TN-12

# METHODOLOGY FOR ESTIMATION OF DESIGN STORM

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1984-85

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# ABSTRACT

Estimation of 'Design Flood is a first and vital step in the design process for a large range of water resources development works. The design flood is generally derived from the design storm using some rainfall-runoff procedure. The design rainfall comprises of three components namely the design rainfall magnitude, its distribution in time and areal pattern.

While the 'Design Storm' is derived by both statistical and physical methods, the type and magnitude of the design storm is decided by the type of structure and the magnitude of risk which could be associated with it. The intensity-duration-frequency (i-d-f) relationship falls under the category of statistical methods while the probable Maximum Precipitation (PMP) estimation is done by both statistical and physical analysis. Both methods have certain limitations on account of the subjectivity inherent in the analysis, assumptions made and constraints imposed by data availability.

The methods available and those in practice in different countries are reviewed in this technical note and the advantages and limitations are identified and highlighted. More often, the scepticism in respect of design storm concept was the comprehensiveness of the concept for covering the risk which the engineer assumed it would provide. The other limitations arise out of the uncertainty of an intensity picked up for a certain duration and for a particular recurrence interval providing flood of corresponding recurrence interval

This, as is to be expected depends on the rainfall-runoff procedure/ model used for deriving the runoff from rainfall. While the limitations of the rational formula are well known, the usage of synthetic rainfall hyetograph also has its due share in influencing the magnitude of the runoff. The other approximation arises when the intensity-duration-frequency relationships which are developed from point rainfall values are extended to provide areal estimates.

In the case of the physical approach the main limitation arises out of the small data sample available at the disposal of the analyst and the extent of representativeness of the sample to the problem area. Other approximations relate to use of surface dew point temperatures as representative of the precipitable water in the atmosphere above and extending these procedures for use in tropical areas.

The alternatives suggested include storm modelling, which of course would place a demand on data of a number of parameters at a number of locations and at frequent intervals.

## 1.0 INTRODUCTION

Design flood estimation is a first and vital step in the design process for a large range of water resources development works. It is a hypothetical or typical event that represents rare occurrence. It need not correspond with any specific event or time as it is essentially a maximum value which could be expected over a long period of time. However, for assigning a magnitude it could be expressed in terms of a probability or some return period. The methods used for estimating the design flood ought to be general in nature and should be concerned with broad hydrologic conditions rather than mere physical details as associated with specific events.

While trying to estimate the design flood a matter of conjecture is the relative merits of frequency studies of observed floods versus use of design storm. Both the methods are in reality complementary and are not competitive. It is desirable that design flood is estimated directly from observed stream flow data wherever possible. The main advantage of the flood frequency approach is that it allows a direct estimate of the flood peak discharge of a given probability. In practice, this method could not be applied widely especially to small watersheds because most of the streams and rivers generally happen to be ungauged. Besides, there are other difficulties in the flood frequencies approach arising out of missing data, presence of outliers and uncertain frequency distribution to which the data could be fitted to. However, these are beyond the scope of this technical note which is confined only to the discussion on the concept and philosophy of design storm approach, the methods of its estimation, its advantages and limitations.

## 2.0 PROBLEM DEFINITION

The concept of using the meteorological information for deriving the design floods dates back to the mid nineteen thirties. The overall purpose of a 'Design Storm' is to provide the engineer with a means of estimating the peak discharge and volume of the design flood with the help of some rainfall-runoff relationship. The concept while also being used with modern computerised models, however, was subject to criticism at the seminar on 'Design storm concept' held at the Ecole Polytechnique de Montreal, Canada in May 1979. Some of the ideas presented at this seminar as well as in other publications are referred to at relevant points later in this note.

The design rainfall (storm) is a rainfall event which is developed for the design of specific types of objects (structures) and has three components namely(i) the amount, (ii) its areal distribution and (iii) time distribution.

### 2.1 Scale of Design Storm

The scale of design storm is linked to the scale of the design flood, which in turn would be linked to the scale of the structure to be built and the risk to be associated with it. The type of catchment urban, semi-urban or forested catchment would also partly influence the decision of the scale of the storm. A new dimension is added to the problem because of modern developments and the exigencies arising out of them. Thus, the urban drainage systems which were hitherto being designed only to convey the surface runoff, have also to cater to the protection of flooding at downstream and limiting pollution in the stream into which they discharge.

The book of planning of Japan(Anonymous) makes the following classification of design scale of rainfall depending on the importance of rivers and scales of plans.

| Importance of River | Probability of design rainfall |
|---|---|
| Class A | More than 200 |
| Class B | 100 to 200 |
| Class C | 50 to 100 |
| Class D | 10 to 50 |
| Class E | less than 10 |

In the United Kingdom (National Environmental Research Council, 1975) designs are commonly based upon rainfall events with a frequency of between once in 2 years and once in 100 years. However, for some structures where high degree of safety is required an estimate of 1000 yr return period or estimated maximum precipitation is recommended.

It has generally been accepted that for minor projects or for projects which do not imply any risk to human life, design floods obtained by flood frequency analysis are satisfactory, but if human lives are in jeopardy, flood frequency methods are not satisfactory. In such cases, it was said, the design flood be based on the maximum probable flood which in turn is based on the PMP. The probable maximum' concept began as 'maximum possible' because it was considered that maximum limits exist for all the elements that act together to produce rainfall, and that these limits could be set by experience and based on some limited recorded meteorological data. The concept of probable maximum or maximum possible, however, came to be questioned as it is not a scientifically or engineering wise sound statement and places an infinite value on human life (Benson, 1972 and Pilgrim and Cordery, 1974).

In 1972, a Task Committee set up by the hydrometeorology committee of the Hydraulics Division, ASCE, issued a report on 'Re-evaluation of the adequacy of spillways of existing dams'. An important part of the recommendations is that human life values should be assigned in making the economic studies necessary to evaluate spillways adequacy. Also, the committee tentatively decided the probable maximum flood as corresponding to 10000 year frequency.

## 2.2 Types of Design Storm

The basic types of design storm could be categorised as (i) statistical and (ii) physical. The statistical methods include stochastic and probabilistic approaches. The conventional physical methods were storm analysis, transposition and/or maximisation. But the conceptual modelling approach which is deterministic could be considered as physical. Further subdivision of the types is based on their scale and approaches used for estimation.

In the conventional physical approach two types of storms were considered for design purpose, the criteria being the scale. They are the 'Maximum Probable Storm (MPS)' or 'Probable Maximum Precipitation (PMP)' and 'Standard Project Storm (SPS)'.

The US National Weather Service, US Army Corps of Engineers and US Bureau of Reclamation defined PMP as

> 'the theoretically greatest depth of precipitation for a given duration that is physically possible over a given

size storm area at a particular geographical location at a certain time of the year'.

The standard project storm is one which is reasonably capable of occurring over the basin in question.

## 3.0 REVIEW OF METHODOLOGY

As mentioned earlier, the design rainfall comprises of three components namely the design rainfall magnitude, its distribution in time and its areal distribution. However, one more important aspect of the design storm is selection of appropriate duration.

### 3.1 Duration of Design Storm

The duration of design rainfall shall be determined by taking into consideration the size of the drainage basin, duration of the flood, the mode of flood runoff and the types of design structures. Of the meteorological aspects, the characteristics of the rainfall and its causes (thunderstorm, typhoon or frontal type) need to be examined critically. In case of urban watersheds and small catchments where the time of concentration is generally of the order of a few hours, the response would be quick and the storm duration has to be considered by examining the floods and the causative short duration rainfall bursts.

It is essential that the selected duration be atleast as long as the supply duration. Based on studies conducted for small watersheds in Western USA, Bell (1968) concluded that the volume/peak ratio may be the most appropriate duration of design rainfall. Effective durations greater than the volume/peak ratio were found to be relatively inefficient as producers of flood peaks and are not likely to be typical of extreme floods. If the duration by volume/peak ratio was found to be longer, the representative lag could be considered which would be less than the volume/peak ratio and longer than the supply duration. A simple measure of representative lag is the 'time of concentration' which could be estimated from the length and slope of the main channel.

### 3.2 Magnitude of Design Rainfall

As mentioned in earlier section the methods for determining design rainfall magnitude in use in different countries are either statistical or physical.

#### 3.2.1 Statistical techniques

The statistical procedures are simple both from data requirement and analysis points of view. These methods only require data of annual or partial series of rainfall maxima at a point and can generally be applied irrespective of climatic differences and hence it has resulted in their world wide application.

The two methods in practice are

i. The intensity -duration-frequency (i-d-f)relationships/ curves, and

ii. the Hershfield technique of estimating PMP.

##### 3.2.1.1 Intensity-duration-frequency(i-d-f)relationships

Intensity-duration-frequency relationships give the probability of obtaining rainfall intensity longer than a specified intensity for a given duration. The i-d-f-relationships which are usually derived from point rainfall measurements have long been used in synthesizing the design storms. As the title implies, the relationship is drawn between the following three components:

i. the rainfall depth or intensity,
ii. duration of the rain and
iii. the frequency or return period (recurrence interval) ascribed to the given intensity.

While developing these relationships it is to be ensured that the rainfall data is derived from as large a sample as possible.

The time duration of the rainfall sample depends on the design duration which is dependent on the design requirements as outlined in section 3.1.

There are a number of frequency distributiuons which could be fitted to hydrological data. Some of the well known distributions which fit extreme rainfall values are

i. Gumbel's Extreme type I,
ii. Log-Pearson Type III
iii. Log-normal and
iv. Jenkinson's extreme value distribution

These methods are described in literature by Gumbel (1958) Kite (1977), WMO Tech.Note 98, WMO Operational Hydrology Rept.15 and the Hydrometeorology Manual of India Meteorological Department(1972).

There are essentially three methods for estimating the parameters of a particular distribution as follows:

1. Method of moments
2. Method of least squares
3. Method of maximum likelihood.

Of these the later two are widely used.

Gumbel's extreme value distribution was used in several reports of US Weather Bureau for durations of 5 min. to 24 hrs

(Frederick et al.,1979) and by Hershfield (1982) for 2 minute rainfall extremes.

In Australia, the Bureau of Meteorology (Pierrehumbert, 1972 and Hall, 1984) had developed procedures for the estimation of rainfall intensity-frequency-duration values for return periods of upto 100 years and durations upto 72 hrs.

The frequency distribution of extreme value developed by Jenkinson (1955) and described in WMO technical note 98 has widely been used for application to rainfall extremes in Australia, East Africa and United Kingdom and forms the essence of rainfall studies in volume II of the UK Flood Studies Report (National Environmental Research Council, 1975).

Niemczynowicz (1982) used Log Pearson type III distribution with the method of moments for preparing areal intensity-duration-frequency curves for short term rainfall events in Lund, Sweden.

In India, Harihara Ayyar and others (1971(a), 1971'b), 1973 and 1974) have used the Gumbel's extreme value type I distribution for preparing rainfall intensity -duration maps for return periods of 2 to 50 years for short duration rainfall data ranging from 15 mts to 24 hrs and for 1 day rainfall for return periods of 2 to 100 years.

Hall (1984) reported the use of Log normal distribution for preparation of intensity-duration-frequency relationships in Papua New Guinea by Snowy Mountains Engineering Corporation.

### 3.2.1.2 Estimation of probable maximum precipitation by Hershfield technique

The procedure was developed by Hershfield (1961) and uses the general frequency formula

$$X_L = X_x + K S_x \qquad ...(1)$$

where,

$X_L$ : rainfall for return period L,

$X_x$ : mean of the annual series of maximum rainfall events,

K : frequency factor; and

$S_x$ : standard deviation of annual series of maximum rainfall events.

The K value used in determining PMP estimates is determined from a survey of data for all stations within a very broad homogenous region. For each station, the mean and standard deviation are computed without the largest observed value. This mean and standard deviation together with the largest value are used in the general frequency equation to solve for K. The largest K value wihin the region or some slightly larger value is used to compute PMP estimates. Several investigators in different countries have used the Hershfield's technique.

