SURFACE WATER ANALYSIS AND MODELLING

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1.0 INTRODUCTION

The hydrological behaviour of catchments is a very complex phenomenon which is controlled by a large number of climatic and physiographic factors that vary in time and space. The basic problem of hydrology is the establishment of relationships between rainfall and runoff. The application of systems concept has led to studies in hydrology using deterministic, probabilistic and stochastic approaches to deal with problems of hydrological analysis, simulation and synthesis.

In the absence of historical data and the computational facilities most of the hydrological studies carried out in India, before independece, involve the application of the empirical formulae and envelope curves for planning and design of water resources structures.Subsequenly improvement in hydrological data base and availabilty of computer facilities encouraged the hydrologists for taking up the various hydrological studies in order to develop the better methodolgy for planning, design and operation of the water resources projects.

Most of the hydrological studies carried out in India since independence in surface water hydrology relate to hydrologic analysis and synthesis. In this section some of the studies carried out in the following areas of Surface Water Hydrology have been reviewed:

(a) Unit Hydrograph Analysis

(b) Hydrological Modelling

(i) Deterministic Hydrological Models and (ii) Stochastic Models

2.0 UNIT HYDROGRAPH ANALYSIS

Flood estimation is a very important component of water resources project planning, design and operation. Estimation of design flood peaks is needed for comprehensive water resources planning, flood flow forecasting, design of various drainage systems, flood control, design of hydraulic structures etc.

Design of structures to control river flows must consider both extremes of runoff (that is, droughts and floods). Analyses are required to size the capacity of outlet works (spillways, bypasses etc.) to cater for floods. It is often necessary in hydrologic design

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to have details of both the peak flows and the distribution of flow with time, in other words, the hydrograph, so that the runoff volume can be estimated. As streamflow records are somewhat limited for most locations, it is necessary to relate runoff to rainfall. Knowing rainfall rates, a function to convert rainfall to runoff is required. Unit Hydrograph (UH) is such a tool. Unit Hydrographs can be derived from analysis of rainfall and runoff records in those catchments where such data are available. The procedures used to derive a unit hydrograph are dependent upon whether the storm from which a unit hydrograph is to be calculated is a simple or single-period storm, or a multi-period storm.

Thunder-storms are usually intense and of short duration, and more likely to be treated as single period storms. Frontal storms are usually of longer duration and therefore, are generally not suitable for single period analysis. A multi-period approach should be followed for such storms. Generally, the unit hydrographs derived from various events are not the same. The estimation of design flood requires a representative unit hydrograph for the watershed. There are two possible approaches for the derivation of the representative unit hydrograph for a watershed. In first approach, the unit hydrographs derived from various events are averaged by the conventional averaging method. However, the second approach considers the joint event, obtained from clubbing the various events together for the analysis and provides a single representative unit hydrograph for the watershed.

During late nineteenth century and early part of twentieth century, empirical formulae developed for specific regions were used for estimation of floods. These formulae were developed for the specific regions using the flood peaks available within the range of measurements. The application of these formulae for other regions could provide only an approximate estimate of floods. Sherman introduced unit hydrograph theory where the watershed is considered to be linear time invariant system in order to compute runoff from excess rainfall. These methods can be categoriesed into two groups viz. (i) Parametric, and (ii) Non- parametric system analysis. The conventional method, Matrix method, Transform method, time series method and Linear Programming methods are well known approaches under the non- parametric category, whereas the conceptual models and synthetic unit hydrograph are considered under the Parametric category.

The unit hydrograph for gauged catchments can be derived by analysing the available rainfall-runoff data. However, for many small catchments the streamflow data are limited and for ungauged catchments it is not at all available. Therefore, the unit hydrograph for such catchments can only be derived using their physical and storm characteristics. This necessitates the development of suitable regional relationships for unit hydrograph derivation. The procedure used for this purpose involves the derivation of the parameters that describe the unit hydrograph for gauged catchments; and then the development of the regional relationships between unit hydrograph parameters with pertinent physiographic and storm characteristic of the ungauged catchments. The catchments considered for such regional study have to be similar in hydrological and meteorological characteristics.

Some of the typical studies carried out in India since independence are briefly reviwed here under.

Choube (1971) assumed the rainfall excess-surface runoff process to be linear. Inverse analysis of rainfall excess-surface runoff process was carried out by using some of the methods of linear system. Some of the existing methods and models which have been used in finding unit hydrograph and instantaneous unit hydrograph for hydrologic basin were verified and compared on the basis of predicted rainfall excess. The aim was to investigate the possibility of developing a system for verifying and comparing the existing methods. A method for system inversion was investigated and preliminary analysis was carried out.

