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REVIEW OF METHODOLOGY FOR LOWFLOW FORECASTING

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PREFACE

The availability of water resources is highly variable both in space and time. This aspect is more pronounced in tropical countries. Obviously, it is very much essential to have a sound knowledge and the understanding of the riverflow and their characteristics. In particular, the availability of riverflow during the lean period or the non monsoon period is of vital importance for the planning of a water resources development project.

The quality of the environment often depends on the avialbaility of the low river flows particularly in the areas of urban living or on the problems of public health as well as for thermal or chemical pollution and salinity problems.

The importance of lowflow forecasting is being increasingly felt for efficient management of the existing water resources projects and for the optimal planning for the future projects.

In the recent years, considerable work has been done in the field of lowflow modelling and forecasting. In this report, an attempt has been made to critically review the various techniques for lowflow modelling and forecasting with a view to identify the most suitable approach to be adopted for Indian river system.

This report entitled "Review of Methodology for Lowflow Forecasting" is a part of the work programme of Hydrologic Design Division of the Institute. The study has been carried out by Shri M. E. Haque & Shri Rakesh Kumar Scientists and Shri Mathew K.Jose, Sr.Research Assistant.

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ABSTRACT

In order to develop agriculture based economy and to meet the demands of growing population; in terms of irrigation, drinking water, hydropower generation and industrial use etc.a sound knowledge of the water availability and its time distribution is is essential .In particular,the flows during the non-monsoon months,commonly known as lowflows play very vital role in the over all development.Lowflow modelling is also necessary for dealing with problems of environmental impact evaluation and stream pollution.The availability of lowflows is highly variable both within the year as well as over the years and the importance of lowflow forecasting is being increasingly felt for proper regulation of the existing water resources projects as well as for the optimal planning of the future projects

Considerable work has been carried out in recent years for the analysis of the characteristics of the lowflows and development of suitable models to represent these characteristics. A number of models for real time forecasting of the riverflows including the lowflows have also been recommended in recent times.

In this report, an attempt has been made to review the various studies related to lowflow forecastingand briefly describe some of the important models with special reference to their suitability for Indian Conditions.

CHAPTER-I

INTRODUCTION

The average annual surface runoff from the various river basins of our country is assessed to be about 188 million ha m.But about 85% of the annual runoff is generated during the monsoon period of about four months only. As there is no adequate provision for storage, a considerable portion of the runoff goes waste. Further, the availability of flow is highly variable both in space and time. For example, the western regions of India receives less than 10 cms and Cherapunji in the east recives over 1000 cms per year. Similarly the ratio of Maximum and minimum discharges at a particular site is found to be more then 5000 in some of the perennial rivers of coastal regions. Even the variations in flows during the non monsoon months are quite considerable. The above features lead to occurrence of flood-drought-flood syndrome in various parts of the country.

There is no clearly defined term "Low Flow" as such. Theoretically, whenever the river flow or the water level in the river is below a specific discharge or critical water level, the flows are called low flows. This is irrespective of the time of occurrence of such phenomenon. However, for all practical purposes, for Indian river basins, the term low flow applies to the flows in river during the non-monsoon period or during the lean season irrespective of the discharge rate during this period.

Assessment of river flow during non-monsoon months along with its time distribution is essential for planning and development of water resources and related schemes. In addition to this, low flow modelling is also necessary for dealing with the problems of environmental evaluation and stream pollution. The analysis of low flows is equally important for Municipal and Industrial water supply schemes, both from the view points of quantity as well as quality.

Besides,efficient management of existing projects and optimal planning of the future projects attach great importance to low flow modelling and forecasting. Forecasting is concerned with predicting at some level of confidence the lowflow state of a river in terms of stage or discharge at some specific time in the future conditional upon the present state. After prediction the forecast is then used for example to operate a hydraulic structure along the river or to allow withdrawal of water from the river. Depending upon subsequent hydrologic conditions, an amended forecast may be issued at a later date.

In India, the Riverflow Forecasting generally refers to either Flood Forecasting or the Inflow Forecast to the Reservoir. But the river flow forecast covers the domains of low flow forecasts, the water quality forecasts, the forecast for the hydrological effects of the man-made changes in the river catchments. However, in India the organised forecast operation is generally limited to flood forecasts and inflow forecast to a few reservoirs. Recently the lowflow forecast model have been developed for a few sites in India and the forecasts are being formulated. In view of increasing importance of the forecasts for various purposes, the advanced countries are extensively using the river flow forecast services.

A survey of forecasting system in Europe carried out by WMO has revealed as follows :

A. The various purposes of flow forecast were

1.	Flood Protection	43%
2.	Energy	19%
3.	Navigation	12%
4.	Water supply & sanitation	12%
5.	Irrigation	6%
6.	Water pollution control	4%
7.	Ice problems	4%

B. The elements to be forecast were

1.	Surface water level	42%
2.	Discharge	36%
3.	Volume of runoff	21%
4.	Ice, groundwater, water quality	Seldom

C. The Forecasting periods were

1.	Upto 24 hours	33.5%
2.	1 day to 1 week	37.5%
3.	Medium Term	15%
4.	Long term	14%

Thus it may be observed that the most commonly used forecast in European countries also are the flood forecast of water level for a period between 24 hours to about one week.

However, the importance of forecast of other elements and for other purposes is beding increasingly felt and considerable work is being carried out in many countries.

In this report an attempt has been made to review the various literature available on the low flow analysis & forecasting, particularly those dealing with the problems of India, with a view to prepare a concise reference on the subject.

1.1 Importance and Need for Low flow Studies

At onset it is required to make a very clear distinction between flood forecast and low flow forecast. The term "flood forecast" gives a general impression that these forecasts are related to operations required to avoid or reduce the possible damages as a result of incoming floods. Obviously the flood forecasts are issued only when the river stage is above a certain level, known as the warning level, beyond which the river flow may cause miseries to people residing in the flood plains. On the other hand, "low flow forecasts" refer to the forecasts of river flow when the discharge the water level of a river is below a specific discharge or critical water level. In India, for major part of the country, the rainy season, commonly known as the monsoon season or non-rainy season are very clearly defined and for all practical purposes the forecast of the flow or the stage of the river during the non-monsoon period may be termed as low flow forecast. The role of lowflow forecast becomes quite significant during the drought period when the water level is considerably depleted. The major objectives of the low flow forecast are :

(1) Optimum utilization of scarce water resources;
(2) Deciding priorities in respect of various uses of water;
(3) Assessment and evaluation of drought conditions and forecast for the possible drought situations;
(4) Improvements in the operation policies for the water resources projects;
(5) Solution of water sharing problems in respect of International and Interstate rivers; and
(6) Pollution control and other environmental studies.

The importance and need of detailed and thorough analysis of lowflow is felt frequently as the water requirement is increasing with increase in population and related developmental activities. The availability of water resources, particularly during the non-monsoon period generallyremains unaltered. As a matter of fact, some of the studiesindicate a gradual reduction in the availability of water during the non-monsoon period due to various factors such as deforestation and urbanisations etc.

The cost effective reliable operation of watershed systems requires real time forecasts of river flows. Low flow forecasts are formulated round the year to plan or modify operating procedures keeping in view the available storage and the water use comprising hydel power generation, domestic water supply etc. Low flow forecasts are very much needed in planning seasonal utilization of water and periodic regulation schedule to match the plan of utilization. When the forecasting is extended to cover river flow throughout the year, it provides useful information for reservoir operations.

While hydrological data and their statistical analysis play very significant role in the planning of water resources projects; the low flow forecasts are necessary for efficient operation of these projects. The use of observed historic data serves to provide possible range and probable situations. Such exercises have got relevance in evaluating the economic viability of a project and formulating guidelines for reservoir operations regarding conservation purposes.

Low flow in natural rivers is qualitatively indicated by a low water level. Low flow periods in rivers are significant for various aspects of economy and ecology. The quantitative aspects include water supply for domestic, industrial and agricultural purposes, hydroelectric power generation and navigation. Chemistry and biology of the water courses and ecosystems constitute the qualitative aspects.

Timely evaluation and forecasting of flows greatly helpin decision making processes on appropriate water uses. Both the demand for information concerning low flow and the need for a given accuracy of prediction may vary from case to case. It is desirable to have a prior knowledge of the amount of water available that could be drawn from reservoirs for various purposes in several months ahead, particularly for drought prone regions.

The fields of application of low flow studies and forecasting are manifold. Some of them are :

(a) Domestic water supply;
(b) Irrigation;
(c) Hydro-power generation;
(d) Navigation;
(e) Industrial purposes ;
(f) Reservoir operation ;
(g) Ecosystems ;
(h) Water quality management;
(i) Pollution control;
(j) Urban water treatment systems;
(k) Recharge of ground water aquifer;
(l) Drought management; and
(m) In-stream flow maintenance.

The wide range of application further stresses the necessity and need for elaborate low flow studies.

1.2 Low flow Modelling and Forecasting - Applications and Limitations

Planning and control of water resources systems are of vital importance in practical applicability .Inflow forecasts are major pre-requisite for all application purposes. Seasonal stream flow models and forecasts are developed and utilized to serve the purpose.

Utility of forecasts is dependant on the timeliness and accuracy. Hence an adequate data network as well as dissemination facilities are very much desired in flow forecasting processes. The data network includes hydrological and hydrometeorological observations on the basis of an optimal design of such stations.

A hydrological forecast has got six main characteristics:

(a) The forecast variable;
(b) Forecast period or lead time;
(c) Computation methods;
(d) Purpose of forecast;
(e) The form of presentation, like single expected value, total hydrograph, probability distribution etc; and
(f) The desired degree of accuracy for the forecast.

Low flow forecasts are generally based on the following principles:

- presence of a relationships between the river and its associated groundwater storages;
- effect of the preceding hydrometeorological conditions upon the river discharge at the time under consideration;
- availability of stored water from natural storage on and below the ground surface for low flow replenishment.

In addition, the effects of existing regulatory structures are also to be given due consideration.

However, in case of larger river systems, it becomes very difficult to seperate out the contributions from various sources. Many a times, the contributions from snowmelt, groundwater reservoirs, irrigation recharge etc. cannot be estimated precisely. It gets further complicated, where major regulatory structures exist. In view of above, a suitable statistical method may be convenently adopted with very encouraging results. However, due care must be taken to separate out the effects of regulatory structures. Similarly the effects of local factors such as short duration and/or localised intense rainfall are also to be given due considerations.

The hydrological modelling techniques are mathematical simulation of natural hydrological phenomena which are considered as processes or systems undergoing continuous changes in time. These models are broadly classified into two categories viz; the deterministic models and the probablistic models based on the concept of certainty and probability criteria respectively.

The representation of the physical processes involved in the formation & propagation of the river flow is possible only when real time information about precipitation, evaporation, snow melt and detaialed basin and channel characteristics etc. are available. This can be definitely achieved with modern developments in instrumentation and computing technology. In mathematical models, simulation of processes with certain amount of conceptualization, has been brought down to computational procedures. Such models require extensive data sets for calibration of various parameters, validation and for operational use at a later stage.

A number of hydrological models are available and are in use. The effectiveness of a model lies in the degree of extent to which the model simulates the natural processes. Generally, the hydrologic systems are so complex that no exact physical laws have yet been formulated to explain completely and precisely the natural development of a phenomenon.

Simulation by stochastic hydrologic system allows the uncertainty factor of the hydrological processes whereas in parametric (deterministic) approach, the chance of occurrence of the variables involved in a phenomenon is ignored and the model is considered to follow a definite law of certainty.

The problems of analysis of deterministic hydrologic system include the problem of predicting an unknown output, the problem of identifying an unknown system operation and the problem of determining an unknown input. The problem of predictions is simple while the problem of finding the response of an unknown system is complicated. In reality, all hydrological systems are nonlinear,stochastic and time variant processes.

The effectiveness of a forecasting technique may be evaluated using certain measures. The accuracy of the forecast is the most important one. The accuracy is determined by analyzing forecast errors. In statistical forecasting methods, the 'forecast error' is considered as a random variable. A forecast is said to be unbiased when the mean of errors is zero.

Updating procedures are to be adopted for more accuracy. Also due importance is to be given in designing appropriate data communications, operations and processing system. In short, the accuracy and timeliness of a forecast depend on the amount and reliability of hydrological and meteorological information, the procedure on which the forecasts are based, speed of processing, and the time taken to disseminate the forecast to the users.

The decision making task is conceptually related to the forecast by the expressions:

Actual Decisions = A + B

Where; A is generally represented by a deterministic model and B is for the random component.

