MANUAL

On

RAINFALL ANALYSIS

FOR

STORM WATER DRAINAGE SYSTEMS

Prof. Shashikant D. Chawathe

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ये रे ये रे पावसा
तुला देतो पैसा
पैसा झाला खोटा
पाउस आला मोठा

ये ग ये ग सरी
माझे मडके भरी
सर आली धावून
मडके गेले वाहून

This Book is affectionately dedicated to my

Alma Mater

VJT Institute, Mumbai

26/7/2005, Mumbai

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PREFACE

The failure of the Storm Water Drainage System in Mumbai, India in coping with the torrential rains of 26^{th} and 27^{th} July 2005 generated a lot of concern and interest in the subject of Storm Water Management in India. Rainfall Analysis is a pre-requisite to designing an efficient storm water management system. A need was felt to have a book or manual which would illustrate the most common methods of Rainfall Analysis and would also present the Rainfall Intensity - Duration – Frequency (IDF) Relationships for Indian Cities.

The Manual explains the methodology of developing IDF Relationships in a step-by-step way. The author had the opportunity to develop these relationships for a few cities in India such as Mumbai, Pune and Ahmedabad. He had the opportunity to develop a software 'RAIN' which saved manual labour in performing various computations for the Rainfall Analysis. However, EXCEL can also be used in performing various computations illustrated in this Manual.

The author wishes to put on record the great assistance rendered by Miss Manasi Bapat and Mr. Rajesh Singh in performing various computations and in preparing graphic diagrams. I am very much thankful to both of them for this assistance. Based on a famous miniature painting, Miss Tejaswini Raval designed the front cover for this manual. I am thankful to her for the same.

I am also thankful to Mrs. Joan Gonsalves for preparing the manuscript of this manual with due care for mathematical equations and symbols.

The manual has been made available for free download on website puzzleland.in. The author hopes that Consultants, Professors, Students and Researchers will find this book useful in the analysis of rainfall leading to execution of adequate Storm Water Drainage Systems in Cities.

Mumbai, India

Shashikant D Chawathe

July 2011

CHAPTER 1 : INTRODUCTION

1.0 RATIONAL METHODS OF DESIGN

The manual design of a Storm Water Drainage System is carried out using the 'Rational Method'. Strictly speaking, this method is suitable for small catchments. However, in practice, in the manual design of the system, this method is also used for larger catchments. If one has access to commercial software for the design of the Storm Water Drainage System then the same should be preferred for use with larger catchment areas. A typical Storm Water Drainage Tree Network is shown in Figure 1.1.

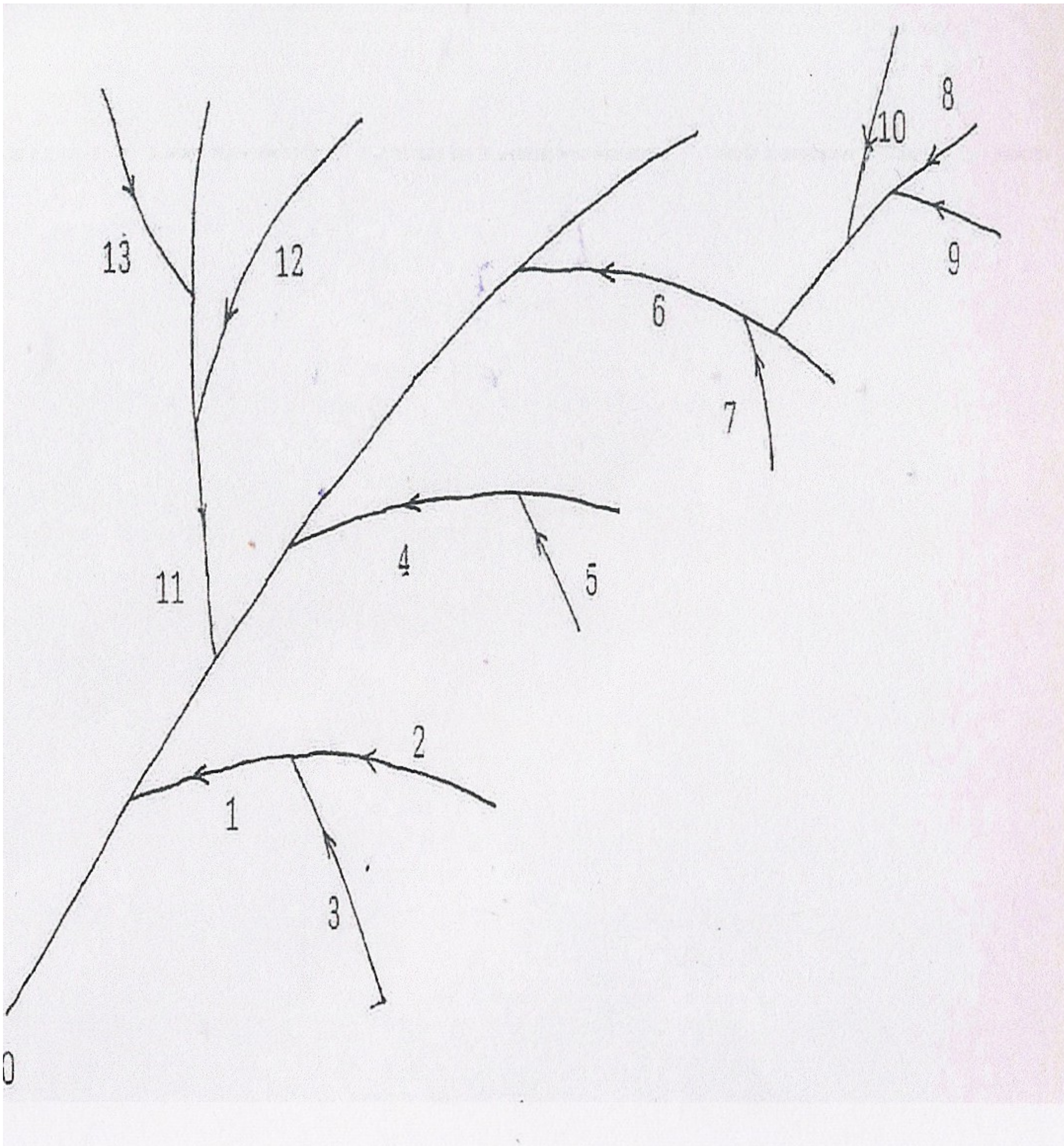

Figure 1.1 – Typical Storm Water Drainage System

2.0 DESIGN RUN-OFF

The Rational Method involves repeated use of the following equation :

$$Q = C \times i \times A \qquad (1.1)$$

Where, 'Q' is the design runoff of stormwater,

'C' is the coefficient of runoff,

'A' is the area tributary to the point on the Storm Water Drain under design,

And 'i' is the intensity of rainfall of a storm with a specific duration and specific frequency of occurrence.

The intensity of rainfall is assumed to be uniform over the duration of the storm. The duration of the storm is generally taken to be equal to the concentration time for the point on the storm water drain under design. The concentration time is the sum of the inlet time or the time required for the runoff to gain entrance to the storm water drain and the time of travel in the drain upto the point under design. The time of travel in the drain increases as points further away from the entry point are considered for design. Fig. 1.2 shows the concept of the concentration time.

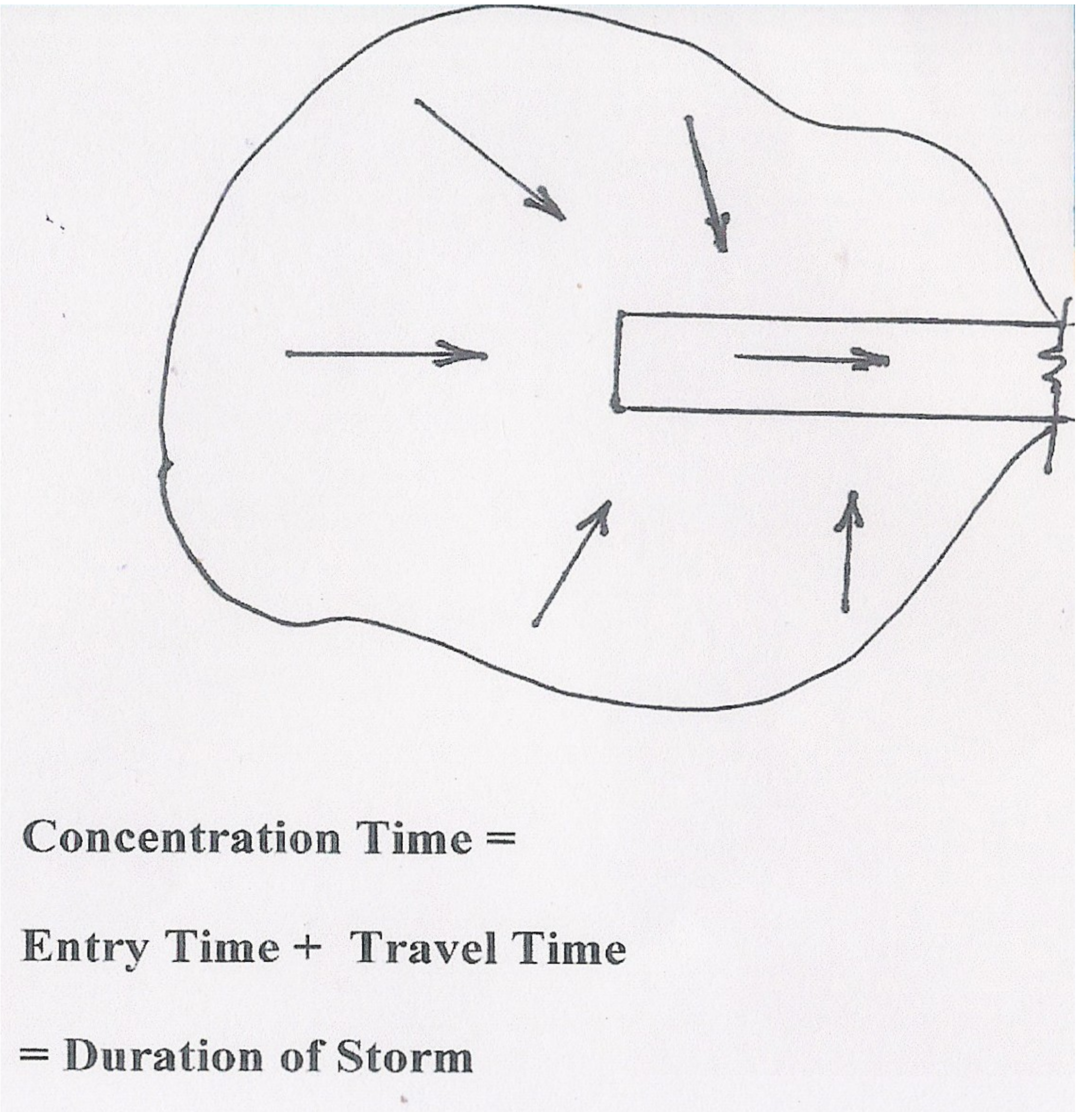

Fig 1.2 : Concept of Concentration time

3.0 COEFFICIENT OF RUN-OFF

The coefficient of run-off indicates the shedding characteristic of the catchment area. The actual quantum of run-off to be handled by the storm water drain is a fraction of the total quantum of rainfall falling on the catchment. A part of the water may get absorbed by the land depending upon its soil characteristics and again another part may get evaporated. The rest of the run-off enters the storm water drain. The coefficient of run-off which is normally less than 1.0 accounts for this phenomenon. The manual on Sewerage and Sewage Treatment published by C.P.H.E.E.O of the Government of India recommends design values of coefficient of run-off as per Table 1.1.

Table 1.1 : Design Values of Coefficient of Run-off

Type of Area	Coefficient of Run-off
Commercial	0.70 to 0.90
Residential High Density	0.60 to 0.75
Residential Low Density	0.35 to 0.60
Parks and Undeveloped Land	0.10 to 0.20

4.0 INTENSITY OF RAINFALL

The Intensity of Rainfall to be used in computing the design run-off in equation 1.1 is related to the concentration time and the frequency of occurrence of the storm. The frequency of occurrence has to be selected by the designers at the start of the design exercise. The cost of the system depends upon this decision. Considering a rarer storm will increase the cost of the system because the intensity of rainfall will be high. Recommended frequencies of occurrence (Return Periods) by various authorities are as given in Annexure 'A' to this chapter. It is seen that C.P.H.E.E.O Manual suggests design frequencies between 2 in 1 year to 1 in 2 years depending upon the value of the area. Most of the foreign countries suggest frequencies of occurrence which necessitate higher intensities of rainfall to be adopted for the design.

A point to point design of the Storm Water Drainage System requires repeated selection of the Intensity of Rainfall for increasing Concentration Time intervals. This is possible if the relationship of the Intensity of Rainfall with the concentration Time for a given Frequency of Occurrence is known for the particular catchment. This relationship is known as Intensity – Duration – Frequency (IDF) relationship and can be expressed in the form of a formula or in the form of a graphic curve. Such a relationship can be developed by conducting an analysis of past rainfall records for this area under study.

5.0 LIMITATIONS OF 'RATIONAL METHOD'

The 'Rational Method' being described here has its drawbacks. The method ignores the fact that the computed design run-off flow at a point may be less than that at a point further upstream, if the time of travel between the two points is sufficiently large. Also the run-off flow for which a particular drain in the system is being designed, may reach the maximum value at a time other than that at which the whole system reaches the maximum value.

The ‘Rational Method’ also assumes a uniform intensity of rainfall over the duration of the storm (concentration time). In an actual case, the intensity will vary through the total quantity of rainfall during the concentration time will be the same for both cases. This variability is normally considered if commercial software is available for design.

The Rational Method of design is still favoured for the manual design of the Storm Water Drainage Network by the designers. C.P.H.E.E.O. recommends this method in their manual.

ANNEXURE – A

FREQUENCIES OF OCCURRENCE AS RECOMMENDED BY AUTHORITIES

- Storm Water Drainage Manual, Drainage Service Dept. Govt. of Hongkong, Dec. 2000
  Urban Drainage Trunk System – 1 in 200 years
  Urban Drainage Branch System – 1 in 50 years
- Drainage Manual, Dept of Transportation, State of Florida, USA, 2008
  General Design – 1 in 3 years
  General Design involving replacement of road side ditch with pipe system – 1 in 10 years
  General Design of interstate facilities – 1 in 10 years
  Interstate facilities for Sag Vertical Curves – 1 in 50 years
- Georgia Storm Water Management Manual, Atlanta Regional Commission, 2001, USA
  Overbank Flood Protection – 1 in 25 years (24 hr storm)
  Extreme Flood Protection – 1 in 100 years (24 hr storm)
- George Town Country, South Carolina, USA, 2006
  Storm sewers crossing under arterials and multi lane collector road ways – 1 in 50 years.
  All remaining storm sewer systems – 1 in 25 years
- New York State Storm Water Management Design Manual, New York State Dept. of Environment Conservation, New York, 2003
  Overbank flood control – 1 in 10 years (24 hr storm)
  Prevention of impact on buildings and other structures ; Extreme storm – 1 in 100 years (24 hr storm)
- Storm Water Management Manual, Public Woks Dept. City of Memphis, Shelby Country, Tennessee, USA, 2006
  Minor Drainage System – 1 in 10 years
  Major Drainage System – 1 in 100 years
- American Society of Civil Engineers, ASCE Manual 37
  Residential Area – 1 in 2 to 15 years, Commercial (hi8gh value) Area – 1 in 10 to 15 years.
- CPHEEO, Manual, Govt. of India
  Residential Peripheral Area – 2 in 1 year
  Residential Central (high value) Area – 1 in 1 year
  Commercial Area – 1 in 2 years
- Fact Finding Committee Report, Maharashtra State Government
  Major Corridors used in emergency evacuation - 1 in 100 years
  Other major Roads - 1 in 25 years

Small Catchments - 2 in 1 year
River Channel Areas - 1 in 10 years
River Bank Area - 1 in 25 years
CD works on Main Roads - 1 in 100 years

- Project Report on Repetitive Water Logging in Thane City, Engineering Solutions and Environmental Management Plan : Hariyali, Thane, April 2007

  Open Channel and underground drainage system – 1 in 10 years

- Storm Drainage and Environmental Criteria Manual, Town of Parker, Colorado, Dec 2002.

Type of Area	Initial Storm (*)	Extreme Storm (**)
Residential Area	1 in 2 years	1 in 100 years
Commercial / Business/ Industrial	1 in 5 years	1 in 100 years

* Minimum disruption to the Urban Environment

** Minimum threat to health and life, damage to structure, interruption to traffic and services

- Drainage Manual, Nevada Dept. of Transportation USA, Dec 2006

Inter State Highways - 1 in 25 years
Principal Arterials, other Freeways, expressways, - 1 in 25 years
Other principal arterial - 1 in 25 years
Minor arterial - 1 in 10 years
Rural major collector - 1 in 10 years
Urban or rural minor collector - 1 in 10 years

- Storm Water Management Manual City of Charleston, South Carolina, USA, Feb 2009

Contributory Area	Return Period
≤ 40 area	1 in 10 years
> 40 acres, ≤ 100 acres	1 in 25 years
> 100 acres, ≤ 300 acres such as channel improvements, culverts, bridges	1 in 50 years

- Storm Water Management Manual, City of Alabama, USA, April 2003.

  All systems - 1 in 25 years

  Unless under jurisdiction of Alabama Dept of Transportation which requires 1 in 50 years

- Queensland Urban Drainage Manual, Queensland Govt. Australia, 2007.

