STATE OF ART REPORT

Scientific Contribution
No. : INCOH/SAR-24/2002

REGIONALISATION OF HYDROLOGICAL PARAMETERS

N.K. Goel
Subhash Chander

INDIAN NATIONAL COMMITTEE ON HYDROLOGY
(Committee Constituted by Ministry of Water Resources, Govt. of India)

INCOH SECRETARIAT
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE - 247 667, INDIA

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PREAMBLE

The Indian National Committee on Hydrology is the apex body on hydrology consituted by the Government of India with the responsibility of coordinating the various activities concerning hydrology in the country. The Committee is also effectively participating in the activities of UNESCO and is the National Committee for International Hydrological Programme (IHP) of UNESCO. In pursuance of its objective of preparing and periodically updating the state-of-art in hydrology in the world in general and India in particular, the Committee invites experts in the country to prepare these reports on important areas of hydrology. Realising the importance of regionalisation in hydrology, the Committee considered it appropriate to get prepared a state-of-art in this important area.

This state of art report is devoted to regionalisation of hydrological parameters. Regionalisation of hydrological parameters facilitates transfer of information from gauged sites to ungauged sites. It also helps in effective planning of hydrological data networks for efficient use of available funds, which is particularly important for developing countries like India.

Practical application of regionalisation of hydrological data requires many sequential steps such as problem definition, system identification, regional discrimination, evaluation of available data and selection and application of an appropriate regionalisation mode. Keeping in view the data limitations, many regional relationships have been developed throughout the world. These relationships have been categorised as (i) regional relationships for estimation of peak flow and runoff, (ii) regional unit hydrograph relationships, (iii) regional flood frequency relationships (iv) regional relationships for rainfall intensity - duration - frequency and (v) regional relationships for catchment soil erosion.

The Indian National Committee on Hydrology with the assistance of its Panel on Surface Water and Water Resources Systems has identified this important topic for preparation of this state-of-art report and the report has been prepared by Dr. N.K. Goel, Professor, Department of Hydrology, Indian Institute of Technology, Roorkee and Dr. Subhash Chander, Former Professor, Civil Engineering. Indian Institute of Technology, Delhi. The report presents the developments in the area up to mid nineties. The report has been compiled and finalised by Dr. K.K.S. Bhatia, Scientist F & Member Secretary, INCOH and Sri R.Mehrotra, the then Scientist in Charge, INCOH.

Various regional relationships used in India for estimation of peak flow and runoff have been discussed in this report. The report also contains basic steps involved for developing regional unit hydrograph relationships along with a review of various regional unit hydrograph studies conducted in India and abroad. Regional flood frequency analysis is an important tool for estimating flood quantiles at ungauged or inadequately gauged sites. The report gives a detailed discussion of various methods for regional flood frequency analysis along with a review of typical studies conducted in India. This report also deals with rainfall intensity-duration-frequency analysis mostly for short duration. Soil erosion process and sediment yield prediction equations have been discussed in a separate chapter.

It is hoped that this state-of-art report would serve as a useful reference material to practising engineers, researchers, field engineers, planners and implementation authorities, who are involved in correct estimation and optimal utilisation of the water resources of the country.

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N.K. Goel
Subhash Chander

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

The 'Surface Water' panel of Indian National Committee on Hydrology, identified and recommended the thrust areas of research in the field of Surface Water Hydrology, in its meeting held on April 16, 1991 at National Institute of Hydrology, Roorkee. The panel recommended that as a first step, the experts working in the respective fields prepare the state of art.

The thrust areas identified by the panel are

(i) Real time high flow forecasting
(ii) Regionalisation of hydrological parameters
(iii) Surface drainage aspects of agricultural areas
(iv) Distributed physically based models
(v) River flow measurements
(vi) Regional flood frequency analysis
(vii) Low flow forecasting
(viii) Flood plain zoning and mapping- hydrological considerations
(ix) Design flood for mountainous areas
(x) Water yields of river basins- methodological guidelines and
(xi) Rain water harvesting.

The present report is sequel to the above recommendations.

1.2 NEED OF REGIONALISATION

Hydrological regionalisation is concerned with spatial extension of hydrological records and has been used as a standard tool to facilitate extrapolation of hydrological data from gauged sites to ungauged sites. The need for regionalised hydrological data has increased manifold in recent times as most of the catchments either do not have any hydrological record at all or have a record for very short period. The economic considerations, many a times do not justify the detailed hydrological and meteorological investigations at every new site on a large scale and on a long - term basis. The hydrologic engineering evaluation and decisions cannot be delayed for non-availability of systematic records or to obtain longer record. For these reasons hydrologists have resorted to regionalisation, i.e.

combining the hydrological data of the gauged sites from a homogeneous zone or region. This leads to a realistic estimation of hydrological parameters, which may be extrapolated to the basins where short records are available or where records are not at all available. Again hydrologists are interested in accurate estimation of some hydrological parameters because of their relative importance (e.g. the magnitude and frequency of rare flood events). Limitations of a single site systematic record are that a sequence may be too short to represent the population of the events adequately. In addition critical values in the records may be subjected to serious errors in measurement. This has led the hydrologists to search for records outside the at-site systematic records to improve upon their estimates. Regionalised hydrological data are used in such cases for a more realistic estimation of hydrological parameters.

1.3 TECHNIQUES FOR REGIONALISATION

For hydrological data regionalisation efforts in the past have been made mainly in the following four directions:

(i) Representative basins
(ii) Landscape units
(iii) Cluster analysis
(iv) Split sample techniques

1.3.1 Representative basins

In view of the time consuming and costly nature of data collection, the idea of selecting a few representative basins for intensive instrumentation and study gained a firm ground and formed the basis of the original international "Representative Basins Programme" within which a representative basin was defined as a catchment which contains within its boundaries a complex of land forms, geology, land use and vegetation that can be recognised in many catchments of a similar size throughout a particular region. The programme was initiated for rational data collection to-

(a) Extrapolate to similar basins in the same region.
(b) Extrapolate to basins with different combinations of geology, landform, soils and vegetation.
(c) Forecast possible effects of changes in land use on any catchment, within the range of land use types sampled by the representative basin network (Bell and Vorst, 1981).

However, subsequent experience has shown many deficiencies in the representative basin concept. The major deficiencies of the representative basin concept are because of

(a) Field heterogeneity of various hydrological parameters (Mosley, 1981)
(b) Varying scale between the research basins and the catchments to which results are to be applied. (Bell, & Vorst, 1981 and Pilgrim, 1983)

It was therefore concluded that generalization on a catchment scale with respect to basin dynamics is not possible.

1.3.2 Landscape units

In view of the deficiencies of the original representative basins concept, a number of authors now consider 'Landscape Units', which are independent of the catchment boundaries as the basic framework for hydrological homogeneity. There are three distinct approaches in this direction.

(a) Map Analysis of Natural Physical Boundaries:

Map analysis is carried out for collection of hydrological data to form a number of relatively homogeneous units. Here it is necessary to preserve high within unit homogeneity so that lumped field estimates of hydrological parameters also represent physical reality within each unit. As shown by Rot et al (1983) the general trend is for sub-area homogeneity to increase with grid density. However, for the same grid density homogeneity can be high or low, dependent on the design. If the overlap between grid and natural homogeneous sub-areas is great, the unit homogeneity will be correspondingly high.

(b) Use of Geometric Grid Cells and Statistical Analysis:

In this approach geometric grid cells form the landscape units. The grid design, in general, depends upon the required application. For example Bell and Vorst (1981) consider, for their purpose, that 50 grid intersections within a catchment comprise a satisfactory density. Enderlein et al. (1982) concluded that a sampling spacing of 0.5 to 1 km is sufficiently precise.

A new approach in the field of landscape classification and regionalisation has been adopted by Laut et al. (1982) to provide a standardized hydrologically oriented landscape description and classification and to use this to classify sub-basins.

Grid cells of 4 km formed the basic data collection units. Each grid-cells data set included continuous (e.g. altitude, relief and slope), disordered multi-state (e.g. lithology, land cover) and non-exclusive ordered multi-state (e.g. aspect) type of attributes. A numerical classical technique was adopted to compute a data set dissimilarity matrix and resultant classification of grid cells. The sub-basins were classified according to the grid-cell composition of which they were composed.

In summary, the use of `landscape units' as a framework for hydrological homogeneity and regionalisation has a number of distinct advantages over the representative basins approach.

1.3.3 Cluster analysis

Hydrologists are often required to develop regional regression models, which can be used to estimate flow characteristics at ungauged stream sites. Data from the gauging stations in the region are gathered to make sample estimates of the regression parameters.

Decoursey (1973) and Decoursey and Deal (1974) used "cluster analysis" to define sub-regions. Cluster analysis is the exploration and organization of data to identify clusters of objects that are in some sense similar within clusters and dissimilar between clusters. Tasker (1982) gives further details of this method.

1.3.4 Split sample techniques

When the number of gauges in a region of interest, N is very large then there are many ways in which this set of N stations may be divided into sub-regions. The problem is to decide which of the several ways of dividing the set of N stations is best in terms of predictive accuracy of the model. The observed standard error is not adequate for comparing models because the error inherent in defining sub-regional boundaries is not reflected. Data splitting, reservation of a portion of available data to obtain an independent measure of the model prediction accuracy, is an effective method for comparing models (Tasker, 1982).

The objective of data splitting is to divide the data into two sets, which cover approximately the same region and have similar statistical properties. One data set, the "estimation data" is used to estimate model parameters and other data set, the "prediction data" is used to measure the accuracy of prediction of the model. Although a half-and-half split is usual, a smaller or larger prediction data set could be used.

1.4 STEPS FOR REGIONALISATION

Because of the complexity inherently associated with the practical application of hydrological data regionalisation, the concepts and steps of regionalisation need to be rationalized in some logical and systematic perspective. The following steps (Simmers, 1984) may help greatly in hydrological data regionalisation.

(i) Problem definition
(ii) System identification
(iii) Problem oriented regional discrimination
(iv) Evaluation of available data
(v) Selection and application of an appropriate regionalisation model.

Problem definition

It is essential to define the purpose for which regionalisation is required (e.g. water resources master planning, irrigation/drainage design, flood control or forecasting, hydro- power design, watershed management etc.). Further the required application of regionalised data (e.g. extension of streamflow time series, groundwater extraction, pollutant/sediment transport, mean annual runoff, low flow estimation etc.) should be defined.

System identification

In order to facilitate rational decisions within subsequent phases one needs to define which elements of the hydrological system (given in Table 1) are of interest for a particular problem and whether these need to be considered in a lumped or (semi) distributed manner.

Problem oriented regional discrimination

Depending upon the problem one must define the level of regionalisation, as there may be many levels of regionalisation. For defining broad scale hydrological regions qualitative map analysis of large relatively homogeneous regions may be quite sufficient. For the problem, which requires preservation of high within unit homogeneity, the map analysis of natural physiographic units may be important. The use of geometric grid cells with or without supporting statistical analysis is useful in physically based models.

Evaluation of available data/information

This phase serves as a bridge between phase (i) and (v) and must be satisfied to ensure acceptable end results. In this step one has to check the following:

(a) Whether the total information available is consistent with that required by the defined purpose and application, Table 1.1 (after Lane et al., 1979) may serve as a guide in this respect.
(b) Whether the available data is sufficient by statistical analysis to meet the desired precision.
(c) Whether a continuous time series is required for the application.

Selection and application of an appropriate regionalisation model

With a wide range of hydrological models available the choice of a model for a particular problem is not simple. Some models are ideal for initial estimation of water resources but unusable in an operational mode. Others present problems of translation to basins of varying size. Again in case of some other models the computing requirements are so great that their practical application is restricted due to economic reasons.

However, Simmers (1984) distinguished the following four categories of application dependent regionalisation models representing the "simulation" and "event based" techniques.

(a) Generalized water balance determinations
(b) Regional statistical generation of descriptive variables or model parameters.
(c) Lumped catchment models
(d) (Semi) distributed physically based catchment models.

The matrix presented in Table 1.2 illustrates the approach required.

Having chosen a particular category of model, which is suited to the required application, the only remaining decision is thus which specific model or combination of models for a given type should be adopted.

TABLE 1.1
Examples of a 'Regionalisation' Application Data Matrix (after Lane et al., 1979)

Type of data required	Application of "Regionalisation Data"			
	Food peaks/ volumes	(Mean) annual runoff	Sediment transport	Water quality
Precipitation				
Annual	C	A	B	B
Seasonal	C	B	B	A
Storm	A	B	A	A
Run-off				
Annual	C	A	B	B
Seasonal	C	B	B	A
Storm	A	B	A	A
Quality	C	B	B	A
Sediment/Erosion				
Rates	C	C	A	A
Transport	C	C	A	A
Yield	B	C	A	A
Evapotranspiration				
Annual	C	A	B	B
Seasonal	C	B	B	A
Short Term	C	B	B	A
Ground Water				
Yield	C	A	C	A
Recharge	C	A	C	A
Quality	C	B	C	A

A = Essential, B = Desirable; C = Marginal

Table - 1.2
“Regionalisation” Methods Appropriate to Examples of Required Application

Application of “Regionalised Data	“Regionalisation“ method*			
	“Event-based” Methods		“Simulation” Methods	
	(1)	(2)	(3)	(4)
Extension of stream flow time series			X	X
Streamflow hydrographs			X	X
Real-time runoff prediction			X	
Spatially variable hydrological process/ parameters				X
Hydrological effects of localized Land use change				X
Ground water extraction and transfer			X	X
Pollutant/Sediment transport			X	X
Water quality models (surface/ groundwater)			X	X
(Mean) annual runoff	X	X		
(Mean) monthly runoff	X	X		
Low -flow studies		X		
Flood peaks/volumes etc.		X		

*(1) = water balance model
(2) = Regional Statistical model (univariate or multivariate)
(3) = Lumped catchment model (deterministic / stochastic)
(4) = (Semi-) distributed physically based model.

1.5 TYPE OF REGIONAL RELATIONSHIPS COVERED IN THE REPORT

Primarily for Indian conditions, the following relationships are complied:

(i) Regional relationships for estimation of peak flow and runoff.
(ii) Regional unit hydrograph relationships
(iii) Regional flood frequency curves
(iv) Regional relationships for rainfall intensity duration frequency relationships
(v) Regional relationship for catchment soil erosion

The results drawn from such relationships give only the initial estimates of hydrologic parameters and may be quite misleading in some cases and hence should be used with due care. These are explained in subsequent chapters of this report.

CHAPTER - II

REGIONAL RELATIONSHIPS FOR ESTIMATION OF PEAK FLOW AND RUN-OFF

2.1 GENERAL

Peak flow and annual run-off from catchments are required for assessment of water resources and planning and design of hydraulic structures. In developing countries like India, one of the problems which emerges in hydrologic analysis is non-availability of systematic discharge data of rivers. In such cases hydrologists have to resort to various regional relationships for estimation of peak flow and seasonal run-off. These relationships are discussed in this chapter.

2.2 ESTIMATION OF PEAK FLOW

Several regional approaches are available for estimation of peak flow from catchments where adequate run-off data are not available. These include rational method, empirical equations, envelope curve method and regional unit hydrograph method. Rational method and empirical formulae are still used extensively because of their simplicity. Here the details of the rational method, empirical equations and envelope curves are being discussed. The details of the regional unit hydrograph are given later in the chapter on regional unit hydrograph.

2.2.1 Rational method

The rational method of estimating peak flow on small watersheds is based, on the criterion that for storm of uniform intensity, distributed evenly over the basin, the maximum rate of run-off equal to a certain percentage of rainfall intensity occurs when the entire basin area is contributing at the outlet. This condition is met after the elapsed time is equal to the time of concentration. The equation is-

$$Q_P = 2.78\ CiA \qquad \text{....(2.1)}$$

Where,

Q_P = peak run-off rate (m /s)
C = run-off coefficient
i = rainfall intensity (cm/hr.) of a storm whose duration is equal to the time of concentration of the basin.
A = Area of watershed (km^2)

The following are the limitations of method

(i) Maximum rate of run-off occurs when the duration of the intensity is equal or longer than the time of concentration.

(ii) The maximum run-off as a result of rainfall intensity with a duration equal to or greater than the time of concentration is a simple fraction of such rainfall intensity, i.e., it assumes a straight line relation between Q and i, and $Q = 0$ when $i = 0$.

(iii) The frequency of peak discharges is the same as that of the rainfall intensity for the given time of concentration.

(iv) The relationship between peak discharges and size of drainage area is the same as the relationship between the duration and intensity of rainfall.

(v) The co-efficient of run-off is the some for storms of various frequencies on a given watershed.

(vi) Q is only a point value and the relationship gives nothing of the nature of the rest of the hydrograph.

2.2.2 Empirical formulae

Most of empirical formulae use the following form:

$$Q = CA^n \qquad \ldots(2.2)$$

Where,

Q = peak flow rate associated with given return period (m^3/sec)
A = Drainage area (km^2)
n, C = Regression constants.

Popular formulae in the form of equations are described below:

(i) Dicken's formula:

$$Q = C\,A^{3/4} \qquad \ldots(2.3)$$

The formula is commonly used in the Central and Northern India. Mutreja reported the value of constant 'C' in M.K.S. units, which varies from 2.80 to 5.60 for plain catchments and 14 to 28 in mountainous regions according to catchment characteristics. He has also produced a map of India (Fig. 2.1), which shows the value of Dicken's constant 'C' in M.K.S. units for different parts of India.

Beale (quoted by Mutreja, 1986) reported the value of constant 'C' for the catchments in Western Ghats and Madhya Pradesh as follows (Table 2.1a).

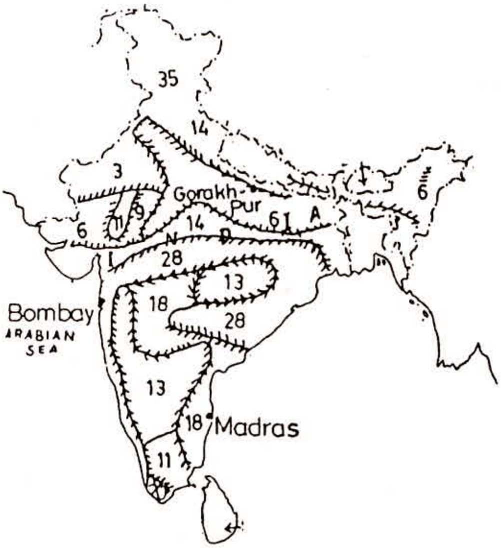


Fig. 2.1 Dicken's constant for different parts of India

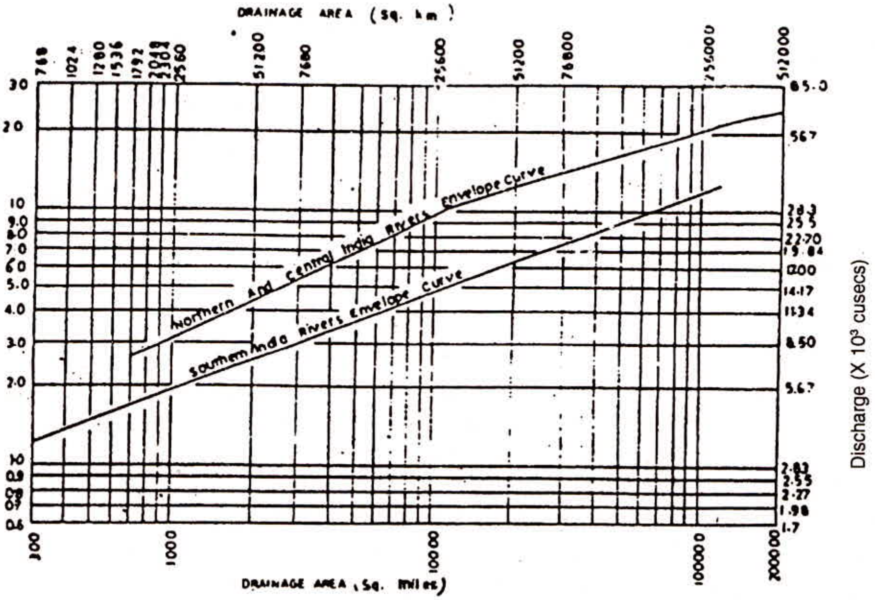


Fig. 2.2 Envelope curves for Indian rivers

Table 2.1(a)

Coefficient 'C' of Dicken's formula for the catchments in Western Ghats and Madhya Pradesh

Region	Value of C (M.K.S.Units)
Western Ghats	20 - 40
Madhya Pradesh	14 - 20

To make Dicken's formula applicable to different parts of India, the following constants (in M.K.S. Units) are suggested (Table 2.1b).

Table 2.1(b)

Dicken's Constant 'C' for Different Type of Watersheds

Type of watershed	Dicken's constant
Bare catchment covered with precipitous hills	19.6 - 28.0
Catchments with Hills or the skirts with undulating country	14.0 - 16.8
Undulating country with hard indurate clay soil	11.2 - 14.0
Flat, sandy, absorbent or cultivated plains	2.8 - 7.0

The co-efficient 'C' used for the computation of maximum flood flow for some of the catchments in U.P. are given in Table 2.2.

The Central Water Commission has recommended criteria to be adopted for estimation of design flood for waterways of rail and road bridges in North Bengal on the basis of analysis of rainfall run-off data. Accordingly, the value of 'C' in Dicken's formula is given by:

$$C = 10.14 (s)^{0.3} \qquad \dots (2.4)$$

Where, s = Statistical or mean stream slope in meters / km.

Table 2.2

Coefficient 'C' in Dicken's formula for some catchments in U.P. used for maximum flood flow computation.

Location	Coefficient 'C' in F.P.S. system
River Bhagirathi at Pala	1400
River Yamuna at Dakpathar	1400
River Sarda at Banbassa	904
River Ganga at Hardwar	725
River Ramganga at Kalagarh	1820
River Yamuna at Tajewala	1020
River Ken at Gangao	798
River Betwa at Paricha	740
River Karamnasa at Silhat	1746
River Rihand at Pipri	1004

(ii) Ryve's formula

$$Q = C A^{2/3} \qquad \ldots (2.5)$$

Where,

C = 6.8 for areas within 80 km from east coast
= 8.5 for areas with 80 to 160 km from east coast
= 10.2 for limited areas near hills
Q = maximum flood discharge in m^3 /sec for South Indian Conditions
A = catchment area in km^2.

(iii) Inglis formula

The formula is derived for old Bombay State and the formula is:

$$Q = 124 A / \sqrt{A + 10.24} \qquad \ldots (2.6)$$

Where,

Q = Discharge in m^3 /sec
A = Drainage area in km^2.

The Inglis formula is generally used for small and medium catchments in Maharashtra and Gujarat and it is applicable for fan shaped catchments only.

The modified Inglis formula (eq. 2.7) takes into account the shape of the catchment area, but the value of k has to be found from available data. The form of the modified Inglis formula in F.P.S. units is

$$Q = K^{1/3} \frac{7000A}{\sqrt{A+4}} \qquad \dots (2.7)$$

Where,

K = Shape factor, ratio of diameter of standard semi circular catchment having the same area to actual stream length of catchment (L)

$$= \frac{2}{\pi} \cdot \frac{\sqrt{A}}{L}$$

For the Deccan catchments, the exponent of K is 1/3 as shown in equation 2.7. The modified formula deals with normal shape correction. It does not take into account the superimposed effect of flood absorption in a long river. In such cases the catchment area may be divided into two fan shaped catchment areas and a co-efficient of 0.707 may have to be applied to equation 2.7.