Mishra (1972) applied some of the methods to the Ganga catchment at Hardwar for verifying their suitability. The unit hydrograph for Ganga basin has been derived using data of three storms. The unit hydrograph has also been synthesized by using Snyder's approach, U.S. Soil Conservation Service equations and Commons's equations. One linear model (Nash's) and one non-linear model (Kulandai Swamy's) have been used to derive 1-h UHs. The observed and computed direct runoff hydrographs have been compared and the suitability of the models examined.

Agarwal (1975) developed methods correlating catchment characteristics with the unit hydrograph elements such as time lag, period of rise, peak flow and time base based on the data from catchment in U.S.A.. Snyder, Commons, Soil Conservation Service, and Mitchell methods have been used. The rainfall-runoff data from catchments located in Himalayan range and in eastern U.P. have been used to check the applicability of these methods . The argument that regional values in place of constants given by various investigators, will yield better results is substantiated. Dimensionless graph using United States S.C.S. method, have been prepared for catchments under study. The shape of unit hydrograph is retained in all the cases. If these graphs are used after period of rise and peak flow have been ascertained using appropriate correlation for known values of topographic characteristics, these describe actual unit graph to a high degree of accuracy. Dimensionless graphs as suggested by Gray have been constructed to facilitate the development of unit hydrograph and distribution graph for ungauged catchments. An approach based on dimensional analysis has also been tried to find a correlation among variables affecting surface runoff.

Narayan (1976) applied the synthetic unit hydrograph technique to seven sub-basins of the upper Cauvery catchment in Karnataka (ranging from 9 sq. miles to 1408 sq. miles in area) to find the maximum flood discharge value. Relationships correlating the C_p and C_t coefficients of the synthetic unit hydrograph with the area of catchment, drainage density, shape index factor and percent forest cover have been obtained.

Shriniwas (1977) analysed hydrologic data from two experimental watersheds, G1 and F2 of 5.25 and 2.47 ha at the Crop Research Centre, Pantnagar collected during the monsoon seasons in 1975 and 1976. Parametric system synthesis and black box analysis were carried out in order to derive the instantaneous unit hydrograph analysing the events with single peaked short duration runoff hydrograph. A peak runoff rate formula was developed for estimating peak runoff rates from small watershed. Out of the two approaches, namely, parametric system synthesis and black box analysis, used for the generation of surface runoff hydrographs, black box analysis yielded more accurate results. The peak runoff rates formula resulted in slightly higher values of peak rates and was next to the short duration unit hydrograph method in accuracy. The peak rates obtained by instantaneous unit graph method were lower than the observed rates. Rational method gave very high peak rates whereas the peak rates determined by hydrologic soil cover complex method showed wide departure on both lower as well as higher sides of the observed rates.

Murthy and Dev (1980) developed unit hydrographs of the ungauged catchments in reach areas of Tapi basin to facilitate accurate and timely flood forecasting. The results developed for Burhanpur/ Bhusawal reach have been reported. It is observed that in this reach unless the rainfall exceeds 10 mm, there is no contribution to surface flow. Over and above every 10 mm of rainfall contributes about 1000 cumecs of peak discharge. The order of magnitude of the unit hydrographs developed for different storms is same.

Massangya (1980) carried out hydrologic model studies for the catchment 454/7 of Bridge site. Unit hydrographs have been developed from available rainfall runoff records. The conceptual model proposed by Clark (1945) has been further modified. The derived hydrographs have been compared and the models have been tested.

Mathur and Kumar (1981) related the physical characteristics of 20 small and medium catchments in Mahanadi, Brahmani and Baitarni basins with basin lag of 2 hr unit hydrographs of these catchments with an objective to find out the most effective parameters representing the synthetic UH relationship.

Haq, Kumar and Sil (1981) attempted to develop generalised synthetic unit hydrograph relationships for Indian catchments with moderately steep slopes. The parameters of representative unit hydrographs were related with suitable combination of the physical characteristics of catchments through regression analysis.

Kumar (1983) used hourly gauge data, discharge data and hourly rainfall data available for ten small catchments (area less than 200 sq. km.) of Krishna and Pennar basins and proposed a model, the IUH has been assumed as a unit hydrograph of a short duration. The model developed may be used to predict the design flood hydrographs and flood forecasting.

Singh and Seth (1984-85) conducted a study where the suitability of using various methods for deriving unit hydrographs for the small catchments was investigated. Authors have used two approaches, parametric system synthesis and non-parametric system analysis in the study. The flood events of six small catchments (Br.No.807/1, 51, 604/2, 969, 228 and 566) of Godavari basin sub zone 3 (f) have been analysed using five methods. Three methods based on parametric system synthesis approach are Nash Model, Clark Model and Singh Model. Other two methods are Collin's method and Least Square method which are based on non-parametric analysis approach. From the study it was seen that the Nash Model was relatively more efficient and gave less standard error for the catchment of relatively larger size (area ranges between 340-823 sq.km.).