  Major System Design - 1 in 50 or 1 in 100 years

  Minor System Design

  - Central Business / Commercial 1 in 10 years
  - Industrial - 1 in 2 years
  - Urban Residential,
    High density - 1 in 10 years
    (> 20 dwellings/ha)
  - Urban Residential,
    Low density - 1 in 2 years
    (5 to 20 dwellings/ha)
  - Rural Residential - 1 in 2 years
    (2 to 5 dwellings/ha)
  - Open spaces/parks - 1 in 1 year
  - Major Road - 1 in 10 years
    (kerb and channel)
  - Major Road (Culverts) - 1 in 50 years
  - Minor Road (Culverts) - 1 in 10 years

- Urban Storm Drainage Criteria Manual Urban Drainage and Flood Control District Denver, Colorado, USA, April 2008

  Initial Storm Drainage System - 1 in 2 to 10 years

  Major Storm provisions - 1 in 100 years

  to avoid property damage

  loss of life

CHAPTER 2 : METHODS OF RAINFALL ANALYSIS

1.0 IDF RELATIONSHIPS

The most common IDF relationships used in the Rainfall Analysis are as follows :

a) Relationship 1

$$i = \frac{a}{t^n} \qquad (2.1)$$

b) Relationship 2

$$i = \frac{a}{(t+b)^n} \qquad (2.2)$$

c) Relationship 3

$$i = \frac{CT^m}{(t+d)^n} \qquad (2.3)$$

Where, i = intensity of rainfall (mm/hr)

t = duration of storm (min)

T = Frequency of occurrence (Return Period in Years/months)

And, a, b, C, d, m and n are constants.

Normally Relationships 1 and 2 above are developed for a specific frequency of occurrence the values of constants a, b and c being applicable for that frequency. The values of these constants vary from frequency to frequency.

In the Relationship 3, the values of the set of constants C, m, d and n are the same for frequencies lying in a given range. For other ranges the values will vary. A Graphical Method as well as a method based on Least Squares Principle are available to find out the magnitudes of the constants.

1.1 A method which uses the annual maximum magnitudes of rainfall is also available for rainfall analysis. The same is termed as Annual Maxima Method.

2.0 METHOD BASED ON RELATIONSHIP 1

The method uses the following relationship:

$$i = \frac{a}{t^n} \qquad (2.4)$$

Where, i = intensity of rainfall (mm/hr)

t = duration of storm (min)

And, ‘a’ and ‘n’ are constants for a given frequency of occurrence (Return period) (year). Equation 2.4 can be converted into a straight line relation by taking logarithums of both sides as follows :

$$\log i \ = \ \log a - n \log t \qquad (2.5)$$

or $$\log i \ = -\, n \ \log t \ + \ \log a \qquad (2.6)$$

The constants ‘a’ and ‘n’ can be determined as intercept on Y axis and slope of the line respectively if we have a number of pairs of values for ‘t’ and ‘i’. A straight line can then be fitted to the points. The methodology to generate these pairs is described below.

2.1 Data

Automatic Rain Gauges have the facility to plot cumulative rainfall on strips of paper wound around a drum. These plots of Hyetograms for the past several years for a location are collected from the Meteorological Station. They form the raw data for the rainfall analysis. A typical automatic rainfall gauge is shown in Fig. 2.1. A typical Hyetogram is shown in Fig. 2.2. In India, some Meteorological stations make available rainfall data at 15 min intervals or 1 hr intervals. The same can also be used for rainfall analysis.

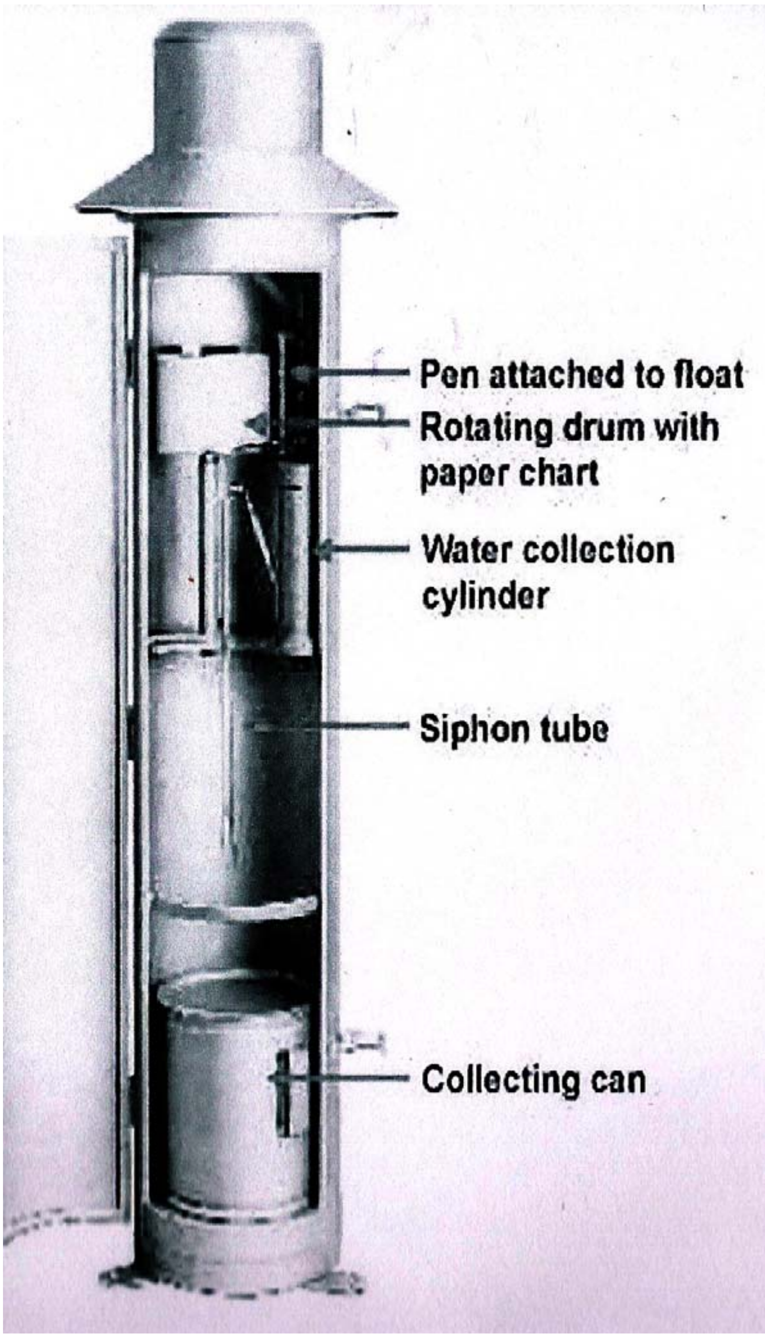

Figure 2.1 : Typical Automatic Rain Gauge

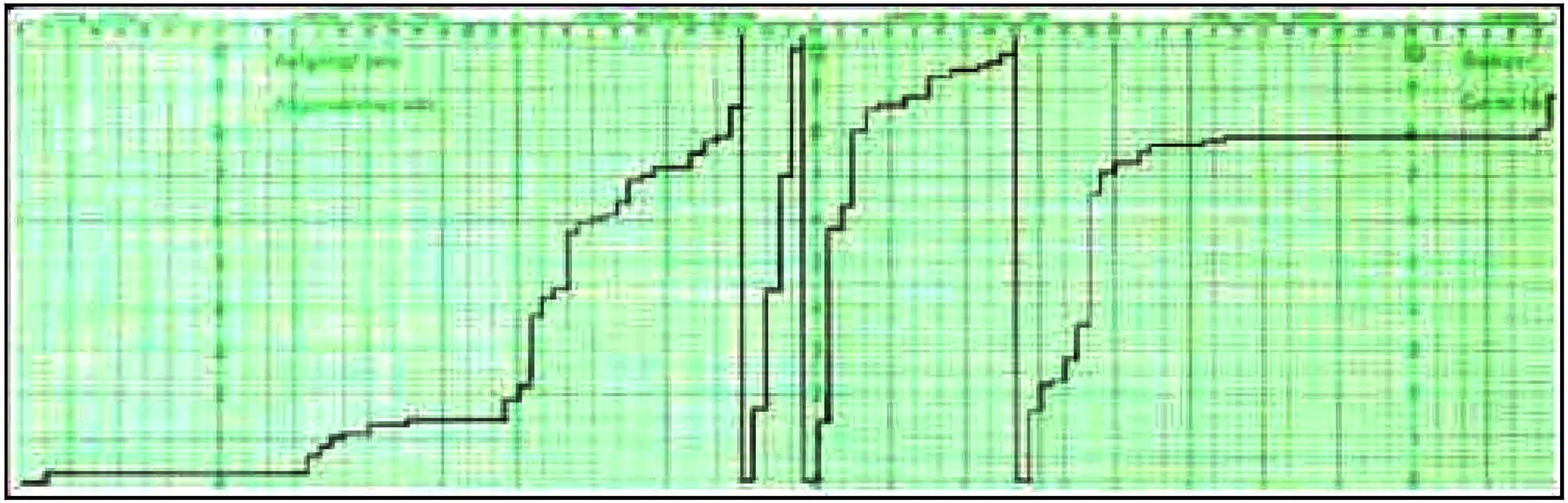

Figure 2.2 : Typical Hyetogram

2.2 Methodology

A single Hyetogram shows cumulative rainfall over a day. The plot can be subdivided into a number of continuous segments during which rainfall is present. Segments of the plot when there is no rainfall, or negligible rainfall can be omitted. Thus a single plot of Hyetogram for a day will yield a number of individual storms of various durations. Tables similar to Table 2.1 have to be prepared one each for every such individual storm for all Hyetograms of past several years for a location.

Table 2.1 shows the processed data for a single segment of a typical Hyetogram.

Table 2.1 : Typical Conversion of a Hyetogram Segment into individual Storms

Duration (min)	Cumulative Rainfall (mm)	Rainfall in successive 5 min (mm)	Continuous Time Intervals (min)	Maximum Rainfall in Continuous Time Intervals	
				mm	mm/hr
5	1.2	1.2	5	3.2	38.4
10	4.4	3.2	10	5.1	30.6
15	6.3	1.9	15	6.3	25.2
20	7.2	0.9	20	8.7	26.1
25	9.9	2.7	25	10.0	24.0
30	11.2	1.3	30	11.2	22.4
35	12.1	0.9	35	12.1	20.7
40	12.9	0.8	40	12.9	19.4
45	13.6	0.7	45	13.6	18.1
50	13.9	0.3	50	13.9	16.7
55	14.0	0.1	55	14.0	15.3
60	14.2	0.2	60	14.2	14.2

It is seen from Table 2.1 that a single storm of 60 min duration has been further subdivided in the last two columns of the table into 12 individual storms of 5 min to 60 min durations with their specific rainfall intensities expressed in mm/hr. The past data of Hyetograms will thus yield several such individual storms of various durations and intensities.

Even if the past data consists of records of either 15 min rainfall or hourly rainfall, similar tables can be prepared. Table 2.2 shows a typical example of conversion of a 4 hr rainfall stretch into individual storms of 1 to 4 hr durations and their specific intensities (mm/hr).

Table 2.2 : Conversion of a Typical 4 hr storm

Duration (hr)	Cumulative Rainfall (mm)	Rainfall in successive 1 hr (mm)	Continuous Time Intervals (hr)	Maximum Rainfall in Continuous Time Intervals	
				mm	mm/hr
1	15	15	1	20	20.00
2	35	20	2	35	17.50
3	45	10	3	45	15.00
4	53	8	4	53	13.25

Thus, with the formation of Tables similar to 2.1 and 2.2, we have several individual storms with their durations and intensities as shown in the last two columns of the tables. It is now necessary to prepare a two-way frequency table by counting them according to their durations and intensities. Tables 2.3 (a) and 2.3 (b) shows the number of storms of stated durations and stated intensities or more for a typical meteorological station based on past hourly rainfall data.

Table 2.3 (a) : Records of Rainfall showing Number of Storms of Stated Durations and Stated Intensities or more

Duration (Hours)	Intensity (mm/hour)																	
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95
1	10921	1686	852	505	318	211	134	92	62	36	23	17	11	9	8	6	5	5	5
2	4849	1162	571	307	173	108	61	40	25	16	10	7	7	5	4	4	3	3	2
3	2686	862	382	198	109	60	35	18	12	7	6	5	5	3	3	2	2	3	1
4	1755	658	288	135	67	38	15	11	7	5	3	3	3	3	2	1	1	1	1
5	1225	531	218	96	46	19	10	6	4	4	3	3	1	1	1	1	1	1	1
6	903	432	161	68	28	10	7	4	4	3	1	1	1	1	1	1	1	1	1
7	706	353	128	55	18	10	5	4	3	1	1	1	1	1	1	1	1	1	1
8	555	294	102	38	13	6	4	2	1	1	1	1	1	1	1	1	1	1	1
9	438	255	87	26	9	5	4	1	1	1	1	1	1	1	1	1	1	0	0
10	344	211	60	18	7	4	2	1	1	1	1	1	1	1	1	1	0	0	0
11	270	174	46	14	5	4	2	1	1	1	1	1	1	1	1	1	0	0	0
12	221	134	36	10	4	3	1	1	1	1	1	1	1	1	1	0	0	0	0
13	176	103	26	7	3	2	1	1	1	1	1	1	1	1	0	0	0	0	0
14	134	84	22	6	2	1	1	1	1	1	1	1	1	0	0	0	0	0	0
15	107	59	17	3	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0
16	82	48	14	3	2	1	1	1	1	1	1	1	0	0	0	0	0	0	0
17	67	39	11	3	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
18	50	31	10	2	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
19	41	25	6	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
20	35	20	6	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0
21	23	13	3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
22	17	10	3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
23	12	9	3	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0
24	9	7	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2.3 (b) : Records of Rainfall showing Number of Storms of Stated Durations and Stated Intensities or more

Duration (Hours)	Intensity (mm/hour)																		
	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190
1	2	2	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1	1	1
2	2	2	2	2	2	2	1	1	1	1	1	0	0	0	0	0	0	0	0
3	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
4	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Intensities and durations of individual storms need to be now related to their frequencies of occurrence (Return Periods).

For example, if the data represented by Tables 2.3 (a) and 2.3 (b) is for past 38 years, Intensities and Durations for storms with frequencies of 2 in 1 year, 1 in 1 year, 1 in 2 years, 1 in 5 years, 1 in 10 years, 1 in 15 years, and 1 in 30years can now be interpolated from the above mentioned tables as follows:

The storms with frequencies listed above will occur 76, 38, 19, 7.6, 3.8, 2.53 and 1.27 times in the above frequency tables during the period of 38 years. As an example, considering the frequency of 2 times in 1 year, intensities of rainfall were interpolated for various durations of storm from 60 min (1 hr) to 1440 min (24 hrs), referring to Table 2.3 (a) it is seen that the storm with frequency of 2 times in a year will occur 76 times in 38 years and if it has a duration of 60 min (1 hr), its intensity lies between the range of 40 min/hr (92 times) to 45 min/hr (62 times). The magnitude of the actual intensity of storm (occurring 76 times) can be linearly interpolated between the range of 40 – 45 mm/hr. This is equal to 42.67 mm/hr. Similarly, the intensities of rainfall for the 2 times in a year frequency for durations upto 1440 min (24 hr) can be interpolated wherever the occurrence of the storm is 76 times. This exercise can be repeated for other frequencies of occurrence. Conversely the exercise of interpolating the durations of storms for Intensity ranges of 5 mm/hr to 190 mm/hr was carried out. Thus magnitudes of rainfall intensities for various durations of storms with various frequencies of occurrence ranging between 2 times in a year to once in 30 years were generated. Tables 2.4 (a) and 2.4 (b) show the interpolated intensities based on Tables 2.3 (a) and 2.3 (b).