Dr O N Dhar and his associates at the Indian Institute of Tropical Meteorology have used Hershfield's technique extensively for determining PMP for different locations in India. Dhar et al (1973) found the value of K to vary from 3 in high rainfall areas to 16 in low rainfall areas. Changraney and Hem Raj (1978) in a study for Madhya Pradesh obtained values of 3 to 7 for K.

A value of 30 was reported by Canadian workers and 15 in Malaysia (Miller ). Hershfield (1961) used the technique for preparation of Rainfall Frequency Atlas of United States.

### 3.2.1.3 Regional frequency analysis

It is known that regional flood frequency analysis was used to overcome the problem of short length of flow data available at gauged points and the problems encountered in extending the information to ungauged catchments which is characteristic of most urban and small catchments. Similar approach in case of rainfall also has come to be used.

Folland et al (1981) made special mention of the notable contribution of Jenkinson's development of the statistical techniques to extreme value analysis in general and regional frequency analysis in particular. Schaefer (1982) applied the concept of regional hydro-meteorological analysis to the precipitation data in mid western USA and western Washington and concluded that extreme storms could be more reliably analyzed on a regional rather than a point basis.

### 3.2.1.4 Empirical formula

Through a personal communication J,Niemczynowicz has described a formula for design rainfall intensity in use in Sweden.

$$F(X,T,Z) = (A(T)+Z.B(T))\ C(X).X^{b'} \qquad \ldots(2)$$

where,

$F(X,T,Z)$ is design rainfall intensity in mm/hr

$X$ = duration in hours

$T$ = return period in months

$Z$ = regional parameter from map

$A(T) = 1.7 \times T^{0.47} - T^{-1}$

$B(T) = 0.32 - 0.72\ (T+3)^{-1}$

$C(X) = 1+0.1(X-0.167)(|X-0.167| + 0.01)^{-1}$

$b = -0.72$

### 3.2.1.5 Areal reduction factors

Design storms derived from point i-d-f curves have no areal dimensions. It need not be emphasized that using the values picked up from these curves as such for design purpose is no less than absurdity as it is difficult to imagine one single design storm occurring simultaneously on thousands of square kilometers. The factor which, when applied to point rainfall for specified duration and return period, gives the areal rainfall for the same duration and return period may be termed 'areal reduction factor' for the given area. Areal reduction factors of some kind need to be considered which would reflect the areal character of rainfall while using the point rainfall intensity-duration-frequency values.

Several authors, Rodriguez-Iturbe and Mejia (1974) and Bell (1976) have carried out studies on the areal reduction factor in rainfall frequency estimation. Horton (1924) showed that average rain depth in a rain storm is exponentially related to storm area and this relationship can be written as:

$$\bar{P} = P_m . \exp(-KA^n) \qquad \ldots(3)$$

where,

$\bar{P}$ is the average rain depth over an area A,

$P_m$ is the maximum point rainfall at the centre of the rain storm and

K and n are constants.

On the basis of 42 severe-most rain storms, Dhar and Bhattacharya (1975) evaluated the constant K and n by employing least squares method. For area in sq.miles, the values of K and n for different durations in the north Indian plains were obtained as below:

| Duration | Values of K | Values of n |
|---|---|---|
| 1 Day | 0.0016 | 0.6614 |
| 2 Day | 0.0018 | 0.6306 |
| 3 Day | 0.0030 | 0.5691 |

Raghavendra (1982) found values of K and n as .004472, .599 and .009152, .50683 respectively for 1 day and 2 days duration storms in the Brahmaputra basin for area in sq. kms.

Niemczynowicz (1982) sugested three different ways to improve the design rainfall intensity input to hydrological models. They are:

i. Developing areal intensity-duration-frequency curves for the relevant time and space scale.

ii. Developing area-rainfall depth relationship from which factors reducing rainfall from point to areal values could be obtained for different areas, durations and return periods. These factors could then be used to reduce the design storm from point to areal values.

iii. Developing a statistical model simulating a rainfall series, a model which gives due consideration to temporal, spatial and dynamical variations in the rainfall pattern.

In chapter 5 of the UK Flood Studies report volume II, the area reduction factor has been described as the concept by which the areal design rainfall of a nominated return period should be obtainable in a simple way from a point design rainfall of the same return period, the point being located within the specified area. However, it is obvious that a specific event which produces a point rainfall of a given return period is not necessarily that which produces rainfall of the return period over some surrounding area.

Niemczynowicz (1982) used 12 gauges in the city of Lund to develop areal i-d-f-curves using a combination of 2,3,4 ....12 gauges. The point and areal mean values of maximum intensity for different durations and return periods were fitted to log pearson type III distribution function and factors reducing point rainfall values to areal values were given . For example, the return period for a given point rainfall has to be increased by 50% for a catchment size of 25 km$^2$ for durations upto 30 mts for the areal rainfall. The Swedish studies confirmed other findings that areal reduction factors really depend on the return period.

In India, the India Meteorological Department has suggested the following relationship for areal reduction of point rainfall for areas upto 300 km$^2$ for durations of 30 mts to 24 hrs in a publication of Central Water Commission (1973). The values are shown in table 1.

$$P = e^{(-A^{1/3}/8T^{\frac{1}{2}})} \qquad \ldots(4)$$

where, P = areal to point rainfall ratio,

A = area of the basin in sq. miles and

T = duration of storm in hours.

The values for 1 hr duration for example varied from 43% to 76%. The curves for 3 hours and 6 hours durations given in the publication are shown in figures 1(a) and 1(b). It was assumed that the time of the year, return period and magnitude of storm, shape and orientation of the area etc. have no significant effect on the relationship

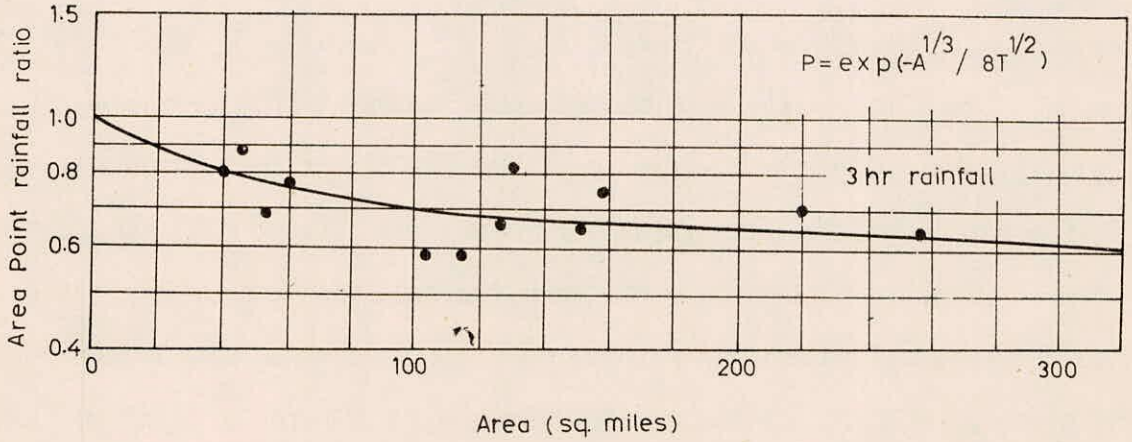

FIGURE 1(a)-AREAL/POINT RAINFALL RATIOS FOR 3 Hr. DURATION
(Reproduced from Central Water Commission, 1973).

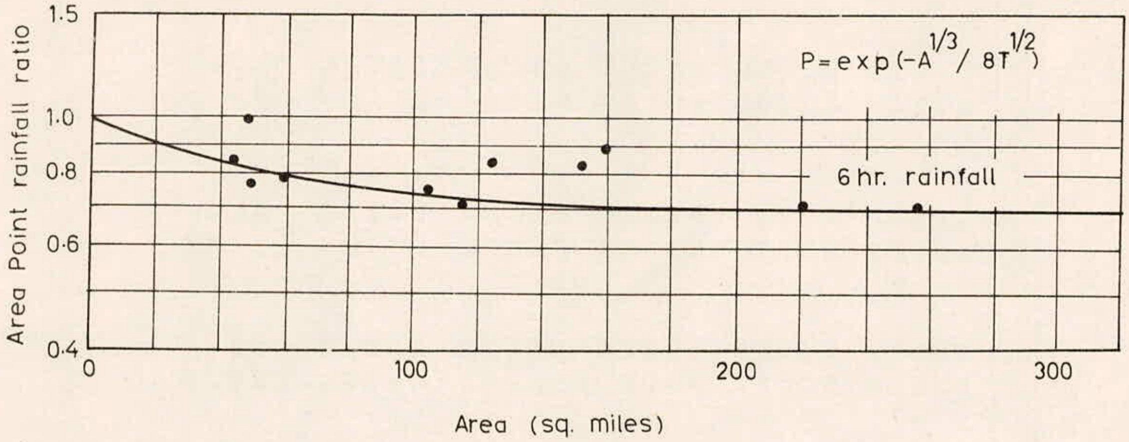

FIGURE -1(b) - AREAL/POINT RAINFALL RATIOS FOR 6 Hr.DURATION
(Reproduced from Central Water Commission, 1973)

Changraney and Jain (1978) by carrying out depth-area-duration analysis obtained the areal reduction factors for durations from 3 hrs to 48 hrs for areas upto 5000 km$^2$. The graphical relationship as given by them is shown in figure 2.

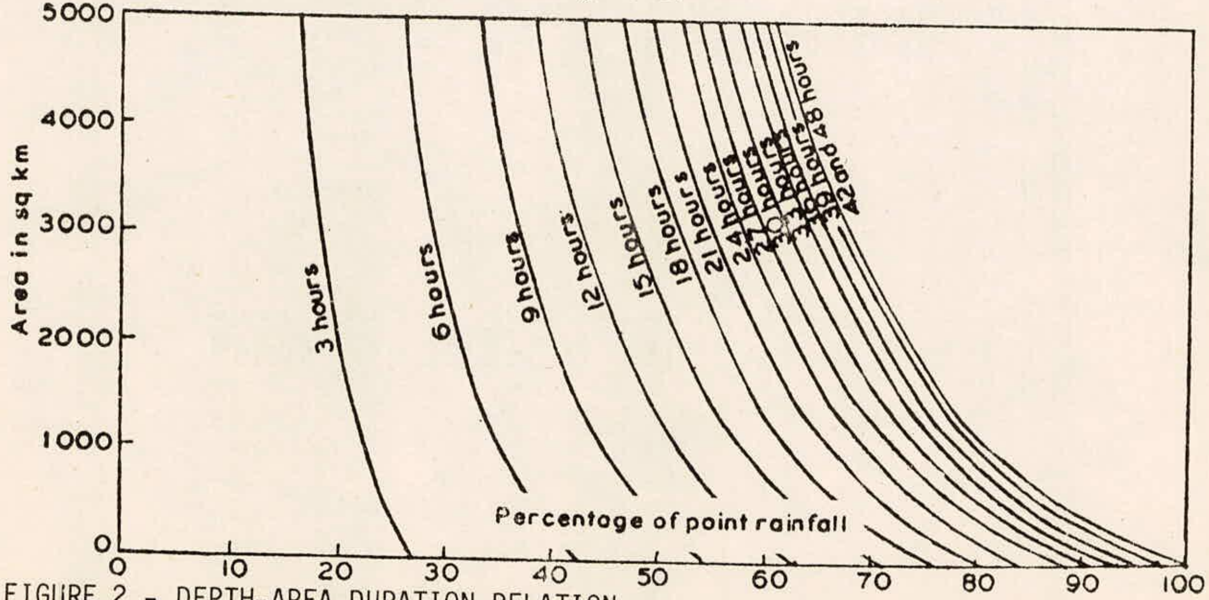

FIGURE 2 - DEPTH-AREA-DURATION RELATION
(Source: Changraney and Jain (1978))

