (L/LMAX - CLOF) / (1 - CLOF) & \text{for } L/LMAX > CLOF \\ 0 & \text{for } L/LMAX < CLOF \end{cases} \qquad (3.2)$$

where

CQOF = a positive coefficient for overland flow, less then unity, determines the extent to which the excess rainfall runs off as overland flow. It has a small value for flat basins and permeable soils and vice versa,

CLOF = a positive constant less than unity, threshold for overland flow.

PN = net excess rainfall.

The evapotranspiration demands are first attempted to be met with at the potential rate from the surface storage. If the moisture content in this storage is not enough to meet these requirements, the remaining fraction is assumed to be withdrawn from the lower zone storage through root activity at an actual rate Ea given by

$$Ea = Ep * L/LMAX \tag{3.3}$$

The fraction of net excess rainfall PN which does not run off as overland flow, ie, (PN - QOF) infiltrates into the lower zone storage. A portion, DL, of the infiltrating water goes to the lower zone storage. The remaining amount of the infiltrating water, G, is assumed to percolate deeper and recharge the ground water storage. These components are computed using the following

$$G = \begin{cases} (PN - QOF) * (L/LMAX - CLG) / (1 - CLG) & \text{for } L/LMAX > CLG \\ 0 & \text{for } L/LMAX < CLG \end{cases} \tag{3.4}$$

$$DL = (PN - QOF) - G \tag{3.5}$$

where
CLG = a positive constant less than unity, representing threshold for recharge.

Knowing the time constant of a linear reservoir, outflow from it can be calculated by

$$Qo(t) = Qo(t-1) * \exp(-dt/CK) + Qi(t)*(1-\exp(-dt/CK)) \tag{3.6}$$

where,
Qo(t) = outflow from the linear reservoir at the end of time t,
Qi(t) = inflow to the reservoir at time t,
CK = time constant of the linear reservoir.
dt = length of time step.

The time constant of the two linear reservoirs are denoted by CK1, CK2 as shown in Fig. 3.1.

The parameters of NAM model are adjusted by the user during calibration which is carried by following the trial and error approach. The observed and simulated hydrographs at the basin outlet can be compared and the appropriate parameters can then be adjusted to obtain best match. This approach has been recommended because it allows the model calibration according to the objectives of a particular study and at the same time, the parameters values can be physically realistic.

The input to the NAM model consists of rainfall data, potential evaporation data, and the initial conditions of the basin at the start of the simulation.

The further details of quantitative relations and computational steps of the model are described in the model documentation, DHI(1982).This model has been applied to Indian basins by Jonch - Clausen & Refsgaard (1984) and Jain (1990).

3.3 THE NWSRFS MODEL

The National Weather Service River Forecasting System ,USA (NWSRFS) model is of the deterministic, lumped input, lumped parameter type. The model, however, accounts for variable impervious area and an incrementation of lower zone free water when tension water is not completely satisfied. These two features give the model some of the characteristics of a distributed parameter model.

Two zones, upper and lower, are defined. The upper zone represents the upper soil layer and interception storage while the lower zone represents the bulk of the soil moisture and longer ground water storage, ref. Fig. 3.2.Each zone is thought of as storing moisture in two forms, "tension water" and "free water". Tension water is that which is closely bound to the soil particles in contrast to the water that is free to move. For any zone, the maximum amounts of tension water and free water which the zone can hold are specified as model parameters. The basic storage mechanics are that moisture entering a zone is stored as tension water until the tension capacity is filled. In the lower zone, however, a portion of the water entering that zone may be diverted to free water storage before tension water is filled. Once tension water capacities are filled,additional water will be stored as free water. Depletion of free water occurs vertically as percolation, horizontally as channel inflow and non-channel ground water outflow or as evapotranspiration. Tension water is depleted only as evapotranspiration.

Channel Flow from Ground water

In this model, two lower zone free water storages are defined ; primary, which is slow draining and longer lasting, and supplementary, which is faster draining. The outflow from each of these in each computational time period, is the product of the contents and a constant withdrawal parameter. The two parameters (primary and supplementary) are not equal to each other. While the depletion functions are simple, the total ground water outflow is governed by these functions acting in combination with some rather involved mechanics which apportion inflow to the lower zone between the two free water storages, and balance tension and free water storages. The originators of the model believe the concept of two separate ground water components to have some basis in fact and have had a degree of success in identifying them from observed streamflow records.

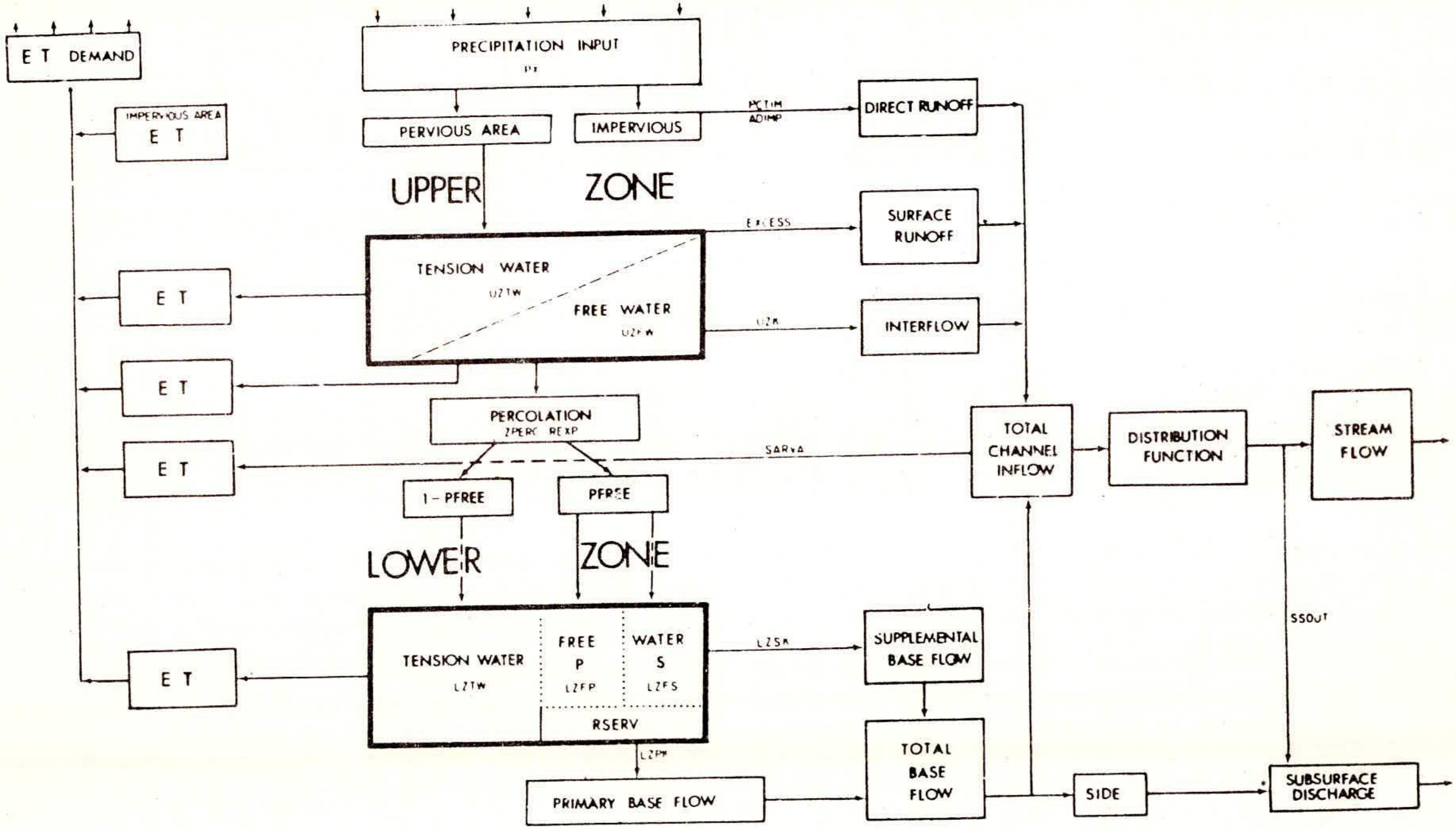

FIGURE 3.2 NWSRFS CATCHMENT MODEL (SACRAMENTO), ADOPTED FROM PECK (1976)