(iv) Ali Nawaj Jung Bahadur formula:

This is derived for Hyderabad Deccan catchments and it states that

$$Q = c\,(0.3906\,A)^{(0.925 - (1/14)\log 0.3906A)} \qquad \dots (2.8)$$

The value of c is roughly 49 and 60 for south and north India respectively.

(v) Coutagne formula:

In France the following formula for area between 400 and 3000 km^2 is suggested.

$$Q = 150\,A^{0.5} \qquad \dots (2.9)$$

(vi) Meyer's formula:

$$Q = 177.05\,A^{0.50} \qquad \dots (2.10)$$

The area should be more than 10 km^2. This formula is quite popular in U.S.A.

(vii) Creagar's formula:

$$Q = 46\ C\ A^{(0.89A\ -\ 0.048)} \quad \text{... (2.11)}$$

Where,

Q = Discharge in ft^3/sec.
A = Drainage area in sq. miles

The values of the coefficient C are given in table 2.3 below.

Table 2.3

Coefficient 'C' in Creagar's formula for some of the catchments in U.P.

Location	Coefficient 'C' in F.P.S. unit
River Sarda at Banbassa	100
River Yamuna at Tajewala	100

(viii) Military Engineering Service formula:

The form of this empirical formula is

(a) When A is less than 9.5 sq. miles

$$Q = 1200\ A^{3/4} \quad \text{... (2.12)}$$

(b) When A is between 9.5 and 12000 sq. miles.

$$Q = 2100\ A^{1/2} \quad \text{... (2.13)}$$

(ix) G.C. Khanna's formula:

$$Q = 3000\ A^{3/4} \quad \text{... (2.14)}$$

Where,

Q = Discharge in cusecs
A = Drainage area in sq. miles

This is recommended for hilly areas and it is found to give high value of flood for catchment areas of medium size. However, it is not applicable for a catchment exceeding 625 sq. miles in area.

(x) Boston Society formula

The formula, developed in 1927, is of the form:

$$Q = C_F . R \sqrt{A} = C. \sqrt{A} \quad \text{... (2.15)}$$

Where, C_F is the constant for flood producing characteristics of the catchment and its value depends upon the average rainfall and nature of catchment. It is the average run-off for the catchment per day from a worst storm.

Wahi has derived the value of 'C' in the above formula for 5 different regions of Punjab depending upon rainfall during monsoon months. The values of 'C' for different zones of Punjab are given in Table 2.4.

Table 2.4

Values of co-efficient 'C' in Boston Society formula for different zones of Punjab

Zone	Nature of Catchment	Average rainfall monsoon months (inches)	R	C_F	$C = C_F*R$
I	Hilly area	30	6	756	4500
I(a)	Sub-mountain area	30	5	300	1500
II	Plains	20-30	3	150	450
III	Plains	15-20	2	100	200
IV	Plains	10-15	1	80	80
V	Plains	under 10	3/4	60	45
VI	Sandy areas with water table more than 50'	1/2	1/2	3	15

For the catchments of the size less than or equal to 4 sq. miles, the modified Boston Society formula being used, is:

$$Q_m = \frac{C}{2} . A \quad \text{... (2.16)}$$

Here the value of 'C' is taken from the same table, i.e., Table 2.4.

(xi) Flood determination for ungauged watersheds with frequency relationship.

Some of the most common relationships are discussed below:

(a) US Geological Survey Index - flood method:

The USGS Index flood method is a graphical regional correlation of the recurrence interval with peak discharge ratio. In this method, first the mean annual flood, having a return period of 2.33 years is determined. Mean annual floods from ungauged watershed can be found from the relationship.

$$Q_{2.33} = CA^{0.7}/68.16 \qquad \text{... (2.17)}$$

Where, $Q_{2.33}$ = Mean annual flood corresponding to 2.33 years return period.
C = Regression constants whose values are given for different US watersheds.

After computing the mean annual flood the floods of different return periods are obtained from the approximate index flood curve by Regional flood frequency analysis.

(b) Horton's formula:

$$q_{tr} = \frac{71.20\ T^{0.25}}{A^{0.50}} \qquad \text{... (2.18)}$$

Where,

q_{tr} = Flood equalled or exceeded (Cumecs / sq. km.)
A = Drainage area (sq. km.)
T = Return period (years)

(c) UPIRI formula

The Irrigation Research Institute, Roorkee, U.P. has carried out frequency studies on Himalayan rivers and suggested the following relationship to compute Dicken's constant 'C' for the desired return period.

$$C = 2.342 \log(0.6T) \times \log(1185/P) + 4 \qquad \text{... (2.19)}$$

Where,

$$P = \frac{a+6}{A+a} \times 100$$

a = Perpetual snow area (sq. km.)

A+a = Total catchment area (sq. km.)

After computing the value of 'C' for desired return period 'T' the peak flood for the corresponding return period may be obtained using Dicken's formula.

2.2.3 Envelope curves

The maximum flood per sq. km. experienced in one basin is quite likely to be experienced in a nearby basin in the same region and possessing similar hydrometeorologic characteristics. A smooth curve enveloping the plotted points on log-log paper against the drainage area provides the most concise description. The curves are not associated with frequencies, but within the region to which they apply. They give the magnitude of flow that has occurred. Kanwar Sain and Karpov (as reported in the CWC) collected data of Indian Rivers and developed two enveloping curves, one to suit basin of South India and the other for those of Northern and Central India (Fig.2.2).

Generalized curves of this nature may be useful as a rule-of-Thumb estimate of potential flood risk. They are not definitive enough to justify their use in specific engineering applications.

There is a need of updating the envelope curves from time to time as more and more data are collected, since there is possibility of occurrence of still higher flood.

In case of rivers where snowmelt contributes significantly to run-off, it would be necessary to prepare two sets of envelope curves; one showing floods caused by snowmelt and rainfall which occurs during that season and, the other for floods due to rainfall only.

2.3 ESTIMATION OF RUN-OFF

Annual run-off from catchments is one of the important informations needed for realistic assessment and optimal utilization of water resources. The planning and design of structure related to irrigation, water power generation, navigation, wild life preservation etc. require the knowledge concerning the annual run-off from catchments besides other hydrological parameters. This has necessitated the formulation of regional rainfall and run-off estimation with additional parameters for climate & catchment characteristics. Some of the relationships are described in subsequent sections in Indian context.

2.3.1 Binnie's percentages

Sir Alexander Binnie measured the run-off from a small catchment near Nagpur (Area of 16 km^2) during 1869 and 1872 and developed curves of cumulative run-off against cumulative rainfall. The curves based on these observations were found to be similar. From these he established percentages of run-off from rainfall. These percentages have been used in Madhya Pradesh and Vidarbha region of Maharashtra for the estimation of yield. Table 2.5 shows the Binnie's run-off percentages for different values of annual rainfall.

Table 2.5

Binnie's run-off coefficients

Annual rainfall in mm	Run-off % in mm	Annual rainfall	Run-off%
500	15	900	34
600	21	1000	38
700	25	1100	40
800	29		

2.3.2 Barlow's tables

Barlow carried out studies (during 1915) of catchments under 130 km^2 and expressed runoff R as

$$R = K_b P \qquad \dots (2.20)$$

Where, K_b = Run-off coefficient which depends upon the type of catchment and nature of monsoon rainfall. Values of K_b are given in Table 2.6.

Table 2.6

Barlow's run-off coefficient K_b in percentage (Developed for use in U.P.)

Class	Description of catchment	Values of K_b (%age)		
		Season 1	Season 2	Season 3
A	Flat, cultivated and absorbent soils	7	10	15
B	Flat, partly cultivated stiff soils	12	15	18
C	Average catchment	16	20	32
D	Hills and plains with little cultivation	28	35	60
E	Very hilly, steep and hardly any cultivation	36	45	81

Season 1 :	Light rain, no heavy downpour
Season 2 :	Average or varying rainfall, no continuous downpour
Season 3 :	Continuous downpour

2.3.3 Strange tables

W.L. Strange evolved some ratios between rainfall and run-off (Table 2.7) based on data in Maharashtra. He accounted for the geological conditions of the catchments as good, average and bad and the surface condition as dry, damp and wet prior to rain.

Table 2.7

Daily run-off according to Strange

Daily rain-fall (mm)	Runoff percentage and yield for original stage of ground as					
	Dry		Damp		Wet	
	%age (mm)	Yield (mm)	%age (mm)	Yield (mm)	%age	Yield
5	-	-	4	0.20	7	0.35
10	1	0.10	5	0.50	10	1.0
20	2	0.40	9	1.80	15	3.0
25	3	0.75	11	2.75	18	4.5
30	4	1.20	13	3.90	20	6.0
40	7	2.80	18	7.20	28	11.2
50	10	5.00	22	11.00	34	17.0
60	14	8.40	28	16.80	41	24.6
70	18	12.60	33	23.10	48	33.6
75	20	15.00	37	27.75	52	41.25
80	22	17.60	39	31.20	55	44.0
90	25	22.50	44	39.60	62	55.8
100	30	30.00	50	50.00	70	70.0

NOTE: For good or bad catchment, add or deduct upto 25% of yield.

2.3.4 Empirical formulae for estimation of run-off

(i) Inglis and De Souza formula

From 53 stream gauging sites in Western India, Inglis and De Souza, during 1929, evolved two regional formulae between annual runoff R in cm and annual rainfall P in cm. as follows:

1 For Ghat regions in Western India,

$$R = 0.85\,P - 30.5 \qquad \text{... (2.21)}$$

2 For Deccan Plateau,

$$R = \frac{1}{254} P(P-17.8) \qquad \ldots (2.22)$$

(ii) Lacey's formula

$$R = \frac{P}{1+\frac{304.8}{P}(F/S)} \qquad \ldots (2.23)$$

Where,

S = a catchment factor
F = Monsoon duration factor

Lacey's values for the factor F/S for Barlow's classification of catchments are given in Table 2.8.

Table 2.8

Lacey's factor (F/S)

S. No.	Monsoon class	Class of catchments				
		A	B	C	D	E
1.	Very short	2.0	0.83	0.50	0.23	0.14
2.	Standard length	4.0	1.67	1.00	0.58	0.28
3.	Very long	6.0	2.50	1.50	0.88	0.43

(iii) Khosla's formula

Khosla's relationship developed in 1960 (Subramanya, 1984) for monthly runoff is

$$R_m = (P_m - L_m) \qquad \ldots (2.24)$$

$L_m = 0.48\ T_m$ for $T_m > 4.5\ ^\circ C$

Where,

R_m = Monthly runoff in cm. and $R_m \geq 0$
P_m = Monthly rainfall in cm.
L_m = Monthly losses in cm.
T_m = Mean monthly temperature of the catchment in C.

For $T_m \le 4.5\,^{\circ}C$, the loss L_m may provisionally be assumed as

T°C	4.5	-1	-6.5
L_m(cm.)	2.17	1.78	1.52

Annual Runoff = $\sum R_m$

Khosla's formula is indirectly based on the water-blance concept and the mean monthly temperature is used to reflect the losses due to evapotranspiration. The formula has been used on a number of catchments in India and is found to give fairly good results for the annual yield for use in preliminary studies.

(iv) R.D. Dhir, P.R. Ahuja and K.C. Majumdar's relations (1958)

The equations derived by them (converted in metric units) for different basins of India are given herein:

(a) Gerina river basin (6200 sq. km.)

$$R = (13150\,P - 133{,}000) \qquad \ldots (2.25)$$

(b) Machkund River basin (2220 sq. km. A.P.)

$$R = (13.18\,P + 86.5) \qquad \ldots (2.26)$$

(c) Chambal River basin (22,500 sq. km. , Rajasthan)

$$R = (120\,P - 4945) \qquad \ldots (2.27)$$

(d) Tawa river basin (5950 sq. km., Madhya Pradesh)

$$R = (34.6\,P - 1510) \qquad \ldots (2.28)$$

(e) Manjra river basin (21,700 sq. km., Andhra Pradesh)

$$R = (90.5\,P - 4800) \qquad \ldots (2.29)$$

(f) Maniari river basin (805 sq. km.)

$$R = (4270\,P - 254000) \qquad \ldots (2.30)$$

(g) Tapti river basin (64,400 sq. km., Gujarat)

$$R = (435\ P - 17200) \qquad \text{... (2.31)}$$

(h) Damodar river basin (19,900 sq. km.), W.B.

$$R = (13400\ P - 5.75 \times 10^5) \qquad \text{... (2.32)}$$

(i) Ghatprabha river basin (248 sq. km.)

$$R = (3330\ P - 383{,}000) \qquad \text{... (2.33)}$$

(j) Kangsabati river basin (5850 sq. km.)

$$R = (9000\ P - 284000) \qquad \text{... (2.34)}$$

In these relationships R and P represent annual precipitation in cm. and annual run-off in million cubic m. respectively.

(v) U.P.I.D.'s formula

The Rihand Design Directorate of U.P. Irrigation Department developed the following correlation between rainfall and run-off for Rihand river in U.P.

$$R = (P - 1.17\ P^{0.86}) \qquad \text{... (2.35)}$$

Where, R & P = Run-off and rainfall in cm.

(vi) U.P. Irrigation Research Institute formulae (1960):

U.P. Irrigation Research Institute, Roorkee, has developed following relationships between runoff and precipitation:

A. Himalayan rivers

(a) Ganga basin at Hardwar (23,400 sq. km.)

$$R = 5.45\ P^{0.60} \qquad \text{... (2.36)}$$

(b) Yamuna basin at Tajewala (11,150 sq. km.)

$$R = 0.354\ P^{1.1} \qquad \text{... (2.37)}$$

(c) Sharda basin at Banbassa (14,960 sq. km.)

$$R = 2.7\ P^{0.8} \quad \text{... (2.38)}$$

B. Bundelkhand rivers

(a) Garai basin at Husainpur (290 sq. km.)

$$R = 0.58\ P - 2.8 \quad \text{... (2.39)}$$

(b) Ghori basin at Ghori (36 sq. km.)

$$R = P - 62.3 \quad \text{... (2.40)}$$

(c) Ghaghar basin at Dhandraul (285 sq. km.)

$$R = 0.38\ P \quad \text{... (2.41)}$$

(d) Sukhra basin at Sukhra (15 sq. km.)

$$R = 0.47\ P-2.8 \quad \text{... (2.42)}$$

(e) Karamnasa basin at Silhat (518 sq. km.)

$$R = 0.49\ P \quad \text{... (2.43)}$$

where, R is runoff in cm and P is rainfall in cm.

(vii) Indian Council of Agricultural Research's formulae for small watersheds

Run-off and rainfall from 17 nos. of sub-watersheds in the Nilgiri Hills, gauged by the Govt. of Tamilnadu, India have been analysed by the Central Soil and Water Conservation Research and Training Institute, Dehradun of ICAR. Reliable regression equations have been reported for the estimation of nine important physiographic characters of catchments, exhibited in Table 2.9.

Table 2.9

Values of nine physiographic characteristics for ungauged sub-catchments in the Nilgiries

Area (sq. km.)	L_P (km.)	L_S (km.)	C_e	R_F	F_F	S_I	R_T (m)	D_D (km/km^2)	T_C (min)
1	4.03	0.96	1.00	0.61	1.00	1.01	169.60	3.19	8.61
2	5.87	1.48	1.00	0.71	0.90	1.16	219.49	3.25	12.15
3	7.31	1.91	1.00	0.78	0.82	1.25	255.22	3.92	14.85
10	14.06	4.05	1.11	1.07	0.58	1.65	427.45	3.43	29.54
50	33.69	11.07	1.28	1.52	0.40	2.19	726.84	3.57	59.85
100	49.09	17.07	1.36	1.79	0.33	2.51	960.64	3.64	84.55

Where,

L_P = perimeter of the catchment km.
L_S = Main stream length, km.
C_e = Compactness coefficient
R_F = Roundity Factor
F_F = Form Index
S_S = Shape Index
R_T = Total watershed relief, m.
D_D = Drainage density, km/km^2
T_C = Time of concentration, minutes.

The regression equation developed is given by:

$$Q = \frac{P^{1.44} A^{0.63} R_T^{0.66}}{15.19\, F_F^{2.05} L_S^{2.05} T_m^{1.34}} \qquad \dots (2.44)$$

Where,

Q = annual runoff (cm.)
P = annual rainfall (cm.)
A = watershed area (sq. km.)
R_T = Total relief (m)
F_F = Length of the main stream (km.)
T_M = Mean annual temperature (°C)

It has been found that

$$R_T = 169.6\ A^{0.372} \qquad \text{...(2.45)}$$
$$L_S = 0.96\ A^{0.625} \qquad \text{...(2.46)}$$
$$F_F = 1.081\ A^{0.257} \qquad \text{...(2.47)}$$

By substituting equations 2.45, 2.46 and 2.47 in equation 2.44
We get,

$$Q = \frac{1.511\, P^{1.44}}{T_m^{1.34}\ A^{0.0613}} \qquad \text{...(2.48)}$$

(viii) Relationship developed by U.C. Kothyari, R.J. Garde and S.M. Seth (1985)

Hydrologic data from 39 catchments spread over twelve different states of India were compiled from various sources by Kothyari et al. (1985). Table 2.10 below gives the ranges of data used for study by the authors.

Table 2.10

Range of data used in Study

Parameter	Abbreviation	Range
Annual rainfall	P	27.7–672.3cm.
Mean annual rainfall	P_m	63.8–455.6cm.
Annual runoff	R	1.1–513.1cm.
Mean annual runoff	R_m	5.4–362.0cm.
Coefficient of variation of annual runoff	V_R	0.17–1.04
Vegetal cover factor	F_V	0.100–0.844
Catchment area	A	347–132090 km^2
Catchment length	L_C	46–661a km.
Drainage density	D_d	0.043–0.248 km./km^2
Land slope	S	0.005–0.382
Coefficient of variation of annual rainfall	V_P	0.12–0.46
Mean annual temp.	T	17.5 ^{0}C–28.6 ^{0}C

The relationship obtained for annual runoff 'R' using multiple regression was

$$R = \frac{F_V^{0.49}(P-0.5T)^{0.57}(P-0.5T)}{26.4} \qquad \text{... (2.49)}$$

The multiple correlation coefficient for the relationship of equation 2.49 is 0.9183 and standard deviation of residuals is 0.0457.

The land use in the catchments classified under the following types have been considered for the purpose of the study, (i) Forest area F_F (ii) Arable area F_A (iii) Grass and scrub area F_g and (iv) Waste area F_w . The vegetal cover factor (F_v) for the catchment has been defined as

$$F_V = \frac{a_1F_F + a_2F_A + a_3F_g + a_4F_W}{A} \qquad \text{....(2.50)}$$

Where, a_i , i = 1 to 4 are the weighing factors assigned to the above mentioned land uses. Values of the weighing factors were determined using grid search technique. Different sets of values were given to the coefficients a_1, a_2, a_3 and a_4 and the correlation coefficient between log R and log F was obtained. The combination of value of these weighing factors which gave maximum correlation coefficient were $a_1 = 1.0$, $a_2 = a_3 = a_4 = 0.1$. This indicates a relatively greater importance of forest cover in determining runoff. The runoff is also influenced by annual precipitation and annual average temperature.

2.4 CONCLUSIONS

Empirical formulae are extensively used for the estimation of peak flow and run-off, because of their simplicity. However, most of these empirical formulae are quite inadequate from the point of view of providing results consistently within the accuracy required for hydrologic analysis and design. But in the absence of any other information, these formulae may be used for initial estimation of hydrological parameters.

CHAPTER - III

REGIONAL UNIT HYDROGRAPH RELATIONSHIPS

3.1 INTRODUCTION

Unit hydrograph is one of the most popular and simple technique for computation of run-off from the catchment. It represents the characteristics of a given watershed and it represents the integrated effect of various physical features on the routing of the rainfall input through the catchment system. The unit hydrograph for gauged catchments can be derived by analysing the available rainfall-runoff data. However, for many small catchments the stream flow data are limited and for ungauged basins it is not at all available. Therefore, the unit hydrographs for such catchments can only be derived using their physical and storm characteristics. This necessitates the development of suitable regional relationship 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 the unit hydrograph parameters with pertinent physiographic and storm characteristics of the catchments. The catchments considered for such regional study have to be hydro-meteorologically homogeneous. Further knowing the catchment characteristics for an ungauged catchment in the region from the available topographical sheet and climatological data, the unit hydrograph for that catchment can be derived using relationships derived for the region.

3.2 BASIC STEPS FOR REGIONAL UNIT HYDROGRAPH DEVELOPMENT

Development of a regional unit hydrograph requires following sequential steps.

(i) Choice of catchments:

In regional study catchments should be selected from a hydro-meteorologically homogeneous region. A minimum of eight to ten nos. of catchments are generally required for the regional study.

(ii) Split Sample Test for the region

In order to test the performance of the developed regional relationships, the data of at least two to three gauged catchments should be kept independent. It means that those catchments should be treated as ungauged catchments and they should not be considered while developing the regional relationship.

(iii) Rainfall-runoff data

The rainfall-runoff data of different catchments for each of the major past flood events should be considered for analysis. If the catchment underwent some major changes due to human activities, then the rainfall runoff data of only recent past flood events should be considered for analysis.

(iv) Computation of excess rainfall

A suitable technique should be adopted to seperate the loss from total rainfall to get the excess rainfall hydrograph.

(v) Base flow separation

The base flow should be separated from the stream flow hydrograph using a consistent base flow separation technique to get the direct surface runoff hydrograph.

(vi) Derivation of unit hydrograph

The unit hydrograph should be derived by analysing the excess rainfall-direct surface runoff data for each event of different catchments using a suitable technique.

(vii) Derivation of representative unit hydrograph

The representative unit hydrograph derived by averaging the unit hydrographs obtained from different events of the catchment. However, if considerable variations are observed in unit hydrographs derived from different events in the catchment, then unit hydrograph parameters of each event should be considered, along with the catchment and storm characteristics in the regional study.

(viii) Split sample test for storms

The performance of the representative unit hydrograph of the catchment should be tested by reproducing the two or three independent storms, which were not used for deriving the representative unit hydrograph.

(ix) Development of regional unit hydrograph relationships

Stepwise multiple linear regression analysis can be performed, taking the unit hydrograph parameters of different catchments as dependent variables, and the catchment and/or climatic characteristics as independent variables to develop the optimal regional unit hydrograph relationships.

(x) Representative unit hydrograph for ungauged catchments

The regional relationships developed at step (ix) are used for split sample test for the region as described in step (ii). Further the representative unit hydrograph for the ungauged catchments of the hydro-meteorologically homogeneous region can be derived using measurable catchment and/or climatic characteristics in the generalized relationships developed in step (ix).