### TABLE 1. AREAL TO POINT RAINFALL RATIOS (%)

| Area (Sq.miles) / Duration (Hrs) | 0.50 | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 |
|---|---|---|---|---|---|---|---|
| 10.0 | 68.33 | 76.39 | 82.66 | 85.60 | 87.40 | 88.65 | 89.59 |
| 20.0 | 61.89 | 71.23 | 78.67 | 82.21 | 84.40 | 85.92 | 87.06 |
| 30.0 | 57.74 | 67.81 | 75.98 | 79.91 | 82.35 | 84.05 | 85.34 |
| 40.0 | 54.63 | 65.21 | 73.91 | 78.13 | 80.76 | 82.60 | 83.99 |
| 50.0 | 52.14 | 63.10 | 72.21 | 76.65 | 79.43 | 81.39 | 82.86 |
| 60.0 | 50.05 | 61.30 | 70.75 | 75.39 | 78.30 | 80.34 | 81.89 |
| 70.0 | 48.26 | 59.74 | 69.47 | 74.27 | 77.29 | 79.42 | 81.03 |
| 80.0 | 46.69 | 58.36 | 68.33 | 73.27 | 76.39 | 78.59 | 80.26 |
| 90.0 | 45.28 | 57.11 | 67.29 | 72.37 | 75.57 | 77.84 | 79.56 |
| 100.0 | 44.02 | 55.98 | 66.35 | 71.54 | 74.82 | 77.15 | 78.91 |
| 110.0 | 42.87 | 54.94 | 65.47 | 70.77 | 74.12 | 76.50 | 78.31 |
| 120.0 | 41.81 | 53.98 | 64.66 | 70.05 | 73.47 | 75.90 | 77.75 |
| 130.0 | 40.84 | 53.09 | 63.91 | 69.38 | 72.86 | 75.34 | 77.22 |
| 140.0 | 39.94 | 52.25 | 63.19 | 68.75 | 72.29 | 74.81 | 76.72 |
| 150.0 | 39.09 | 51.47 | 62.52 | 68.15 | 71.74 | 74.30 | 76.25 |
| 160.0 | 38.30 | 50.73 | 61.89 | 67.58 | 71.23 | 73.82 | 75.80 |
| 170.0 | 37.56 | 50.03 | 61.28 | 67.05 | 70.74 | 73.37 | 75.38 |
| 180.0 | 36.86 | 49.37 | 60.71 | 66.53 | 70.27 | 72.93 | 74.97 |
| 190.0 | 36.19 | 48.74 | 60.16 | 66.04 | 69.82 | 72.52 | 74.57 |
| 200.0 | 35.57 | 48.14 | 59.64 | 65.57 | 69.38 | 72.11 | 74.20 |
| 210.0 | 34.97 | 47.57 | 59.13 | 65.12 | 68.97 | 71.73 | 73.84 |
| 220.0 | 34.40 | 47.02 | 58.65 | 64.68 | 68.57 | 71.36 | 73.49 |
| 230.0 | 33.85 | 46.49 | 58.18 | 64.26 | 68.19 | 71.00 | 73.15 |
| 240.0 | 33.33 | 45.99 | 57.74 | 63.86 | 67.81 | 70.65 | 72.82 |
| 250.0 | 32.84 | 45.50 | 57.30 | 63.47 | 67.45 | 70.32 | 72.51 |
| 260.0 | 32.36 | 45.03 | 56.88 | 63.09 | 67.11 | 69.99 | 72.20 |
| 270.0 | 31.90 | 44.58 | 56.48 | 62.72 | 66.77 | 69.68 | 71.90 |
| 280.0 | 31.46 | 44.14 | 56.09 | 62.37 | 66.44 | 69.37 | 71.62 |
| 290.0 | 31.03 | 43.72 | 55.71 | 62.02 | 66.12 | 69.07 | 71.34 |
| 300.0 | 30.62 | 43.31 | 55.34 | 61.69 | 65.81 | 68.78 | 71.06 |

(Reproduced from Central Water Commission,1973).

Table 1 (Contd.)

| Area (Sq. miles) / Duration (hrs) | 9.00 | 12.00 | 15.00 | 18.00 | 21.00 | 24.00 |
|---|---|---|---|---|---|---|
| 10.0 | 91.41 | 92.52 | 93.28 | 93.85 | 94.29 | 94.65 |
| 20.0 | 89.31 | 90.67 | 91.61 | 92.31 | 92.86 | 93.31 |
| 30.0 | 87.86 | 89.39 | 90.46 | 91.25 | 91.87 | 92.38 |
| 40.0 | 86.72 | 88.39 | 89.55 | 90.41 | 91.09 | 91.64 |
| 50.0 | 85.77 | 87.55 | 88.79 | 89.71 | 90.44 | 91.03 |
| 60.0 | 84.95 | 86.83 | 88.13 | 89.11 | 89.87 | 90.49 |
| 70.0 | 84.22 | 86.18 | 87.55 | 88.57 | 89.37 | 90.02 |
| 80.0 | 83.57 | 85.60 | 87.02 | 88.08 | 88.91 | 89.59 |
| 90.0 | 82.97 | 85.07 | 86.53 | 87.63 | 88.49 | 89.19 |
| 100.0 | 82.42 | 84.58 | 86.09 | 87.22 | 88.11 | 88.83 |
| 110.0 | 81.90 | 84.12 | 85.67 | 86.83 | 87.75 | 88.49 |
| 120.0 | 81.42 | 83.70 | 85.28 | 86.47 | 87.41 | 88.17 |
| 130.0 | 80.97 | 83.29 | 84.92 | 86.14 | 87.09 | 87.87 |
| 140.0 | 80.55 | 82.91 | 84.57 | 85.81 | 86.79 | 87.59 |
| 150.0 | 80.14 | 82.55 | 84.24 | 85.51 | 86.51 | 87.32 |
| 160.0 | 79.76 | 82.21 | 83.93 | 85.22 | 86.24 | 87.06 |
| 170.0 | 79.39 | 81.88 | 83.63 | 84.94 | 85.98 | 86.82 |
| 180.0 | 79.04 | 81.57 | 83.34 | 84.67 | 85.73 | 86.58 |
| 190.0 | 78.70 | 81.27 | 83.07 | 84.42 | 85.49 | 86.36 |
| 200.0 | 78.37 | 80.98 | 82.80 | 84.17 | 85.26 | 86.14 |
| 210.0 | 78.06 | 80.70 | 82.54 | 83.94 | 85.03 | 85.93 |
| 220.0 | 77.76 | 80.43 | 82.30 | 83.71 | 84.82 | 85.72 |
| 230.0 | 77.47 | 80.16 | 82.06 | 83.48 | 84.61 | 85.53 |
| 240.0 | 77.19 | 79.91 | 81.83 | 83.27 | 84.41 | 85.34 |
| 250.0 | 76.91 | 79.67 | 81.60 | 83.06 | 84.21 | 85.15 |
| 260.0 | 76.65 | 79.43 | 81.38 | 82.86 | 84.02 | 84.97 |
| 270.0 | 76.39 | 79.20 | 81.17 | 82.66 | 83.84 | 84.80 |
| 280.0 | 76.14 | 78.97 | 80.97 | 82.47 | 83.66 | 84.63 |
| 290.0 | 75.90 | 78.75 | 80.76 | 82.28 | 83.48 | 84.46 |
| 300.0 | 75.66 | 78.54 | 80.57 | 82.10 | 83.31 | 84.30 |

Studies reported in the U K Flood Studies Report Vol.II indicated that areal reduction factor increases with increasing rainfall duration and decreases with size of area but its variation with return period and geographical location was found to be insignificant. The areal reduction factor for 60 mts duration was found to vary from 0.96 to 0.35 for areas of 1 to 30,000 km$^2$.

### 3.2.2 Probable maximum precipitation by physical analysis

The definition of basin PMP is slightly different than storm PMP defined in 2.3. The basin PMP is defined as 'theoretically the greatest depth of precipitation for a given duration that is physically possible over a particular drainage basin at a certain time of the year'.

In regions where comprehensive records are available for a long period, some events might have approached the limit of PMP or extreme precipitation. However, experience of the PMP estimates being exceeded within a couple of years after their estimation tends to give the belief that extreme storms might not have occurred during the period of the data considered.

Meteorologists and hydrologists the world over have adopted the concept of Probable Maximum Precipitation for water resources planning and developed site specific PMP estimates for particular basin and sites using conventional techniques.

On the question as how to determine the PMP, Meteorologists were not able to identify entirely which of the meteorological parameters individually or collectively would be responsible to produce extreme rainfalls. The ignorance is, therefore, covered up through some assumptions and procedures and the PMP is, therefore, referred to only as an estimate and not an absolute value.

Details of the procedures and methods used in determining PMP are described in the Hydrometeorological Report series of the National Weather Service (formerly US Weather Bureau) USA. These methods were also summarised in the Technical Note 98 (WMO, 1969) and Operational Hydrology Report NO. 1 (WMO, 1973). Basically, PMP estimates are obtained by storm transposition and/or moisture maximisation of recorded major storm rainfalls.

Based on detailed studies, the US National Weather Service has developed generalized estimates of PMP for different geographical regions in USA such as east of 105° Meridian, West of 105° Meridian, Hawaian island, Alaska etc.

Use of the methods described in Hydrometeorology reports of National Weather Service, USA and Operational Hydrology Report 1 of WMO has extensively been made for estimation of site specific PMP in India by India Meteorological Department, Central Water Commission, Indian Institute of Tropical Meteorology and others; in Canada (Pugsley, 1981), Australia (Hall, 1984) and other countries. Some of the methods recommended were also used in the UK flood studies report Vol.II (National Environmental Research Council, 1975) for estimating what was called 'Estimated Maximum Precipitation'.

### 3.2.2.1 Storm selection and analysis

The basic step in the storm analysis is a thorough understanding of the meteorology of large storms in the region of analysis. Extensive and detailed study of the synoptic and dynamic features of all major storms is required. A judicious selection of a few storms which are representative for the whole catchment shall be made. The selection of the storms has to be based on a threshold value objectively chosen based on experience. Some criteria have been indicated in the Hydrometeorology Manual (IMD, 1972) for Indian storms.

Before deciding on an appropriate storm depth for design purposes, storm analysis either basin centered or storm centered, are carried out. The two methods used are

i. depth-area-duration analysis and

ii.depth-duration analysis.

The depth-area-duration analysis procedures have been described in the Manual for depth-area-duration analysis of storm precipitation' (WMO,1969) and other text books on hydrology.

Also the depth-duration analysis are described in the Hydrometeorology Manual (IMD,1972) and other text books on Hydrology.

### 3.2.2.2 Storm transposition

The transfer or transposing of storms from locations where they occurred to other areas where they could occur is called 'storm transposition'. The storm transposition is carried out from and to regions with relatively flat topography. The concept has emanated from the exigency arising out of limited sample of storm data which normally becomes available over the region of the study basin. The data sample over the basin is enhanced by considering all such severe storms over regions meteorologically homogeneous with the study basin and resulting from similar or near similar meteorological situation/storm systems. It is assumed that the rainfall depth (volumes) from the storms which occurred over the surrounding regions could have as well occurred over the basin of study after adjusting for the location, topography, barrier and moisture.

The size of the meteorologically homogeneous area could be different for different storms. Coastal storms are transposed along the coast, but only a limited distance inland. Inland storms are so placed that major mountain barriers do not block the inflow of moisture from the sea unless such a disposition was also present at the original location of the storm. Some limitation is placed on latitudinal transposition in order not to involve excessive changes in air mass characteristics.

Transposing storms from plains behind extremely high mountain barriers is not advisable because of the dynamic influence of the mountains on the storm rainfall depths and pattern. Storms are not usually transposed to locations where the differences in elevation are greater than 500 m. This limitation is one of the reasons that this procedure is most applicable to regions of little or no orographic controls. While selecting storms from a contiguous geographic region is preferable, Schwarz(1972) has suggested that data from many regions subject to tropical storms can be combined to develop reliable estimates of PMP. Thus, with advancement of knowledge on storm dynamics it may be possible to broaden the transposition limits to larger areas to ensure adequate storm sample.