Percolation

The flow of water from the upper zone to the lower zone is expressed by a formula considered to be the "heart" of the model. In this formula, a percolation rate PERCM is defined as the maximum lower zone flow-through rate. This is numerically equal to the outflow from the lower zone under saturated conditions.

Under conditions of unlimited moisture availability in the upper zone, the actual percolation rate may vary between PERCM when the lower zone is full, and a maximum value which would occur if the lower zone were empty. This maximum rate is defined by a percolation parameter, ZPERC, such that the maximum rate is equal to the product of PERCM and 1+ZPERC.

The variation of percolation rate between the minimum and maximum values thus defined occurs as a function of the lower zone deficiency ratio. This ratio (DEFR) is the difference between lower zone contents and capacity divided by the capacity. The ratio may vary from zero (lower zone full) to unity (lower zone empty). In its computation, both tension and free water are considered. To permit the effect of the deficiency ratio to be non-linear and to vary among catchments, a parameter REXP, which is dependent upon soil type, is applied to the ratio as an exponent. Thus, the actual percolation rate under conditions of unlimited moisture availability in the upper zone is given by :

$$\mathrm{RATE} = \mathrm{PERCM}(1 + \mathrm{ZPERC}*\mathrm{DEFR}^{\mathrm{REXP}}) \qquad (3.7)$$

Where

RATE is the percolation rate as defined above
DEFR is the lower zone deficiency ratio.

The true percolation rate is equal to the product of RATE and the "upper zone driving force", which is the ratio of upper zone free water contents to upper zone free water capacity. Thus, the percolation will be zero if upper zone free water is empty and equal to RATE if the upper zone is full.

The formula involves eight model parameters. Two of them, ZPERC and REXP, appear only in this formula. The remaining six serve their primary purpose in other parts of the model. Four model variables, related to storages in both zones, also appear. The formula interacts with other model components in such a way that it controls the movement of water in all parts of the soil profile, both above and below the percolation interface and is, in turn, controlled by the movement in all parts of the profile.

Variable Impervious Area:

A portion of the water entering the basin is assumed to be deposited on impervious areas directly connected or adjacent to the channel system and thus becomes channel flow. This portion is defined by two parameters representing its minimum and maximum values. The actual area used in the computation varies between these limits as a function of the amount of water in storage.

Flow Components

The model generates five components of flow:

1. Direct runoff, resulting from moisture input being applied to the variable impervious area.
2. Surface runoff, when moisture input is supplied at a rate faster than it can enter the upper zone, the excess appears as surface runoff.
3. Interflow, lateral drainage from upper zone free water.
4. Supplementary base flow, lateral drainage from lower zone supplementary free water.
5. Primary base flow, lateral drainage from lower zone primary free water.

Evapotranspiration

Evapotranspiration rates in the Sacramento model may be estimated from meteorological variables or from pan observations. Either day-by-day or long-term values may be used to derive the demand curve. The catchment evapotranspiration - demand curve is a product of the computed evaporation index and a seasonal adjustment curve. The seasonal adjustment curve reflects the state of the vegetation. The moisture accounting within the model applies the evapotranspiration loss, directly or indirectly, to the various storages and/or to the channel. The amount taken from each location in the model is determined by a hierarchy of priorities and is limited by the availability of the moisture as well as by the computed demand.

Computational Technique

The movement of moisture through the soil mantle is a continuous process. The rate of flow at various points varies with the rate of moisture supply and with the contents of various storages. This process is modeled by a quasi-linear, open form computation. A single time step computation of the drainage and percolation loop involves the implicit assumption that the movement of moisture during the time step is defined by the conditions at the beginning of the time step. Since this assumption is not valid, the resultant approximation can be made acceptable only by the use of a short time step. In the model, the length of the step is volume dependent. and is selected in such a way that no more than 5mm of water may be involved in any single execution of the computational loop. The 5mm limit is arbitrary and was selected by the originators as being small enough to logically fulfill its function, and not so small as to cause excessively long execution times on the computer (IBM 1130) which was used to develop the model. Sensitivity tests to determine the optimal size of this limit should have a dependency upon soil type. The current limit represents a compromise to eliminate the need for an additional parameter.

Parameters :

The soil moisture accounting portion of the Sacramento model, exclusive of the evapotranspiration demand curve, involves seventeen parameters. The demand curve can be defined by a series of ordinates, twelve in number, or by a formula involving five parameters. The temporal distribution function, which converts runoff volumes to a discharge hydrograph, involves a unit hydrograph, and, in some applications, a channel routing function.

The application of the model in the NWSRFS involves moisture input in 6-hour time periods and computed 6-hour runoff volumes. The short, repetitive computational time step described above is a subdivision of the 6-hour period and has mathematical significance only. The computations are accumulated over a 6-hour period and applied to a unit hydrograph function representing a 6-hour duration event.

Calibration :

The National Weather Service uses a combination of manual and automatic optimization techniques for model calibration. The term "manual" refers here to a procedure in which subjective adjustments to various parameters are made on the basis of specific characteristics of the output of previous computer runs. Automatic techniques are those in which the computer itself adjusts parameters in a semi-random manner, based on changes in the value of a single numerical error function. The method used is an application of the "Pattern Search" technique.

There is no doubt that a good set of parameters can be obtained using only manual methods. However, the procedure is time consuming in terms of man-hours and requires a degree of interplay with the computer often not available. In addition, the hydrologist performing the optimization must posses a considerable degree of skill acquired through experience with the model. Automatic methods, on the other hand, are fast and simple to use. Besides being expensive from a computer usage standpoint, they have some inherent disadvantages. Some of these are: complete dependency on one error function, failure to attain an optimal solution due to non-convexity of the response surface in the vicinity of the starting point, and failure to recognize the effect of perturbing a group of parameters simultaneously. At its worst, such a procedure can degenerate into pure curve fitting and produce a set of parameters which fit the calibration data reasonably well, but which are hydrologically unrealistic.

Experience in fitting the model to a large number of catchments under operational conditions indicates that the procedure should be one involving both manual and automatic fitting where the strong points of each compensate the weak points of the other. Generally, much more is achieved by fitting manually first, then using the automatic optimizer after a reasonable fit has been obtained.

Data requirements for the model are somewhat greater than for simpler "event" type models, since the model utilizes a continuous record rather than a fragmentary one covering selected periods. The length of the data base required for adequate calibration depends on a number of factors including the hydro-climatic characteristics of the catchment and the amount of hydrologic activity during the period in question. Typically, however, it runs 8 to 10 years.

