Chapter 2

PRECIPITATION

2.1 INTRODUCTION

The term *precipitation* denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew. Of all these, only the first two contribute significant amounts of water. Rainfall being the predominant form of precipitation causing stream flow, especially the flood flow in a majority of rivers in India, unless otherwise stated the term *rainfall* is used in this book synonymously with precipitation. The magnitude of precipitation varies with time and space. Differences in the magnitude of rainfall in various parts of a country at a given time and variations of rainfall at a place in various seasons of the year are obvious and need no elaboration. It is this variation that is responsible for many hydrological problems, such as floods and droughts. The study of precipitation forms a major portion of the subject of hydrometeorology. In this chapter, a brief introduction is given to familiarize the engineer with important aspects of rainfall, and, in particular, with the collection and analysis of rainfall data.

For precipitation to form: (i) the atmosphere must have moisture, (ii) there must be sufficient nuclei present to aid condensation, (iii) weather conditions must be good for condensation of water vapour to take place, and (iv) the products of condensation must reach the earth. Under proper weather conditions, the water vapour condenses over nuclei to form tiny water droplets of sizes less than 0.1 mm in diameter. The nuclei are usually salt particles or products of combustion and are normally available in plenty. Wind speed facilitates the movement of clouds while its turbulence retains the water droplets in suspension. Water droplets in a cloud are somewhat similar to the particles in a colloidal suspension. Precipitation results when water droplets come together and coalesce to form larger drops that can drop down. A considerable part of this precipitation gets evaporated back to the atmosphere. The net precipitation at a place and its form depend upon a number of meteorological factors, such as the weather elements like wind, temperature, humidity and pressure in the volume region enclosing the clouds and the ground surface at the given place.

2.2 FORMS OF PRECIPITATION

Some of the common forms of precipitation are: rain, snow, drizzle, glaze, sleet and hail.

RAIN It is the principal form of precipitation in India. The term *rainfall* is used to describe precipitations in the form of water drops of sizes larger than 0.5 mm. The maximum size of a raindrop is about 6 mm. Any drop larger in size than this tends to break up into drops of smaller sizes during its fall from the clouds. On the basis of its intensity, rainfall is classified as:

Type	Intensity
1. Light rain	trace to 2.5 mm/h
2. Moderate rain	2.5 mm/h to 7.5 mm/h
3. Heavy rain	> 7.5 mm/h

SNOW *Snow* is another important form of precipitation. Snow consists of ice crystals which usually combine to form flakes. When fresh, snow has an initial density varying from 0.06 to 0.15 g/cm^3 and it is usual to assume an average density of 0.1 g/cm^3. In India, snow occurs only in the Himalayan regions.

DRIZZLE A fine sprinkle of numerous water droplets of size less than 0.5 mm and intensity less than 1 mm/h is known as drizzle. In this the drops are so small that they appear to float in the air.

GLAZE When rain or drizzle comes in contact with cold ground at around 0º C, the water drops freeze to form an ice coating called *glaze* or *freezing rain.*

SLEET It is frozen raindrops of transparent grains which form when rain falls through air at subfreezing temperature. In Britain, *sleet* denotes precipitation of snow and rain simultaneously.

HAIL It is a showery precipitation in the form of irregular pellets or lumps of ice of size more than 8 mm. Hails occur in violent thunderstorms in which vertical currents are very strong.

2.3 WEATHER SYSTEMS FOR PRECIPITATION

For the formation of clouds and subsequent precipitation, it is necessary that the moist air masses cool to form condensation. This is normally accomplished by adiabatic cooling of moist air through a process of being lifted to higher altitudes. Some of the terms and processes connected with the weather systems associated with precipitation are given below.

FRONT A *front* is the interface between two distinct air masses. Under certain favourable conditions when a warm air mass and cold air mass meet, the warmer air mass is lifted over the colder one with the formation of a front. The ascending warmer air cools adiabatically with the consequent formation of clouds and precipitation.

CYCLONE A *cyclone* is a large low pressure region with circular wind motion. Two types of cyclones are recognised: tropical cyclones and extratropical cyclones.