Therefore any forecasting technique should provide a description of forecast error as well as a forecast. Unfortunately this can not be attained always, as the mathematical expressions representing complexity of various hydrological processes, involve problems arising out of the complex interaction processes in space and time.

Low flow periods in the summer season are more frequent. In India, precisely, the non-monsoon periods account mainly for the low flow seasons. Since the Indian monsoon season is for the period from June to October, the low flow period may be considered from November to May for major part of the country. Evapotranspirations and ground water recharges are to be estimated for the purpose of low flow analysis.

Though lowflow is primarily dependant on natural parameters, man made effects can also influence the situation in one or the other way. The storage of water in storage basins can cause low flow, while release of water from reservoirs can increase the discharge. Water use in power plants and irrigation areas are enormous and an considerable part of the water extracted from the system evaporates. The direct withdrawals like pumping from wells near the river causes underground infiltration of surface water and the prevention of the flow of ground water into the river. All the above facts are to be kept in view while formulating low flow models and forecasts.

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CHAPTER -II

LITERATURE REVIEW

2.1 Definitions

Hydrological forecast may be defined as the prior estimate of the future state of hydrological phenomena. This can be achieved, based on the knowledge of their underlying physical laws and the modifying effects of specific geographical conditions. (WMO, 1974).

River forecasting provides advance information about the water level and/or discharges of the river at selected points during all stages of the river flow (Kraijonhoff, 1986).

Flood forecasting is the prediction of stage, and/or discharge,and the time of its occurrence and duration of a flood, at a specified point on a stream, resulting from precipitation and/or snow melt. Whenever the water level is above a specific value generally known as warning level. The most important aspect of flood forecasting is the forecast of peak and its time of occurrence.

Lowflow in natural streams may be qualitatively indicated by a low water level. This low water level is obvious. The quantitative relation between water level and discharge can only be revealed by measurement (Kraijonhoff, 1986). Theoretically, whenever the river flow or the water level in the river is below a specific discharge or critical water level, the flows are called low flows. This is irrespective of the time of occurrence of such phenomenon. However, for all practical purposes, for Indian river basin, the term low flow applies to the flows in river during the non-monsoon period or during the lean season irrespective of the discharge during this period.

The warning time may be defined as the basic unit time for which the forecasts are made; for example, the warning time for flood forecasts in larger river may be of the order of 2 days. Where as, for a small flashy river this time may be only about 4 to 6 hours. The warning time in case of low flow forecast may be of the order of 1 month to 6 months.

The forecasting period is the basic unit time for which the forecasts are made, for example we may be interested in forecast of average flow of each 10 day period during non-monsoon season. On the other hand our main concern is hourly forecast during the flood season. Thus in this case, the forecasting period is 10 days for the low flow forecast and one hour for the flood forecast.

The forecasting interval is the frequency with which new forecasts are prepared. Often, the forecasting interval is the same as the forecasting period, so that the forecasts are revised after each period using the most recent period's actual inflow and other current information as the basis for revision.

The lead time or forecasting horizon is the number of periods in the future covered by the forecast. For example, if we require the forecasts next 6 months, broken down by month. The forecast period is a month and the forecast horizon or lead time is 6 months.

Forecast error is the difference between actual observed flow and the forecasted flow for a particular period. For example, if the actual stream flow in a season t is x_t, while the forecast for that season made at same prior time is $\hat{x}_t$, then, the forecast error for the season t is:

$$e_t = x_t - \hat{x}_t \qquad \ldots. (1)$$

In statistical forecasting methods, this error is considered as a random variable. The forecasting method is unbiased if the mean (or expected value) of e_t is zero. According to this criterion, forecast values larger than actual values are to be compensated by forecast values which are smaller than the actual ones. Clearly this is a desirable criterion. However, it is more important that large forecast errors should not be frequently experienced. Hence a quantity such as the mean absolute deviation (MAD).

$$\text{MAD} = E\,[\,|\,e_t\,|\,] = E[\,|\,x_t - \hat{x}_t\,|\,] \qquad \ldots(2)$$

or the mean squared error (MSE)

$$\text{MSE} = E\,[e_t^2] = E\,[(x_t - \hat{x}_t)^2] \qquad \ldots(3)$$

is commonly used as a measure of forecast accuracy. In eqs. 2 and 3, the expected operator E is used. In practical situations, when n forecasts ($x_1, x_2 \ldots, x_n$) are made, the mean absolute deviation and mean squared error are computed as follows.

$$\text{MAD} = \frac{1}{n} \sum_{t=1}^{n} |\,x_t - \hat{x}_t\,| \qquad \ldots(4)$$

$$\text{MSE} = \frac{1}{n} \sum_{t=1}^{n} (\,x_t - \hat{x}_t)^{2} \qquad \ldots(5)$$

Among different forecasting methods, the one which gives the smallest value of MAD or MSE is frequently considered the best.

Input-output or black box models identify a relationship betwee the input and output without attempting to describe the transofmation processes. In other words a black box model is developed without any consideration of the physical processes in the catchment. The model is merely based on analyses of concurrent input and output time series.

A statistical models is based on the approach involving functional relationships between various measured data. Statistical methods in hydrology have been developed extensively with support from basic statistical theory developed and applied in other fields.

A stochastic model has some component of random character, having a distribution in probability through time. Identical inputs may result in different outputs if the same is run through the model under identical conditions.

A deterministic model is one in which no uncertainties in prediction are admitted, so that two equal sets of input always yield the same output if run through the model under identical conditions. The model has no component with stochastic behaviour, i.e. the variables are free from random variation and have no distribution in probability.

A conceptual model is based on some consideration of the physical processes in the catchment. In a conceptual model, physically sound structures and equations are used together with semi-empirical ones. However, the physical significance is not so clear that the parameters can be assessed from direct measurements. Instead, it is necessary to estimate the parameters from calibration, applying concurrent input and output time series. A conceptual model, which is usually a lumped type model, is often called a grey box model.

A lumped model is a model where the catchment is regarded as one unit. The inputs, variables and parameters represent average values for the entire catchment.

A fully physically based distributed model describes the system using the basic equations governing the flows of energy and water in the catchment. A fully physically based model in practice also has to be a fully distributed model which takes into account the spatial variations in all variables and parameters.

2.2 An Overview of Lowflow Analysis and Forecasting Techniques:

In low flow analysis hydrologists are concerned with three main characteristics, namely (UNESCO, 1982).

1. the magnitude of low flow,
2. the duration of low flow, and
3. the frequency of occurrence of low flow.

The magnitude of low flow is the quantity of water flowing through a given section of stream for a specified period of time and it determines the amount of water available for use. The duration depends on natural conditions as well as man-made effects and may reflect some specified water use practices (for example, irrigation cycles). The duration also depends on period of water difict tolerable to the user or some other requirements. The frequency occurrence of low flow reflects the risk of failure of a water supply scheme.

For low flow studies, therefore, data are normally specied in terms of the magnitude of flow for a given period of time (the duration) within a year or a season. The given period of time is usually taken as 1 day, 7 days, 10 days or 30 days. Other periods of time may also be used. One day flows are used as data in flow duration analyses while periods upto one year or longer are required for some storage-yield studies. For other studies, 7-days or 10-days flow are employed.

The techniques used for low flow forecasting depend upon a number of factors. such as:

a) The major source of low flows i.e. whether the dominating facter is the snowmelt, the groundwater contribution or the rain during the non-monsoon period;

b) The extent of extractions either through major reservoirs, diversion projects or from medium projects; and

c) Major changes in landuse and vegetal cover of the basin. (In case of snow fed rivers, the overall changes in the snow covered areas are also to be taken into account.)

In case of major rivers of India, the flows during the lean period are generally due to ground water, sub-surface flow and/or snowmelt contribution. The effect of rainfall during the lean period is generally very nominal. However, the abstractions in many cases are quite considerable and are required to be taken into account. In view of well defined monsoon season, appropriate models can be developed for low flow forecasting of different basins with varying lead time. However it is necessary to identify the various factors which in one way or the other affect the lowflows in a river.

2.3 Factors Affecting Lowflows

The regime and discharge during a lowflow period are affected by many factors. With present knowledge, the effects of majority of these factors can not be differentiated as a rule, since the laws governing them have not been adequately elucidated and their magnitudes are not, in general, known. From a practical point of view, these factors can be grouped together in two main categories: climatic and azonal. Climatological factors are often more important than basin characteristics. However the influence of man's activity on the catchment, and hence on lowflow, is of enormous importance.

The factors affecting lowflows as described by McMahon and Arenas (UNESCO, 1982).

2.3.1 Natural Factors

The first category which is related to the generation of flow determines directly the minimum discharge. The major factor is precipitation. This is the principal source of surface flows and groundwater. Groundwater, of course, depends upon the surface flows and determines the low flow in the absence of precipitation over a prolonged period. The second group of factors affects the regime and discharge of lowflow through temporal and spatial reduction or distribution of precipitation. These are called indirect factors and include all those that do not directly contribute to the formation of the lowflow but affect the variation of its rate. This category includes: evaporation losses, type of soil and plant cover, relief, number of lakes and swamps and hydrogeological characteristics of the basin. The third category is composed of factors that determine the relationship between river discharges and the subsequent impact of the direct and indirect factors described above. This category includes factors that are most frequently used for practical computation purposes and comprises the azonal characteristics of the basin, such as: area, mean altitude, slope, drainage density etc. and the characteristics of flow such as: annual runoff, annual groundwater flow to river, self-regulation of streamflow etc. The various important factors are briefly described hereunder.

a) Climatic Factors

i) Precipitation

Precipitation forms the source of all water occurring as river flow. During lowflow rivers are fed essentially from water contained below the ground surface. This storage is repleted by precipitation that occurred prior to the period in which the surface flow has substantially diminished or ceased altogether.

The effect of precipitation on streamflow can be directly observed in the basin's discharge characteristics. For example, natural characteristics of the basin such as: topography, soil vegetation characteristics, hydrogeology etc. determine the time it takes for saturated flow to reappear in the form of surface runoff. This may range from a short time in case of a small karst basin to a month or considerably longer in other types of basins. Another important factor affecting lowflows is the intensity of rainfall. Precipitation as snow contributes directly to formation of runoff only at the time of thaw, in case of snowfed basins. This process begins in spring and continues throughout summer and sometimes extends to the following autumn or winter.

ii) Evaporation

Evaporation is an extremely important factor in the hydrological cycle, since it largely determines the river discharge and reduces the flow during lowflow periods. The effect of evaporation is the most significant at the beginning of summer, when a large mass of water returns from the surface soil and from open water bodies to the atmosphere. In regions where the rate of evaporation cannot be compensated by a higher rate of rainfall, an appreciable reduction in river discharge occurs. However, during lowflow periods, when rivers are fed almost exclusively by groundwater, evaporation is practically insignificant. The amount of evaporation depends mainly on solar radiation, temperature of air and water and of surface soil water, humidity, vapour pressure, wind velocity and quality of water etc.

iii) Air and Soil Temperature

Air and soil temperatures affect the total runoff by influencing other climatic factors, especially evaporation and rainfall. Also air temperature affects the flow distribution through freezing. Thus it is one of the principal regulatory elements in temperate and cold countries through temporary retention of water within the soil in the form of snow and ice. During the winter season, the influence of air temperature upon minimum discharge is the largest.

iv) Humidity and Wind

Humidity and wind affect the total runoff of streams and influence other climatic factors, particularly precipitation and evaporation. Evaporation is closely related to air moisture deficit, and any increase therein causes an increase in evaporation, which in turn reduces soil moisture and possible ground recharge. Air moisture deficit plays an important role only in dry regions. In some countries, the persistance of particular winds significantly affects rainfall and hence lowflow period. Wind also affects the distribution of flow of rivers fed by large lakes. The quantity of water flowing into a river from a lake will vary with wind speed and direction.

b) Hydrogeological Factors

i) Geology of basin

Geology of any catchment is one of the major factors influencing lowflows. Areas where surface geology includes unconsolidated sands and gravels produce a sustained flow during periods of drought which constrasts to these streams in which surface formations consist of unfractured igneous rocks, clays and shales. In crystallized rocks where little fissuring has occurred, there is little groundwater flow. For two adjacent basins with the same meteorological conditions, the basin underlain by the more impervious formations will have lower discharges during lowflow periods. The influence of karst on lowflow is very significant in small basins.

ii) Hydrogeological regime

The type of soil and its composition largely determine the basin absorption capacity. For soils with large effective porosity*, soil retention is low but water yield and permeability are high. This explains the great dissimilarity in the behaviour of rivers in sandy or loam areas compared with those that are located in clay regions. With greater infiltrtion capacity, the water is able to penetrate further into the sandy soils. Consequently, there is a very clear dependence of lowflow on infiltration. Basins with friable, porous or fissured rock are most favourably placed for groundwater storage, which subsequently contribute baseflow to the river during lowflow periods.

iii) Ground water

Groundwater is the main source of lowflow. It is available in the form of contribution as artesian groundwater and as phreatic water. The volume of groundwater dpends basically on the climate of the region, geological structure and hydrogeological conditions of the basin. During the lowflow period, the groundwater regime is characterised by a gradual reduction of seasonal reserves. As these diminish, the velocity of flow and hence the groundwater discharge decreases. In addition to the volume of groundwater storage, the transmissivity of an aquifer also affects groundwater discharge and hence river flow.