Further details of this model are given in Peck(1976). This model was used for Indian Catchment by Gosain & Chander (1984).

3.4 THE HBV MODEL

The HBV model was developed by Bergstrom (1984). This model is basically framed on the physical considerations of catchments but parts of it have the character of a black box approach. It considers only the most significant parts of runoff generating processes to avoid complexities in the model. A schematic sketch of HBV-3 model which is a submodel in the framework of HBV-6 model is shown in Figure 3.3. It consists of subroutines for snow accumulation and melt, a soil moisture accounting procedure,

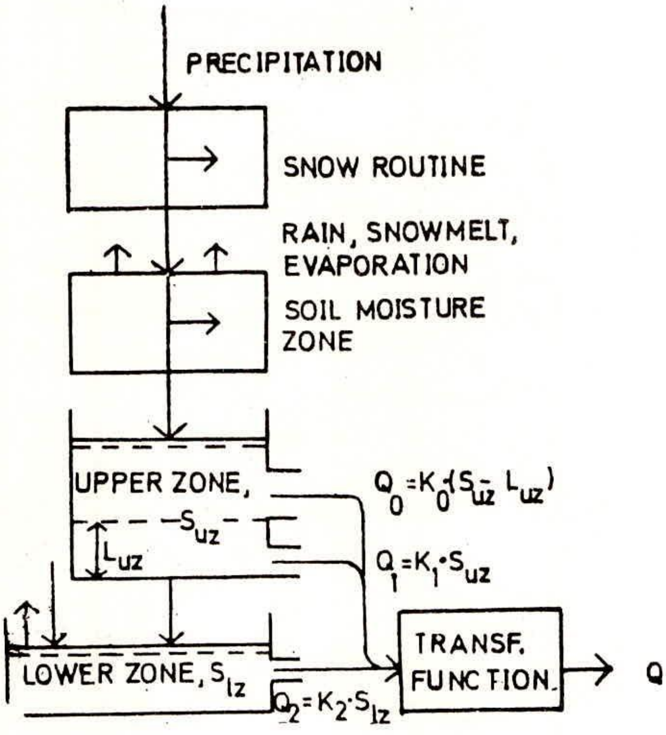

Fig.3.3 Box diagram of the HBV-6 Model, taken from Jain and Bhatia (1986)

routine for runoff generation, and finally a simple routing procedure. The model first considers snow accumulations and melt. The meltwater is then fed into the soil moisture accounting routine.to determine runoff volumes. Finally the volumes are given an appropriate shape in the response function including routing of the water through a series of reservoirs and damping of the hydrograph by means of a transformation function.

The snow accumulation and melt routine is based on the degree-day approach using air temperature as an index representing convection, radiation and condensation components of the heat exchange taking place during snow accumulation and its melt. The air temperature below or above a certain threshold value is used to determine whether there should be accumulation or melting of snow. The snowmelt in this model is computed using a simple relation.

$$M = C_o(T - T_o) \qquad \text{........(3.8)}$$

Where

M = snowmelt (mm/day)
C_o = degree-day factor (mm/^{o} C.day)

T = Surface air temperature
and T_o = threshold value of the temperature(^{o}C)

The degree-day factor C_o depends on the latitude and aspect of the catchment and the day of the year. The C_o and T_o parameters, being strongly correlated , are determined specifically for each catchments.

The retention of the snowmelt water in the snow pack, while percolating through it, is considered through the water-holding capacity of the snow pack. The water accumulation under the snow in its lowest layer which causes a further delay in runoff is considered through a bottom storage under the snow pack. In real situation, the water-holding capacity is a function of the aggregate structure of the snow pack. and decreases with the melting process along with the metamorphoses of the snow.

The snowmelt estimation equation (3.8) has also been used to take care of the refreezing effect of cold air on snowmelt water. This relation automatically yields negative melts at low temperatures, reducing the liquid water content and adding to the snow pack. The melting and freezing are different processes but the restriction on the number of free parameters justifies this approach.

The soil moisture accounting routine controls the runoff formation. It is based on the contributing area concept, (Fig 3 4) which considers different soil cover zones of a catchments to have different maximum soil storage F_c and each zone to contribute as soon as its soil moisture exceeds the respective F_c value. According to this, the contributions from rainfall or snowmelt P to the soil moisture zone S_{sm} and the upper zone S_{uz} are taken as shown in the figure 3.5. It has the effect that the contribution to runoff from rain or snowmelt is small when the soil is dry (low values) and great at wet conditions. Mathematically it can be expressed as

$$\frac{S_{uz}}{P} = \left(\frac{S_{sm}}{F_c}\right)^{\beta} \quad \text{and} \qquad (3.9)$$

$$\frac{S_{sm}}{P} = 1 - \left(\frac{S_{sm}}{F_c}\right)^{\beta} \qquad ....(3.10)$$

where

β = an empirical coefficient

and F_c = maximum available water content of the soil (field capacity -wilting point).

It is a non-linear function, so the soil moisture routine is fed with snowmelt and rainfall mm by mm with subsequent adjustments of the moisture state. The amount S_{uz} passes through the soil moisture zone to contribute to runoff or evaporation from the lower zone. S_{sm} contributes to the soil moisture storage with evaporation as the only exit from the system.

The reduction in potential evapotranspiration E_p to actual E as the soil dries out, is considered a simple function f the total computed soil moisture conditions as shown in figure 3.6.

It can be expressed as:

$$E_a = E_p \qquad \text{if,} \quad S_{sm} > L_p \qquad ....(3.11)$$

$$E_a = E_p \frac{S_{sm}}{L_p} \qquad \text{if;} \quad S_{sm} < L_p \qquad ....(3.12)$$

