HYDROLOGIC DESIGN

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INTRODUCTION

Hydrology is one of the earth sciences which deals with studies of the waters of the earth, their occurrence, circulation and distribution, their chemical and physical properties and their relation to living things. Engineering hydrology uses hydrologic principles in the solution of engineering problems arising from human exploitation of the water resources of the earth. It seeks to establish relations defining the spatial, temporal, seasonal, annual, regional or geographical variability of water, with the aim of ascertaining social risks involved in sizing hydraulic structures and systems. Engineering hydrology seeks to answer following types of questions:

(i) What is the maximum probable flood at a proposed dam site?

(ii) How does a catchment's water yield vary from season to season and from year to year?

(iii) What is the relationship between a catchment's surface water and groundwater resources?

(iv) When evaluating low flow characteristics, what flow level can be expected to be exceeded 90 % of time?

(v) Given the natural variability of stream flows, what is the appropriate size of an instream storage reservoir?

(vi) What hydrologic hardware eg. rainfall sensors and software (computer models) are needed for hydrological forecasting?

There are many approaches to engineering hydrology and all formal models for dealing with hydrological problems are generally mathematical in nature. These could be deterministic, probabilistic, conceptual or parametric, and involve assumptions regarding linearity, time invariance, lumped nature and discrete time intervals. Catchment models can be either (i) event driven (or event) and (ii) continuous process models. Event models are short term and are designed to simulate individual rainfall-runoff events. Continuous process models take explicit account of all runoff components and aim at accounting of the catchments overall moisture balance on a long term basis. Continuous process models are suited for simulation of daily, monthly or seasonal streamflow, usually for long term runoff volume forecasting and estimation of water yield.

Hydrologic design and hydrologic forecasting form important components of hydrology. In hydrologic design, the objective is to predict the behaviour of hydrologic variables

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under a hypothetical extreme condition such as the 100 year flood or the probable maximum flood. In hydrologic forecasting the aim is to predict the behaviour of hydrologic variables within a shorter time frame, either daily, monthly, seasonally or annually. Hydrologic design precedes hydraulic design i.e. the output of hydrologic design is the input to hydraulic design. Hydrologic design determines streamflow, discharges and headwater levels from which hydraulic design derives flow depths, velocities and pressures acting on hydraulic structures and systems. In practice, hydrologic design translates into hydrologic design criteria i.e. a set of rules and procedures used by various agencies and organisation dealing with water resources development and management. These criteria may vary depending upon the charter and jurisdiction as well as the size and scope of individual projects. Ponce (1989) has given an excellent review and description of selected design criteria and procedures used by (i) NOAA National Weather Service (ii) U.S. Army Corps of Engineers (iii) USDA Soil Conservation Service (iv) U.S. Bureau of Reclamation, (v) Tennessee Valley Authority and (vi) U.S. Geological Survey. These include criteria for probable maximum precipitation, standard project flood determination, spillway design criteria, synthetic unit hydrographs, dimensionless unit hydrographs, flood hydrograph development, probable maximum flood and flood peak estimation for ungaged sites using frequency approach.

The Central Board of Irrigation and Power brought out a manual on river behaviour control and training in year 1956 to give comprehensive information to the field engineer and also to provide food for thought to the research worker to further his studies. This manual was compiled by Sh. D.V Joglekar, Director, Central Water and Power Research Station, Poona assisted by Sh. C.V. Gole and Dr. A.S. Apte. The manual was revised by Dr. D.V. Joglekar himself in 1971. The chapter on flood and sediment control provided information; formulae and guidelines for various aspects including the following :

(i) Adequate minimum number of raingauges.

(ii) Flood flow determination using envelope curve method, empirical formulae (Inglis formula, Dicken's formula, Ryve's formula etc.), rational method, probability method and unit hydrograph method.

(iii) While stressing the need for correct assessment of the design infiltration loss, graphical relations derived by plotting infiltration index against soil moisture index plus antecedent precipitation index with duration of rainfall as parameter was suggested.

(iv) The design flood discharge was defined as the maximum flood that would occur under average physiographic conditions of the watershed due to a design storm of given frequency. The design storm was defined as the storm which gives rise to the design flood for the particular catchment and has to be selected based on 'basin lag time' and the desired return period of the flood for which the structure is to be designed.

(v) The mean annual maximum flood was defined as that flood which would normally occur once in every 2.3 or 2 years on an average under normal physiographic conditions of the watershed due to a design maximum storm of 32.4 or 32 years frequency. It was suggested that the mean annual maximum flood can be computed from (a) the synthetic unit hydrograph derived for the particular catchment, and (b) the maximum 2 year t hour rainfall, where t is the basin lag in hours. The use of maximum 3 year 24 hour rainfall worked out by Parthasarathy (1958) and Krishnan, Raman and Vernekar (1958) of India Meteorological Department was recommended.

(vi) Realising that a flood of higher magnitude than the 50 year design flood can occur in the life time of a bridge, for design of foundations, an arbitrary empirical approach of increasing 50 year value by certain percentage upto 30 percent was suggested. It is also mentioned that the Khosla Committee of Engineers (1959) have suggested use of probable maximum flood for this purpose.

(vii) For the design of dams for flood control, omission of 10 percent of the highest storms of record was suggested and using the next lower one to determine the standard project flood was recommended.

(viii) For the safety of the dams with the storage of over 61.7 million cubic meter (50000 acre-feet), it was recommended that the spillway capacity provided should be sufficient to pass the maximum probable flood.

(ix) For flood embankments, it was suggested that a flood of return period of 100 years could be adopted depending on their importance.

The manual emphasized close cooperation between hydrological and meteorological agencies as well as interdisciplinary exchange of knowledge to evolve the most economical and efficient hydrologic designs of structures such as culverts, bridges, aqueducts and spillways.

Over the years, there have been many research projects of relevance to hydrologic design studied under research schemes of CBIP and under various schemes at State Research Stations, academic institutions, etc. These include: mathematical modelling, flood estimation, flood frequency analysis, rational and empirical approaches, morphometric studies, basin studies, water balance studies, computerised data systems, rainfall runoff relationships, flood routing studies, etc. In recent years, brief particulars of various research projects under study have been compiled by CBIP (1988). These include development of data base management system, software development, flood routing studies, multistation daily rainfall generation, design flood computation with limited data, hydrograph derivation using correlation technique, mathematical models for small tank catchments, development of hydrological models, effects of land use on hydrological regime, flood frequency studies, etc. Significant contributions have been made through such studies by University of Roorkee, Anna University, Bihar College of Engineering, Center for Water Resources Development and Management, Kozhikode and various other research stations.

DESIGN DISCHARGE AND YIELD FOR SMALL AND MEDIUM CATCHMENTS

In the post independence period, and even after independence empirical formulae and approaches have been in use for flood and yield estimation for small and medium catchments. These are briefly discussed and recent developments in hydrometeorology and derivation of representative unit hydrographs for various sub-basins are described in following sections:

Empirical Flood Formula

Varshney (1979) has reviewed various empirical flood formulae including the more important formulae used in India even after independence. These include (i) Dickens formula which is generally applicable for moderate size basins in North and Central India, (ii) Ryves formula which was derived from a study of river basins in South India, (iii) Inglis formula which was derived on the basis of data of rivers of Maharashtra, (iv) Ali Nawaz Jung formula which was derived for application in South and North India.

UP IRI (1976) had carried out flood frequency studies on Himalayan Rivers having some snowbound catchment viz. Tons at Kishau, Yamuna at Tajewala, Bhagirathi at Tehri, Ganga at Hardwar, Sharda at Banbassa, Ramganga at Kalagarh and a relationship was suggested for computing Dicken's constant C for given return periods and proportion of snow covered area. Varshney (1979) also mentions about studies of Kanwar Sain and Karpov who suggested use of envelope curves of plots between peak flood and catchment area, one for basins in Northern and Central India and the other for South India. These curves were used as a guidance in determining the maximum flood discharge for Nagarjun Sagar (A.P.), Matatila (U.P.), Deonar (Karnataka) projects, etc.

Empirical Formulae and Tables for Yield Estimation

Varshney (1979) mentions about work of Sir Alexandar Binnie who was probably the first to develop annual rainfall runoff relation based on observations of two rivers in Madhya Pradesh. T.G. Barlow carried out studies of small catchments in U.P. and suggested values of runoff coefficient as a percentage for different catchment conditions, viz. (i) flat, cultivated black cotton soils, (ii) flat, partly cultivated soils, (iii) average, (iv) hills and plains with little cultivation, (v) very hilly and steep with hardly any cultivation, as well as for different nature of seasons, viz. (i) light rain, no heavy downpour, (ii) average or varying rainfall, no continuous downpour, (iii) continuous downpour. He also divided special tropical rainfall into four classes. W.L. Strange evolved some ratios between runoff and rainfall based on data of Maharashtra. He accounted for the geological conditions of the catchment as good, average and bad and the surface condition as dry, damp and wet prior to rain. Khosla (1949) suggested a formula relating runoff and rainfall including mean temperature as a variable to account for losses due to evaporation.