Jain and Singh (1986) dealt with the derivation of optimum and physically realizable Unit Hydrograph from rainfall runoff events using linear programming approach. Two isolated rainfall runoff events of catchment Br.No.807/1 of Godavari basin sub-zone 3 f have been considered for the study.

Panigrahi (1991) derived the Nash model parameters from Geomorphological Instantaneous Unit Hydrograph (GIUH) for Kolar sub-basin of river Narmada. An approach has been developed for deriving the complete shape of GIUH by linking it to the Nash model. For this purpose, the parameters of the Nash model n and k have been derived from q_p and t_p of the GIUH. The results for prediction of peak discharge and time to peak are found to be satisfactory.

Hydrology (small catchments) Directorate of Central Water Commission has carried out the analysis of selected storm rainfall and floods. Representative 1-hr. unit hydrographs have been obtained for each of the gauged catchments. The characteristics of the catchments and their unit hydrographs prepared for several catchment in a sub-zone have been correlated by regression analysis and the equations for synthetic unit hydrographs for the sub-zone have been derived. For this purpose, the country has been divided into 26 hydrometeorologically homogeneous sub-zones, Flood estimation reports have been prepared for many of the sub-zones (out of 26 sub-zones).

3.0 HYDROLOGICAL MODELLING

Hydrological modelling is a powerful technique of hydrologic system investigation for both the research hydrologists and the practicing water resources engineers involved in the planning and development of integrated approach for the management of water resources. Hydrologic models are symbolic or mathematical representation of known or assumed functions expressing the relationships of segments of the hydrologic cycle, or expressing the effects of a watershed on the runoff portion of the hydrologic cycle. The rainfall runoff process in a catchment is a complex and complicated phenomenon governed by a large number of known and unknown physiographic factors that vary both in time and space. The rain or snow falling on a catchment undergoes a number of transformations and abstractions through various component processes such as interception, detention, evapotranspiration, overland flow, infiltration, interflow, percolation, sub-surface flow, base flow and emerges as runoff at the catchment outlet. Application of hydrological modelling techniques to the constituent processes involved in the physical processes of runoff generation have led to better understanding of these processes and their interaction.

Hydrological models can be classified in different ways. Broadly many of the models presented in the literature can be divided into deterministic and stochastic. Deterministic models are those whose operation characteristics are in the form of known physical laws or empirical relationships, while the operating characteristics of a stochastic model are expressed by probability functions. Both model types play important roles in hydrologic simulation and analysis, however, the deterministic model is more readily adoptable to the examination of land use changes and provides more insight into the physical processes of the hydrologic cycle. Also, using a deterministic model which closely follows known physical laws and relationships, it is much easier to define the relationships between model parameters and basin physical characteristics. The better this degree of association between parameters and the basin, the more adoptable is the model for use on ungauged basins.

[a] Deterministic Hydrological Models

Deterministic models are further classified as shown below:

Deterministic Models

- Empirical Models
  - Based on Input variables and parameters
    - Lumped
    - Distri-buted
  - Based on Transfer function
    - Linear Time invariant
    - Linear Time variant
    - Non-linear Time invariant
    - Non-linear variant
- Conceptual Models
  - Lumped
  - Distri-buted
- Distributed Physically Based Models

Various terms used for the classification of the deterministic models are explained below:

Emperical models

Empirical models are developed without any consideration of the physical processes in the catchment. These models are merely based on analyses of concurrent input and output time series. Such models usually depend upon establishing a relationship between input and output, directly or indirectly using aew parameters, calibrated from existing hydrometeorological records. Within the range of calibration data such models may be successful, often because the formal mathematical structure carries with it an implicit understanding of the underlying physical system. However, in extrapolating beyond the range of calibration, the physical link is lost and the predicting then relies on mathematical technique alone. Given the inherent linearity of many empirical models (or black box models), which contrast with the non-linearity of hydrological systems, such extrapolation is of dubious worth and is not recommended. Thus, for example, empirical models can not be used to predict the effects of a future change in land use.

Conceptual models

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 black box analysis. 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 togather with semi empirical one in a conceptual model. 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 using either manual or numerical optimisation technique applying concurrent input and output time series.

Physically based models

Such models describe the system using the basic equations governing the flows of energy and water. These are based on our understanding of the physics of the hydrological processes which control catchment response. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss etc.) while black box models can offer only one output. Also these models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. On the other hand, such models make huge demands in terms of computational time and data requirements and are costly to develop and operate. These type of models, also called a white box model, thus consists of a set of linked partial differential equations together with parameters which, in principle, have direct physical significance and can be evaluated by independent measurements.

Lumped model

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.

Distributed model

Distributed model includes spatial variations in all variables, input and parameters within the catchment.