Phreatic Water

Phreatic water is found in the active zone of groundwater storage, that is, in the shallower sub soil layers. It seeps to the river sytem and constitutes the main source of river replenishment during the lowflow period. This may involve one or more water bearing sediments. The regime of deep phreatic aquifers is more steady, since they are fed by deep percolation. Where phreatic water is in direct contact with surface water bodies of the basin, such as lakes and reservoirs, it has a marked influence on the discharge and runoff regime during the lowflow period.

Water is Unconsolidated Sediment

From the point of view of river flow, alluvial groundwater is very important. Here the water occurring in permeable formations, is generally discharged over large areas, although in some places it may take the form of concentrated outflows. This type of groundwater is characteristics of large river vallyes.

Crack or fissure water

Crack or fissure water is formed in massive igneous rocks and in highly metamorphosed sedimentry rocks where water accumulates and circulates in fissures. It is of great importance in small and mountain rivers as well as in the middle reaches of valley rivers. In karstic regions concentrated outflows of groundwater predominate.

Artesian water

Artesian water is not subject to sudden changes in time and represents an important supply source for base flow. This water, confined under pressure between impervious layers or in fissures in the earth's crust, is found in horizons that are deeper than those where phreatic water is located. In small sectors of a basin, it can rise as a spring yielding a considerable amount of water. Nevertheless, during times of minimum flow of the majority of rivers its contribution is slight.

Karstic water

Karstic ground water varies considerably depending, among other factors, on its relation with the surface, the development of fissures and internal galleries and the storage capacity of the host rock.

Karstic water is important constituent of river base flow during lowflow periods in years of little precipitation. In basins where karst is well developed, it works as a natural regulator, maintaining a relatively a high stable flow during the lowflow season. In some areas, however, instead of contributing to surface runoff, it may cause the loss of part of the flow, and in small basins the total disappearance of the streamflow through sink holes or fissures may occur. Karstic water exhibits greater influence in small basins.

Permafrost groundwater

In cold regions river flow may also be affected by formation of ice in permafrost zones. In such a case underground flow is transformed into ice which, on thawing during the warm season, flows into the stream.

c) Morphological factors

Morphological factors such as : relief of basin, presence of lakes, swamps, and plant cover influence the flows during lowflow period. Variations in altitude over a basin produce variations in precipitation. Lakes and other water bodies modify river flow and have an stablising effect on discharge.Lakes that are located close to the outlet yield greater specific basin discharge than those situated farther away.

The vegetation of a basin affects riverflow mainly through transpiration of water stored in the ground. This effect reduces the runoff. Further, vegetation increases soil storage and permeability by its roots breaking up the soil. Also, a surface layer of dead leaves and humus has high infiltration capacity and retards overland flow and promotes infiltration. Crop with shallow roots rapidly exhaust water in upper soil layers. Also some plants extract moisture from deeper zones. In both cases, water is transpired that would otherwise contribute to lowflow.

d) Morphometrical factors

Morphometrical factors such as: basin area, altitude, slope, orientation, drainage density and channel embedment also affect the lowflows. Studies have shown that for most of rivers there is a direct relation between basin area and minimum discharge during lowflow periods. The surface of the basin constitutes the catchment area for precipitation. Generally, rainfall increases with altitude, thus creating more favourable conditions for groundwater recharge. In some areas, where altitude exceeds a certain limit, precipitation occurs as snow, basin slopes are steeper, rock are more impervious and therefore lowflow is much lower than in basin lying at lower altitudes. Slope of the basin affects mainly the quantity of infiltration and the rate of overland flow. Basins with steeper slopes allow less time for infiltration, and the supply of groundwater is therefore reduced. The drainage system is directly related to efficiency of water removal. The greater the basin area and more highly developed its channel system, the greater will be probability that surface water derived from rainfall will contribute to flow during lowflow periods. Increased embedment of the channel throughout a river course may tap deeper water bearing horizons and thereby the yield of groundwater basin to streamflow increases.

2.3.2 Factors Due to Human Activity

The influence of man's activity on the regime and discharge of lowflows of a river varies in nature and intensity, according to the level of development, type of economic activity involved, climatic conditions governing the basin and hydrological regime of the river. The various factors as a result of human activity such as : urbanisation, irrigation, hydraulic works, water transfer schemes, hydro-electric stations, mining, navigation, treatment of urban and industrial effluents, drainage works and landuse changes etc. influence the flows during lean season.

Large cities and industries exert a significant influence on lowflows downstream of water intakes or effluent outfalls. With urbanisation and increase in population densities, residential and commercial buildings etc., impervious area increases and hydrological regime get significantly changed. Irrigation consumes a large amount of water. The influence of irrigation is greater in years of low rainfall than those of high rainfall because irrigation demands are higher and water applications are more frequent. Irrigation water is supplied from rivers, reservoirs and wells. Whatever be the method, it results in a substantial increase in both evapotranspiration from fields and evaporation from the distribution system, hence reducing the outflow from a basin. The hydraulic works modify the lowflows, but their effect varies according to the purpose of works and degree of regulation. For example, the use of hydraulic works for controlling urban water supply also results in reduction of lowflow. The use of dams for -purposes of power generation generally causes an increase in lowflows.

River navigation requires the regulation of flows so that an adequate depth of water is available to allow the navigation. When natural flows are inadequate, water stored upstream is released. In this way, flows during lean season get increased. A significant change in landuse alters the regime and discharge of the river draining the basin. In various tropical regions deforestation has led to a reduction of lowflows and in some cases to the cessation of flow altogether. In respect of landuse changes, lowflow depends on a balance between infiltration which is affected by plant cover and losses through transpiration.

2.4 Methods for Lowflow Forecasting

The conventional methods make use of statistical techniques in the analysis of the data. The formulations may be represented either graphically or mathematically. The most commonly used method is based on the relation between the present state of the river and the past state of the river at the same site. In some case, the upstream sites or the sites on the tributary are also taken into consideration. A direct relation between gauges or discharges of upstream station with down stream station can also be established, but on many occasions such gauge to gauge correlation would not yield suitable results due to the effect of additional parameters such as intermediate catchment rainfall, the contributions from major tributories and variations in the soil moisture conditions. In direct correlation method, generally the gauge and discharge data of forecasting stations and base stations only are utilised in different forms. However this method is not as effective in case of lowflow forecast as that for the flood forecasts.

Regression analysis is widely used for development of such relationships. There are many forms in which this statistical technique is used. In the simplest form, the forecasting variable is expressed as a simple function of time. But for practical purposes, seasonal stream flow should be expressed as a function of several explanatory variables. The basic relation is written as:

$$Q_{t+k} = f\ (I_{i,t}) \qquad \ldots(6)$$

where,

k = lead time

$I_{i,t}$ = the explanatory variables describing the state of the basin at time t.

One form of such equations often used is:

$$Q_{t+k} = f\ (Q_{(t-j*k)}) \qquad \ldots(7)$$

where j has values 0, 1, 2, 3 etc.

Q_{t+k} is the forecast of the discharge of the river k days ahead

Some other commonly used methods based on Regression Analysis are briefly described below.

Phase Regression

Hino (1977) applied this method called phase regression the Sagami-gawa river in Japan. For stream flow data, generally strong periodicities exist. Regression equations expressing the value in a season as a function of those in other seasons should be constructed for every phase of the cycle, for instance for every month in the case of monthly stream flows. It may be expressed as :

$$X_{i,j} = a_1(i)x_{i,j-1} + a_2(i)\ x_{i,j-2} + \ldots + a_{11}(i)\ x_{i,j-11} + a_{12}(j)x_{i-1,j} + e_{i,j} \qquad \ldots(8)$$

where the stream flow in month j is expressed as a linear function of 12 antecedent stream flows prior to this month at the same site.

Factor analysis

This method was applied to the stream flow data of the Sagami-gawa river in Japan by Hino (1977).

Let $Q_{i,j}$ denote the stream flow in the j^{th} season of ith year. These could be transformed into a sequence of normal flows $Y_{i,j}$ under some suitable transformation. The statistics mean ($\bar{Y}_j$) and variance (S_j^2) are defined and by standardization we get :

$$x_{i,j} = (Y_{i,j} - \bar{Y}_j) / s_j \qquad \ldots(9)$$

which forms a sequence of variables with mean=0 and variance = 1

Now, let x_i denote the row vector of seasonal stream flows in year i:

$$x_i = \{x_{i1}, x_{i2}, \ldots\ldots\ldots, x_{ip}\} \qquad \ldots(10)$$

where, p is the number of seasons in a year (p=12 fer monthly data).

This vector is considered to be explained by a hypothetical factor f_i whose components are independent of each other :

$$x_i = f_i F + e_i \qquad \ldots(11)$$

or $f_i = \{f_{i1}, \ldots\ldots\ldots\ldots, f_{iq}\}$

$$x_{i,j} = \sum_{k=1}^{q} f_{ik} F_{kj} + e_{ij} \qquad \ldots(12)$$

where the matrix F (the factor leading matrix) is constant irrespective of year i, and the vector f_i(vector of factor scores) varies from year to year. The K^{th} row vector of matrix F is

$$F_k = \{F_{k1}, \ldots\ldots\ldots, F_{kp}\} \qquad \ldots(13)$$

This may be considered to be the k^{th} fundamental pattern of stream flow.

The stream flow in a year is assumed to be determined by a weighted sum of the fundamental patterns with the weights being the factor scores. The weights are obtained in terms of streamflow by means of the equation:

$$f_i F = x_i$$

or ,

$$\sum_{k=1}^{q} f_{ik} F_{kj} = x_{i,j} \quad ; \; j = 1, \ldots, p \qquad \ldots(14)$$

If x_i^* denotes a subvector of x_i then

$$x_i^* = \{x_{i1}, \ldots\ldots, x_{im}\} \quad ; \text{ where } m < p \qquad \ldots(15)$$

The factor score vectors may be estimated from the following truncated relationship :

$$f_i F = x_i^* \qquad \ldots(16)$$

The remaining components of X_i can be estimated by

$$x_{ij} = \sum_{k=1}^{q} f_{ik} F_{kj} \quad ; \; m < j < p . \qquad \ldots(17)$$

Regression methods are very much in use for snow fed basins (Dyhr - Niles, 1982), where indices for snow cover, winter precipitation and radiation are of primary importance. The basic relation for this case may be represented by:

$$Q_J = A\, Q_M + B\, R_M + C\, T_M + D\, IA_M + E \qquad \ldots(18)$$

Where,

Q_J = forecast for runoff in a particular month say, June;
Q_M = runoff in antecedent months (e.g., May);
T_M = average temperature in May;
IA_M = irrigated area in May; and
R_M = rainfall in May.

A, B, C, D and E are constants to be derived with the help of historical data.

It is always desirable to develop the relationship based on the physical process involved in the lowflows generation. However many a times, it is not possible to very clearly identify the various factors responsible for the lowflow and it becomes necessary to use a stochastic models for generation & forecasting of such flows.

The operating characteristics of a stochastic model are expressed by probability functions. That is to say, the stochastic component consists of chance and chance dependant events due to the erratic behaviour of the parameters affecting a forecast. Such models consist of a deterministic part and an error term. Such models can be expressed by

$$Y_t = \phi_1 Y_{t-1} + \ldots\ldots + \phi_p Y_{t-p} + \theta_1 x_{t-1} + \ldots\ldots + \theta_q x_{t-q} + \varepsilon_t \qquad \ldots(19)$$

Where Y_t is the current state of variable (e.g. discharge) and is assumed to depend on the values of rainfall data x_{t-1}, $x_{t-2}, \ldots\ldots x_{q-2}$, the discharge data Y_{t-1}, $Y_{t-2}, \ldots\ldots Y_{t-p}$. and error term ε_t.