Varshney (1979) also mentions about studies by R.D. Dhir, P.R. Ahuja and K.C. Majumdar in 1958 for development of annual rainfall runoff relationships for 10 basins using linear regression approach. U.P. Irrigation Research Institute also carried out studies on similar lines for Himalayan rivers using nonlinear relationship and for Bundelkhand rivers using linear relationships. Soil Conservation Research, Demonstration & Training Center, Dehradun analyzed rainfall and runoff data of 17 sub-watersheds (areas less than 100 sq. km.) in Nilgiri Hills and developed multiple nonlinear regression relation for annual rainfall and runoff including parameters like catchment perimeter, stream length, relief, drainage density, time of concentration, etc.

Hydrometeorological Activities

The foundation of hydrometeorology in India was laid down from the year 1890. During the first half of the 20th century, some eminent engineers studied the relationships of runoff to rainfall. Pioneering work was done in this direction by Binnie, Strange, Inglis and Desouza and Lacey. Various empirical formulae and procedures/ methods developed by them are still in use in many parts of the country. Khosla (1949) worked out the total water potential of India based on the concept that runoff is the residual after deduction of losses caused by evaporation and transpiration. Immediately after independence in 1947, a number of multipurpose river valley projects were taken up by the Central and State Governments. Some of these projects which have been completed and are in full operation are: Hirakud in Orissa, Bhakhra Nangal and Pong in Punjab and H.P., Rihand and Matatitla in U.P., D.V.C. Projects, Mayurakshi in West Bengal, Rana Pratap Sagar and Jawahar Sagar in Rajasthan, Koyna in Maharashtra, Gandhi Sagar in M.P., etc. These all involved improvement in hydrometeorological network, and use of various procedures and technologies for hydrological analysis and design.

Various studies on hydrometeorology carried out since independence include: (i) Rainfall distribution over contiguous Indian area, (ii) Basin rainfall studies, (iii) Studies of intense rainstorms, (iv) Probable maximum point precipitation, (v) Rainfall intensity, duration frequency studies, (vi) Variability of rainfall, etc. Dhar (1987) had discussed these activities and had also suggested future activities for hydrometeorological studies. These include: (i) Creation of Central agency for rainfall organization in India, (ii) Self recording raingauge network, (iii) Generalized charts of areal PMP, (iv) Seasonal snow cover information using satellite imageries.

Representative Unit Hydrographs - Studies by Central Water Commission

In the early years, the design discharges for road and railway bridges crossing a number of small and medium catchments were calculated by well known empirical formulae viz. Dickens, Ryves, Inglis, Ali Nawaz Jung, etc. The need to evolve a method of estimation of design flood peak of desired frequency knowing the physical characteristics of the catchment and storm rainfall was recognized and the Committee of Engineers under the Chairmanship of Dr. A N Khosla had recommended in 1959, detailed studies to evolve a method based on unit hydrograph principle to derive the design flood. Systematic and sustained collection of hydrometeorological data from the representative catchments in different zones of the country was started in 1965. For this purpose, the country was divided into 7 major zones and which are, in turn sub-divided into 26 hydrometeorologically homogeneous subzones of moderate size. Out of 26 subzones, gauging was carried out in 22 subzones and in each subzone 10 to 25 catchments were selected for collection of data. The list of hydrometeorological subzones is given in Appendix-1.

For each catchment representative unit hydrographs have been derived utilising the observed rainfall and runoff. To enable the computation of design flood for ungauged catchments, the parameters of the unit hydrographs have been correlated with the physical characteristics of the catchment by regression analysis and equations were derived for a synthetic unit hydrograph of the subzone. The reports prepared for each subzone for which studies have been carried out so far, also include the rainfall depth-duration-frequency studies as well as point to areal distribution ratios and time distribution of storms studies made by Hydromet cell of India Meteorological Department. The reports also deal with loss rate studies and general methodology to be adopted for estimating a design flood.

The reports for following 17 subzones have so far been completed and published. The results are generally applicable for small and medium catchments of sizes as indicated in each report.

1.	Lower Gangetic Plains subzone (Subzone lg)	-		1978
2.	Lower Godavari basin subzone (Subzone 3f)	-	June	1980
3.	Lower Narmada and Tapi (Subzone 3b)	-	May	1982
4.	Upper Mahanadi (Subzone 3d)	-	May	1982
5.	Upper Narmada & Tapi (Subzone 3c)	-	July	1983
6.	Krishna & Pennar (Subzone 3h)	-	Sept.	1983
7.	South Brahmaputra (Subzone 2b)	-		1984
8	Upper Indo Ganga Plains (subzone le)	-	Dec.	1984
9.	Middle Ganga Plains (Subzone lf)	-	Oct.	1985
10.	Kaveri Basin (Subzone 3i)	-	Jan.	1986
11.	Upper Godavari (Subzone 3e)	-	July	1986
12.	Mahi and Sabarmati (Subzone 3a)	-	Jan.	1987
13.	Eastern Coast Region (Upper, Lower and South) (Subzones 4 a, b & c)	-	Jan.	1987
14.	Sone (Subzone ld)	-	Aug.	1987
15.	Chambal (Subzone 1b)	-	Dec.	1988
16.	Betwa (Subzone lc)	-	June	1989
17.	North Brahmaputra (Subzone 2a)	-	Jan.	1991

During last 45 years since independence there have been a number of studies involving some aspects of hydrologic design and various levels of sophistication and technologies: (i) as a part of preparation of hydrology of projects at State or Central level; (ii) as dissertations/thesis under academic programs, (iii) under various R & D activities in research institutions, and (iv) under technology transfer and consultancy research projects and programs. It is not feasible and also relevant to try to make a complete review of all such studies. An attempt has, therefore, been made to make a brief review of some typical studies which have been published in journals or proceedings and were readily available. This in no way reflects on many other excellent studies made in the country over all these years and are not specifically reviewed.

SOME TYPICAL STUDIES

Flood Frequency Studies

Panchang (1967) refers to the problem of inaccuracy involved in estimating two parameters of Gumbel's extreme value distribution from the available short term data using method of moments procedure. It is pointed out that application of the method of maximum likelihood as per procedure developed by Panchang and Agarwal (1962) reduces all the routine computational steps to a schematized format for evaluating the parameters. The author also illustrates the efficacy of the computational procedure using peak flood series data of river Sabarmati at Dharoi for 1935 to 1952, as well as by comparison of flood estimates for different return periods by two methods for 16 sites on different rivers in India.

Bhatnagar (1967) used annual stage data for 20 bridge sites in Central India for regional stage frequency analysis. The author presented the results as a set of two curves, one correlating annual stage as ratio to mean annual flood stage with recurrence interval and the other correlating mean annual stage with catchment area for two zones comprising the region. It was stated that stage and frequency of floods for any catchment in this region can be determined by the use of these two curves.

Seth and Sheshaprasad (1980) considered the high outlier effect in flood frequency analysis for annual peak flood series of four river sites in Cauvery basin and three river sites in Ganga basin. The percentage variations in the estimation of floods with and without outlier effect varied from six to sixteen per cent.

Agarwal et al (1984) dealt with the problem of limited data availability while estimating design flood for Tehri Dam. The available data and information on same river at other sites as well as data for similar catchments on other streams was utilized. Probable maximum flood was evaluated using conventional unit hydrograph based approach and the results were compared with frequency flood estimates using various approaches, viz. empirical, index station, log of peak, Langbein log deviation method, regional analysis, etc. The authors recommended a judicious judgment based approach for dealing with data limitations.

Singh and Seth (1985) fitted five parameter Wakeby distribution to the annual maximum flood series of rivers Pagladiya, Pachnoi and Manas. The results were compared with those for Gumbel EV1 and log Pearson Type III distributions. The Wakeby distribution was found to be more consistent.

Goel et al (1986) highlighted details of a study for estimation of flood magnitudes of different return periods for Narmada Sagar Dam using partial duration series approach.

Goel et al (1989) carried out regional flood frequency analysis using data of sites in Jhelum river basin and made an intercomparison of the performance using USGS (least squares method), USGS (method of moments) and NERC approaches. The USGS (LSM) method was found to perform better for data used in the study.

Goel (1990) studied various flood characteristics such as flood peak, volume, duration, etc. and their interdependence for a typical flood series using daily discharge data of river Narmada at Garudeswar for 1949-79. The methodology for stochastic modelling of flood flows developed in this study provides flexibility of selecting any threshold level, any flood volume and any flood peak magnitude. This enables simultaneous determination of flood peak, volume and duration of specified frequency.

