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FLOOD FORECASTING MODELS

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ABSTRACT

A hydrological forecast is the prior estimate of the future state of hydrological phenomena based on the knowledge of underlying physical laws and the modifying effects of specific geographic conditions. The report gives various elements of flood forecasting i.e.necessity of flood forecasting and flood warning, types of river forecasts, development of hydrological forecasting, data requirements for forecasting etc.

The report briefly describes and reviews various flood forecasting models. The available models for flood forecasting can be broadly classified in three categories i.e.(i) The models that make use of equations of continuity, energy and momentum to describe the movoement of water in the hydrological cycle (ii) conceptual models or watershed models which represent component processes in the hydrological cycle and (iii) Input-output models or black box models which identify a relationship between the input and output without attempting to describe the transformation process.

The review of literature reveals that models based on unit hydrograph and ARMAX type models are very simple to use and have shown good potential for online flood forecasting. The suitability of these models should be tested on broader data base.

1.0 INTRODUCTION

Hydrological forecast is 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.

Flood forecasting may be defined as 'the process of estimating the future stages or flows and its time sequence at selected points along the river during the floods' CWC(1980). Flood forecasts are prediction of (i) the crest and its time of occurrence; and (ii) the stages 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

India is traversed by a large number of rivers, the major ones being the Brahmputra, Ganga, Yamuna, Narmada, Mahanadi, Godavari, Krishna and Kaveri. Most of the Indian rivers derive their supplies from the monsoons, which occur during the months of June to October. During these months all the 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, which bring great misery to the people at large.

The Rashtriya Barh Ayog estimated that 40 million ha in the country are prone to floods. Till 1985 reasonable degree of protection has been afforded to an area of 13 million ha. The value of flood losses from 1953 to 1980 has been estimated to be Rs.9154 crores. As a result an average of Rs.327 crores of flood damage occur annually.

Various flood control and flood protection works such as dams, detension basins, river diversions, channel improvements, embankments and levees, river training works etc. offer a positive method of reducing the damage caused by flooding. All these protection works are normally 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 floods impractical or unjustifiable. However, there is always the possibility of an occurrance of a flood higher than the design flood. In such cases, the flood control works offer protection to the areas to a limited extent. Hence an absolute or permanent immunity from flood damage is not physically attainable by the flood protection works. Therefore, in addition to the flood protection measures, 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.

1.1 Classification of River Forecasting

Depending upont the length of period covered by forecast, it can be identified in following three groups:

(i) short term,

(ii) intermediate-term,

(iii) long-term.

Short-term forecasts of several hours or days provide flood warning and are used to warn, the people likely to be affected by inundation, to operate dams and emergency flood ways and to keep vigil on the engineering works on and along the rivers.

Intermediate-term forecasts of several days or weeks are used to plan or modify operating procedures keeping in view the storage available and the water uses comprising hydro power generation, navigation and domestic water supply etc.

Long-term streamflow forecasts of several months or a full season are used to plan seasonal utilization of water likely to be available and for chalking out apropriate and periodic regulation schedule to match with the plan of utilization.

The river forecasting can be classified as shown in Fig.1.

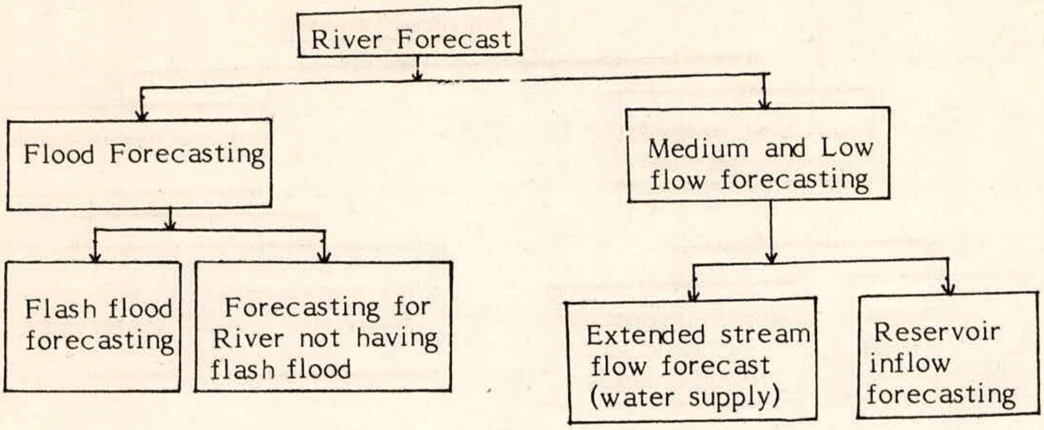

Fig.1 CLASSIFICATION OF RIVER FORECASTING
(Reproduced from Fig.1.1, CWC, 1980)

Flash flood forecasting essentially refers to the flash flood guidance and it is generally needed for smaller river basins (having basin area < 1200 km^2 and time of peak <6 hours).

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

1.2 Need for Flood Forecasting

Warning of the approaching floods provides sufficient time for the authorities:

(i) To evacuate the affected people to the safer places.

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

(iii) To regulate the floods through the barrages and reservoirs, so that the safety of these structures can be taken care of against the higher return period floods.

(iv) To operate the multipurpose reservoirs in such a way that an encroachment into the power and water conservation storage can be made to control the incoming flood.

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

All of these warrant accurate and time flood forecasts.

1.3 Development of Hydrological Forecasting

The development of methods and preparation of hydrological forecasts became possible when sufficient scientific knowledge was acquired ,on the most important phenomena occuring in rivers and lakes and observations of these phenomena were recorded.

The first hydrological forecasting service was organized in France in 1853 for the Loire. Forecasts were prepared mainly on the basis of corresponding stages. They were also based on an empirical evaluation of the effect of precipitation, on the formation of the floods.

The first scientific investigation, regarding the short range forecasting of the water stage on the navigable rivers of Russia, was conducted in 1890, In this work solutions to certain problems of forecasting water stages and water depths at shallow were thoroughly examined on the basis of data from upstream gauging stations. At the end of the 19th century, routine forecasting began in Germany.

Among the western countries, the U.S.A. has at present the most advanced hydrological forecasting services. The U.S.Weather Bureau includes hydrological departments which conduct research on forecasting methods and systematically divert the daily forecasting activity of field stations.

Extensive studies were initiated in recent years on the techniques of short range forecasting of storm floods, and on the technique of long range forecasting of various hydrological phenomena by the Chinese Ministry of Water Economy.

In Russia, the hydrological forecasting service, which consists of various departments prepares the forecasts and conducts the research.

One of the principal aim of scientific efforts has been to establish the basic laws governing the physical processes which determine the state of bodies of water, define these processes quantitatively and finally, develop on the basis of these data, a technique of hydrological forecasting. This approach has greatly increased the role of theory and experiments in the development of hydrological forecasting methods. Accordingly, statistical methods, which were the basic investigation tools in pre-war period, became an auxiliary implement and the genetic analysis of the phenomena has begun to acquire decision importance.

In the post-war period, much attention has been paid to the investigation of the time of flow and storage of water in river systems on thebasis of water balance methods. These studies permitted a theoretical substantiation and a considerable development of forecasting by the method of corresponding stages.

Methods of forecasting summer runoff of low land rivers were also imporved during this period. Much attention, in forecasting low-water runoff, has been given to a close analysis of the recession curves; these are considered integral characteristics of the storage capacity and the rate of its depletion in a basin. Due consideration of the water storage capacities of a drainage basin and ground water storage capacities made it possible to develop more accurate methods of forecasting summer and autumn-runoff.