Some of the important stochastic methods which are recommended for forecasting are briefly discussed hereunder.

Box-Jenkins Method

Box and Jenkins (1970, 1976) proposed that a multiplicative Auto regressive Integrated Moving Average (ARIMA) model may be used for seasonal forecasting of time series.

Auto regressive models are extensively used for data generation. An autoregressive model is one in which the value of a variable is dependant on the variate values at antecedent time intervals. This is expressed as

$$\bar{Y}_t = \sum_{i=1}^{p} \phi_i Y_{t-i} + a_t \qquad \ldots(20)$$

where Y_t is the value of variable at time t and ϕ_i is, the auto regressive parameter for the i^{th} independent variable.

The moving average method expresses the variable as linearly dependent function of previous random shocks given by

$$Y_t = \sum_{j=1} \theta_j a_{t-j} + a_t \qquad \ldots(21)$$

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. The auto regressive as well as moving average models can be combined effectively to produce the model suggested by Box and Jenkins. Such models are capable of simulating the behaviour of complex systems in hydrology.

The mathematical formulations for this type is given by

$$Y_t = \sum_{i=1}^{p} \phi_i Y_{t-i} + \sum_{j=1}^{q} \theta_j a_{t-j} + a_t \qquad \ldots(22)$$

where p & q denote the extent of auto regressive and moving average schemes respectively.

Thomas Fiering Model

This model, proposed by Thomas and Fiering (1962), was intended for data generation purposes. However this model can be used for forecasting purposes also.

This model can be represented as :

$$x_{i,j+1} = r_{j+1} x_{i,j} + \left[1 - r^2_{j+1}\right]^{1/2} e_{j+1} \qquad \ldots(23)$$

where r_{j+1} is the correlation between flows in seasons j+1 and j and e_{j+1} is a variable with zero mean and unit variance. When the data in season j are not normally distributed, they should be rendered normal by some suitable transformations such as the logarithmic or square root transformations; so e_{j+1} may be assumed to be normally distributed. The forecast lead time equal to L is obtained as

$$X_{i,j+L} = r^L_{j+1} x_{i,j} \qquad \text{or}$$

$$\hat{Y}_{i,j+L} = \bar{Y}_{j+L} + s_{j+L} r^L_{j+1} x_{i,j} \qquad \ldots(24)$$

using the standardization formula.

For increasing values of L, the forecast value tends to the seasonal mean Y_{j+L} This model may be considered to be a special case of the phase regression method.

Rao-Kashyap Model

Rao and Kashyap (1973, 74) proposed a method to obtain multi lead stream flow forecasts. If $Q_{i,j}$ denotes the stream flow in month j of year i, then the model is expressed as :

$$\left.\begin{aligned} Q_{i,j} &= \sum_{k=1}^{m_1} a_k Q_{i,j-k} + U_j + V_{i,j} + \sum_{k=1}^{m_2} b_k V_{i,j-k} \\ &\qquad \text{for } i = 1,2,\ldots\ldots \\ &\qquad\qquad j = 1,2,\ldots.12 \end{aligned}\right\} \quad \ldots(25)$$

where

$$\left.\begin{aligned} Q_{i,j-k} &= Q_{i-1,\,12+j-k} \\ V_{i,j-k} &= V_{i-1,\,12+j-k} \end{aligned}\right\} \quad \text{if } j-k \leq 0 \qquad \ldots(26)$$

$$U_j = a_o + \sum_{k=1}^{m_3} \left[A_k \operatorname{Cos} \frac{2\pi kj}{12} + B_k \operatorname{Sin} \frac{2\pi kj}{12} \right] \ldots(27)$$

$$V_{i,j} = \Psi_j W_{i,j} \qquad \ldots(28)$$

$$\Psi_j = b_o + \sum_{k=1}^{m_4} \left[C_k \operatorname{Cos} \frac{2\pi kj}{12} + D_k \operatorname{Sin} \frac{2\pi kj}{12} \right] \qquad \ldots(29)$$

In these equations m_1, m_2, m_3, m_4 are the structural parameters and a_o, b_o, a_k, b_k, A_k, B_k, C_k, D_k are the model parameters. The random sequence $W_{i,j}$ is assumed to satisfy the following conditions:

$$E\,(W_{i,j}) = 0,\ V_{i,j}$$

$$\left.\begin{aligned} E\,(W_{i,j}, W_{i'j'}) &= \sigma^2\, \delta_{ii'}\, \delta_{jj'}\ V_{i,i',j,j'} \\ E\,(W_{i,j}\ Q_{i,j-k}) &= 0,\ V_{i,j}, \quad k > 0, \end{aligned}\right\} \qquad (30)$$

where σ is a constant and δ is the Knonecker delta function. The deterministic function U_j has a period of 12. It is used to reflect the annual variation of monthly means. The *noise term* V is used to account for the part of the flow which is *stochastic*. The multiplication factor ψ_j in eq. 29 also has a period 12 and is included to account for the annual variation of monthly standard deviations.

Let $l = 12(i-1) + j$, then eq. 30 can be rewritten as:

$$Y_l = \sum_{k=1}^{m_1} a_k y_{l-k} + U_j + V_l^* + \sum_{K=2}^{m_2} b_k V_{l-k}^* \tag{31}$$

where

$$Y_l = Q_{i,j} \tag{32}$$

$$V_l^* = V_{i,j} \tag{33}$$

For a given set of historical data, the structural parameters can be identified, and the model coefficients estimated. The multi-lead forecasts may then be made using the following recursion equation:

$$\hat{Y}_{n+L} = \sum_{k=1}^{m_1} a_k E\,[Y_{n+L+k} \mid n] + U_j \Big|_{n+L} \tag{34}$$

Fiering-Jackson Model

This model is a generalization of the Thomas Fiering model to incorporate the multi lag effect (Fiering and Jackson, 1971).

$$Q_{i,j} = \sum_{k=1}^{m_1} a_k Q_{i,j-k} + U_j + V_{i,j} \tag{35}$$

where m_1 is a function of i. This is quite similar to the phase regression model for which $m_1 = 12$.

When the historical data is short, estimation of large number of parameters may be difficult.

Roesner-Yevjevich Model

Roesner and Yevjevich (1966) discussed this model with the form :

$$X_{i,j} = (Q_{i,j} - U_j) / S_j \qquad (36)$$

$$X_{i,j} = \sum_{k=1}^{m_1} a_k X_{i,j-k} + W_{i,j} \qquad (37)$$

$$S_j = \sum_{k=1}^{m_2} \left[C_k \text{ Cos } \frac{2\pi k j}{12} + D_k \text{ sin } \frac{2\pi k j}{12} \right] \qquad (38)$$

where U_j is the same as in Rao-Kashyap model.

ARMAX Model

The Auto regressive moving average with exogenous inputs model (ARMAX) is a suitable model for representing the transformation between the input and output in many hydrological premises. It is stochastic model and can be used for adaptive hydrological forecasting using a number of adaptive algorithms.

An ARMAX may be expressed as :

$$q_t = \phi_1 q_{t-1} + \phi_2 q_{t-2} + \dots\dots\dots + \phi_p q_{t-p} + \theta_1 P_{t-T} + \theta_2 P_{t-T-1} + \dots\dots + \theta_q P_{t-T-q+1} + \varepsilon_t \qquad (39)$$

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 no. of time intervals

p, q are the order of the model, which identifies the structure of the model. Different combinations of p and q are considered and parameters are estimated for each combination. For each combination, discharges are simulated and compared with that of the observed values. The combination (p,q) which gives the minimum mean square error is identified as the order of the model. The model is considered adequate when the residual errors are uncorrelated. If the residual errors are found to be correlated then the order of the model is increased till the residual errors become uncorrelated, or an error model is incorporated in the equation.

Deterministic Methods :

Deterministic methodsare those whose operation characteristics are in the form of known physical laws, empirical relationships, trends or cyclicities. Deterministic models are more adaptable and provide more insight into the physical processes of the hydrologic cycle. Using a deterministic model, it is easier to define the relationship between model parameters and basin physical characteristics of a basin.

Conceptual models are based on some consideration of the physical processes in the catchment. These occupy an intermediate position between the fully physically based approach and empirical methods. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modelled. Physically sound structures and equations are used together with semi-empirical one in a conceptual model. It is required to estimate the parameters by calibration using optimization techniques applying concurrent input and output time series.

Recession Curves :

Low flow is determined by the following phenomena:

(a) Depletion of underground reserve, which is related to recession curve and represented by the relationship:

$$Q(t) = Q_0 e^{-c_r(t-t_0)} \qquad (40)$$

where Q_o is the discharge at time to and cr is the recession coefficient.

b) Slight runoff from small rainfall occurring during the recession period. For rivers with well determined rainy (or snowmelt) season it is possible to find to time t_o near the end of the rainy season, and near the beginning of the recession.

After determination of Q_o it is easy to estimat the parameter of the recession curve with the observed values of the discharge plotted on logarithm coordinates. The residual between the observed discharge and the recession curve is correlated with monthly rainfall of the dry season for determining the regression between this residual and the precipitation for various months. Based on this, it is possible to compute low flow discharges for specified periods by projecting seasonal rainfall on the basis of historical record.

Under certain conditions depletion of the seasonal water storage can be expressed by the exponential equation (Nash, 1957).

$$Q_t = (Q_o - Q_b)e^{-C_r t} + Q_b \qquad (41)$$

Q_o is the initial discharge, Q (t) is the discharge at time t, Q_b is the base flow due to inflow of deep ground waters., C_r is a constant.

Snowmelt Runoff:

Snowmelt is a significant component of the hydrological cycle for river systems in snow fed rivers. In India, a number of rivers originate from the Himalayas such as Indus, Ganges, Brahmputra and their tributaries are supplemented significantly with snowmelt water. In many cases the summer runoff, comprising mostly of snow melt is a major source of water for power generation as well as domestic and irrigation purposes.

Point estimation of snow melt in a watershed may not be adequate for forecasting runoff. However, reliable snow melt estimates from snow pillows. Snow course water equivalent data, etc. can be used to simulate distributed snow melt watershed models.

A rational approach in estimating rate of snow melt is based on energy budget. Heat is transmitted to snow by absorbed solar radiation, net long wave radiation, convective heat transfer from air, latent heat of vapourization by condensation and relatively small amounts of heat from rain and the underlined ground. The knowledge of variation in snow cover (spatial as well as temporal) is also a requirement for the estimation.

Basin models that simulate snow melt runoff have two important components .viz; snow melt estimation model and a transformation model. Both the parts may be lumped, distributed or combined.

Lumped models use one set of mean basin parameter values to define the physical and hydrologic characteristics of a basin. A distributed model attempts to account for the special variability in these features and moisture by dividing a basin into sub areas. The rain and snow melt are the two basic input variables for the transformation models in forecasting snow melt runoff.

The accuracy of the runoff forecasted not only depends upon the accuracy of forecast of rain and snow melt, but also on the capabilities and estimated values of the parameters of the transformations model also.

The UBC watershed model developed for mountainous snow melt forecasting (Quick M.C. and A.Pines, 1972) is briefly described here.

The model is designed for forecasting runoff from mountainous catchments and hence it is divided into area elevation bands. The model estimates snow pack accumulation and depletion and operates on meteorological inputs of daily maximum and minimum temperature and precipitation. Ground water and soil moisture characteristics are used to control runoff components. The model can be used for low flow forecasting. In this case the fast runoff component may be separated from the model to modify it for the purpose.

Additional facilities are available to describe lake storage and lake routing techniques. The model normally uses a constant lapse rate for the calculation of snow melt with the availability of data, the model permits calculation of lapse rates too. A number of parameters are fairly constant in the model and do not vary considerably from basin to basin. The remaining parameters such as runoff parameters during recession periods can be determined. A schematic structure of the model for low flow forecasting is showing in Fig.1.