Agarwal et al (1991) carried out regional flood frequency analysis of hydrometerologically homogeneous region of Northern region rivers using power transformation technique.

The annual peak flood series data of 18 years from 1971 to 1988 for 16 gauged catchments with drainage areas varying from 1600 to 21794 sq.km. were used.. A comprehensive study was also made with results obtained using index flood method and five parameter Wakeby distribution using data of 15 sites for calibration and remaining one site for testing the performance. The authors recommended use of the regional relationships for hydraulic design for ungauged catchments in the region.

Lal and Tiwari (1991) suggested use of power transformation approach to transform the annual peak flood series data to suit the extreme value distribution with skewness = 1.139, for use in flood frequency analysis. Based on this approach, the authors presented a generalized formula.

Rainfall Runoff Models

Kharod (1971) analysed data of thirteen river gauging stations for South Gujarat River Basin and developed regional relationships for derivation of unit hydrograph.

Mathur (1972) carried out a study involving use of a series combination of linear channels to represent the catchment action and uneven spatial distribution of rainfall. The conceptual model was tested on four gauged catchments located in different meteorological zones of India.

Mutreja (1972) carried out a study for prediction of daily runoff at Kalagarh site for Ramganga river catchment using unit hydrograph based approach involving use of unit hydrographs for each of sub-basins, their conversion to flood hydrographs and superimposition to obtain flood hydrograph at outlet.

Babu Rao (1973) made a detailed investigation of the parameters of Kulandaiswamy model considering non-linearity directly and indirectly. The investigation of rainfall-runoff relationship consisted mainly of (i) estimation of rainfall excess, and (ii) conversion of rainfall excess to surface runoff and the combination of baseflow with the surface runoff to obtain runoff. A total of 227 storms over 19 natural basins were used in the study, which provided a significant contribution in evaluation of model parameters.

Rao (1975) presented a model of complex network of non-linear reservoirs with appropriate areas and storage discharge relationships to represent nonlinear behaviour of drainage basins. The theory of linear systems was applied for analysis of non-linear systems and the concepts developed in the study were tested with observed hydrologic data of a few catchments.

Ranjodh Singh (1976) presented a study involving use of a linear hydrological model for snowfed Himalayan catchment of Beas river.

Suri and Kumar (1976) extended the work of Holtan and Overton by considering parameters like storage coefficient and rainfall duration for flood events selected from catchments located in Krishna, Narmada, Brahmaputra and Indo Gangetic basins. High degree of correlation was obtained in estimated and observed peaks

Seth and Buragohain (1978) studied the regeneration performance of the Nash model in simulation of the excess rainfall direct runoff process for a catchment having non-uniform areal distribution of rainfall. Two alternatives were considered. In the first alternative the whole catchment was considered as one lumped unit, while in the second approach, the catchment was divided into sub-areas on the basis of tributary drainage areas and each sub-area was represented by Nash model. The second alternative gave a better performance in dealing with non-uniform areal distribution of rainfall.

Seth and Goswami (1980) considered the translation effect and areal non-uniformity of rainfall for a small basin with limited data using isochrones to divide the basin into sub-areas. Different alternative criteria for separation of obstructions from rainfall were also studied. The time area diagram was routed using hydrological routing of the Muskingum type.

A study of estimation of design flood for Rajghat dam on Betwa river was carried out at School of Hydrology (1980), University of Roorkee. This study involved use of storm transposition technique for the establishment of probable maximum precipitation over the basin and representative unit hydrograph using available storm rainfall runoff data, for estimation of the design flood. It also involved use of the Nash model for derivation of unit hydrograph for the basin. The study conducted with somewhat limited data, brought out the need for short duration storm rainfall and runoff data.

Subramanyam (1981) conducted unit hydrograph based studies of certain basins (having areas of 80 to 1400 sq. km.) in Saurashtra and developed a relation between catchment area and peak discharge of the form:

$$Qp = 53.27\ A^{0.7331}$$

where

Qp = peak discharge in m^3/sec.
and A = catchment area in sq. km.

It was also pointed out that Inglis formula that is widely used in Western India gives much lower values of peak discharge and as such is not suitable. The design storm depths adopted in study were derived from envelope curve of five historical storms.

Singh and Seth (1984) carried out regional unit hydrograph study for Godavari subbasin using Clark model. Regional graphical relationship of average values of model parameters and watershed characteristics was developed using data of five catchments and tested for independent data set of sixth catchment.

Desai et al (1984) presented results of estimation of probable maximum flood for Narmada river at Sardar Sarovar Dam site, having a catchment area of 88000 sq km. The hydrometeorological studies for determining PMF was done using two different modelling approaches, viz. (i) HEC-1 model based on Clark's instantaneous unit hydrograph developed by U.S. Army Corps of Engineers, and (ii) OPSET hydrologic model, which is revised version of the Stanford Watershed model. The estimated value of PMF was around 141560 cumecs and the results of both modelling approaches were found to be in fair agreement.

Mistry et al (1984) studied the effect of usual practice of adopting a single G-Q curve for estimation of annual yield of the rivers. The authors recommended that wherever the hydraulic conditions and observed data indicate looped rating curves, the same should be established and used for conversion of stage data to discharge data.

Sinha and Seth (1984) applied Nash model for unit hydrograph analysis using lumped and multiple input approaches for two small catchments in Godavari basin. Two alternatives of separation of infiltration in lumped input system approach were also studied. The multiple input system approach was found to be more efficient. It was also seen that inherent limitations of method of moments, procedure for separation of abstractions and non-uniformity of rainfall lead to variation in values of model parameters from storm to storm in a catchment.

Datta and Seth (1985) applied Tank model for flood and daily runoff analysis to some basins in India, namely: Belkheri, Jamtara and Ginnore subbasins of river Narmada. It was demonstrated that a 4 x 4 tank model structure is better suited for simulation of daily runoff.

Singh et al (1986) presented a study of relative performance of integer Nash model for deriving the unit hydrographs using the rainfall runoff data of six isolated storm events of a railway bridge catchment in Godavari basin. The simple approach of integer Nash model was found to perform well for the simulation of observed storm events.

Patel (1987) presented salient features of a computer program for design flood estimation using the known unit hydrograph, design storm and its distribution. The program incorporates facilities to arrange the rainfall excess values in a critical sequence.

Singh and Seth (1989) have made a comparative study of various methods for derivation of unit hydrographs for the small catchments. In all five methods, namely: Nash Model, Clark Model, Singh's Model, Collin's Method and least squares method were tested, using data for flood events of six small catchments of Godavari basin sub-zone 3f. The average unit hydrograph for each catchment were estimated using the average parameters obtained by taking the geometric means of the parameters for individual storm unit hydrograph in case of three conceptual models. However, the standard averaging procedure was used to estimate the average unit hydrograph for the Collins and least squares methods. The study indicated good performance of conceptual models in providing non-oscillating physically realizable unit hydrograph.

Singhsamant and Patra (1989) carried out a case study involving application of Kulandaiswamy model for estimation of inflow design flood for a typical dam for a catchment of area 168.5 sq.km. The model was used for obtaining instantaneous unit hydrograph and which was in turn used to obtain unit hydrograph. The results of the study were compared with the results obtained by using Clark's model.

Rao (1991) presented a methodology for estimating probable maximum flood due to monsoon rainfall storm in a large catchment with complex orography through a case study of Tsangpo-Dihang-Brahmaputra basin. A network of six linear reservoirs was used to account for the uneven distribution of rainfall in space. This study based on limited data identifies the data requirement to calibrate the model for this large basin.

Synthetic Data Generation

Mohan et al (1987) used multisite rainfall generation procedures for three stations to generate alternate sequence of daily rainfall data for monsoon period for 12 raingauge stations of the Beas basin. This was used for yield studies in Beas catchment with simple monthly/seasonal rainfall runoff relationships.

Design Storm Studies

Pareek and Mehra (1977) dealt with the problem regarding objective criterion of homogeneity for the purpose of storm transpositions for analysing past storms and use them in the the determination of spillway design flood. They suggested use of one parameter exponential density function as best fit distribution and comparison of probability of occurrence of some rain event in two catchments for deciding about transposability of storms from one catchment to other.

Dhar et al (1978) reported an interesting study for estimation of spillway design storm for the Betwa Basin upto Rajghat Dam site using both frequency analysis and storm transposition and maximization approaches. It was found that 3 day PMP rain depth upto Rajghat dam site has a return period of the order of 2.5 x 10^8 years while the 3 day envelope basin rain depth actually experienced by the basin during 1891 to 1966 has a return period of the order of 170 years only.

Seth and Obeysekera (1979) used six years of daily rainfall data of Naula catchment of Ramganga basin to develop a stochastic multistation rainfall generation model. Computer software was developed and synthetic rainfall sequences were generated for monsoon season.