3.3 UNIT HYDROGRAPH PARAMETERS

The following parameters are generally considered for describing the shape of the representative unit hydrograph.

t_P = time to peak of the unit hydrograph in hours.
Q_P = Peak discharge of unit hydrograph in m^3 /sec
t_r = Unit rainfall duration adopted in a specific study.
T_B = Base width of the unit hydrograph in hours.
W_{50}= Width of unit hydrograph measured at discharge ordinate to 50% of Q_P in hours
W_{75}= Width of unit hydrograph measured at discharge ordinate equal to 75% of Q_P in hours.
WR_{50}= Width of the rising side of the unit hydrograph measured in hours at discharge ordinate equal to 50% of Q_P in hours.
WR_{75}= Width of the rising side of the unit hydrograph measured in hours at discharge ordinate equal to 75% of Q_P in hours.

A typical unit hydrograph describing the above parameters is shown in Fig. 3.1.

3.4 PARAMETERS FOR CONCEPTUAL MODELS OF IUH

Various researchers such as Clark (1945), O' Kelly (1955), Nash (1957) and Laurenson (1964) have proposed a number of conceptual models for IUH. Some of the more commonly used models are described as follows:

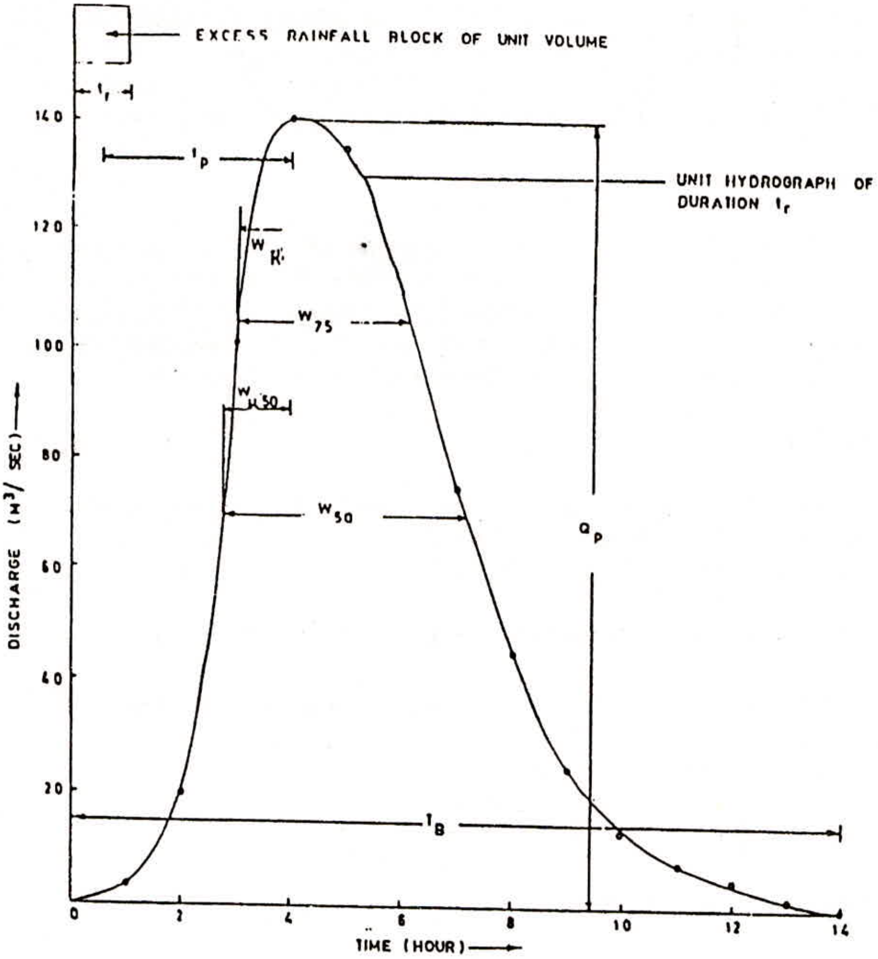


Fig. 3.1 A typical unit hydrograph

(i) Clark's model

The instantaneous unit hydrograph is derived by routing the time area diagram of the catchment through a single linear reservoir. The time of concentration has been defined as the time that elapses between the instants when the rainfall excess ends to the 2nd point of contraflexure of the hydrograph. The model requires knowledge of T and K in addition to the time area diagram of the catchment, which can be derived using topographical characteristics.

(ii) O'Kelly's model

O'Kelly (1955) suggested that Instantaneous Unit Hydrograph could be obtained by routing an isosceles triangular inflow of the unit volume and having a base width of T hours through a single linear reservoir having a storage coefficient of K hours. Therefore, T and K are the two parameters, which describe the shape of the instantaneous unit hydrograph based on O'Kelley's approach.

(iii) Nash model

Nash (1957) derived the IUH by routing the unit impulse input through 'n' linear reservoirs of equal storage coefficient 'K'. Therefore the two parameters 'n' and 'K' define the complete shape of the IUH.

3.5 BASIC TECHNIQUES FOR REGIONAL UH DERIVATION

The basic techniques for regional UH derivation are based on Correlation method and include the following:

(i) Graphical correlation
(ii) Simple linear regression
(iii) Multiple linear regression.

(i) Graphical correlation

In graphical correlation technique unit hydrograph parameters are plotted as a function of the physical characteristics of the catchments. Usually logarithmic graph paper is used, and a best-fit line is drawn.

(ii) Simple linear regression

In simple linear regression, it is assumed that the parameters (or their logarithms) are linearly related to each other given by

The regression equation is-

$$Y = a + bX \quad \text{... (3.1)}$$

where, Y = the dependent variable or its logarithm. The unit hydrograph parameters of different catchments are considered as dependent variables.

a = Regression constant
b = Regression coefficient
X = The independent variable or its logarithm and the physical characteristics of the basins are considered as the independent variables.

(iii) Multiple linear regression

The relationship is given by

$$Y = B_0 + B_1X_1 + B_2 X_2 + B_3X_3 + \ldots\ldots + B_m X_m \quad \text{....(3.2)}$$

Where, Y = The dependent variable (or its logarithm)
B_o = Regression constant
$B_1, B_2 \ldots B_m$ = Regression Coefficients
$X_1, X_2 \ldots X_m$ = Independent variables

When several watershed parameters are being considered, the above form is used. Parameters having little effect should be dropped from consideration, and the final expression should include only those parameters which significantly effect the result. Thus the objective of a multiple linear regression is to select an optimal equation combining independent variables and coefficients from which a response may be estimated.

3.6 APPROACHES FOR REGIONAL UNIT HYDROGRAPH DEVELOPMENT

For development of regional unit hydrograph many approaches have been reported in literature. Following are some of the commonly used approaches.

(i) Bernard's approach (1935)
(ii) Snyder's approach (1938)
(iii) Clark's approach (1945)
(iv) Taylor and Schwartz approach (1952)
(v) O' Kelley's approach (1955)
(vi) Minshal's approach (1960)
(vii) Nash's approach (1960)
(viii) Gray's approach (1961)

These approaches are described in NIH review note. no. 17 (1985-86).

3.7 REGIONAL UNIT HYDROGRAPH RELATIONSHIP FOR URBANISING CATCHMENTS

The unit hydrograph parameters are modified to predict runoff that would occur because of urbanisation within a watershed. Effect of urbanisation is generally reflected in the unit hydrograph by a reduction of lag time and an increase of peak flow.

Some of the regional unit hydrograph relationships for urbanising catchments are given below:

3.7.1 Snyder's relationship:

Snyder essentially considered rural drainage basins in his analysis. For urban watersheds the following relationships for estimation of C_t and C_p have been suggested:

$$C_t = \frac{7.81}{(I_a)^{0.78}} \qquad \text{... (3.3)}$$

$$C_P = \alpha\, t_P^{-0.92} \qquad \text{... (3.4)}$$

where, I_a = percentage of impervious area
q_P = peak discharge of the unit hydrograph in $m^2/sec/km^2$, and
$\alpha = 4.137$

3.7.2 Relationships by Texas Water Development Board

$$T_R = \alpha.\, U.L_f^{0.29}\, S_f^{-0.11}\, I^{0.61} \qquad \text{... (3.5)}$$

where, T_R = Total time to peak
α = 29.26
U = 1.0 (for natural conditions)
= 0.8 (storm sewered areas)
= 0.6 (watershed extensive urbanisation)
L_f = Stream length in m.
S_f = slope m/m
I = Impervious area %

Range of regression

L_f = 60.0 m to 16,700 m.
S_f = 0.0064 to 0.0104
I = 2.7 to 100
T_R = 30 to 270 minutes

Estimation of peak:

$q_P = \beta . A^{-0.12} T_R^{-0.30}$ For rural areas ... (3.6)

and

$\beta = 1.91 * 10^3$
$q_P' = \beta ' A^{-0.09} \; T_R^{-0.94}$ For urban areas ... (3.7)
$B' = 2.1 \times 10^4$

The other parameters of the unit hydrograph for urban and rural areas are as given below in Table 3.1.

Table 3.1

Parameters of unit hydrograph given by Texas water Development Board

	For rural areas	For urban areas
1.	$W_{50} = \dfrac{\beta}{q_P^{1.13} A^{0.2}}$ $\beta = 7.615$	$W_{50} = \dfrac{\gamma}{q_P^{1.4} A^{0.01}}$ $\gamma = 6.35$
2.	$W_{75} = \dfrac{\beta'}{q_P^{1.13} A^{0.07}}$ $\beta' = 4.805$	$W_{75} = \dfrac{\gamma'}{q_P^{0.94} A^{0.02}}$ $\gamma' = 3.25$
3.	Time base = $T_B = \dfrac{\delta A^{0.11}}{q_P^{0.53}}$ $\delta = 10.11$	$T_B = \dfrac{\delta'}{q_p^{1.19} A^{0.02}}$ $\delta' = 34.94$

3.7.3 U.K. Flood studies report

NERC (1975) represented the dimensionless 1 hr. unit hydrograph by straight line rising and recession limbs. The unit hydrograph was completely defined in terms of time to peak, t_P by the equations:

$$t_P = 46.6\, S^{-0.48} \quad RSMD^{-0.42}\, L^{0.14}\, (1+IMP)^{-1.99} \qquad \dots (3.8)$$
$$Q_P.\, t_P = 220 \qquad \dots (3.9)$$
$$T_B = 2.525\, t_p \qquad \dots (3.10)$$

Where,

L = the length (km.),
S = is the slope (m/km) of the main channel,
RSMD = is the 1-day rainfall excess having a return period of 5 years,
IMP = is the fraction of the urbanised area in the catchment,
Q_P = is the peak discharge of the unit hydrograph (m^3/sec/100 km^2),
and
T_B = the time base of the unit hydrograph

Equation (3.8) to (3.10) have also been utilised by the Institute of Hydrology to synthesis the unit response of the urbanising catchment areas.

Espey et al. (1965, 1969) discuss urbanisation effects on unit hydrograph and runoff from small watersheds.

3.8 GEOMORPHOLOGIC AND GEOMORPHOCLIMATIC IUH

A very powerful approach of development of instantaneous unit hydrograph based on geomorphologic and geomorphoclimatic factors is gaining tremendous importance now days. This is an attempt to discover simplifying principles of geomorphological equilibrium that produce simple regularities at the catchment scale. The basis of this is followed by the studies on quantitative geomorphology by Horton (1945). The quantitative analysis of drainage networks led the way for a theoretical foundation of Horton's well-known empirical laws and provided a new perspective for many other problems in fluvial geomorphology. Thereafter, an attempt was made by Rodriguez-Iturbe and Valdes (1979) for a unifying synthesis of the hydrological response of a catchment to surface runoff and it is attempted by linking the (IUH) with the geomorphologic parameters of the basin.

Horton's Laws

In a channel network in a basin the 'sources' are the points farthest upstream, and the 'outlet' is the point farthest downstream. The point at which two channels combine to form one is called a 'junction'. The channels in the network can be numbered (or ordered) according to Strahler scheme as follows:

1. Channels that originate at source are called the first order channels.
2. When two channels of order i join, a channel of order (i+1) is created.
3. When two channels of different orders join, the channel immediately downstream of the junction retains the higher of the orders of the two joining channels.

If N_i , i = 1,2,.......... Ω denote the number of streams of order i and if L_{ji} , j = 1,2,..........N_i , i = 1,2........... Ω represents the length of the jth stream of order i, then the mean stream length of order i, $\overline{L}_i$ is given by the formula,

$$\overline{L}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} L_{ji}$$

Using the above ordering scheme, Horton's well known laws of drainage may be expressed as follows.

The law of stream numbers is given by-

$$R_B = \frac{N_{i-1}}{N_i}, i = 2,3\ldots\ldots\ldots\Omega, \qquad \ldots (3.11)$$

Where R_B is called the Horton bifurcation ratio.

The law of stream length is given by:

$$\frac{L_i}{L_{i-1}} = R_L, i = 2,3\ldots\ldots\ldots\Omega \qquad \ldots (3.12)$$

Where R_L is the Horton stream length ratio. For natural basins the values of R_B range from about 3 to 5, and the values for R_L range from about 1.5 to 3.

In a spirit similar to the one behind the above laws, a law of drainage areas was proposed by Sehumm and is given by

$$\overline{A}_i / \overline{A}_{i-1} = R_A \; ; \; i = 2,3,\ldots\ldots\ldots\ldots\ldots \Omega \qquad \ldots (3.13)$$

Where $\overline{A}_i$ is the mean area of the basin region of order i. Specifically.

$$\overline{A}_i = \frac{1}{N_i}\sum_{j=1}^{N_i} A_{ji}, \; i = 1,2,\ldots\ldots\ldots \Omega \qquad \ldots (3.14)$$

The constant R_A is the Strahler basin area ratio. A_{ji} refers to the total area that drains into the jth stream of order i and not the area of the surface region that drains directly into the jth stream of order i only. Consequently $\overline{A}_i > \overline{A}_{i-1}$. For natural basins R_A is observed to range from 3 to 6.

Fig. 3.2 shows a third order basin with Strahler's ordering system. In this figure C_i denotes a channel state of Strahler order i, that is, an ensemble of all the channels of order i. Similarly, r_i denotes an overland region state of order i, that is, an ensemble of the overland flow areas and/ or creeks smaller than the first-order channels defined above, which flow directly into the channels of order i.

Parameters of the Geomorphologic IUH

Rodriquez - Iturbe et al. (1979) gave the following relationships for estimation of peak discharge and time to peak of the geomorphologic IUH.

$$q_P = \frac{1.31}{L_\Omega} R_L^{0.43} v \qquad \ldots (3.15)$$

$$t_p = \frac{0.44}{v} (R_B / R_A)^{0.55} R_L^{-0.38} \qquad \ldots (3.16)$$

Where,

L_Ω = length in km. of the highest order stream.
v = Mean velocity of the response in m/sec.
R_L = Length ratio
R_B = Bifurcation Ratio
R_A = Stream area ratio

Units of q_P is inverse of time i.e. $(\text{Time})^{-1}$ & Units of t_P is in hours.

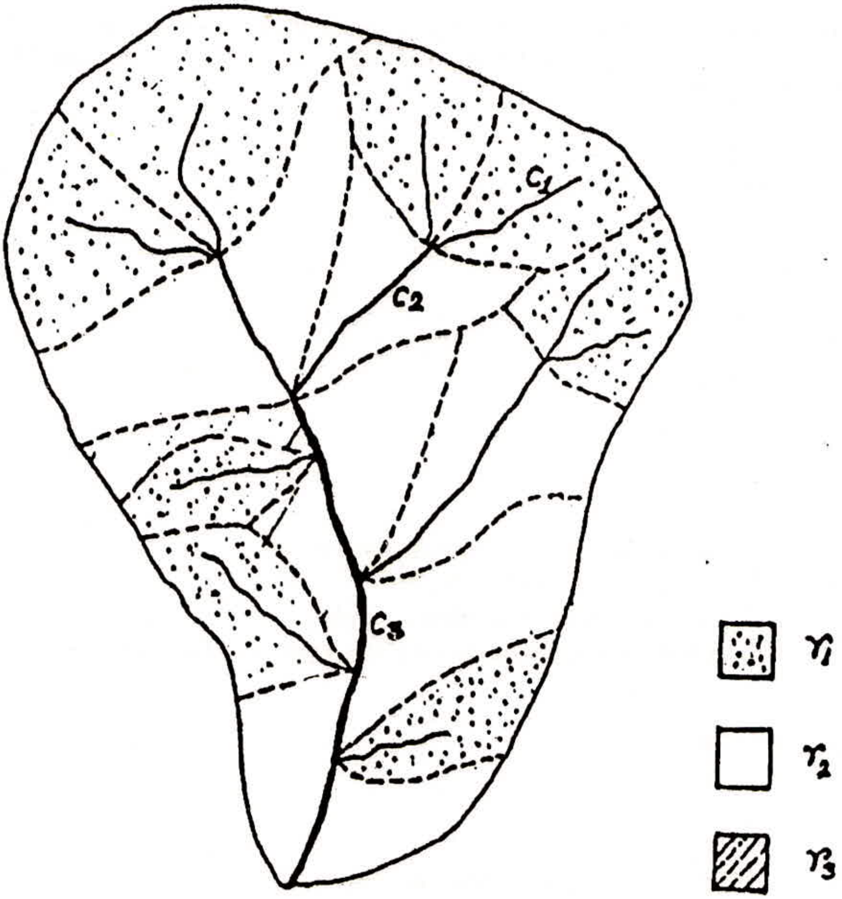


Fig. 3.2 A third order basin with Strahler's ordering system

Equations 3.15 and 3.16 are of general character and express the parameters of the IUH as a function of Horton's numbers R_A, R_B and R_L; an internal scale parameter L_Ω ; and a mean velocity of streamflow v.

Parameters of Geomorphoclimatic IUH

Because of the difficulty in estimating the dynamic parameter velocity (v) of the GIUH, concept of geomorphoclimatic IUH (G_cIUH) came into picture (Rodriguez et al., 1982), in which,

$$q_P = \frac{0.871}{\pi_i^{0.4}} \qquad \dots (3.17)$$

$$t_P = 0.585\, \pi_i^{0.4} \qquad \dots (3.18)$$

Where,

$$\pi_i = \frac{L_\Omega^{2.5}}{\tau_j A_\Omega R_L \alpha_\Omega^{1.5}} \qquad \dots (3.19)$$

Where,

L_Ω = Length of the highest order stream in km.
A_Ω = Area of highest order in sq. km.
τ_j = Intensity of effective rainfall in cm/hr.
α_Ω = Kinematic wave parameter for the stream of highest order.

$$\alpha_\Omega = \frac{S_\Omega^{1/2}}{n_\Omega b_\Omega^{2/3}} \qquad \dots (3.20)$$

Where,

S_Ω = Slope of the highest order stream
b_Ω = Mean width of the highest order stream in meter.
n_Ω = Manning's roughness coefficient.

The relationship for q_P and t_P given by the equations 3.17 & 3.18 are devoid of 'v', i.e. the mean velocity of response and as such may be conveniently derived from geomorphologic characteristics of the basin.

3.9 REGIONAL UNIT HYDROGRAPH RELATIONSHIPS FOR SOME INDIAN BASIN.

Collection of adequate data to derive unit hydrographs for every site is impossible. Hence Snyder has proposed synthetic unit hydrograph (SUH) approach by which transform models for homogeneous regions could be developed.

SUH relationships have been established for 22 sub-zones covering 90% of Indian Railways net work as shown in Fig. 3.3 by Research Design and Standards Orgainsation (RDSO) and Central Water Commission (CWC). These relationships are documented in various flood studies reports brought out by CWC. The names of sub-zones are given in the table 3.2. The relationships can be used for catchments between 25 km^2 to 5000 km^2 to estimate discharges.

Hydro-meteorologically homogeneous regions or sub-zones are first identified. Representative UHs are derived for a few selected representative sites based on actual rainfall runoff data. The parameters of UHs so derived for 12 to 15 sites in a region are then correlated with their corresponding catchment characteristics. Then equations are developed to derive the SUH using only the catchment characteristics instead of rainfall-runoff data.

Notations used for SUH relations

The unit hydrograph has been specified by 8-parameters, viz. t_P , t_r , T_B , Q_P, W_{50}, W_{75}, WR_{50} ,WR_{75} with same units as mentioned in section 3.3.

Catchment characteristics are specified by the parameters A,L,L_C , S_e & S_{st} where

A = catchment area in km^2

L = length of longest stream (km)

L_C = length of the main stream from a point near to the centre of gravity of catchment to the site.

S_e = equivalent stream slope in m/km^2 i.e., slope of the line being drawn such that areas below & above are equal

$$= \frac{\sum L_i\left[D_{i-1} + D_i\right]}{L^2} \qquad \dots (3.21)$$

L_i = length of each river segment

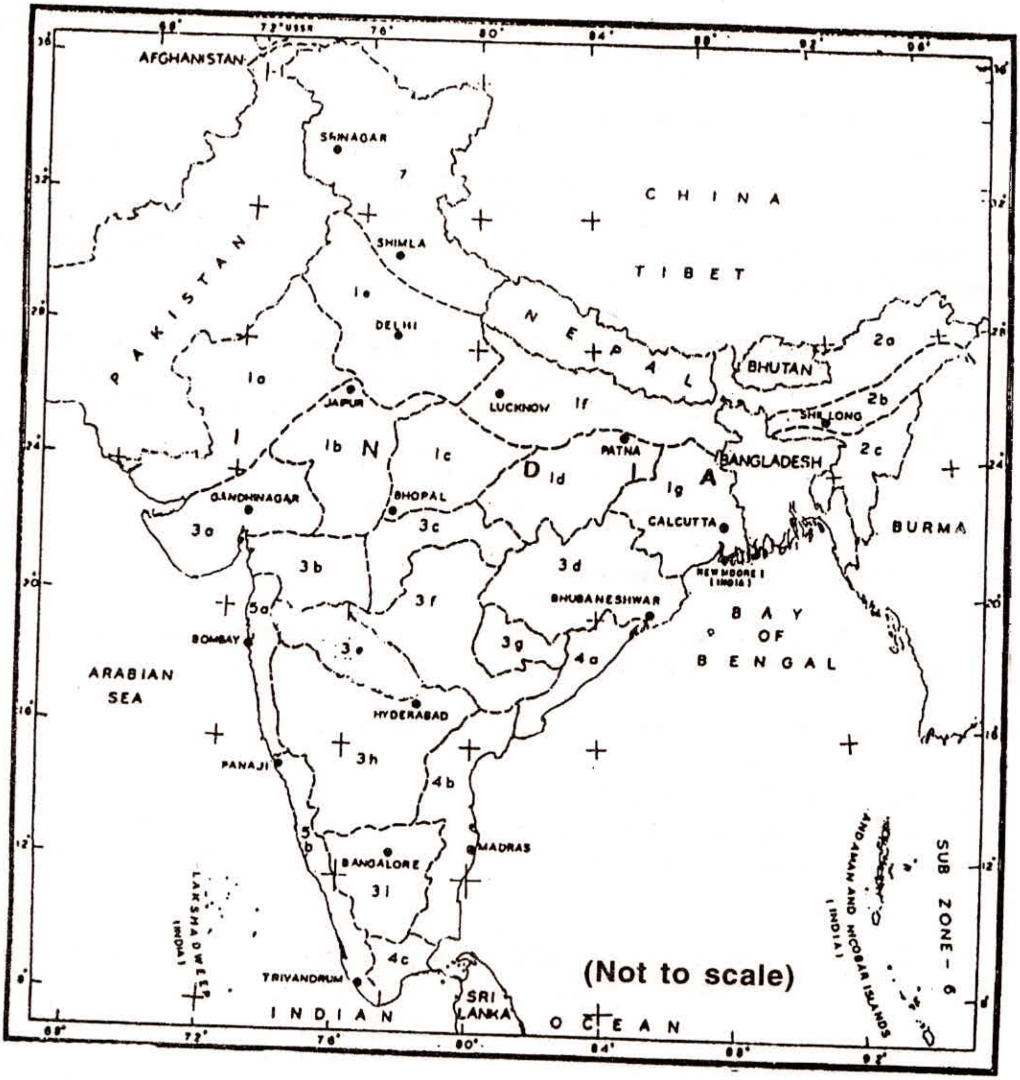


Fig. 3.3 Hydrometeorological subzones of India

D_i = height above datum.
S_{st} = statistical stream slope in m/ km.

$$= \left[\frac{L}{\sum \frac{L_i}{\sqrt{S_i}}} \right]^2 \quad ; \; S_i = \text{slope of segment} \qquad \ldots (3.22)$$

The sub-zonal relations for deriving SUH parameters have been tabulated in Table 3.3 for 16 sub-zones. Procedure for derivation of SUH is explained with help of an example in section 3.10.