Linear time variant model

Linear time variant model is based on the linearity principle but its parameters do change with time.

Non-Linear time invariant model

Non linear time invariant model is based on the concept of non-linear catchment response and the parameters of the model do not change with time.

Non-Linear time variant model

Non-linear time variant model is also able to take into consideration the non-linear catchment response but the parameters of the model do change with time.

The planning and management of water resources projects depend upon the spatial and temporal distribution of hydrologic phenomena. In India, due to poor hydrological and hydrometeorological network, it is difficult to extract the precise information about the hydrologic phenomena in space and time from the available hydrologic data base. Therefore, the planning and management decisions are subjected to hydrologic uncertainty. A more feasible course of action is to develop mathematical models of hydrologic processes keeping in mind the available hydrological data base and use those models in order to extrapolate and interpolate information overtime step.

The development of hydrological models has got its own historical perspective in India. During late 19th Century and early 20th Century, the empirical formulae such as Dickens, Ryves, Inglis etc. were used for estimating the peak flow for design of hydrologic structures. The scope of application of these formulae was somewhat limited as they were derived using the data of the catchment of specific region within the range of flood peaks. In mid twentieth century, the unit hydrograph theory was introduced and runoff computation was made by many investigators using the approaches based on the unit hydrograph theory, subsequently, synthetic unit hydrograph approaches were adopted for the computation of runoff from the catchments which were ungauged or catchments with limited or scanty data. Further, unit hydrograph based models were developed and used for estimating the catchment runoff. Regional unit hydrograph studies were carried out by many investigators, where the model parameters were related directly or indirectly, with physiographic and storm characteristics for the catchments of a region. With the advent of digital computers and improvement in hydrological data base, hydrologists and researchers are now a days giving more attention towards the modelling of hydrological processes using conceptual and physically based models. Most of the developments in the field of modelling of hydrological processes have taken place at universities and research institutions in India. However, scope of their applications is somewhat limited in planning and management of water resources systems because of poor data base and lack of co-ordination between water resources management and researchers. As such, hydrological models have, in general, not been judged in terms of their data, computer or expertise requirements, or weather or not their use leads to better management decisions. The technical evaluation of models has mostly been in terms of how well the model fits historic hydrological data. In India, due to poor status of hydrological data base, difficulties are often encountered in estimating the models parameters accurately and also in transferring the use of a model from one region to another.

Some of the typical studies carried out in India since independence are briefly revewed here under.

Ilangovan (1970) used a few mathematical models proposed for the evaluation of the kernel function and applied them to actual basins in order to compare their practical usefulness and the accuracy of their results. The study also presents a brief review of a large number of mathematical models proposed so far.

Mathur (1972) used a series combination of linear channels to represent the catchment response. Parameters of this conceptual model are derived from one of the recorded events on the catchment. As each channel in this series combination represents a certain portion of the catchment, it has been possible to account for the uneven spatial distribution of rainfall input. The model evolved has been tested on four gauged catchments located in different meteorological zones of India. It has been shown that close agreement between the computed and observed hydrographs can be achieved even in the case of most unevenly distributed rainfall inputs.

Jaiswal (1973) presented a study dealing with the Ramganga drainage basin (catchment area 1210 sq.miles) and Brahmani drainage basin (catchment area 277.5 sq.miles) taken as a linear system and three techniques of mathematical modelling known as conceptual model, polynomial method and black box method have been applied to generate unit graphs for three storms of Ramganga basin, the flood hydrograph for each storm has been developed for the comparison of the methods. It is found that polynomial method is better suited to the Ramganga basin and black box method to the Brahmani basin.

Viswanathan (1975) reviewed some of the models on rainfall-runoff relationship using systems approach and summarized some of the techniques adopted in systems analysis of rainfall-runoff relationship. The study is confined to deterministic system models only.

Rao (1975) evolved a model for achieving computational efficiency and for facilitating its use in the solution of engineering problems. It has been found that the dimensionless instantaneous unit hydrograph is unique for a given non-linear network model. The relationship between the response of the non-linear network model and that of a single non-linear reservoir, both having same area and recession parameters, has been worked out. The sensitivity of the network model to different empirical/subjective techniques of baseflow separation and rainfall excess evaluation is examined and the significance of the results for practical application is evaluated. The relationships between the parameters of a network of linear reservoirs those of a network of non-linear reservoirs, both networks having practically the same response when fed with the same input also have been investigated.

Bairathi (1976) discussed the various rainfall runoff relationships and some of the hydrologic simulation models that synthesise streamflow record from precipitation and other climatological data. Author also applied a continuous daily stream flow model, developed by Tennessee Valley Authority, to a Rajasthan catchment after making suitable modifications. Further more, daily stream flow for Wagli watershed was simulated using the above model.