Dhar and Nandargi (1989) analysed severe rainstorms of the Indian region roughly north of latitude 15° N and arranged their depth area duration (DAD) data statewise. For each state, envelope values of the DAD data are determined and tabulated for standard areas upto 38850 sq. km. for durations of 1, 2 and 3 days. The authors have also pointed out about absence of the generalized PMP charts for India, which are very much needed for estimation of design floods for hydraulic structures.

Mohile (1989) reviewed the status regarding need for an objective and standardised procedure for determination of hypothetical design storms to be used as a basis for the spillway design floods. It was noted that the main national organisations involved operationally in determination of design storms and the hydrology organisation of the Central Water Commission and the Hydrology/Hydrometeorology unit of the India Meteorological Department. The CWC documented its practices in regard to estimation of design flood in 1972 and the IMD has also standardised its procedure. However, these documents have not been updated subsequent to recent publications of WMO (1986) on determination of probable maximum precipitation. The ;author has pointed out urgent need for cataloguing of transposability limits and persistent dew points for major storms, preparing maps for maximum persistent dew points and for barriers etc. The author has also suggested that a working team of engineering hydrologists and hydrometeorologists could be set up to work on the various issues and to come up with an acceptable documental and standardised procedure for design storm determination.

Kulkarni and Kathuria (1990) have critically examined the status regarding the procedures adopted by Central Water Commission, India Meteorological Department and Indian Institute of Tropical Meteorology for the determination of design storms including issues related with storm analysis, transposition, maximisation, and temporal distribution of storm depth. It is seen that there is general similarity of approach in storm analysis. However, differences in assumptions regarding storm transposition, maximisation and temporal distribution make a substantial difference in the design flood estimates. The authors point out need for rationalisation and uniformity of approach.

Rao (1990) has critically examined the problem of temporal distribution of design storm rainfall and compared recommendations of Manuals of WMO (1986), CW & PC (1969) and IMD practice. The approximations involved in use of enveloping percentage depth duration curves for temporal distribution of 1 day, 2 day and 3 day storms are illustrated with typical examples. The author recommends that: (i) the sequence of rainfall depths to be adopted should be in accordance with storms characteristics of the area, (ii) the sequence should be such that the maximum summation of increments for any duration may be less than or equal to but not more than the PMP (Probable Maximum Precipitation) for the same duration, and (iii) increments of rainfall should be areal rainfall values and not be point rainfall values.

Upadhyay et al (1990) discussed some important aspects of design storm evaluation related with selection of storm and storm transposition. For snow bound catchments, the authors recommend that the depth of snowmelt during the storm period should be added to SPS (Standard Project Storm) and PMP (Probable Maximum Precipitation) values. It is also recommended that optimum conditions for snowmelt should be taken into account alongwith the optimum storm conditions. These would include both the snowpack condition as well as the meteorological condition.

Rao (1991) discussed the important role of the design storm depth of selected duration and frequency besides other parameters like loss rate, basin response function and baseflow. The author also made indepth examination of need for clock hour correction to 1 day design storm depth as per practice adopted by India Meteorological Department which involves increase of 1 day depth by 15% to obtain 24 hour depth. The author concludes that for higher 1 day rain depths, the correction factor decreases and approaches unity. It is recommended that the pattern of chronological distribution with 'one bell' for each day of the design storm may be adopted for catchments in India. The author also recommends thorough examination and discussion so as to formulate appropriate guidelines.

Rao and Madan (1991) used the information regarding maximum 1 day rainfall values, envelope DAD curves and IMD/IITM Atlas for 1 day point PMP estimates for arriving at standard project storm depth for Lodhari basin and corresponding design flood peak. It as indicated that the use of the IMD recommendations on design storm depth and its temporal distribution leads to much higher design flood peak. The authors recommended that design storm and flood evaluation procedures be codified so as to made them more objective and rational.

Snow Hydrology Studies

Seth (1981) presented results of a study for development of a snowmelt runoff model using information regarding areal extent of permanent and temporary snow covers by comparison of satellite imageries and observed data of daily precipitation, daily flow and daily temperature for premonsoon season for Beas basin. The parameters of the model were estimated using pattern search optimisation technique using least squares criteria. The model gave encouraging results.

Rao and Madan (1989) presented a study for review of design storm and flood studies for Salal dam in Chenab basin. It was stated that in PMF hydrograph development, many elements enter the analysis and the effect of each of these elements on the shape of the hydrograph and on the structural design features should be investigated through some sensitivity analysis. For a storage project, volume and duration above a certain discharge are more important than the flood peak as the damaging power and maximum water level after routing through storage are decided by the former The flood peak and hydrograph shape are determined by the time distribution of PMP storm adopted and the basin response function.

Roohani and Seth (1989) presented a study involving development of regression relationships between hydrological and morphometric parameters in the Chenab basin. The hydrological parameters invluded average annual peak flow, maximum peak flow and average annual flow, while the morphometric parameters were area, main stream length and Hickok parameter involving area, main stream slope and drainage density.

Design Flood Estimation

Ramasastri and Seth (1986) estimated design flood for Narmada Sagar and Sardar Sarovar projects using HEC1 model of subdividing the Narmada basin into a number of sub-catchments, estimating unit hydrograph and routing parameters and calibration of stream network model. The calibrated model was used to estimate the flood peaks due to alternate design storms recommended for Narmada Sagar and Sardar Sarovar. The study indicated the importance of the critical placement of the storm centre and consideration of storm movement in arriving at critical peak floods.

Design Flood Criteria

Ahuja & Shenoy (1967) have examined the criteria for the estimation of design floods for different types and categories of structures and discussed both when there is enough hydrometeorological data, and in cases when there is lack of data. The classification of dams, from the point of view of potential damage on failure and the corresponding recommended design floods, is based on the storage volume. Reservoirs which have storages above 50,000 acre-feet are classified in one category as major and medium projects and those below 50,000 acre-feet are termed as minor projects. In the case of major and medium dams, the 'maximum probable flood' is recommended for a spillway design flood, while for permanent barrages and minor projects the 'standard project flood' or a 100 year flood whichever is higher has been recommended. The design flood for coffer dams is determined on the basis of floods of 5 to 25 years frequency depending upon the period for which they are required and the risk of the damage resulting from their failure. For limited/scarce data situations, the authors mention about the assumption of a 50 year storm giving a 50 year flood for smaller basins, while for larger basins, a 25 year storm is adopted. They also mention about appointment of Expert Committee of Engineers in 1957 by Indian Railways as a consequence of several major railway disasters due to failure of bridges.

The Committee of Engineers in their report suggested a comparative study to evolve one selected formula or procedure for the whole of India, and also recommended formation of special cells in concerned government departments. A number of bridge sites (numbering around 275) were observed for accurate flood gauging for the past 7 to 8 years and this number was increased to 540 sites (of which 326 to be observed by the Indian Railways and the rest by the Roads Department). Raingauge network for bridge catchments have also been set up by installing both ordinary and self recording raingauges. The authors further mention that to obtain an integrated picture of the hydrological characteristics in different basins and subbasins, India has been divided into 7 major zones and 23 sub-zones, based on hydrometeorological similarities. Unit hydrograph studies have been undertaken for a large number of catchments ranging from 50 sq. miles to 1000 sq. miles and storm frequency analysis have also been started by Railways Designs and Standards Organisation.

Central Board of Irrigation & Power (1989) publication on river behaviour, management and training also provides a comprehensive chapter on Floods - Hydrology and Management. Under the methods of computation for design flood, empirical, rational, flood frequency, unit hydrograph, and watershed models are mentioned. It also distinguishes between small, medium and large catchments while commenting on applicability and suitability of different methods the concept of risk analysis and broadly follows the same general principle as were suggested by CWC (1972).

Rao (1990) dealt with various aspects of problems related with dam safety concerns from flood point of view. It was pointed out that flood frequency methods without theoretical base are highly unsatisfactory in their application to abnormally high floods with very low probability of occurrence. The hydrometeorological approach of probable maximum flood on the other hand gives an estimate of maximum flood based on data available upto the time of analysis and with no associated probability. While stressing the need for rationalisation of procedures for estimation of probable maximum precipitation and corresponding flood hydrograph, the author draws attention towards possibility of large errors with tendency to overestimate due to use of various assumptions regarding critical storm patterns (temporal and spatial), maximum possible storm rainfall with typically low loss rates besides those involved in unit hydrograph approach. The author advocates use of the statistical procedure for evaluation of probable maximum precipitation and suggests a modified procedure for temporal distribution of design storm rainfall to suit Indian conditions. It is suggested that general guidelines be drawn up with a view to rationalise PMF evaluation procedures so as to maintain consistency and objectivity. For this purpose some specific studies using data from representative catchments of different sizes and located in different climatic subzones is also recommended.