1.3.1 Development of flood forecasting in India

In 1969, the Govt. of India created a Central Flood Forecasting Directorate, headed by 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. The Brahmputra, the Narmada the Tapti, the Teesta and coastal rivers of Orissa. By the year 1977, the Central Flood Forecasting Organisation comprised of 1 Chief Engineer's office, 3 circles and 11 divisions.

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 systems 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 Hirakud in Orissa, DVC projects in Bihar/Bengal, Bhakra in Punjab, forecasting techniques have been evolved using the data of rainfall and stream gauges in the catchment 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 systems have also been set-up for Yamuna in Delhi, Koshi in Bihar, and Krishna and Godavari in Andhra Pradesh.

1.4 Status of Setting of Interstate Flood Forecasting System

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

The data of the river gauges 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.

A schematic diagram showing the operational flood forecasting system is shown in Fig.2. Some of the salient features of the existing flood forecasting organization under Central Water Commission are given in Appendix I.

1.5 Data Requirement

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.

For network design of river gauges the following points should be kept in mind:

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

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 gauges on the tributaries should be such that the time of the travel from base station to forecasting station in respect of tributaries as well as main stream

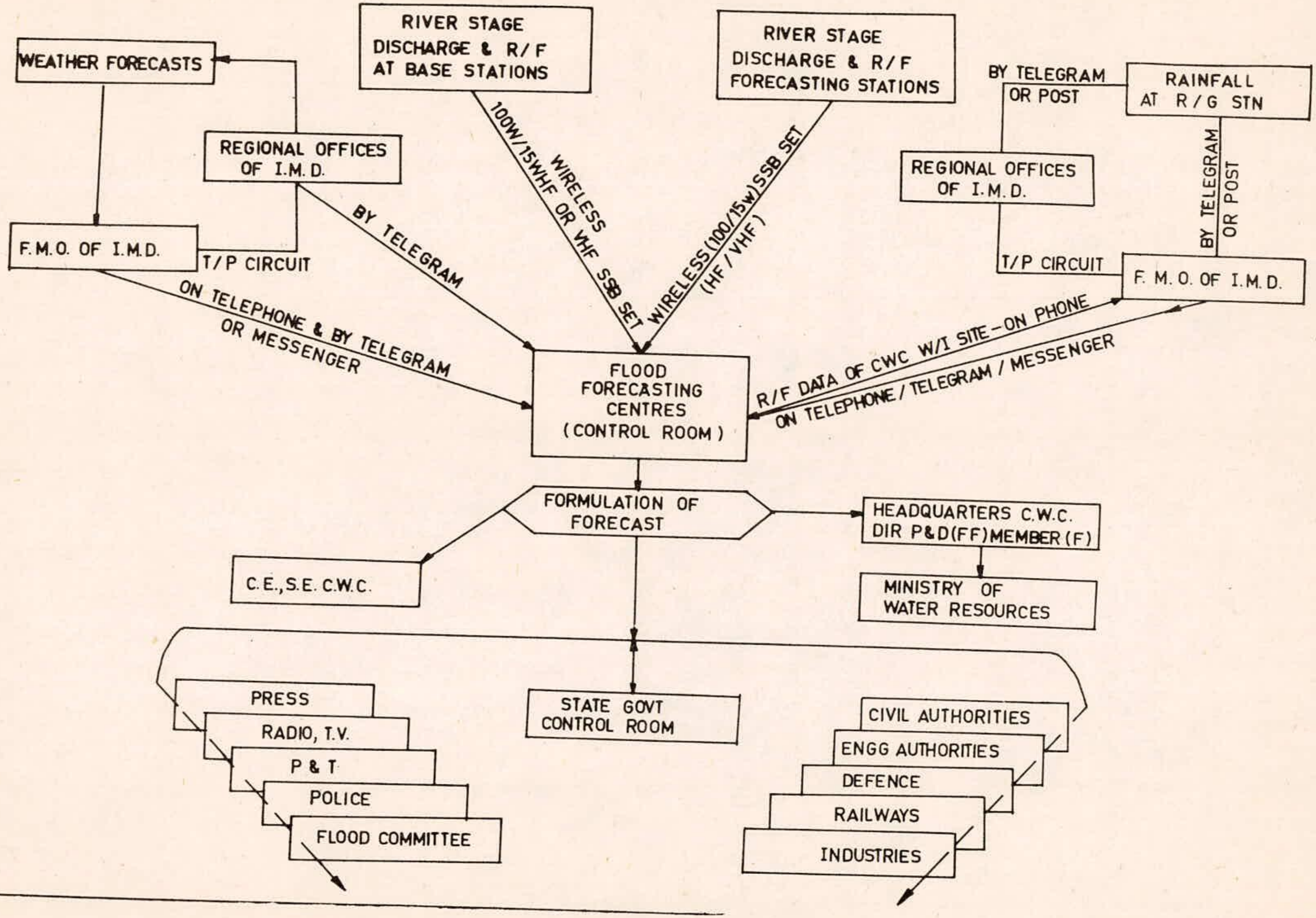

Fig. 2 Existing Flood Forecasting System in India

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 subreach, 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, one gauge has to be installed. If the channel is not well designed it will be imperative to install adequate number of raingauges to account for the contribution from the intervening catchment.

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. Some of the most commonly used data transmission system all over the world are:

(i) Land-line communication,

(ii) HF and UHF wireless network, and

(iv) Telemetry system including ATRG(automatic transmitting raingauges), satellite radar, meteor-burst technology.

1.6 Flood Dissemination

The organisations 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.

2.0 REVIEW OF LITERATURE

2.1 Definitions

Prediction involves the estimation of occurrance of some prescribed condition of a particular hydrological variable and it is used for planning and design of water resources projects.

'Forecasting' involves the estimation of the magnitude of some hydrological variable at a prescribed instant of time. It is useful for operational purposes.

There are three related terms in forecasting hydrologic occurrences viz., river forecasting, flood forecasting and hydrological forecasting. These terms have slight difference in definition, scope and in purpose.

River forecasting indicates providing advance information on the levels and/or discharges of the river at selected points during all stages of the river flow. Flood forecasting is river forecasting when river is in floods. Hydrological forecasting is a more general and comprehensive term signifying advance information on the magnitude as well as times of occurrences of hydrological processes related to or contributing to runoff from a basin or a part of it. The present study is mainly concerned with flood forecasting.

2.1.1 Classification of flood forecasting models

All the models of flood forecasting use the techniques of modelling the hydrological processes in the catchment. These techniques of modelling can be broadly classified into three categories.

1. The models that make use of equations of continuity, energy and momentum to describe the movement of water in the hydrological cycle.
2. Input-output models or black box models which identify a relationship between the input and output without attempting to describe the transformation process.
3. Conceptual models or watershed models which represent component processes in the hydrological cycle.

The first type of models result in a system of partial differential equations which are solved numerically at all points on a three dimensional grid representation of a catchment. These models are still in development stage (Abbot, 1979), and because of enormous requirement of computational time and storage have limited use in flood forecasting.

Input output models identify a relationship between input and output without attempting to describe the internal mechanism whereby this information takes places. The input can take the form of rainfall and/or discharge or gauge values till the time of forecast. The output can be discharge or gauge. These models are broadly classified as

i. Methods based on statistical approach or graphical methods
ii. Deterministic rainfall-runoff models
iii. Flood routing methods
iv. Stochastic models
v. Adaptive filter models
vi. State-space models and Kalman filtering

These models require limited data for estimation of the parameters. These models are capable to take into account the error between the observed and calculated value of the forecast in determining parameters.

So far as the conceptual models are concerned there are several models available. A good description of these models is given by Fleming(1975), Haan et al (1982). This review note is restricted only to the use and application of some of these models in flood forecasting for Indian rivers. All the above input-output models and use of conceptual models in flood forecasting are described in brief in subsequent sections.