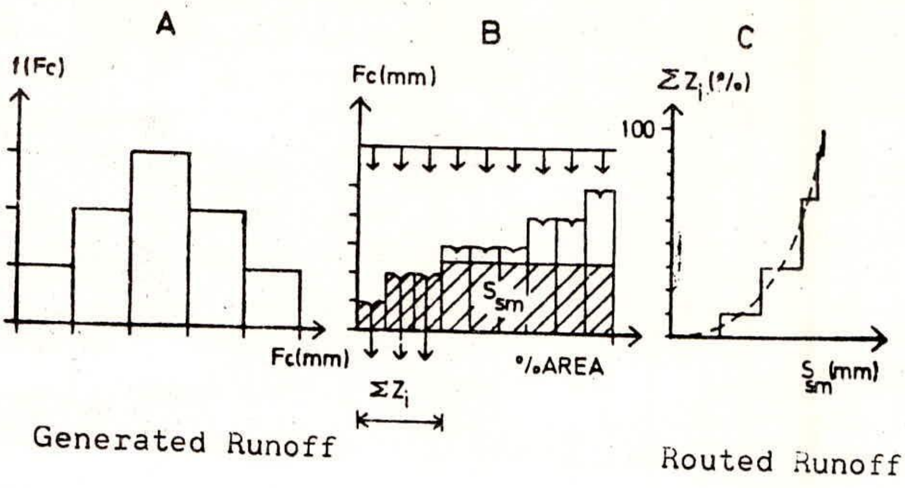

Fig. 3.4 DISTRIBUTION OF THE SIMPLE RESERVOIR SOIL MOISTURE ROUTINE

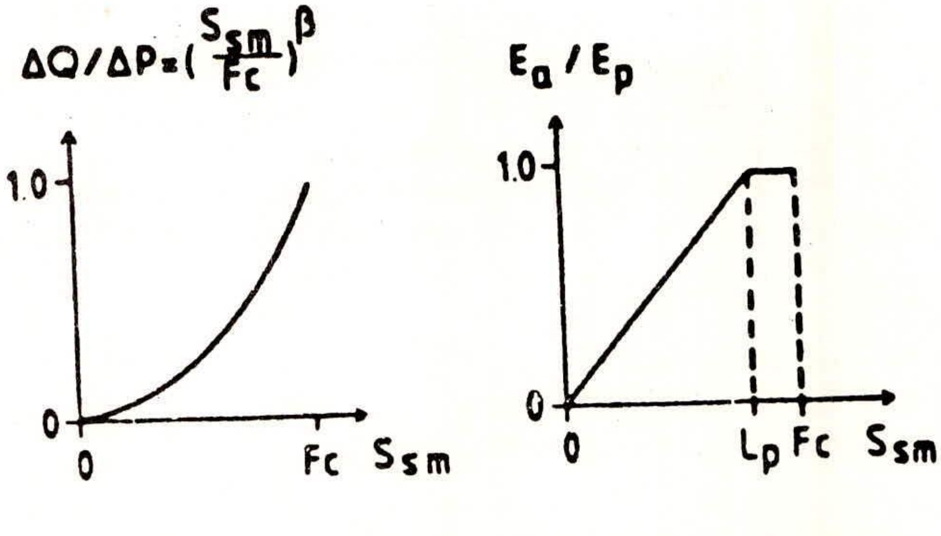

Fig.3.5 SCHEMATIC PRESENTATION OF THE SOIL MOISTURE ACCOUNTING SUBROUTINE

where,

S_{sm} = actual computed soil moisture storage

L_p = soil moisture value above which evapotranspiration reaches its potential value.

The actual evaporation is estimated from the arithmetic mean of the computed soil moisture conditions before and after the processing of rain or snowmelt. It is reduced in proportion to the number of elevation zones with snow cover. In an entirely snow covered catchment it gets reduced to zero.

The distribution of soil moisture according to area-elevation curve is also required to be carried out in accordance with the distribution of snow as the snowmelt is simulated differently in different elevation zones of the catchments. In HBV-3, the lumped version of the model, all the snowmelt is fed into one common soil moisture zone. It is questionable and calls for separate soil moisture accountings in different elevation zones. This is done in the distributed version of the model, HBV-6. The separate accounting increases the number of free parameters, making it difficult to obtain stable parameters estimates. In order to avoid this problem β and L_p/F_c are generally regarded as invariable with the altitude. The procedure for calibration generally, is to start with adjustments of β, with L_p equal to F_c and with F_c at a value regarded as reasonable from considerations of the soil and vegetation cover in the catchments. Thereafter L_p is adjusted and finally, if found necessary, different values of F_c are tested.

Generation of Runoff and Transformation of the hydrograph

The runoff generation routine is the response function which transforms excess water from the soil moisture zone to runoff. It also includes the effect of direct precipitation and evaporation on a part which represents lakes, rivers and other wet areas. The function consists of one upper and one lower quasilinear reservoirs, as shown in Figure 3.5. These are the origin of the quick and slow runoff components of the hydrograph.

The upper zone considers that if yield from the soil exceeds a certain percolation capacity C_{PERC}, the water starts draining through more superficial channels and thus reaches the rivers and streams with a higher drainage coefficient K_1 .At a storage in the upper zone exceeding L_{uz} ,even more rapid drainage according to K_o starts. The lower zone, on the other hand, represents to total ground water storage of the catchments contributing to the base flow. C_{PERC} is thus a parameter governing ground water recharge. A slightly modified version of the response function is now under use in Sweden for ground water simulations.

In HBV-6 model, each one of the subbasins has individual soil moisture, upper and lower zones. The runoff is generated independently from each of the subbasins and is then routed through a transformation function in order to get a proper shape of the hydrograph. The transformation function is a simple filter technique with a triangular distribution of weights, as shown in Fig 3.6. If a translation of the hydrograph due to travel time is needed, this is accounted for by a parameter BLAG. Finally the discharge from each subbasin is combined by superposition to arrive at total discharge at the outlet.

The first approximate values of the recession coefficients in the response function are obtained by recession analysis of the recorded hydrograph. The hydrograph analysis is also used to get a first estimate of the C_{PERC}.These values are adjusted after visual comparison between the computed and the observed hydrographs.

Bhatia (1986) has appplied the HBV model to a sub basin of Narmada river.

3.5 REAL-TIME USE OF RAINFALL RUNOFF MODELS

In the context of real-time use, a rainfall runoff model can operate in two modes, Wood and O'Connell(1985). These are simulation mode and adaptive mode.

In the simulation mode, the model output is computed using the previous model inputs, like rainfall, evapotranspiration. The previous model output is not used while computing the current model output. In the adaptive mode, the previous observed outputs are also used to calculate the current model output.

A rainfall-runoff model is characterized by a set of parameters, the values of which are usually established by some calibration procedure which is based on the agreement between observed and model output. In the context of real-time use it is important to distinguish between two modes in which a model can operate:

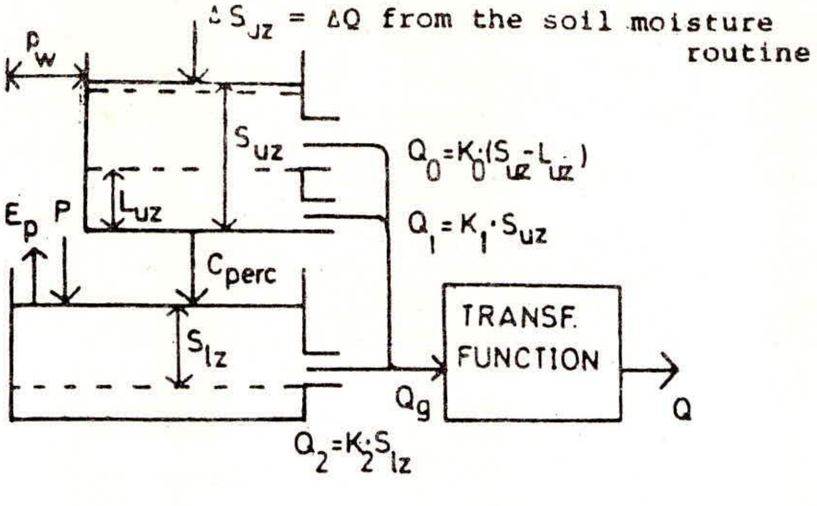

Fig. 3.6 THE RESPONSE FUNCTION OF THE HBV-6 SUBMODEL

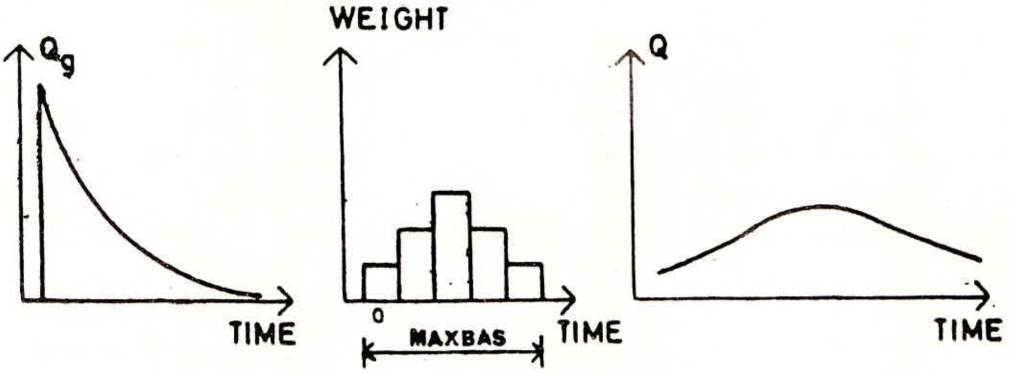

Fig.3.7 SCHEMATIC PRESENTATION OF THE EFFECT OF THE TRANSFORMATION FUNCTION ON THE COMPUTED HYDROGRAPH

a) Simulation mode: here the model output is based on previous model inputs (e.g. rainfall, evaporation,etc.) and also possibly on previous model outputs, depending on the form of the model. No use is made of previously observed output in calculating current model output, although for calibration purpose use will frequently be made of observed output.