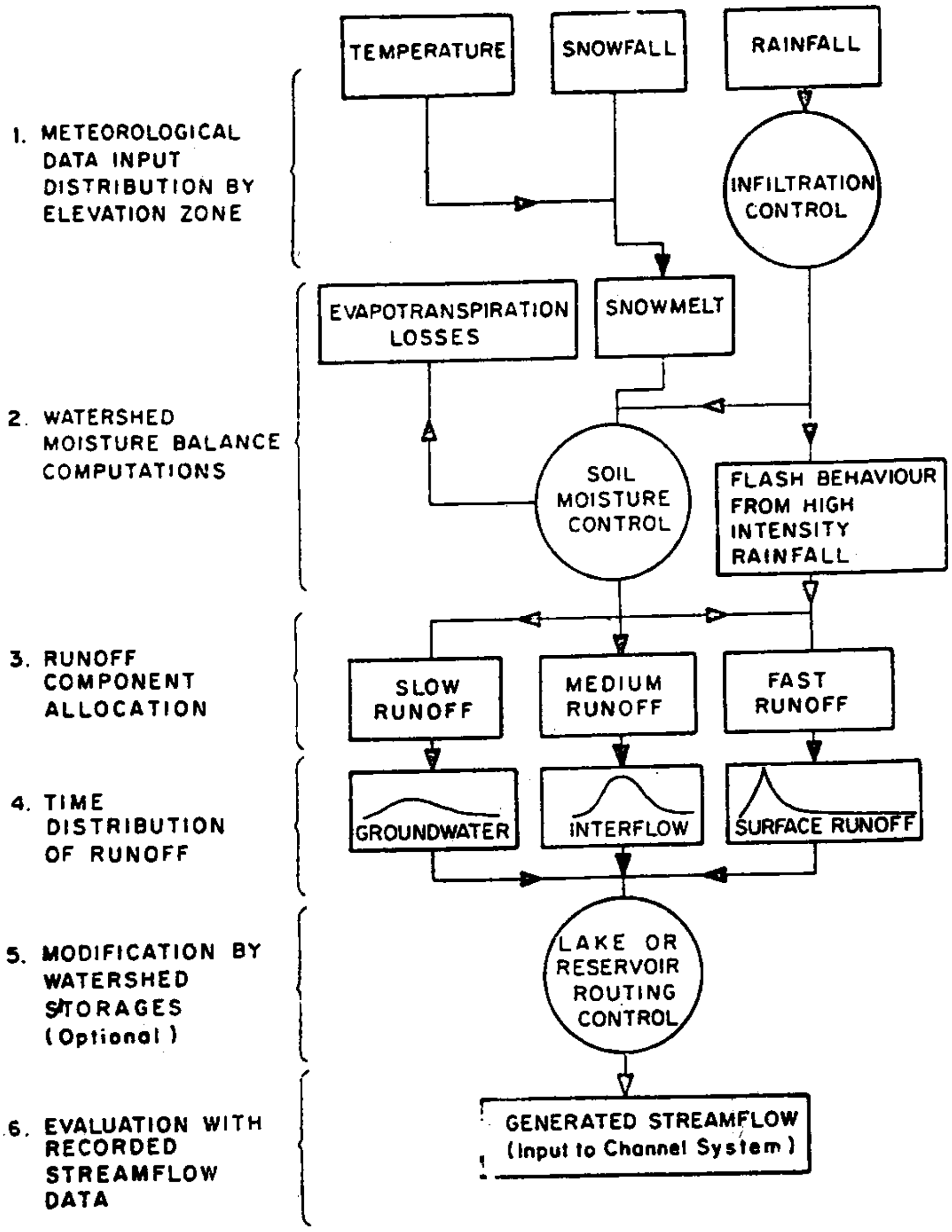

Fig. 1 - U B C Model

The model is divided into area elevation bands. Soil moisture deficit is assumed to be an important variable in the model. The soil moisture deficit is used to allocate snow melt or rain in each band to the various zones of runoff. Some runoff will be allocated to inter flow and the remainder to slow base flow ground water runoff.

Snow melt rates depend mainly on (a) convective heat transfer from a warm air mass, (b) net radiant heat transfer and (c)latent heat changes associated with evaporation or condensation of water vapour. Temperature data may be utilised to estimate the contributions from these sources.

In case of the snow melt runoff models the particular problem is the determination of the melt rates. Since melt rates are determined by the components of the energy balance equation it seems obvious that the model component to determine the melt rates should be an energy balance approach. It needs observation of data including net radiation which is sparse. Use of energy balance approach with inaccurate input data will not yield desirable results.

The other way is to use a simple model, which only uses operationally available data. Experience showed that more sophisticated models need not provide better results than simple models with the same data basis. Information about the real physical processes and the climatological conditions of a basin can be helpful in the appropriate use of simple and sophisticated models.

Base flow - Surface water Ground water interaction:

Low flow is marked by scarcity or lack of rainfall and results from interaction processes between ground water and surface water systems. during the non-rainy seasons the low flows are generally base flows in the streams derived from precipitation during the antecedent rainy season as ground water recharges. In addition to the base flow, there can be some contribution from snowmelt or rainfall, which may occur during the lean season, to sustain the low flow.

The ground water system may be considered as a reservoir that gains water from recharge and loses water through discharge to surface water systems. Under effluent conditions ground water exfiltrates into surface water courses and under influent conditions surface water infiltrates into the sub surface. Within the sub surface water system, the unsaturated (aerated) zone is a region where water originated from infiltrating rain water seeps to the ground water or ground water rises by capillary action into the root zone. Within the saturated (ground water) zone there is a horizontal movement of water.

The ground water regime is considered to be of three zones viz; recharge zone,transition zone and discharge zone. Within the recharge zone water from surface watersystems recharges the ground water. Recharge depends on the soil characteristics, land use and vegetation, evapotranspiration and morphology. In the transition zone, impermeable layers near the surface can prevent recnarge. In the discharge zone ground water comes up and exfiltrates into drainage systems or into the river itself.

For effluent conditions the ground water system can be compared with a reservoir from which water flows into surface water systems.This interaction process is the basis for base flow. During low flow periods the out flow is greater than the recharge and the discharge. in river decreases gradually. The rate of decrease depends on the transmissivity of the aquifer, the storage coefficient and the geometric parameters of the system.

Seasonal effects as well as man made effects can influence low flow situations. Storage of water in reservoirs, release of water from reservoirs, withdrawal of water from rivers, pumping of ground water from wells etc. are examples of man made effects. As far as seasonal effects are concerned snow melt is important. During melting season, water goes down the rivers and high recharges are resulted.

Temperature changes may be predicted earlier with comparatively more accuracy than precipitation. For medium term forecasting of low flow the fluctuations of recharge is to be considered. Ground water models may be used for the purpose. If there is a mixture of impervious, consolidated and permeable sedimentary aquifers, the application of ground water models is impossible. This restricts the use of ground water models as a tool for low flow predictions to flat land river systems.

For real time forecasting the ground water systems, from which water is released into rivers, are regarded as reservoirs. As long as the depletion curve of a reservoir is not distributed by a rapidly changing recharge (rainfall or snowmelt) low flow can indeed be forecasted with considerable accuracy.

Medium and long term forecasting can only take into consideration trends of those factors which influence low flow. Such trends originates from seasonal fluctuations of rainfall and evapotranspiration, from seasonal storage of snow, and from the storage capacity of the aquifer. Dependent on the storage capacity, the ground water system has a tendency to persist in an established state. This tendency is the background for medium and long term forecasting of low flow.

.5 Low Flow as Component of Hydrologic Models :

The demarcation between low flow and high flow is vaguely defined. The seasonal low flow is commonly considered to be the mean flow for a month or more during the low flow season of the year. The main source of water in a stream when it is low is water stored in the ground.

The low flow duration as well as the quanta vary from basin to basin and region to region. In India the non-monsoon season can be considered as the low flow period, as nearly 90% of the annual runoff is received during the monsoon months (June to October). A predetermined normal value may be fixed as a dividing line to define low flow and distinguish it from the high flow for a particular case and period.

The rainfall and amount of direct runoff are the major factors in analysis of high flows. On the other hand, the baseflow which ismainly due to groundwater contribution (as also the snowmelt in case of snowfed rivers) are dominant in the lowflows of the rivers. All hydrologic models formulated for forecasting purposes include the base flow as a component as it is inseparable from the description of the system. During the high flow, the contribution from the low flow component is less compared to the direct runoff. During low flow season the high and medium components diminish considerably and the low flow component predominates. Hence low flow forecasting may be considered as a special case of the hydrological forecasting models and a forecast of the same may be achieved with a reasonable degree of accuracy.Further, the lead time can also be increased considerably by assuming either no rain or normal rain during the non monsoon period. This may affect the accuracy in case of very small catchments in the hilly areas but for medium and large catchments arror may not be much.The factors contribution to the lowflows will vary from basin to basin and for the region to region depending upon the hydrometeorological and physiographical characteristics. However, a typical sketch which may be considered to represent the lowflow formations for majority of Indian river system is shown in Fig. 2.

Some of the models which may be used for lowflow forecasting are discussed briefly hereunder.

The SSARR Model

The Stream low Synthesis and Reservoir Regulation (SSARR) model was developed initially to provide mathematical hydrological simulation for system analysis in planning, design and operation of water control works. The model was further extended for operational river forecasting. The model is divided into three parts.

i) A river system model for routing stream flows from upstream to downstream;

ii) A reservoir regulation model for outflow from reservoirs;and

iii) A generalized watershed model for synthesizing runoff from snowmelt, rainfall or both.

Rainfall data can be input at any number of stations in the basin. Runoff is partitioned into base flow, inter flow and surface runoff. The division is based on various indices and on

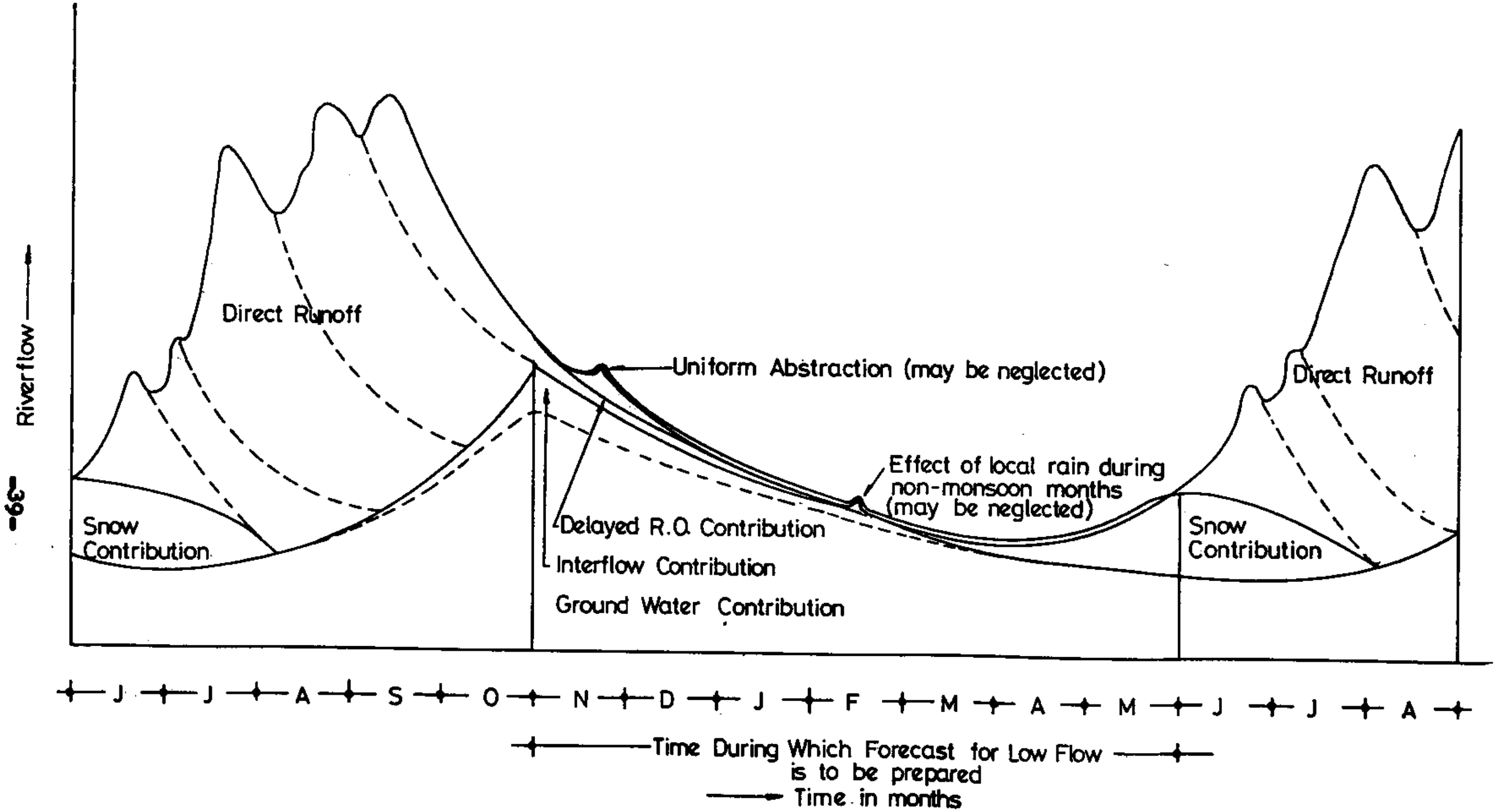

FIG. 2 SCHEMATIC REPRESENTATION OF THE MAJOR COMPONENTS OF FLOW HYDROGRAPH FROM VIEW POINT OF THE LOW FLOW FORECASTING.

the intensity of direct runoff. Each component is subject to the different processes to produce a combined final outflow. The schematic representation of the model is shown is Fig.3.