2.2 Methods Based on Conventional Approach:

The methods based on conventional approach make use of statistical techniques to analyse the historical data. The method so developed for formulation of flood forecasting can either be represented graphically or by mathematical relationships. The various types of graphs can be broadly classified as

(i) direct correlation between gauges or discharges of upstream station with downstream station.

(ii) correlation between gauges or discharges at upstream and downstream with additional parameters.

In direct correlation between gauges or discharges of upstream station with downstream station, only gauge and discharge data of forecasting station and base station are utilized in different forms.

Sometimes gauge to gauge correlation is not possible because of (i) intermediate catchment rainfall (ii) tributary contribution (iii) varying soil moisture conditions etc. An example of this type of model is the multiple variable coaxial diagrams developed by U.S.Weather Bureau and C.W.C.(1980). Richards and Strahl (1969) enumerated a detailed procedure for developing such diagrams. Betson et al (1969) provided analytical solution for the development of coaxial correlation graphs. These methods are useful in estimating peak discharges or stages.

They do not provide any information about the time distribution of runoff. This method can also be used to determine rainfall excess which in trun can be used in conjunction with the deterministic models to forecast time distribution of runoff.

2.3 Deterministic Rainfall-runoff Models

These can be expressed mathematically by the equation.

$$Y_{t+k} = f\,(Y_t, Y_{t-1} \dots, Y_{t-p}, X_{t-1} \dots X_{t-q}, \dots \phi_1 \dots, \phi_p, \theta_1, \theta_2 \dots \theta_q) \quad \dots(1)$$

where $X_t \dots, x_{t-q}, Y_t, \dots, Y_{t-p}$ are the input and output variables upto time t; Y_{t+k} is the forecast at lead time k. The parameters $\phi_1, \dots \phi_p, \theta_1 \dots \theta_q$ are determined using past data. Choosing a function form f(.) adequate for forecasting flood is actually an art in mathematical modelling. Though the hydrologic systems to be modelled are complex, it may be adequate for many purposes to adopt some relatively simple form of f(.). Fairly large number of studies assume this function to be linear(Dooge, 1973). Unit hydrograph model is a typical example of deterministic rainfall-runoff model used extensively and successfully for flood forecasting. The unit hydrograph is explained in subsequent section.

2.3.1 Unit hydrograph model

The unitgraph is one of the oldest, most widely and most practical techniques used. It is a linear system model which assumes that a distributed parameter natural hydrologic system can be treated as a lumped parameter (uniform areal rainfall excess) system and that the principles of invariance and superimposition apply. In this approach the overall operation of the system is examined without taking into account all the complex details of the system or all the complex physical laws involved. Moreover it deals with the sub-system of the hydrologic system involving surface runoff response only.

The unit hydrograph can be represented by the convolution integral which can be expressed by specific hydrologic notation as

$$Q(t) = \int_{o}^{t} p\,(\tau)\; U\,(T, t-\tau)\, d\tau \qquad \dots(2)$$

where

Q is the direct surface runoff(output),

P is the rainfall excess(input),

U is the T-hour unit hydrograph or response function and τ is the dummy time variable.

Once the unit hydrograph is available for the catchment, the above equation can be used easily as a prediction tool without any reference to the nature of the catchment or the physical laws involved. However, it has not been possible to use this method for operational forecasting because of the difficulty in estimating rainfall excess as the rainstorm progresses in time. This difficulty is overcome by evolving a procedure for the on-line computation of rainfall excess, which can be convolved with the response function to formulate the forecasts. The response function which is a unit hydrograph in this case, is identified using the input and output data.

Real time Forecasting with Unit Hydrograph Model

The unit hydrograph can be applied to the net rainfall on the subcatchment to produce the direct surface runoff from the catchment. In discrete form the following equation is applied.

$$Q_i = \sum_{j=1}^{i} R_{i-j+1} \; U_j \qquad \ldots(3)$$

where

Q_i = Direct surface runoff at time (i),

R_i = Rainfall excess in the catchment at time (i),

U_j = T-hour unit hydrograph ordinates, (j=1,2..m),

m = number of unit hydrograph ordinates,

T = the time step of the discrete interval.

In order to apply the above equation, an estimate of rainfall excess value is required for each time interval. This is achieved through applying the above equation to find the loss rate at each successive step such that the sum of squares between the observed and the previously forecasted values is minimum. The procedure is explained below.

Let P_1 be the total rainfall in the first interval over the catchment. Its response will be realised at the observation point depending upon the initial lag. If the initial lag is (L) intervals then the response of rain in first interval shall be realised after (1+L) intervals, the direct surface runoff(DSRO) can be expressed as

$$Q_{1+L} = (P_1 - F)U_1 \qquad \ldots(4)$$

where, F is the average rate of abstraction.

If the initial lag is zero, i.e. the response is simultaneous then the DSRO at the end of the first interval will be

$$Q_1 = (P_1 - F)\,U_1 \qquad \ldots(5)$$

where all other quanitities except F are known and thus F can be computed. At the end of the second period the equation(3) shall take the form

$$Q_{2+L} = (P_1 - F)U_2 + (P_2 - F)\,U_1 \qquad \ldots(6)$$

The value of F is determined from equation (4) and (6) using the least squares error criterion between the observed and forecasted values. At the end of k^{th} period the value of F using the above criterion is given by equation (6) as

$$F_k = \frac{\sum_{j=1}^{k} (Q_{j+L} - \sum_{i=1}^{k} (P_{j-1+i}U_i) \sum_{i=1}^{j} U_i)}{\sum_{j=1}^{k} (\sum_{i=1}^{j} U_i)^2} \qquad \ldots(7)$$

$U_i = 0$ for $i > m$ where m is the number of unit hydrograph ordinates.

The unit hydrograph based forecast model has successfully been applied to Krishna-Wunna river and Martur river by Chander and Shankar(1984) and to Yamuna river by Gosain and Chander(1984). It has been reported by Gosain that for Yamuna catchment the unit hydrograph model gives reasonably good forecasts upto a lead time between 9 and 12 hours and the peaks are usually well matched. Chander and Shanker(1984) suggest the procedure for on line determination of ϕ -index and rainfall excess and conclude that unit hydrograph can be successfully used for real time forecasting. The model has been found satisfactory even in those storm events where the chosen unit hydrograph does not truly represent the response function. The forecasts deteriorate as lead time of the forecast increases partly because the assumption of no rainfall beyond the time of forecast is not valid.

Perumal et al(1984) proposed a methodology which involves use of the unit hydrograph of Nash's n linear equal reservoirs cascade model in discrete form, with two parameters, n and k coupled with a constant loss rate model for taking into account the rainfall to losses. They test the methodology for Krishna-Wunna catchment and claim that performance of the proposed method is quite encouraging.

Chopra(1984) presents result of application of HEC1-Fcomputer programme for flood forecasting on Yamuna. In HEC 1 -F a river basin is subdivided into an interconnected system of stream network components using topographic maps and other geographic information. Each sub-basin is intended to represent an area, which on an average has the same hydraulic/hydrologic properties. Precipitation excess over sub-basins is computed by substracting infiltration and detention losses based on soil water infilteration rate function. The resulting rainfall excesses are then routed by the unitgraph to the outlet of the sub-basin. A unitgraph can be directly input to the programme or a synthetic unitgraph can be computed from user supplied Snyder's parameters. The programme uses Clarke method to affect a Snyder unitgraph. A dimensionless time area curve is used by the Clarke method if user does not supply the same.The programme combines or links together outflows from different components.