Table 2.4 (a) : Interpolated Intensities of Rainfall

2 in 1		1 in 1		1 in 2		1 in 5		1 in 10		1 in 15		1 in 30	
Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr	Duration minutes	Intensity mm/hr
60	42.67	60	49.61	60	58.33	60	76.00	60	97.00	60	99.12	60	157.40
78	40.00	99	45.00	78	55.00	66	75.00	84	85.00	109	95.00	89	130.00
108	35.00	120	40.67	111	50.00	81	70.00	96	95.00	120	92.35	120	127.40
120	33.40	125	40.00	120	48.34	102	60.00	120	81.00	148	90.00	149	95.00
160	30.00	173	35.00	148	45.00	111	65.00	126	80.00	148	85.00	180	92.40
180	28.37	180	34.40	177	40.00	120	59.00	132	75.00	164	80.00	209	80.00
227	25.00	240	30.00	180	39.70	176	50.00	156	70.00	180	77.35	240	77.40
240	23.45	300	26.48	228	35.00	180	49.40	180	81.00	208	75.00	269	75.00
300	22.00	327	25.00	240	34.13	192	55.00	216	65.00	240	72.35	284	70.00
343	20.00	360	23.75	300	30.00	233	45.00	216	60.00	254	65.00	300	63.70
360	19.57	420	22.29	360	27.50	240	44.25	224	55.00	300	61.18	344	60.00
420	18.56	480	20.00	414	25.00	281	40.00	240	68.00	314	55.00	360	53.70
480	17.03	540	19.01	420	24.86	300	38.00	300	51.00	360	51.18	404	50.00
540	15.90	600	17.62	480	23.80	348	35.00	312	50.00	374	50.00	420	48.70
564	15.00	660	17.62	540	22.05	360	34.00	360	45.00	420	46.18	464	45.00
600	14.47	708	15.00	593	20.00	420	32.40	372	45.00	434	45.00	480	42.40
660	13.83	720	14.89	600	19.88	456	30.00	420	41.00	464	40.00	509	40.00
720	12.96	780	14.22	660	19.21	480	28.85	426	40.00	480	38.68	540	38.27
780	11.75	840	13.70	720	18.26	540	26.75	480	35.50	540	37.45	600	37.40
840	10.65	900	12.50	780	16.84	582	25.00	540	35.33	584	35.00	689	35.00
859	10.00	960	11.47	840	15.93	600	24.72	546	35.00	600	33.68	720	33.70
900	8.23	1020	10.17	876	15.00	660	23.56	600	30.50	660	27.35	780	32.40
960	5.88	1027	10.00	900	14.76	720	22.00	660	30.50	720	31.18	809	30.00
984	5.00	1080	8.15	960	14.26	768	20.00	672	30.00	748	30.00	840	27.40
		1140	5.93	1020	13.57	780	19.84	720	26.00	780	27.35	989	25.00
		1170	5.00	1080	12.85	840	19.50	732	25.00	808	25.00	1020	23.70
				1140	11.58	900	18.35	780	24.00	840	24.34	1080	22.40
				1200	10.35	960	17.91	840	33.75	900	22.35	1109	20.00

Table 2.4 (b) : Interpolated Intensities of Rainfall

2 in 1		1 in 1		1 in 2		1 in 5		1 in 10		1 in 15		1 in 30	
Duration	Intensity	Duration	Intensity	Duration	Intensity	Duration	Intensity	Duration	Intensity	Duration	Intensity	Duration	Intensity
minutes	mm/hr	minutes	mm/hr	minutes	mm/hr	minutes	mm/hr	minutes	mm/hr	minutes	mm/hr	minutes	mm/hr
				1209	10.00	1020	17.13	884	20.00	960	22.35	1140	19.48
				1260	7.00	1080	16.71	900	19.71	1020	17.35	1260	18.70
				1300	5.00	1116	15.00	960	19.64	1048	20.00	1440	15.48
						1140	14.58	1020	19.50	1080	19.15		
						1200	14.43	1080	18.88	1140	18.47		
						1260	12.70	1140	17.20				
						1320	11.71	1200	17.20				
						1380	11.17	1244	15.00				
						1428	10.00	1260	14.60				
						1440	8.50	1320	14.43				
								1380	14.33				
								1440	13.20				

It is now necessary to fit the following equation to the data given in Tables 2.4 (a) and 2.4 (b)

$$\log i = -n \log \mathrm{t} + \log a \qquad (2.7)$$

For fitting a straight line to the data, plots of log i versus log t can now be produced on log - log paper one each for various frequencies of occurrence and constants 'a' and 'n' can be determined by reading intercepts on Y axis and slopes of the straight lines. A typical plot is shown in Figure 2.3 for the frequency of twice in a year.

Table 2.5 shows the values of 'a' and 'n' for various frequencies of occurrence based on above exercise.

Table 2.5 : Magnitudes of Constants 'a' and 'n'

Frequency of occurrence	'a'	'n'
2 in 1 year	731.64	0.64
1 in 1 year	1070.78	0.67
1 in 2 year	1117.38	0.65
1 in 5 year	1274.09	0.63
1 in 10 year	2208.00	0.68
1 in 15 year	2612.16	0.69
1 in 30 year	4306.26	0.75

Figure 2.4 shows IDF curves for the above data based on Table 2.5

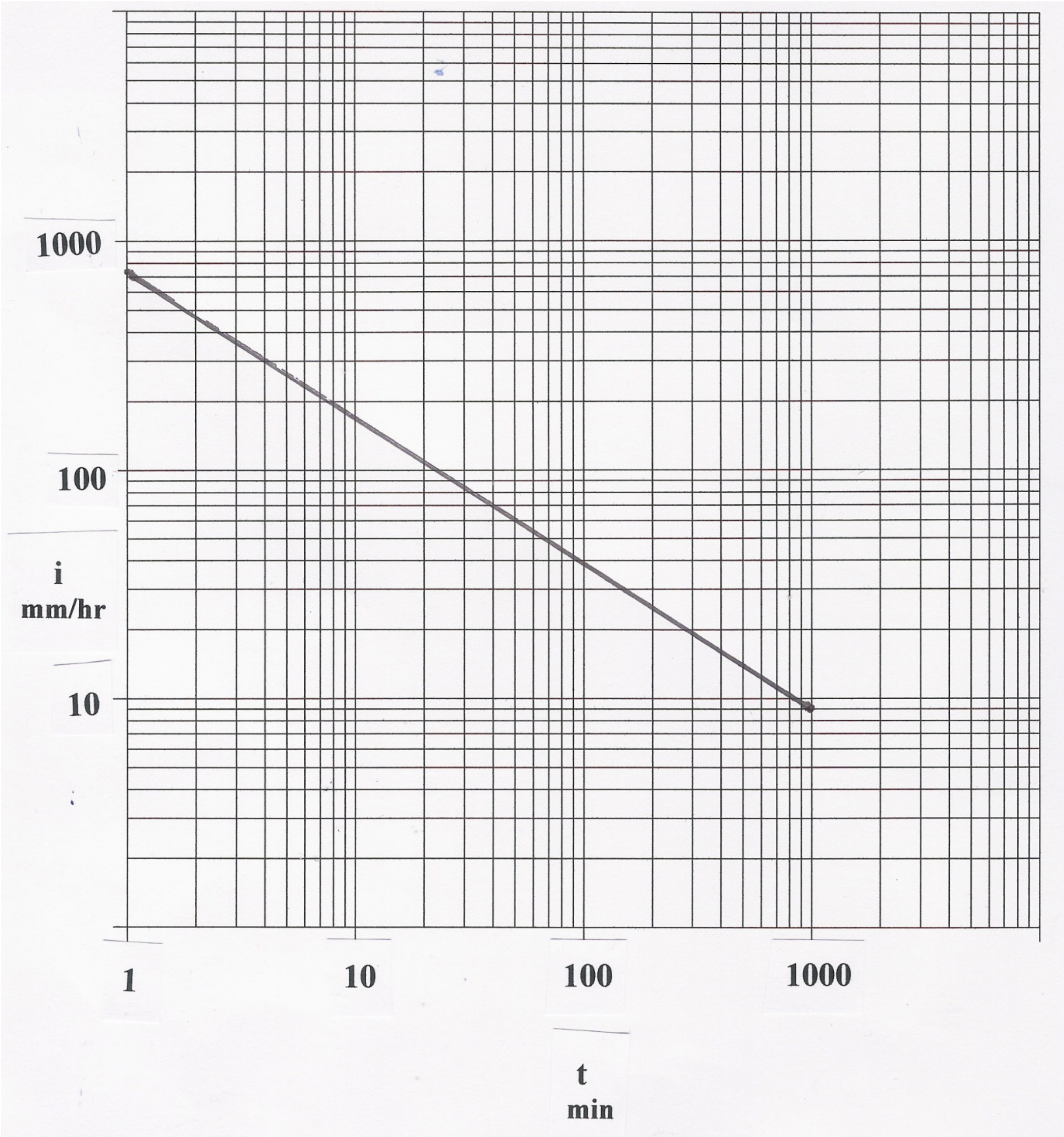

Fig 2.3 : A typical plot to determine ‘a’ and ‘n’

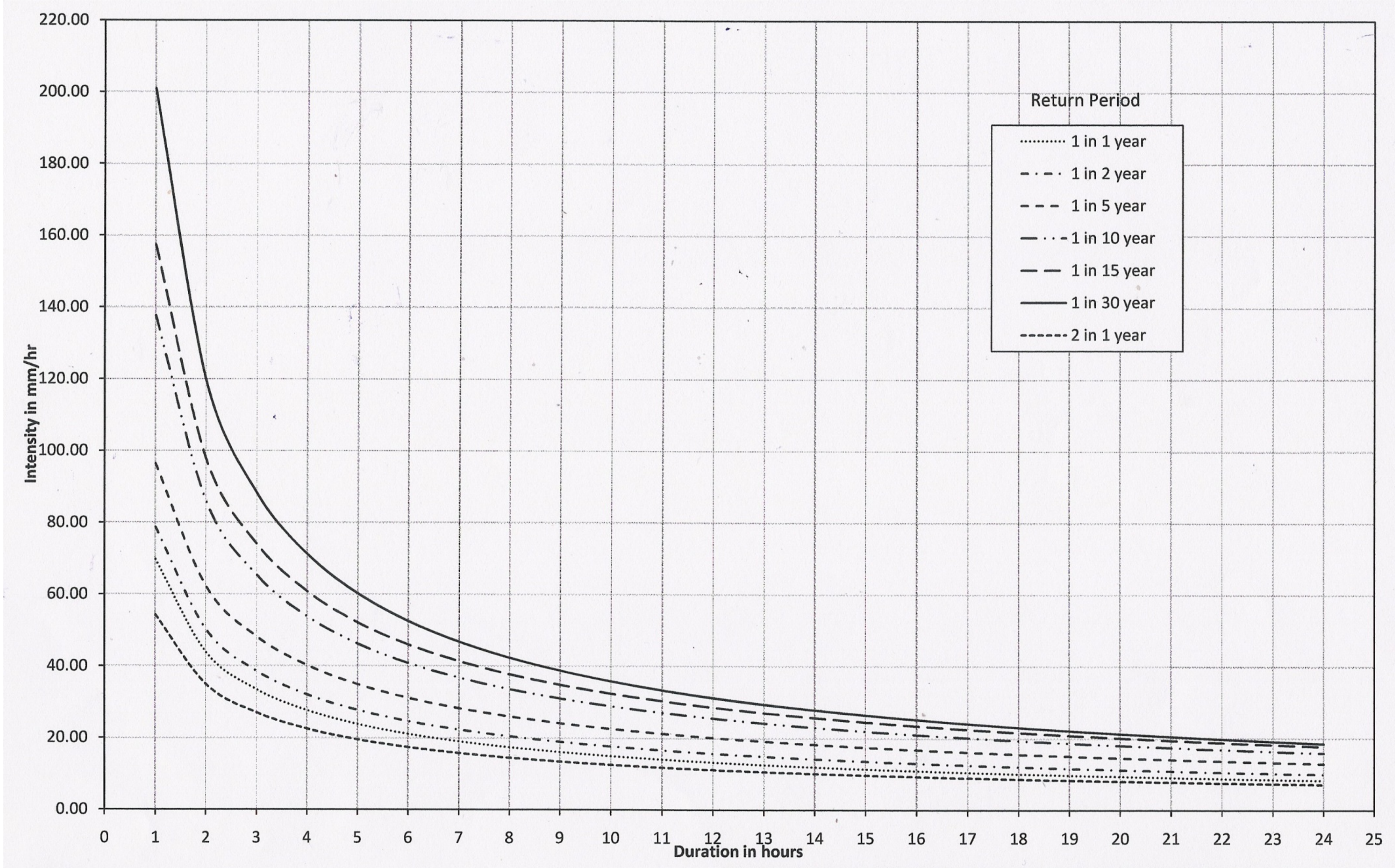

Fig. 2.4 : IDF Curves

3.0 METHOD BASED ON RELATIONSHIP 2

The relationship between intensity of rainfall and duration of the storm for a given frequency of occurrence is described by the following condition.

$$i = \frac{a}{(t+b)^n} \qquad (2.8)$$

In the method based on relationship 1 described earlier values of the intensity of rainfall 'i' and the duration of storm 't' are plotted on a log – log paper to get a plot. A straight line is fitted to the plotted points by eye judgment. Sometimes if a trial value of 'b' is added to 't' then a better fitting straight line can be obtained. Various values of 'b' can be tried till the best fitting straight line can be drawn through the points. This will lead to determination of values of a, t, and n in the above equation suitable for a given frequency of occurrence. Similar relationships can be then developed for other frequencies of occurrence. For a given location, a possibility exists that a common value of 'b' would work well for all frequencies of occurrence.

4.0 METHOD BASED ON RELATIONSHIP 3

There are two techniques available under this method. The first technique utilizes graphical fitting while the other utilizes Least Square Principle.

4.1 Graphical Fitting Method.

Based on Fair and Geyer's technique, the method uses the following relationship:

$$i = \frac{CT^m}{(t+d)^n} \qquad (2.9)$$

Where i = Intensity of Rainfall (mm/hr)

T = Frequency of occurrence (Year)

t = Duration of Storm (min)

and C, m, d and n are constants.

The above equation can be rewritten as follows:

$$i = A\,(t+d)^{-n} \qquad (2.10)$$

Where, $A = CT^m$

Equation 2.10 can be transformed as follows;

$$\log i \;= \log A - n \;\; [\log(t + d)] \qquad (2.11)$$

The data in the form of individual storms for past several years need to be processed to finally have interpolated magnitudes of intensities of rainfall for various durations of storms for various frequencies of occurrence as illustrated earlier in tables 2.4 (a) and 2.4 (b). These interpolated intensities are further used in this method.

A direct plot of ‘i’ against ‘t’ on log – log paper for various frequencies of occurrence produces curves that can be converted into straight lines through the addition of trial values of ‘d’ to the observed values of ‘t’. A simple value of ‘d’ must be found that will place the resultant values of (t + d) along a family of straight lines having the same slope for all frequencies. The slope establishes the value of ‘n’. Values of ‘A’ can then be calculated, or they can be read as ordinates at (t + d) = 1, if this point appears on the plot. To determine ‘C’ and ‘m’ the derived values, of ‘A’ are plotted on log-log paper against ‘T’ for the frequencies of occurrence studied.

Since log A = log C + m log T, the slope of the resulting straight line of best fit gives the values of ‘m’ and the value of ‘C’ is read as the ordinate at T = 1.

4.2 Method based on Least Squares Principle

The method fits following Horner’s equation as per technique illustrated by Fair and Geyer

$$i = \frac{CT^m}{(t + d)^h} \qquad (2.12)$$

Where, i = intensity of rainfall (mm/hr)

t = duration of storm (min)

T = frequency of occurrence (years)

and C, m, d and n are consonants..

It is possible to consider a range of frequencies and fit the above equation to the data with a set of common values of C, m, d and n. For other ranges of frequencies there will be different sets of constants. This way the fit is better than considering a common set of values of C, m, d and n for all frequencies together.

This method is illustrated below for the case of Mumbai where rainfall data in the form of hyetograms was collected for past 24 years from Colaba observatory and 33 years from

Santacruz observatory. Figure 2.5 shows the locations of Colaba and Santacruz the method is further illustrated for Santacruz though similar method was used for Colaba. Program ‘RAIN’ developed by the author was used in the analysis. However the analysis can be performed by using ‘EXCEL’. Individual storms from these hyetograms were identified and by using the methodology given in this Chapter in Tables 2.1 and 2.3, two way frequency tables were prepared both for Colaba and Santacruz.

Table 2.6 (a) and 2.6 (b) show the two way frequency table prepared for Santacruz.

Rainfall Intensities were than interpolated for various durations of storms for given frequencies of occurrence and Rainfall durations were interpolated for various intensities for given frequencies of occurrence and Tables similar to table 2.4 were prepared for Colaba and Santacruz. Table 2.7 is a typical table prepared for Santacruz using duration range of 5 min to 60 min for further analysis.

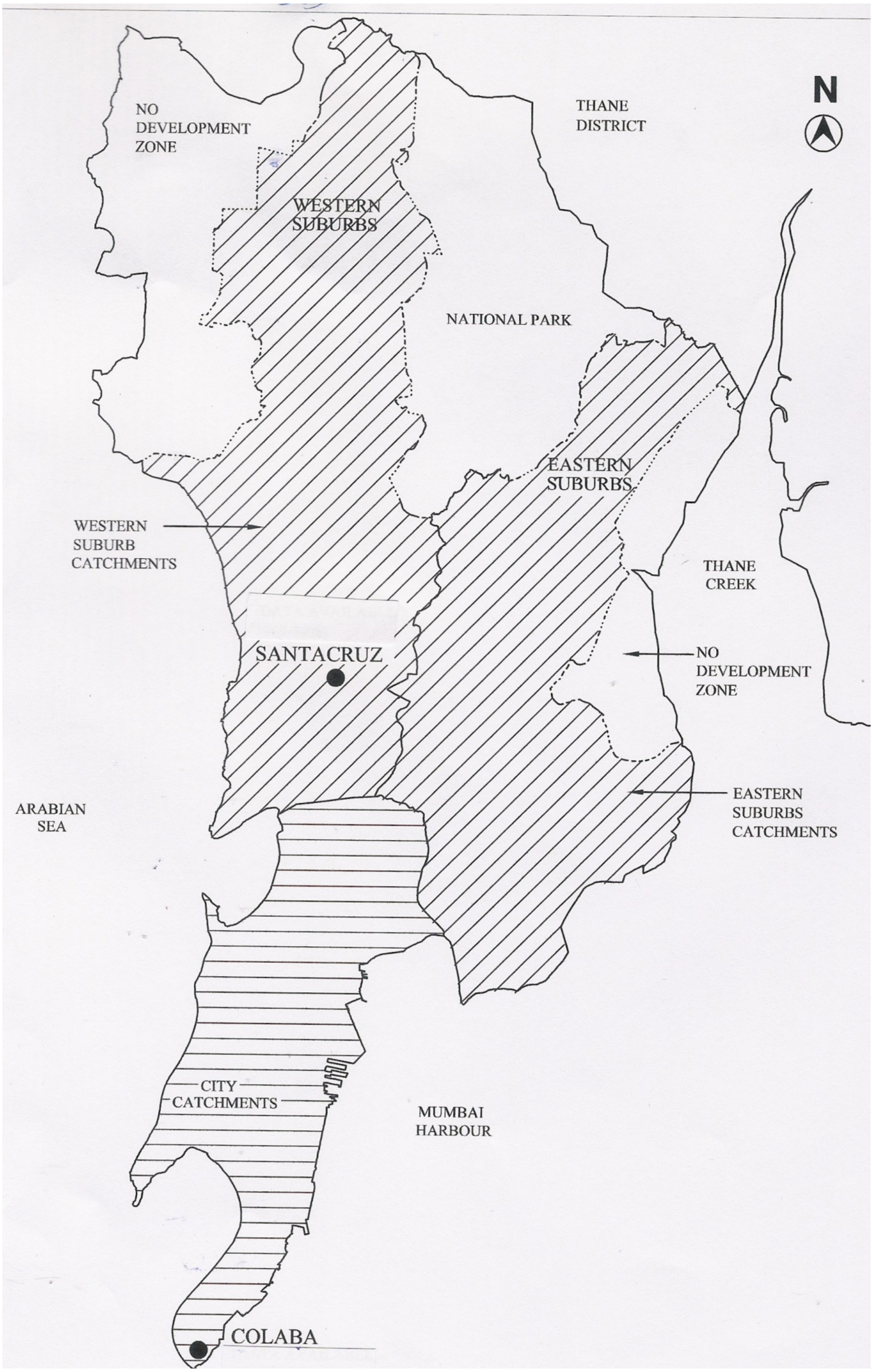

Fig 2.5 : Locations of Colaba and Santacruz.