A 'transposition adjustment' is a ratio by which the precipitation magnitudes in a storm are multiplied when it is transposed to compensate for variations in climatic or topographic conditions at the storm site and those at the project basin. The adjustments applied are

i. moisture adjustment for relocation

ii. elevation adjustment and

iii.barrier adjustment

The steps of storm transposition and the procedures of adjustment are described in detail in the WMO Technical Note No.98, Operational Hydrology Report No.1 of WMO and Hydrometeorology Manual of IMD (1972).

### 3.2.2.3 Storm maximisation

The WMO Technical Note No.98 mentions about three methods of storm rainfall maximisation: statistical, physical and composite. The statistical maximisation is already discussed in section 3.2.1. The other two methods are described here.

The physical method used for maximising observed storm rainfall to estimate PMP involves moisture adjustment with or without storm transposition and envelopment. The convergence model considered to be responsible for controlling precipitation in non-orographic areas has essentially a cloud system into which air converges radially at the lower levels and rises aloft to some great heights with adiabatic expansion which results in cooling, culminating in the condensation of moisture as precipitable water. Within the cloud, the decrease of temperature would be at saturation adiabatic lapse rate. The rate of precipitation is thus essentially controlled by the vertical velocity and precipitable water, which in turn depend on the rate of moisture inflow into the system at lower levels. Two types of maximisation were, therefore, conceived of; the 'moisture' maximisation and 'wind' maximisation. The hypothesis of the wind maximisation is that convergence of wind is proportional to the surface wind speed. The wind maximisation is rarely used alone but occasionally used in combination with moisture maximisation. Moisture adjustment is the primary and commonly used maximisation. Other factors such as convergence, inflow winds, vertical velocities, condensation etc. which could collectively be termed as 'storm efficiency' or 'storm mechanism' are equally if not more important. However, with the present knowledge and availability of data it is difficult to maximise these elements either individually or collectively to achieve a 'maximum storm efficiency'. It is, therefore, assumed that when a number of storms are analysed atleast one of them might have been associated with the so called 'maximum storm efficiency'.

Maximisation for storm efficiency has been carried out to prepare estimated maximum precipitation maps of 2 hr and 24 hr duration in the UK Flood Studies Report (vol.II and vol.V).

The moisture content or precipitable water is defined as the total atmospheric water vapour in a vertical column of unit cross sectional area between any two specified levels. The precipitable water between 1000 mb and any pressure level, corresponding to 1000 mb dew point temperature is given in Appendix I. For the purpose of moisture maximisation studies, the moisture between surface and 300 mb level is considered, as the moisture availability above 300 mb level is negligible. While it is realised that the total amount of water vapour cannot be realised as precipitation, an assumption is made that an increase in total moisture content would result in a proportionate increase in the magnitude of the precipitation.

Because of paucity of upper air observations at a larger number of locations it was customary to use surface dew point temperature as an index of precipitable water assuming saturated adiabatic lapse rate through the atmosphere. Both for maximum and observed storm cases, the surface dew point is used as an index of the moisture content. Though in many countries it is customary to determine maximum dew point for specific storm and duration, it would be convenient to have generalized charts of maximum dew point for different regions and different parts of the rainy season as was done by the US National Weather Service.

Miller suggested the use of other alternatives in the absence of reliable records of storm intensity; one of them was the transposition of moisture maximised values expressed as a percent of the normal annual or seasonal precipitation.

The steps and procedures of the moisture maximisation are described in Operational Hydrology Report 1 and Hydrometeorology Manual of IMD. While values of 2 to 13 were obtained in the UK flood studies report for the ratio of storm efficiency, the values of moisture maximisation ratio obtained in the United States were in the range of 1.20 to 1.80. In India also the values obtained by IMD and Dhar et al (Appendix III) were in the same range. Gole et al (1976) used combined moisture and wind maximisation for storms in Mahanadi basin as an experimental study and the values obtained were in the range of 1.35 to 3.5.

The composite method of maximisation is comprised of sequential maximisation and spatial maximisation. Sequential maximisation involves reduction of the time interval between bursts in a single storm or between separate storms. In spatial maximisation, the isohyetal pattern in a single storm is revised so that separate centres are made to occur over the same location or atleast distance between the centres is significantly decreased. In some cases, isohyetal patterns for separate storms are combined as given in the Operation Hydrology report No.1. This technique has been used perhaps for the first time in India for the estimation of design storm in Narmada basin (India Meteorological Department, 1981).

### 3.3 Storm Modelling and Other Approaches

In orographic regions, indirect approaches and storm modelling techniques were used for estimating PMP which is supposed to comprise of two components, orographic precipitation and convergence precipitation.

#### 3.3.1 Indirect approaches

In the indirect approaches, the non-orographic precipitation values are modified by use of various rainfall indices to account for orographic effects. This method has been used more often by the US National Weather Service for estimating PMP in Hawaian islands (Schwarz, 1963), Tennesse river basin (Schwarz, 1965), Mekong river basin (1970) and South east Alaska (1984).

As is well known the effect of orography on precipitation would be a net increase or decrease in precipitation due to the slope and its relative orientation with respect to the moisture inflow. The orography influences the precipitation pattern of many small to moderate size storms as much as it influences the rather infrequent storm events. The mean annual or seasonal precipitation, therefore, could be used as a basis for assessing the influence of orography by comparison of precipitation in different locations of the catchment The procedure of the indirect approach is given for the case study of Tennesse valley in the Operational Hydrology Report No.1 and other references cited above.

### 3.3.2 Orographic model

In orographic regions, since precipitation data records are generally short and possibility of storm transposition is limited, usually hypothetical models were developed on the basis of the knowledge of the storms and orographic influence. The models utilise such of the meteorological parameters observed daily and those topographic factors known to influence precipitation in mountainous areas.

Unlike the orographic modification method described in the section 3.3.1, the orographic separation method consists of estimating each precipitation component i.e. the convective and orographic separately and then adding them appropriately.

#### 3.3.2.1 Convergence model

The techniques of storm transposition and maximisation described in sections 3.2.2.2 and 3.2.2.3 could be used for determining the non-orographic component (convective precipitation). The moisture maximisation and wind maximisation were simple and crude methods of obtaining maximum precipitation. On the other hand such of the hurricane/storm models used operationally by weather forecasters could be used by using maximum values of inflow wind and precipitable water and optimising the vertical velocity parameter. However, application of these models requires an understanding of the dynamics of the storms types common to the region in order to select an appropriate model and to define the optimum inflow winds or wind fields, moisture charge and other parameters used in the model.

3.3.2.2 Another simple method of obtaining the non-orographic PMP especially for small size basins using extreme observed point rainfalls is the use of 'P/M ratio' or 'storm effectiveness ratio' (WMO Tech. Note 98) which is the ratio of precipitation in a storm to the precipitable water in the air surrounding the storm. The ratio is thus related to a specific duration, location and area of the rainfall value. If the P/M ratios are developed and regional envelopes determined, non-orographic estimates of PMP could be prepared using precipitable water.

### 3.3.2.3 Orographic laminar flow model

The orographic model described by Miller (1972) and Operational Hydrology Report No.1(WMO,1976) treats the precipitation resulting from forced ascent of moist air over an unbroken mountain ridge as a simplified two dimensional model. The air passing over the mountain peak would accelerate as the air from deep upwind layer has to pass through a relatively shallow layer at the peak. Thus, in the model the air is assumed to be lifted over the mountain ridge as a laminar flow. A simple diagram of inflow and outflow winds over a mountain barrier as given by Miller (1972) is shown in figure 3. At a great height in the atmosphere, the nodal surface (taken as 300 mb layer) the air is assumed to flow horizontally.

The model considers the flow of air in a vertical plane at right angles to a mountain chain or ridge. The plane has a Y coordinate in direction of flow and a Z coordinate in the vertical. The flow may represent an average over a few kilometers of stretch in transverse or X direction. The wind at ground level is assumed to move along the surface. The slope of the air streamlines above a given point on the mountain slope decreases with height, becoming horizontal at the nodal surface.

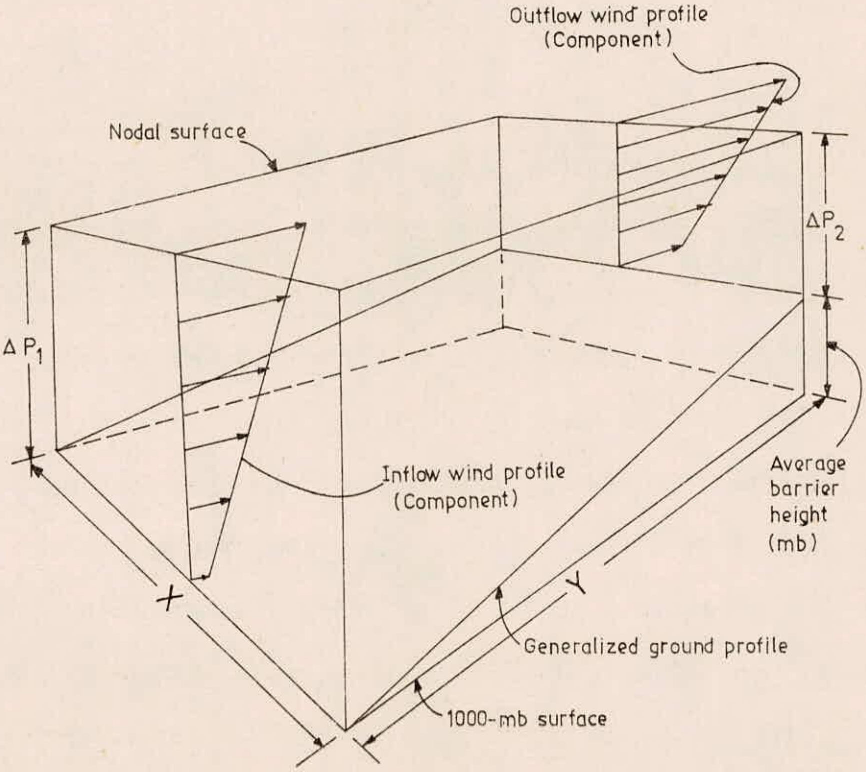

FIGURE 3 - SCHEMATIC WIND-FLOW MODEL FOR OROGRAPHIC PRECIPITATION
(Reproduced from paper of Miller (1972))

The model divides the complete column of air into several layers of flow. The rate of precipitation from each of these layers is given by the equation (5).

$$R = \frac{\bar{V}_1 \quad p_1 \ (\bar{q}_1 - \bar{q}_2)}{y} \qquad \frac{1}{q\,\rho} \qquad \ldots(5)$$

where,

$R$ = the rainfall rate in cm/sec,

$\bar{V}_1$= the mean inflow wind speed in cm/sec. through the layer

$p_1$= the thickness of the air in mb at inflow,

$\bar{q}_1$= the mean specific humidity in g/kg,

$\bar{q}_2$= the mean specific hudimity in g/kg at outflow,

$\rho$ = the density of water in gm/cc and

$y$ = the horizontal distance in cm.

Further, assuming laminar flow across the mountain and knowing the vertical profile of the horizontal wind, the lift impacted to the air, and the levels at which rain and snow are formed and their drift with the air before striking the ground, the trajectory of the precipitation could be determined. The computation of the precipitation trajectories is described in the Operational Hydrology Report NO.1.

For estimating the orographic PMP for a particular region, the maximum values of moisture and wind are used in the orographic model for computing this component of the total PMP estimate. The maximum moisture could be determined from radiosonde data where available or from surface dew points as in the case of moisture maximisation for non-orographic PMP. Similarly in the case of wind, the maximum inflow winds are determined from upper air wind observations immediately upwind of the slope. If such observations are not available, the surface wind data together with upper air pressure gradients are used for estimation of upper wind. This procedure has been used by the US National Weather Service (Hydrometeorology Report No.36 and 43) and was in use by the Hydrometeorology Division of the Atmospheric Environment Service, Canada (Pugsley, 1981 and Hogg, 1981).