Ponnambalam and O'Connor (1981) compared the efficiencies of discrete analogy of Nash Cascade Model, Descrete form of Muskingum Channel routing model, continuous Muskingum Channel routing model and modified Muskingum Channel routing model for storm runoff from effective rainfall. The six storms of Kateri basin (Tamil Nadu) were selected for the study.

Sakthivadivel, Rao, Lakshamanan and Venugopal (1981) used a methematical model for estimating the basin runoff, based on the channel routing and basin routing equations proposed by Chow and Kulandaiswamy. The model parameters are expressed as functions of known input characteristics and a method for their estimation using step wise regression and polynomial fits, is presented. The model is applied to 8 storm events in Duck River basin.

Datta and Mishra (1982) verified the relationship between the outflow and detention storage at equilibrium and during unsteady states as proposed in Horton Izzard using method of characteristics.

Ekbote and Bhave (1982) verified suitability of tank model in a study. The efficiency of the model is tested for Western Ghats catchment.

Soni and Mishra (1982-83) applied Betson and USGS model for simulating the runoff from Kasurnala basin in Punjab. From this study, authors found that Betson model simulated the peak value and recession limb satisfactorily. However, the simulated rising limb did not match very well with observed rising limb. Also it was observed that the basin response for small storms was negligible at the beginning and end of the monsoon. The U.S.G.S. model was calibrated for different combination of flood events. It has simulated the peak flow and direct runoff volume quite accurately.

Datta and Seth (1983-84) carried out a study where 4 x 4 Tank model developed by Sugawara was used to simulate daily runoff for two sub-basins Jamtara and Ginnore in Narmada basin. From the analysis it was observed that the 4 x 4 Tank model is a suitable daily rainfall runoff model for simulation of daily runoff for basins in India which experience nearly 75% to 90% of annual rainfall during monsoon season followed by long dry period in non-monsoon months.

Seth, Datta and Singh (1984-85) mentioned that application of mathematical modelling techniques to the constituent processes involving physical processes of runoff generation have led to better understanding of the processes and their interaction. The authors have carried out a comparative study of model structures for various processes considered in different watershed models to ascertain model structure for each component process for typical physiographic and hydrometeorological conditions of river basins in India. Different simplified techniques and model structures for component processes have been identified which may be considered for developing rainfall runoff models suited to Indian conditions.

Singh and Seth (1984-85) stated that the accurate estimation of the direct surface runoff provides better estimates of flood peaks and frequencies. Numerical model based upon kinematic wave equations can be used to calculate runoff hydrographs resulting from rainfall on small watershed as it overcomes the deficiencies associated with the linear models. The kinematic wave approximation model has also advantages over the linear model for predicting runoff for ungauged watersheds. A general review has been made for different numerical schemes utilized by various investigators for modelling the overland flow. The advantages and limitations of these numerical schemes have also been described.

Singh and Seth (1984-85) described step by step procedure to estimate the model parameters using the physiographic characteristics of the catchments. A computer programme MULTI.FOR is given which can be used for the above purpose. The programme has been implemented and tested on VAX-11/780 system. The programme could be run on other computer systems having, FORTRAN compiler after making suitable modifications in the programme.

Singh and Seth (1984-85) developed software for the derivation of unit hydrograph using Nash cascade model approach. The programs developed have been tested on VAX-11/780 system available at National Institute of Hydrology, Roorkee. The program, input and output specifications and test input and test output are given in this User's Manual.

Seth and Ramasastri (1985-86) reviewed rainfall runoff relationships covering empirical formulae, the graphical and statistical relationships including some of the rainfall-runoff relationships used by the state and central water resources organisations. It has been indicated that except for a few, most of the rainfall-runoff relationships use only rainfall for relating with runoff. The need for incorporation of appropriate climatic and physiographic factors either directly or through their derivatives has been highlighted.

Singh (1986) presented a method for estimating the parameters of Discrete Cascade Model. The method uses a particular quasi Newton method optimization procedure developed by Davidon et al. The data used in the study is obtained by calculating an exact input (excess rainfall) output (direct surface) relationship for two events and adding spurious noise to output series. The optimum parameters are estimated minimising the objective function obtained after combining together the input-output series for each event. The reproduction of the events using the optimum parameters of the Discrete Cascade Model are reported to be satisfactory.

Ramasastri and Seth (1986) attempted a sensitivity analysis study using HEC-1 stream network model to assess the influence of change in the values of unit hydrograph, loss rate and routing parameters for the large, elongated catchment of river Narmada upto Sardar Sarovar dam site. It is observed that changes in Clarks unit hydrographs parameters Tc and R, Muskingum Routing parameters x and loss rate values have relatively more influence on estimated flood peak in comparison to Muksingum parameter K, which lags the u/s hydrographs.