Table 2.6(a) : Record of Intense Rainfall Showing no. of storms of stated duration and stated intensity or more for Santacruz

	Intensity (mm/hr)																	
Duration Min	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85
5	2731	2708	2450	2191	1852	1512	1346	1179	1000	821	686	550	470	389	332	275	217	159
10	2731	2663	2309	1955	1602	1249	1015	781	622	462	377	292	224	155	127	98	82	66
15	2659	2588	2140	1692	1301	910	712	513	403	293	242	190	147	104	78	51	38	20
20	2403	2315	1831	1347	1034	720	553	386	318	249	187	125	93	60	48	35	24	12
25	2293	2186	1776	1173	890	606	463	321	258	190	142	94	68	41	33	24	17	9
30	2182	2057	1621	998	745	491	373	255	193	130	96	62	42	22	17	12	9	6
35	2006	1860	1435	885	658	430	324	217	162	107	78	49	33	17	13	9	7	5
40	1831	1663	1249	772	571	370	274	178	132	84	60	35	24	12	10	6	5	4
45	1655	1466	1063	659	484	309	225	140	101	61	42	22	15	8	6	4	3	2
50	1521	1338	967	595	435	274	198	121	86	49	34	18	13	7	5	3	2	2
55	1386	1209	871	532	386	240	172	103	70	38	26	14	10	6	4	2	2	1
60	1252	1081	775	468	337	205	145	84	55	26	18	10	8	5	3	1	1	0

Table 2.6 (b) : Record of Intense Rainfall showing number of storms of stated duration and stated intensity or more for Santacruz.

	Intensity (mm/hr)																
Duration Min	90	95	100	105	110	115	120	125	130	135	140	145	150	155	160	165	170
5	149	138	112	86	77	67	37	6	0	0	0	0	0	0	0	0	0
10	58	50	39	27	22	16	9	2	0	0	0	0	0	0	0	0	0
15	18	16	12	8	7	5	5	1	0	0	0	0	0	0	0	0	0
20	8	4	4	3	3	3	3	1	0	0	0	0	0	0	0	0	0
25	6	3	3	2	3	2	2	0	0	0	0	0	0	0	0	0	0
30	4	2	2	2	2	2	1	0	0	0	0	0	0	0	0	0	0
35	3	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
40	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
45	2	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
50	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0
55	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 2.7 Interpolated intensities of Rainfall (mm/hr) for Santacruz.

Frequency months	Duration (min)											
	5	10	15	20	25	30	35	40	45	50	55	60
6	115.17	85.00	72.22	64.09	60.37	54.41	52.07	48.75	44.38	42.70	40.63	38.10
8	117.92	95.23	75.50	69.38	63.43	58.13	54.91	52.10	48.03	44.93	43.20	40.95
10	119.57	99.73	78.80	73.23	65.88	60.60	57.94	54.08	50.60	48.13	44.75	42.66
12	120.65	102.50	80.94	75.91	70.00	62.25	60.00	55.91	52.25	50.31	47.09	43.79
15	121.71	105.60	83.00	78.91	73.67	63.90	62.06	58.91	53.90	52.38	49.83	44.93
18	122.42	110.00	84.38	80.83	76.43	65.00	63.44	60.83	55.00	53.75	51.67	47.50
21	122.93	112.62	87.86	82.14	78.67	68.14	64.42	62.14	57.24	54.73	52.98	49.46
24	123.31	114.58	93.75	83.13	80.31	70.50	65.63	63.13	58.93	56.50	53.96	50.94
27	123.60	115.95	96.67	83.89	81.46	72.33	67.92	63.89	60.24	58.33	54.72	52.08
30	123.84	117.00	98.50	84.50	82.38	73.80	69.75	64.50	61.29	59.80	56.00	53.00
33	124.03	117.86	100.00	85.00	83.13	75.00	71.25	65.00	62.14	60.83	57.50	53.75
36	124.19	118.57	101.25	86.25	83.75	76.67	72.50	67.50	62.86	61.67	58.75	54.38
39	124.33	119.18	102.31	87.31	84.28	78.08	73.56	69.62	63.46	62.37	59.81	54.90
42	124.45	119.69	103.21	88.21	84.73	79.29	74.46	70.71	63.98	62.98	60.71	56.43
45	124.55	120.14	104.00	89.00	85.33	80.33	75.50	71.50	64.43	63.50	61.50	58.00
48	124.64	120.54	104.69	89.69	86.25	81.25	76.88	72.19	64.82	63.96	62.19	59.38
60	124.90	121.71	111.00	91.75	89.00	84.00	81.00	74.25	68.50	66.00	64.25	62.33
72	125.42	122.50	113.75	93.13	90.83	86.25	83.75	77.50	71.25	68.75	66.25	64.17
96	126.56	123.48	121.09	94.84	93.13	89.69	87.19	84.38	74.69	72.19	69.69	67.19
120	127.25	124.07	122.13	103.50	94.50	91.75	89.25	86.75	78.50	74.25	71.75	69.25

As earlier explained in para 4.1 under the method based on graphical fitting, the following equation is valid

$$i = A\,(t + d)^{-n} \qquad (2.13)$$

Where, $A = CT^{m}$ (2.14)

The straight line from the equation (2.13) is as follows

$$log\left(-\frac{di}{dt}\right) = \log n - \left(\frac{1}{n}\right)\log A + \left(1 + \frac{1}{n}\right)\log i \qquad (2.15)$$

If storm intensities are recorded at uniform intervals of time, slopes $\left(-\frac{di}{dt}\right)$ of the IDF curves at i_{K+1} are closely approximated by the following relation

$$-\frac{di}{dt} = \frac{(i_k - i_{k+2})}{(t_{k+2} - t_k)} \qquad (2.16)$$

Where, the subscripts k, k+1 and k + 2 denote the sequence of the pairs of observations in the series. A better fit is obtained if data below 60 min are considered for the analysis

A slope matrix was therefore created based on equation 2.16. For example the slope i_{k+1} for a frequency of occurrence of 6 months was calculated by referring to earlier Table 2.7 and considering $i_k = 115.17$, $i_{k+2} = 72.22$, $t_{k+2} = 15$ and $t_k = 5$.

The slope $\left(\frac{i_k - i_{k+2}}{t_{k+2} - t_k}\right)$ was calculated as 4.2944 and was entered against duration 10 min and frequency of occurrence 6 months. Table 2.8 shows the table of slopes $\left(\frac{-di}{dt}\right)$

We now have to calculate the constants in the following straight line equation for various frequencies of occurrence

$$\log\left(\frac{-di}{dt}\right) = \log n - \left(\frac{1}{n}\right)\log A + \left(1 + \frac{1}{n}\right)\log i \qquad (2.15)$$

These can be calculated by the least square principle. Following tables were prepared for this purpose. Table 2.9 shows the values of $\log\left(\frac{-di}{dt}\right)$ for various frequencies of occurrence.

Table 2.10 shows log i values based on earlier table 2.7.

Table 2.8 : Slopes $\left(\frac{-di}{dt}\right)$

	Duration (mins)									
Frequency months	10	15	20	25	30	35	40	45	50	55
6	4.2944	2.0909	1.1852	0.9679	0.8301	0.5662	0.7694	0.6047	0.3750.	0.4599
8	4.2417	2.5852	1.2074	1.1250	0.8512	0.6025	0.6887	0.7168	0.4823	0.3984
10	4.0767	2.6497	1.2925	1.2631	0.7938	0.6520	0.7338	0.5947	0.5850	0.5478
12	3.9708	2.6591	1.0938	1.3659	1.0000	0.6341	0.7750	0.5597	0.5167	0.6519
15	3.8710	2.6691	0.9333	1.5009	1.1604	0.4991	0.8162	0.6534	0.4067	0.7444
18	3.8044	2.9167	0.7946	1.5833	1.2991	0.4167	0.8438	0.7083	0.3333	0.6250
21	3.5069	3.0476	0.9184	1.4000	1.4254	0.6000	0.7175	0.7411	0.4269	0.5268
24	2.9556	3.1458	1.3438	1.2625	1.4688	0.7375	0.6696	0.6625	0.4970	0.6556
27	2.6935	3.2063	1.5208	1.1556	1.3542	0.8444	0.7679	0.5556	.0.5516	0.6250
30	2.5339	3.2500	1.6125	1.0700	1.2625	0.9300	0.8464	0.4700	0.5286	0.6800
33	2.4032	3.2857	1.6875	1.0000	1.1875	1.0000	0.9107	0.4167	0.4643	0.7083
36	2.2944	3.2321	1.7500	0.9583	1.1250	0.9167	0.9643	0.5833	0.4107	0.7292
39	2.2022	3.1868	1.8029	0.9231	1.0721	0.8462	1.0096	0.7244	0.3654	0.7468
42	2.1233	3.1480	1.8482	0.8929	1.0268	0.8571	1.0485	0.7738	0.3265	0.6548
45	2.0548	3.1143	1.8667	0.8667	0.9833	0.8833	1.1071	0.8000	0.2929	0.5500
48	1.9950	3.0848	1.8438	0.8438	0.9375	0.9063	1.2054	0.8229	0.2634	0.4583
60	1.3903	2.9964	2.2000	0.7750	0.8000	0.9750	1.2500	0.8250	0.4250	0.3667
72	1.1667	2.9375	2.2917	0.6875	0.7083	0.8750	1.2500	0.8750	0.5000	0.4583
96	0.5469	2.8638	2.7969	0.5156	0.5938	0.5313	1.2500	1.2188	0.5000	0.5000
120	0.5125	2.0571	2.7625	1.1750	0.5250	0.5000	1.0750	1.2500	0.6750	0.5000

Table 2.9 : $Y = \log\left(\frac{-di}{dt}\right)$

	Duration (mins)									
Frequency months	10	15	20	25	30	35	40	45	50	55
6	0.6329	0.3203	0.0738	-0.0142	-0.0808	-0.2471	-0.1139	-0.2184	-0.4260	-0.3373
8	0.6275	0.4125	0.0819	0.0512	-0.0700	-0.2200	-0.1619	-0.1446	-0.3167	-0.3997
10	0.6103	0.4232	0.1114	0.1014	-0.1003	-0.1858	-0.1345	-0.2257	-0.2328	-0.2614
12	0.5989	0.4247	0.0389	0.1354	0.0000	-0.1979	-0.1107	-0.2521	-0.2868	-0.1858
15	0.5878	0.4264	-0.0300	0.1764	0.0646	-0.3018	-0.0882	-0.1848	-0.3908	-0.1282
18	0.5803	0.4649	-0.0998	0.1996	0.1136	-0.3802	-0.0738	-0.1498	-0.4771	-0.2041
21	0.5449	0.4840	-0.0370	0.1461	0.1539	-0.2219	-0.1442	-0.1301	-0.3697	-0.2784
24	0.4707	0.4977	0.1283	0.1012	0.1670	-0.1322	-0.1742	-0.1788	-0.3036	-0.2547
27	0.4303	0.5060	0.1821	0.0628	0.1317	-0.0734	-0.1147	-0.2553	-0.2584	-0.2041
30	0.4038	0.5119	0.2075	0.0294	0.1012	-0.0315	-0.0724	-0.3279	-0.2769	-0.1675
33	0.3808	0.5166	0.2272	0.0000	0.0746	0.0000	-0.0406	-0.3802	-0.3332	-0.1498
36	0.3607	0.5095	0.2430	-0.0185	0.0512	-0.0378	-0.0158	-0.2341	-0.3865	-0.1372
39	0.3429	0.5034	0.2560	-0.0348	0.0302	-0.0726	0.0042	-0.1400	-0.4373	-0.1268
42	0.3270	0.4980	0.2668	-0.0492	0.0115	-0.0669	0.0206	-0.1114	-0.4861	-0.1839
45	0.3128	0.4934	0.2711	-0.0621	-0.0073	-0.0539	0.0442	-0.0969	-0.5334	-0.2596
48	0.2999	0.4892	0.2657	-0.0738	-0.0280	-0.0428	0.0811	-0.0846	-0.5794	-0.3388
60	0.1431	0.4766	0.3424	-0.1107	-0.0969	-0.0110	0.0969	-0.0835	-0.3716	-0.4357
72	0.0669	0.4680	0.3602	-0.1627	-0.1498	-0.0580	0.0969	-0.0580	-0.3010	-0.3388
96	-0.2621	0.4570	0.4467	-0.2877	-0.2264	-0.2747	0.0969	0.8590	-0.3010	-0.3010
120	-0.2903	0.3133	0.4413	0.0700	-0.2798	-0.3010	0.0314	0.0969	-0.1707	-0.3010

Table 2.10 : $X = \log i$

	Duration (mins)									
Frequency (Month/s)	10	15	20	25	30	35	40	45	50	55
6	1.9294	1.8587	1.8068	1.7808	1.7357	1.7166	1.6880	1.6472	1.6305	1.6088
8	1.9788	1.8780	1.8412	1.8023	1.7644	1.7397	1.7169	1.6815	1.6526	1.6355
10	1.9988	1.8966	1.8647	1.8187	1.7825	1.7630	1.7331	1.7042	1.6825	1.6508
12	2.0107	1.9082	1.8803	1.8451	1.7942	1.7782	1.7475	1.7181	1.7017	1.6729
15	2.0237	1.9191	1.8972	1.8673	1.8055	1.7929	1.7702	1.7316	1.7191	1.6975
18	2.0414	1.9262	1.9076	1.8833	1.8129	1.8024	1.7842	1.7404	1.7304	1.7132
21	2.0516	1.9438	1.9146	1.8959	1.8334	1.8090	1.7934	1.7578	1.7383	1.7241
24	2.0591	1.9720	1.9198	1.9048	1.8482	1.8171	1.8002	1.7703	1.7521	1.7321
27	2.0643	1.9853	1.9237	1.9110	1.8594	1.8320	1.0854	1.7799	1.7659	1.7382
30	2.0682	1.9935	1.9269	1.9158	1.8681	1.8436	1.8096	1.7874	1.7767	1.7482
33	2.0714	2.0000	1.9294	1.9198	1.8751	1.8528	1.8129	1.7934	1.7842	1.7597
36	2.0740	2.0054	1.9358	1.9230	1.8846	1.8604	1.8293	1.7984	1.7901	1.7690
39	2.0762	2.0099	1.9411	1.9257	1.8925	1.8667	1.8427	1.8025	1.7950	1.7768
42	2.0781	2.0138	1.9456	1.9281	1.8992	1.8720	1.8495	1.8061	1.7992	1.7833
45	2.0797	2.0171	1.9494	1.9311	1.9049	1.8780	1.8543	1.8091	1.8028	1.7889
48	2.0811	2.0199	1.9528	1.9358	1.9098	1.8858	1.8585	1.8117	1.8059	1.7937
60	2.0854	2.0453	1.9626	1.9494	1.9243	1.9085	1.8707	1.8357	1.8196	1.8079
72	2.0882	2.0560	1.9691	1.9583	1.9358	1.9230	1.8893	1.8528	1.8373	1.8212
96	2.0916	2.0831	1.9770	1.9691	1.9528	1.9405	1.9262	1.8733	1.8585	1.8432
120	2.0937	2.0868	2.0150	1.9755	1.9626	1.9506	1.9383	1.8949	1.8707	1.8558

To find the straight line of best fit by least squares, $XY \; and \; X^2$ were calculated, Table 2.11 shows the XY values

Table 2.12 shows x^2 values for various frequencies of occurrence.

The values of sums were seperately calculated for XY and x^2 and the same were averaged out. Tables 2.13 and 2.14 show the sums and averages for XY and x^2 values for various frequencies of occurrence.

The above straight lines have to pass through the geometric means GMY and GMX of the ordinates and the abscissas respectively. The geometric means can be found out by separately summing up the values of Y and X from tables 2.9 and 2.10, averaging out the values and taking antilogs of these averages. Table 2.15 gives the sums, averages and GMX values for various frequencies of occurrence. Table 2.16 gives the sums, averages and GMY values for various frequencies of occurrence.