Tropical cyclone: A tropical cyclone, also called *cyclone* in India, *hurricane* in USA and *typhoon* in South-East Asia, is a wind system with an intensely strong depression with MSL pressures sometimes below 915 mbars The normal areal extent of a cyclone is about 100–200 km in diameter. The isobars are closely spaced and the winds are anticlockwise in the northern hemisphere. The centre of the storm, called the *eye,* which may extend to about 10–50 km in diameter, will be relatively quiet. However, right outside the eye, very strong winds/reaching to as much as 200 kmph exist. The wind speed gradually decreases towards the outer edge. The pressure also increases outwards (Fig. 2.1). The rainfall will normally be heavy in the entire area occupied by the cyclone.

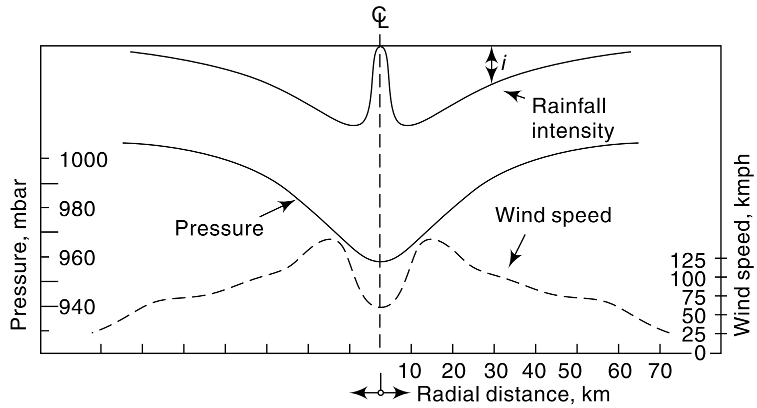


Fig. 2.1 Schematic Section of a Tropical Cyclone

During summer months, tropical cyclones originate in the open ocean at around 5–10° latitude and move at speeds of about 10–30 kmph to higher latitudes in an irregular path. They derive their energy from the latent heat of condensation of ocean water vapour and increase in size as they move on oceans. When they move on land the source of energy is cut off and the cyclone dissipates its energy very fast. Hence, the intensity of the storm decreases rapidly. Tropical cyclones cause heavy damage to life and property on their land path and intense rainfall and heavy floods in streams are its usual consequences. Tropical cyclones give moderate to excessive precipitation over very large areas, of the order of 10^3 km^2, for several days.

Extratropical Cyclone: These are cyclones formed in locations outside the tropical zone. Associated with a frontal system, they possess a strong counter-clockwise wind circulation in the northern hemisphere. The magnitude of precipitation and wind velocities are relatively lower than those of a tropical cyclone. However, the duration of precipitation is usually longer and the areal extent also is larger.

ANTICYCLONES These are regions of high pressure, usually of large areal extent. The weather is usually calm at the centre. Anticyclones cause clockwise wind circulations in the northern hemisphere. Winds are of moderate speed, and at the outer edges, cloudy and precipitation conditions exist.

CONVECTIVE PRECIPITATION In this type of precipitation a packet of air which is warmer than the surrounding air due to localised heating rises because of its lesser density. Air from cooler surroundings flows to take up its place thus setting up a convective cell. The warm air continues to rise, undergoes cooling and results in precipitation. Depending upon the moisture, thermal and other conditions light showers to thunderstorms can be expected in convective precipitation. Usually the areal extent of such rains is small, being limited to a diameter of about 10 km.

OROGRAPHIC PRECIPITATION The moist air masses may get lifted-up to higher altitudes due to the presence of mountain barriers and consequently undergo cooling, condensation and precipitation. Such a precipitation is known as *Orographic precipitation.* Thus in mountain ranges, the windward slopes have heavy precipitation and the leeward slopes light rainfall.