Table 3.2

Name of hydro-meteorological sub-zones of India

Sub Zone	Name of Sub-zone
1(b)	Chambal Basin
1(c)	Betwa Basin
1(d)	Sone Basin
1(e)	Upper Indo-Ganga Plains
1(f)	Middle Ganga Plains
1(g)	Lower Ganga Plains
2(b)	South Brahmaputra Basin
3(a)	Mahi & Sabaramati Basin
3(b)	Lower Narmada & Tapi
3(c)	Upper Nartmada & Tapi
3(d)	Mahanadi Basin
3(e)	Upper Godavari Basin
3(f)	Lower Godavari Basin
3(h)	Krishan & Penner Basin
3(i)	Kavari Basin
4(a)	Upper Eastern Coast
4(b)	Lower Eastern Coast
4(c)	South Eastern Coast

TABLE-3.3
SUH RELATIONS IN SUBZONAL FLOOD ESTIMATION REPORTS

S. No.	SUB ZONE	t_r	SUH PARAMETER						
			T_p	q_p	Tb	W_{50}	W_{75}	$W_{R(50)}$	$W_{R(75)}$
1	1[b]	1	$0.339(L/\sqrt{Se})^{0.826}$	$1.251/(\sqrt{tp})^{0.610}$	$6.662\,(tp)^{0.613}$	$2.215/(q_p)^{1.034}$	$1.191/(q_p)^{1.057}$	$0.834/(q_p)^{1.077}$	$0.502/(q_p)^{1.065}$
2	1[c]	1	$2.195(q_p)^{0.944}$	$1.331/(L/\sqrt{Se})^{0.492}$	$3.917\,(tp)^{0.990}$	$2.04/(q_p)^{1.026}$	$1.25/(q_p)^{0.864}$	$0.739/(q_p)^{0.968}$	$0.500/(q_p)^{0.813}$
3	1[d]	1	$0.314(L/\sqrt{Se})^{1.012}$	$1.664/(tp)^{0.965}$	$5.526\,(tp)^{0.866}$	$2.534/(q_p)^{0.976}$	$1.478/(q_p)^{0.860}$	$1.091/(q_p)^{0.750}$	$0.672/(q_p)^{0.719}$
4	1[e]	2	$1.858/(q_p)^{1.038}$	$2.030/(L\sqrt{Se})^{0.649}$	$7.744\,(tp)^{0.779}$	$2.217/(q_p)^{0.990}$	$1.477/(q_p)^{0.876}$	$0.812/(q_p)^{0.907}$	$0.606/(q_p)^{0.791}$
5	1[f]	6	$1.217/(q_p)^{1.034}$	$0.409/(L\sqrt{Se})^{0.456}$	$16.432\,(tp)^{0.646}$	$1.743/(q_p)^{1.104}$	$0.902/(q_p)^{1.108}$	$0.736/(q_p)^{0.928}$	$0.478/(q_p)^{0.902}$
6	1[g]	1	$1.13(LL_C/\sqrt{Sst})^{0.2769}$	$0.315A^{0.93}\,Sst^{0.53}/A$	$4.39(LL_C/\sqrt{Sst})^{0.28}$	$2.18/(q_p)^{1.12}$	$0.81(w_{50})^{0.72}$	$0.69(w_{50})^{0.69}$	$0.605/(W_{R50})^{.95}$
7	2[b]	1	$3.39/(q_p)^{0.71}$	$1.171(A)^{0.7}/A$	$2.245(tp)^{1.19}$	$2.206/ q_p)^{1.06}$	$1.270/(q_p)^{1.008}$	$0.625/(q_p)^{1.17}$	$0.380/(q_p)^{1.13}$
8	3[a]	1	$0.433(LL_C/\sqrt{Se})^{0.704}$	$1.161/(tp)^{0.635}$	$8.375(tp)^{0.512}$	$2.284/(q_p)^{1.00}$	$1.331/(q_p)^{0.991}$	$0.827/(q_p)^{1.023}$	$0.561/(q_p)^{1.037}$
9	3[b]	1	$0.523(LL_C/\sqrt{Sst})^{0.323}$	$1.92/(tp)^{0.78}$	$6.908(tp)^{0.592}$	$1.83/(q_p)^{0.97}$	$0.924/(q_p)^{0.792}$	$0.745/(q_p)^{0.725}$	$0.436/(q_p)^{0.616}$
10	3[c]	1	$0.856(LL_C/\sqrt{Ss})^{0.28}$	$2.009/(tp)^{0.85}$	$4.84(tp)^{0.74}$	$2.259/(q_p)^{1.08}$	$1.519/(q_p)^{0.99}$	$0.844/(q_p)^{1.24}$	$0.583/(q_p)^{1.19}$
11	3[d]	1	$1.97(LL_C/\sqrt{Sst})^{0.24}$	$1.12/(tp)^{0.66}$	$5.72(tp)^{0.77}$	$2.195/(q_p)^{1.008}$	$1.221/(q_p)^{0.95}$	$0.995/(q_p)^{.94}$	$0.532/(q_p)^{0.93}$
12	3[e]	1	$0.727(L/\sqrt{Se})^{0.59}$	$2.070/(tp)^{0.88}$	$5.405(tp)^{0.73}$	$2.228/(q_p)^{1.04}$	$1.301/(q_p)^{0.96}$	$0.880/(q_p)^{1.01}$	$0.540/(q_p)^{0.96}$
13	3[f]	1	$0.353(LL_C/\sqrt{Sst})^{0.45}$	$1.968/(tp)^{0.842}$	$4.572(tp)^{0.90}$	$2.3/(q_p)^{1.018}$	$1.356/(q_p)^{1.007}$	$0.954/(q_p)^{1.078}$	$0.581/(q_p)^{1.035}$
14	3[h]	1	$0.258(LLC/\sqrt{Sst})^{0.49}$	$1.017/(tp)^{0.52}$	$7.193(tp)^{0.53}$	$2.396/(q_p)^{1.08}$	$1.427/(q_p)^{1.08}$	$0.75/(q_p)^{1.25}$	$0.557/(q_p)^{1.12}$
15	3[l]	1	$0.353(LLC/\sqrt{Se})^{0.405}$	$2.043/(tp)^{0.872}$	$5.083(tp)^{0.733}$	$2.197/(q_p)^{1.067}$	$1.325/(q_p)^{1.088}$	$0.799/(q_p)^{1.138}$	$0.536/(q_p)^{1.109}$
16	4(a.b& C)	1	$0.376(LLc/\sqrt{Se})^{0.434}$	$1.215/(tp)^{0.691}$	$7.621(tp)^{0.623}$	$2.211/(q_p)^{1.07}$	$1.312/(q_p)^{1.003}$	$0.808/(q_p)^{1.053}$	$0.542/(q_p)^{0.985}$

3.10 EXAMPLE DERIVATION OF SUH

1. Bridge No. 59 on Kharagpur -Nagpur section of South Eastern Railway, Subzone 3(d)

(a) $A = 136.0\ Km^2$
(b) $L = 28.17$ km
(c) $L_C = 11.26$ Km
(d) $S_{st} = 4.27$ m/ km.

2. Determination of SUH parameters

$$t_P = 1.97 \left[\frac{L\,Lc}{\sqrt{S_{st}}}\right]^{0.24}$$

$$= 1.97 \left[\frac{28.17 * 11.26}{\sqrt{4.27}}\right]^{0.24}$$

= 6.5 hours

(b) $q_P = 1.12\,(t_P)^{-0.66}$
$= 1.12\,(6.5)^{-0.66}$
$= 0.33\ m^3/s\ /km^2$

The peak of SUH ordinate is given by

$Q_P = q_P.A$
$= 0.33 * 136$
$= 44.88\ m^3/s$

(c) $T_B = 5.72\ t_P^{0.77}$
$= 5.72 * (6.50) = 24.17$ h

(d) $W_{50} = 2.195 * q_P^{-1.008}$
$= 2.195 * (0.33)^{-1.008}$
$= 6.71$ h

(e) $W_{75} = 1.221 * q_P^{-0.95}$
$= 1.221 * (0.33)^{-0.95}$
$= 3.50$ h

(f) $W_{B(50)} = 0.995 * q_P^{-0.94}$
$= 0.995 * (0.33)^{-0.94}$
$= 2.82$ h

(g) $W_{B(75)} = 0.532 * (q_P)^{-0.93}$
$= 0.532 * (0.33)^{-0.93}$
$= 1.49$h

The SUH parameters arrived at in steps 2(a) to 2(g) above are with 1 h unit duration and for 1 cm effective rainfall.

3.11 CONCLUSIONS

Regional unit hydrograph relationship, is a powerful tool to derive the unit hydrograph for ungauged catchments. Conceptual models such as Nash model and Clark model define the standard shape of the hydrograph using minimum number of parameters. It avoids subjective sketching of unit hydrograph shape in order to satisy the constraints to unit volume. However, in India, very little work has been done for developing unit hydrograph relationships using conceptual models. The effect of forest, agricultural urbanisation and other land uses on the shape of the unit hydrograph should be studied in catchments located in different geographical locations.

Derivation of IUH from geomorphological characteristics of the basin, is a recent development. With this technique it is possible to predict the unit hydrograph of a catchment on the basis of small number of parameters capable of being determined from readily measurable catchment characteristics. Further work in this direction is required for determination of velocity parameter. Application of GIUH approach for Indian basins would be quite infomative.

The synthetic unit hydrograph approach is of great use for Indian context, as the SUH relationships have been established for 22 sub-zones out of 26 hydro-meteorologically homogeneous regions and thus it covers over 90% of the Indian Railway network. This is very helpful for ungauged catchments.

CHAPTER IV

REGIONAL FLOODS FREQUENCY ANALYSIS

4.1 GENERAL

Flood quantities for different return periods are required for planning and design of hydraulic structures. Hydrologists have extensively used flood frequency methods for this purpose. This is carried out in the following ways:

(i) at-site flood frequency analysis using data of a particular site only.
(ii) at-site regional flood frequency analysis using data of the site in question and other sites in the region and
(iii) regional analysis using the data of all the sites in the region.

The only difference in at-site regional and regional analysis is that in regional analysis mean annual flood is calculated from the catchment characteristics while on the case of at-site regional analysis it is calculated from the observed data of the site.

For the regional analysis, various methods have been proposed in literature and still there is a lot of controversy regarding choice of distribution, type of parameter estimation, testing homogeneity of the regions etc.

4.2 TECHNIQUES OF AT-SITE REGIONAL AND REGIONAL FLOOD FREQUENCY ESTIMATION

Some of the methods of at-site/regional flood frequency analysis are listed below (Cunnane, 1988).

(i) Station year methods
(ii) Modified USGS method
(iii) Methods based on dimensionless moments
(iv) Methods based on order statistics/NERC method
(v) Record extension (joint estimation) methods
(vi) United states Water Resources Council method
(vii) Bayesian methods
(viii) Method based on standardised probability weighted moments (PWMS)
(ix) Two-component extreme value (TCEV) method

(x) Regional application of Box-Cox transformation
(xi) Threshold and censored sample methods
(xii) Simultaneous at-site and regional parameter estimation.

A brief account only on four commonly used methods is given in this section. For details of the other methods Cunnane (1988) may be referred to.

4.2.1 Modified USGS method

The USGS method otherwise known as the Index Flood method (Dalrymple, 1960) for estimating design flood of ungauged watersheds consists of eight sequential steps as given below:

(i) Select gauged catchments within the region having similar characteristics.
(ii) Determine the time base period to be used for the study
(iii) Establish flood frequency curves for data at each gauging site using Gumbel EV1 distribution probability paper. In other words parameters of EV1 distribution are estimated using method of least squares.
(iv) Estimate the mean annual flood $Q_{2.33}$ at each station.
(v) Test homogeneity of data using homogeneity test as proposed by Dalrymple (1960) (section 4.3).
(vi) Establish the relationship of mean annual flood and catchment characteristics usually drainage area at each station.
(vii) Rank ratios of selected return period flows to the mean annual flood at each station, and
(viii) Compute median ratio for each of the selected return period of step (7), multiply the estimated mean annual flood of the gauged catchment and plot them against return periods on Gumbel probability paper.

The end result of these eight sequential steps is a flood frequency curve for an ungauged catchment.

The modifications in the above method include (a) the replacement of Q by mean annual flood $\overline{Q}$ and (b) the replacement of the median ratio by the mean ratio $Q_T/\overline{Q}$ and (c) variable length of data instead of fixed length of data.

Modified USGS method using method of moments

In this method parameters are estimated by method of moments using following equations:

$$u = \mu - 0.5772\,\alpha \qquad ...(4.1)$$

$$\sigma^2 = \frac{\pi^2\alpha^2}{6} \qquad ...(4.2)$$

Where,

μ = location parameter,
α = scale parameter,
μ and σ are mean and standard deviation of the annual flood series
The remaining procedure is same as in case of modified USGS.

4.2.2 NERC (1975) method

The NERC method involves the following steps of computation.

(I) Select the gauged catchments in a hydrologically homogeneous region.
(ii) Compute the mean of annual peak flows for each station of the region.
(iii) Find the best fit equation for $\overline{Q}$ with catchment characteristics using multiple regression technique or as described in USGS method.
(iv) For each station in the region plot the rank annual maximum series $Q_i / \overline{Q}$ against EV1 reduced variate Y_i.
(v) Select intervals on Y scale (reduced variate) namely, (-2.0 to -1.5, -1.5 to -1.0, -1.0 to -0.5...) and for each interval compute mean of all Y_i and mean of all $Q_i / \overline{Q}$ and plot them as a smooth mean curve.
(vi) Use the curve as the regional curve for quantile estimation of ungauged catchments.

4.2.3 Methods based on standardized probability weighted moments:

As for the method based on probability weighted moments (PWM), firstly at site sample probability weighted moments are computed. The at-site sample values of PWM, for a sample (Q_i, i=1,...N) are satisfactorily given by:

$$M_{1r0} = \frac{1}{N}\sum_{i=1}^{N} w_i^r Q(i,N) \qquad ....(4.3)$$

$$M_{10s} = \frac{1}{N}\sum_{i=1}^{N}\left(1-w_i\right)^s Q(i,N) \qquad ....(4.4)$$

where Q(i,N) represents sample values ranked from the smallest to the largest and

$$W_i = \frac{i-0.35}{N} \qquad ...(4.5)$$

is the weighting function.

In this notation, M_{100} is the ordinary sample mean. The probability weighted moment method of parameter estimation consists of deriving expressions for M_{1r0} or M_{10s} in terms of the parameters of the assumed parent distribution. Equating as many of these as there are unknown parameters, to sample PWM values calculated from data, and solving the resulting equations, parameters of the unknown population can be obtained. This procedure is similar in structure to the estimation by ordinary moments but results in parameter estimates, which are superior to those obtained by moments (Landwehr et al. 1979).

For regional estimation Wallis (1980) proposed that at-site values of PWMs be standardized by division by the at-site mean M_{100} and that the resulting standardized values be average across the sites in the region.

Thus,

$m_{(r)} = M_{1r0}/M_{100}$

or $m_{(s)} = M_{10s}/M_{100}$

are calculated for each site and then averaged across the M sites by

$$\begin{aligned} \overline{m}_{(r)} &= \sum_{j=1}^{N} m_{(r)j}\left[N_j/L\right] \\ \overline{m}_{(s)} &= \sum_{j=1}^{N} m_{(s)j}\left[N_j/L\right] \end{aligned} \qquad ...\ (4.7)$$

Here N_j is the length of record and L is the sum of record lengths at all the sites. Thus each site contribution is weighted in proportion to its record length. These regional weighted average values of $\overline{m}_{(r)}$ or $\overline{m}_{(s)}$ can be used to estimate parameters of distributions which are expressible in inverse form, such as EV1, GEV, Weibull or Wakeby quite easily.

Quantiles X_T of such distributions can be scaled by at site mean $\overline{Q}$ to give a quantile estimate for any particular site.

$$Q_T = X_T \overline{Q} \qquad \text{... (4.8)}$$

4.2.4 Regional application of Box-Cox transformation

Box-Cox transformation was, suggested for flood hydrology by Chander et al., (1978). Kuczera (1983) used the same and called it power normal (PN) distribution. For suitable λ, which may be regarded as a shape parameter, the variate:

$$\begin{aligned} X &= \frac{Q^{\lambda}-1}{\lambda} \qquad \lambda \neq 0 \\ &= \ln Q, \qquad \lambda = 0 \end{aligned} \qquad \text{...(4.9)}$$

is assumed to be normally distributed as $N(\mu_x , \sigma_x^2)$. From a given sample of Q values λ, 1_x^4 and σ_x may be estimated jointly by method of maximum likelihood (Box and Cox, 1964) or as suggested by Chander et al., (1978).

Flood quantiles are then estimated by:

$$\overline{X}_T = \overline{\mu}_x + \overline{\sigma}_x y_T \qquad \text{...(4.10)}$$

where y_T is the N(0,1) variate value for exceedance probability of 1/T and:

$$Q_T = [1+\lambda x_T]^{1/\lambda} \qquad \text{...(4.11)}$$

Chander et al., (1978) expressed satisfaction with PN for estimating flood quantiles on the basis of 15 long records of floods examined by them. Hadgraft (1982) found that the PN method provides a better fit to flood data of Queensland than did any other of twelve tested candidate distributions.

Box-Cox transformation has been used for carrying out regional flood frequency analysis also (Kuczera, 1987; Perumal and Seth, 1985; Cadavid et al., 1987).

4.3 HOMOGENEITY TESTS

There are many methods to identify flood regions not in geographical space, but in a data space defined by either flood statistics or basin characteristics. Some of the prominent methods are-

(i) USGS method
(ii) C.V. based test
(iii) Multivariate techniques

The first two methods are based on flood statistics data whereas the use of multivariate techniques (Wiltshire & Beran, 1985) is based on basin characteristics and can be extended for a weighted quantile estimation. This section presents a brief description of the above methods.

4.3.1 USGS method of homogeneity test

The ratio of the 10-year flood to the mean discharge is used to measure homogeneity of the runoff data from gauged catchments.

The 10-year flood is estimated from the flood frequency curves. Each 10-year flood should be divided by the mean flood to get the 10-year ratio and a regional average of these ratios should be obtained. For each station of the region the return period corresponding to a discharge equal to the regional average flood ratio times the mean flood is computed.

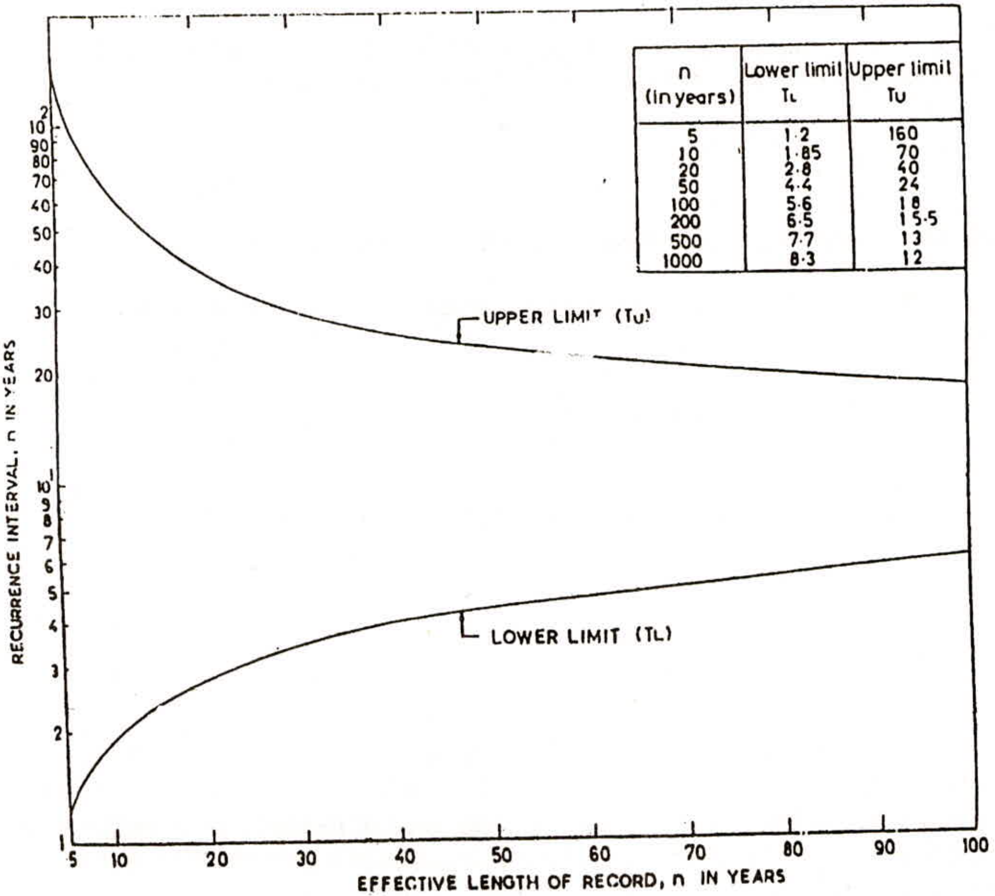
The computed return period or EV1 reduced variate is plotted against its length of record (years). If the plotted points for all stations under consideration fall within the upper and lower regional confidence limit Y_u and Y_l developed by the USGS, then the data are regionally homogeneous and applicable for analysis.

Any station for which the plotted point lies out side the envelope curve is excluded from the homogeneous region and hence from the analysis.