The hydrologic elements which are evaluated individually for analysis are net basin precipitation, soil moisture, evapotranspiration loss, runoff excess, surface storage, sub surface storage, ground water storage and flow separation relationship. The baseflow is separated using a relationship of base flow infiltration index versus base flow percent.

Stanford Watershed Model

This model was originally developed at Stanford University in the sixties and successfully improved to the Stanford Watershed Model (Crawford & Linsley, 1966).The structure of the model is shown in Fig. 4.

It represents an effort to simulate continuously the movement of water over, into and through the soil according to the best knowledge of these hydrological processes. It uses as input either rainfall, snowmelt or a combination of the two. Initially, interception and depression storage losses must be satisfied. A certain amount of runoff occurs from impervious areas, a portion of which runs directly into channels, and the rest flows over pervious land and is subject to the soil moisture conditions. Infiltration capacities are assumed to vary Water detained in the upper zone percolates into the lower zone which in turn contributes to ground water storage and baseflow. Potential evapotranspiration is assumed to be equal to the estimated lake evaporation. Evapotranspiration is assumed to occur from interception storage and the upper zone at a potential rate, from the lower zone at a variable rate, and from ground water storage at a very low rate. The different flow components are routed separately to produce the out flow hydrograph.

SACRAMENTO Model

This model was developed by the staff of National Weather and River Forecasting Centre at Sacramento, California, USA.

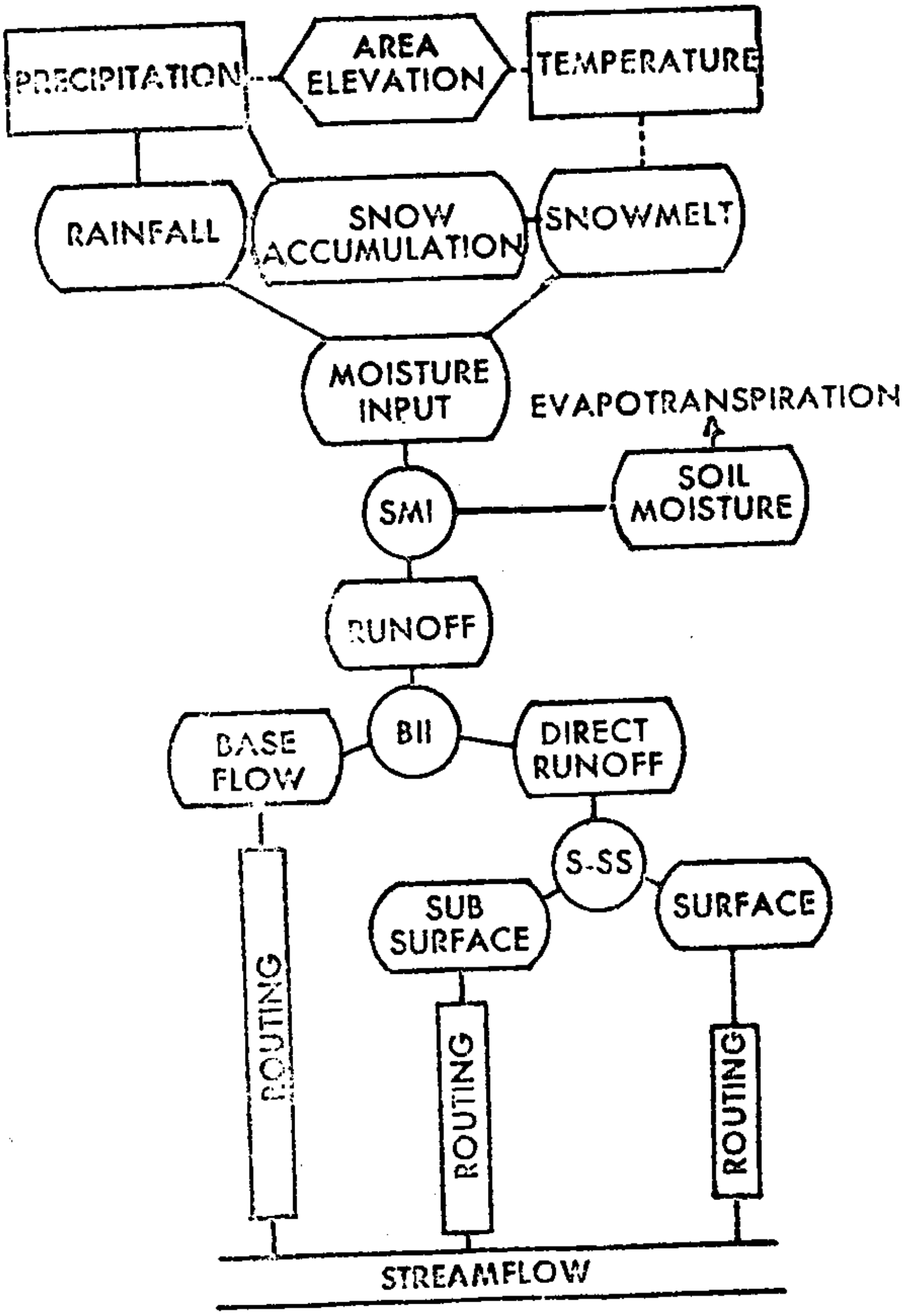

Fig. 3 – SSARR Model

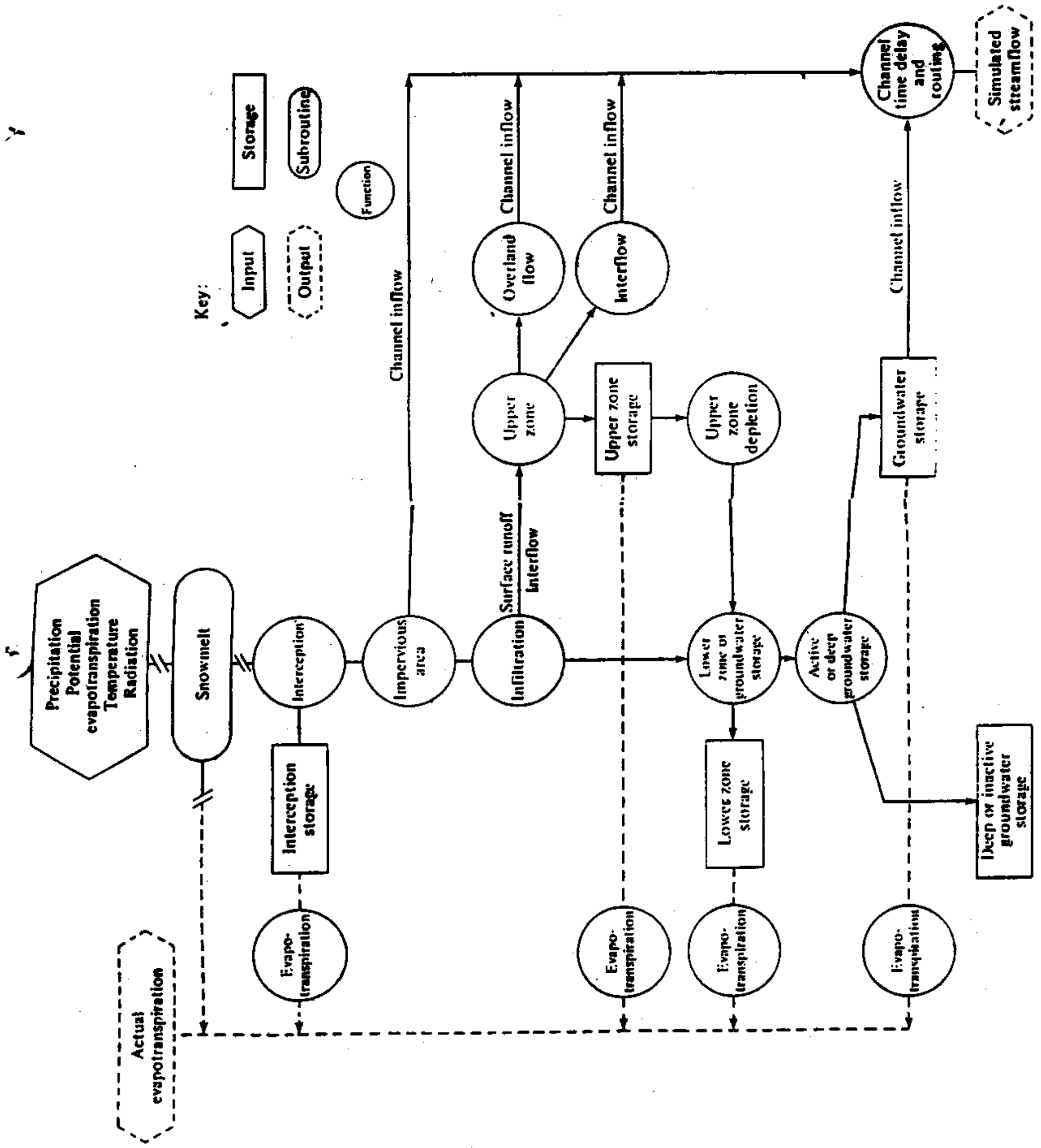

Fig. 4 – STANFORD Model

A complex moisture accounting algorithm is employed to derive volumes of several runoff components, while a simple and empirical method is used to convert their inputs to the outflow hydrograph. Rainfall over the catchment is considered as falling on one of the two types of surfaces, permeable or impervious areas connected to the stream flow channel. Runoff is produced from the impervious areas from any rainfall event, while runoff occurs from the permeable area only when the rainfall intensity exceeds infiltration rate. The soil mantle is treated as two parts an upper zone and a lower zone with each part having a capacity for free water and tension water (initial soil moisture storage which is depleted only by evapotranspiration). The upper zone tension storage must be filled before water is available to enter other storage.

All rainfall and snowmelt, other than that diverted to direct runoff, enters the upper zone. Free water in the upper zone is depleted either as inter flow or as percolation to the lower zone. Free water in the lower zone is divided between primary storage and secondary storage.

Evapotranspiration rates are estimated from meteorological variables or from pan observations. The moisture accounting within the model extracts the evapotranspiration loss from the contents in the various storage elements and/or from the channel system. The loss is distributed according to priorities.

Five components of runoff are derived in the model. The direct, surface and inter flow components are summed up and transformed by a unit hydrograph. The two components from the lower zone, primary and supplementary base flow are added directly to the outflow hydrograph derived from the other components. Provision is made for routing the resultant hydrograph with variable routing coefficients. A schematic representation of the Sacramento model is given in Fig.5.

TANK Model

Tank model, developed by Sugwara (1967), is a conceptual runoff model for simulation of flood as well as daily runoff.A schematic representation of the model is shown in Fig. 6.