Datta (1978) proposed a synoptic technique for determination of PMP in tropics through the following steps.

a. Prepare a set of composite charts for all known recurving monsoon depressions from the day the first recurvature is noticed. The charts may be for all mandatory levels from 1000 mb to 300 mb. A circular grind of 1000 km is taken with centre as the centre of the depression. The grid which is a moving grid has 8 octants each of $45^o$ and 10 radial zones of 100 km each. The various meteorological elements are averaged for various sectors.

b. Using the composite chart, compute the vertical motion field and with the knowledge of temperature and dew point depression field compute the rate of precipitation. To maximize the rate of precipitation provide an efficiency of about 2% and generate wind field by conversion of latent heat into kinetic energy.

c. Provide physically least possible speed of the movement of composite system.

d. Check with the PMP values derived by other techniques for applying subjective adjustments and verification. The above mentioned technique will be worthwhile to test over basins with gentle topography.

## 3.4 Time Distribution

As described earlier one of the components of the design rainfall is the time distribution. The time distribution finds its use not only with the probable maximum precipitation but also the depth-duration-frequency values, when they are not used with the rational formula. This is because PMP values either developed for site specific purpose or read from generalised charts and intensity-duration-frequency curves, provide the maximum accumulated amount for any given duration. Thus, the maximum amounts determined for 3 hourly or 6 hourly period could be at any part of a 24 hr total storm duration. From the point of view of producing maximum flood (runoff) it would be more realistic to try and obtain more critical arrangements of rainfall increments than those indicated by observed storms. This is usually obtained from historical storms producing critical runoff amount and rates in or near the project basin. In table 2, a hypothetical critical distribution is shown which is reproduced from the Operational Hydrology Report No.1( World Meteorological Organisation, 1971).

The other approach was using synthetic hyetographs the like of which were the Chicago Hyetograph, US Soil Conservation Service Type II hyetograph and quartile hyetographs adopted by Illinois State Water Survey (Terstriep and Stall, 1974) of USA. Huff (1967) used heavy storms for point rainfall and for mean rainfall on areas of 50, 100,200 and 400 sq. miles. The 261 storms on the east central Illinois

Table 2- Chronological Distribution of PMP for a Hypothetical $3000\ km^2$ basin

| Duration hr | PMP | 6 hour increments | | Maximum accumulation |
|---|---|---|---|---|
| | | PMP | arranged | |
| 0 | 284 | 284 | 16 | 284 |
| 12 | 345 | 61 | 28 | 345 |
| 18 | 384 | 39 | 20 | 384 |
| 24 | 419 | 35 | 12 | 419 |
| 30 | 447 | 28 | 39 | 431 |
| 36 | 467 | 20 | 61 | 451 |
| 42 | 483 | 16 | 284 | 479 |
| 48 | 495 | 12 | 35 | 495 |
| 54 | 505 | 10 | 5 | 500 |
| 60 | 513 | 8 | 8 | 508 |
| 66 | 521 | 8 | 10 | 518 |
| 72 | 526 | 5 | 8 | 526 |

Note: Increment in fourth column assumed to be arranged according to sequence of increments in critical storm producing maximum runoff in project basin. It may be noted that the summation of the arranged maximum rainfalls for any duration would be less than or equal to the corresponding PMP estimates in column 2 but not more.

(Reproduced from WMO Operational Hydrology Rept. No.1,1973) dense raingauge network during the 11 years 1955-66 were grouped according to quartile in which rainfall was heaviest to provide four basic types of distribution. Marsalek (1979) and Wenzel (1979) discussed the results obtained by the use of the different synthetic hyetographs on the production of flood hydrograph in comparison to the actual flood hydrograph at the seminar 'On the design storm concept' held at 'Ecole Polytechnique De Montreal' (1979).

Chow (1964) described a time distribution of 24 hr SPS rainfall. The sequence of rainfall as shown in figure 4 was said to produce critical runoff from most basins. In order to assure safe estimates of peak discharges to be expected from SPS rainfall over drainage areas less than approximately 300 sq.miles on the average, the maximum 6 hour rainfall of the SPS is broken down into shorter unit periods and higher intensities are assumed for the shorter intervals as shown in Table 3.

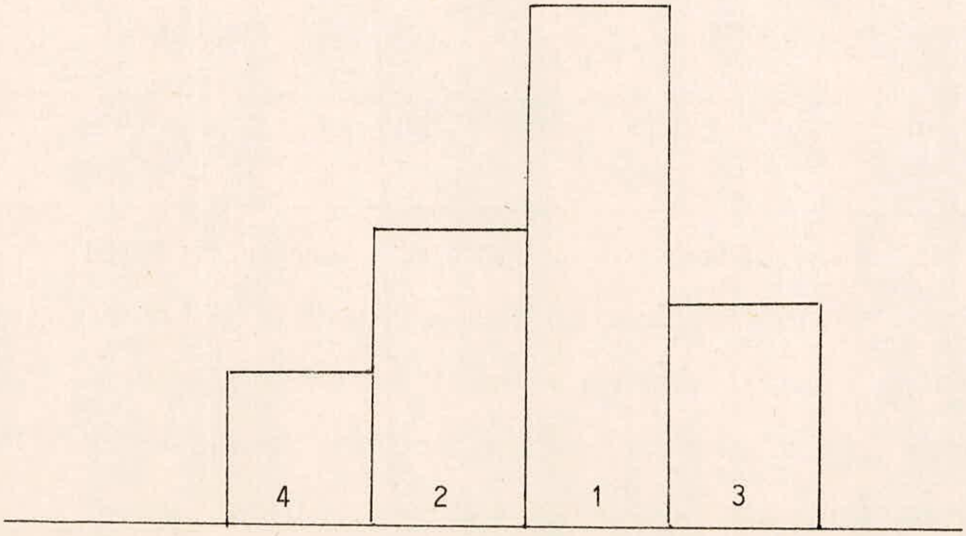

FIGURE 4 - TIME DISTRIBUTION OF 24 Hr. SPS RAINFALL. TYPICAL ARRANGEMENT FOR 6 Hr. RAINFALL INCREMENTS.

Table 3 - Time Distributioin of Maximum 6 hr SPS Rainfall in per cent of Total 6 hr Rainfall

| Rainfall period (subdivision of 6 hr period) | Selected unit rainfall duration | | | | |
|---|---|---|---|---|---|
| | 6hr | 3 hr | 2 hr | 1 hr | 0.5 hr |
| 1st | 100 | 20 | 19 | 6 | 3 |
| 2nd | | 80 | 69 | 8 | 3 |
| 3rd | | | 12 | 14 | 4 |
| 4th | | | | 55 | 5 |
| 5th | | | | 11 | 6 |
| 6th | | | | 6 | 12 |
| 7th | | | | | 43 |
| 8th | | | | | 8 |
| 9th | | | | | 6 |
| 10th | | | | | 4 |
| 11th | | | | | 3 |
| 12th | | | | | 3 |
| Total | 100 | 100 | 100 | 100 | 100 |

(From Hand Book of Hydrology, Chapter 25, pp.30)

The Japanese Book of Planning suggests either enlarging or contracting several observed rainfall patterns. It further suggests adjustment of the rainfall pattern depending on whether duration of design rainfall determined in section 3.1 is longer or shorter than observed rainfall pattern.

If the duration of actual rainfall is shorter than that of design rainfall, the duration of the actual rainfall is left as it is and the rainfall amount only is enlarged upto that of the design rainfall amount. This adjustment is shown in figure 5 (a). If the duration of actual rainfall is longer than that of design rainfall, the enlargement is done as above but is restricted only to the time that corresponds to the duration of design rainfall and a rainfall corresponding to initial loss is added before that, as shown in figure 5(b).

Several other studies are reported in literature on the use of time distribution for obtaining design floods by Pilgrim and Cordery (1975), Hogg (1980) and Hall (Personal communication).

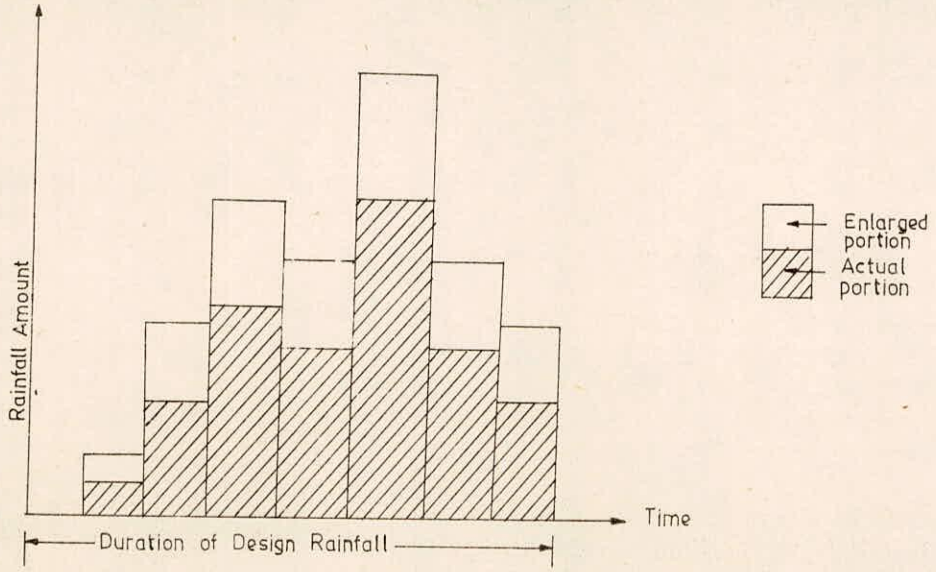

FIGURE 5 (a) - WHEN DURATION OF ACTUAL RAINFALL IS SHORTER
(From 'Book of Planning')

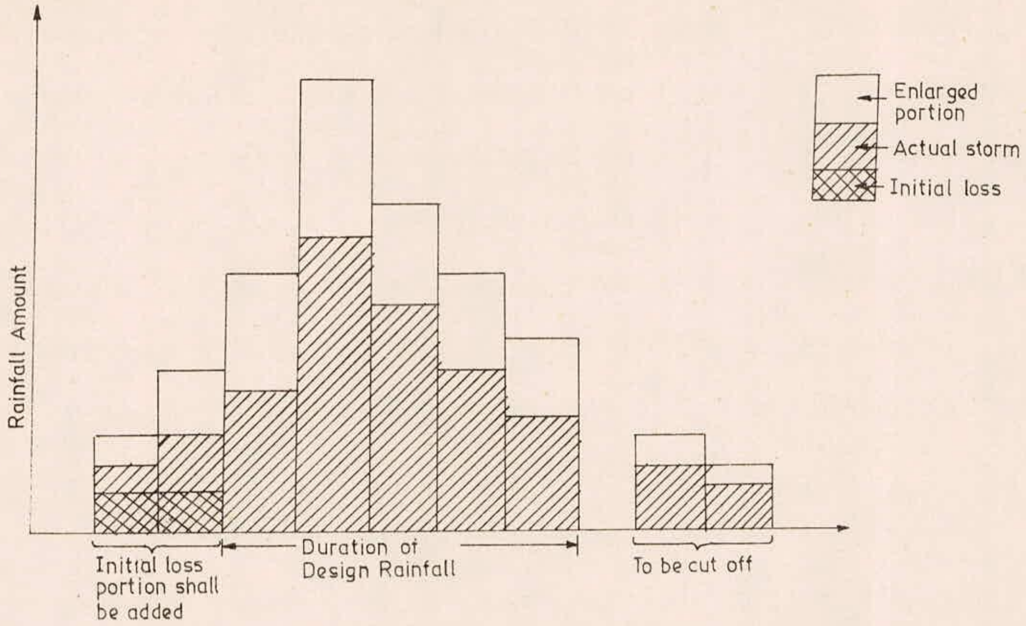

FIGURE 5(b) - WHEN DURATION OF ACTUAL RAINFALL IS LONGER
(From 'Book of Planning')

## 4.0 DESIGN STORM PRACTICES IN INDIA

In India, design storm studies are mainly carried out by India Meteorological Department and by Dr Dhar and his associates at the Institute of Tropical Meteorology, Poona. At the time of technical examination of project proposals submitted by State Govt. the Hydrology Directorate in Central Water Commission reviews the design storm for examining its adequacy. The Central Water Commission (1969) has recommended different types of design floods based on the criteria of the type of structure:

i. major structures ( those having a reservoir capacity of 50,000 acre feet and more) to be designed for probable maximum flood,

ii. medium structures (those having a reservoir capacity of less than 50,000 acre feet), barrages etc. to be designed for standard project flood or 100 years return period value whichever is higher and

iii. minor structures like railway bridges, road bridges etc. to be designed for 50 years return period value and culverts, tidal walls etc. for 25 years return period flood.