INSTITUTIONAL CONTRIBUTIONS

Estimation of Design Flood - Recommended Procedures

The Central Water & Power Commission (1972) realising the importance of hydrology and its fundamental role in the planning, development and rational utilisation of water resources brought out a concise publication on recommended procedures for estimation of design flood. This included explanation about data requirements and the procedures to be adopted in estimating design floods for dams and other hydraulic structures, for use in hydrologic design.

Proper selection of the design flood is of utmost importance as this affects both the safety and cost of any structure, not only those primarily for flood control. Too small a design flood for a major structure involves a high risk, not only of total failure of the structure and the services rendered by it, but also to the safety of persons and properties located downstream. An excessive design flood, on the other hand, will result in an unnecessarily costly structure, which may adversely affect the economic feasibility of the project.

Thus, in cases where virtually no risk can be accepted probable maximum flood is commonly adopted as the design flood, and in projects where the release of water due to structural failure or over topping will not endanger life or cause disastrous damage downstream design flood of lesser magnitude is adopted as it would be uneconomic to design such structures to withstand the probable maximum flood.

The criteria for design flood of dams and other hydraulic structures as recommended by the Central Water & Power Commission included the following:

(a) In the design of spillways for major and medium projects with storages more than 50,000 acre feet (6167 hectare meters) the probable maximum flood which is the maximum flood for which there is a reasonable chance of occurring at the site should be used. The method of estimation of the probable maximum flood is the one using the unit hydrograph principle and the probable maximum storm.

(b) The probability method when applied to derive design floods for long recurrence intervals several times larger than the length of data has many limitations. In certain cases, however, like that of very large catchments where unit hydrograph method is not applicable and where sufficient long term discharge data is available, the frequency method may be the only course possible. In such cases, the design flood to be adopted for major structures should have a frequency of not less than once in 1,000 years. Where annual flood values of adequate length are available they are to be analysed by the Gumbel's method, and where the data is short, either partial duration method or regional frequency technique is to be adopted as a tentative approach and the results verified and checked by hydrological approaches.

(c) While planning there may be some projects where there is hardly any discharge data available. In such circumstances for preliminary studies the peak flood may be estimated by empirical formulae.

(d) In the case of permanent barrages, and minor dams with less than 50,000 acre feet (6167 hectare meters) storage, the standard project flood or a 100-year flood, whichever is higher, is to be adopted. The standard project storm, which forms the basis of the standard project flood, is not as definitive a description as that of the probable maximum storm. It may be taken generally as the largest storm which has occurred in the region of the basin during the period of weather records. It is not maximised for most critical atmospheric conditions but it may be transposed from an adjacent region to the watershed under consideration.

(e) For pick-up weirs, a flood of 50-100 years frequency should be adopted according to its importance, and level conditions. Waterways for canal aqueducts should be provided to pass a 50-100 year flood, but their foundations and freeboard should be for a flood of not less than 100 years' return period. In case of cross drainage works which carry highways or railways, waterways provided should also satisfy the respective standard code of practice of highways or railways.

(f) Each site is individual in its local conditions, and evaluation of causes, and effects. While, therefore, the norms, mentioned herein above, may be taken as the general guidelines, the hydrologist, and, the designer would have the discretion to vary the norms, and the criteria in special cases, where the same are justifiable on account of assessable and acceptable local conditions; these should be recorded, and, have the acceptance of the competent authority.

The Indian Standard Guidelines

In recent rimes, realising the need for a more exhaustive criteria, the Indian Standards Institute finalised its 'Guidelines for Fixing the Spillway Capacity of Dams', which is applicable for new storages (IS 11223:1985). The guidelines recognize that every artificial storage can be a potential hazard to downstream life and property and state the primary purpose of the spillway to reduce the hazard to a negligible or acceptable level. The guidelines also recognise different inflow design floods for various safety criteria viz. dam, energy dissipation arrangement, upstream submergence, downstream damage, etc. It classifies the reservoirs by both gross capacity or hydraulic head as follows for deciding the type as the more severe of the two criteria of classification:

Type	**Gross Capacity**	**Hydraulic Head**
Small	0.5 to 10 million m^3	7.5m to 12 m
Intermediate	10 to 60 million m^3	12m to 30m
Large	Greater than 60 million m^3	Greater than 30m

It also specifies the inflow design flood for safety of dam as 100 year flood for small dams, standard project flood (SPF) for intermediate dams and probable maximum flood (PMF) for large dams.

Mohile (1988) discussed about the consistency of guidelines with safety of dam covering both new and existing structures. While monitoring about specific requirements not adequately covered by the existing standard, recommendation were made for their inclusion in the standard to make it broader. These included: (i) cases involving a series of reservoirs, (ii) citing of nuclear power plants, (iii) dam break studies, (iv) gate operation provision of non-operative gates, (v) reservoir operation policy for flood control, (vi) reservoir operation policy for extreme floods, and (vii) consideration of incremental flood hazard.

Central Water & Power Research Station, Pune

CWPRS conducts basic and client sponsored research studies in the fields of hydrology and hydraulics. The different types of problems studied in the CWPRS are: i) Hydrologic modelling of river basins using general purpose models, (ii) Development of flood routing and flood forecasting using analogue computers, (iii) Reservoir operation modelling, and (iv) Study of backwater effects of reservoirs.

The work of development of Stanford Watershed Model (SWM) is considered as pioneering work in the field of digital computer simulation of river basins. It is an elaborate, explicit, soil moisture accounting type, rainfall-runoff model. OPSET model is a self calibrating version of SWM. In this model there are series of functions which attempt to reproduce all the steps in the runoff process. CWPRS adopted OPSET model and put efforts to apply it to Indian catchments. OPSET model was then successfully applied to calibrate Narmada Basin, for determining Probable Maximum Flood (PMF) at Navagam, Narmadasagar, Omkareshwar and Maheshwar on Narmada river. Narmada basin was divided into twenty sub-basins. OPSET model was then calibrated for these sub-basins for different water years. As input, data on weighted daily and hourly rainfall, daily evaporation, streamflow and other land parameters was fed. The set of calibrated parameters represented the sub-basins. PMP was then fed as input to the calibrated model to get PMF's from every sub-basin. The PMF from individual basins were then routed down upto the Navagam and Narmadasagar project sites to obtain PMF.

Currently OPSET is being used for estimation of PMF of Tapi river at Ukai Dam site. Software to process the hydrometeorological data has been developed in CWPRS. CWPRS has successfully designed and developed, for the first time in the country, an electronic analogue computer for flood routing which can be used for flood forecasting. This computer is based on Muskingum storage equation and is modular. It is designed using latest integrated circuit technology and indigenous components. The knowhow developed in the process is available within the country. In the analogue computer, different river reaches are represented by modules. Inflow in terms of discharge of upstream most site is fed to the first module and tributary flows and local flows at appropriate module there after. While flood routing, the computer gives same treatment to this input as the river channel would have given to the actual flood wave. Outflow is then recorded at the desired outflow point to give outflow hydrographs. This type of computer was used to obtain PMF for Navagam and Narmadasagar projects.

The flood routing analogue computer works on fast timescale and hence can be used in flood forecasting to give timely flood warnings to the affected area. Electronic analogue computer for flood routing and flood forecasting has been developed for two river basins in our country, namely: Tapi and Godavari. In the case of Tapi river, it simulates the Burhanpur-Surat portion of the river by feeding the discharge at Burhanpur as inflow, local flows and tributary flows, it will give forecasted inflow to the Ukai reservoir. Operation of reservoir gates can be planned accordingly. The proposed releases from the Ukai dam are then fed to the Ukai-Surat section to get flood hydrographs at Surat. Forecast will be issued based on this hydrographs.

An electronic analogue computer to issue flood forecast to Nanded City on river Godavari has been designed, developed and installed in the office of Superintending Engineer, IPI Circle, Aurangabad.

An electronic analogue computer, based on the principle of kinematic wave routing has been designed and developed specifically for the study of backwater effects of Paithan reservoir on Toka bridge, on river Godavari in Maharashtra. This type of computer works on a fast time scale and gives accurate results in terms of peak discharges and maximum levels at all upstream sections. For backwater studies or Srisailam reservoir also, this methodology was used.

Realistic assessment of available water resources and allocation of the same to various end users, keeping in view regularity, adequacy and equity form the most important aspects of research studies for command area development. CWPRS has recently completed such studies for Chambal Ayacut Development Project. Computer oriented procedures were developed for accounting, planning and scheduling the available water resources, through computer programs developed at CWPRS.