The upper and lower limits in Fig. 4.1 have been computed for a return period of 10-years. The reduced variate (Y_T) for T = 10 years in the Gumbel distribution is 2.25 and its standard error is given by

$$SE\ (Y_T) = 2e^{Y_T} / \sqrt{N(T-1)}$$

Where, N = length of record



n (In years)	Lower limit T_L	Upper limit T_U
5	1·2	160
10	1·85	70
20	2·8	40
50	4·4	24
100	5·6	18
200	6·5	15·5
500	7·7	13
1000	8·3	12

Fig. 4.1 Homogeneity test chart

Therefore,

$$Y_u = 2.25 + 6.33 / \sqrt{N} \qquad \text{...(4.12)}$$

and $Y_l = 2.25 - 6.33 / \sqrt{N}$

4.3.2 CV - based test

Let n_j denote the record length at site j and CV_j the sample coefficient of variation at the jth site. Then U_j, the sampling variation of CV_j, is given by

$$U_J = \frac{V}{n_j}$$

Where, V is the regional variance of CV and is taken as 1/12.

It is natural to express the total variation, S of CV within a region of N sites by:

$$S = \sum_{j=1}^{N} \frac{(CV_j - CV)^2}{U_j} \qquad \text{...(4.13)}$$

Where, CV. is the weighted region-average value of CV given by

$$CV = \frac{\sum_{j=1}^{N} CV_j / U_j}{\sum 1 / U_j} \qquad \text{...(4.14)}$$

The statistic S, of equation (4.13) has the form of a χ^2 statistic and S is expected to be distributed as χ^2 with (N-1) degrees of freedom. If the value of S exceeds the critical value of χ^2 for (N-1) degrees of freedom for a particular level of significance then the hypothesis of a homogeneous region must be rejected. If S is less than χ^2 at (N-1) for a particular level of significance, then the data is regionally homogeneous and applicable for analysis.

4.3.3 Multivariate techniques

Mosely (1981) used cluster analysis to form groups of basins characterised by specific mean annual flood $\overline{Q}_{SP}$, and the coefficient of variation C.V. in New-

Zealand. $\overline{Q}_{SP}$ describes the spatial intensity of the average maximum flood while CV characteristics the year to year variability of the annual maxima. Basins which plot close to each other in the figure can be combined together to form groups for the purpose of regional flood frequency analysis. Wiltshire and Beran (1985) have applied the clustering process to 376 nos. of British basins with prerequisite numbers of clusters specified as ten. From homogeneity statistics most of the clusters were found to be homogeneous at the 1% level of significance with only two clusters displaying heterogeneity.

Practical flood frequency estimation techniques must be geared to the ungauged case and an ungauged basin will not have $\overline{Q}_{SP}$ and CV statistics variables to indicate in which group or cluster it naturally belongs. However, basin characteristics data can be derived for any basin within the overall study area and these data can be used to infer cluster membership, given that each cluster can itself be described by a set of average basin characteristics values.

4.3.4. Comment on regionalisation approaches

A novel regionalisation approach avoids the use of fixed regions. This approach allows each catchment to have a potentially unique set of catchments that constitutes the region for the target site. This methodology involves the transfer of extreme flow information from similar sites to the catchment of interest and was first suggested by Acreman and Wiltshire (1987) and Acreman (1987). The method was refined and referred to as the region of influence (ROI) approach by Burn (1990). This approach requires the choice of a threshold value that functions as a cut-off point for a dissimilarity measure. All sites that have dissimilarity measure with the target site that is greater than the threshold value are excluded from the region of influence for that particular catchment.

The regionalisation approaches that are most commonly used today require the selection of variables that are used to define the similarity (or dissimilarity) for the catchments. The two most common general types of variables used in similarity measures are physiographic catchment characteristics (such as the drainage area, catchment slope, etc.) and flood statistics (such as the L-moment ratios, or other statistical measures, calculated from the available flood series). Data for a sufficient number of physiographic catchment characteristics are not always available, particularly for applications in remote areas or in developing countries. As a result, the groupings formed using the available physiographic variables may not be hydrologically homogeneous. The resulting regions are often hydrologically homogeneous when flood statistics are used as the variables in the similarity measure. However with this approach, the flood statistics are often used both to form the regions and to subsequently evaluate the homogeneity of the catchments in the region. This can result in regions that are homogeneous but not necessarily effective for regional flood frequency analysis.

4.4 REGIONAL FLOOD FREQUENCY STUDIES IN U.K.

The comprehensive report brought out by NERC (1975) presents methods, results and the analysis of flood records from British Isles.

In the NERC (1975) report a region curve has been defined as a frequency distribution of $Q/\overline{Q}$. It associates a return period T with $Q/\overline{Q}$ and this relation is assumed to be valid for all catchments in a region. A region curve has been derived for each of the 10 regions in Great Britain and one for Ireland. A curve has also been prepared for the whole of Great Britain.

For ungauged catchments the region curve may be used with an estimate of mean annual flood from catchment characteristics.

For regional applications, extensive studies were carried out for flood estimation from catchment characteristics. A detailed study of various catchment characteristics including morphometric characteristics as well as rainfall characteristics was carried out. For estimation of mean annual flood hydrologically relevant characteristics were chosen, keeping in view that they should be uncorrelated as far as possible and should be capable of being measured simply for a large number of catchments.

The catchment indices thus selected and included were as follows:

1. Catchment area (AREA)

2. Taylor-Schwarz (TAYSLO) and 10-85% (S1085) slope in m/km were both tried. Though S1085 is easily calculated but as it depends on the two points on the profile, it is more liable to be affected by measurement errors. The Taylor-Schwarz slope is based on the square root of gradients and it uses the fact that velocity for each reach of a sub-divided mainstream is related in the Manning's equation to the square root of slope. The index is equivalent to the slope of a uniform channel having the same length as the largest watercourse and an equal time of travel. TAYSLO is given by the following equation:

TAYSLO = (Number of equal length reaches / $\Sigma \frac{1}{\sqrt{s_i}}$)^2

3. Drainage network: The stream frequency (STMERQ) has been used as an index, which is defined as the number of junctions per square km. of the catchment.

4. Climate: On the basis of available information two rainfall indices were considered. The first was available rainfall for a standard period 1916-50, (SAAR), which was easily available from published maps. The other index was "RSMD' based upon daily rainfall and soil moisture deficit. The soil moisture deficit is calculated from a water balance between daily rainfall and the estimate of actual transpiration.

5. Soil: The proportion of catchment covered by each class of soil was determined from soil map and a composite runoff index, (SOIL) was derived from the formula as below:

$$\text{Soil} = \left[\frac{0.15\ S_1 + 0.30S_2 + 0.40S_2 + 0.40S_3 + 0.45S_4 + 0.50S_5}{S_1 + S_2 + S_3 + S_4 + S_5}\right] \quad \text{... (4.15)}$$

   where, S_1, S_2 , S_3, S_4 and S_5 denote the proportion of the catchment covered by each of the soil class 1-5. The factors in this formula were derived from a consideration of storm runoff data.

6. Land use: The proportion of the catchment in an urban area (URBAN) was used as a parameter.

7. Lakes: The proportion of the catchment draining through a lake was used as an index (LAKE), for including the effect of lakes.

The mean annual flood and coefficient of variation as obtained from annual maximum series were chosen for regression with catchment characteristics.

The multiple regression analysis was carried out for different regions using mean annual flood as dependent variable and the catchment characteristics described above as the independent variables. A typical relationship obtained for the central region of the U.K. is as follows:

$$Q_{2.33} = 0.0213\,(AREA)^{0.94}(STMERQ)^{0.27}(S1085)^{0.16}(SOIL)^{1.23}(RSMD)^{1.03}(1 + LAKE)^{-0.85} \quad ...(4.16)$$

4.5 REGIONAL FLOOD FREQUENCY STUDIES IN INDIA

4.5.1 Typical studies during 1970-84:

(i) Goswami (1972) carried out regional flood frequency analysis for Brahmaputra basin in North East India, using USGS procedure. He analysed annual peak flood series data for 25 sites for 1955-70 for catchment areas ranging from 63 to 69230 km^2. The mean annual flood $\overline{Q}$ (m^3/sec) for 2.33 year return period was graphically related with catchment area. This could be represented by the following expression:

$$Q_{2.33} = 0.523\,A^{0.884} \quad ...(4.17)$$

The study considers very large catchment of 69, 230 km^2 along with other small catchments of the same basin, which does not seem to be appropriate.

(ii) Thiruvendegachari et al. (1975) carried out regional frequency analysis using (USGS) procedure and annual flood series data for 10 small and medium catchments ranging in size from 133 to 8500 km^2 in magnitude having exceedance probability of 0.43 as index flood $Q_{0.43}$ (m^3 /sec.) which was related to catchment area A (km^2) and mean annual rainfall R(cm) as follows:

$$Q_{0.43} = 0.0055A^{0.79}R^{1.11} \quad ....(4.18)$$

The frequency curves were derived only for two ranges of index flood (i) $Q_{0.43} > 93.8$ m^3/sec. and (ii) $Q_{0.43} < 357.0$ m^3/sec.

(iii) Seth and Goswami (1979) carried out regional flood frequency analysis for ten tributaries of the river Brahmaputra in North East India with available annual flood series varying in length from 11 to 25 years. The techniques utilized in the study include: (a) using annual flood series of all the stations in the region having more than 10 years of record (b) extensions of short records of some streams by developing suitable relationships with concurrent peak flood records of streams with long record, and (c) adjustment of statistical parameters obtained from short records by means of statistical parameters obtained from longer records of neighboring stations.

The relationship between mean annual flood $\overline{Q}$ (m^3/sec) and catchment area A (km^2) and length of stream L (km.) was expressed as:

$$\overline{Q} = 0.2752\, A^{0.251}\, L^{1.329} \qquad \text{...(4.19)}$$

Multiple correlation coefficient R for this relationship was estimated as 0.983.

(iv) Jakhade et al. (1984) applied regional flood frequency approach of USGS to analyse the data of fourteen sites (having data for 10 or more years) in Brahmaputra valley. The rivers were divided into two different hydro-meteorological regions as Group A and Group B rivers. For these two groups the following relationship were obtained.

Group A rivers :

$$Y = 16.66\, X^{0.5783};\ r = 0.9765 \qquad \text{...(4.20)}$$
$$RQ_{10} = 1.5228$$
$$RQ_{100} = 2.2347$$
$$RQ_{1000} = 2.9497$$

Group B rivers :

$$Y = 1.1080\, X^{0.7968};\ r = 0.9628 \qquad \text{...(4.21)}$$
$$RQ_{10} = 1.389$$
$$RQ_{100} = 1.9225$$
$$RQ_{1000} = 2.4409$$

where,

X = catchment area in sq. km.
Y = Mean annual flood in m^3/sec.
r = correlation coefficient

RQ_{10}, RQ_{100}, RQ_{1000} are respectively the mean ratios for 10, 100, 1000 years return period flood to mean annual flood for the region.

The details of catchments are tabulated in Table 4.1.

Table 4.1

Details of catchment studied by Jakhade et al. (1984)

Sl.No.	Site and river	Catchment area (sq. km.)	Length of record (yrs.)
	Group A Rivers		
1.	Mathanguri, Manas	29424	31
2.	N.T.Road, Puthimari	940	10
3.	N.T.Road, Jea-Bharelli	14197	22
4.	Chowldhowa ghat, Subansiri	27000	19
5.	Pasighat,Dehang	249586	17
6.	N.T. Road, Borgong	409	16
7.	Khowang, Buridihing	4923	18
	Group B Rivers		
1.	NH Crossing, Dasang	3549	16
2.	NH Crossing, Dikhow	3610	17
3.	NH Crossing, Bhogdoi	600	20
4.	Numaligarh, Dhansiri	10242	16
5.	Dharamtul, Kapili	14537	21
6.	Pandu, Brahmaputra	424130	27
7.	Srirampur, Sankosh	9920	19

4.5.2 Typical studies after 1984

The area of the regional flood frequency analysis picked up well in India after 1984. Various studies broadly fall under following three categories:

(A) general aspects
(B) application of conventional techniques.
(C) new techniques.

(A) General aspects:

(i) Seth and Goel (1985) discussed the general issues of regional frequency analysis and mentioned about the problems due to non-availability of satisfactory methodology for regionalizing flood parameters and data limitations. For a country like India with great diversity in hydro-meteorological and hydrological conditions, the authors recommended comprehensive studies to develop suitable procedures and guide-lines for regional flood estimation, so as to ensure consistent flood estimation within each region.

(ii) Perumal and Seth (1985) have discussed various distribution used for fitting the peak flood series. The influences regarding the best fit distribution for peak flood series at a particular site is influenced by a prior assumption regarding the peak flood data, method of parameter estimation, goodness of fit texts, sampling variability, presence of outliers etc. Different hydrologists would arrive at different flood estimates depending on adopted methodology. The authors recommended adoption of uniform procedures for the country as a whole or for different regions.

(iii) Goel and Seth (1985) have discussed various data related problems in flood frequency analysis viz. broken record, incomplete record, zero flood years, presence of outlier etc. The causes of these problems and possible rectification are also discussed.

(iv) Rao and Goel (1986) while discussing regional flood frequency analysis mentioned about decrease in coefficient of variation of annual peak flood series with increase in the area of catchment. It is small for large catchments as they represent highly damped systems. The authors recommend that the area range of catchments chosen for regional analysis has to be necessarily restricted in order to ensure the absence of significant difference in coefficient of variations.

(B) Conventional techniques:

(i) Huq (1985) carried out regional flood frequency studies of Cauvery basin subzone 3(i) using multiple regression technique for developing relationship between mean annual flood as dependent variable and physiographic parameters like catchment area A(km^2), slope of the main stream S(m/km), percent of surface storage area of tanks plus 0.5 percent S_t, length of the main stream L (km), shape factor of the catchment $S_h = L^2 / A$, 24 hour rainfall in cm. having a recurrence interval of T years I_T as independent variables. The data of 23 catchments ranging in size from 66 to 10619 km^2 was used for analysis using Gumbel distribution. It was observed that relationship involving A, S and S_t provided better and reliable estimates. Some typical relationships are as follows:

Return period T = 2 years

$$Q_2 = 0.628\,(A)^{0.902},\ r = 0.8844$$
$$Q_2 = 0.38\,(A)^{0.98}\,(S)^{0.007}\,(S_t)^{-0.42}\ ;\ R = 0.893 \qquad \text{...(4.22)}$$

where, r and R are simple and multiple correlation coefficients, respectively.

(ii) Venkataraman and Gupta (1986) used USGS method for deriving relationship between 50 year return period flood Q_{50} (m^3/sec) and catchments characteristics in sub-Himalayan region. They used data from Railway bridge sites with catchment area ranging from 6 to 2072 km^2. The following relationship was obtained.

$$Q_{50} = 15.84\,(A)^{0.75} \qquad \text{...(4.23)}$$

They also developed a regional dimensionless frequency curve by plotting median values of ratios of floods of 50, 25, 10 and 5 years return period to mean annual flood ($Q_{2.33}$). The relationship for mean annual flood ($Q_{2.33}$) (m^3/sec) with catchment area was obtained as follows:

$$Q_{2.33} = 5.89\,A^{0.75} \qquad \text{...(4.24)}$$

The authors indicated various limitations of the study due to inadequate samples and length of data, filling up of missing data, extension and extrapolation and the stability of stage discharge curves.

(iii) Venkatararaman et al (1986) presented a regional flood study for subzone 3(f) in Lower Godavari basin using 26 years data of 14 small and medium railway bridge catchments with area ranging from 15 to 824 km^2. At these sites, the daily peak flood stages are observed during monsoon and are converted to discharge values using rating curves. The rating curves are based on regular gauging observations of both stage and discharge. Before proceeding for analysis the length of peak flood data for all 14 sites was brought to common length. They examined choice between (i) general extreme value (GEV) and Gumbel EV1 distribution (ii) regional pooling of data vis-a-vis averaging of ratios of floods for particular return periods to mean annual flood obtained at individual sites; and (iii) using parameters like catchment area A(km^2), length of main stream L(km.), statistical slope S, 50 years 24 hours point rainfall R_{24} (cm), 2 years one hour point rainfall R_1 (cm) for developing regression relationship with mean annual flood $Q_{2.33}$ (m^3/sec). The authors concluded that for subzone 3(f), the mean annual flood can be expressed satisfactorily as a function of A and R_1 or only A, as follows:

$$Q_{2.33} = 1.23\,A^{0.74}\,R_1^{-0.98} \qquad \text{...(4.25)}$$

$$Q_{2.33} = 7.10\,A^{0.55} \qquad \text{...(4.26)}$$

It was further concluded that 50 years return period flood could be obtained from graphical approach as per USGS method. For less important structures, where economic considerations may decide the choice, the authors suggested use of GEV growth curve.

(iv) Thirumali and Sinha (1986) carried out regional frequency analysis for 14 small and medium railway bridge catchments in Krishna Basin, having catchment areas ranging from 30 to 730 km^2 and flood series from 6 to 26 years. Mean annual flood $\overline{Q}$ (m^3 /sec.) was related with catchment area A(km^2) and 2 years 24 hour point rainfall R_{24} (cm) as follows:

$$\overline{Q} = 3.25\,A^{0.682} \qquad \text{...(4.27)}$$

$$\overline{Q} = 1.009\,A^{0.664}\,R_{24}{}^{0.64} \qquad \text{...(4.28)}$$

(v) Mehta and Sharma (1986) have presented results of flood frequency analysis of annual peak series for four sites of river Sutlej and Beas in Himachal Pradesh using normal, Gamma, log normal, Pearson type - III and log-Pearson type-III distributions, Method of moments has been used to evaluate the parameters of these distributions. Sample statistics on all the four sites considered on these rivers showed high value of coefficient of skewness.

The fitting performance of LP-III distribution was found to be better compared to normal, log-normal, gamma and Pearson type-III distributions. The authors recommended use of log-Pearson for return periods higher than 100 year and suggested further studies by carrying out flood frequency analysis of other Himalayan rivers.

(vi) Gupta (1987) has used USGS procedure for studying annual peak flood series of twelve bridge sites with catchment areas varying from 19 km^2 to 1094 km^2 for sub-zone 3(a) Mahi and Sabarmati Basin. A dimensionless curve giving ratios of return period flood peaks to mean annual flood peak ($Q_{2.33}$) has been developed. The relationship between $Q_{2.33}$ (m^3 /sec) and catchment area A(km^2) is expressed by:

$$Q_{2.33} = 8.02\,A^{0.63} \qquad \text{...(4.29)}$$

(vii) Saseendram et al. (1988) have carried out regional flood frequency studies for Kerala by dividing Kerala state in five regions.

(viii) Ghosh (1990) has carried out regional flood frequency analysis for rivers of North and Central parts of West Bengal.

(C) New approaches

(i) Perumal and Seth (1985) suggested a regional analyis approach in which the annual peak flood data of each gauging site is standardised with reference to the site specific mean annual flood, and flood frequency analysis is carried out using combined series of all sites using power transformation method. This study, using data of 18 railway bridge sites in Mahanadi basin subzone 3(d) of size 23 years each and catchment areas varying between 17 to 1150 km^2, indicated that Box-Cox power transformation could be considered as a useful technique for regional flood frequency analysis. The following regional relationship was obtained for mean annual flood $\overline{Q}$ (m^3 /sec.) and catchment area A (km^2)

$$\overline{Q} = 4.142\, A^{0.7484} \qquad ...(4.30)$$

(ii) Singh and Seth (1985) carried out regional frequency analysis for Mahanadi basin subzone 3(d) using five parameter Wakeby distribution. The annual peak flows for 23 years from 1958 to 1980 for 18 bridge catchments of subzone 3(d) were used in the study. The data for 15 sites were used to estimate the regional parameters of the Wakeby distribution with the average probability weighted moments and the remaining data of 3 sites were used as test data. The James - Stein corrected means JSM (m^3 /sec.) for flood series of 15 sites were computed and the following relationship was obtained with catchment area A (km^2).

$$JSM = 5.00\, A^{0.71} \qquad ...(4.31)$$

The floods of 2,5,10,20 and 50 years recurrence intervals were estimated using regional parameters of Wakeby distribution and JSM. The fitting performance of the regional parameters were tested on the basis of efficiency computed for each of the 15 sites and also for 3 independent sites. Errors of less than 13% were found in estimation of 50 year flood using regional approach with the Wakeby distribution.

(iii) Huq et al. (1986) attempted to evolve the frequency flood formulae for countrywide application using the frequency storm rainfall and runoff (flood) models. They used concurrent rainfall runoff data of 219 small and medium catchments located all over the country. For developing relationship for 50 year flood peak in m^3/sec. taking into account catchment area A (km^2), statistical or mean slope (S) (m/km) of the stream, and 50 year return period rainfall of 24 hour duration R_{24} (cm) for use in ungauged catchments up to 5000 km^2 in size. The country was divided into following four distinct categories of areas for evolving respective flood formula:

(a) Alluvial plains of Indus, Ganga and Brahmaputra river system with equivalent slope of up to 1.5 m/km
(b) for equivalent slopes above 1.5 m/km
(c) for remaining areas (excluding alluvial plains) with statistical slope up to 3.5 m/km and for
(d) statistical slope above 3.5 m/km.

The formulae for Q_{50} (m^3/sec.) for these four categories were obtained using multiple regression approach as follows:

Category (a)

$$Q_{50} = 0.765\, A^{0.738}\, S^{0.338}\, R_{24}^{0.713} \qquad \text{...(4.32)}$$

Category (b)

$$Q_{50} = 1.468\, A^{0.594}\, S^{0.425}\, R_{24}^{0.751} \qquad \text{...(4.33)}$$

Category (c)

$$Q_{50} = 0.921\, A^{0.731}\, S^{0.100}\, R_{24}^{0.927} \qquad \text{...(4.34)}$$

loss rate = 0.4 cm/hr

Category (d)

$$Q_{50} = 1.932\, A^{0.714}\, S^{0.134}\, R_{24}^{0.717} \qquad \text{...(4.35)}$$

loss rate = 0.4 cm/hr.

The authors also indicated design loss rates adopted in these studies for converting rainfall into excess rainfall for correlating with synthetic unit hydrograph for the concerned basin to derive flood peak value. It was also mentioned that Q_{25} is about 0.85 times Q_{50} and Q_{100} is 1.15 times Q_{50} on an average for similar loss rates. The study is subject to various limitations of unit hydrograph assumptions, conversion of point rainfall to areal rainfall, time distribution curves for rainfall, constant loss rates and base flow etc.