Table 2.11 : Values of $XY = \log i \ \log\left(\frac{-di}{dt}\right)$

	DURATION (MINS)									
Frequency (Month/s)	10	15	20	25	30	35	40	45	50	55
6	1.2212	0.5954	0.1333	-0.0252	-0.1403	-0.4241	-0.1922	-0.3598	-0.6945	-0.5427
8	1.2418	0.7747	0.1507	0.0922	-0.1234	-0.3828	-0.2780	-0.2432	-0.5233	-0.6537
10	1.2199	0.8026	0.2078	0.1845	-0.1788	-0.3275	-0.2330	-0.3847	-0.3918	-0.4315
12	1.2042	0.8105	0.0732	0.2499	0.0000	-0.3518	-0.1934	-0.4331	-0.4880	-0.3108
15	1.1896	0.8182	-0.0568	0.3293	0.1167	-0.5411	-0.1561	-0.3200	-0.6718	-0.2176
18	1.1846	0.8955	-0.1904	0.3759	0.2060	-0.6853	-0.1316	-0.2606	-0.8256	-0.3497
21	1.1180	0.9407	-0.0708	0.2770	0.2822	-0.4013	-0.2586	-0.2288	-0.8427	-0.4799
24	1.9692	0.9815	0.2463	0.1928	0.3086	-0.2403	-0.3135	-0.3166	-0.5320	-0.4412
27	0.8883	1.0046	0.3503	0.1200	0.2448	-0.1345	-0.2071	-0.4544	-0.4563	-0.3548
30	0.8351	1.0204	0.3998	0.0563	0.1891	-0.0581	-0.1310	-0.5861	-0.4920	-0.2928
33	0.7888	1.0333	0.4385	0.0000	0.1399	0.0000	-0.0736	-0.6819	-0.5945	-0.2635
36	0.7480	1.0218	0.4705	-0.0355	0.0964	-0.0703	-0.0289	-0.4210	-0.6918	-0.2427
39	0.7119	1.0117	0.4969	-0.0669	0.0572	-0.1354	0.0077	-0.2524	-0.7849	-0.2253
42	0.6796	1.0029	0.5190	-0.0949	0.0218	-0.1253	0.0380	-0.2011	-0.8746	-0.3280
45	0.6505	0.9951	0.5284	-0.1200	-0.0139	-0.1012	0.0820	-0.1753	-0.9615	-0.4645
48	0.6242	0.9882	0.5189	-0.1428	-0.0535	-0.0806	0.1808	-0.1534	-1.0464	-0.6078
60	0.2985	0.9748	0.6721	-0.2158	-0.1865	-0.0210	0.1813	-0.1534	-0.6762	-0.7878
72	0.1398	0.9622	0.7092	-0.3187	-0.2899	-0.1115	0.1831	-0.1074	-0.5531	-0.6171
96	-0.5482	0.9519	0.8831	-0.5664	-0.4421	-0.5331	1.1867	0.1609	-0.5595	-0.5549
120	-0.6078	0.6537	0.8892	0.1384	-0.5492	-0.5872	0.0609	0.1836	-0.3193	-0.5587

Table 2.12 : Values of $x^2 = \log^2 i$

	Duration (min)									
Frequency (Month/s)	10	15	20	25	30	35	40	45	50	55
6	3.7228	3.4547	3.2646	3.1714	3.0127	2.9467	2.8493	2.7131	2.6585	2.5883
8	3.9156	3.5268	3.3901	3.2482	3.1131	3.0266	2.9476	2.8274	2.7310	2.6750
10	3.9954	3.5969	3.4772	3.3078	3.1773	3.1081	3.0035	2.9042	2.8307	2.7252
12	4.0431	3.6411	3.5356	3.4045	3.2190	3.1619	3.0538	2.9519	2.8958	2.7986
15	4.0953	3.6830	3.5992	3.4868	3.2599	3.2143	3.1336	2.9985	2.9555	2.8816
18	4.1674	3.7104	3.6390	3.5467	3.2867	3.2485	3.1832	3.0289	2.9943	2.9352
21	4.2092	3.7784	3.6657	3.5943	3.3615	3.2726	3.2163	3.0897	3.0216	2.9725
24	4.2401	3.8888	3.6855	3.6283	3.4159	3.3018	3.2408	3.1341	3.0698	3.0001
27	4.2614	3.9414	3.7007	3.6518	3.4572	3.3562	3.2596	3.1680	3.1185	3.0213
30	4.2775	3.9739	3.7129	3.6704	3.4897	3.3987	3.2746	3.1947	3.1567	3.0562
33	4.2906	4.0001	3.7228	3.6855	3.5159	3.4329	3.2867	3.2163	3.1832	3.0965
36	4.3015	4.0217	3.7473	3.6980	3.5518	3.4609	3.3464	3.2342	3.2044	3.1295
39	4.3107	4.0398	3.7678	3.7085	3.5817	3.4844	3.3956	3.2491	3.2221	3.1509
42	4.3185	4.0553	3.7852	3.7175	3.6070	3.5043	3.4208	3.2619	3.2371	3.1802
45	4.3253	4.0685	3.8002	3.7293	3.6287	3.5268	3.4385	3.2728	3.2501	3.2002
48	4.3312	4.0801	3.8133	3.7473	3.6475	3.5563	3.4540	3.2824	3.2613	3.2175
60	4.3488	4.1835	3.8519	3.8002	3.7029	3.6424	3.4996	3.3698	3.3108	3.2685
72	4.3604	4.2270	3.8773	3.8348	3.7473	3.6980	3.5696	3.4329	3.3757	3.3168
96	4.3749	4.3395	3.9087	3.8773	3.8133	3.7655	3.7104	3.5091	3.4540	3.3973
120	4.3836	4.3549	4.0601	3.9024	3.8519	3.8050	3.7570	3.5906	3.4996	3.4442

Table 2.13 : Sums and averages for XY values

Frequency (Month/s)	SXY ($\sum XY$)	SXYM (Average XY)
6	-0.4289	-0.0429
8	0.0549	0.0055
10	0.4676	0.0468
12	0.5605	0.0561
15	0.4903	0.0490
18	0.2187	0.0219
21	0.5359	0.0536
24	0.8549	0.0855
27	1.0009	0.1001
30	0.9408	0.0941
33	0.7869	0.0787
36	0.8465	0.0846
39	0.8204	0.0820
42	0.6374	0.0637
45	0.4196	0.0420
48	0.1976	0.0198
60	0.0861	0.0086
72	-0.0035	-0.0003
96	-1.0216	-0.1022
120	-0.6964	-0.0696

Table 2.14 : Sums and averages for x^2

Frequency (Month/s)	SX2 ($\sum X^2$)	SX2M (Average X^2)
6	30.3821	3.0382
8	31.4014	3.1401
10	32.1262	3.2126
12	32.7052	3.2705
15	33.3077	3.3308
18	33.7404	3.3740
21	34.1818	3.4182
24	34.6051	3.4605
27	34.9362	3.4936
30	35.2054	3.5205
33	35.4306	3.5431
36	35.6956	3.5696
39	35.9167	3.5917
42	36.0877	3.6088
45	36.2404	3.6240
48	36.3907	3.6391
60	36.9785	3.6978
72	37.4397	3.7440
96	37.1499	3.8150
120	38.6492	3.8649

Table 2.15 GMX Values for various frequencies of occurrences

Frequency (Month/s)	SXXX ($\sum X$)	SXXXM (Average X)	Geometric Mean GMX
6	17.4026	1.7403	54.9865
8	17.6908	1.7691	58.7603
10	17.8948	1.7895	61.5863
12	18.0569	1.8057	63.9278
15	18.2241	1.8224	66.4373
18	18.3420	1.8342	68.2659
21	18.4619	1.8462	70.1764
24	18.5757	1.8576	72.0400
27	18.6651	1.8665	73.5381
30	18.7379	1.8738	74.7811
33	18.7987	1.8799	75.8351
36	18.8700	1.8870	77.0907
39	18.9292	1.8929	78.1487
42	18.9748	1.8975	78.9732
45	19.0154	1.9015	79.7142
48	19.0551	1.9055	80.4476
60	19.2095	1.9209	83.3580
72	19.3309	1.9331	85.7222
96	19.5153	1.9515	89.4399
120	19.6440	1.9644	92.1291

Table 2.16 : GMY Values for various frequencies of occurrence.

Frequency (Month/s)	SYYY $(\sum Y)$	SYYYM (Average Y)	Geometric Mean GMY
6	-0.4106	-0.0411	0.9098
8	-0.1399	-0.0140	0.9683
10	0.1059	0.0106	1.0247
12	1.1647	0.0165	1.0387
15	0.1314	0.0131	1.0307
18	-0.0264	-0.0026	0.9939
21	0.1477	0.0148	1.0346
24	0.3213	0.0321	1.0768
27	0.4070	0.0407	1.0982
30	0.3776	0.0378	1.0908
33	0.2955	0.0295	1.0704
36	0.3346	0.0335	0.0801
39	0.3252	0.0325	1.0778
42	0.2263	0.0226	1.0535
45	0.1082	0.0108	1.0252
48	-0.0114	-0.0011	0.9974
60	-0.0504	-0.0050	0.9885
72	-0.0763	-0.0076	0.9826
96	-0.5665	-0.0566	0.8777
120	-0.3900	-0.0390	0.9141

The normal equations of straight lines of best fit take the following forms.

$$na + b\sum X - \sum Y = 0 \qquad (2.17)$$

$$a\sum X + b\sum X^2 - \sum XY = 0 \qquad (2.18)$$

Where $a = (\log n) - \left(\frac{1}{n}\right)(\log A) \qquad (2.19)$

And $b = \left(1 + \frac{1}{n}\right) \qquad (2.20)$

The range of frequencies of occurrence which lie between 6 months to 120 months were divided into five groups as follows:

Group 1 : 6 months, 8 months, 10 months, 12 months

Group 2 : 15 months, 18 months, 21 months, 24 months

Group 3 : 27 months, 30 months, 33 months, 36 months

Group 4 : 39 months, 42 months, 45 months. 48 months

Group 5 : 60 months, 72 months, 96 months, 120 months.

Within each of the above five groups, the pairs of equations 2.17 and 2.18 were solved to evolve values of ‘a’ and ‘b’, for each of the four frequencies of occurrence in that group. Since ‘n’ has to have a unique value for each of the above five groups of frequencies, averages of four values ‘b’ for each group of frequencies were considered and specific values of ‘n’ for the five groups of frequencies were computed based on their average ‘b’ values. Table 2.17 gives the specific values of ‘n’ for the five groups of frequencies.

Table 2.17 : Values of ‘n’ for groups of frequencies

Average ‘b’	Group	n'
2.7825	I	0.5609
2.6639	II	0.6011
2.4815	III	0.6754
2.5552	IV	0.6433
1.7008	V	1.4273

The intensity – duration – frequency relationships now are as follows for five groups of frequencies

$$i = \frac{A_1}{(t + d_1)^{0.561}} \quad for\ Group\ I \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.21)$$

$$i = \frac{A_2}{(t + d_2)^{0.601}} \quad for\ Group\ II \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.22)$$

$$i = \frac{A_3}{(t + d_3)^{0.675}} \quad for\ Group\ III \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.23)$$

$$i = \frac{A_4}{(t + d_4)^{0.643}} \quad for\ Group\ IV \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.24)$$

$$i = \frac{A_5}{(t + d_5)^{1.427}} \quad for\ Group\ V \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2.25)$$

The values of A1 to A5 and d1 to d5 are still to be found out.

The straight lines of slopes average ‘b’ must pass through the intersections of the geometric means M_y and M_x of log (-di/dt) and log I respectively.

The intercept a = $(\log n) - \left(\frac{1}{n}\right)(\log A)$ was therefore determined for each frequency. With 'n' fixed for each group of frequencies the value of 'a' is given by the slope.

$$b = \left(\frac{\log GMY - a}{\log GMX - \log 1.0}\right) \qquad (2.26)$$

$$a = (\log GMY - b \log GMX) \qquad (2.27)$$

Thus 'a' for each frequency was computed for example, for the first group of frequencies. values of average b, log GMY and log GMX are as given in table 2.18 were considered. Values of GMX and GMY are taken from tables 2.15 and 2.16

Table 2.18 : Average 'b' $\log GMY$ and $\log GMX$ for Group I frequencies

Frequency Months	Average 'b'	Log GMY	Log GMX
6	2.7825	-0.0411	1.7403
8	2.7825	-0.0140	1.7691
10	2.7825	0.0106	1.7895
12	2.7825	0.0165	1.8057

Table 2.19 gives the computed 'a' values for this group, based on equation 2.27.

Table 2.19 : Computation of Value 'a'.

Frequency Months	a' Value
6	-4.8835
8	-4.9365
10	-4.9687
12	-5.0079

Further values of ‘A’ were computed using the following relationship.

$$a = \log n - \left(\frac{1}{n}\right) \log A \qquad (2.28)$$

or $$\log A = n\,(\log n - a) \qquad (2.29)$$

Table 2.20 gives the values of ‘A’ for the first group of frequencies by considering n = 0.561 for this group as per table 2.17

Table 2.20 : Computation of Value ‘A’

Frequency Months	‘A' Value
6	396.7084
8	424.8954
10	442.9350
12	465.9497

Computations similar to tables 2.18, 2.19 and 2.20 were carried out for the other groups of frequencies. The values of ‘A’ for all groups are shown in table 2.21.

Table 2.21 : Values of ‘A’ for all groups of frequencies

Group	Frequency (Months)	‘A' Value
I	6	396.7084
	8	424.8954
	10	442.9350
	12	465.9447
II	15	598.5911
	18	638.9988
	21	651.9657
	24	663.7630
III	27	965.0524
	30	997.0842
	33	1033.8530
	36	1056.2543
IV	39	925.5026
	42	955.4940
	45	987.3933
	48	1020.2864

Group	Frequency (Months)	'A' Value
V	60	77685.0733
	72	83852.4238
	96	109201.1920
	120	110729.3880

To find the values of 'C' and 'n' the relationship A = CT^m can be rewritten as :

$$\log A = \log C + \text{m} \log T \qquad (2.30)$$

Computations can proceed to fit a straight line as per table 2.22 shown for group I.

Table 2.22 : Computation to fit a straight line

T (Months)	Log T (x)	A	Log A (y)	Log^2T (x^2)	Log T Log A (yx)	Calculated A = CT^m
6	0.7782	396.7084	2.5985	0.6055	2.0221	396.82
8	0.9031	424.8954	2.6283	0.8156	2.3736	423.62
10	1.0000	442.9350	2.6464	1.0000	2.6464	445.65
12	1.0792	465.9447	2.6684	1.1647	2.8797	464.50
ums	$\sum x$ 3.7605	1730.4835	$\sum y$ 10.5416	$\sum x^2$ 3.5858	$\sum xy$ 9.9218	
Means	0.9401	432.6209	2.6354	0.8965	2.4804	

The normal equations for the straight line of best fit are.

$$\text{na}' + b' \sum x - \sum y = 0 \qquad (2.31)$$

$$a' \sum x + b' \sum x^2 - \sum y\, x = 0 \qquad (2.32)$$

For the first group of frequencies these can be rewritten as

$$4a' + 3.7605\, b' - 10.5416 = 0 \qquad (2.33)$$

$$3.7605a' + 3.5868\, b' - 9.9218 = 0 \qquad (2.34)$$

The equations were solved to yield values of a' and b'.

$$b' = m \; and \; a' = \log c$$

Thus for the first group of frequencies the values of 'm' and 'C' were obtained. Similar computations were undertaken to yield values of 'm' and 'C' for other groups of frequencies.

Table 2.23 gives the values of ‘b’ and ‘C’ obtained for all groups.

Table 2.23 : Values of ‘m’ and ‘C’

Group	frequency months	C	m
I	6	264.12	0.2272
	8		
	10		
	12		
II	15	338.06	0.2149
	18		
	21		
	24		
III	27	335.24	0.3209
	30		
	33		
	36		
IV	39	165.39	0.4697
	42		
	45		
	48		
V	60	7606.12	0.5680
	72		
	96		
	120		

Using the above values of ‘C’ & ‘m’ calculated ‘A’ values have been computed and entered into the last column of earlier table 2.22.

To complete the values of ‘d’ for all frequency groups, following procedure was adopted.

The relationship $i = A\,(t + d)^{-n}$ can be written in a straight line form as follows:

$$\left(\frac{A}{i}\right)^{1/n} = d + t \ = y \qquad (2.35)$$

The coefficient of ‘t’ or the slope of the line is fixed at 1.0 and the line must pass through the intersection of the means Mx and My of the coordinates $y = \left(\frac{A}{i}\right)^{1/n}$ $and\ x = t$ respectively.

The slope $= 1.0 = \frac{(My-d)}{(Mx-o)}$ (2.36)

And therefore $d = My - Mx$ (2.37)

Table 2.24 shows observed and calculated values of rainfall intensities for Group I frequencies, 'A' calculated have been taken from table 2.22. 'i' observed values have been taken from table 2.7.