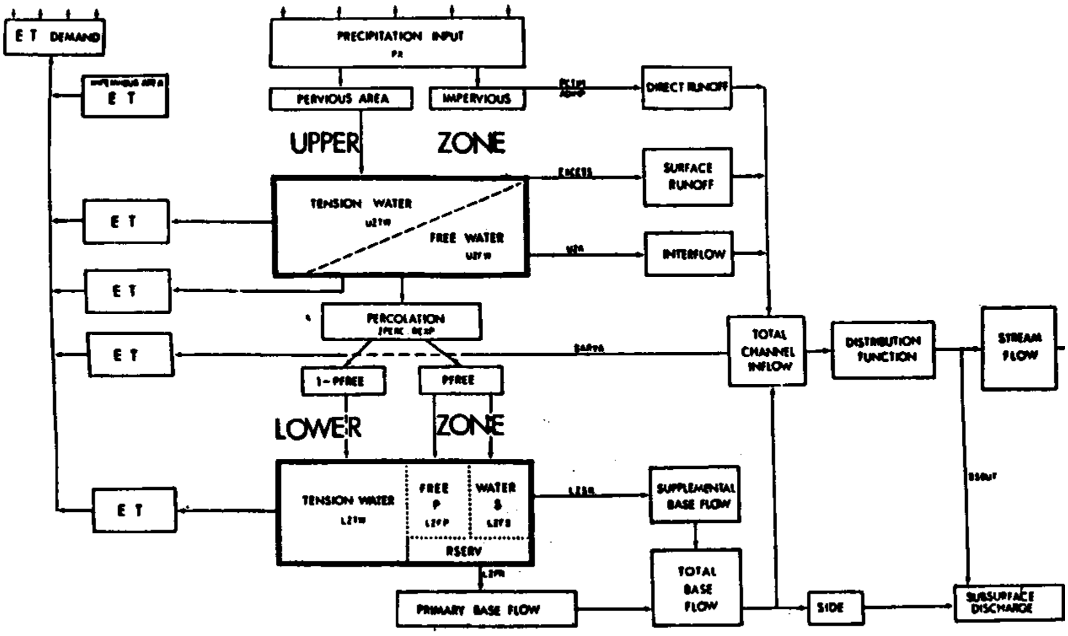

Fig. 5 - NWSRFS (Sacramento Model)

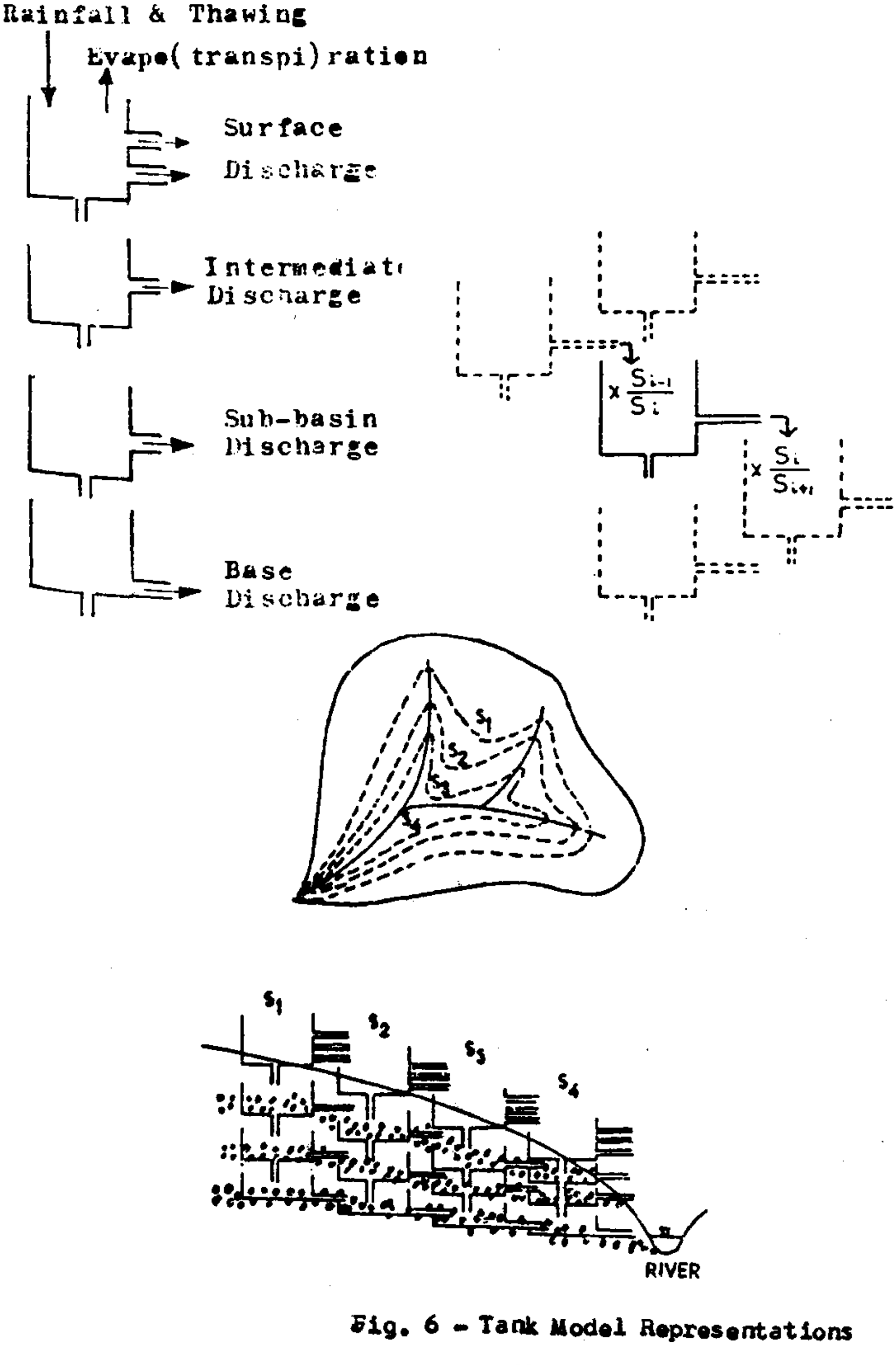

Fig. 6 - Tank Model Representations

The data requirement of the model includes daily precipitation data, daily temperature data, evapotranspiration data and discharge data (for calibration purposes).

The catchment is represented by a number of tanks placed vertically one above the other. The input to the tank is mainly precipitation. The tanks are supposed to have outlets at the bottom or on sides to represent vertical or horizontal water movement. Generally, the top tank corresponds to surface flow, the intermediate tanks and the bottom tank corresponds respectively to sub surface flow and base flow. Hence the bottom most tank has outlet only on sides and the upper tanks have outlets on sides as well as at their bottoms. Each tank receives water from the upper tank and free water moves in the horizontal and vertical directions.

The output from the tank model goes into the river channel, where its hydrograph is deformed by storage effect of the channel.

This model found its application in many river basins in Japan, Thailand, Malaysia, Indonesia and India. In India, Tank Model for daily runoff simulations for Jamtara and Ginnore basins was applied by NIH, Roorkee.

Tangborn-Rasmussen Model

Tangborn and Rasmussen (1976) proposed a forecasting model based on the annual water balance of the basin. The difference between the precipitation and runoff during the rainyfall season approximates to be the storage of the next to come non-rainy season eventually produces the low flow runoff during the lean season which corresponds to the summer. The evapotranspiration, the contribution of summer precipitation to runoff and ground water and snow cover effects are assumed to be constant for different years.

The summer runoff forecast is given by :

$$R\,s^* = a_s(P_w + P_l) + b_s - R_w - R_l \qquad (42)$$

where ; P_w = winter precipitation

P_t = spring precipitation
R_v = winter runoff
R_t = spring runoff
A_s, b_s = model parameters by linear regression

There are large forecasting errors resulting from the above calculations due to seasonal variations in basin storage. To improve the forecast a test season forecast equation was introduced and based upon that the summer runoff forecast model was improved.

The NAM/System 11 Model

The NAM model is a traditional lumped-conceptual model to describe rainfall runoff process from a catchment. The model is useful in extension of stream flow records based on long rainfall records and in real time rainfall runoff simulations.

This model, developed by Danish Hydraulic Institute and Central Water Commission, India (1985), consists of four parts: viz; a hydrologic rainfall runoff model (NAM), a hydrodynamic model for river routing, an updating procedure for real time operations and a data management package for data processing.A schematic representation of the model is shown in Fig.7.

The rainfall runoff model operates by accounting continuously for the moisture content in different storage elements.

The hydrodynamic model (System 11) is used for the simulation of flows and water levels in rivers, reservoirs, canals etc. It is based upon the St. Venant's equation of mass-energy.

The updating procedure is based on "noise model", simulating the deviations between observed and simulated runoff through a linear auto regressive model. The simulated deviation (noise) is used to adjust the stream flows simulated by NAM prior to the routing by System 11.

Monash Model

Like the Stanford Model, this model developed by Porter and Mc.Mahon (1971) at Monash University in Melbourne, attempts to

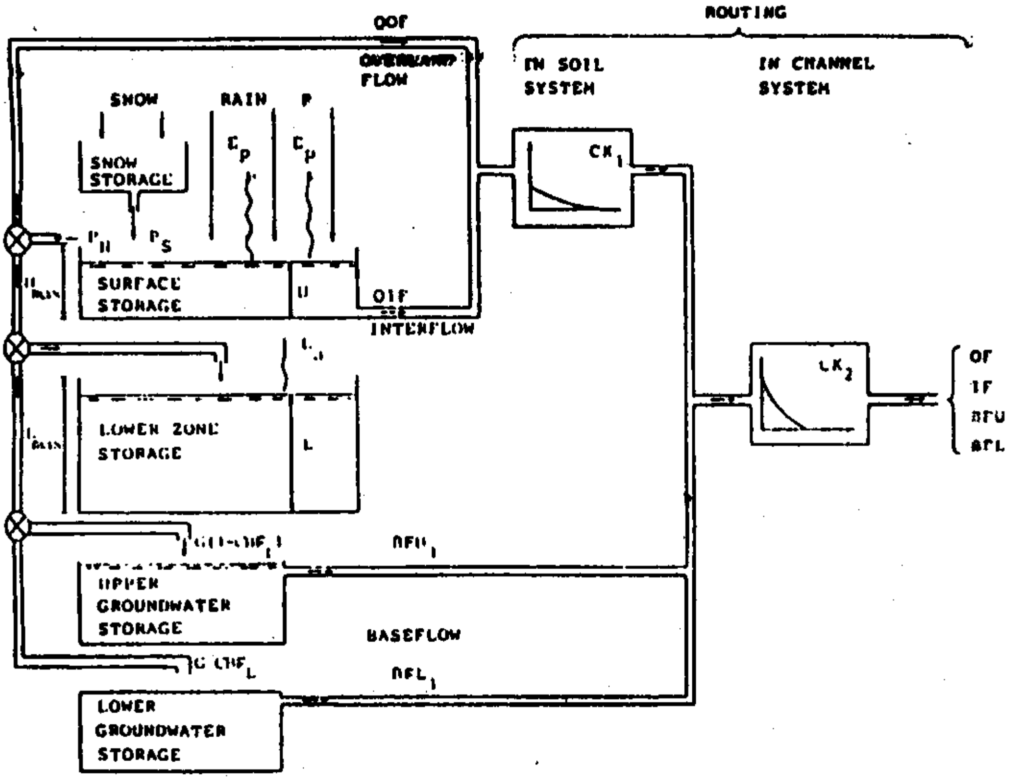

Fig. 7 — NAM Model

physically simulate the catchment process but like the Sacramento Model it is a reasonably simple to operate too.

HBV Model

The HBV was developed at the Swedish Meteorological and Hydrological Institute (SMHI) Norrkoping, Sweden by Bergston (1976). It is a conceptual model for continuous computation runoff. Input data are observations of precipitation, our temperature and estimate of potential evapotranspiration. The time scale is one day. Air temperature data are needed for snow accumulation and ablation calculation only and can be ommitted in snowfree areas. The model comprises of sub-routines for snow accumulation and melt, a soil moisture accounting procedure, routines for runoff generation. The basin needes to be sub-divided into elevation zones, if it is considerable elevation zones. The characterised by sub division is made for the snow and soil moisture routines. Each elevation zone again needs to be divided into different vegetation zones (forested and unforested areas). A schematic sketch of the HBV model is shown in Fig.8.

It is possible to run the model separately for several sub-basins and then add the contribution from all the sub-basins. The model has been applied to river Baitarani of Orissa (basin area = 8570 sq.kms). Also Bergstorm etal. (1985) applied the HBV -6 model is upper Narmada basin (area = 16576 sq.kms).