The guidelines for estimation of PMP have been provided in Manual of Hydrometeorology by India Meteorological Department (1972), Rao (1982) and partly in the manual of Central Water Commission recommended procedures (1969).

## 4.1 Intensity-Duration-Frequency Analysis

In India, while the rainfall data at totalling (ordinary gauges) is available for a length of nearly 100 years at a number of locations, data of durations less than 1 day is not available for more than 15-20 years at many of the 600 odd self-recording raingauges in operation at this time.

### 4.1.1 Frequency of observational day rainfall

Dr O N Dhar and his associates at the Indian Institute of Tropical Meteorology have used the Hershfield technique to determine the probable maximum precipitation and also 2,5,10,25,50 and 100 years values in some regions of India. Dr Dhar had carried out some studies using Gumbel's extreme value, Chow's frequency factor and Alexander's techniques also.

Dr D V L N Rao and his associates at the office of the Dy. Director General of Meteorology (Hydrometeorology), India Meteorological Department used the Gumbel's extreme value distribution to determine the 1000 yr and 10000 yr return period value of 1 day rainfall at point locations in some regions of India.

Krishnan and Kushwaha (1975) had made a comparative study of Gumbel's and Jenkinson's methods of estimating probable maximum precipitation intensities over India for different return periods.

Harihara Ayyar and Tripathi (1974) have prepared maps of observational day maximum rainfall for return periods of 2,5,10,25,50 and 100 years using records of about 1600 raingauge stations having daily data for at least 50 years, using Gumbel's extreme value distribution.

Besides, some other authors also have used either the Hershfield or Gumbel's technique for estimating the return period values of rainfall in some parts of India.

### 4.1.2 Studies for shorter duration intensities

For durations of less than one day, however, the technique has been to develop a relation of 24 hr. (1 day corrected to 24 hr.) to shorter duration rainfall at the long period autographic stations and extend it to meteorologically homogeneous regions to obtain shorter duration rainfall from one day rainfall at totalling raingauges.

Raman and Krishnan (1958) have carried out the frequency analysis with autographic raingauge records of New Delhi, Alipore (Calcutta) and Madras for a period of 10 years (1946-1955) to obtain the maximum intensity of rainfall which may be expected for various durations once in 1,2,5, and 10 years. An empirical relationship of the form given by Sherman (1931) has been derived as

$$I = KT/(t+a)^b \qquad \ldots(6)$$

where,

$I$ = Rainfall intensity in inches per hour,

$t$ = duration ( time in minutes,

$T$ = average number of years in which $I$ is equalled or exceeded,

$K$, $a$ and $b$ are constants depending on geographical situation.

In the studies carried out by the Central Soil and Water Conservation Research and Training Institute (1980, 1983) for rainfall data at Vasad and Kota the following relations were obtained.

Vasad:- $$I = \frac{7.506\ T^{0.1393}}{(t+0.5)^{0.3857}} \quad \ldots.(7)$$

Kota:- $$I = \frac{5.79\ T^{0.23}}{(t+0.5)^{0.85}} \quad \ldots(8)$$

Parthasarathy and Gurbachan Singh (1961) have prepared generalised charts of 2 years return period rainfall of duration 1,2,3 6 and 24 hrs using simple empirical relationships between 1 hour and 24 hour rainfall of a few stations in India.

Based on 15 mts tabulations of rainfall for 50 stations and hourly tabulations for 67 self-recording raingauge stations in India, Harihara Ayyar and Tripathi (1974) have prepared generalised charts of 2,5,10,25 and 50 year return period values of 15,30,45 mts, 3,6,9,12 and 15 hours rainfall. These have been improved upon subsequently by using data of 60 stations of 15 mts tabulations and hourly values at 100 self-recording raingauge stations in the report submitted to tne Directorate of Hydrology (small catchments) in Central Water Commission.

### 4.1.3 Inventory of depth-duration-frequency analysis

From the aforesaid description it may be seen that the study of probable maximum precipitation and depths of rainfall for different return peiod values has been done for most parts of India by either, Sherman, Jenkins, Chow , Hershfield or Gumbel's method with most of the studies following the later two methods.

The studies of the depth-frequency, however, are limited and some of them are localised. In Appendix II, an inventory of these studies is provided.

## 4.2 Probable Maximum Precipitation Estimation

The storm transposition, moisture maximisation techniques of estimating PMP for non-orographic areas has widely been used in India in an operational way for the estimation and review of design floods of a number of proposed as well as existing hydraulic structures in different parts of India.

During the past 30 years a number of authors, principal among them being Dr O N Dhar, now emeritus scientist at the Indian Institute of Tropical Meteorology,Pune have carried out the depth-area-duration analysis of a number of severe storms which have occurred in different parts of India since the rainfall recording has started in India which dates back to about 1875. Dhar and his associates have also estimated PMP using Hershfield's technique.

For the purpose of estimation of design storm for Narmada Sagar and Sardar Sarovar dam sites in the Narmada basin, probably, for the first time in India sequential combination of historical storms has been used by India Meteorological Department, Central Water Commission and other agencies (National Institute of Hydrology, 1982-83; Desai et al, 1984).

An inventory of the depth-area-duration and depth-duration studies carried out for major river basins in India by several authors are given in Appendix III basinwise. The inventory is only indicative and not exhaustive.

# 5.0 REMARKS

## 5.1 Advantages

The approach of flood estimation using design rainfall has some advantages over the frequency analysis of observed floods. The different parameters affecting the flood runoff could be considered in a more realistic and explicit way and the catchment characteristics of different sub basins contributing to the flood flow in the main river could be determined more thoroughly and added appropriately. The necessary parameters (unit hydrograph and routing) could be estimated even from a short length of record and the parameters thus derived could be extended to the other ungauged subbasins. The design storm approach also allows for maintenance of consistency in a given geographical area.

### 5.1.1 Conservative estimates

An advantage mentioned often is that the design storm approach provides conservative estimates of the peak flood and volume thereby allowing the engineers to play it safe. This of course is a matter of conjecture as the degree of conservativeness of the estimate of the design flood depends on the length of record of precipitation and method used for design storm estimation.

### 5.1.2 Data availability

Rainfall frequency studies are more advantageous than flood frequency studies because longer records of precipitation are generally available at a larger number of rain gauges more so in case of daily rainfall. Extreme rainfall values are more easily defined from physical consideration.

### 5.2 Limitations

A number of limitations were noticed in practice in spite of the wide spread and continued use of the design storm approach by design engineers. These relate to almost all aspects of the design storm starting from the approach and risk criteria to the time distribution and others. While some related to inadequacy, others were regarding the inconsistency and inappropriateness of the method.

### 5.2.1 Probability of rainfall and probability of flood peak

The major criticism of the design rainfall approach is that in the process of deriving design flood from design storm a series of steps are involved which would introduce some error and, therefore, may not provide the expected results. Thus, a design rainfall of a given frequency might not produce flood of the desired frequency. Besides, some of the limitations of fitting a frequency distribution to the flood data apply equally well to the extreme rainfall values too.

Studies carried out by Bell (1968), Larson and Reich (1972) and Niemczynowicz (1982) using concurrent data of storm events and associated rainfall have shown a wide scatter of the recurrence intervals of rainfall versus recurrence intervals of corresponding peak flows. As shown in figure 6, although the scatter is very broad,

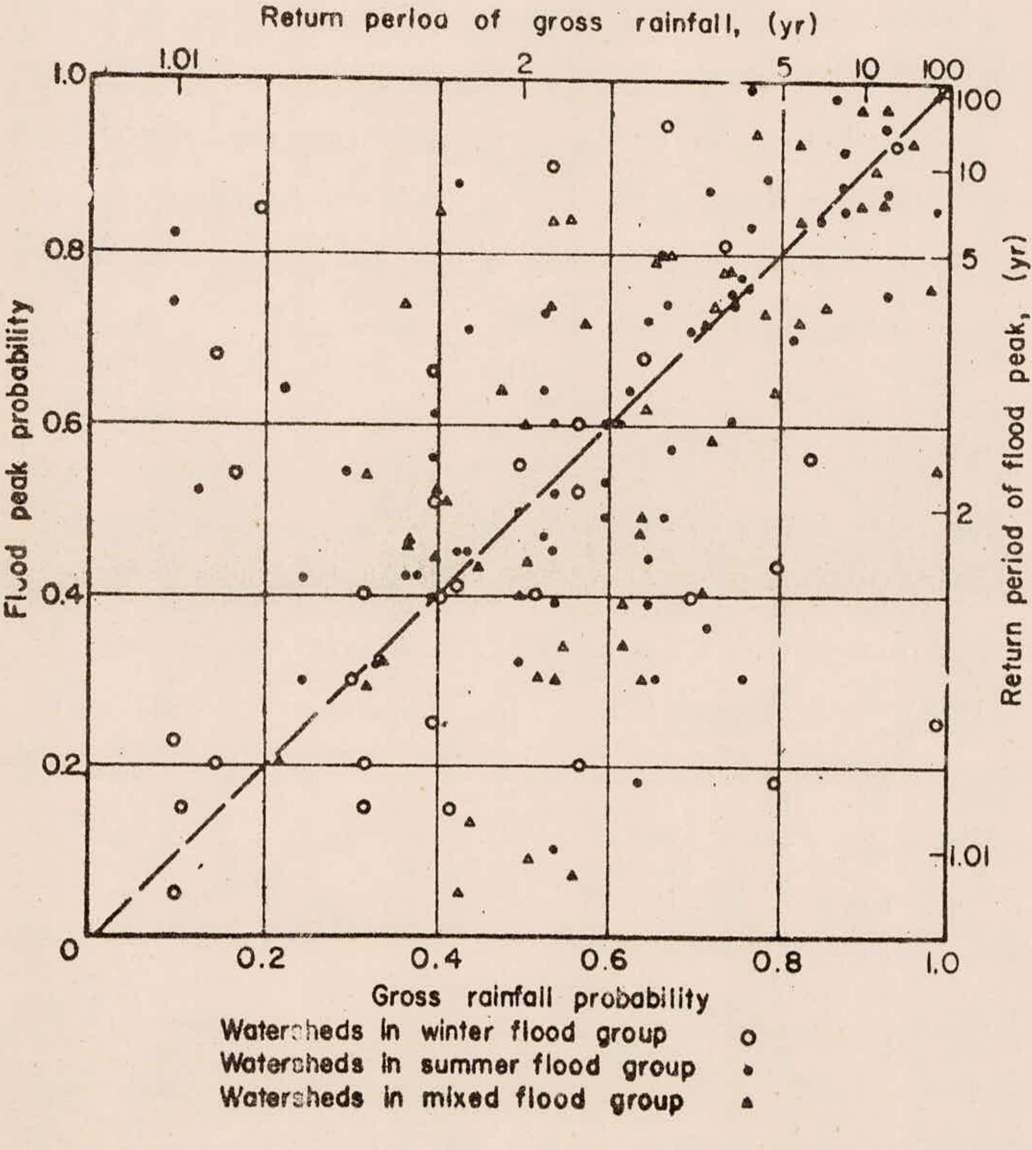

FIGURE 6 - PROBABILITY OF RAINFALL AND PROBABILITY OF ASSOCIATED FLOOD PEAK (Reproduced from Bell, 1968)

it may be seen that approximately the same number of points fall on each side of the $45^{0}$ line for the full range of values, indicating that, on the average, the probability of a particular design rainfall and the associated floods would be the same. The average 100 year flood for example, corresponds with the average 100 year rainfall for the watersheds considered.