Singh and Perumal (1986) applied integer Nash Model which is a simplified form of conventional Nash model for deriving the unit hydrographs using the rainfall-runoff data of six isolated storm events of the catchment Bridge No.807/1 of Godavari basin sub-zone-3 (f). The results obtained using integer Nash Model compare well with those obtained by conventional Nash Model which requires the use of Pearson incomplete gamma function tables or computer programme.

Palaniappan and Ramasastri (1986-87) applied a distributed model using method of characteristics and a concept of a homogeneous response units. A watershed used by Ross and others in 1978 for testing their model was chosen for the application of the present model, considering the availability of data necessary for the model. Results showed good performance of the model. The computed hydrograph nearly matches that of Ross and others.

SHE model which is a deterministic, distributed and physically based modelling system for all land phase components of hydrologic cycle has been used by National Institute of Hydrology Roorkee (1988) to simulate the response of six sub-basins of Narmada Basin and two other Indian sub-basins.Its applications have been successful for simulating the response of different sub-basins within the constraints of data availability and inconsistencies associated with the data. The model is capable of providing the solutions to more complicated hydrological problems and it has also been applied to study the effect of land use changes on hydrological regimes for Kolar sub-basin of Narmada river basin and irrigation return flows in Barna command area.

(b) Stochastic Hydrological Models

Hydrologic data of sufficiently long duration are essential for taking better decisions in planning, design and operation of water resources projects for optimum development and to avoid risks of under-designing or uneconomic costs of over-designing. However, these objectives cannot be fulfilled with the generally available data base and usually adoped design procedures. To overcome this deficiency and because of inadequacy of traditional deterministic methods of hydrologic analysis, research investigators have made developments in the fields of mathematical statistics and probability theory to evolve a field of specialization called 'stochastic hydrology'. The modelling techniques developed in this field provide methods to generate a number of streamflow sequences for a longer period using the statistical information of observed short term data. All hydrologic processes are phenomena that change with time and are more or less stochastic in nature. If the available data record is of sufficient length so that it can be considered as a representative sample, the statistical parameters derived from it will enable the formulation of a reliable stochastic model. The data generated by this model will qualitatively be no way better than the historical observed data. But the major advantage of data generation techniques of stochastic hydrology is that many combinations of different patterns of data sequences can be synthetically generated for a length longer than the observed data.

The sequence of values of any hydrologic phenomenon, such as streamflow, arranged in order of their time of occurrence constitute a hydrologic time series. Example of hydrologic time series are sequences of annual or monthly or daily values of streamflow. In comparison with annual streamflow, the monthly streamflow series is twelve times longer. Moreover, a series of monthly streamflow values displays a cycle of twelve months and its subharmonics, which are marked in annual discrete series. Though continuous series or daily flow values give more statistical information, the information provided by monthly flow values are generally sufficient and are used in water resources planning projects where flow regulation within the year is involved.

The hydrologic time process and the time series are termed as stationary if their probability distribution does not change with time, otherwise the time series is non-stationary. All hydrologic time series have some degree of non-stationarity which may be due to natural or man made changes in basins or inconsistency of data. The sequences of natural annual runoff from river basins may be regarded as approximately stationary time series.

The characteristics feature of time series in contradiction to other statis ical subjects is that the observations occur in temporal order. The analysis of time series have been in use in extracting information on hydrologic and water resources data. Both short memory models include Auto regressive (AR), Moving Average (MV), Auto regressive Moving Average (ARMA) Models. Log Memory Models such as fast fractional Gaussian noise, filtered fractional Gaussian noise and broken line models are also in use.

Synthesis of rainfall data

The adequate development of water resources requires the use of planning techniques which depend to a large extent on reliable estimates of key hydrologic variables such as streamflow. Although many streams have been gauged to provide continuous streamflow records, very often little or no information is available for point of interest. For areas with inadequate streamflow data, techniques have been developed, which synthesize the sequences of rainfall data and use such generated sequences to obtain streamflow sequences. This technique which combines synthesis with simulation enables the synthetic generation of streamflow data samples of periods longer than that of historical data for better design of projects by providing possible patterns of extreme cases. Moreover, the generation of synthetic sequences of rainfall data provides the best alternative since rainfall records constitute the largest data base. The rainfall records are also generally unaffected by watershed developments and hence the parameters derived from them are more stable.