2.4 Flood routing method

Lawler(1965) defines Flood routing as the procedure where by the time and magnitude of a flood wave at a point on a stream is determined from the known or assumed data at one or more points upstream. Flood routing may be broadly classified as reservoir routing and open channel routing. Reservoir routing provides methods for evaluating the modified effects on a flood wave passing through a reservoir. Open channel routings are used to determine the time and magnitude of flood waves in rivers. Various methods of flood routing are

(i) Muskingum method of flood routing

(ii) Kalinin Miliyukov method (Kalinin,1957)

(iii) Muskingum cunge method (NERC, 1975)

(iv) Hayami's method (Hayami, 1951)

(v) Lag and route method (Chow, 1964)

(vi) Successive routing method

Muskingum method of streamflow routing is most commonly used. The method is explained briefly:

The method uses two following basic equations i.e.storage equation and water balance equation.

Storage equation

$$S = K (x I + (I - x)0) \qquad \text{...(8)}$$

Water balance equation:

$$\frac{I_t + I_{t+1}}{2} \Delta t - \frac{O_t + O_{t+1}}{2} \Delta t = S_{t+1} - S_t \qquad \text{...(9)}$$

In the above equations

S= storage (L^3)

K = constant which expresses the ratio between storage and discharge. It is a measure of the lag or time of travel through the reach and the slope of the storage-discharge curve(T)

X = Dimensionless factor which defines the relative weights given to inflow and outflow

I = Inflow rate (L^3/T)

O = Outflow rate (L^3/T)

I_t = Inflow at time t (L^3/T)

I_{t+1} = Inflowat time $t+\Delta t$ (L^3/T)

O_t = Outflow at time t (L^3/T)

O_{t+1} = Outflow at time $t + \Delta t$ (L^3/T)

S_t = Storage at time $t(L^3)$

S_{t+1} = Storage at time $t + \Delta t(L^3)$

combining storage and water balance equation one get

$$O_{t+1} = C_o I_{t+1} + C_1 I_t + C_2 O_t \qquad \text{...(10)}$$

where

$$C_o = \frac{0.5 \Delta t - Kx}{K-Kx + 0.5 \Delta t}$$

$$C_1 = \frac{0.5 \Delta t + Kx}{K-Kx + 0.5\, 0_t}$$

$$C_2 = \frac{K-Kx - 0.5 \Delta t}{K-Kx + 0.5 \Delta t}$$

and $C_o + C_1 + C_2 = 1$

The value of parameters of K and x can be evaluated either empirically or analytically.

The Muskingum method of flood routing has been improved subsequently and a very effective method is the successive routing through subreaches. In this method the reach between U/S station and the D/S station is divided into several reaches and the successive routing is carried out through each sub-reach. The details of other routing methods can be seen in the references cited.

2.5 Stochastic Models

These models take into account the stochastic nature of the data and the errors in progress. Stochastic models used in forecasting (Chander et al ,1980; Gosain and Chander, 1984; Goel, 1982; Goel and Chander, 1984; Gosain, 1984; Kumar, 1980; Kumar and Devi, 1982; Hipel ,1977) consist of a deterministic part and error term. Such models can be expressed by an ARMA (p q) model as in equation (7).

$$Y_t = \phi_1 Y_{t-1} + \ldots\ldots + \phi_p Y_{t-p} + \theta_1 X_{t-1} + \ldots\ldots \theta_p X_{t-2} + \varepsilon_t$$

where Y_t is the current state of variable (discharge/stage) and 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 error term ε_t. 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 11. The detailed procedure of identification and estimation is given by Hipel(1977).

Such models have limited data requirements and can be identified using objective models. They have the capability of operation with interrupted data and require a mini-computer system or a programmable calculator for their use. 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 as indicated by the additional data. Chander et al (1980) and Goel(1982) used models belonging to this family in forecasting stage differences on the tributaries as an input and in another case used it for forecasting stages using previous rainfall as the input.

2.6 Adaptive Filter Models

Adaptive filter models are used for on-line identification where the output model is continuously assessed against the actual system output. The adaptive hydrological forecasting can be defined as follows(O'Connel and Clarke ,1980)

We suppose

(a) That it is necessary to provide forecasts of river discharge in the near future (say for the next 6 h) for a basin instrumented with telemetering rainfall recorders and a telemetering water level gauge, for which a reliable stage-discharge curve is available;

(b) That water level is recorded at intervals Δt, commonly, equal but not necessarily equal, and that the rainfall accumulated by each recorder is available for the same time intervals;

(c) That a model $q_t = f(\{P_t\}, \theta) + \varepsilon_t$ has been identified which describes the transformation by which mean aerial rainfall P_t in the interval $(t-\Delta t, t)$ becomes runoff q_t;

(d) That at time t, estimates $\hat{\theta}$ of the model parameters have been calculated from past observations of P_t and q_t;

(e) That the model is to be used to make forecasts $q_{t+1}, q_{t+2}, \ldots$, of runoff during future time intervals $(t, t+\Delta t), (t+\Delta t, t+2\Delta t)$.

And if

(a) The estimates $\hat{\theta}$ are correlated at the end of the time interval $(t\ t+\Delta$, when P_{t+1}, q_{t+1} become available for use to give a new estimate $\hat{\theta}_{t+1} = \hat{\theta}_t + \varepsilon$;

(b) The forecasts of future runoff q_{t+2}, q_{t+3} are also corrected by the use of P_{t+1} and q_{t+1}. Then we have adapative estimation of the parameters , and adaptive forecasting of future runoff.

Difference between non-adaptive and adaptive estimation and forecasting is that in nonadaptive forecasting recalculation of model parameters and forecasts occur at irregular intervals, or possibly not at all, using the entire records of rainfall and runoff in the recalculation. While in case of adaptive forecasting recalculation of model parameters and forecasts occurs whenever new observations become available, and the new estimates of parameter values are obtained by using the most recent data to correct the old estimates.

The main contiributors for adaptive filter models are Lambert, 1978:, Moore and Weiss, 1980; Jones and Moore, 1980; O'Connell, 1980; Cameron 1980; Szollosi-Nagy, 1976a b; Szollosi-Nagi et al, 1977: Todini and Wallis, 1978; Kitanidis and Bras, 1978, 1980; Chander et al, 1980;and Bolzern et al, 1980.

Conceptual models and Transfer function noise (TFN) models can be used for adaptive forecasting. A good description of the parameter estimation and upgrading has been given by O', Connell and Clarke(1980).

Many recursive algorithms(adaptive filter algorithms) are available (Kalman, 1960; Sage and Melsa, 1969; Kashyap and Rao, 1976; Saridis, 1977) for sequential estimation of parameters. These algorithms can be used both in deterministic and stochastic models. Bolzern etal (1980) and Kumar and Devi(1982) have compared the performance of some of these algorithms and have concluded that complex algorithms don't necessarily improve the forecast. However, it is evident from the results of Chander et al(1980) and above two papers that updating improves the forecasts appreciably.

Over the last one decade ARMAX type of stochastic models are gaining popularity for rainfall runoff modelling and adaptive hydrological forecasting. In the subsequent section ARMAX type of models are explained in the light of development of model, model identification, parameter estimation and parameter upgradation.

2.6.1 ARMAX model

While designing a practical flood forecasting system, the efforts are put to develop an appropriate mathematical model of the rainfall-runoff process to allow more reliable and sophisticated forecasts of flow to be made in a real-time context. The ARMAX(Auto regressive moving average with exogeneous inputs) model has been increasingly employed as a suitable model for representing the transformation between input and output in many hydrological situations. ARMAX Model is a stochastic model which can be used for adaptive hydrological forecasting using number of adaptive algorithms.

Development of the Model

In hydrology auto regressive models have been used extensively for data generation(Goel ,1982). An autoregressive model is one in which the value of a variable is dependent on the variate values at antecedent time intervals. This can be written as

$$Y_t = \sum_{i=1}^{p} \phi_i \; Y_{t-i} + a_t \qquad \text{...(12)}$$

where

Y_t is the value of variable (eg.stage) at time t,

ϕ_i is the autoregressive parameter for the ith independent variable.