(iv) Seth and Singh(1987) have further used this approach with the Wakeby distribution using data of catchments for three typical regions viz. (a) Lower Godavari basin subzone 3(f), (b) Brahmaputra basin and (c) Sub-Himalayan region. The following relationships were obtained:

(a) Lower Godavari sub-zone 3(f)

$$JSM = 9.02\ A^{0.71} \qquad ...(4.36)$$

(b) Brahmaputra Basin

$$JSM = 3.32\ A^{0.75} \qquad ...(4.37)$$

(c) Sub-Himalayan region

$$JSM = 10.17\ A^{0.63} \qquad ...(4.38)$$

Where JSM is James Stein corrected mean annual flood (m^3 /sec) and A is catchment area in km^2

Lone (1988) derived the following regional relationships for the regions of Jhelum river basins-

Region - 1 (from Khanabal to Padshahibag)

(a) $$\overline{Q} = 0.266\ (A)^{0.969} \qquad ...(4.39)$$

(b) $$Q_T = \overline{Q}\ [\,0.257\ (1-(\frac{1}{T})^{18.750})+2.788(1-(\frac{1}{T})^{0.372})] \qquad ...(4.40)$$

Region - 2 (from Padshahibagh to Wullur Lake)

(a) $$\overline{Q} = 0.013\ (A)^{1.272} \qquad ...(4.40)$$

(b) $$Q_T = \overline{Q}\ [\,0.456\ (1-(\frac{1}{T})^{15.640})+3.338(1-(\frac{1}{T})^{0.207})] \qquad ...(4.41)$$

Region - 3 (With Wullur lake and the outfall channel from Wullur Lake to Khadanyar)

(a) $$\overline{Q} = 0.167\ (A)^{0.964} \qquad ...(4.42)$$

(b) $$Q_T = \overline{Q}\ [\,0.300\ (1-(\frac{1}{T})^{45.578})+6.482(1-(\frac{1}{T})^{0.122})] \qquad ...(4.43)$$

In these relationships

$\overline{Q}$ = Mean annual flood in m^3 /sec

A = Catchment area in sq. km.

Q_T = Flood magnitude for return period 'T'

Ikoi (1989) carried out at site/regional flood frequency analysis of 102 sites drawn from different regions using USGS, NERC and standardised probability weighted moment method. From the study the following conclusions have been drawn:

1. For at-site flood frequency methods Wakeby distribution with 5 parameters or 4 parameters seems to be the best method followed by General Extreme Value distribution.

2. For at-site regional methods again Wakeby distribution is performing better than other methods. Surprisingly modified USGS method with method of moments is performing very well on the basis of efficiency as criteria. The Wakeby distribution perfomed better than GEV distribution for the data sets used.

3. For regional flood frequency methods, method based on standardised probability weighted moments using Wakeby distribution out-performed the rest of the contending methods. So far the ungauged watersheds where data is not at all available the method based on standardised probability weighted moments using Wakeby distribution may be employed.

4.6 CONCLUSIONS

In India, most of the regional flood frequency studies are based on USGS procedure. Few studies have been attempted using Wakeby distribution and transformation techniques. Identification of homogeneous flood frequency regions is a pre-requisite for application of USGS procedure. Gauged basins are grouped together into homogeneous flood frequency regions by statistical analysis of hydrological data. An ungauged basin is allocated to a region on the basis of geographical space while it may be altogether different from the gauged basins. The use of multivariate techniques discussed in section 4.3.3. may provide a framework for flood estimation for ungauged basins that is more flexible than conventional regional analysis and is intuitively more reasonable. However the efficiency of the technique is limited by the availability of basin characteristics data. In India, there is a need for taking up systematic regional flood frequency studies using large data base, so that flood frequency curves for different regions are readily available.

CHAPTER - V

REGIONAL ESTIMATION OF RAINFALL INTENSITY-DURATION - FREQUENCY RELATIONSHIPS

5.1 INTRODUCTION

Rainfall intensity of a particular frequency and duration is required for estimation of average annual flood and sediment yield from the catchments. The design engineers do not have simple and reliable method for estimation of rainfall intensity, particularly for short duration. This necessitates going for the regionalisation of IDF relationships. The limitation of such study is the scarcity of data from self-recording raingauges for sufficiently long time. Again, studies for less than 1-hour data are also scarce. However, an effort has been made to briefly put forth the IDF relationships for various regions (mostly for Indian contexts) in the forthcoming sections.

5.2 REVIEW OF LITERATURE

Sherman in 1931 developed an empirical relationship of the form,

$$I = \frac{KT^a}{(t+c)^b} \qquad ...(5.1)$$

t = duration in minutes
T = Return period
K, a, b, and c are constants depending on geographical location.

This is the most common form of IDF relationship, which is still being used widely.

Bernard (1932) developed an empirical relationship in the form of:

$$I_t^T = \frac{a_o T^{a_1}}{t^{a_2}} \qquad ...(5.2)$$

Where, I_t^T = rainfall intensity having duration 't' and return period 'T'
a_o, a_1 & a_2 are constants and depend upon geographical location.

Bilham (1935) published his well - known article on the IDF relationship for U.K. and the frequencies were calculated from the formula as (converted in S.I. Units).

$$n = 1.214 * 10^5 \ t \ [\ R + 2.54\ ]^{-3.55} \qquad \text{...(5.3)}$$

Where,

R = depth of rainfall in mm
n = no. of occurrences in 10 years
t = duration of rain in hours

Bilham's work was modified by Holland (1967), who showed that Bilham's equation over estimates the probabilities of high intensity rainfall (> 35 mm/hr).

Yarnall (1935) presented such data in the form of maps of a region with isohyetal lines indicating total rainfall depth that may be expected in a time 't', at a frequency once in N-years for United States.

In Australia, the Bureau of Meteorology (Hall, 1984) had developed procedures for estimation of IDF values for return period up to 100 years and duration up to 72 hours.

General extreme value (GEV) distribution has been widely used for application to rainfall extremes in Australia, East Africa and U.K. This also forms the essence of rainfall studies in volume - II of U.K. Flood studies report (National Environmental Research Council, 1975). Gumbel distribution (a specific case of GEV distribution) has also been used in several reports of U.S. weather Bureau for durations ranging from 2 minutes to 24 hours.

Bell (1969) proposed the following the following depth - duration - frequency formula:

$$R_t^T = [0.21 \ln T + 0.52][0.54t^{0.25} - 0.50]R_1^{10} \qquad \text{...(5.4)}$$

For $2 \leq T \text{ (years)} \leq 100 \ \& \ 5 \leq t \text{ (min.)} \leq 100$

Where,

R_t^T = T-year and t-hour rainfall depth in inches

R_1^{10} = 10-year and 1-hour rainfall depth in inches

Baghirathan and Shaw (1978) made rainfall depth-duration-frequency studies for Sri Lanka. Chen (1983) provided a general relationship for rainfall intensity in U.S.A. Raudkivi of New Zealand presented regional relationship on IDF in 1979. All these authors used Bell's equation in their studies. Ferreri and Ferro (1990) verified the applicability of Bell's equation for Sicily and Sardinia in the Mediterranean.

Neimczynowicz (1982) used Log Pearson Type-III distribution with method of moments for preparing areal IDF curves for short-term rainfall events in Lund, Sweden.

Steel & Mc Ghee (1979) gave the empirical relationship for United States for duration less than 2 hours and for any given frequency as:

$$I = \frac{A}{t+B} \text{ (unbalanced)} \qquad ...(5.5)$$

Where,

I = intensity in inches/hour,
t = duration in min
A & B are constants depending on frequency and climatic condition.

Rao et al. (1983) obtained relationship between short duration rainfall and 24 hour rainfall as:

$$I(t) = a + b R_{24} + C R_{24}^{2} \qquad ...(5.6)$$

Where,

a,b,& c = constants

Gert et al., (1987) obtained the following relationships for Pennsylvania, U.S.A.

$$(t) = (1 + 0.42 \log^{t} 24) R_{24} \qquad ...(5.7)$$

Where,

$I(t)$ = rainfall amount for a duration of 't' hours
R_{24} = 24 hours rainfall amount

Mc Cuen (1989) gave the mathematical representation of IDF curves for computerizing the elements in hydrologic design for Baltimore in Maryland and the equations are:

$$I = \frac{A}{t+b} \text{ for } t \leq 2 \text{ hours}$$

$$I = c\,t^{d} \text{ for } t > 2 \text{ hours} \qquad ...(5.8)$$

Where I = intensity in inches/hour,
t = duration in hours and
a, b, c & d are coefficients that vary with frequency.

Chen's (1983) represented IDF as:

$$I_t^T = \frac{a\, I_1^{10} \log\left(10^{2-x}\ T^{x-1}\right)}{(t+b)^c} \qquad \text{...(5.9)}$$

Where,

I_t^T = Rainfall intensity in inches/hour for T-year and t-min storm duration

x = depth of frequency ratio (R_t^{100} / R_t^{10})

a, b & c = storm parameters that are dependent on regional ratio (R_t^{100}/ R_t^{10})

Chen showed that the 10-year, 1 hr rainfall R_1^{10} used in Bell's equation alone can not measure the geographical variations of rainfall and equation (5.8) produces more accurate results.

A comparison of available IDF relationships for short durations, given by Chow (1964), Raudkivi (1979), Gert et al. (1987), and Chen (1983) reveals that the values of exponents of variables 't' & 'T' in Bernard's equation do not vary much from place to place for shorter duration rainfalls. The exponent of 'T' ranges between 0.18 & 0.26. For 't' the exponent varies from 0.7 to 0.85.

5.3 REGIONAL IDF RELATIONSHIPS FOR INDIAN REGIONS

Parthsarathy and Singh (1961) prepared rainfall intensity duration frequency curves for India for local drainage design.

Based on 15 min tabulations of rainfall for 50 stations and hourly tabulations for 67 self-recording raingauges in India, Ayyar and Tripathi (1973,1974) have prepared generalized charts of 2,5,10,25 & 50 year return period values of 15, 30, 45 min, 3, 6, 9, 12 & 15 hours rainfall.

Ram Babu et al. (1979), after analysing rainfall characteristics for 42 stations, presented IDF equations and nomographs. With the equations and/ or nomographs, the intensity for any desired duration for a given frequency may be determined. Its general form is:

$$I = \frac{K\,T^{a}}{(t+b)^{n}} \qquad ...(5.10)$$

Where,

I = intensity in cm/hr
T = return period in years
t = storm duration in hours.

K, a, b & n are constants developed for various stations and zones of India. The values of K, a, b and n are presented in Table 5.1 for different stations and zones of India.

Table 5.1
Intensity duration return period relationship, India

Zone	Station	K	a	b	n
Northern	Agra	4.911	0.1667	0.25	0.6293
zone	Allahabad	8.57	0.1692	0.5	1.019
	Amristar	14.41	0.1304	1.4	1.2963
	Dehradun	6	0.22	0.5	0.8
	Jaipur	6.219	0.1026	0.5	1.1172
	Jodhpur	4.098	0.1677	0.5	1.0359
	Lucknow	6.074	0.1813	0.5	1.0331
	New Delhi	5.208	0.1574	0.5	1.1072
	Srinagar	1.503	0.273	0.25	1.0636
	Northern Zone	5.914	0.1623	0.5	1.0127
Central	Bagra-tawa	8.5704	0.2214	1.25	0.9331
zone	Bhopal	6.9296	0.1892	0.5	0.8767
	Indore	6.928	0.1394	0.5	1.0651
	Jabalpur	11.379	0.1746	1.25	1.1206
	Jagdalpur	4.7065	0.1084	0.25	0.9902
	Nagpur	11.45	0.156	1.25	1.0324
	Punase	4.7011	0.2608	0.5	0.8653
	Raipur	4.683	0.1389	0.15	0.9284
	Thikri	6.088	0.1747	1	0.8587
	Central zone	7.4645	0.1712	0.75	0.9599

Western zone	Aurangabad	6.081	0.1459	0.5	1.0923
	Bhuj	3.823	0.1919	0.25	0.9902
	Mahabaleshwar	3.483	0.1267	0	0.4853
	Nandurbar	4.254	0.207	0.25	0.7704
	Vengurla	6.863	0.167	0.75	0.8683
	Veraval	7.787	0.2087	0.5	0.8908
	Western Zone	3.974	0.1647	0.15	0.7327
Eastern zone	Agarthala	8.097	0.1177	0.5	0.8191
	Dumdum	5.94	0.115	0.15	0.9241
	Gauhati	7.206	0.1557	0.75	0.9401
	Gaya	7.176	0.1483	0.5	0.9459
	Imphal	4.939	0.134	0.5	0.9719
	Jamshedpur	6.93	0.1307	0.5	9.8737
	Jharsuguda	8.598	0.1392	0.75	0.874
	North Lakhimpur	14.07	0.1256	1.25	1.073
	Sagarisland	16.524	0.1402	1.5	0.9635
	Shillong	6.728	0.1502	0.75	0.9575
	Eastern Zone	6.933	0.1353	0.5	0.8801
Southern zone	Bangalore	6.275	0.1262	0.5	1.128
	Hyderabad	5.25	0.1354	0.5	1.0295
	Kodaikanal	5.914	0.1711	0.5	1.0088
	Madras	6.126	0.1664	0.5	0.8027
	Mangalore	6.744	0.1395	0.5	0.9374
	Tiruchirapalli	7.135	0.1638	0.5	0.9624
	Trivandrum	6.762	0.1536	0.5	0.8158
	Visakhapatnam	6.646	0.1692	0.5	0.9963
	Southern Zone	6.311	0.1523	0.5	0.9465

Rambabu et al. (1979) also give monograph (Fig 5.1) to convert one hour rainfall intensity into rainfall intensities of other durations.

For Vasad and Kota, the following relationships have been obtained by Central Soil Water Conservation Research and Training Institute.

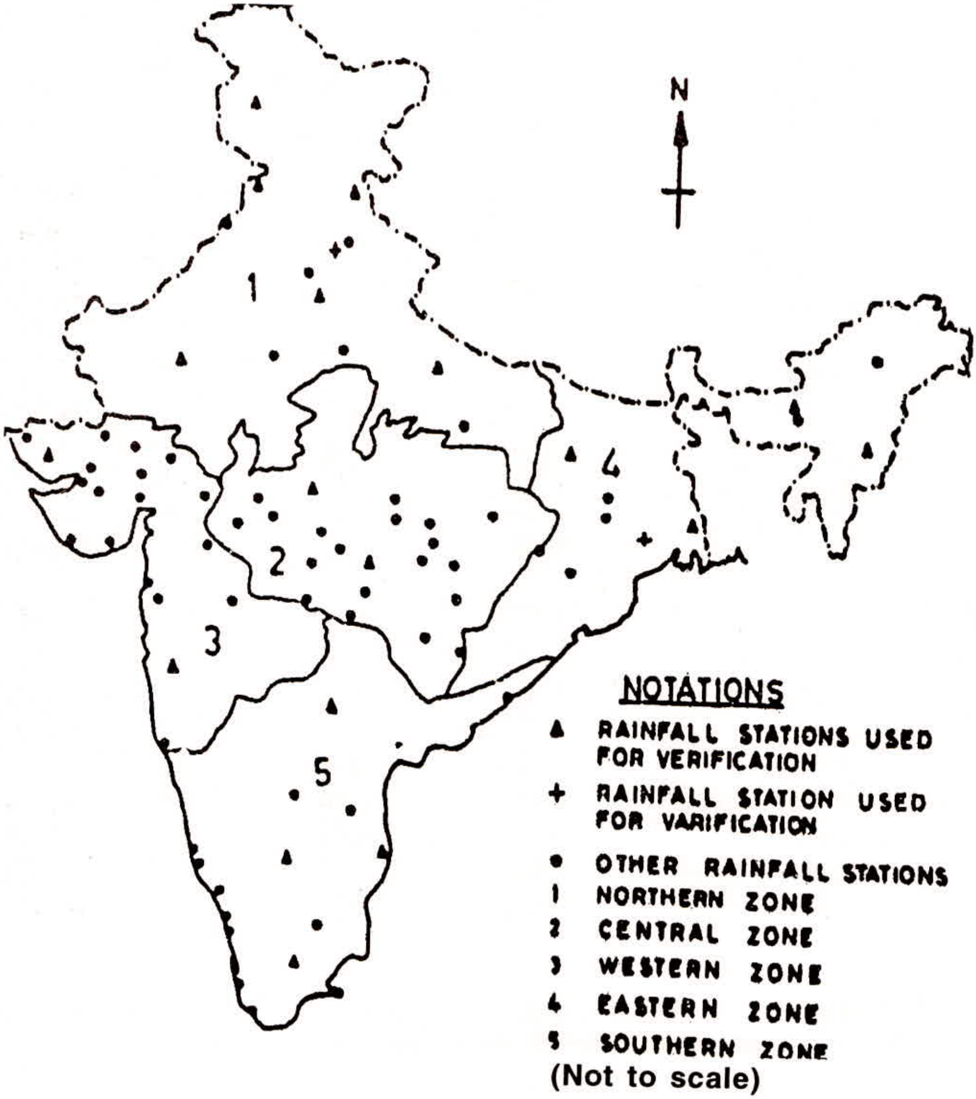


Fig. 5.1 Locations of raingauge stations and zonal boundaries in India

Vasad

$$I = \frac{7.506\ T^{0.1393}}{(t + 0.5)^{0.3857}} \qquad ...(5.11)$$

Kota

$$I = \frac{5.79\ T^{0.23}}{(t + 0.5)^{0.85}} \qquad ...(5.12)$$

Kothyari & Garde (1992) developed a general relationship on IDF after analysing 80 raingauge stations (Fig. 5.2) in India. They have made use of the assumption that general properties of convective cells that are associated with short - period rainfalls are similar in different hydrologic regions Raudkivi (1979). The formula is of the form:

$$I_t^T = C\,\frac{T^{0.20}}{t^{0.71}}(R_{24}^{2})^{0.33} \qquad ...(5.13)$$

Where,

I_t^T = rainfall intensity in mm/hr for T-year return period & t - hours duration

C = constant having value 8.31 for the whole of the considered stations (Values for different regions are given in Table - 5.2)

R_{24}^{2} = 2-year return period & 24 hr. rainfall in mm .

In India, number of studies have been carried out to analyse the data of individual stations e.g. Rama and Krishna (1958) for Delhi, Alipore and Madras Stations, Rama and Bandyopadhyay (1969) for Calcutta.

Table 5.2

Values of 'C' for different regions of India

Geographical region	Zones in figure 5-1	Value of C
Northern India	1	8.0
Eastern India	4	9.1
Central India	2	7.7
Western India	3	8.3
Southern India	5	7.1

5.5 CONCLUSIONS

Gumbel's extreme value distribution has been most oftenly used for analysis of the short duration rainfall data. The IDF relationships developed for Indian regions are based on limited data of very few stations and there is need to further improve upon the relationships based on larger data base.

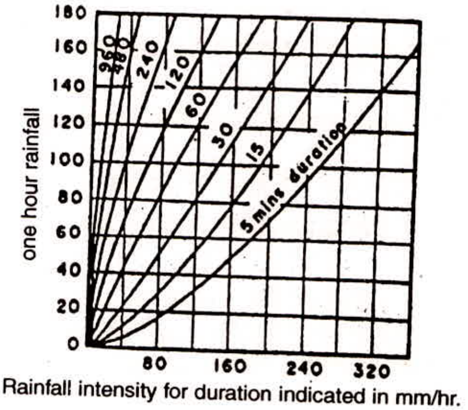


Fig. 5.2 Relation to convert one hour rainfall to intensities for other durations

CHAPTER - VI

REGIONAL RELATIONSHIP FOR CATCHMENT SOIL EROSION

6.1 SOIL EROSION ROCESS AND SEDIMENT TRANSPORT

Erosion is essentially a smoothening or leveling process, with soil and rock particles being carried, rolled or washed down by the force of gravity. The main agents, which loosen or break down the particles, are wind and water. Wind does not by itself wear away rocks, but abrasion, even of hard rocks results from grains of sand or soil. Water, however, is probably the most important single agent of erosion. Rainfalls, streams and rivers all scour away soil. Erosion and sedimentation process not only removes the top most fertile soil from agricultural land, but also it causes the deposition of sediments in water bodies. The soil degradation by erosion effects enormous area of the world. Nearly 31% of the land surface of the globe is subjected to water erosion. It washes away about 60 million tons of the soil to the oceans every year. This has necessitated the development of erosion prediction models, which can be used for a variety of purposes such as modelling of water quality, erosion control planning, reservoir sedimentation, aggradation in rivers, canals, and harbors etc.

Soil erosion and transport of sediment by water, primarily involve the process of detachment, transport and deposition of sediment by raindrop impact and flowing water. Soil detachability increases with the size of particles and transportability increases with a decrease in particle size. The relative importance of these processes depends on whether the processes are occurring on inter-rill or rill areas and in the level of controlling variables. Various types of water erosion are discussed as follows:

6.1.1 Raindrop erosion

This is soil splash resulting from the impacts of water drops directly on soil particles or on thin water surface. The raindrop momentum provides a consolidating force to soil particles compacting the soil. Also it imparts velocity to soil particles. Splash detachment depends upon the kinetic energy of raindrops.

6.1.2 Erosion by overland flow

Overland flow detaches the soil particles when its erosive hydrodynamic forces exceed the resistance of soil to erosion.

6.1.3 Sub-surface flow erosion

In this type, finer particles are washed when it moves through pore space in the soil. Essential plant nutrients along with fertilizers can be removed in the process.

6.1.4 Rill & gully erosion

Rill erosion is the removal of soil by water from small but well-defined channels or streamlets when there is concentration of overland flow. Rills are small enough to be easily removed by normal tillage operations. Detachability & transportability are more serious with involvement of higher runoff velocities. Hence this is the most serious form of erosion as regards to agriculture.

Gully erosion produces channel larger than rill erosion that carry water during and after rains, which can not be obliterated by tillage operations. This is the most serious form of erosion on the point of view of high sediment load and silting.

6.2 SOIL EROSION MODELLING

Various approaches have been proposed to predict soil loss & sediment transport under current and alternate hydrological conditions. The specific needs for soil loss predictions are so varied that no single model is able to meet the results satisfactorily. So the models vary greatly in complexity from simple regression relationships linking spatial variations in annual sediment yield to climatic and physiographic characteristics, to complex distributed simulation models. Haan, et al. (1982), Bhatia (1984), Walling (1988) and Singh (1989) have reviewed such models. In this report, the models have been classified on the basis of methodology used and are grouped as empirical prediction models, physically based prediction models, dynamic simulation models & stochastic models. The review of literature, particularly in Indian context, follows in subsequent sections.

6.2.1 Empirical prediction equations

These are used to estimate the mean annual erosion rates from catchment characteristics and local hydrometeorological conditions. They predict the variation in erosion rate for a given catchment in a region. Some commonly used models are:

(i) Musgrave equation, (1947)
(ii) Universal soil loss equation (USLE), by Wischmeier and Smith

(iii) Modified universal soil loss equation (MUSLE), by Williams (1975 to 1978)
(iv) Revised universal soil loss equation (RUSLE)
(v) Sediment delivery ratio method (SDRM)
(vi) Sediment rating curves by Walling (1977)
(vii) Regression models by Flaxman (1972), Singh (1973), Khosla (1953), Dhruv Narayan et al., (1983), Garde & Kothyari (1987), Williams (1977) and Renard (1980).

6.2.2 Physically based prediction models

These models are developed on the basis of catchment-transport concepts of Meyer and Wishchmier (1969) for rill and inter-rill erosion and also various transport equations for sediment movement in channel. U.S. Department of Agricultural Water Erosion Prediction Project (WEPP) initiated in 1985 is currently working to replace USLE.