2.6 Physically Based-Distributed Models

Physically based-distributed models in principle be applied to any kind of hydrological problem. Obviously, there are many problems for which the necessary solutions can be obtained using cheaper and less sophisticated empirical, lumped conceptual or statistical models. But, for the more complicted problems use of physically based distributed models acquires a great importance. Physically based models are based on our understanding of the physics of the hydrological processes which

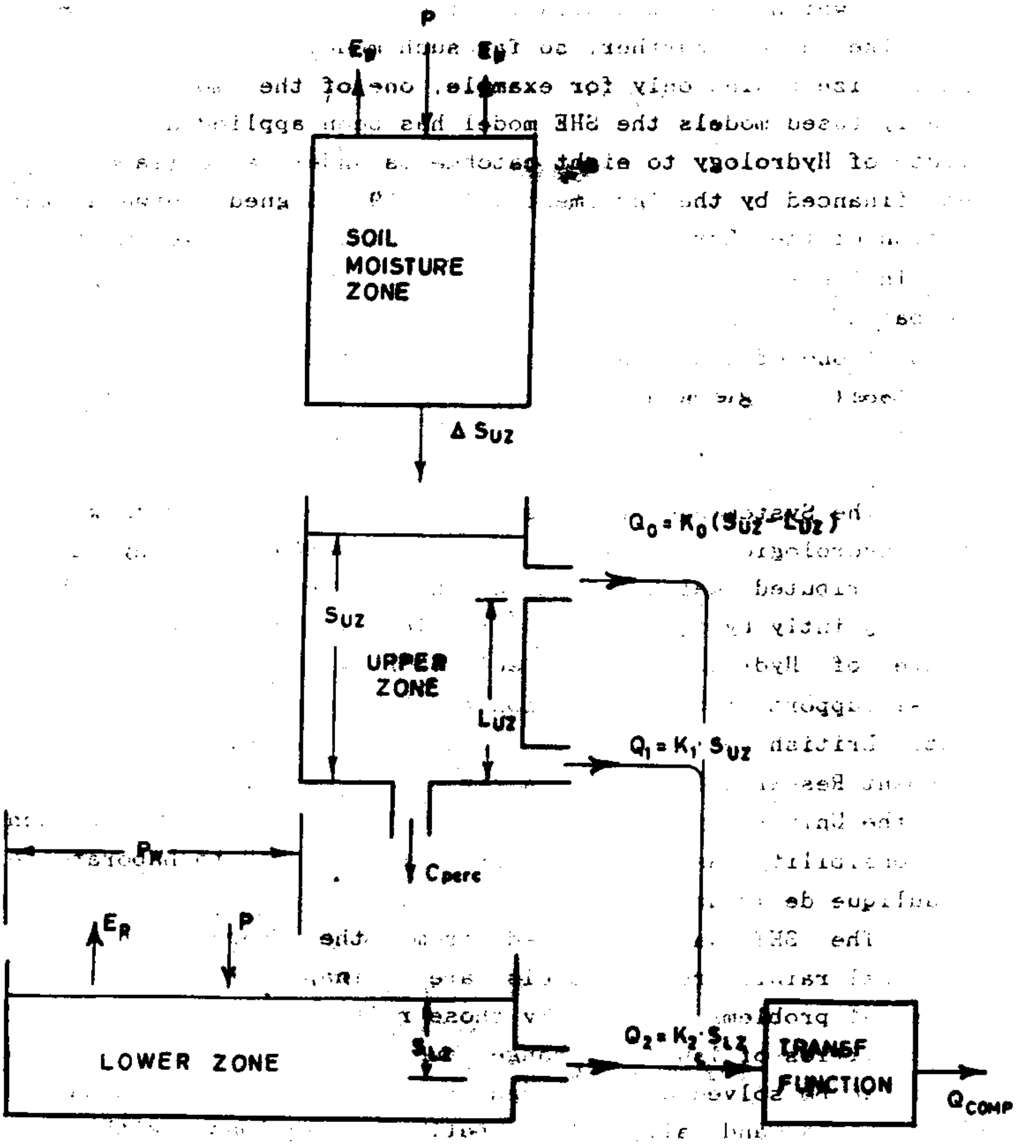

Fig. 8 - HBV Model

control catchment response and use physically based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs e.g. river discharge, phreatic surface level, evaporation and transpiration loss and soil moisture variation etc.

However, these models call for enourmous computing facilities, which are not available at many places in a developing country like India. Further, so far such models have been used for small size basins only for example, one of the most advanced physically based models the SHE model has been applied at National Institute of Hydrology to eight catchments under a collaborative project financed by the Agreement ALA 86/19, signed between the Commission of the European Communities and the Government of India. In the above mentioned studies the model has been applied to the basins upto a size of about 5000 sq.kms. The salient features of one of the physically based distributed models viz. the SHE model are given as follows.

SHE model

The System Hydrologique Eropean (SHE),commonly known as European Hydrological System model is an advanced, physically based, distributed catchment modelling system. It has been developed jointly by the Danish Hydraulic Institute, the British Institute of Hydrology, U.K. and SOGREAH (France) with the financial support of the commission of the European Communities. Currently British responsibility for the SHE lies with the Natural Environment Research Council's Water Resources System Research Unit at the University of Newcastle upon Tyne (UON). In Franch the responsibility has been tranferred from SOGREAH to Laboratorie d'Hydraulique de France (LHE).

The SHE was developed from the perception that conventional rainfll/runoff models are inappropriate to many hydrological problems, especially those related to the impact of man's activities of land use change and water quality. These problems can be solved only through the use of models which have a physical basis and allow for spatial variations within a catchment. The SHE is physically based model in the sense that the hydrological processes of water movement are modelled either by finite difference representations of the partial differential equations of mass, momentum and energy conservation, or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. River channels are superimposed on the grid element boundaries. Parameters must be evaluated as appropriate for each grid element, river link and subsurface layer. Basic processes of the land phase of the hydrological cycle are modelled in separate components viz. interception, by the Rutter accounting procedure; evapotrasnpiration, by the Penman-Monteith equation or by an approach developed by Kristensen and Jensen (1975); overland and channel flow by simplifications of St.Venant equations; unsaturated zone flow, by one dimensional Richards equation; saturated zone flow by the two dimensional Boussinesq equation and snowmelt, by an energy budget method. The SHE software is structured in such a manner that each hydrological process is allowed its sown component and simultaneous operation of each component is controlled by a central frame component. For flexibility,, the components can be modified or omitted i.e. replaced by dummy exchange components in any given application, depending on davailability of data and hydrological conditions.The structure of the SHE model is shown in Fig.9.

The SHE has a modular structure in order to incorporate improvements or additional components such as irrigation return flow, sediment yield and water quality etc. in future. Considerable operating flexibility is available through the ability to vary the level of sophistication of the calculation model to make use of as many or as few data as are available and also to incorporate data related to topography, vegetation and soil properties which are not usually incorporated in catchment models. The SHE does not require long term hydrometeorological data for its calibration and its, distributed nature enables spatial variability in catchment inputs and outputs to be

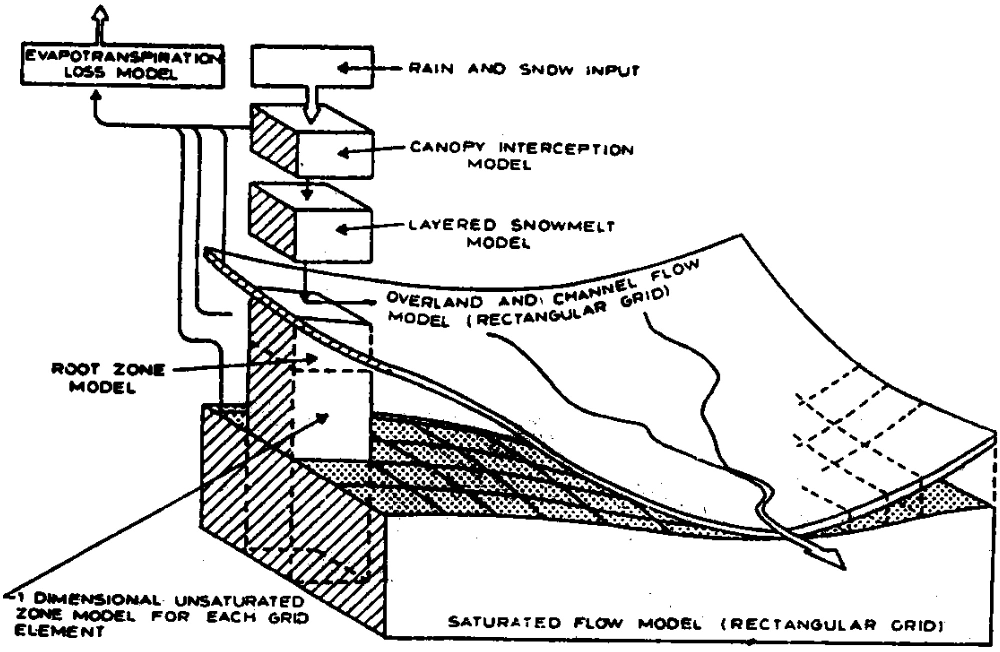

Fig. 9 - SHE Model

simulated. (Abbott et al. 1986).

The SHE is designed as a practical system for application in a wide range of hydrological resource conditions. Its physical and spatially distributed basis gives it advantage over simpler regression and lumped models in simulating land use change impact, ungauged basin, spatial variability in catchment inputs and outputs, groundwater and soil moisture conditions, and water flows controlling the movements of pollutants and sediment.

CHAPTER - III

CONCLUDING REMARKS

The review of the various literatures related to low flow analysis and lowflow forecasting indicates that in majority of cases, the studies are directed towards the assessment of dependable flows during the lean period or the lowflow period or particularly the non-monsoon period for Indian river systems. Perhaps, this is one reason why the maximum number of the methods or the models suggested are stochastic in nature. Almost all the hydrologic system models which are continuous in nature include the suitable representation of flow conditions during the lean period. However such component of the comprehensive hydrological model gets a, rather, poor treatment at the time of calibration of the model as a uniform criterian is generally adopted for the evaluation of the parameters.

It remains a fact that the major contribution to the lowflows in the river is either from the groundwater storage and/or from the snowmelt (in case of snowfed rivers). In both the cases, the response due to any type of input is generally very very slow. Another important factor is the effect of the man made regualtory structures which complicate the flow system to a great extent and particularly, the disturbance of the time distribution process is quite considerable. This resulsts in greatdifficulty in identification of the characteristics of the lowflows and their proper representation through a physically based model. Many a times, simple statistical relations using limited number of variables have been found to gives better results. This is more so in case of larger alluvial river system where the response time is too large. In view of the above, the various techniques for the lowflow forecast can be classified as :

1. Statististical methods;
2. Stochastic methods; and
3. Deterministic approaches including the conceptual models.

The methods based on statistical approaches are indeed simple and they are likely to yield reasonably good result in case of large river system, if the independent variables are selected with due care.

The stochastic methods are generally recommended for estimation of lowflows to be used in project planning etc. However, for operational purposes, the deterministic component of such models can be effectively used. The results with the help of stochastic models can definitily be used in proper decision making.

For smaller river systems, it would be necessary to use a physically based model or a conceptual model. However, in such cases, it would be difficult to have forecast with considerably longer warning time.

The choice of the model will be also guided to a great extent by the objective of such forecast and the desired degree of the accuracy. In addition, the following ideal requirements of an effective model (crawfold & Linsley, 1966) should also be kept in view while identifying &eveloping a model.According to them a model should:

A model should.

i) represent the hydrological regime on a wide variety of catchments with a high order of accuracy;

ii) be easily applied to any catchment for which hydrological data was available;and

iii) be physically realistic so that in addition to streamflow, estimates of other variables, such as soil moisture and ground water recharge are determined.

For the purpose of the development of a lowflow forecasting model, the river systems in India can be broadly classified into following three categories.

i) the rivers originating from Himalayas in which snowmelt contribution is quite considerable and its effect are dominent;

ii) the rainfed river having rains mostly concentrated during the monsoon season; and

iii) the coastal rivers of Tamil Nadu and Kerala where the contribution from the pre-monsoon and the post-monsoon rains are dominant.

While the statistical methods, can be used with advantage for the larger river systems, the physically based models which are distributed in their approach are considered to be more suitablke for medium & small size catchments.

A number of riverflow models are available for real time forecasting purposes. Most of them are mainly used for flood forecasting services. The concept of sub dividing the river flow into components of "direct runoff" and "baseflow", introduced by Wemelsfelder (1963), envisages lowflow forecasting using the general models. But the lowflow forecast based upon base flow component needs the extreme assumption that no effective precipitation would occur during the lead time and that the component of direct runoff would have vanished altogether Obviously, this assumption will not yield the most probable river flow at the end of the lead time. Hence allowances are to be made to accommodate the possible factors which may influence the flow during the lead time.

Precisely, when developing mathematical models for flow forecasting, these should be so designed that these can be of optimum use in practice. This implies that models should require only input data which exist, and that they should be flexible, such that they work even if parts of the required input data are not at the time of the forecast formulation.

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