The other type of stochastic formulation is called the moving average scheme which expresses the variable as linearly dependent function of previous random shocks and is given by

$$Y_t = \sum_{j=1}^{q} \theta_j \; a_{t-j} + a_t \qquad \text{...(13)}$$

where θ_j is the j^{th} moving average parameter and a_t is the random component at time t. Such models have found application in hydrology but on a more limited scale (Quimpo, 1967). An important category of models called the auto regressive cum moving average models denoted by ARMA(p,q) (Box and Jenkins ,1970) results from a combination of equation 12 and 13. Such models can simulate the behaviour of complex systems actually found in practice. The mathematical formulation for this group is given by the equation.

$$Y_t = \sum_{i=1}^{p} \phi_i \, Y_{t-i} + \sum_{j=1}^{q} \theta_j \; a_{t-j} + a_t \qquad \text{...(14)}$$

In the above equation, p and q signify the extent of autoregressive and moving average schemes respectively.

Model Identification

An ARMAX model can be expressed as

$$q_t = \phi_1 q_{t-1} + \phi_2 q_{t-2} \cdots\cdots + \phi_p q_{t-p} + \theta_1 P_{t-T} + \theta_2 P_{t-T-1} + \cdots\cdots + \theta_q P_{t-T-q+1} + \epsilon_t$$

where

q_t is the runoff at time t,

P_{t-T} is the rainfall at time t-T,

ϵ_t is the noise,

T is the initial lag in terms of number of time intervals and

p and q define the order of the model.

The identification of the structure of the model requires the determination of the order of model as defined by p and q. To achieve this different combination of p and q are considered and parameters are estimated for each combination by using least squares technique as explained subsequently. For each combination simulation is carried out using corresponding parameters and the simulated discharges are compared with observed discharges and the residual errors are computed. That model of order(p,q) is identified which gives the minimum mean square error. In the event of two different combinations of order(p,q) giving nearly the same mean square error, the model with lower order is tentatively chosen. The model is considered adequate if the residual errors are uncorrelated. If the residual errors are found to be correlated then, either the order of the model is increased till the residual errors become uncorrelated, or an error model is incorporated in the above equation.

Estimation of Parameters

The flood discharge q at any time t is described as a linear function of past values of q(.) and rainfall w(.) as

$$q_t = \sum_{i=1}^{n} \theta_i \, q_{t-i} + \sum_{j=1}^{m} \theta_{n+j} \, W_{t-j} + \varepsilon_t \qquad \text{...(16)}$$

where,

θ (.) are the parameters of the model,

n,m are the order of the system model , and

ε_t is random variable with zero mean and constant variance. Alternatively, equation, (16) can be written as

$$\begin{bmatrix} q_t \\ q_{t-1} \\ \vdots \\ q_1 \end{bmatrix} = \begin{bmatrix} q_{t-1} & \cdots\cdots & w_{t-1} & \cdots & w_{t-m} \\ q_{t-2} & & w_{t-2} & & w_{t-m-1} \\ \vdots & & \vdots & & \\ q_o & & w_o & & w_{1-m} \end{bmatrix} \begin{bmatrix} \theta_1 \\ \theta_2 \\ \vdots \\ \theta_{n+m} \end{bmatrix} + \begin{bmatrix} \varepsilon_t \\ \vdots \\ \vdots \\ \varepsilon_1 \end{bmatrix}$$

In matrix notation

$$\underline{q}(t) = H(t)\,\underline{\theta}(t) + \underline{\varepsilon}(t) \qquad \text{...(18)}$$

$\underline{q}(t)$ = (Nxl) observation vector, N being the number of observations,

$\underline{\theta}(t)$ = (n+m) x 1 parameter vector,

$H(t)$ = N x (n+m) past observation matrix,

$\underline{\varepsilon}(t)$ = N x 1 error vector.

The parameter vector θ (.) is estimated from the available data on rainfall and runoff using minimum square error principle such that ε_t^2 is least.

$$J_t(\theta) = \Sigma\,\varepsilon_t^2 = [\underline{q}(t) - H(t)\underline{\theta}(t)]^T[q(t) - H(t)\underline{\theta}(t)] \qquad \text{...(19)}$$

$$\frac{\partial J_t(\theta)}{\partial \theta} = -H^T(t)\,\underline{q}(t) + H^T(t)\,H(t)\,\underline{\theta}(t) = 0$$

$$\underline{\theta}(t) = [H^T(t)\,H(t)]^{-1} H^T(t)\,\underline{q}(t)$$

If $P(t) = [H^T(t)\,H(t)]^{-1}$, then

$$\underline{\theta}(t) = P(t)\,H^T(t)\,\underline{q}(t) \qquad \text{...(20)}$$

Recursive Estimation of Parameters

There are number of algorithms for recursive estimation of parameters. Kumar and Devi(1982) evaluated adaptive filter algorithms of different complexity to recursively update the parameters of an ARMAX model and concluded that the use of a complicated algorithm does not significantly improve the forecast. Recursive least squares algorithm which is very simple to apply is being explained.

The recursive least squares algorithm is used to update estimate of $\underline{\theta}(t)$ with every additional information q(t+1). For this additional information q(t+1) equation (18) gets modified as

$$\underline{q}\,(t+1) = H\,(t+1)\underline{\theta}\,(t+1) \qquad \text{...(21a)}$$

The parameters$\underline{\theta}\,(.)$ using (t+1) observations can be estimated using equation 20 which will now take the form

$$\underline{\theta}\,(t+1) = P(t+1)\,H^{T}\,(t+1)\ \ \underline{q}(t+1) \qquad \text{...(21b)}$$

where$\underline{\theta}\,(t+1)$ is the updated estimate of the parameters.

The updated estimates of parameters $\underline{\theta}$ (t+1) can be obtained by solving equation 21b but involves in repetitive calculations after every step as each new observation becomes available. Alternatively, recursive estimation of $\underline{\theta}$ (t+1) using the previous estimate$\underline{\theta}\,(t)$ can be obtained by relating P(t+1), H(t+1) and q(t+1) in equation 17 to P(t), H(t) and q(t) as follows:

Let q(t+1) is the new observation available and h(t+1) is the (n+m) vector of past values, the equation 21b can be written as

$$\underline{q}(t+1) = \left[\frac{q(t+1)}{q(t)}\right] = \left[\frac{h(t+1)}{H(t)}\right]\ \underline{\theta}\ \ (t+1) \qquad \text{...(22)}$$

$$\begin{aligned} \text{and} \qquad P(t+1) &= [H^{T}(t+1)\ H\ (t+1)]^{-1} \\ &= [\underline{h}^{T}\ (t+1)\ h\ (t+1) + H^{T}(t)\ H(t)]^{-1} \\ \text{or} \quad P^{-1}(t+1) &= \underline{h}^{T}(t+1)\ \underline{h}\ (t+1) + H^{T}\ (t)\ H(t) \qquad \text{... (23)} \end{aligned}$$

$$P^{-1}\ (t+1) = \underline{h}^{T}(t+1)\ \underline{h}\ (t+1) + P^{-1}\ (t) \qquad \text{... (24)}$$

substituting equation 22 and 24 in equation 17 and on some modification we get

$$\underline{\theta}\ (t+1) = \underline{\theta}\ (t) + P\ (t+1)\ \underline{h}^{T}\ (t+1)\ [q(t+1)-h(t+1)\underline{\theta}\ (t)] \qquad \ldots(25)$$

Equation (25) can be used for updating parameters, knowing θ (t), h(t+1) and q(t+1), but needs two inversions to obtain P(t+1). The computation can be further simplified using the matrix lemama (Chander, et al, 1980) to obtain

$$\begin{aligned}\underline{\theta}\ (t+1) = \underline{\theta}(t) + P(t)\ \underline{h}^{T}(t+1)[\underline{h}\ (t+1).\\ P(t)h^{T}(t+1) + 1]^{-1}[q(t+1)-\underline{H}(t+1)\ \theta\ (t)]\end{aligned} \qquad \ldots(26)$$

Equation (26) reduces the computation as $[h\ P\ h^{T}+1]$ is a scalar quantity and can be easily used for updating the parameters $\underline{\theta}$ (t) recursively.