b) Adaptive mode: here model output may also be based on previous model inputs, but will also utilize previous observed outputs in calculating current model output. This can be done in either of two ways:

i) by expressing current model output as a function of previous observed outputs as well as model inputs;
ii) by using the discrepancy between the latest observed and model outputs as feedback in calculating future model outputs.

For real-time forecasting it is necessary to have a model that can operate within the adaptive mode. Invoking condition (i) this implies a model structure with a 'feedback' structure; that is outputs at the current time step are related to previously observed outputs.

Another characteristic that is often invoked in the formulation of real-time forecasting models is that of linearity. The basic assumption is that a 'law of large systems' can be applied to complex hydrological systems. The multitude of non-linear, distributed elements can often be represented in a lumped macro-representation by a linear model with additive stochastic disturbances. Attention is therefore restricted to discrete-time models that can be represented by difference equations rather than differential equations. In hydrology observations are usually made and forecasts issued at discrete time instants.

The class of discrete-time models that are applicable to the adaptive forecasting problem has as its mathematical structure a prototype in systems theory known as Gauss-Markov discrete time system. Where mathematical models are to be used in real-time forecasting and control, particularly important considerations are the following :

i) the models should be adaptive in the sense that they should be able to update their parameters and forecasts in real time according as additional data are recorded,

ii) the models should be capable of supplying measures of error associated with their forecasts,

iii) the models should be capable of implementation on small, mini- or micro-computers with minimal storage facilities,

iv) the models should be capable of operating with interrupted data sequences.

Taking into account the foregoing considerations, a technique called Kalman Filtering offers considerable promise for use in the real-time hydrological forecasting. Developed originally by control engineers for problems associated with controlling the trajectories of space vehicles, water engineers and scientists have applied the Kalman filter to forecasting of the above problems. The Kalman filter is not in itself a model which can be used for real time forecasting; rather, it has to be used in conjunction with a model which is assumed to be an imperfect representation of some underlying process, as is usually the case in practice. The model of the process must be formulated within a particular framework of equations referred to as a state-space representation, inherent in this representation is the description of the state of a system by one or more state variables (eg. flow and/or water quality measurements, reservoir levels, etc). The state-space representation consists of:

i) a system equation (or model) which represents a process in terms of known quantities and a system error which reflects the imperfect representation of the system by the model;

ii) a measurement equation which can be used to represent measurements of model inputs and outputs as subject to measurement error.

Given measurements on the behaviour of a system up to the present time, the Kalman filter then specifies:

i) how forecasts of the future behaviour of the system, with associated error variances, can be made by filtering out the noise in the measurements;

ii) how, as each successive measurement or set of measurements becomes available, the previously forecasted behaviour of the state and its error variance can be updated in the light of this new information.

The computational requirements of the Kalman filter are minimal and a typical algorithm can easily be programmed for use on a mini-computer; thus the state-space/Kalman filter approach readily meets the main requirements for models to be used in the time forecasting and control of water resource systems.

A Gauss-Markov system may be described by the state-space equations

$$X_{t+1} = F_t x_t + B_t u_t + w_t \qquad (3.13)$$

$$Y_t = H_t x_t + v_t \qquad (3.14)$$

where y_t is a (k*1) vector of systems output at time t, u_t is a (m*1) vector of inputs (or external controls) and x_t is a (n*1) vector of system states. The variables F_t , B_t and H_t are weighting matrices of suitable dimension, and may be either time varying or time invariant. The matrix F_t is usually referred to as the state transition matrix. The variables w_t and v_t are noise disturbances of the state equation and output equation, respectively. It is often assumed that these noise terms are zero mean Gaussian processes.

It is important to recognize that the only variables that have a physical representation are the inputs and the outputs, since they can be observed and measured. The states need not represent physically measurable quantities. The concept of a state is introduced as a mathematical convenience. For example, the use of model parameters as states has appeared in Wilson et.al (1978), Wood and Szollosi-Nagy (1978), Kitanidis and Bras(1978,1980a, & b), TASC (1980). On the other hand, many formulations use variables such as runoff as system states and their observed values as the measured outputs. In this situation the noise term w_t represents model noise - the state equation does not represent the hydrological processes exactly, due to either linearization of the process dynamics or the lumping of spatial processes. The noise term v_t then represents errors in measuring the states. The inclusion of the model error is consistent without earlier discussion of invoking a 'law of large systems' for our model formulation.

The choice of a suitable model, whether distributed parameter, physically based, lumped conceptually based or input-output, 'black-box' based, is rarely governed by the constraint of formulating the model within a state-space framework. Examples of state-space formulations for all three types of models are given in Chiu(1978), Wood(1980) and IAHS(1980). The critical constraint concerning the model's representation and adequacy has to do with parameter identification and deals with the problem of uniquely estimating the model parameters given the measured inputs and outputs.

Now the real-time hydrological forecasting problem is : given a noisy model of the state dynamics of the hydrological system and a noisy measurement system, find an optimal (a forecast that minimizes the forecast error variance). The Kalman filter balances the model and output error terms to provide the minimum error variance estimator for the state vector, given the measurements.

3.5.1 Filtering, Smoothing and Prediction

In the overall model specified by equation (3.13) and (3.14) a state x behaves according to a system equation and is measured, with noise, by a process z. Given measurements $z_1,......z_t$, the objective is to overcome the presence of measurement noise (filter out the noise) and to form estimates for x. These estimates are of three kinds:

i) Pure filtering :
The measurements $z_1,.....,z_t$ are used to form an estimate $\hat{x}_{t/t}$ of x_t.

ii) Smoothing :
The measurements $z_1,....z_t$ are used to form an estimate $\hat{x}_{s/t}$ of the state x_s at some past time point for $1 \leq s < t$.

iii) Prediction :
The measurements $z_1....z_t$ are used to form an estimate $\hat{x}_{t+s/t}$ of the state x_{t+s} at some future time point $t+s > t$.

3.6 THE KALMAN FILTER

The Kalman filtering was introduced in the control theory literature by Kalman (1960) and Kalman and Bucy(1961). The original theory of Kalman presented a new solution to the linear Gaussian filtering problem, equivalent to the Wiener filter while further developments have extended it to non-linear and non-Gaussian problems.