In the beginning of twentieth century the study of stochastic structure of time series of rainfall data began. It was observed that the wet and dry weather have persistence. Pattison developed a method for the generation of hourly rainfall series at a raingauge station. He divided the year into periods and assumed that each period has a uniform probability. Grace and Eagleson studied rainfall of ten minute time intervals for summer storms. Raudkivi and Lawgun developed a stochastic model consisting of dependent stochastic component and non-normally distributed random component, for generation of rainfall sequences for ten minute time intervals. A systematic methodology for synthesis of spatially distributed short time increment rainfall sequences was proposed by Tavares and Wilkinson. Cole and Sheriff used single and multisite models for the synthesis of rainfall records. In 1971, Krager presented a methodology to generate synthetic sequences of daily rainfall at more than one station. It is observed from these studies that suitability of method for multi-station rainfall generation will depend on its adequacy to account for rainfall variability in space and also computer time involved. In order to economise on computer time and also due to general availability of data, daily rainfall generation is feasible for developing countries.

Modelling of monthly stremflow series

The first approach is that of time series models wherein it is assumed that a non-stationary hydrologic process can be decomposed into a deterministic component and a stationary stochastic process. The study of Roesner and Yevjevich following this approach showed that the description of periodic component in monthly runoff series usually required five or all the six harmonics of the twelve month period. Yevjevich presented a detailed analysis of the structure of hydrologic time series on these lines and showed that this approach does not perpetuate various biases which are present in historic samples. The basic assumption of this approach is that causative forces responsible for the production of the deterministic and stochastic components operate independently. The second approach is based exclusively on the non stationarity of the time series. One such approach is that of Thomas and Fiering.

Some of the typical studies carried out in India since independence are briefly reviewed here under.

Agarwal (1972) applied the modern hydrologic technique known as 'Sequential Generation' for the time dependent series of rainfall data, recorded at Lucknow for ten years and for the runoff data at Bhimgoda Head Works for 21 years. In this study non-stationary Morkov-chain model was found satisfactory. The data were generated for all hours in case of rainfall and for all months in case of runoff for all 100 years with the help of pseudo random numbers. The sequentially generated series is found to be fairly representative of the characteristics of the historical data thus providing a usefull method for studying random characteristics of rainfall and other hydrologic data.

Spolia (1972) applied Markovian-chain probability model to generate streamflow for three rivers, namely Beas, Sutlej and Ravi. Preservation of mean and variance and agreement between the probability distribution functions for the recorded and simulated sequences is depicted. Statistical parameters of 100 year simulated sequences generated based on statistical parameters obtained from 49, 40, 30, 20 and 10 years of record are compared with those of the corresponding historical sequence. Multiple regression method has been applied to establish deterministic relationship for each month between streamflow for the current month and streamflow for the previous month, precipitation for the previous and current month, and cumulative precipitation up to the month under consideration.

Pahuja (1974) formulated a mathematical model for time series of monthly runoff values for river Yamuna at Tejawala to generate synthetic stream flows. The monthly time series are first analysed for trend by using moving average process. This analysis has not indicated any definite long term pattern. Periodicities are detected by constructing correlogram and spectral analysis, which have showed that the cyclic component consists of a predominant 12 months cycle, with sub harmonics of 6, 4 and 3 months. A fourier series model with eight parameters has been fitted to the cyclic component. As the correlogram of the residual series, after removal of cyclic component has indicated first lag to be significant, a first order Markov model is fitted to the stochastic component . The variance of the recorded time series explained by cyclic component is 74%, by stochastic component is 0.8%, and by random component is 25.2%. The model so formulated considering both the deterministic and stochastic components has been used to generate synthetic monthly stream flows and the performance of the model in maintaining the statistical properties is founded to be generally satisfactory.

Murthy (1976) attempted to analyse and compare formulation of models of monthly runoff sequences by stationary and non-stationary approaches. Time series model is used for stationary approach and Thomas Fiering model is used for non-stationary approach. The statistical parameters of observed and generated series compare favourably for Thomas-Fiering model fitting to the historical data and its square root transformation as compared to log transformation. Elimination of negative values in generated data by Thomas-Fiering model does not distort the population statistics significantly. The effect of elimination of negative values in the generated data by time series model is significant which is attributed to short period of observed data.

Krishnasami (1976) carried out decoupled multivariate time series modelling for multisite streamflows using concurrent annual, monthly and ten day stream flows data for three tributaries to a major river in north India after normalisation when necessary and non-parametric standardization. Author decoupled within the station variation at each site, after fitting univariate models and among stations variations fitting a multivariate model to the univariate residuals.

Ammanagi (1976) carried out a stochastic analysis of monthly streamflows at three locations in Krishna Basin: Dhupdal, Lakkavalli and Vijaywada. Convergence of the mean and standard deviation of the streamflows was tested at each location. Standardised monthly flows were found to be nearly normally distributed in all cases. Correlograms and power spectra were constructed for the standardised flow series and the flows were found to have periodicities of 12, 24, 36 and 48 months, in general, at 95% confidence level.