Table 2.24 : Observed and calculated values of rainfall Intensities

Frequency Months	x = t (min)	i (observed) (mm)	A = CT^m (Calculated)	d + t = y y = $(A/i)^{1/n}$
6	5	115.17	396.82	9.08
8	5	117.92	423.62	9.78
10	5	119.57	445.65	10.44
12	5	120.65	464.50	11.06
6	10	85.00	396.82	15.60
8	10	95.23	423.62	14.31
10	10	99.73	445.65	14.45
12	10	102.50	464.50	14.79
6	15	72.22	396.82	20.86
8	15	75.50	423.62	21.65
10	15	78.80	445.65	21.96
12	15	80.94	464.50	22.54
6	20	64.09	396.82	25.81
8	20	69.38	423.62	25.18
10	20	73.23	445.65	25.03
12	20	75.91	464.50	25.27
6	25	60.37	396.82	28.71
8	25	63.43	423.62	29.54
10	25	65.88	445.65	30.22
12	25	70.00	464.50	29.20
6	30	54.41	396.82	34.50
8	30	58.13	423.62	34.52
10	30	60.60	445.65	35.67
12	30	62.25	464.50	36.00
6	35	52.07	396.82	37.38
8	35	54.91	423.62	38.20
10	35	57.94	445.65	38.00
12	35	60.00	464.50	38.44
6	40	48.75	396.82	42.03

Frequency Months	x = t (min)	i (observed) (mm)	A = CT^m (Calculated)	d + t = y y = $(A/i)^{1/n}$
8	40	52.10	423.62	41.95
10	40	54.08	445.65	42.97
12	40	55.91	464.50	43.60
6	45	44.38	396.82	49.71
8	45	48.03	423.62	48.51
10	45	50.60	445.65	48.38
12	45	52.25	464.50	49.19
6	50	42.70	396.82	53.23
8	50	44.93	423.62	54.62
10	50	48.13	445.65	52.88
12	50	50.13	464.50	52.62
6	55	40.63	396.82	58.18
8	55	43.20	423.62	58.58
10	55	44.75	445.65	60.22
12	55	47.08	464.50	59.22
6	60	38.10	396.82	65.22
8	60	40.75	423.62	64.45
10	60	42.66	445.65	65.60
12	60	43.79	464.50	67.39
Sum	$\sum t = 1560.00$		Sum	$\sum y$ = 1776.15
Geometric. Mean	Mx = 32.50		Geometric. Mean	My = 37.00

Therefore

'd' = My – Mx = 37.0 – 32.5 = 4.5

This applies to the first group of frequencies of 6, 8, 10 and 12 months. Similar computations were carried out for the other groups of frequencies. The values of 'd' for all groups of frequencies are given in Table 2.25.

Table 2.25 : Values of 'd' for various groups of frequencies

Frequencies Group	Value of 'd'
I	4.50
II	10.75
III	16.99
IV	19.44
V	101.97

The IDF relationships evolved are summarized below

Group I

Frequency Range 6 months to 1 year

$$i = \frac{264.12\, T^{0.2272}}{(t + 4.50)^{0.5609}} \qquad (2.38)$$

Group II : Frequency Range 1.25 years to 2.0 years

$$i = \frac{338.06\ T^{0.2149}}{(t + 10.75)^{0.6011}} \qquad (2.39)$$

Group III : Frequency Range 2.25 years to 3.0 years

$$i = \frac{335.24\, T^{0.3209}}{(t + 16.99)^{0.6754}} \qquad (2.40)$$

Group IV : Frequency Range 3.25 years to 4.0 years

$$i = \frac{165.39\ T^{0.4697}}{(t + 19.44)^{0.6433}} \qquad (2.41)$$

Group V : Frequency Range 5.0 years to 10.0 years

$$i = \frac{7606.12\, T^{0.5680}}{(t + 101.97)^{1.4273}} \qquad (2.42)$$

Where in all above equations,

i = intensity of rainfall in mm/hr

T = frequency in months

t = duration of storm in min.

4.2.1 Goodness of Fit

Goodness of fit was manually observed by comparing the observed values of intensity of rainfall 'i' in the third column of table 2.24 and calculated values of intensity 'i' based on the IDF relationship equation 2.38 for the Group I frequency range of 6 months to 12 months. Similar comparisons were also made for other groups of frequencies. The comparisons showed that the observed intensities of rainfall more or less matched with the calculated intensities of rainfall using the above IDF relationships.

5.0 METHOD BASED ONANNUAL MAXIMA

It is necessary to have magnitudes of yearly maximum rainfall depths corresponding to storm durations of say 1 to 24 hrs for all past years for which data is available. One has to go through hourly magnitudes of rainfall for each past year and identify the maximum rainfall in continuous 1 hr duration to obtain rainfall depths and arrange them in a decreasing order of magnitudes. The exercise has to be repeated for other continuous durations such as 2 hr, 4 hr, 8 hr and 24 hr. Table 2.26 shows the 38 year data for a typical meteorological station arranged as explained above.

Table 2.26 : Annual Maximum Rainfall Data for 38 years

Rank	Rainfall Depth in mm					
	Duration in hours					
m	1	2	4	8	12	24
1	190.30	290.50	481.20	731.10	865.70	944.21
2	153.00	250.00	296.00	302.00	303.10	305.30
3	94.00	179.50	273.70	295.20	297.20	376.60
4	93.00	174.00	211.00	272.00	332.70	368.30
5	93.00	151.50	195.70	204.50	234.70	303.50
6	92.50	125.00	162.90	242.20	310.10	350.30
7	80.00	121.00	161.40	177.00	197.60	249.40
8	68.90	103.00	160.00	256.80	297.00	379.50
9	67.50	101.00	158.00	217.00	248.50	312.30
10	63.70	97.30	143.70	149.30	156.50	195.50
11	63.50	91.90	143.00	191.30	214.40	264.70
12	60.80	91.80	133.70	162.50	180.00	214.40
13	58.10	88.00	122.00	143.00	155.30	189.90
14	57.50	87.30	118.90	160.00	181.40	292.60
15	57.30	87.00	117.00	174.30	228.70	330.60
16	55.30	83.00	116.80	134.60	135.50	208.70
17	54.00	83.00	111.10	146.00	172.00	246.90
18	52.00	80.00	110.30	166.70	209.30	227.20
19	51.00	76.80	110.10	129.20	159.50	201.10
20	48.00	76.00	105.50	174.20	226.00	325.10
21	47.00	74.00	104.70	133.80	158.40	201.60
22	45.90	73.00	102.30	122.00	125.00	183.80
23	45.50	71.60	101.90	138.80	144.10	195.50
24	45.00	71.00	101.00	129.40	138.70	177.20
25	45.00	69.10	101.00	115.50	133.90	194.20
26	43.80	68.30	100.70	122.30	145.80	251.00
27	43.50	67.00	100.30	108.50	118.70	165.60
28	43.50	66.00	99.00	99.20	109.10	181.90
29	43.10	64.20	97.00	161.50	186.00	225.20
30	43.00	60.50	96.00	107.80	145.80	163.00
31	43.00	57.60	86.80	105.10	143.00	194.90
32	42.50	57.20	83.10	122.00	124.50	193.00
33	41.00	56.80	81.70	124.70	140.90	163.00
34	40.30	53.70	70.80	105.20	129.70	162.30
35	36.70	51.00	65.00	86.70	91.20	134.60
36	36.00	49.90	59.30	77.20	100.80	162.40
37	27.00	42.70	58.50	102.10	122.50	155.90
38	25.20	30.20	46.50	66.60	66.69	73.30

The data series thus obtained are then fitted with a probability density function. The extreme value Gumbel Type I distribution is commonly used for rainfall analysis for a given rainfall duration 't_d'. The extreme value type I distribution for annul maximum rainfall depth is expressed by the following equation:

$$P_T = P_M + KS \qquad (2.43)$$

Where, P_T = rainfall depth for specified frequency of occurrence 'T'

P_M = mean of annual maximum depth

S = Standard deviation of annual maximum depths

And K = frequency factor

$$K = \left(\frac{\sqrt{6}}{3.14}\right)(0.5772 + \ log_e)\left[log_e\left(\frac{T}{T-1}\right)\right] \qquad (2.44)$$

The method is applied for rainfall analysis of the data shown in Table 2.26. The mean and standard deviation values are computed and are presented in Table 2.27.

Table 2.27 : Values of mean and standard deviations of rainfall depths

Duration (hr)	1	2	4	8	12	24
Mean (mm)	61.64	94.58	133.47	172.24	199.14	255.00
Standard deviation (mm)	31.52	52.46	77.37	108.65	127.50	133.56

Values of K are computed for various frequencies of occurrence and are presented in Table 2.28

Table 2.28 : Values of K for various frequencies of occurrence

Frequency of occurrence	1 in 2 years	1 in 5 years	1 in 10 years	1 in 15 years	1 in 20 years	1 in 30 years	1 in 50 years	1 in 100 years
K	-0.16	0.72	1.31	1.64	1.87	2.19	2.59	3.14

Rainfall depths are calculated using equation 2.43 and using proper K value for various frequencies of occurrence for various durations. The depths are converted to rainfall intensities by dividing the rainfall depths (mm) by durations (hr). Thus sets of values of rainfall intensities are generated for corresponding sets of durations and it is then possible to draw IDF Curves using the above sets of values. Figure 2.6 shows the IDF Curves based on the above analysis.

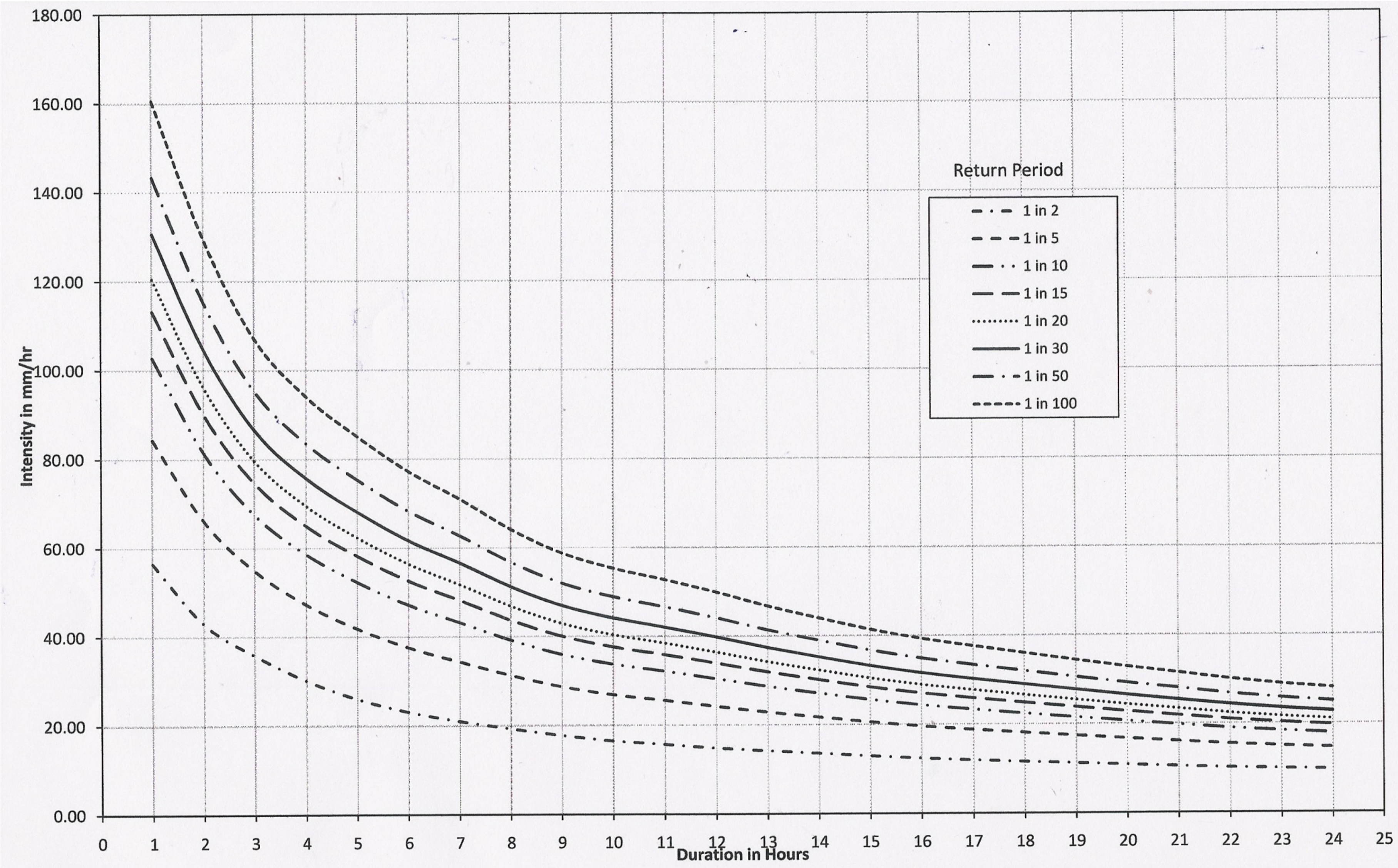

Fig 2.6 : IDF Curves based on Annual Maximum Method

CHAPTER 3 : CHICAGO CURVES

1.0 IDF Curves indicate the average rainfall intensities over a given duration of the storm for a given frequency of occurrence. They are suitable for use with the Rational Method of design of storm sewers undertaken either manually or with the help of EXCEL..

In a realistic situation, the intensity of rainfall over the duration of the storm is not constant but varies. There are a number of methods to account for this variation. One of the favourite methods to recognize the variation of the intensity of rainfall over the duration of a storm is to use Chicago Curves. They are named after the city in USA where they were first used in design. The concept of Chicago Curves can be used only in a sophisticated computerized design of Storm Water Drainage System under dynamic conditions. It is necessary to have access to commercial software for use in this design exercise.

A typical Chicago Curve assumes that the rainfall intensity initially increases, reaches the peak and then decreases over the duration of the storm but the total amount of rainfall over the duration of the storm equals the total rainfall with constant average intensity shown by the IDF curve for the same duration of the storm for a given frequency of occurrence.

It is necessary to develop IDF curves in the first step using the method based on Relationship 2 illustrated in para 3.0 in Chapter 2. Sets of values for constants ‘a’, ‘b’ and ‘n’ for various frequencies of occurrence then are available for use as input to commercial software which automatically generates Chicago Curves.

2.0 Alternately, Chicago Curves can be developed by using the following equation which defines them:

$$i = F(t) = \frac{a\,[(1-c)t+b]}{(2t+b^{1+c}} \qquad (3.1)$$

$$i = F(-t)\ for \quad -\frac{td}{2} \le t \le 0 \qquad (3.2)$$

Where, i is the intensity of rainfall (mm/hr)

‘t_d’ is the duration of rainfall (min)

‘t’ in the time (min)

and a, b, and ‘C’ are constants in the corresponding IDF curve for a given frequency of occurrence. Figure 3.1 shows a typical Chicago Curve for a location.

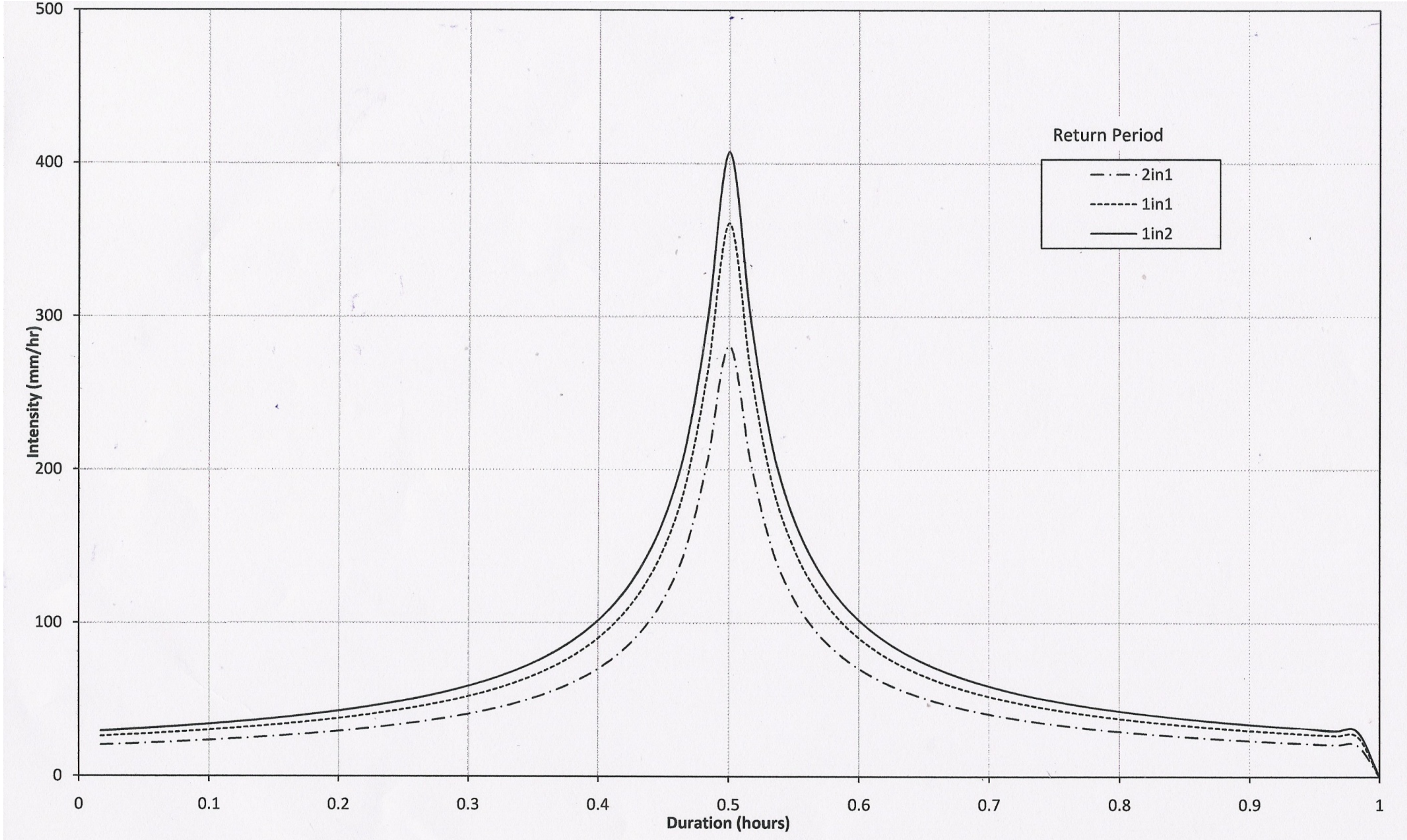

Figure 3.1 Typical Chicago curves for a location

3.0 Rainfall Intensities for various durations of storms for various frequencies of occurrence are sometimes available based on relationship shown below

$$i = \frac{a}{t^n} \qquad (3.3)$$

It is then possible to fit the following relationship to these intensities

$$i = \frac{a}{(t+b)^n} \qquad (3.4)$$

This will enable developing of Chicago Curves for the above rainfall intensities using following methodology.