### 5.2.2 Inadequacy of risk coverage

In some instances, the values of PMP were known to have been exceeded by later day storms while some others were found to be exceptionally high. In the case of June 1983 storm over Saurashtra, the depths have exceeded PMP values (National Institute of Hydrology, 1983-84). The method was, therefore, subject to serious criticism from both technical and practical points of view. The methods in practice suffered from subjectivity and lack of specific meaning and consistent results. The methods were deceptive from practical point of view because of the implication that the said design values assured risk free operation. A number of authors (Ackerman, 1964; Alexander, 1963 and Yevjevich, 1968) have questioned the 'Probable Maximum Precipitation' concept. However, Miller (1972) felt there was no need to change the basic concept of PMP. The methods and procedures in use had produced answers which were found to be reasonable estimates of what nature could ultimately produce.

Miller felt there were no absolute criteria to determine the adequacy of any PMP estimate and reported the results of study by Riedel and Schreiner (1980) wherein the maximum rainfalls observed in Eastern United States were compared with the PMP estimates. Nearly 700 storms in the Eastern United States were studied of which 177 storms had observed values within 50 percent of PMP estimates. Very few storms had values within 10 percent of the estimate of PMP. Table 4 shows the summary of the number of storms that exceeded various percentages of PMP for 10 square miles for durations of 6 hours and 24 hours.

Table 4 - Number of Storm Rainfall Cases in the United States east of the 105th meridian exceeding various percentages of PMP (10 $mi^2$,6 and 24 hours).

| 50% | 60% | 70% | 80% | 90% |
|---|---|---|---|---|
| 50 | 32 | 19 | 7 | 3 |

Jenkinson (1975) working for the flood studies report preferred to use the term Estimated Maximum Precipitation (EMP) rather than the more usual Probable Maximum Precipitation (PMP).←

### 5.2.3 Hershfield's PMP estimates

Like the intensity-duration-frequency values, the PMP values estimated by Hershfield's technique are point values and cannot be extended to areas more than 500-600 sq.km. The estimates of PMP by this method are dependent to a large extent on the value of K which in turn is dependent on the length of the record of data. Records of atleast 20 years are required to provide tentative estimates of PMP. Views were also expressed that the value of PMP could be related to factors other than mean annual maximum rainfall and duration.

### 5.2.4 Moisture maximisation

Folland et al (1981) reported that Jenkinson in a personal communication took the view that maximisation of both dew point and storm efficiency to values larger than those recorded, led to excessive estimates of maximised rainfall. He did not consider that such large values of dew point and storm efficiency could occur together in the same storm. It was not thought appropriate to use maximum surface dew points when the air was not saturated in a deep layer of overlying atmosphere.

Another consideration is the adequacy of any moisture adjustment in regions where the moisture supply is normally in plenty. The assumption of saturated atmosphere by use of surface dew points might not be valid in tropical regions. Comparison by Schwarz (1963) using data from the Hawaiian Islands indicated a difference in the observed and estimated precipitable water to be about 0.8 in. for rainy days. Though this and other similar comparisons were not conclusive, the available evidence suggests that the assumption of a saturated atmosphere with a pseudo-adiabatic lapse rate is not reasonable in tropical regions.

Also, the propriety of maximisation of sequentially combined storms for moisture needs careful consideration, because certain amount of maximisation is already involved while transposing the storms and sequentially combining them. A case in point is the maximisation of sequentially combined storms used for estimation of alternative design storms in Narmada basin for moisture (India Meteorological Department, 1981 and Desai et al, 1984). One of these storms has been transposed from a region close to the moisture source (Arabian Sea) and further maximised for moisture by 1.13.

On the other hand, PMP estimates using moisture maximisation factor have been exceeded by later day storms as in the case of the June 1983 storm over the Saurashtra region (National Institute of Hydrology, 1983-84).

### 5.2.5 Time distribution and antecedent conditions

Two other problems which are common to both the probabilistic and deterministic methods are the use of synthetic storm hyetograph patterns for deriving design flood from design rainfall and the assumption of antecedent precipitation conditions preceding the design storm/design flood.

#### 5.2.5.1 hyetograph pattern

The problem of using the synthetic storm hyetograph is of particular relevance in the small rural catchments and urban catchments where the catchment response is quick. Marsalek (1979) summarised the studies carried out by him earlier (Marsalek, 1978) on the influence of synthetic hyetographs in the reproduction of the peak floods in comparison to observed floods which has shown that peak runoff generated by the synthetic hyetographs was higher by 15 to 25% than the corresponding peak flows for the same return period. The two distributions used were (i) the Chicago design storm and (ii) the advanced hyetograph or the Huff distributiuon as given in ILLUDAS user manual (Terstriep and Stall 1974).

To substantiate the anomaly arising out of fitting synthetic hyetograph patterns, the case of an observed storm pattern was quoted where in the 5 minutes intensity corresponded to an 8 yr frequency, the 10 minutes to a 20 yr frequency, the 15 minutes to an 80 yr frequency, the 60 minutes to a 40 yr frequency and the 60 minutes to about a 5 yr frequency which, naturally, is contrary to the assumption of the synthetic hyetograph wherein all the peak intensities assigned to the design hyetograph have the same return period.

#### 5.2.5.2 antecedent conditions

Antecedent moisture conditions have a major influence in providing the design flood of a desired magnitude from a given rainfall. Dry conditions preceding a storm would, naturally, produce a moderate flood not commensurate with the design risk. However, the probabilities associated with the attendent conditions would make the task of assigning a particular return period to the resultant flood difficult because the synthetic storm regroups under a single event, intensity-depth relationship resulting from conditions attendant to the different storm events forming the data base for such relationships.

Wenzel (1979) reported on studies carried out on two urban catchments, one of 2,300 acres and the other of 23 acres using different antecedent moisture conditions and synthetic hyetographs. It was reported that by judiciously choosing a combination of the two variables (hyetographs and antecedent moisture conditions) one could match the historical frequency curve with the design storm curve.

## 6.0 CONCLUSIONS AND RECOMMENDATIONS

The general opinion seems to be that design rainfall approach for the estimation of design floods has a far wider range of application and it is more promising as the factors affecting flood runoff can be varied directly and with greater flexibility.

### 6.1 Statistical Analysis

For obtaining flood of a desired frequency from a storm of the same frequency the effects of joint probabilities introduced by the different components of design models is essential. This could be accomplished by using median or average values of the parameters other than rainfall.

An option available is to use a set of observed rainfall events taken from an extensive record of observations and estimate the corresponding peak flows through some rainfall runoff process and determine the peak flows corresponding to desired return period.

### 6.2 Storm Modelling

Research is needed to understand the various factors that combine to produce extreme storms with critical depths, their interactions and the probabilities associated with each of them and the resultant probability of storm rainfall and consequent runoff. Over a major portion of the tropics, tropical cyclones are one of the major causes of extreme rainfalls. A convergence model as developed by the US Weather Bureau could be improved by incorporating latest knowledge on these storms and this could be used to develop a base non-orographic PMP for the coastal portions of tropical regions where the PMP results from this storm type. Away from the coast, particularly in orographic parts of regions affected by tropical storms, a generalised storm model that may be approprate for coastal regions could not represent all the geographic and orographic effects. For these regions, it would be necessary to refine the results obtained from the model by empirical relations between physiographic factors and major precipitation events.

Namias (1969) showed that anomolous sea surface temperature could play an important role in subsequent weather, Schwarz(1972) had suggested that sea surface temperature anomalies could be considered as a factor in arriving at PMP estimates over broad regions where tropical storms are important. Other workers have shown the importance of sea surface temperature in determining the precipitation intensities over tropical areas. Analysis of data collected during the monsoon experiments has showed the monsoon precipitation in India to be related to the sea surface temperatures prevailing in Indian seas. It is, therefore, necessary to establish what sea surface conditions would lead to increase in rainfall due to a particular weather system. A thorough study of synoptic sea surface temperatures at the time of major storms may reveal how significant the sea surface temperature anomaly is with respect to moist air flow into extreme storm.

Also, new forms of analysis which combine the concepts of storm time structure and sequence storm return period and possibly storm structure may be needed. Numerical modelling of thunderstorm rainfall could provide a better understanding of extreme rainfalls over urban catchments.

The general circulation models on a limited scale could be exploited for the derivation of regional PMP and to study various adjustment with respect to various physical parameters. When the knowledge of the atmosphere increases, the ability to model the atmospheric process and understanding the precipitation process increases which would provide the meteorologist and hydrologist with the necessary flexibility and the flood hydrograph resulting from desired combination of precipitation and antecedent conditions with varied sequencing, intensities and time distribution could be obtained at the desired locations. This would facilitate generation of flood events of a wide spectrum ranging from frequency floods of low return period to probable maximum floods which would eventually hep in effective utilisation and management of the water resources.

## 6.3 Moisture Maximisation

For carrying out objective moisture maximisation studies, attempts are to be made to develop regional relationships between surface moisture measurements and precipitable water computed from upper air (radiosonde) observations. Alternatively, moisture adjustment ratios should be determined only from observed precipitable water values.

## 6.4 Antecedent Conditions

To overcome the uncertainities involved in the assumption of antecedent moisture conditions it is generally recommended that continuous watershed models may be used. However, the computer time and other time involved in such operation does not merit such a method considering the degree of accuracy achieved.

## 6.5 Time Distribution

The time sequence of rainfall is one aspect which could be developed in a more systematic way. At present these are used in very simple form. Similarly a great understanding of the physical basis of local climate and the study of the sequential behaviour of rainfall would influence future decisions on design scale and duration. For this purpose studies on modelling of moving storms on the lines carried out by Niemczynowicz (1982) are essential to incorporate them into the design considerations.

## 6.6 Urban Design Considerations

New methods of urban sewer design involving extensive use of on-line and offline storm tanks may be needed to be designed especially for large urban catchments.

While attempting design for urban catchments, rainfall for durtions less than 5 mts duration would be required. The syphon type raingauge in use in India has a resolution of 15 mts. Suitable weighing type raingauges or telemetering gauges with a resolution of less than 15 mts would be required to be installed in major urban catchments to design the drainage system of the major metropolitan cities.