6.2.3 Dynamic simulation models

Because of the close dependence of erosion process on surface and channel runoff these models are commonly developed to take care of simulation of complex interaction of general hydrology and rainfall/runoff response of a catchment. Thus these models may be self-contained or part of more general non-point pollution models. Some of these models are:

(I) Colorado State University Model (CSU) by Li(1977)
(ii) Stanford Sediment Model by Negev (1967)
(iii) Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) by Beasley et al. (1977)
(iv) A field scale model for chemical runoff and erosion from Agricultural Management System (CREAMS) by Kinisel (1980).
(v) System Hydrologique European Model (SHE)
(vi) Finite Element Storm Hydrograph Model (FESHM)

6.2.4 Stochastic models

For application of various stochastic and time series modelling procedures to erosion process, long duration record of erosion rate is essential. The short database poses a constraint. Some attempts are made through ARMA model (Box & Jenkins, 1970) to model suspended sediment concentration. Sharma, et al. (1979) used the ARMA model for modelling monthly and daily sediment yield.

Mathur et al. (1992) gives details of various models under this category.

6.3 PREDICTION OF EROSION RATES FROM INDIAN CATCHMENTS

The complexity and data requirement of water & sediment yield models tend to vary directly with the amount of predictive details the model exhibit. The approaches used in India, have been mostly empirical, because of limited data availability. These are discussed as follows:

6.3.1 Universal soil loss equation (USLE)

The equation estimates annual sediment yields and is designed to predict long term average annual soil losses by sheet & rill erosion under specified physical conditions, land use & management practices. Gully & channel erosion is added to get the total erosion, for which guidelines (USDA, 1971) are available. USLE has been widely used for estimating erosion rates for Indian catchments.

The USLE has the following form:

$$A = R.K.LS.C.P \qquad ...(6.1)$$

Where,

A = average annual soil loss in metric tons/ha

R = Rainfall & runoff erosivity index. This is a numerical value, which express the capacity of locally expected rainfall to erode soil from an unprotected (fallow) land.

K = Soil erodibility factor. This is the rate of soil loss per erosion index unit for a specified soil on a unit plot of 9% slope and 22.1 m long.

LS = Slope length & steepness factor. This is the ratio of soil loss per unit area from a field slope, to that from a 22.1 m long stretch of uniform 9% slope under otherwise identical conditions.

C = Cropping management and cover factor. This is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilted continuous fallow.

P = Supporting practice factor. This is the ratio of soil loss with a supporting practice like contouring etc. to that of straight up & down slope cultivation.

Based on 21 observed and 64 estimated soil loss data points spread over different land resource regions of the country and by superimposing eight maps (i.e. available maps of soil, rainfall erosivity, slope, land- use, forest & vegetation, degraded land, sand dunes & irrigation), Singh et al. (1992) prepared iso-erosion soil lines using USLE. The factor 'R' was taken from 1978 iso-eroded map of India by Ram Babu et al. (1978). The factor 'K' was obtained from a nomograph by Wischmeier & Smith (1978). The factor 'LS' was obtained from Wischmeier & Smith (1978). The 'CP' factor was taken from ICAR bulletin.

The map is shown in figure 6.1. It indicates the water erosion rate values ranging from 5 Mt/ha/yr for dense forest, snowclad cold deserts to 80 Mt/ha/yr. in the arid region of Western Rajasthan.

6.3.2 Khosla's equation

Khosla proposed a relationship for sediment yield for Indian catchments, after analysing 5 reservoirs from India and 33 from foreign countries and the following revised empirical relationship was given in 1953:

$$V_s = 5.95 * 10^{-8} A^{1.72} \qquad ..(6.2)$$

Where,

V_s = sediment yield in m^3/year
A = catchment area in m^2
The formula is applicable for areas lesser than 2600 km^2.

The equation however does not consider variables like rainfall, shape of catchment, slope of catchment and soil characteristics. In many cases, the formula gives much higher annual silt deposits than actually found.

6.3.3 CBIP research committee method

Research Committee of the Central Board of Irrigation & Power (1978, 1981) has suggested 2-tentative methods for estimating sediment accumulation in reservoirs in absence of long term records.

(a) For catchments below 1000 square miles

$$\begin{aligned} S &= 0.5\,A^{3/4} && \text{for rocky catchments} \\ S &= 1.7\,A^{3/4} && \text{for normal catchments} \qquad ...(6.3) \\ S &= 5.5\,A^{3/4} && \text{for soil catchments} \end{aligned}$$

Where 'S' is silt accumulation in acre ft/year & A is catchment area in square miles.

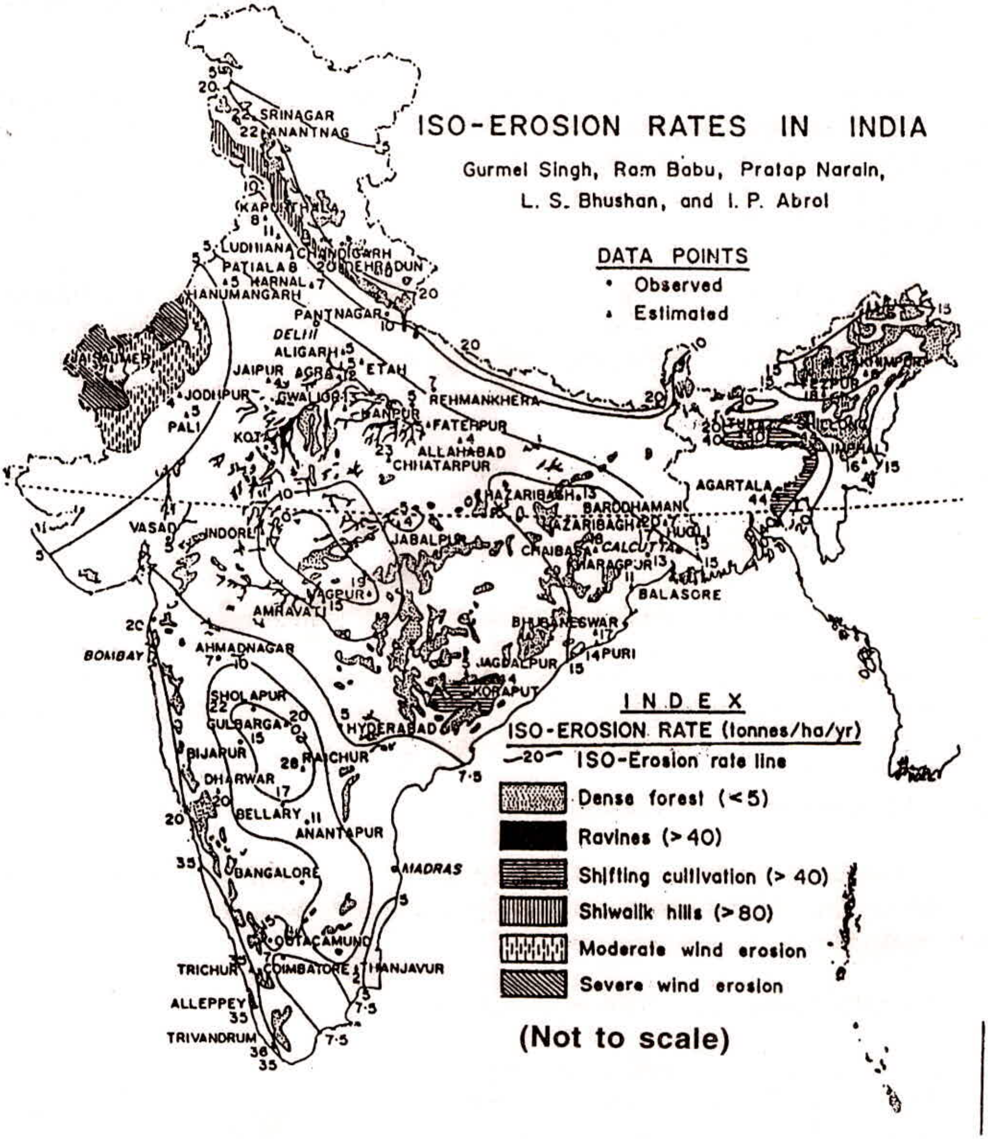


Fig. 6.1 Iso-erosion rates in India

(b) For catchments over 1000 square miles in area, the maximum rate of silting was proposed to be 75-acre ft/100 sq. miles/year.

6.3.4 Varshney's method

Varshney (1970, 1986) has given regional sedimentation curves for Indian catchments, determined on the basis of data collected from Indian reservoirs. For catchment areas greater than 5000 sq. km. and for Himalayan River, the following relationship has been given:

$$S = \frac{141}{A^{0.264}} \qquad \text{...(6.4)}$$

6.3.5 Empirical relationship by Dhruv Narayan & Ram Babu (1983)

Data from 17 major reservoirs in India were analysed by them to obtain the relation for annual sedimentation rate as:

$$T_1 = 5.5 + 11.1\,Q \qquad \text{..(6.5)}$$

in which Q is the annual runoff in M ha m and T is the erosion rate in m Tons per year. This equation was further refined as:

$$T_1 = 5.3 + 12.7\,QW \qquad \text{...(6.6)}$$

Where, W = T/A & A is the catchment area in m-ha.

Average value of 'W' was found to be 1.25M Tons/m- ha. Also using data from 18 river basins, the following relationships were obtained, for annual sediment loads of various rivers.

$$\begin{aligned} & T = 0.014\,A^{0.84}\,P^{1.37} \\ \text{or,}\ & T = 14.25\,Q^{0.84} \\ & T = (0.342 * 10^{-6})\,A^{0.84}\,(EI_{30})^{1.65} \end{aligned} \qquad \text{...(6.7)}$$

in which P is the average annual rainfall in cm, A is the catchment area in m- ha and EI_{30} is the product of average annual value of the sum of maximum 30 minute rainfall intensity in cm/hr and kinetic energy value E given by

$$E = 210 + 89\,\log_{10}(I_{30}) \qquad \text{...(6.8)}$$

Where, E is in tons per ha-m.

Ram Babu et al., estimated soil loss for each of the land resource regions of India (Fig. 6.2). Using data for 21 rivers of Himalayan regions and 15 of non-Himalayan regions, along with the data on catchment areas, average annual discharge and rainfall, the authors computed the average annual erosion index values, EI_{30} in metric tons per ha for various regions of country and prepared iso-erodent map of India (Fig. 6.3).

6.3.6 Empirical relationship by Garde & Kothyari (1987)

The authors have carried out a more rigorous analysis of sediment yield from Indian catchments. Using data from 50 small and large catchments in India, they have developed the following relationship for sediment yield erosion rate Y in cm.

$$Y = 0.02\, P^{0.60}\, Fe^{1.70}\, S^{0.25}\, D_d^{\;0.10}\ (P_{max}/P)^{0.19} \qquad ...(6.9)$$

Where P is the average maximum monthly rainfall in cm, S is the average catchment slope defined and Fe is the erosion factor defined as:

$$S = \frac{\sum A_i S_i}{A}$$

$$Fe = \frac{1}{\sum A_i}[0.8A_A + 0.6Ag + 0.3A_F + 0.1A_W] \qquad ...(6.10)$$

Where,

A_A = catchment area = 347 km^2 to 132090 km^2
Fe = erosion factor = 0.26 to 0.79
D_d = drainage density = 0.04 km^{-1} to 0.31 km^{-1}
S = average catchment slope = 0.005 to 0.045
P = mean annual rainfall = 38.6 cm to 455.6 cm.
A_A = arable area in km^2
A_g = Scrub & grass area in km^2
A_W = waste area in km^2
A_F = protected forest area in km^2

The authors used data from 154 catchments and prepared an iso-erosion rate map for the country (Fig. 6.4). High erosion rate values as in North Eastern region, parts of Punjab, U.P. & Bihar and in certain ranges of Andhra Pradesh were attributed partly to higher rainfall in these regions and partly to the geological

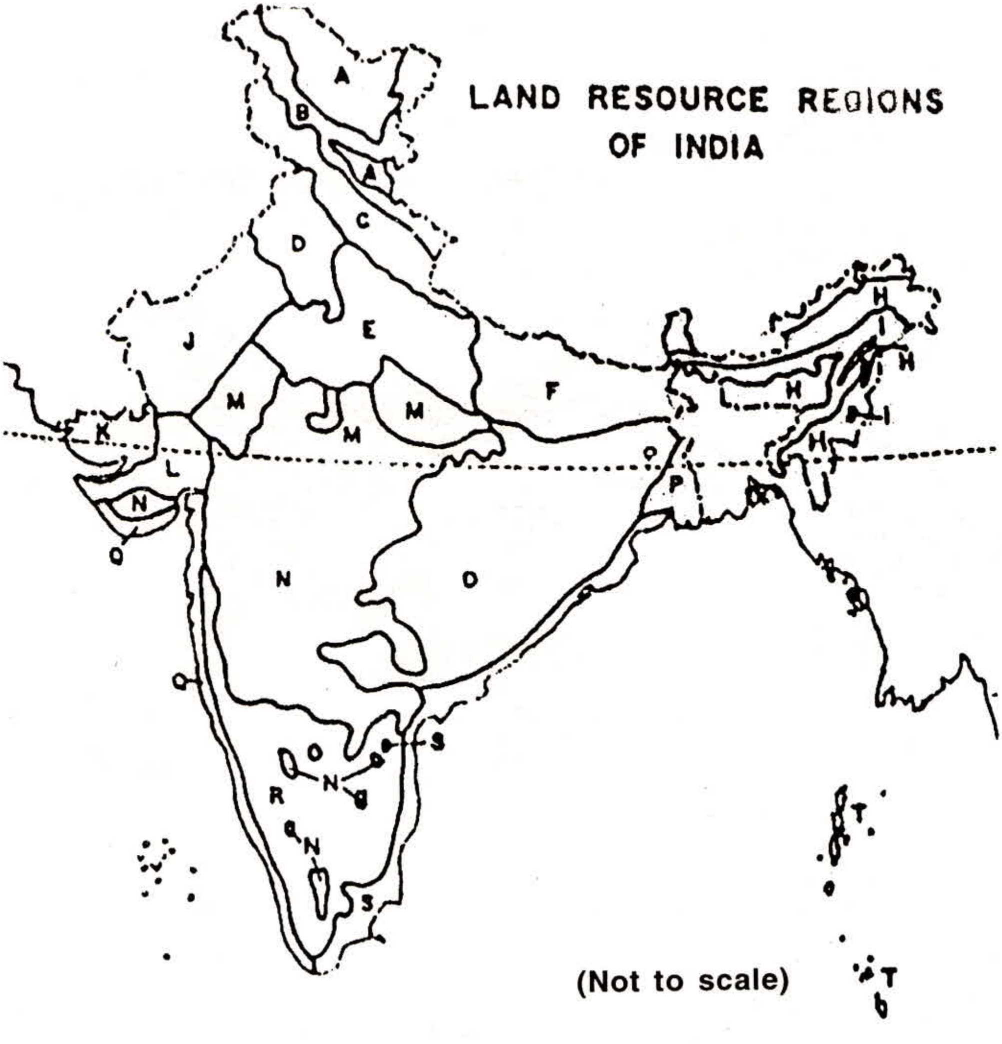


Fig. 6.2 Land resource regions of India

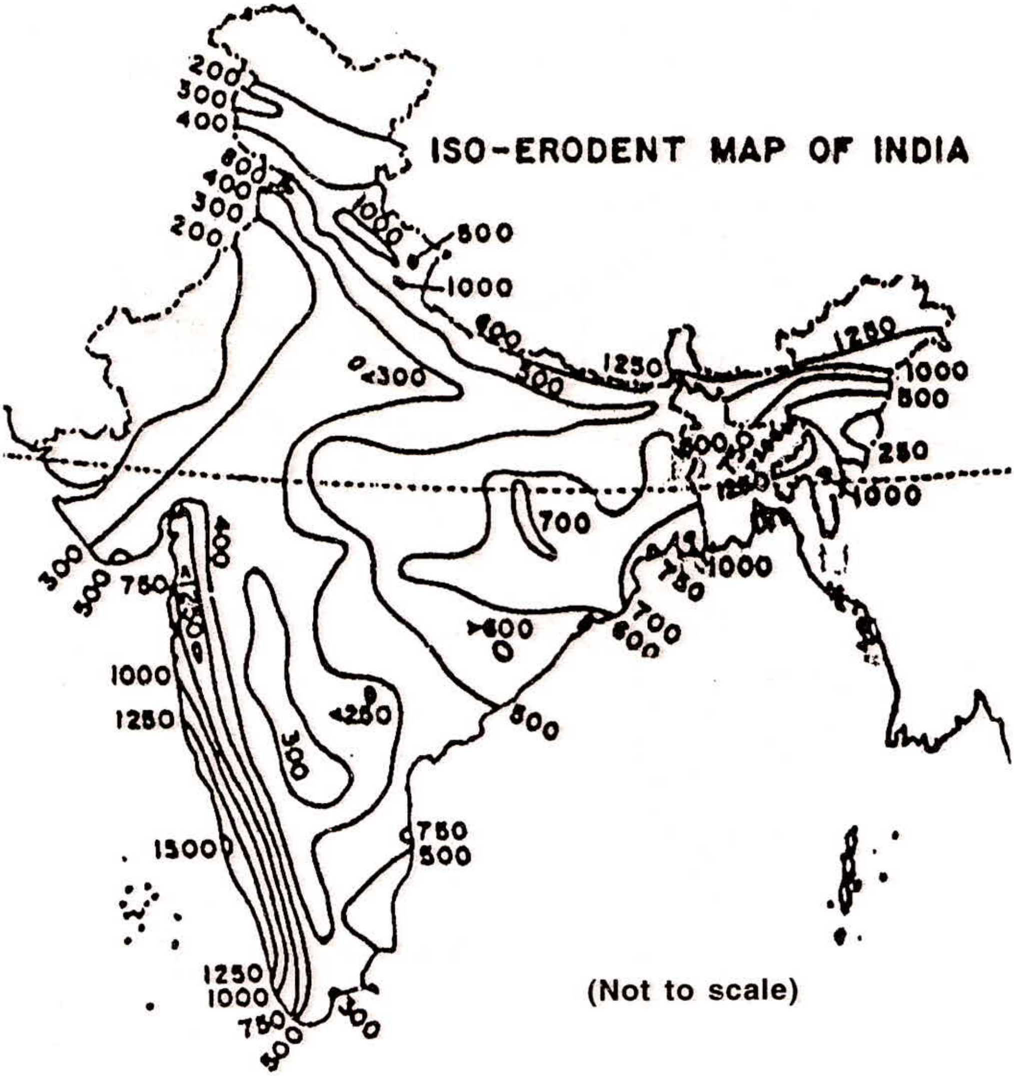


Fig. 6.3 Iso- erodent map of India

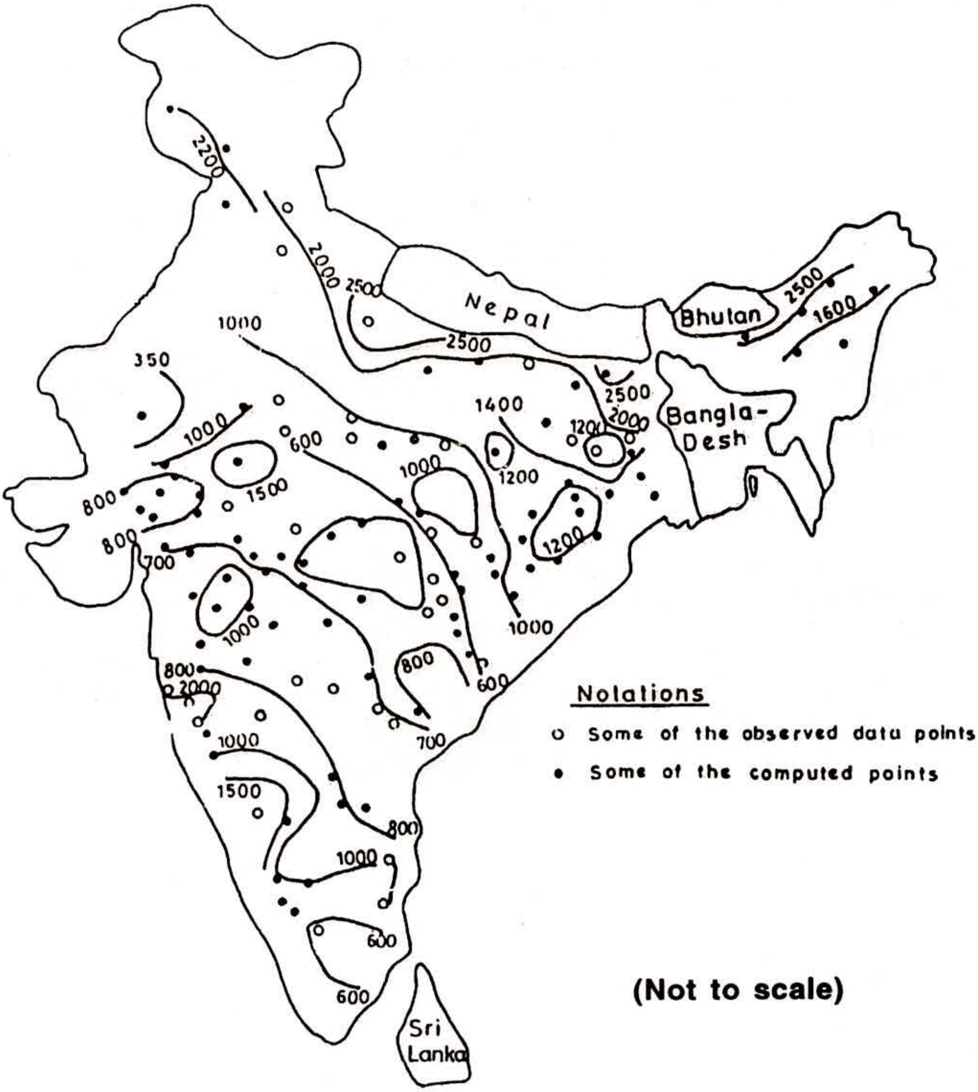


Fig. 6.4 Iso-erosion rate lines in Tonnes/km²/yr.
(Garde & Kothyari, 1987)

conditions & land use. The authors recommended the figure 6.4 as long as land use pattern does not change from that prevalent at the time of investigation, although the equation (6.9) remains valid for all time.

Further, the authors derived the following equation for prediction of annual sediment yield.

$$Ya = [0.02\, Fe^{1.7}\, S^{0.25}\, D_d^{0.10}\, (P_{max}/P)^{0.19}\,]P_a^{m} \qquad ...(6.11)$$

Here Ya is the annual sediment yield in cm & Pa is the annual rainfall in cm. The value of 'm depends on how rainfall varies from one year to other. This is quantified by the coefficient of variation of annual rainfall C_V. Studies have shown that 'm' varies from 0.600 to 0.607 as C_V changes from 0.10 to 0.70. For future year wise prediction of sediment yield, one must generate annual rainfall series for known P & C_V and then compute sediment yield using equation (6.11) and known 'm' value. The annual rainfall series can be assumed to follow the normal distribution.