Central Water Commission

A. Modernisation of Flood Forecasting System

Flood forecasting in India commenced in 1958 with the establishment of a unit in the Central Water Commission. With the advent of sophisticated computers hydrological models are increasingly being used for inflow and flood forecasting. Both catchment models and channel routing models are used for this purpose. With the assistance of UNDP/WMO, Central Water Commission has successfully implemented a project (1980-1990) on improvement of flood forecasting system on river Yamuna. This also involved adaptation of a number of hydrological models to suit Indian conditions. These include NAM model, hydrodynamic modelling system, HEC-1F model, Nonlinear Cascade Non-linear Model SSARR Model, etc. In collaboration project (1981-85) with Danish Hydraulic Institute, knowhow has been obtained for computerised modelling system involving use of NAM, S11FF and S11FC models and this has been used on the two focus projects of Upper Damodar upto Durgapur Barrage and Lower Damodar downstream of Durgapur Barrage. In 3rd phase, the project is extended to cover Godavari basin and dam break modelling studies have been included. With a view to modernising the data processing and techniques, all the field divisions of CWC have been provided with personal computers. These developments and efforts have also contributed significantly in various aspects of hydrologic design of projects (Rao et al, 1989).

B. System Engineering Project

The UNDP assisted system engineering project at CWC started in May 1982. It aimed at development of technology useful for water resources studies through adaptation and development of computer models. During the course of studies carried out and training under this project, technology for a number of hydrological models was acquired, adapted and also used for development of appropriate models for Indian conditions (Pendse, 1985). These included models developed by Texas Water Development Board, Stanford University, U.S. Army Corps of Engineers, U.S. National Weather Service and Colorado State University. Rao (1985) has discussed main features of a rainfall runoff conceptual model for water yield.

National Institute of Hydrology, Roorkee

In December 1978, National Institute of Hydrology as a Scientific Institution was set up by the Government of India, registered as a Society with the main objective to undertake, aid, promote and coordinate systematic and scientific studies in theoretical and applied hydrology so as to improve the present practices in planning, design and operation of water resources projects. The establishment of the Institute was assisted by UNDP under a five year project amounting to U.S. $ 98,9716. The research activities of the Institute right from the initial period included:

(a) Development of systematic procedures including computer oriented procedures for use by field agencies;

(b) Theoretical and basic studies in hydrology for understanding the component processes of hydrologic cycle and their interactions;

(c) Studies involving measuring techniques, as well as data collection and processing procedures;

(d) Development of standardised and systematic procedures for hydrologic analysis and synthesis and their documentation;

(e) Assistance and advice to field organisations in the application of procedures and through sponsored consultancy research projects.

With effect from the year 1984-85, the Institute had embarked on a much larger programme covering field and laboratory oriented studies and research. Studies in wider areas of hydrology have been taken up to develop methodologies and systematic procedures, and also to standardise methods of analysis, planning and design. Besides more than 20 scientific divisions dealing with various aspects of hydrology, the Institute has also established regional centers to deal with specific regional hydrological problems. Over last 13 years, the Institute has made significant contributions through studies and technology transfer activities. Consultation capabilities have been created in different areas including water yield studies, flood routing and forecasting hydrologic water balance computations, design storm and design flood estimation, watershed modelling and simulation, dam break flood studies, flood frequency analysis, and reservoir operation and planning. Some of the important sponsored projects in the area of hydrologic design handled by the Institute include

(a) 'Design flood studies for Narmada projects' sponsored by Narmada P & P Cell, Ministry of Water Resources, Govt. of India;

(b) 'Water availability studies of Mahanadi basin', sponsored by National Water Develolpment Agency, Delhi;

(c) 'Design flood estimation of Kishau Dam', sponsored by Govt. of U.P.

(d) 'Reservoir Operation Studies for Machhu II Reservoir'

The Institute has also recently acquired latest technology of distributed modelling using SHE (System Hydrologique European) model under a project funded by the Commission of European Communities and successfully used it for case studies using data of six subbasins of river Narmada, Hemavathy basin in Karnataka and Beti basin in Gujarat. This model provides an important tool for studying effects of land use changes on hydrologic regime and hence its implications for hydrologic design.

DEVELOPMENT OF INDIA'S RIVER BASINS

Chitale (1991) while delivering the third A.N. Khosla Memorial Lecture made a comprehensive review of various aspects of development of India's river basins, including those having much relevance to development of hydrologic design. In India the concept of basin as a unit of development was first propounded by Dr. A N Khosla in 1945 when he was the Chairman of the Central Water Irrigation and Navigation Commission of the Government of India. (That was the earlier name of the present Central Water Commission). In a broadcast to the nation in 1945, he said: 'Planning should be on a regional basis and the drainage basins should be treated as units.... In so doing, account should be taken of other social benefits like economic, general as well as special and potential benefits. For the purpose of preparing comprehensive and integrated water plans for the various river basins of India, the Government of India had set up the Central Waterway, Irrigation, and Navigation Commission to deal with the problems of flood control, soil erosion, drainage and land reclamation, irrigation and navigation and the Central Technical Power Board to deal with power including water power. The Central Waterways, Irrigation and Navigation Commission will be a central fact finding, planning and coordinating organisation which will examine the potentialities of Indian rivers from all relevant aspects and will assist in the coordinated and integrated development of rivers passing through more than one prince of State".

Chitale (1991) also mentions about the important recommendations of the Irrigation Commission and views of National Flood Commission. The irrigation Commission recommended that:

(a) The basin plan should present a comprehensive outline of the development possibilities of land and water resources to meet the anticipated regional and local needs.

(b) The plan should: (i) indicate a broad frame-work of various engineering works to be taken up in the basin, the reasons why they are preferred to alternatives and the inter-relationship between them; (ii) establish priorities in respect of water use for various purposes; (iii) indicate inter se priority of projects; and (iv) indicate the need for earmarking water for any specific future purposes.

(c) The plan should be periodically reviewed and revised as required in the light of changing needs and supplies.

Subsequently, the Rashtriya Barh Ayog in its report in 1980 also observed that as a 'flood plan' forms the part of 'water plan', the basin is an apt unit for planning for flood works also. It also pointed out that a river basin has been universally accepted as the most suitable and proper unit in the preparation of a water plan.

The National Water Policy adopted in September 1987 laid down that resource planning in the case of water has to be done for a hydrological unit such as a drainage basin and appropriate organisation should be established for comprehensive planned development and management of the river basins as a whole. All individual developmental projects and proposals should be formulated by the States and considered within the framework of such an overall plan for a basin or a sub-basin, so that the best possible combination of options can be made.

It has been rightly pointed out by Chitale (1991) that enough attention was not paid to many important issues of hydrology in the past when 'demands' and 'drawals' were small compared to the availability of water in nature. With growing demands and increasing exploitation, it has become very necessary to have correct appreciation of the exact hydrological cycle of the specific region for proper hydrologic design. Some of the important areas which need attention are snow hydrology, coastal aquifers, dam break floods, interaction of river water quality and quantity, ground water recharge, lake management, use of modern instrumentation and computational aids, etc. Inter basin water transfer and associated hydrological problems also form an important area which needs attention. Flood plain zoning measures also constitute a crucial area of activity and require appropriate hydrologic design criteria for estimation of flood levels corresponding to various risk levels.

GENERAL REMARKS

Hydrologic design forms an important part of all aspects of planning, development and operation of water resources projects, particularly for design of hydraulic structures. Though in initial years after independence, there was greater use of empirical and semi-empirical approaches in the country, there have been significant developments in last 15-20 years. This has been possible due to increasing emphasis on hydrologic education, training and research under UNESCO programs, starting of Post Graduate level education and training in hydrology and establishment of National Institute of Hydrology. Under various bilateral and international programs technology and expertise have also been acquired from abroad and suitably adapted for use not only at research level but also for field applications. These efforts have gained further momentum due to wide scale awareness of influence of man's activities on hydrologic regime, developments in modelling and computation, and availability of computers of various sizes, configurations and capabilities.

Various individual studies and institutional efforts have made significant contributions. However, it is necessary to consolidate these efforts further through development of appropriate manuals, guidelines and standards with appropriate software, so that modern hydrologic design techniques find their desired level of use in field practice. Technology transfer activities of National Institute of Hydrology and

Central Water Commission are significant steps in this direction. These have to be supported with corresponding emphasis on data collection, data banks, instrumentation, software development and manpower education and training.

On the basis of this review, some specific remarks could be made regarding contributions in various aspects of hydrologic design as follows:

(i) In the area of **flood frequency analysis** significant developments have taken place. In the initial stages, Gumbel distribution was widely used and investigated. In recent years there have been a number of studies involving use of Log Pearson type III, General Extreme Value and Wakeby distributions. Regional frequency analysis studies have also been carried out and provide better relationships in place of empirical approaches used earlier. PC based computer software has also been developed for use of these approaches at field level.

(ii) In the area of **conversion of effective rainfall to direct runoff** mostly the studies are based on use of unit hydrograph theory. Further developments in this area have been the use of Nash and Clark models and regional unit hydrograph studies. For rainfall-effective rainfall process to account for abstraction most of the studies involve use of conventional phi index approach. There are however a few studies which have attempted overall modelling of rainfall runoff process using lumped as well as distributed modelling approaches. These include use of NAM, Tank, HEC1, Kulandaiswamy, OPSET, SHE Models, etc. Notable achievement in this area is implementation of computer programs, their adaptation and successful use with Indian data as available in specific cases.