2.4 CHARACTERISTICS OF PRECIPITATION IN INDIA

From the point of view of climate the Indian subcontinent can be considered to have two major seasons and two transitional periods as:

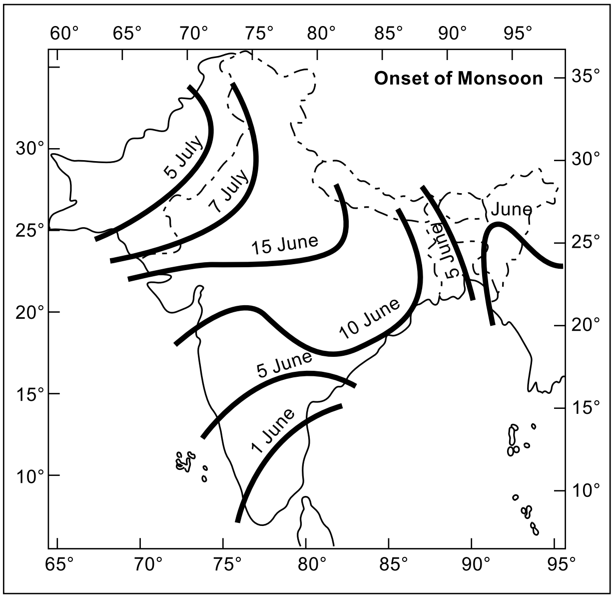
- South-west monsoon (June–September)
- Transition-I, post-monsoon (October–November)
- Winter season (December–February)
- Transition-II, Summer, (March–May)

The chief precipitation characteristics of these seasons are given below.

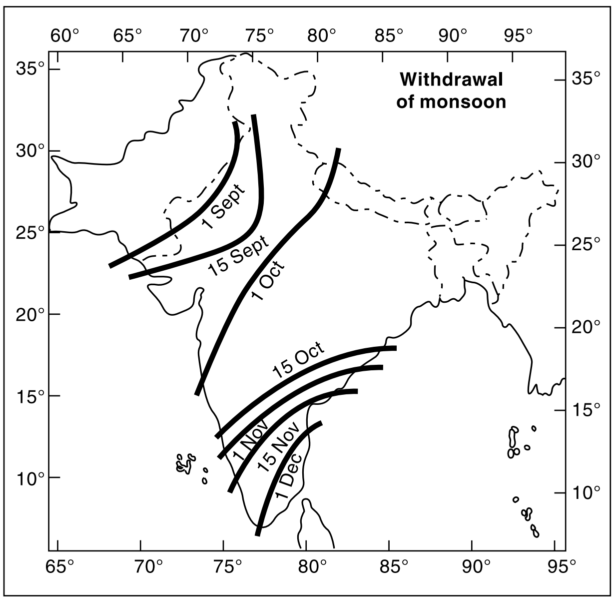
South-West Monsoon (June–September)

The south-west monsoon (popularly known as *monsoon*) is the principal rainy season of India when over 75% of the annual rainfall is received over a major portion of the country. Excepting the south-eastern part of the peninsula and Jammu and Kashmir, for the rest of the country the south-west monsoon is the principal source of rain with July as the month which has maximum rain. The monsoon originates in the Indian ocean and heralds its appearance in the southern part of Kerala by the end of May. The onset of monsoon is accompanied by high south-westerly winds at speeds of 30–70 kmph and low-pressure regions at the advancing edge. The monsoon winds advance across the country in two branches: (i) the Arabian sea branch, and (ii) the Bay of Bengal branch. The former sets in at the extreme southern part of Kerala and the latter at Assam, almost simultaneously in the first week of June. The Bay branch first covers the north-eastern regions of the country and turns westwards to advance into Bihar and UP. The Arabian sea branch moves northwards over Karnataka, Maharashtra and Gujarat. Both the branches reach Delhi around the same time by about the fourth week of June. A low-pressure region known as *monsoon trough* is formed between the two branches. The trough extends from the Bay of Bengal to Rajasthan and the precipitation pattern over the country is generally determined by its position. The monsoon winds increase from June to July and begin to weaken in September. The withdrawal of the monsoon, marked by a substantial rainfall activity starts in September in the northern part of the country. The onset and withdrawal of the monsoon at various parts of the country are shown in Fig. 2.2(a) and Fig. 2.2(b).