A schematic description of the filtering problem is given in Fig. 3.8. A process x_t is observed through a noisy measurement z_t, and a filter is used to produce an estimate $\hat{x}_t$ of x_t from the

88

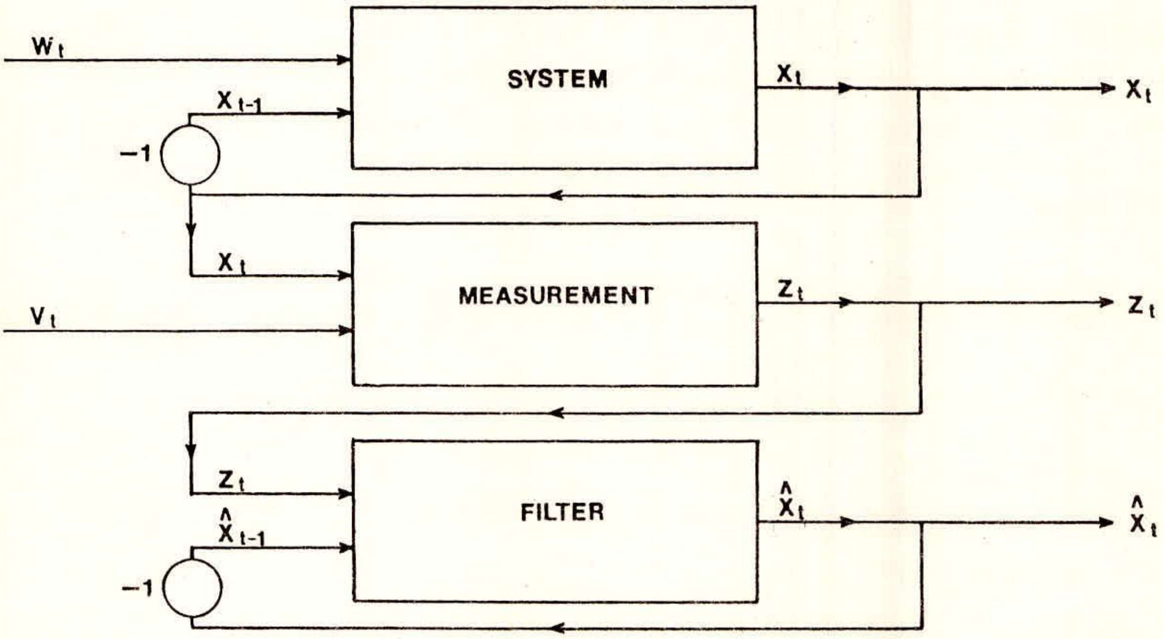

Fig.3.8 Schematic representation of filtering problem

observations. The main feature of the Kalman filter is that x is thought of as the state of the system and is described by a first order differential of difference equation (according to whether t is continuous or discrete); as a result the operation of the filter is recursive. This contrasts with the Wiener formulation where x_t is described by its correlogram and filtering consists of solving the Wiener-Hopf integral equation.

The merits of the Kalman filter are :

- the state-space formulation is flexible and allows many applications as well as providing insight,
- system noise and measurement noise are handled,
- calculations are carried out recursively so very few data need to be stored,
- optimal estimates and forecasts can be achieved,
- the accuracy of the filter is calculated recursively,
- a recursive test on the adequacy of the filter is easily obtained.

The derivation of the Kalman filter is simple. It is available in several texts such as O'Connell (1980), Chander et al(1980) and Wood & O'Connell(1985). The former also provides a number of interpretations of Kalman filter. The quantity

$$\upsilon_t = y_t - H_t \hat{x}_{t/t-1} \qquad (3.15)$$

is referred to as filter innovation. Here $\hat{x}_{t/t-1}$ denotes the estimate of x_t using measurements up to and including time t-1. The innovation consists of the error in the forecast of the state based on the observations $\{y_1, y_2, \ldots y_{t-1}\}$ and in the observations at time t. If the filtering algorithm is optimal then υ_t is independent of υ_s and y_s for $s < t$. The innovation properties

$$E\,[\upsilon_t] = 0; \quad E\,[\upsilon_t \; \upsilon_s^T] = 0; \text{ and } E\,[\upsilon_t y_s^T] = 0 \qquad (3.16)$$

permit a test the filter performance. Statistical tests can be used to check whether the innovation properties hold good.

The Kalman filter algorithm has also been derived for non-linear systems. The resulting algorithm is termed as Extended Kalman Filter.

3.7 REVIEW OF SELECTED RECENT APPLICATIONS

A brief review of selected works in the area of flood forecasting follows.

Lundberg(1982) presented a formulation in which a conceptual model (HBV model) has been used with an autoregressive model for improved flood forecasting. The autoregressive model was used on the residuals of the conceptual model. It was reported that the short time forecasting can be considerably improved with this arrangement. For a test case, the regression coefficient which was 0.86 for the original model improved to 0.99 for one day ahead forecast.

Refsgaard, Rosbjerg and Markussen (1983) applied the NAM model for real-time operation. The NAM model was reformulated in state-space form and supplemented by a Kalman Filter algorithm. This permits updating of runoff forecasts. The uncertainties of input rainfall and selected model parameters can also be taken into account. It was shown that updating improves the forecasts considerably. Further it was found that the input uncertainty is significantly predominant in the resulting uncertainty of simulated runoff values.

Georgakakos(1986a) presented a stochastic hydrometeorological model for flood forecasting. The components of this model include a local quantitative precipitation model, a soil moisture model and a channel routing model with an automatic updating routine (extended Kalman filter). The input to the model consist of surface meteorological data. The model was applied to a basin of size 2344 sq. km., Georgakakos(1986b). It was reported that excellent forecasts of the times of occurrence and magnitudes of rising limb, fallling limb and peak discharges was achieved. The feedback state correction algorithm prevented major errors in discharge prediction even the precipitation prediction was erroneous.

Puente and Bras (1987) applied nonlinear filter on a conceptual stochastic watershed model. The Sacremento model was used for soil moisture accounting. It was found that the noise components of the watershed model are very important and depending on these components, the runoff predictions could range from excellent to unacceptable. The approximate nonlinear filters did perform better in reproducing the discharge hydrograph than a deterministic model. Further, when effective, the simpler of the nonlinear filters was found to be as good as other more complicated filters. It was also reported that all the approximate nonlinear filters resulted in forecasts which had timing errors.

The use of semi-distributed rainfall runoff models for flood forecasting has been advocated by Corradini et al (1987). They compared the reliability of two simple on-line flood forecasting models. These adaptive rainfall runoff models of semi-distributed type provide reasonable forecasts for a large basin. It was reported that the model which better models the infiltration process gives better results.

Hoos et al (1989) presented a model named ASPIRE for real-time flood forecasting. This model was based on routing of diffusive wave through a channel using explicit finite difference scheme. The performance of this model was compared with the Muskingum model. The results given by the authors show that this model gives slightly improved forecasts of peaks as compared to the Muskingum model; the simulation of recession did not show any marked improvements. It was also reported that the Kalman Filter did not improve the forecasting accuracy.

Galeati (1990) compared the performance of the nearest neighbour method with an autoregressive model with exogenous inputs for runoff forecasting. It was reported that both these models give equally good results. The nearest neighbour method was advocated as it has a simpler structure.

Hasebe et al (1989) presented a flood forecasting system with or without rainfall data using the filter separation autoregressive method. The runoff series were separated sequentially into two components. The filter separation AR method is composed of linear subsystems and the nonlinearity of the total system is explained by the nonlinearity of the rainfall separation process into subsystems and a multicomponent model.