Ayyappaswamy (1978) carried out water balance studies and synthetic generation of monthly yield from anicuts catchment area using the available data spanning over 13 years. From the water balance studies of Tambaraparani basin, the total annual mean yield of the basin works out to 1054 M cum. (37216 Mc ft.) Out of this mean annual flow of 128 M cum (4530 Mc ft) goes as surplus at Srivaikuntam anicut. The percentage contribution of Tambaraparani river, Manimuthar and anicuts catchment yield including other tributaries works out to 54%, 10% and 36% respectively. Analysis of inflow and outflow discharge for each anicut indicates that in more than 50 percent of the anicuts, there is considerable amount of return flow.

Seth and Mihaya (1981) decomposed the time series of daily flows for monsoon season for data of 10 years of Kalagarh into deterministic and stochastic components. Correlogram analysis has been used in order to identify the order of dependent stochastic component.

Rao, Srivastava and Singh (1981) generated streamflow data of intermittent streams situated in forested mountainous watershed of upper Brahmani Basin by Modified Thomas Fiering model.

Goel, Bhatia and Seth (1984-85) generated monthly streamflow data for Chaliar basin using first order Thomas Fiering model. Four cases, i.e. (i) without any transformation (including negative flows), (ii) with square root transformation, (iii) with logarithmic transformation and (iv) without any transformation but excluding negative flows have been studied. Authors observed that Thomas Fiering model with square root transformation was able to produce monthly means in a better way for most of the sites of Chaliyar river basin of Kerala.

Seth and Goel (1985-86) gave a brief review of a time series models and steps used for time series modelling. Various criteria for the classification of time series models have been described. Available time series models are explained in the light of short memory models and long memory models. Disaggregation model and multisite models have been explained. Some of the areas in which further study and research are needed have also been identified.

Seth (1986) discussed that the assessment and forecasting of surface water yield using the pattern emerging from past flow observations is based on assumption of stationary time invariant stochastic process. In principle, it is a problem of water balance under effects of landuse and management with given or forecasted input precipitation and evapotranspiration demand. The success of long term forecasting would depend on the presence of persistence in concerned time series due to carryover effects of soil moisture, snow groundwater or surface water. Prior knowledge of the meteorological conditions increases the accuracy and reliability of forecasts. The author remarked that inspite of recent developments in numerical weather prediction, reliable method for use in hydrological forecasting is yet to be evolved.

NIH (1986) on 'Water Availability Studies for Mahanadi River Basin at Three Sites' describes that the main objective of the project was to evolve long term yield series and determine the water availability at three sites on Mahanadi river, namely: Hirakud, Tikarpara and Naraj, using stream flow data, rainfall data and other information, and applying appropriate statistical and other techniques. The scope of the study included examination of streamflow data for its general consistency and gap filling, and also included processing and analysis of rainfall data. The study also included effect of Hirakud dam on the discharge observed downstream and evolved appropriate yield series for virgin flow and the series resulting from effect of reservoir storage. The National Institute of Hydrology submitted an interim report describing the development of methodology in March 1984, followed by a technical note on the 'Rainfall Analysis of Mahanadi River Basin between Hirakud and Naraj' in May 1984.

Goel, Seth, and Nirupma (1986-87) developed the computer program for Bivariate Thomas Fiering model based on the algorithm given by Clarke. This has been used for 11 years, 37 years and 100 years, simultaneous generation of monthly streamflows at (i) Hirakud and Salebhata, and (ii) Hirakud and Kantamal using 11 years concurrent period (1972-82) observed data. The results indicate good performance of the Bivariate Thomas Fiering model for the generation of monthly stream flows at two sites simultaneously. The model satisfactorily preserves monthly means, standard deviations. correlation with previous month and cross correlation structure between the sites.

Seth, Singh and Perumal (1986-87) developed methodology for transforming the peak annual flood series to follow Gumbel EV-1 distribution using Box-Cox transformation. This methodology has been tested using 1000 samples of various sample sizes of randomly gnerated synthetic flood series which follow the Pearson type III distribution. It is seen that population estimates are satisfactorily reproduced by using the proposed method of frequency analysis.

Rao(1988) carried out stochastic modelling of lowflows in Mahanadi basin. the author states that the past studies on lowflows indicate that stochastic models using double exponential distribution function give better fit to these type of data. Hence, in this study an attempt has been made to fit the lowflows, observed at Sambalpur and Naraj in Mahanadi basin, using the above type stochastic model.

REMARKS

Most of the advanced hydrological models have been developed abroad under prevailing conditions and assumptions. Generally Indian Hydrologists and Researchers have been involved in the application of those models to the Indian catchments making necessary modifications in the models wherever necessary to suit the local conditions. There is an urgent need to develop hydroloical models for Indian conditions which should be easily transposable from one hydro-metereological region to the other keeping in mind the problem, data availabilty and computational facilities.

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