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# APPENDIX-I

Precipitable water (mm) between 1 000 mb surface and indicated pressure (mb) in a saturated pseudo-adiabatic atmosphere as a function of the 1 000 mb dew point (°C)  Reproduced from WMO, 1973.

| mb \ °C | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 990 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 980 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 |
| 970 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 |
| 960 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 |
| 950 | 2 | 2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 |
| 940 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 |
| 930 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 |
| 920 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 |
| 910 | 3 | 3 | 3 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 |
| 900 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 |
| 890 | 4 | 4 | 4 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 |
| 880 | 4 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 12 |
| 870 | 4 | 4 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 | 12 | 13 |
| 860 | 4 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 12 | 13 |
| 850 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 |
| 840 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 |
| 830 | 5 | 5 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| 820 | 5 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 15 | 17 |
| 810 | 5 | 6 | 6 | 7 | 8 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 |
| 800 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 12 | 13 | 15 | 16 | 17 | 18 |
| 790 | 6 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 |
| 780 | 6 | 7 | 7 | 8 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 19 |
| 770 | 6 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 |
| 760 | 6 | 7 | 7 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 19 | 21 |
| 750 | 6 | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 |
| 740 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 22 |
| 730 | 7 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 |
| 720 | 7 | 7 | 8 | 9 | 10 | 11 | 11 | 12 | 13 | 15 | 15 | 17 | 18 | 20 | 22 | 23 |
| 710 | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 22 | 24 |
| 700 | 7 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 24 |
| 690 | 7 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 25 |
| 680 | 7 | 8 | 9 | 10 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 25 |
| 670 | 7 | 8 | 9 | 10 | 11 | 11 | 12 | 14 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 26 |
| 660 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 24 | 26 |
| 650 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 |
| 640 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 25 | 27 |
| 630 | 8 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 18 | 20 | 22 | 24 | 26 | 28 |
| 620 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 |
| 610 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 |
| 600 | 8 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 |
| 590 | 8 | 9 | 10 | 10 | 11 | 12 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 29 |
| 580 | 8 | 9 | 10 | 11 | 11 | 13 | 14 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 |
| 570 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 18 | 20 | 21 | 23 | 25 | 27 | 30 |
| 560 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 21 | 23 | 26 | 28 | 30 |
| 550 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 30 |
| 540 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 31 |
| 530 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 17 | 18 | 20 | 22 | 24 | 26 | 28 | 31 |
| 520 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 28 | 31 |
| 510 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 26 | 29 | 31 |
| 500 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 20 | 22 | 24 | 27 | 29 | 32 |
| 490 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 22 | 25 | 27 | 29 | 32 |
| 480 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 15 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 32 |
| 470 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 29 | 32 |
| 460 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| 450 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 32 |
| 440 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| 430 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 17 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| 420 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 15 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| 410 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 27 | 30 | 33 |
| 400 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 390 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 380 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 15 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 370 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 360 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 350 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 340 | 9 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 330 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 320 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 310 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 300 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 290 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 280 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 270 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 260 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 250 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 240 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 230 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 15 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 220 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |
| 210 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 29 | 30 | 33 |
| 200 | 8 | 9 | 10 | 11 | 12 | 13 | 15 | 16 | 18 | 19 | 21 | 23 | 25 | 28 | 30 | 33 |

| mb | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 °C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 990 | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 3 |
| 980 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 |
| 970 | 3 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 6 | 6 | 7 | 7 | 7 | 8 |
| 960 | 4 | 5 | 5 | 5 | 6 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 11 |
| 950 | 6 | 6 | 6 | 7 | 7 | 8 | 8 | 9 | 9 | 10 | 10 | 11 | 12 | 12 | 13 |
| 940 | 7 | 7 | 7 | 8 | 9 | 9 | 10 | 10 | 11 | 12 | 12 | 13 | 14 | 15 | 16 |
| 930 | 8 | 8 | 9 | 9 | 10 | 11 | 11 | 12 | 13 | 14 | 14 | 15 | 16 | 17 | 18 |
| 920 | 9 | 9 | 10 | 10 | 11 | 12 | 13 | 14 | 14 | 15 | 16 | 17 | 19 | 20 | 21 |
| 910 | 10 | 10 | 11 | 12 | 13 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 23 |
| 900 | 11 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 22 | 23 | 24 | 26 |
| 890 | 12 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 20 | 21 | 22 | 24 | 25 | 27 | 28 |
| 880 | 12 | 13 | 14 | 15 | 16 | 17 | 19 | 20 | 21 | 23 | 24 | 26 | 27 | 29 | 31 |
| 870 | 13 | 14 | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 29 | 31 | 33 |
| 860 | 14 | 15 | 16 | 18 | 19 | 20 | 21 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 36 |
| 850 | 15 | 16 | 18 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 |
| 840 | 16 | 17 | 19 | 20 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 36 | 38 | 40 |
| 830 | 17 | 18 | 19 | 21 | 22 | 24 | 26 | 27 | 29 | 31 | 33 | 35 | 38 | 40 | 43 |
| 820 | 18 | 19 | 20 | 22 | 24 | 25 | 27 | 29 | 31 | 33 | 35 | 37 | 40 | 42 | 45 |
| 810 | 19 | 20 | 21 | 23 | 25 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 44 | 47 |
| 800 | 19 | 21 | 22 | 24 | 26 | 28 | 29 | 32 | 34 | 36 | 39 | 41 | 44 | 46 | 49 |
| 790 | 20 | 22 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 40 | 43 | 46 | 49 | 52 |
| 780 | 21 | 23 | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 54 |
| 770 | 22 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 41 | 43 | 46 | 49 | 53 | 56 |
| 760 | 22 | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 55 | 58 |
| 750 | 23 | 25 | 27 | 29 | 31 | 33 | 35 | 38 | 41 | 44 | 47 | 50 | 53 | 57 | 60 |
| 740 | 24 | 26 | 28 | 30 | 32 | 34 | 37 | 39 | 42 | 45 | 48 | 51 | 55 | 59 | 62 |
| 730 | 24 | 26 | 28 | 30 | 33 | 35 | 38 | 40 | 43 | 46 | 50 | 53 | 57 | 60 | 64 |
| 720 | 25 | 27 | 29 | 31 | 34 | 36 | 39 | 42 | 45 | 48 | 51 | 55 | 59 | 62 | 66 |
| 710 | 26 | 28 | 30 | 32 | 35 | 37 | 40 | 43 | 46 | 49 | 53 | 56 | 60 | 64 | 68 |
| 700 | 26 | 28 | 31 | 33 | 35 | 38 | 41 | 44 | 47 | 50 | 54 | 58 | 62 | 66 | 70 |
| 690 | 27 | 29 | 31 | 34 | 36 | 39 | 42 | 45 | 48 | 52 | 55 | 59 | 63 | 68 | 72 |
| 680 | 27 | 30 | 32 | 34 | 37 | 40 | 43 | 46 | 49 | 53 | 57 | 61 | 65 | 69 | 74 |
| 670 | 28 | 30 | 33 | 35 | 38 | 41 | 44 | 47 | 51 | 54 | 58 | 62 | 67 | 71 | 76 |
| 660 | 29 | 31 | 33 | 36 | 39 | 42 | 45 | 48 | 52 | 55 | 60 | 64 | 69 | 73 | 78 |
| 650 | 29 | 31 | 34 | 37 | 39 | 42 | 46 | 49 | 53 | 57 | 61 | 65 | 70 | 75 | 80 |
| 640 | 29 | 32 | 35 | 37 | 40 | 43 | 46 | 50 | 54 | 58 | 62 | 67 | 71 | 76 | 81 |
| 630 | 30 | 32 | 35 | 38 | 41 | 44 | 47 | 51 | 55 | 59 | 63 | 68 | 73 | 78 | 83 |
| 620 | 30 | 33 | 36 | 38 | 42 | 45 | 48 | 52 | 56 | 60 | 65 | 69 | 74 | 79 | 85 |
| 610 | 31 | 33 | 36 | 39 | 42 | 45 | 49 | 53 | 57 | 61 | 66 | 71 | 76 | 81 | 87 |
| 600 | 31 | 34 | 37 | 40 | 43 | 46 | 50 | 54 | 58 | 62 | 67 | 72 | 77 | 83 | 89 |
| 590 | 32 | 34 | 37 | 40 | 43 | 47 | 51 | 55 | 59 | 63 | 68 | 73 | 78 | 84 | 90 |
| 580 | 32 | 35 | 38 | 41 | 44 | 48 | 51 | 55 | 60 | 64 | 69 | 74 | 80 | 85 | 91 |
| 570 | 32 | 35 | 38 | 41 | 45 | 48 | 52 | 56 | 61 | 65 | 70 | 75 | 81 | 87 | 93 |
| 560 | 33 | 36 | 39 | 42 | 45 | 49 | 53 | 57 | 61 | 66 | 71 | 77 | 82 | 88 | 94 |
| 550 | 33 | 36 | 39 | 42 | 46 | 49 | 53 | 58 | 62 | 67 | 72 | 78 | 83 | 90 | 96 |
| 540 | 33 | 36 | 39 | 43 | 46 | 50 | 54 | 59 | 63 | 68 | 73 | 79 | 85 | 91 | 97 |
| 530 | 34 | 37 | 40 | 43 | 47 | 50 | 55 | 59 | 64 | 69 | 74 | 80 | 86 | 92 | 99 |
| 520 | 34 | 37 | 40 | 43 | 47 | 51 | 55 | 60 | 64 | 70 | 75 | 81 | 87 | 93 | 100 |
| 510 | 34 | 37 | 40 | 44 | 48 | 51 | 56 | 60 | 65 | 70 | 76 | 82 | 88 | 95 | 102 |
| 500 | 34 | 37 | 41 | 44 | 48 | 52 | 56 | 61 | 66 | 71 | 77 | 83 | 89 | 96 | 103 |
| 490 | 35 | 38 | 41 | 45 | 48 | 52 | 57 | 61 | 66 | 72 | 78 | 84 | 90 | 97 | 104 |
| 480 | 35 | 38 | 41 | 45 | 49 | 53 | 57 | 62 | 67 | 73 | 79 | 85 | 91 | 98 | 105 |
| 470 | 35 | 38 | 42 | 45 | 49 | 53 | 58 | 62 | 68 | 73 | 79 | 85 | 92 | 99 | 106 |
| 460 | 35 | 38 | 42 | 45 | 49 | 54 | 58 | 63 | 68 | 74 | 80 | 86 | 93 | 100 | 108 |
| 450 | 35 | 39 | 42 | 46 | 50 | 54 | 58 | 63 | 69 | 74 | 81 | 87 | 94 | 101 | 109 |
| 440 | 35 | 39 | 42 | 46 | 50 | 54 | 59 | 64 | 69 | 75 | 81 | 88 | 95 | 102 | 110 |
| 430 | 36 | 39 | 42 | 46 | 50 | 55 | 59 | 64 | 70 | 76 | 82 | 89 | 96 | 103 | 111 |
| 420 | 36 | 39 | 43 | 46 | 50 | 55 | 60 | 65 | 70 | 76 | 82 | 89 | 96 | 104 | 112 |
| 410 | 36 | 39 | 43 | 47 | 51 | 55 | 60 | 65 | 71 | 77 | 83 | 90 | 97 | 105 | 113 |
| 400 | 36 | 39 | 43 | 47 | 51 | 55 | 60 | 65 | 71 | 77 | 84 | 90 | 98 | 105 | 114 |
| 390 | 36 | 39 | 43 | 47 | 51 | 56 | 60 | 66 | 71 | 77 | 84 | 91 | 98 | 106 | 115 |
| 380 | 36 | 39 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 78 | 85 | 92 | 99 | 107 | 115 |
| 370 | 36 | 40 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 78 | 85 | 92 | 100 | 108 | 116 |
| 360 | 36 | 40 | 43 | 47 | 51 | 56 | 61 | 66 | 72 | 79 | 85 | 93 | 100 | 109 | 117 |
| 350 | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 93 | 101 | 109 | 118 |
| 340 | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 93 | 101 | 109 | 118 |
| 330 | 36 | 40 | 43 | 47 | 52 | 56 | 61 | 67 | 73 | 79 | 86 | 94 | 102 | 110 | 119 |
| 320 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 73 | 80 | 87 | 94 | 102 | 111 | 120 |
| 310 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 73 | 80 | 87 | 94 | 102 | 111 | 120 |
| 300 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 67 | 73 | 80 | 87 | 95 | 103 | 111 | 121 |
| 290 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 80 | 87 | 95 | 103 | 112 | 121 |
| 280 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 80 | 88 | 95 | 103 | 112 | 121 |
| 270 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 95 | 104 | 112 | 122 |
| 260 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| 250 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 122 |
| 240 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| 230 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| 220 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 104 | 113 | 123 |
| 210 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 105 | 114 | 123 |
| 200 | 36 | 40 | 44 | 48 | 52 | 57 | 62 | 68 | 74 | 81 | 88 | 96 | 105 | 114 | 123 |

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# APPENDIX III

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