6.4 CONCLUSIONS

In India, the empirical approaches have been developed and used to predict sediment yield from watersheds. Iso- erosion rates map by Singh et al. (1992) is based on USLE utilising 21 observed and 64 estimated soil loss data. Iso-erosion rate map by Garde and Kothyari (1987) is based on the data of 154 small and large catchments. The empirical relationships developed by Garde and Kothyari (1987) may be used for sediment yield estimation. There is strong need to collect long term data of sediment yield and study the stochastic nature of data.

REFERENCES

Acreman, M. C. (1987) - Regional flood frequency analysis in the UK: Recent research-new ideas, Institute of Hydrology, Wallingford, and UK.

Acreman, M. C. & Wiltshire, S. E. (1987) - Identification of regions for regional flood frequency analysis", EOS, 68(44), 1262.

Ayyar, P. S. H & Tripathi, N. (1973) - One day rainfall of India for different return periods, No.5, IMD, N.Delhi.

Ayyar, P. S. H. & Tripathi, N. (1974) - Rainfall frequency maps of India, No.-6, IMD, N. Delhi.

Baghirathan, V. R. & Shaw, E. M. (1978)- Rainfall depth - duration- frequency studies for SriLanka, Journal of Hydrology, 37(3), 223-239.

Beasley, D. B., Monke, E. J. & Huggins, L. F. (1977)- The ANSWERS Model: A planning tool for watershed research, ASAE, Paper No. 77-2532, St. Joseph, Mich.

Bell, F. C. (1969) - Generalized rainfall-duration-frequency relationships, Journal of Hydraulics Engineering, ASAE, 95(1),311-327.

Bell, F. C. & Vorst (1981) - Geomorphic parameters of representative basins and their hydrological significance. Govt. Printing Service, Canberra, A.C.T., Australian Water Resources Council, Tech. Paper No.-58.

Bernard, M. M. (1932) - Formulas for rainfall intensities of long duration, Trans. ASCE, Vol. 96, pp. 592-624.

Bernard, M. M. (1935) - Determination of flood flow by unit hydrograph method. Article in U.S.G.S. W.S.P., 771.

Bhatia, K. K. S. (1984) - Water quality and sediment modelling in surface waters, Report SR-3, NIH, Roorkee.

Bilham, E. G. (1935) - The classification of heavy falls of rain in short periods, H.M.S.O., London, 1962 (republished).

Box, G. E. P. & Cox, D. R. (1964)- An analysis of transformations, Proceedings R. Statistical Soc., B26: 211-252.

Box, G. E. P. & Jenkins, G. M. (1970) - Time series analysis: Forecasting & control, Holden-Day, San Francisco.

Burn, D. H. (1990) - Evaluation of regional flood frequency analysis with a region of influence approach. Water Resources Research, 26(10), 2257-2265.

Cadavid, L., Salas, J. D. & Cunnane C. (1987) - Examination of the Box-Cox transformation for hydrological frequency analysis. Hydrology & Water Resource Programme, Colorado State University, Fort Collins, Colo.

CBIP (1978)- Annual report - technical, Central Board of Irrigation & Power, New Delhi, Publication No. 24.

CBIP (1981)- Annual report - technical Central Board of Irrigation & Power, New Delhi, Publication No. 27.

Chander, S., Spolia, S. K. & Kumar, A (1978) - Flood frequency analysis by Power Transformation. , A.S.C.E, Journal of Hydraulics Engineering, 104(Hy-11):1495-1504.

Chen, C. L. (1983) - Rainfall intensity - duration - frequency formula, J. of Hydraulics Engineering, ASCE, 109(12), 1603-1621.

Chow, V. T. (Ed.) (1964) - Handbook of applied hydrology., Mc Graw Hill, New York.

Clark, C. O. (1945) - Determination of flood flow by unit hydrograph method. Article in U.S.G.S. W.S.P., 771.

Cunnane, C. (1988) - Methods & merits of regional flood frequency analysis, Journal of Hydrology, 100:269-290.

Dalrymple, T (1960) - Flood frequency analysis, U.S. Geological Survey Water Supply Paper, 1543-A.

Decoursey, D. G. (1973) - Objective regionalisations of peak flow rates In: Floods & Droughts. Proceedings of the second International Symposium in Hydrology. Sep 11-13, 1972, Fort Collins, Colorado, Water Resources Publication, Fort Collins, Colorado.

Decoursey, D. G. & Deal, R. B. (1974) - General aspects of multivariate analysis with applications to some problems in hydrology, Proceedings Symp. on Statistical Hydrology, Misc. Publication No. 1275, USDA-ARS.

Dhir, R. D., Ahuja, R. P. and Majumdar, K. C. (1958) - A study on the success of reservoir based on the actual and estimated runoff, CBIP, R&D Session.

Dhruvnarayana, V.V. & Rama Babu (1983) - Estimation of soil erosion in India, Journal of Irrigation & Drainage Engineering, ASCE, 109(4): 419-434.

Ebisemiju, F. S. (1979)- An objective criterion for the selection of representative basins, Water Res. Research, Vol. -15(1)

Enderlein, R., Glugla, G. & Eyrich, A. (1982) - Grid method for calculating ground water recharge from geographical and climatological characteristics in: Application of results from representative and experimental basins, UNESCO, Stud. Rep. Hydrology No.32, 163-176.

Espey, W. H., Morgon C. W. & Masch., F. D. (1965) - A study of some effects of urbanisation on storm runoff from a small watershed, Univ. of Texas, Austin, Center for Res. in Water Res. Tech. Report.

Espey, W. H., Winslow, D. E. and Morgan, C..W. (1969) - Urban effects on unit hydrograph, Proceedings, Water Res. Symposium, No.-2, University of Texas.

Ferreri, G. B. & Ferro, V. (1990) - Short duration rainfalls in Sicily, Journal of Hydraulics Engineering, ASCE, 116(3), 430-435.

Flaxman, E.M. (1972) - Predicting sediment yield in Western United States, Journal of Hydraulics Engineering ASCE, 98(12).

Garde, R. J. & Kothyari, U.C. (1987) - Sediment yield estimation, Journal of Irrigation & Power (India), 44(3).

Gert, A., Wall, D. J., White, E.L. & Dunn, C.N. (1987) - Regional rainfall intensity - duration-frequency curves for Pennsylvania, Water Res. Bulletin, 23(3), 479-486.

Ghosh, T. K. (1990) - Regional flood frequency analysis for rivers of north and central parts of West Bengal. M.E. Special Problem, Department of Hydrology, University of Roorkee, Roorkee.

Goel, N. K. & Seth, S. M. (1985) - Data related problems in frequency analysis, Proceedings, National Seminar on flood frequency analysis, N. Delhi.

Goswami, A. (1972) - Regional flood frequency analysis of Brahmaputra basin in North- East India, Journal of Institution of Engineers (India), Civil Engineering Div., Vol. -52, 169-174.

Gottschalk, L. & Krasovskaia, I. (1980) - Synthesis, processing & display of comprehensive hydrologic information, Sver. Meteorology Hydrology Institute (SMH), Norrkoping, Rep. No. - RH 022.

Gray, D. M. (1961) - Synthetic unit hydrographs for small watersheds, Journal of Hydraulics Division, ASCE, Vol. 87(H44), pp. 33-54.

Gupta, P. N. (1987) - Regional flood frequency approach - estimation of flood peaks for Mahi & Sabarmati basin; Proceedings National Symposium on Hydrology, Roorkee, Vol.-1, 1-26.

Haan, C. T. ed. (1982) - Hydrologic modelling of small watersheds, ASAE, Monograph No.5, ASAE, St. Goseph, Michigan.

Hadgraft. R. G. (1982) - An empirical study of flood frequency distributions, Hydrology report 000716 PR., Surface Water Branch , Queensland Water Resources Commission, Brisbane, Qld.

Hall, A. J. (1984) - Hydrology in tropical Australia & Papua New Guinea, Hydrological Sciences Bulletin, Vol.-29(4).

Hargreaves, G. H. (1988) - Extreme rainfall for Africa and other developing areas, Journal of Irrigation & Drainage Engineering, ASCE, 114(2), 324-333.

Hebson, C. S. and Cunnane, C. (1987) - Assessment of use of at site and regional flood data for flood frequency estimation. In: V. P. Singh (Editor), Hydrologic Frequency Modelling. Reidel, Dordrecht, pp.433-448.

Holland, D. J. (1967) - Rainfall intensity - frequency relationships in Britain, British Rainfall 1961, H.M.S.O.

Horton, R. E. (1945) - Erosional development of streams and their drainage basins: hydrophysical approach to quantitative morphology. Geological Society of America, Bulletin no. 56, pp. 275-370.

Huq, S. M. (1985) - Regional flood frequency analysis of Cauvery basin sub-zone 3(i), Proceedings, 52nd Annual R & D session, CBIP, Aurangabad, Vol.-II,97-108.

Huq, S. M., Nair, R & Sil, S.S. (1986) - Frequency flood formula for countrywide application, Proceedings, 53rd Annual R & D session, CBIP, Bhubaneswar, 405-416.

Huq, S. M., Kumar, V. & Sil, S. S. (1982) - Derivation of synthetic unit hydrograph for moderately steep catchments, Proceedings International Symposium on Hydrological aspects of Mountainous watersheds, UOR, Roorkee, Nov. - 4 to 6.

Ikoi, J. U. (1989) - A comparative study of regional flood frequency methods M.E. Dissertation, Department of hydrology, UOR, Roorkee.

Jakhade, G. S., Murti, A.S. & Sethuraman (1984) - Frequency floods in Brahmaputra valley - regional flood frequency approach, CBIP Journal, N.Delhi, Vol.-41(1).

Khosla, A. N. (1953) - Silting of reservoirs, CBIP, N. Delhi, Publication No. 51

Kinisel, W. G. (1980) - CREAMS: A field scale model for chemicals, runoff and erosion from agricultural management systems, USDA, Cons. Research, R.N. 26.

Kothyari, U. C., Garde, R. J. & Seth, S. M. (1985) - Estimation of annual runoff from catchments, Journal of Irrigation and Power, CBIP.

Kothyari, U.C., and Garde, R. J. (1992), - Rainfall intensity - duration-frequency formula for India, Journal of Hydraulics Engineering, ASCE, 118(2).

Kuczera, G. (1983) - A Bayesian surrogate for regional skew in flood frequency analysis, Water Resources Research 15(5), 1055-1064.

Landwehr, J. H., Matalas, N. C. and Wallis, J. R. (1979) - Probability weighted moment compared with some traditional techniques in estimating Gumbel parameters and quantiles, Water Resources Research, Vol. 15(5), pp 1055-1064.

Lane, L. J., Davis, D. R. & Nnaji, S (1979) - Termination of hydrologic data collection (a case study), Water Resources Research 15(6), 1851-1857.

Laurenson, E. H. (1964) - A catchment storage model for runoff routing, Journal of Hydrology, Vol.2., pp. 141-256.

Laut, P. & Paine, T. (1982) - Results of numerical classification of landscapes and sub-basins in the Macleay Valley, N.S. Wales, Common W. Sci. Ind. Res. Org. (CSIRO), Div. Water Land Resources, Canberra, A.C.T. Tech. Memo 82/12.

Li, R. M. (1977) - Water & sediment routing from watershed, Proceedings of River Mechanics Institute, CSU, Fort Collins, Co. Chapter-9.

Lone, M. A. (1988) - Flood estimation in River Jhelum basin using statistical approach, M.E. Thesis, UOR, Roorkee.

Mannering, J. V. & Wischmeir, W. H. (1969) - Relation of soil properties to its erodibility, Soil Sci. Soc. Am. Proceedings 23:131-137.

Mathur, B. S., Singh, R & Goel, N. K. (1992) - Development of hydrological watershed simulation model (Phase-I), Indo-German Bilateral Project on Watershed Management, UOR, Roorkee.

Mc. Cuen, R. H. (1989) - Hydrological analysis and design, Englewood Cliffs, New Jersey,: Prentice Hall

Mehta, H. L. & Sharma, D. K. (1986) - Flood frequency analysis, Proceedings, workshop on flood estimation in Himalayan region, Roorkee.

Meyer, L. D. and Wischmeier, W. H. (1969) - Mathematical simulation of the process of soil erosion by water, Transactions of ASAE, Vol. 12(6), pp. 754-758.

Minshall, N. E. (1960) - Predicting storm runoff on small experimental watersheds, Journal of the Hydraulics Division, ASCE, Vol. 86, (H48), pp. 17-38.

Mosely, M. P. (1981) - Determination of New Zealand hydrologic regions, Journal of Hydrology 49:173-192.

Musgrave, G. W. (1947) - The quantitative evaluation of factors in water erosion: A first approximation, Journal of Soil & Water Cons., 2(3): 133-138.

Mutreja, K. N. (1986) - Applied Hydrology, Tata McGraw Hill Publishing Co. Ltd., N. Delhi.

Nash, J. E. (1957) - The form of the Instantaneous unit hydrograph, publication no. 42, International Association of Scientific Hydrology, pp. 114-122.

Nash, J. E. (1960) - A unit hydrograph study, with particular reference to British Catchments", Proceedings of the Institution of Civil Engineers (London), vol. 17, pp. 249-282.

National Institute of Hydrology, RN - 15 (1985-86)- Use of catchment characteristics for unit hydrograph derivation, Roorkee.

National Institute of Hydrology, TN - 12 (1984-85) - Methodology for estimation of design storm, Roorkee.

National Institute of Hydrology, (1990)- Assessment of water erosion & sediment transport, Roorkee. National Institute of Hydrology, RN-14(1984-85) - Regional flood frequency analysis, Roorkee

National Institute of Hydrology, RN-17 (1985-86) - Regional unit hydrograph, Roorkee.

National Environmental Research Council (1975)- Flood studies report, Vol.-1, Hydrologic studies, NERC, London.

Negev, M. (1967) - A sediment model on digital computer, Tech. RN-76, Dept. of Civil Engineering, Stanford Univ., C.A.

Neimczynowicz, J. (1982) - Areal intensity-duration-frequency curves for short term rainfall events, Nordic Hydrology, Vol.13(4), 193-204.

O' Kelley, J. E. (1955) - The employment of unit hydrographs to determine the flows of Irish Arterial Drainage channels, Proceedings, Inst. Civil Engineering, Vol.-4(3).

Parthasarathy, K. & Singh G., (1961) - Rainfall intensity-duration-frequency for India for local drainage design - Indian Journal of Meteorology & Geophysics, Vol.-12(2), 231-242.

Perumal, M. & Seth, S.M. (1985)- Need for uniform procedure in flood frequency analysis, Proceedings, Seminar on flood frequency analysis, N. Delhi

Perumal, M. & Seth, S.M. (1985) - Regional flood frequency analysis using power transformation - a case study, Proceedings, Seminar on flood frequency analysis, N.Delhi.

Pilgrim, D. H. (1983) - Some problems in transferring hydrological relationships between small and large drainage basins and between regions, Journal of Hydrology, 65: 49-72.

Raghunath, H. M. - Hydrology, Principles, Analysis and Design, Willey Eastrn Ltd., India.

Ram Babu, Tejwani, K. K., Agrawal, M. C. & Bhusan, L. S. (1979) - Rainfall intensity-duration-return period equations & nomographs of India, CSWCRTI, ICAR, Dehradun, India.

Raman, P. K. & Krishnan, A. (1958) - Intensity-duration-frequecy relationships of rainfall at selected stations in India, Proceedings Symp. on Meteorological and Hydrological aspects of floods & droughts in India, 21-30.

Raman, V. & Bandyopadhya, M. (1969) - Frequency analysis of rainfall intensities for Calcutta, Journal of Sanitary Engineering Dn., ASCE, 95(6), 1013-1030.

Rao, D. V. L. N., Goyal, S. C. & Kathuria, S. N. (1983) - Interpolation of short duratin rainfall from 24 hour rainfall in Lower Godavari basin, Mausam Journal, Meteorological Soc., N. Delhi, 34(3): 291-298.

Rao, P. R. (1975) - Modelling of non-linear behaviour of drainage basins, Ph.D. Thesis, I.I.T., New Delhi.

Rao, P. R. and Goel, R. S. (1986) - Flood frequency analysis-assumptions and limitations, Workshop on Flood Estimation in Himalayan Region, Roorkee.

Raudkivi, A. J. (1979) - An advance introduction to Hydrological Processes and Modelling, Oxford Pergamon Press, N. York, N.Y.

Renard, K. G. (1980) - Estimating erosion and sediment yield from rangeland, Proceedings ASCE Symposium on Watershed Management, Australia, Institution of Engineers, pp. 162-175.

Rendon- Herrero, O. (1978) - Unit sediment graph, Water Resources Research, 14(5): 889-901.

Research Designs and Standards Organisation - Technical monograph no. 50, Handbook for estimation of design discharge for railway bridges, August-1990, Manak Nagar, Lucknow, India.

Rodriguez, I & Valdes J.B. (1979) - The geomorphologic structure of hydrologic response, Water Resources Research, 15(6): 1409-1420.

Rodriguez, I., Sanbria, M. G. & Bras, R. L. (1982)- A geomorphoclimatic theory of the instantaneous unit hydrograph, Water Resources Research, 18(4): 877-886.

Rot, G., Becht, R. & Bouman, D. (1983) - Hydrological regionalisation & prediction by hydropedon cartomodelling, Proceedings, Int. Assoc. Hydrol. Sci., Symp. on Scientific Procedures applied to the planning, design and management of Water Resources Systems, Hamburg.

Saseendran, S. A., Sreedharan, K. E., Ratna Kumari, K., James, E. J. and Jaya Kumar, M. (1988) - Regional flood frequency studies for Kerala. Proceedings of International Seminar on Hydrology of Extremes, Roorkee.

Seth, S. M. & Goel, N. K. (1985) - Regional flood frequency analysis, Proceedings, Seminar on flood frequency analysis, N. Delhi.

Seth, S. M. & Goswami, B. N. (1979) - Regional flood frequency analysis with limited data, Proceedings, Third World Congress on Water Resources, Mexico City.

Seth, S. M. and Singh, R. D. (1987) - Flood estimation in India using regional frequency analysis, Proceedings, National Symposium on Hydrology, Roorkee, Vol.-1

Sharma, T. C., Hines, W. G. S. & Dickinson, W. T. (1979) - Input output model for runoff sediment yield process, Journal of Hydrology, 40:299-322.

Simmers, I. (1984) - A systematic problem-oriented approach to hydrological data regionalisation, Journal of Hydrology, 73:71-87.

Singh G., Babu R., Narain P., Bhushan L. S. & Abrol I. P. (1992) - Soil erosion rates in India, Journal of Soil & Water Cons., Jan. - Feb. (1992), 47(1).

Singh G., Babu R., & Chandra S.(1981) - Soil loss prediction research in India. Bull. No. T-12/D-9, Central Soil & Water Conservation Research and Training Institute, Dehradun, India, 70pp.

Singh, R. D. (1984) - Unit hydrograph analysis for small catchments, M.E.Thesis, U.O.R., Roorkee.

Singh, R. D. & Seth, S. M. (1985) - Regional flood frequency analysis for Mahanadi basin using Wakeby distribution Proceedings, Seminar on flood frequency analysis, N. Delhi.

Singh, V. P. (1973) - Predicting sediment yield in Western United States: A discussion, Journal of Hydraulics Engineering, ASCE, 99(HY10).

Singh, V. P. (1989) - Hydrologic system, Vol.-II, Watershed Modelling, Englewood Cliffs, New Jersey, Prentice Hall.

Snyder, F. F. (1938) - Synthetic unit hydrograph, Trans. A.G.U., 19(2).

Stedinger, J. R. & Taskar, G. D. (1985) - Regional hydrological analysis: Ordinary, weighted and generalised least square compared, Water Resources Research, 21(9): 1421-1432.

Steel, E. W. & McGhee, T. J. (1979) - Water Supply and Sewerage, 5th ed., McGraw-Hill Book Com., New York.

Subramanaya, K. (1984) - Engineering Hydrology, Tata McGraw Hill Publication Co. Ltd., India.

Taskar, G. D. (1982) - Comparing methods of hydrologic regionalisation, Water Resources Bulletin, 18(6): 965-970.

Taylor, A. B. and Schwarz, H. E. (1952) - Unit hydrograph lag and peak flow related to basin characteristics", Transactions of the American Geophysical Union, Vol. 33, pp.235-246.

Thirumalai, S. & Sinha, P. B. (1986) - Flood estimation for small and medium catchments in Krishna basin by Chow's approach modified by Nash, Proceedings, Seminar on flood estimation and control, Roorkee.

Thiruvengadachari, S., Nayak, S. V. & Ranganna, G. (1975) - Cauvery basin flood magnitude & frequency, Proceedings, National Symp. on Hydrology, Roorkee.

Toebes, C & Ouryoaeav, V. ed. (1970) - Representative & experimental basins - An International Guide for Research & Practice, UNESCO Publication.

Varshney, R. S. (1970) - Regional sedimentation surveys for India, Indian Journal of Power & River Valley Development: pp 357-359.

Varshney, R. S. (1986) - Engineering Hydrology, published by Nem Chand Bros., Roorkee, 3rd edition.

Venkataraman, R., & Gupta, P. N. (1986) - Flood estimation for small and medium catchements in Sub-Himalayan Region, Proceedings, Workshop on flood estimation in Himalayan region, Roorkee.

Venkataraman, R. Thirumalai, S. & Gupta, P. N. (1986) - Regional flood frequency analysis for small and medium catchments in Lower Godavari basin, Proceedings, Seminar on flood estimation & control, Roorkee.

Walling, D. E. (1977) - Assessing the accuracy of suspended sediment rating curves for a small basin, Water Resources Research, 13(3): 531-536.

Walling, D. E. (1988) - Sediment yield from watersheds, lectures presented at IRTECS Training Courses.

Wallis, J. R. (1980) - Risk and uncertainties in the evaluation of flood events for the design of hydraulics structures, Keynote address at seminar on Extreme Hydrological Events-Floods and Droughts' Erica, Italy.

Water Resources Council, 1976, 1977, 1982 - Guidelines for determining flood frequency, Water Resources Council Bulletin 17, 17A (revised), 17B (revised) Washington, D. C.

Williams, J. R. (1975) - Sediment yield prediction with USLE using run-off energy factor in present and perspective technology for predicting sediment yields & sources, 244-52, ARS-S-40, USDA, Washington, D.C.

Williams, J. R. (1977) - Sediment delivery ratios determination with sediment and runoff models, IAHS Pub. No. 122:168-178.

Williams, J. R. (1977) - Sediment yield prediction based on watershed hydrology, Trans., ASAE, 20(6): 1100-1104.

Wiltshire, S. & Beran, M. (1985) - Multivariate techniques for the identification of homogeneous flood frequency regions, Proceedings, Int. Symp. on flood frequency and risk analysis, 14-17 May 1986, Louisiana State Univ., USA.

Wischmeier, W. H. and Smith, D. D. (1978) - Predicting rainfall erosion losses- a guide to conservation planning, Agricultural Hand Book No. 537, USDA, Washington, D.C.

Yarnall, D. L. (1935) - Rainfall intensity frequency data, USDA, Misc. Publ. No. 204, Washington, D. C.