****

CHAPTER 4

FLOOD FORECASTING SETUP IN INDIA

4.1 EVOLUTION OF FORECASTING SETUP IN INDIA

In 1969, the Government of India created a Central Flood Forecasting Directorate headed by a Superintending Engineer. In 1970, under Member (Floods), six flood forecasting divisions were set up on inter state river basins. These covered the flood prone basin/ sub-basins of the Ganga. By the year 1977, the Central Flood Forecasting Organization comprising of one Chief Engineers Office, 3 circles and 11 divisions had been setup.

Now, in most of the States there are arrangements for the issue of flood warning from the upstream stations to the downstream stations. These warnings include:

i) Whether the river is rising above a certain specified level, known as danger level or not;

ii) Whether the river is rising or falling,

iii) Whether the stage of the river is "low", Medium" or "High".

The above warnings, issued by telegrams, telephone or wireless system are of purely qualitative in nature and they give only an indication of the nature of the flood. Such procedures are at present being followed in West Bengal, Andhra Pradesh and Bihar States.

After the completion of certain multi-purpose projects like the Hirakund in Orissa, DVC Projects in Bihar/Bengal, Bhakra in Punjab, forecasting techniques have been evolved using the date of rainfall and stream gauge in the catchments upstream of the dam. Correlation diagrams have been prepared with the previous data to predict the inflow into the reservoir. Based upon this, the reservoir operations are carried out. Such flood forecasting system have also been set up for Yamuna in Delhi, Koshi in Bihar, and Krishna and Godavari in Andhra Pradesh.

4.2 STATUS OF SETTING OF INTER-STATE FLOOD FORECASTING SYSTEM

By the year 1985, the Central Water Commission had established a network of 145 flood forecasting and warning sites on various inter-State rivers (Rangachari, 1986).

The data of the river gauge and the rainfall are transmitted to the flood forecasting centres from all the key stations by means of wireless or telegrams. Based on these data and the correlation curves already developed with the previous data, the forecasts are daily issued to the concerned authorities so that they can take the appropriate measures.

4.3 DATA AND LOGISTICS REQUIREMENT FOR FLOOD FORECASTING

Basically gauge/discharge and or rainfall data are required for flood forecasting purposes. The number of reporting stations depend upon hydrologic need and availability of observers and communications.

The number of raingauge stations in the basin should be such that :

(a) The areal rainfall in the catchment can be estimated with the desired accuracy, and

(b) The variation in the areal distribution as well as time distribution can be identified.

The net work design of river gauge, the following points should be kept in mind :

(a) Wherever the forecast is being issued on the basis of gauge correlation, the base station and forecasting station must be equipped with gauge.

(b) In case more than one tributary are joining the main stream and the forecast is based on multiple coaxial diagram,there should be at least one gauge on each of the tributaries. The location of gauge on the tributaries should be such that the time of the travel from base stations to forecasting station in respect of tributaries as well as main stream is constant.

(c) Where the routing model forms the basis of formulation of forecast, the reach has to be divided into various subreaches. For each sub-reach, in addition to the gauge reading discharge observation should also be carried out.

(d) For incorporating the effect of intervening catchment on well designed channel, additional gauges have to be installed.

(e) Apart from gauge/discharge and/or rainfall data interception, evaporation, evapotranspiration, interflow, infiltration, ground water and percolation are used as inputs to several conceptual models which are in operational use in many advanced countries. The data so collected should be transmitted to forecasting centre from base station through a reliable, quick, expandable and cheap transmission system.

A successful application of the real-time operation procedure requires a good telemetry system through which data can be observed on-line. The term "on-line" implies that the data are collected, transmitted and fed to a model and the model's output is obtained and then used in one uninterrupted sequence of activities. This can be accomplished by the use of high capability but low cost process control computers connected with telemetry networks.

Telemetry is defined as the exchange of information between widely separated data collection centres and forecasting centre, and recording of instantaneous values of continuously changing operational quantities at a far away point. Real-time hydrological forecasting depends to a large extent, on the availability of hydrometeorological data at the forecasting station. A sophisticated hydrological model and a fast computer system are useful only if the data acquisition system is reliable and fast. The manually operated point-to-point wireless communication system is becoming outdated day-by-day and hence there is a need to establish more modern communication systems such as telemetry through VHF/UHF/ Microwave or satellite. In such type of systems, no human element is involved for operation, collection and communication of data. This eliminates human error completely and reduces the time of observation and transmission of data. A typical system of forecasting for real-time operation consists of :

i) Observation and collection of operational data at sites,
ii) Transmission of data to forecasting centre,
iii) Formation of forecast.

Various hydrometeorological data acquisition systems and techniques of flood forecasting in river basins in India are:

(i) Manual observation/transmission and forecasting:
(ii) Manual observation/transmission and computer system for forecasting,
(iii) Automatic sensing, transmission and computer system for forecasting,
(iv) Link via Satellite.

Out of the above, a satellite based transmission system is probably the best in terms of economics and reliability. It has the added advantage of overcoming the problem of congestion and widespread interference in all forms of radio communication.

By using satellite communication, the reliability of telemetry system is much more as data from each data collection station is directly transmitted to central station through satellite, i.e. one reporter station only. The specified river gauge, rainfall, temperature readings and other measured quantities are converted into electrical signals for transmission and are converted back at the forecasting station into a suitable form for framing the forecast.

4.4 INFORMATION DISSEMINATION

The organization responsible for flood warning and flood fighting should be informed about the incoming flood as early as possible so that the required action is planned and activities are set into operation with least possible delay. They should also be kept informed of the propagation of a flood wave and of any change in the present as well as anticipated flood situation with respect of flood time. These informations which are supplied by the flood forecasting units in the form of "Flood Forecast Bulletin" must be very clear and include necessary details so that a very realistic picture of the incoming danger is depicted.

Whenever a big flood is likely to occur, the officer-in-charge of the forecasting center should inform the exact details to higher authorities and to communicate the warnings to the administration, Police, Revenue and Panchayat authorities and general public. This will help in taking necessary precautionary measures in respect of alerting and evacuating the people in the area likely to be affected, if required.

Full advantage of real-time forecasting is possible only when a good information dissemination system exists. Forecasts about the likely floods, with sufficient lead time can help in a big way in effectively reducing the damages due to floods .

***

CHAPTER 5

5.1 CONCLUSION

The various models and technniques which are used for flood forecasting have been reviewed in this report. These include simple statistical techniques like gauge-to-gauge correlation, unit hydrograph based techniques and mathematical models.

In India flood forecasting is mostly performed using simple statistical techniques. Although the hydrological literature contains examples of applications of conceptual models also, these applications for Indian catchments are at best scanty so far . The results of a few case studies are available but they are essentially concerned with pilot projects or other projects carried out by/in collaboration with academic institutions or under some research project.

One encouraging aspect is that gradually more applications of rainfall runoff and flood routing studies are appearing in the Indian hydrological literature. Most of the recent study are concerned with simulation of the process. However, this is a pointer to the fact that this type of studies are underway at more number of places. Many of these studies also aim towards development of software rather than just application of imported software. A logical and practical application of these studies will be towards flood forecasting. There is a need for developing software which is suitable for Indian conditions including the data availablity.