(iii) In the area of **water yield studies**, efforts are mostly directed on development of monthly, seasonal and annual rainfall runoff relationships using regression approaches.

(iv) For **design storm estimation**, the methodology adopted is mostly based on WMO procedure involving storm analysis, transposition, maximisation and temporal distribution. The attempts ;have been initiated to compile extreme storm data in a systematic manner.

(v) **For snow covered areas** very few studies have specifically focussed on evolving suitable criteria for hydrologic design. Similar status prevails for Urban areas. There have been some studies and model developments using remotely sensed data.

(vi) **Flood routing studies** have not been specifically reviewed in this paper. In this area significant developments have taken place starting right from use of Muskingum method to use of other approaches like Muskingum Cunge, Kalinin Milyukov, Lag and route, Kinematic and dynamic approaches. Dam break floods are also being studied. Computer software and technology are being made available through technology transfer programs for field use.

(vii) The developments in the area of **preparation of manuals and guidelines**, and issue of recommended procedures has been somewhat slow. There is need for an objective and standardised procedure for various hydrologic design variables, viz. design storm, design flood, yield, etc. for different physiographic and climatic conditions and data availability situations as well as current status of technological and software development.

REFERENCES

Agrwal, C.K., D.K. Agrwal, J.B. Maheswari, M.S. Alam and R.R. Mishra (1991), 'Regional Flood Frequency Analysis By Power Transformation Method', Proc. Fourth National Symposium on Hydrology, Madras, pp.135-142.

Ahuja, P. and Shenoy, R. (1967), 'Estimation of Design Flood Discharges Especially for River Valley Project in India', Floods and their Computation, proc. of the Leningrad Symposium, Aug. 1967, IAHS UNESCO-WMO, Vol.I, pp.252-258.

Babu Rao, T. (1973), 'A Mathematical Model for Basin Runoff', Ph.D. Thesis, College of Engineering, Guindy, Madras.

Bhatnagar, A. (1967), 'Stage and Frequency of Floods in Central India', **Floods** and Their Computation, Proc. of the Leningrad Symposium, IAHS UNESCO-WMO, 1969, Vol.II, pp.925-931.

Central Board of Irrigation & Power (1988), 'Research in Water Resources Development in India', Research Projects under study compiled by CBIP, New Delhi.

Central Board of Irrigation & Power (1989), 'River Behaviour Management & Training', CBIP, New Delhi, Publication No 204, Vol.I.

Central Water & Power Commission (1972), 'Estimation of Design Flood Recommended Procedures', CW&PC Publication No 258, Ministry of Irrigation and Power, Govt. of India.

Chandra, M. and Chandra, S. (1984), 'Design Flood for Tehri Dam', Proc. 51st Annual R & D Session, CBIP, Vadodara, Tech. Session II, Paper No 1, pp.1-13.

Chitale, M.A. (1991), 'Development of India's River Basins', The Third A.N. Khosla Memorial Lecture, Bulletin of the Institution of Engineers (India), Vol.40, pp.19-28.

Datta, B. and Seth, S.M. (1985), 'Application of Tank Model for Flood and Daily Runoff Analysis to Some Basins in India', Proc. International Workshop on Operational Applications of Mathematical Models (Surface Water) in Developing Countries, New Delhi, pp.71-141.

Desai, N.B., Rao, S.G.C. and Mathew, N.T. (1984), 'Estimation of Probable Maximum Flood in the Narmada at Sardar Sarovar', Proc. 51st Annual R & D Session, CBIP, Vadodara, Tech. Session II, Paper No 2, pp. 15-27.

Dhar, O.N., Rakhecha, P.R. and Kulkarni, A.K. (1978), 'An Estimate of Spillway Design Rainstorm for the Betwa Basin upto Rajghat Dam Site', Jour. of Indian Association of Hydrologists, Vol.II, No.1&2, pp.17-23.

Dhar, O.N. and Nandargi, S. (1989), 'Analysis of Severe Rainstorms of Contiguous Indian States', Proc. CBIP Regional Workshop on Unusual Storm Events and Their Relevance to Dam Safety, Bhubaneshwar, pp.II-15-22.

Goel, N.K., S.M. Seth and S. Chandra, (1986), 'Design Flood Estimation for Narmada Sagar Project using Partial Duration Series - A Case Study', Proc. International Symposium on Flood Frequency and Risk Analysis, Louisiana, U.S.A., pp.113-122.

Goel, N.K., B.S. Mathur, and M.A. Lone (1989), 'Flood Estimation in Kashmir Valley using Regional Flood Frequency Analysis Approach', Proc. Second National Symposium on Hydrology, Jammu, Vol. I, pp.B-40 to 56.

Goel, N.K. (1990), 'Modelling for Flood Flows', Ph.D. Thesis, University of Roorkee.

I.S.I. (1985), 'Guidelines for Fixing the Spillway Capacity of Dams', Indian Standard 11223, New Delhi.

Kharod, N.N. (1972), 'Flood Studies of South Gujarat Rivers', M.E. Thesis, WRDTC, University of Roorkee.

Kulkarni, S.D. and Kathuria, S.N. (1990), 'Design Storm Analysis - Status and Need for Review', Proc. CBIP Regional Workshop on Unusual Storm Events and Their Relevance to Dam Safety', Nagarjunsagar Dam Site, pp.95-102.

Lal, P.B.B. and S.P. Tiwari (1991), 'Generalized Formula for Flood Estimation For Indian Rivers', Proc. Fourth National Symposium on Hydrology, Madras, pp.109-113.

Mathur, B.S. (1972), 'Runoff Hydrographs for Uneven Spatial Distribution of Rainfall', Ph.D. Thesis, I.I.T., Delhi

Mistry, J.F., Naik, D.M. and Pathak, R.Y. (1984), 'Estimation of Flood Discharge by Loop Rating Curves', Proc. 51st Annual R & D Session, CBIP, Vadodara, Technical Session II, Paper No 5, pp.57-67.

Mohan, N., Verma, S.C., Singh, R. and Seth, S.M. (1987), 'Generation of Multistation Daily Rainfall Data for Yield Studies in Beas Catchment', Proc. First National Symposium on Hydrology, Roorkee, pp. VI 15-84.

Mohile, A.D. (1988), 'Hydrologic Review of Dam Safety', Proc. Workshop on Designing of Dams for Hydrologic Safety, Nagpur.

Mohile, A.D. (1989), 'Hypothetical Design Storm Determination - Need for Standardisation and Developmental Efforts', Proc. CBIP Regional Workshop on Unusual Storm Events and Their Relevance to Dam Safety, Bhubaneswar, pp.I 1-8.

Mutreja, K.N. (1972), 'Rainfall Runoff Correlation at Kalagarh Site', M.E. Thesis, WRDTC, University of Roorkee.

Panchang, G.M. (1967), 'Improved Precision of Future High Floods', Flood and Their Computation, Proc. of the Leningrad Symposium, IASH UNESCO-WMO, 1969, Vol.I, pp.51-59.

Pareek, R.S. and Mehra, H.C. (1977), 'An objective criteria for Storm Transposition', Jour. of Indian Association of Hydrologists, Vol.I, No.3&4, pp.53-56.

Patel, I.A. (1987), 'A Computer Program for Design Flood', Hydrology, Jour. of Indian Association of Hydrologists, Vol. X, No.283, pp.20-26.

Pendse, Y.D. (1985), 'Systems Approach to Water Resources Development', Lecture Notes, Systems Engineering Workshop for Water Resources Development and Reservoir Operation, New Delhi, pp.1-15.

Ramasastri, K.S. and S.M. Seth (1986), 'Estimation of Design Flood for Narmada Sagar and Sardar Sarovar', Proc. Seminar on Flood Estimation and Control, Roorkee, pp.II-1 to 18.

Ranjodh Singh (1976), 'Hydrological Design of a Snowfed River of Himachal Pradesh', M.E. Thesis, University of Roorkee.

Rao, P.R. (1975), 'Modelling of Non-linear Behaviour of Drainage Basins', Ph.D Thesis, I.I.T., Delhi.

Rao, P.D.H.S. (1985), 'Rainfall Runoff Conceptual Models as Aids for Planning and Better Management Decisions in Water Resources Development', Lecture Notes, Systems Engineering Workshop for Water Resources Development and Reservoir Operation, New Delhi, pp.198-213.

Rao, M.S., Bhola, A.M. and Khanna, R.K. (1989), 'Flood Forecasting and Mitigation', Theme Paper III, Proc. Indo-French Seminar on Management of Water Resources, Jaipur.