Goel (1982) applied ARMAX model for River Marchur for flood stage forecasting. Gosain and Chander (1984) used this model for real time flood forecasting on river Yamuna and concluded that the model performs well upto a lead time of 6 h but as the lead time increases the forecast deteriorates.

2.7 State-Space Models and Kalman Filtering

In recent years, state space modelling and Kalman filtering have attracted considerable attention in hydrology. These techniques are originally from control theory. The merit of the state-space modelling approach is that it allows many different models(physically based, conceptual and black box) to be cast within the mathematical framework of two equations i.e.(i) system equation and (ii) measurement equation. State space models may be formulated for systems which are linear or non-linear and observed in discrete or continuous time. For a linear dynamic system the discrete-time system and measurement equations are

System equation:

$$x_t = \theta_{t-1}\, x_{t-1} + \Lambda_t\, U_t + \Gamma_t\, W_t \qquad \ldots(27)$$

Measurement equation:

$$q_t = H_t x_t + V_t \qquad \text{...(28)}$$

where, x_t and q_t are (nxl) and (mxl) state and measurement vectors, U_t is a (rxl) vector of deterministic inputs or control variables, W_t and V_t are (mxl) vectors of system and measurement errors or noise, ϕ_{t-1} is a (nxm) transition matrix and Λ_t, Γ_t and H_t are (nxr), (nxm) and (mxn) weighting matrices. In the standard exposition of Kalman filter theory, the system and measurement noises are independently and identically distributed Gaussian random variables with the following properties:

$$E(W_t) = 0 \qquad \text{...(29)}$$

$$E(V_t) = 0; \qquad \text{...(30)}$$

$$E(W_t \cdot W_k^T) = Q\,\delta_{tk} \qquad \text{...(31)}$$

$$E(V_t\, V_k^T) = R\,\delta_{tk} \qquad \text{...(32)}$$

$$E(W_t\, V_k^T) = O\, V_{tk} \qquad \text{...(33)}$$

where δ_{tk} is the Kronecker delta defined as

$$\delta tk = 1 \quad \text{for } t = k \qquad \text{...(34)}$$

$$\delta tk = 0 \quad \text{for } t \neq k \qquad \text{...(35)}$$

Finally, the system noise W_t is assumed to be independent of x_s for $s < t$, and the measurement noise V_t is assumed to be independent of x_t. One of the advantages of the state-space formulation is that the system and measurement noises are separated; the problem posed then is the estimation of the system state x_t in the presence of the measurement noise V_t. This probelm is solved by applying the linear Kalman filter to derive filtered state estimates $\hat{x}_{t/t}$, recursively using the measurement obtained upto time t. The flexibility of state space models is that they can be represented in number of ways. This is being explained with the help of an example.

Example: An ARMA(2,3) model can be written as

$$q_t = \phi_1 q_{t-1} + \phi_2 q_{t-2} + \theta_1 P_{t-1} + \theta_2 P_{t-2} + \theta_3 P_{t-3} + \epsilon_t \qquad \text{...(36)}$$

The state space formulation of this model will be as follows:

$$\begin{bmatrix} q_t \\ q_{t-1} \end{bmatrix} = \begin{bmatrix} \phi_1 & \phi_2 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} q_{t-1} \\ q_{t-2} \end{bmatrix} + \begin{bmatrix} \theta_1 & \theta_2 & \theta_3 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} P_{t-1} \\ P_{t-2} \\ P_{t-3} \end{bmatrix} + \begin{bmatrix} W_1 \\ 0 \end{bmatrix}_t \qquad ...(37)$$

measurement equation

$$[q_t] = [1 \;\; 0] \begin{bmatrix} q_t \\ q_{t-1} \end{bmatrix} + v_t \qquad ...(38)$$

In the above equation if q_t is assumed to be runoff and P_t is assumed to be rainfall then in the above formulation the rainfall has been assumed as deterministic error free input. However, rainfall is subject to measurement error and is computed in many cases as a lumped areal average which introduces further errors. Also if forecasts in advance of one step ahead are to be made from the above model, then some assumptions have to be made about the future behaviour of rainfall. An alternative approach is to treat rainfall as a stochastic process; for illustrative purposes a third order autoregressive AR(3) process will be used to represent rainfall. The state space model will be then written as,

System equation :

$$\begin{bmatrix} q_t \\ q_{t-1} \\ P_t \\ P_{t-1} \\ P_{t-2} \end{bmatrix} = \begin{bmatrix} \phi_1 & \phi_2 & \theta_1 & \theta_2 & \theta_3 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & \theta_1 & \theta_2 & \theta_3 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} q_{t-1} \\ q_{t-2} \\ P_{t-1} \\ P_{t-2} \\ P_{t-3} \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} W_1 \\ W_2 \end{bmatrix}_t \qquad ...1(39)$$

measurement equation:

$$\begin{bmatrix} q_t \\ P_t \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}_t \qquad ...(40)$$

Thus, short term rainfall forecasts can be provided within the model using the statistical structure of rainfall, and rainfall noise is also account for.

2.8 Use of Conceptual Models in Flood Forecasting

The conceptual models simulate component processes in the catchment. Their development starts with the selection of a basic structure that defines and links mathematically the major processes of the hydrological cycle. They are deterministic and require the processing of the large amount of past hydrological data for estimation of the parameters of the models. Some of the models which have been used for forecasting (WMO,1975) are:

1. Bureau of Meteorology Model (CBM)
2. Girard I model
3. Serial storage type model (Tank model)
4. The flood forecasting model
5. Streamflow synthesis and reservoir regulation model
6. National weather service hydrologic model(NWSH)
7. Sacramento river forecast centre hydrologic model (SRFCH).
8. Rainfall-runoff model of the hydrometeorological centre of U.S.S.R.(HMC).
9. Constrained linear system model (CLS)

There are several other conceptual models also. Details can be seen in Flemming (1975) and Haan et al (1982). Two typical river forecasting systems (National Weather Serivce River Forecasting System and Forecasting system in River Yamuna) which make use of conceptual models and application of these models for Indian river basins are explained in subsequent sections.

2.8.1 The National Weather Service River Forecast System-update 1976

The primary purpose of the United States National Weather Service (NWS) hydrologic program is to provide accurate and timely hydrologic information to the general public. NWS river forecasts are used for flood forecasting, flood warning, water supply, navigation, irrigation, power, reservoir operation, recreation and water quality interests.

The river forecast centre(RFC) is the focal point of the forecast network (Fig.3). Staffed by professional hydrologists, the RFC receives hydrometeorological data, prepares forecasts and transmits forecasts to other weather Service Forecast offices for dissemination. Reception of accurate and timely forecasts by riverside interests enables decision-making that can minimize loss of life and property due to extreme riverine events.

Twelve RFC's prepare river forecasts and warning for approximately 2500 communities. Approximately 97 percent of the United States(including Alaska) is covered by this service. The area of responsibility of each RFC includes one or more major river system.

Forecasts of seasonal snowmelt or water year runoff are prepared by five RFC's in western United States. Two additional RFC's in the north -west prepare seasonal snowmelt and monthly runoff forecasts. These water supply forecasts for 600 points where snow is the principle source of streamflow are distributed to water users monthly by local WSFO's (Curtis and Smith, 1976).