Table 3.1 shows rainfall intensities for various durations for various frequencies of occurrences for a typical city calculated using relationship in equation 3.3

Table 3.1 : Rainfall Intensities for a Typical City

Duration (hours)	Intensity (mm/hr)						
	2 in 1 year	1 in 1 year	1 in 2 years	1 in 5 years	1 in 10 years	1 in 15 years	1 in 30 years
1	54.32	69.74	78.76	96.44	137.70	157.40	200.98
2	34.98	43.72	50.27	62.30	86.09	97.83	119.63
3	27.04	33.51	38.66	48.25	65.40	74.07	88.31
4	22.52	27.66	32.08	40.25	53.82	60.80	71.21
5	19.55	23.83	27.77	34.96	46.27	52.17	60.25
6	17.41	21.11	24.67	31.17	40.89	46.04	52.57
7	15.79	19.04	22.33	28.28	36.83	41.42	46.84
8	14.50	17.42	20.48	26.00	33.65	37.79	42.38
9	13.46	16.10	18.97	24.14	31.06	34.86	38.81
10	12.59	15.01	17.72	22.59	28.92	32.43	35.86
11	11.85	14.09	16.66	21.27	27.11	30.37	33.39
12	11.21	13.29	15.75	20.13	25.56	28.61	31.29
13	10.65	12.60	14.95	17.14	24.21	27.09	29.47
14	10.16	11.99	14.25	18.27	23.03	25.74	27.88
15	9.73	11.45	13.63	17.49	21.97	24.55	26.48
16	9.34	10.97	13.07	16.79	21.03	23.49	25.23
17	8.99	10.54	12.57	16.17	20.19	22.53	24.11
18	8.67	10.14	12.11	15.59	19.42	21.67	23.10
19	8.37	9.78	11.69	15.07	18.72	20.88	22.18
20	8.10	9.45	11.31	14.59	18.08	20.15	21.35
21	7.86	9.15	10.96	14.15	17.49	19.49	20.58

Duration (hours)	Intensity (mm/hr)						
	2 in 1 year	1 in 1 year	1 in 2 years	1 in 5 years	1 in 10 years	1 in 15 years	1 in 30 years
22	7.63	8.87	10.63	13.74	16.95	18.88	19.88
23	7.42	8.61	10.33	13.36	16.45	18.31	19.23
24	7.22	8.37	10.05	13.01	15.98	17.78	18.62

Equation 3.4 can be rewritten after taking logarithms of both sides to get straight lines as follows:

$$\log i = \log a - n \log(t + b) \qquad (3.5)$$

Sets of frequencies (three or four in a set) can be selected to fit common straight lines. For example, for each of the three frequencies (2 in 1, 1 in 1 and 1 in 2 years), values of 'i' and 't' are plotted on log – log paper. Trial values of 'b' are added to values of 't' and above plots are repeated until the three plots are straight lines with more or less the same slope. The common slope is the value of 'n' and above trial value of 'b' is already identified. Normally the values of 'b' lies between 0 and 10. Fig 3.2 shows a typical plot.

It is seen that a value of b = 5 is very suitable. Values of 'a' can then be calculated by using equation 3.4. Table 3.2 shows the computation of values of a, b and n.

Table 3.2 : Values of a, b and n

		Intensity (mm/hour)		
t (duration in minutes)	t + b	2 in 1 year	1 in 1 year	1 in 2 year
60 (1 hr)	65	54.32	69.74	78.76
120 (2 hrs)	125	34.98	43.92	50.27
240 (4 hrs)	245	22.52	27.66	32.08
480 (8 hrs)	485	14.50	17.42	20.48
720 (12 hrs)	725	11.21	13.29	15.74
'n' =	slope	0.657	0.690	0.670
'a' =	i x $(t+b)^n$	843.911	1244.000	1295.517
'b' =	5			

Chicago Curves can now be developed based on the above magnitudes of a, b and n.

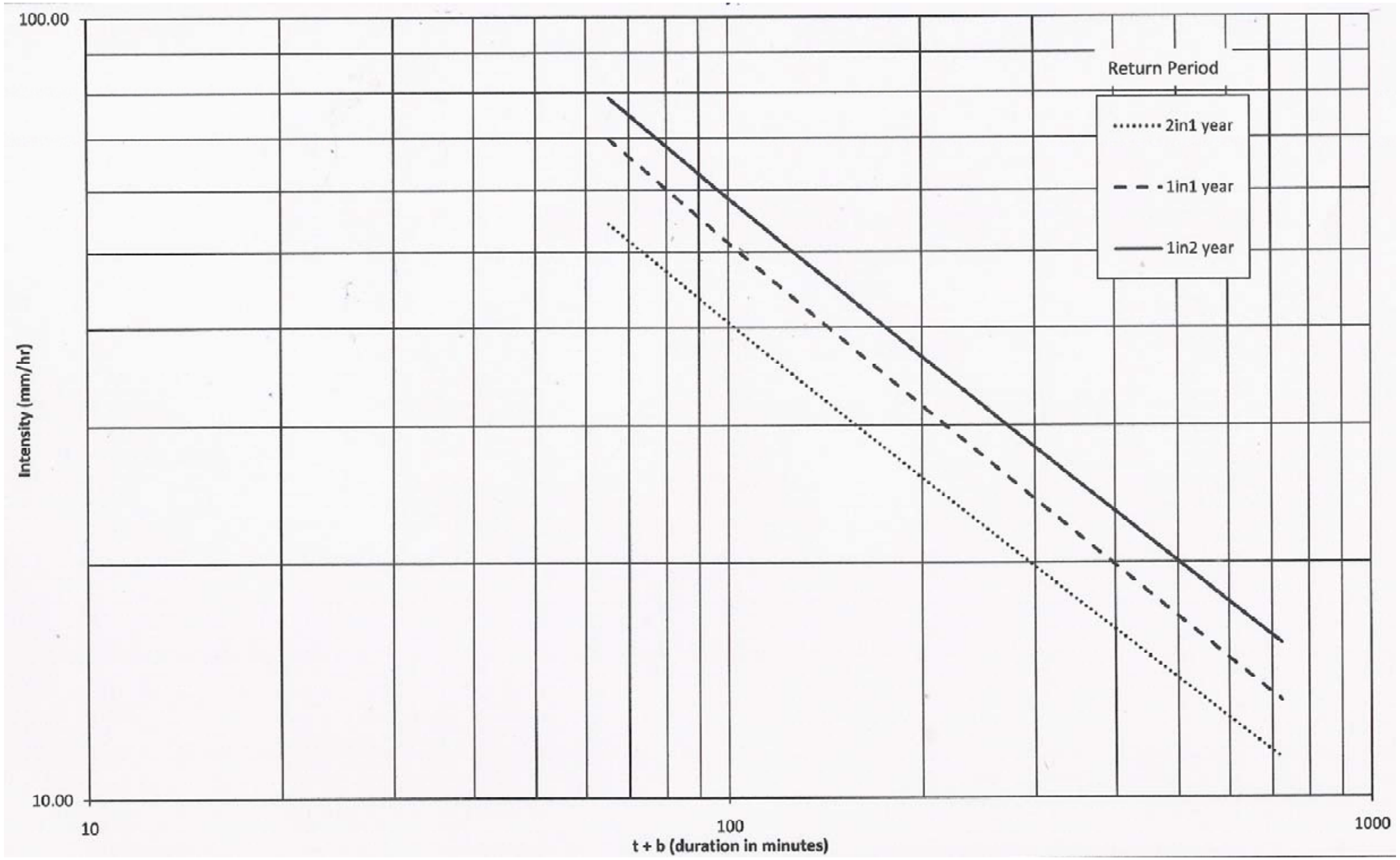

Fig. 3.2 : Typical Plot for Determination of ‘a’, ‘b’, and ‘n’

CHAPTER 4 : IDF RELATIONSHIPS FOR CITIES IN INDIA

1.0 GENERAL

IDF relationships developed by a number of researchers for Indian Cities are available in literature. It may not be always possible for the design personnel to develop these relationships anew for want of data and time. The above relationships then can be used in the design of Storm Water Drainage Systems.

2.0 MUMBAI

Table 4.1 shows the IDF relationships for the city of Mumbai developed by Chawathe et al based on past rainfall data of 24 years from Colaba observatory and 33 years from Santacruz observatory.

Table 4.1 : IDF Relationships for Mumbai

Frequency Range	Intensity, mm/hr	
	Colaba	Santacruz
6 Months to 1 Year	$\frac{458.98\ FREQ^{0.2423}}{(DUR + 18.16)^{0.7182}}$	$\frac{264.12\ FREQ^{0.2272}}{(DUR + 4.50)^{0.560}}$
1.25 to 2 years	$\frac{113.53\ FREQ^{0.1914}}{(DUR + 1.57)^{0.3819}}$	$\frac{338.06\ FREQ^{0.2149}}{(DUR + 10.75)^{0.6011}}$
2.25 to 3 years	$\frac{134.69\ FREQ^{0.1201}}{(DUR - 0.22)^{0.3739}}$	$\frac{335.24\ FREQ^{0.3209}}{(DUR + 16.98)^{0.6754}}$
3.25 to 4 years	$\frac{80.99\ FREQ^{0.2041}}{(DUR - 1.93)^{0.3246}}$	$\frac{165.36\ FREQ^{0.4697}}{(DUR + 19.44)^{0.6433}}$
5 to 10 years	$\frac{105.44\ FREQ^{0.0898}}{(DUR - 3.21)^{0.2793}}$	$\frac{7606.12\ FREQ^{0.5680}}{(DUR + 101.97)^{1.4273}}$

FREQ = Frequency (months), DUR = Duration (min)

3.0 CHENNAI

Figure 4.1 shows IDF curves for Chennai, based on past rainfall data from Meenambakkam meteriorological station.

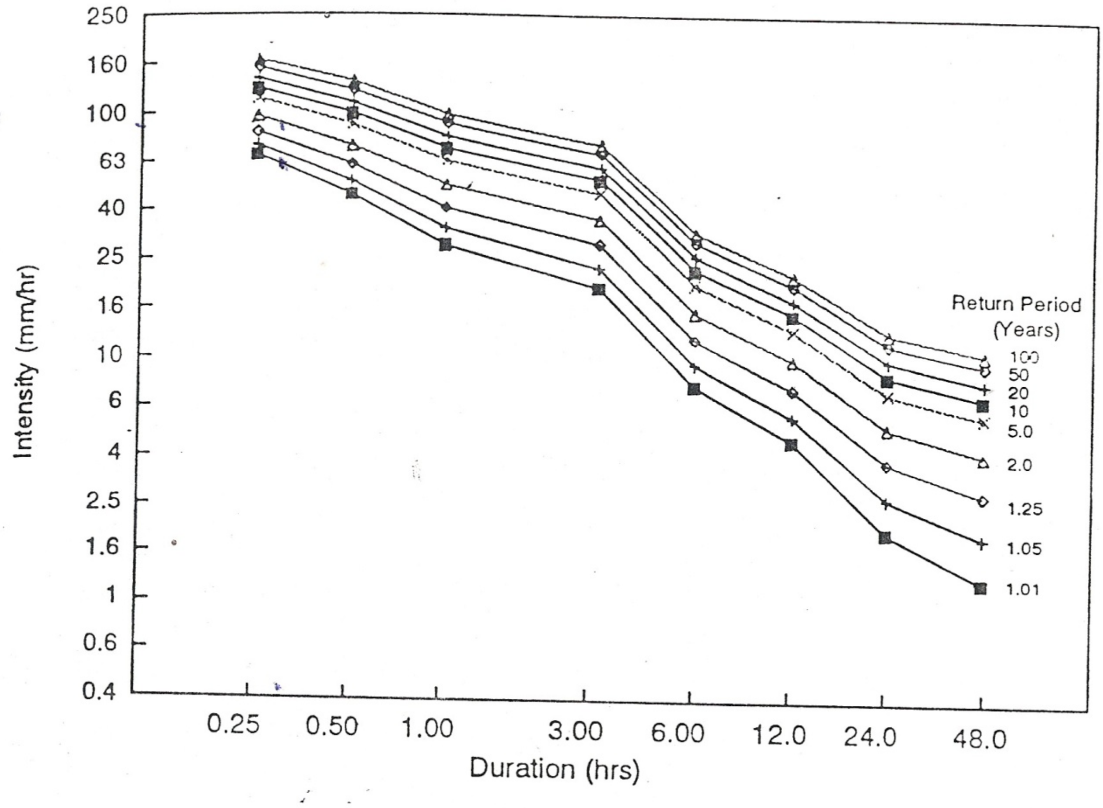

Figure 4.1 : IDF Curves for Chennai

4.0 AHMEDABAD

Table 4.2 shows IDF relationships developed by Chawathe for Ahmedabad based on past rainfall data for 10 years.

Table 4.2 : IDF Relationships for Ahmedabad

Frequency	Intensity
1 to 1.75 years	$i = \frac{3660\, FREQ^{\,0.6338}}{(DUR + 42.32)^{1.3054}}$
2 to 2.75 years	$i = \frac{1524.3\, FREQ^{\,0.3203}}{(DUR + 29.69)^{0.9531}}$
3 to 3.75 years	$i = \frac{1005.6\, FREQ^{\,0.2514}}{(DUR + 18.67)^{0.8374}}$

'i' is in mm/hr, Dur is in min and FREQ is in months

5.0 PUNE

Table 4.3 shows IDF Relationships developed by Chawathe for Pune based on past rainfall data for 10 years.

Table 4.3 : IDF Relationships for Pune

Frequency	Intensity
1 to 1.75 years	$i = \frac{5425\, FREQ^{\,0.4837}}{(DUR + 33.44)^{1.4019}}$
2 to 2.75 years	$i = \frac{107840\, FREQ^{\,0.564}}{(DUR + 69.08)^{2.0029}}$
3 to 3.75 years	$i = \frac{135140\, FREQ^{\,0.6036}}{(DUR + 79.96)^{2.0695}}$
4 to 5 years	$i = \frac{1761900\, FREQ^{\,0.6709}}{(DUR + 115.58)^{2.55}}$
i is in mm/hr, Dur is in min and FREQ is in months	

6.0 KOLKATA

Table 4.4 shows the IDF Relationships developed by Raman et al for Kolkata (Calcutta).

Table 4.4 : IDF Relationships for Kolkata.

Frequency	Intensity
T = 1 to 3 months	$i = \frac{6200\, T^{0.358}}{(t+45)^{1.75}}$
T = 1 to 2 years	$i = \frac{953\, T^{0.157}}{(t+45)^{1.34}}$
T = 5 to 20 years	$i = \frac{290\, T^{0.119}}{(t+45)^{1.05}}$
T = 1 month to 20 years	$i = \frac{810\, T^{0.126}}{(t+45)^{1.31}}$

7.0 NEW DELHI

Table 4.5 shows the IDF Relationships developed by Toshniwal for New Delhi

Table 4.5 : IDF Relationships for New Delhi

T = 1 year	$i = \frac{2.291\ x\ 10^{6}}{(t+188.85)^{6.848}}$
Also	
T = 1 year	i = 0.0004174 (t – 99.28)^2
T = 2 years	i = 0.0001177 (t – 181.9)^2
T = 3 years	i = 0.0003165 (t – 129.18)^2

T = 4 years	$i = 0.0004692\ (t - 119.94)^2$
T = 5 years	$i = 0.0002755\ (t - 149)^2$

8.0 AMRAVATI

IDF relationship developed for Amravati (Maharashtra) by Tatewar et al is shown below

$$i = \frac{30.0\ T^{0.218}}{(t - 52)^{0.1854}}$$

Where, i = intensity, mm/hr

T = frequency of occurrence, year

t = duration of storm, mm

9.0 BANGALORE

IDF relationship developed by Khageshan for Bangalore is shown below :

$$i = \frac{535\ T^{0..345}}{(t - 2)^{0.693}}$$

Where, i = intensity, mm/hr

T = frequency, year

t = duration of storm, mm

10.0 AKOLA

IDF Relationships developed by Dr. Panjabral Deshmukh Krishi Vidyapeeth, for Akola is shown below:

$$i = \frac{6.165\ T^{0.1985}}{(t + 0.5)^{0.8591}}$$

Where, i = Rainfall intensity, mm/hr

T = Return Period, year

t = Time of concentration. hr

Figure 4.2 is the Nomogram based on the above relationship

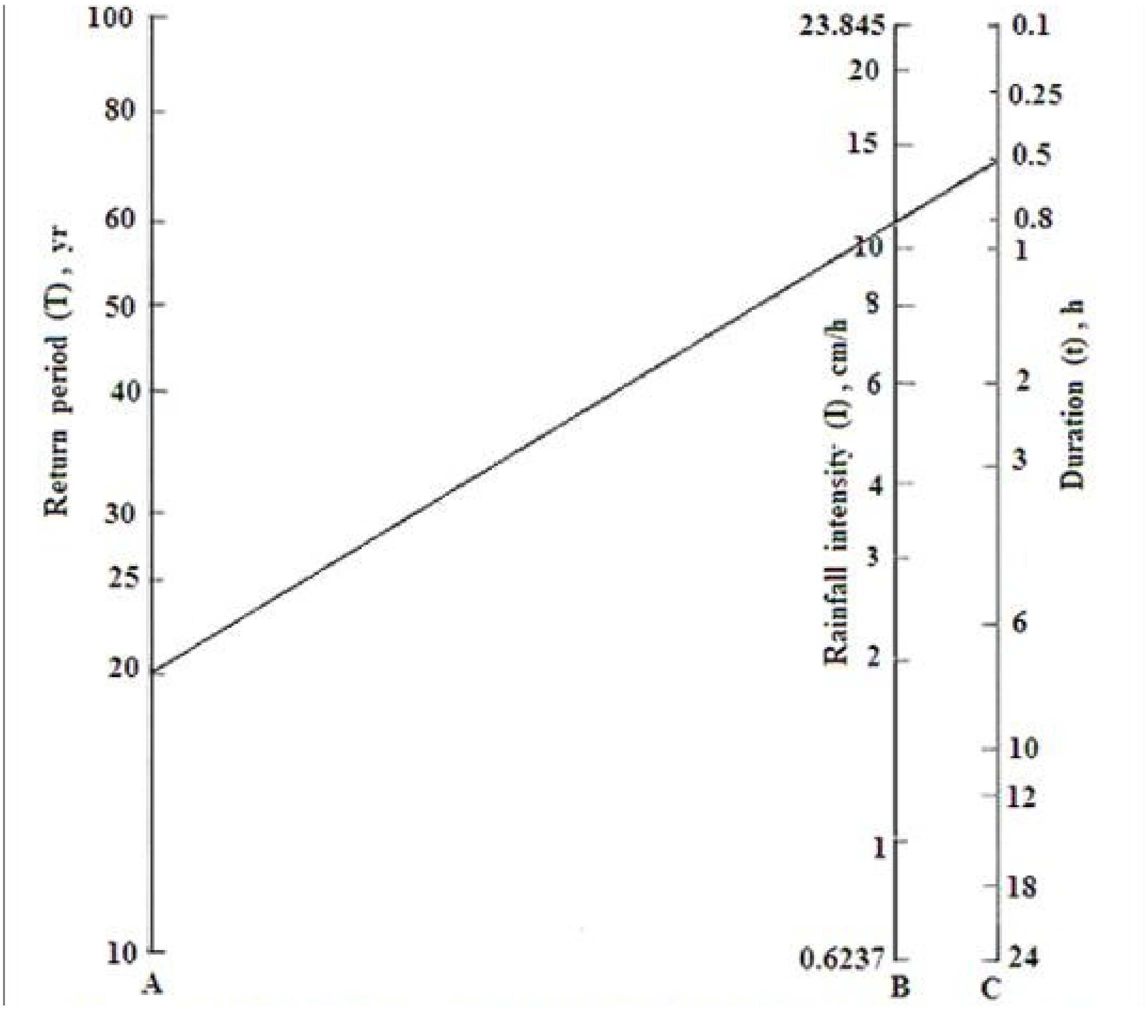

Fig 4.2 : Nomogram for IDF relationships for Akola.