The wider availability of personal computers is also responsible for more number of research and development activities. The use of computers for data processing as well as data storage and retrieval is also increasing. Hopefully this will result in easy availability of reliable and more extensive data in absence of which the researchers had no other option but to use the data of foreign catchments. This will solve a major complaint of the research institutions.

***

REFERENCES

Askew, A.J., F. Geeco, and J. Kindler, Logistics and Benefits of Using the Mathematical Models of Hydrologic and Water Resource Systems, IIASA Proceeding Series No. 13, Pergamon Press, Oxford, 1978.

Blackie, J.R, and C.W.O. Eeles, " Lumped catchment models", in Hydrological Forecasting, M.G. Anderson and T.P. Burt (ed), John Wiley and Sons, New york, 1985.

Anderson,M.G., and T.P. Burt, "Modelling Strategies", in Hydrological Forecasting (M.G. Anderson and T.P. Burt eds), Wiley Chichester, UK, 405-435.

Bergstorm,S., Development and Appraisal of a Conceptual Runoff Model for Scandinavian Catchments, SMHI, Rep. No. RHO-7, 1976.

Beven, K., (1985), "Distributed Models in Hydrological Forecasting", in Hydrological Forecasting (M.G. Anderson and T.P. Burt (eds), Wiley Chichester, UK, 405-435.

Chander,S., S.K. Spolia, and A. Kumar, "Flood stage forecasting in rivers", in Monsoon Dynamics, Ed. by M.J. Lighthill, 1980.

Chander,S.C., and Hari Shankar, "Unit hydrograph based forecast model", Hydrological Sciences Journal, 29(3), 1984.

Chiu,C.L., Applications of Kalman Filtering Theory and Techniques to Hydrology, Hydraulics and Water Resources, Proceedings of AGU Chapman Conference, University of Pittsburgh, 1978.

Corradini,C., F Melone, and L Ubertini, "Some remarks on real time flood forecasting by simplified semi-distributed models", in Water for the Future : Hydrology in Perspective, IAHS Publication Nno. 164, 1987.

CWC, Manual of Flood Forecasting, Central Water Commision, New Delhi, 1980.

DHI, NAM Model Documentation, Danish Hydraulic Institute, Denmark, 1982.

Duckstein,L., S. Ambrus and D.R. Davis, "Management forecasting requirements" in Hydrological Forecasting, Edited by M.G. Anderson and T.P. Burt, John Wiley and Sons, 1985.

Galeati,G., "A comparison of parametric and non-parametric methods for runoff forecasting", Hydrological Sciences Journal, 35(1,2) 79-94, 1990.

Goel,N.K., Flood Stage Forecasting by ARMAX Model, M. Tech Thesis, IIT, New Delhi, 1982.

Gosain,A.K., and S. Chander, "Real-time flood forecasting on river Yamuna using NWSRFS model", National Seminar on Real-time Hydrological Forecasting, New Delhi, 1984.

Gosain,A.K., and S. Chander, "Real-time flood forecasting on river Yamuna using ARMAX model", National Seminar on Real-time Hydrological Forecasting, New Delhi, 1984.

Gosain,A.K., and S. Chander, "Real-time flood forecasting on river Yamuna using unit hydrograph model", National Seminar on Real-time Hydrological Forecasting, New Delhi, 1984.

Georgakakos,K.P., " A generalized stochastic hydrometeorological model for flood and flash-flood forecasting", 1. Formulation", Water Resources Research, 22(13), 2083-2095, 1986.

Georgakakos,K.P., " A generalized stochastic hydrometeorological model for flood and flash-flood forecasting", 2. Case Studies", Water Resources Research, 22(13), 2096-2106, 1986.

Hasebe,M., M. Hino, and K. Hoshi, "Flood forecasting by the filter separation AR method and comparision with modelling efficiencies by some rainfall runoff models", Journal of Hydrolgy, 110(1/2), 107-136, 1989.

Hipel,K.W., et al, "Advances in Box-Jenkins modelling of flood flows", Water Resources Research, 14, 1105-1110, 1977.

HEC, HEC-1F Streamflow Forecasting, Users Manual, 1984.

Hoos,A.B., A.D. Koussis, and G.O. Beale, "A channel dynamics model for real-time flood forecasting", Water Resources Research, 25(4), 691-705, 1989.

Jain, V.K., and P.K. Bhatia, "HBV model - an easy approach to runoff simulation", Workshop on Flood Estimation in Himalayan Region, Held at Roorkee, CBIP, 1986.

Jain, S.K., Flood Control Operation of a Multipurpose Reservoir, Ph D Thesis, University of Roorkee, 1990.

Jonch-Clausen, T., and J.C. Refsgaard, " A mathematical modelling system for flood forecasting", Nordic Hydrology, 15, 307-318, 1984.

Kalman,R.E., "A new approach to linear filtering and prediction problems", Tran. ASME Journal Basic Engg., Series D 82, 1960.

Kitanidis, P.K., and R.L. Bras, Real-time Forecasting of River Flows, Tech. Rep. No. 235, R.M.P. Laboratory for Water Resources, MIT, 1978.

Kitanidis, P.K., and R.L. Bras, "Real-time Forecasting with a conceptual hydrologic model, 1. Analysis of uncertainty", Water Resources Research, 16(6), 1025-1033, 1980a.

Kitanidis, P.K., and R.L. Bras, "Real-time Forecasting with a conceptual hydrologic model, 2. Applications and results", Water Resources Research, 16(6), 1034-1044, 1980b.

Lundberg,A., "Combination of a conceptual model and an autoregresssive error model for improving short time forecasting", Nordic Hydrology, 233-246, 1982.

Nielsen,S.A., and E. Hansen, " Numerical simulation of the rainfall- runoff process on a daily basis", Nordic Hydrology, Vol 5, 171-190, 1973.

O'Connell, P.E.(ed), Real-time Hydrological Forecasting and Control, Proceedings of Ist International Workshop Held at Institute of Hydrology, 1980.

Peck,E.L., Catchment Modelling and Initial parameter Estimation for the NWS River Forecast System, NWS Hydro 31, 1976.

Puente, C.E., and R.L. Bras, "Application of nonlinear filtering in the real-time forecasting of river flows", Water Resources Research, 23(4), 675-682, 1987.

Singh, V.P., Hydrologic Systems, Volume II, Watershed Modeling, Prentice Hall, 1989.

Subramanya,K., Engineering Hydrology, Tata McGraw Hill Book Company, 1984.

TASC, Applications of Kalman Filtering and Maximum Likelihood Parameter Identification to Hydrologic Forecasting, The Analytic Sciences Corporation, 1980.

Wilson,E.M., Engineering Hydrology, Macmillan, 1978.

Wood, E.F., and A. Szollosi-Nagy, "An adaptive algorithm for analyzing short-term structural and parameter changes in hydrologic models", Water Resources Research, 14(4), 577-581, 1978.

Wood, E.F., and P.E. O'Connell, "Real-Time Forecasting", in Hydrological Forecasting, Edited by M.G. Anderson and T.P. Burt, John Wiley and Sons, 1985.

WMO, International Glossary of Hydrology, Report No. 385, World Meteorological Organisation, Geneva, 1974.

WMO, Hydrological Forecasting Practices, Operational Forecasting Report No. 6, WMO No. 425, 1975.

***

DIRECTOR : DR. SATISH CHANDRA

SCIENTIST : DR. S K JAIN
DR. S M SETH

SCIENTIFIC STAFF : T. VIJAY

OFFICE STAFF : T P PANICKER