The NWSRFS is set of techniques and computer programmes, used to produce river forecasts. The following programmes are used to manage large volumes of data associated with a national forecasting system and to perform the hydrologic and hydraulic computations necessary to forecast river system response.

(i) Data management- Routines that store, retrieve, and manipulate data from the appropriate direct access disk file.

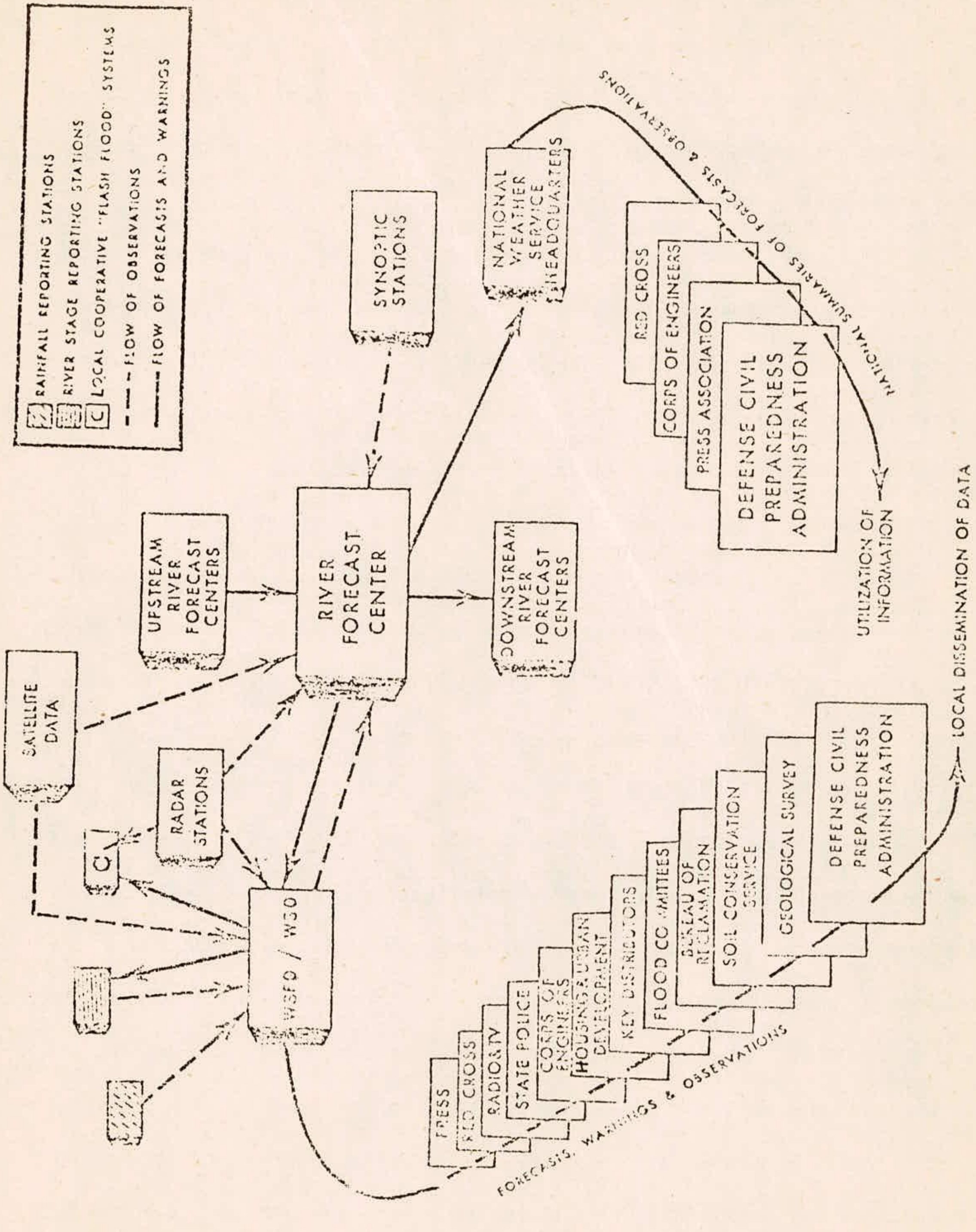

Fig.3 National Weather Service River Forecast System

(ii) Soil moisture accounting-Routines that simulate the movement of water through the soil profile.

(iii) Snow accumulation and ablation-Routines describing the build up and subsequent melt of snow cover.

(iv) Channel routing-Hydrologic and hydraulic techniques to route flows through natural channels.

(v) Mean areal precipitation-Routines converting point precipitation values to areal means.

(vi) Mean areal evapotranspiration -Routines to compute mean areal evapotranspiration.

(vii) Mean areal temperature -Routines to convert point temperature values to areal means.

As new technology becomes available, the NWSRFS updates the adopted technology to improve the quality of the NWSRFS.

2.8.2 Real time hydrological forecasting in the Yamuna river basin

Under the existing system flood forecasts for Delhi are issued on the basis of simple gauge to gauge co-axial correlation with the support of manually operated wireless communication system. However, a pilot project to establish fully automated operational river and flood forecasting system in the Yamuna basin with the assistance of UNDP through WMO, is under implementation. The first phase is already completed. Telemetry system includes 14 reporting (remote sensing) stations throughout the Yamuna catchment upstream of Delhi. These stations will report precipitation, temperature and water level. The principal physical component of the system consists of automatic measuring equipment, 7 repeater stations for the VHF communication, a master teleprocessor at central station Delhi to control the collection of data from remote sensing stations and a mini-computer (HP-1000F) to accomplish computations for utilising mathematical models calibrated on the basis of the past data. Number of conceptual models are being studied for application in the Yamuna catchment (Ghanekar and Chopra, 1984; Rangachari, 1986). The telemetry link in the Yamuna basin is given in Fig.4.

2.8.3 Application of conceptual models to Indian Rivers

Mukhopadhyay(1984) gives the details of transfer/implementation of SSARR model in HP-1000 computer system of Central Water Commission. Ekbote and Bhave(1982) apply tank model for Venna basin and find that final caliberation run had a percentage error in synthesised flow volume of less than 0.5, root mean square error as 11.58 per cent and daily flow correlation coefficient of the order of 0.83.

Seth and Datta(1983) give the details of application of tank model for simulation of daily runoff of Jamtara and Ginnore sub-basins of Narmada and conclude that 4x4 tank model is satisfactory for high flows and low flows . Mishra and Soni(1982) apply Betson and USGS models for modelling daily runoff for Kasurnala basin and find that the models like USGS and Betson are sufficient particularly in understanding the characteristics of the watershed.

Gosain and Chander(1984) apply Sacramento model for real time forecasting on River Yamuna and report that model gives reasonable good forecasts upto a lead time of 9 hours. The corresponding scatter diagrams also show that peaks are well matched as they lie near the 45 degree line.