Rao, P.R. and Madan, D.S. (1989), 'Review of Design Storm and Flood Studies for Salal Dam in Chenab Basin', Proc. 55th Research and Development Session, CBIP, Srinagar, Tech. Session VII, pp. 49-74.

Roohani, M.S. and S.M. Seth, (1989), 'Relationship Between Hydrological and Morphometric Parameters in the Chenab Basin', Proc. Second National Symposium on Hydrology, Jammu, Vol. I, pp.A-110 to 115.

Rao, P.R. (1990), 'Temporal Distribution of Design Storm Rainfall', Proc. CBIP Regional Workshop on Unusual Storm Events and Their Relation to Dam Safety, Nagarjunsagar Dam Site, pp.73-90.

Rao, P.P. (1990), 'Extreme Flood Events and Dam Safety Concerns', Proc., National Workshop on Water Resources Project Management, I.I.T., Madras, Vol.II, pp.98-113.

Rao, P.R. (1991), 'Network of Reservoirs Model for Estimation of PMF', Proc. National Seminar on Use of Computers in Hydrology and Water Resources, New Delhi, Vol.II, pp.4-7 to 17.

Rao, P.R. (1991), 'Clock Hour Correction to 1 Day Design Storm Depth Necessary?', Proc. Fourth National Symposium on Hydrology, Madras, pp.71-83.

Rao, P.R. and D.S. Madaan (1991), 'Standard Project Storm Depth Assessment for Lodhari Basin', Proc. Fourth National Symposium on Hydrology, Madras, pp.84-93.

School of Hydrology (1980), 'Design Flood for Rajghat Dam on River Betwa'. A Consultation Project sponsored by Rajghat Dam Project, Jhansi.

Seth, S.M. and Buragohain, P.C. (1978), 'Conceptual Modelling of Effective Rainfall Runoff Process', Proc. of Symposium on Hydrology of Rivers with Small and Medium Catchments, New Delhi, Vol. III, pp. 24-29.

Seth, S.M. and Obeysekera (1979), 'Multistation Daily Rainfall Generation', Proc. International Conference on Computer Applications in Civil Engineering, Roorkee, pp. VI-47 to 51.

Seth, S.M. and Goswami, A. (1980), 'Hydrological Modelling of a Small Basin with Limited Data', Proc. Symposium on Hydrological Forecasting, Oxford, pp.305-312.

Seth, S.M. and Sheshaprasad, H.S. (1980), 'Flood Frequency Analysis Considering the Outlier Effect', proc. International Symposium on Water Resources Systems, Roorkee, pp.II-7-35 to 39.

Seth, S.M. (1981), 'Daily Snowmelt Runoff During Premonsoon Months in Beas Basin using Limited Data', Proc. International Symposium on Rainfall Runoff Modelling, Mississippi State University, U.S.A., pp. 177-186.

Singh, R.D. and Seth, S.M. (1984), 'Regional Unit Hydroghraph Study for Godavari Sub-basin using Clark Model', Proc. IAH Symposium on Hydrological Analysis of Catchments with Limited Data, New Delhi.

Singh, R.D. and Seth, S.M. (1985), 'Flood Frequency Analysis Using Wakeby Distribution', Proc. 52nd Annual R & D Session, CBIP, Hyderabad, Vol.II, pp.109-120.

Singh, R.D. and Seth, S.M. (1989), 'Comparative Study of Unit Hydrograph Methods', Proc. Second National Symposium on Hydrology, Jammu.

Singhsamant, B.B. and Patra, K.C. (1989), 'Application of Kulandaiswamy model for Estimation of Inflow Design Flood', Proc. 55th R & D Session, CBIP, Srinagar, pp. TSII/25 to 29.

Sinha, A. and Seth, S.M. (1984), 'Application of Nash Model for Unit Hydrograph Analysis Using Lumped and Multiple Input Approaches', Proc. 4th Congress of Asian and Pacific Regional Division of IAHR, Chiang Mai, Thailand.

Suri, T.M. and Kumar, A. (1976), 'Synthesis of Hydrograph from Basin Characteristics Applied to Indian Catchments', Hydrology Review, Vol.2, No.1, pp.47-50.

Subramanyam, R.G. (1981), 'Quick Determination of Standard Project Flood Peak based Unit Hydrograph Studies', Jour. of Indian Association of Hydrologists, Vol.V, No.1 and 2, pp.27-33.

Upadhyay, D.S., Gupta, D.K., Manton, D.C. and Jindal, O.P. (1990), 'Some Aspects of Design Storm Evaluation', Proc. Regional Workshop on Unusual Storm Events and Their Relevance to Dam Safety, Nagarjunsagar Dam Site, pp.41-47.

APPENDIX - 1

LIST OF HYDROMETEOROLOGICAL SUB-ZONES

Sub-zone	Name of Sub-zone (Designated Earlier)	Name of Sub-zone (Designated Now)	River Basins included in the Sub-zone
1(a)	Luni Basin & Thar (Luni & other rivers of Rajasthan and Kutch)	Luni	Luni River, Thar (Luni & other rivers of Rajasthan and Kutch & Banas River)

1(b)	Chambal Basin	Chambal	Chambal River
1(c)	Betwa Basin & other Tributaries	Betwa	Sind, Betwa and Ken Rivers and other South Tributaries of Yamuna
1(d)	Sone Basin & Right Bank Tributaries	Sone	Sone & Tons Rivers and other South Bank Tributaries of Ganga
1(e)	Punjab Plains including parts of Indus, Yamuna, Ganga and Ramganga basins	Upper Indo-Ganga Plains	Lower portion of Indus, Ghaggar, Sahibi, Yamuna, Ganga and Upper portion of Sirsa, Ramganga, Gomti & Sai Rivers.
1(f)	Ganga Plains including Gomti, Ghagra, Gandak Kosi and other	Middle Ganga Plains	Middle portion of Ganga, Lower portion of Gomti, Ghagra, Gandak, Kosi and middle portion of Mahanadi basin.
1(g)	Lower Ganga Plains including Subarnarekha and other east flowing rivers between Ganga and Baitarani.	Lower Ganga Plains	Lower portion of Ganga, Hoogli river system and Subarnarekha.
2(a)	North Brahmaputra Basin	North	North Bank Tributa-Brahmaputra ries of Brahmaputra river and Balason river.
2(b)	South Brahmaputra Basin	South	South Bank Tributa-Brahmaputra ries of Brahmaputra river.
2(c)	Barak and Others	Barak	Barak, Kalden and Manipur rivers.
3(a)	Mahi, including the Dhadhar, Sabarmati and rivers of Saurashtra	Mahi and Sabarmati	Mahi and Sarbarmati including Rupen & Mechha Bhandar, Ozat Shetaranji rivers of Kathiawad Peninsula.
3(b)	Lower Narmada and Tapi Basin	Lower Narmada & Tapi	Lower portion of Narmada, Tapi and Dhadhar Rivers.
3(c)	Upper Narmada and Tapi Basin	Upper Narmada	Upper portion of Narmada and Tapi Rivers

3(d)	Mahanadi Basin including Brahmani and Baitarani river.	Mahanadi	Mahanadi, Baitarani and Brahmani rivers
3(e)	Upper Godavari Basin	Upper Godavari	Upper portion of Godavari Basin.
3(f)	Lower Godavari Basin except coastal region	Lower Godavari	Lower Portion of Godavari basin.
3(g)	Indravati Basin	Indravati	Indravati River.
3(h)	Krishna sub-zone including Penner basin except coastal region.	Krishna	Krishna & Penner rivers except coastal region.
3(i)	Kaveri & East flowing rivers except coastal region	Kaveri	Kaveri, Palar and Ponnaiyar rivers (Except coastal region).
4(a)	Circars including east flowing rivers between Mahanadi and Godavari	Upper Eastern Coast	East flowing coastal rivers between Deltas of Mahanadi and Godavari Rivers.
4(b)	Coromandal Coast including east flowing rivers between Godavari and Kaveri	Lower Eastern Coast	East flowing coastal rivers, Manimukta, South Penner, Cheyyar, Palar, North Penner, Munneru, Palleru, Cundalakama and Krishna Delta.
4(c)	Sandy Coroman Belt (east flowing rivers between Cauvery & Kanyakumari)	South Eastern Coast	East flowing coastal rivers, Manimuther, Vaigani, Arjuna, Tamaraparni
5(a)	Konkan Coast (west flowing rivers between Tapi and Panaji)	Konkan Coast	West flowing coastal rivers between Tapi and Maudavi Rivers.
5(b)	Malabar Coast (west flowing rivers between Kanyakumari and Panaji)	Malabar Coast	West flowing coastal rivers between Mandavi and Kanyakumari
6.	Andaman & Nicobar	Andaman Nicobar	
7.	J & K, Kumaon Hills (Indus basin)	Western Himalayas	Jhelum, Upper portion of Indus, Ravi & Beas rivers