11.0 OTHER CITIES IN INDIA

Rambabu et al have analysed rainfall records for 42 stations in the country and have obtained the values of 'C', 'm', 'd' and 'n' in the following equation

$$\frac{C\,T^{m}}{(t+d)^{n}}$$

Where, i = intensity of Rainfall, (m/hr)
T = Return Period, (year)
d = duration of storm (hours)

and C, m, d, and n are constants
Table 4.6 shows the values of the constants for a few locations in India

Table 4.6 : Values of c, m, d and n for cities in India

Place	C	m	d	n
Allahabad	4.9110	0.1667	0.25	0.6293
Amritsar	14.4100	0.1304	1.40	1.2963
Dehradun	6.0000	0.2200	0.50	0.8000
Jodhpur	4.0980	0.1677	0.50	1.0369
Srinagar	1.5030	0.2730	0.25	1.0636
Bhopal	6.9296	0.1892	0.50	0.8767
Nagpur	11.4500	0.1560	1.25	1.0324
Raipur	4.6830	0.1389	0.15	0.9284
Aurangabad	6.0810	0.1459	0.50	1.0923
Bhuj	3.8230	0.1919	0.25	0.9902
Veraval	7.7870	0.2087	0.50	0.8908
Agarthala	8.0970	0.1177	0.50	0.8191
Kolkata	5.9400	0.1150	0.15	0.9241
Gauhati	7.2060	0.1157	0.75	0.9401
Jarsugnda	8.5960	0.1392	0.75	0.8740
Bangalore	6.2750	0.1262	0.50	1.1280
Hyderabad	5.2500	0.1354	0.50	1.0295
Chennai	6.1260	0.1664	0.50	0.8027
Thiruvanathapuram	6.7260	0.1536	0.50	0.8150

CHAPTER 5 : SPATIAL VARIATION OF RAINFALL

1.0 GENERAL

In smaller cities and towns, rainfall records are normally available for a single location where facilities may have been created by the Meteorological Dept. to measure rainfall. In larger cities and Metropolises, such facilities may be available at more than one location. For example, Mumbai so far had two observatories one at Colaba to the south of Mumbai and the other at Santacruz in the Western Suburbs. The deluge on 26/7/2005 due to torrential rains in Mumbai created an awareness and the Municipal Corporation of the City established Automatic Rain Gauging Instruments at 32 locations in Mumbai

Table 5.1 shows the locations of these instruments in Mumbai.

Table 5.1 : Locations of Automatic Rainfall Gauges in Mumbai

Sr No	Location
1	Memonwada
2	Byculla
3	Worli
4	Dadar
5	Dharavi
6	BKC
7	Bandra
8	Vile Parle, W
9	Vile Parle, WL
10	Marol
11	Andheri
12	Goregaon
13	Malad
14	Kandivali
15	Borivali
16	Borivali wire
17	Chembur
18	Vikhroli
19	Bhandup Complex
20	Mulund
21	Gavanpada
22	Tulsiplant
23	Chincholi
24	Dahisar

Sr No	Location
25	Devnar
26	Kan
27	Kurla
28	Wadala
29	Colaba
30	Dahisar (new)
31	Malbar Hill
32	Dindoshi

In larger cities and Metropolises, it is desirable to recognise spatial variation of rainfall intensities over the areas and use separate sets of IDF Curves for different locations in the city as against a single set of IDF Curves for smaller cities. For example, in the case of Mumbai, it is desirable to develop IDF relationships based on rainfall data from more than the normally considered locations of Colaba and Santacruz. Since now, data from 33 locations is available. Thus ideally, IDF relationships at multiple locations can be developed and used in the design of the Storm Water Drainage System for larger cities. Since such past rainfall data at multiple locations for sufficient number of years may not be available in large cities and Metropolises, actual development of IDF Relationships at these multiple locations may not be practical. However, study of even 1 hr intensities from past rainfall data for 3 to 4 years also may give some indication of spatial variation of rainfall intensities in large cities and metropolises. This will then hopefully lead to adopting a number of sets of IDF curves for a large city. A possible approach in such a case is described below.

2.0 Table 5.2 shows average 1 hr rainfall intensities (mm/hr) at multiple locations for recorded 1 hr rainfall intensity magnitudes for past 3 years for a typical large city.

Table 5.2 : Average 1 hr Rainfall Intensities at 17 locations in a city

Sr. No of Location	Average Rainfall Intensities (mm/hr)	Range mm/hr
1	2.69	2.69
2	3.137	2.906 to 3.182
3	3.182	
4	3.032	
5	3.137	
6	2.906	
7	3.366	3.235 to 3.374
8	3.363	
9	3.278	
10	3.235	
11	3.278	
12	3.374	
13	3.15	
14	3.597	3.514 to 3.904 Average 3.701
15	3.904	
16	3.792	
17	3.514	

Above table shows a marked increase in 1 hr intensities from location 1 to locations 14-17. This indicates that there may be a spatial variation of rainfall from location to location over the area of the city. The table classifies the intensity ranges into 4 groups. It is therefore desirable to consider the city roughly divided into four zones and consider four groups of IDF relationships for further design. It is assumed that rainfall data for sufficient number of past years is available for a few locations (say location Sr. no. 1 and 8) and IDF relationships based on this data have been already developed for these locations. Based on these relationships, further inferences can be drawn.

Table 5.3 shows the four zones and 1 hr average rainfall intensity ranges and applicable IDF relationships for the four groups.

Table 5.3 applicable IDF Relationships for four groups of Municipal Wards

Wards in Zone	1 hr Rainfall intensity Range)mm/hr)	Applicable IDF Relationship
I	2.69	Same as for location 1 from Table 5.2 since this location belongs to this group
II	2.906 - 3.182	If the wards in this locations are located in between locations 1 & 8 then Average IDF Cures can be developed based on IDF Curves at locations 1 & 8
III	3.235 - 3.374	Same as for location 8 from table 5.2, since this location belongs to this group
IV	3.514 - 3.904 (Average = 3.701) This is about 1.1 times 3.363 at location 8 from table	Based on intensities 1.1 times that for location 8

Sets of IDF curves then can be drawn for this typical city based on above considerations. Further Chicago Curves can also be drawn based on these IDF relationships.

In case data for more than 10 years is available for each rain guage station, it is possible to develop IDF Curves directly from the data and use the same in the design.

CHAPTER 6: MUMBAI FLOODS AND AFETRMATH

1.0 BRIMSTOWAD

From 1990 to 1993 Watson Hawksley (now called MWH) in association with AIC India Pvt. Ltd. carried out a major study of the storm water drainage system in Mumbai, India. The BRIMSTOWAD (Brihan Mumbai Storm Water Drainage) master plan was submitted by the consultants to their clients the Municipal Corporation of Greater Mumbai in 1993. Due to limitations of funds the recommendations in the master plan could not be executed by the Corporation.

After the major flooding event caused by the extreme rainfall on 26th & 27th July 2005 in Mumbai, a Fact Finding Committee(FFC) was constituted by the State Government of Maharashtra to investigate into the causes of the floods and to suggest measures for relief. In addition, the Municipal Corporation of Greater Mumbai appointed M/S MWH to update the old master plan and also to carry out detailed Engineering to execute priority works for storm/water Management.

The Fact Finding Committee submitted their final report in March 2006. The report made certain recommendations.

2.0 RECOMMENDATIONS OF FFC

FFC on page 48 recommends design intensities of rainfall as follows:

a) Small Catchments – 50 mm/hr, 2 in 1 year return period as per BRIMSTOWAD
b) River Channel Areas – 70 mm/hr, 1 in 10 year return period
c) River bank Areas and CD works on major roads – 80 mm/hr, 1 in 25 years return period

FFC recommends on page 257, design rainfall intensities as follows:

- Major Corridors of city – 1 in 100 years return period
- Other major roads – 1 in 25 years return period

FFC recommends on page 258, design rainfall intensity as follows:

- River Bank (Occasional flood spread) areas as a risk zone and for all CD works on main through arteries of traffic – 100mm/hr, 1 in 100 years return period.

It is quite understood that one cannot take risks of flooding in important areas. The return period to be adopted for design of storm water drainage system should vary with the degree of importance of these areas.

The intensity of rainfall to be adopted for those areas should therefore increase with increase in the degree of importance of these areas vis a vis the risk of flooding in these areas.

However the basis for the value of 50 mm/hr mentioned on page 48 in FFC Report is not clear. It is mentioned here that the value is for a return period of 2 in 1 year and is from BRIMSTOWAD Report. Ideally the value should be based on IDF relationship where the intensities of rainfall are a function of the concentration time and the return period.

Actually BRIMSTOWAD gives a value of 48 mm/hr (say 50 mm/hr) for a return period 2 in 1 year but for a concentration time of 1 hour only.

FFC on page 258 accepts that for many smaller catchments the time of travel is just 15 minutes. It is a fact that for most of the smaller catchments the concentration time will be smaller than 1 hr. It is thus clear that the intensity to be adopted in the design has to be read from IDF Curve (If 2 in 1 year curve is adopted) for corresponding to concentration time which will vary over the Stormwater Drain Network and which in Mumbai will more or less will be less than 1 hr, going upto may be 15 min for smaller networks.

In fact, BRIMSTOWAD does not recommend 50 mm/hr design intensity for any catchments as assumed by FFC. The methodology used by BRIMSTOWAD is completely different. It uses Chicago curves for durations of 1 hr, 2 hr, 4 hr etc. based on twice in a year return period with 50 mm/hr average rainfall intensity but after converting this rainfall to a peaked Chicago Curve.

The peak Chicago Curves that BRIMSTOWAD uses have peak intensities much larger than 50 mm/hr and the networks are dynamically designed for such peaked rainfall patterns.

It is thus seen that BRIMSTOWAD does not recommend constant intensity of 50 mm/hr in the design.

For smaller catchments therefore for concentration time of less than 1 hr and for twice in a year return period the design intensity of rainfall can be computed by using the relationship given in table 4.1. It is not possible to use IDF Curves given in BRIMSTOWAD for concentration times of less than 1 hr because BRIMSTOWAD presents IDF Curves for contrations times greater than 1 hr only. For a return period of twice in a year the intensities work out to be as per table 6.1

Table 6.1 : Design Intensities of Rainfall (mm/hr) for Mumbai for twice in a year Return Period using IDF relationships as per Table 4.1

Concentration Time (min)	15	20	30	45	60
Colaba	57.30	51.80	43.80	36.10	31.00
Santacruz	75.00	66.00	54.50	44.50	38.30

3.0 RETURN PERIOD FOR MUMBAI

BRIMSTOWAD designs are based on a return period of twice in a year. BRIMSTOWAD provides a detailed economical analysis involving cost benefit aspects for Mumbai. It uses the financial losses suffered in Mumbai due to rainwater flooding on 7th to 11 June 1991 for arriving at twice in a year as the most optimum return period. At present BRIMSTOWAD is being updated in the light of data obtained on financial losses incurred on 26th – 27th July 2005 in Mumbai due to torrential rains. Hopefully the return period of twice in a year would be reconsidered. The return period of twice in a year appears on lower side if international practices as given in Annexure 'A' to Chapter I are considered. If one wants to safeguard the city such as Mumbai which is the Commercial Capital of India against floods, it would be wise to revise the return period to atleast once in ten years notwithstanding the cost benefit analysis. Table 6.2 shows the design intensities which could be adopted for this return period based on relationships in table 4.1

Table 6.2 : Design Intensities of Rainfall (mm/hr) for Mumbai for Once in Ten year return period.

Concentration Time (min)	15	20	30	45	60
Colaba	81.40	73.70	64.70	57.20	52.50
Santacruz	129.00	121.50	108.60	93.10	51.00

BIBLIOGRAPHY

1. ‘Rainfall Analysis for the Design of Storm Sewers in Bombay‘
Journal of Institute of Engineers (India), EN, Oct 1977
S.D. Chawathe et al

2. ‘Rainfall Considerations in Storm Drainage Systems Case studies’
Proceedings of International Afro-Asian Conference, Mumbai, March 1993
S D Chawathe

3. ‘Rainfall Intensities and 26/7 Floods in Mumbai,’
Journal of Indian Water Works Association, July – Sept 2005
S D Chawathe

4. ‘A Second Look at BRIMSTOWAD’
Proceedings of Seminar on Storm Water Drainage System Design and Practice
Sponsored by Indian Water Works Association, Mumbai Centre, Mumbai, Oct 2005
S D Chawathe

5. ‘Basic Design Concepts for Urban Storm Water Drainage Systems’
Proceedings of 40th Annual Convention, Indian Water Works Association, indore, Feb 2008
S D Chawathe

6. ‘Analysis of Rainfall Intensities and Tides for Storm Water Management in Mumbai’
Proceedings of National Seminar on Sustainable Environment, V.J.T.I. Mumbai, Dec. 2009
S D Chawathe

7. ‘Design of Urban Storm Water Drainage Systems,’
Seminar Thane Municipal Corporation, Thane.
S D Chawathe

8. Capacity of Storm Water Drainage Systems in Mumbai,
Report on Assessment of Carrying capacity of Mumbai preparation Conservation Action Trust. 2011
S D Chawathe

9. ‘Storm Water Drainage Systems in Mumbai’
Presentation to Facts Finding Committee, Govt. of Maharashtra, Sept, 2005 on behalf of Indian Water Works Association
S D Chawathe et al

10 ‘Rainfall Intensity – Duration – Frequency Formation for Delhi’
Environmental Health, Vol. 10 July 1968
C. T. Toshniwal

11. ‘Frequency Analysis of Rainfall Intensities for Calcutta.’
Proceedings ASCE, San. Eng. Div. Vol. 1, no. SA6, Dec. 1969
V Raman et al

12. ‘A Rational Approach to the Design of Combined Sewers with special reference to Calcutta’
Journal of Institution of engineers (India), Vol 38, May 1957
S K Kabasi

13. ‘Water Supply & Waste Water Disposal’
John Wiley & Sons Inc. New York, 1954
G M Fair & J C Geyer

14. ‘Storm Water Drainage Manual’
Government of Hongkong, Dec. 2000

15. ‘Final Report on Master Planning for Greater Bombay Storm Water Drainage and Sewer Rehabilitation (BRIMSTOWAD)’
MWH India Private Limited, 1993.

16. ‘Final Report of Fact Finding Committee on Mumbai Floods,’
Govt. of Maharashtra, March 2006

17. ‘Development of Relationship for Intensity – Duration – Frequency of Rainfall for Amravati Region,’
IWWA, Vol 38, Number 3, 2006.

18. ‘Formulation of Rainfall – Intensity – Duration Frequency Relationship for Bangalore Airport’
IWWA, July – Sept 1992 Khageshan P et al

19. ‘Website of Dr. Panjabrao Deshmukh Krishi Vidyapeeth, Akola,’
pdkv.ac.in/SWCE_Dept.php

20 ‘Rainfall – Intensity – Duration – Return Period Equations and Nomographs of India’
Bulletin No. 3, CSWCRTI, Dehradun, India, 1979.

21 ‘Project Report on Repetitive Water Logging in Thane City: Engineering Solutions and Environmental Management Plan.’
Final Report sponsored by MMR, Hariyali, Thane, 2006

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