2.9 Verification of Forecast

The following are the main purposes of forecast verification,

i. To find the degree of accuracy and inaccuracy of the forecast,

ii. To find the possible reason for error and to suggest the possible improvement in the existing system ,

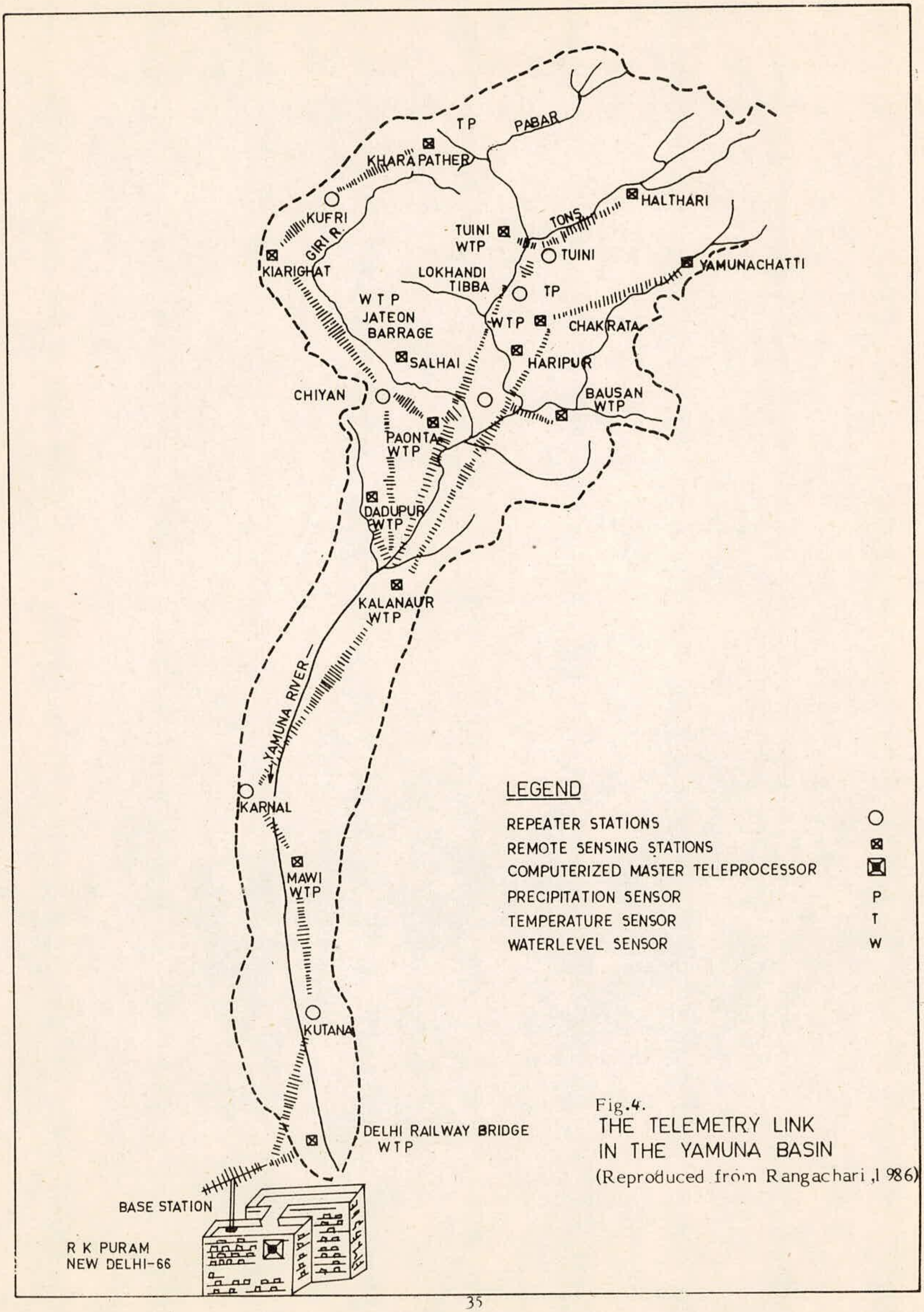

Fig.4.
THE TELEMETRY LINK
IN THE YAMUNA BASIN
(Reproduced from Rangachari, 1986)

iii. To select the most appropriate forecasting method and

iv. To determine the most appropriate model parameter.

The numerical criteria evolved by the WMO during the project on 'Intercomparison of conceptual Models used in Hydrological Forecasting WMO(1975) are given below:

i. Y, coefficient of variation of the residual error,

$$Y = \frac{\left(\frac{\Sigma(Y_o - Y_f)^2}{n}\right)^{1/2}}{\bar{Y}_o}$$

ii. R, ratio of relative error to the mean,

$$R = \frac{\Sigma\ (Y_o - Y_f)}{n\ \bar{Y}_o}$$

iii. A, ratio of absolute error to the mean

$$A = \frac{\Sigma\ |Y_o - Y_f|}{n\ \bar{Y}_o}$$

CWC(1980) gives the following criteria for forecast verification.

i. Relative error i.e.

$R = \Sigma\ Yo - Y_f$

ii. Absolute error, i.e.

$A = \Sigma |\ Y_o - Y_f\ |$

iii. Variance i.e.

$$\text{Variance} = \frac{\Sigma\,(Y_o - Y_f)^2}{n}$$

where

Y_f = Forecast value,

Y_o = Observed value,

n = number of observations.

When two or more methods of forecasting are to be compared or the parameters of a particular method are to be optimized, then it may be very easily done by evaluating the measure of efficiency R^2 given by

$$R^2 = 1 - \frac{F^2}{Fd^2}$$

where, $F^2 = (Y_o - Y_f)^2$

$$F_d^2 = (Y_o - \bar{Y}_o)^2$$

Y_o = mean of the observed values.

It further suggests that forecast effectiveness should be evaluated by

$$E = \frac{1 - (Y_o - Y_f)^2}{(Y_o - Y_n)^2}$$

where,

Y_o = Actual observed level at $(N+T)^{th}$ hour,

Y_f = Forecast level at $(N+T)^{th}$ hour,

Y_n = N^{th} hour level on the basis of which the forecast has been formulated.

Closer the value of E to 1, higher is the effectiveness of forecast. While judging the effectiveness of forecast, the warning time or forecast time should be given due weightage.

3.0 FINAL REMARKS

A review on flood forecasting models has been presented. For conceptual models, only application of these models for Indian rivers and two typical river forecasting system which make use of these models are prescribed. Hardware requirement of different models and the flood forecasting systems of remaining rivers are not covered in the review note. A separate review may be required to cover all these aspects.

The models that make use of equation of continuity, energy and momentum and result in a system of partial differential equations which are solved numerically at all points on a three dimensional grid representation of a catchment are still in development stage. Because of enormous requirement of computation time and storage such models have limited use in flood forecasting.

The review of literature reveals that models based on unit hydrograph and ARMAX type models are very simple to use and have shown good potential for online flood forecasting. The suitability of these models should be tested on broader data base.

Studies are needed to develop criteria for choice of various models in different hydrometeorological conditions and to link forecasting models and decision models. Various conceptual models available should be implemented and tested on flood data of Indian rivers. Applicability of these models should be checked on the basis of criteria given by WMO(1975).

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APPENDIX -I

SALIENT FEATURE OF FLOOD FORECASTING ORGANISATION C.W.C.

(JANUARY, 1986)

1. Establishment of First Scientific Flood Forecasting Unit (F.F.U.Delhi)	November, 1958
2. Date of issue of 'first flood forecast'.	25th July,
3. Name of first forecasting site/river	Delhi Railway Bridge/Yamuna
4. Year of commencement of flood forecasting system on the Inter-state rivers	1969
5. No of Chief Engineers' offices	2
6. No of Superintending Engineers' office including one P & D (Flood Forecasting) Circle, New Delhi	8
7. No of present Flood Forecasting Divisions, excluding Snow Hydrology Division and also other divisions which are engaged in Hydrological observations only	22
8. No. of Control Rooms/Sub-divisions engaged in flood forecasting work under above division.	64
9. No of Inter-State rivers(Main/Tributaries) covered by flood forecasting programme	59
10. No. of States including Union Territories covered under F.F. programme	12
11. No of forecasting sites	145
12. No. of gauge/gauge and discharge sites	380
13. No of rain gauge stations(ordinary/self recording)	500
14. No. of wireless stations	402
15. Maximum no. of forecasts issued in any one year	7385(In 1978)
16. Seventh Five Year Plan outlay	1,000 lakhs (For 1986-90)
Non-Plan	586 lakhs(per year)