The monsoon is not a period of continuous rainfall. The weather is generally cloudy with frequent spells of rainfall. Heavy rainfall activity in various parts of the country owing to the passage of low pressure regions is common. Depressions formed in the Bay of Bengal at a frequency of 2–3 per month move along the trough causing excessive precipitation of about 100–200 mm per day. Breaks of about a week in which the rainfall activity is the least is another feature of the monsoon. The south-west monsoon rainfall over the country is indicated in Fig. 2.3. As seen from this figure, the heavy rainfall areas are Assam and the north-eastern region with 200–400 cm, west coast and western ghats with 200–300 cm, West Bengal with 120–160 cm, UP, Haryana and the Punjab with 100–120 cm. The long term average monsoon rainfall over the country is estimated as 95.0 cm.



(a)



(b)

Fig. 2.2 (a) Normal Dates of Onset of Monsoon, (b) Normal Dates of Withdrawal of Monsoon
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The territorial waters of India extend into the sea to a distance of 200 nautical miles measured from the appropriate baseline

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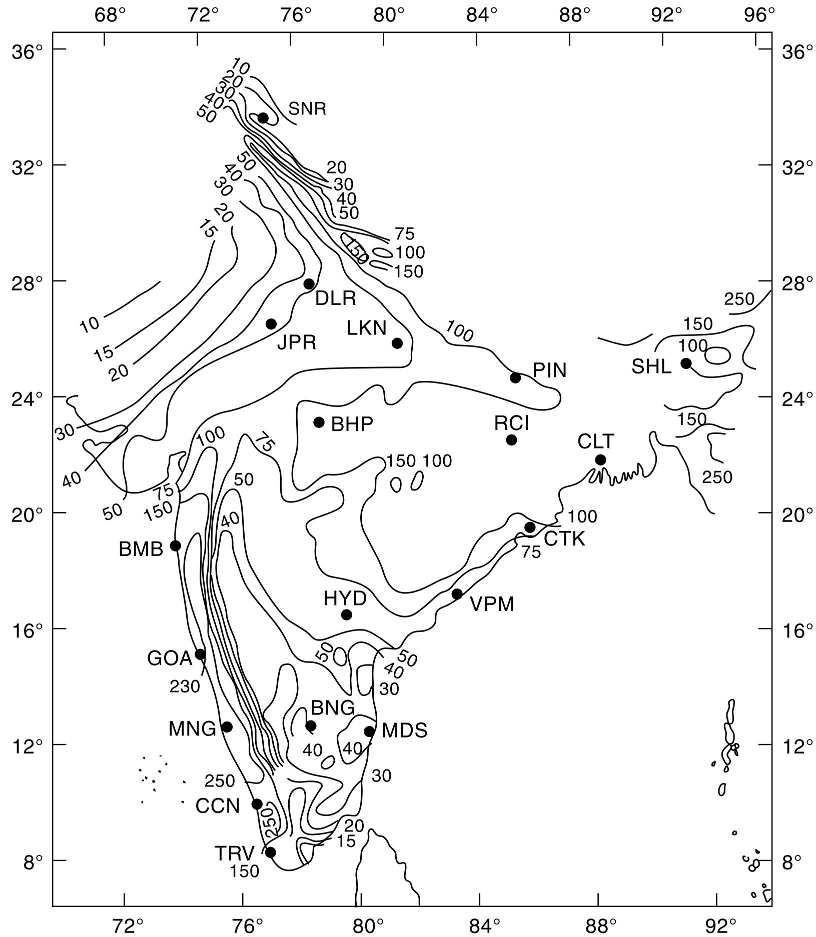

Fig. 2.3 Southwest Monsoon Rainfall (cm) over India and Neighbourhood (Reproduced with permission from India Meteorological Department)

Post-Monsoon (October–November)

As the south-west monsoon retreats, low-pressure areas form in the Bay of Bengal and a north-easterly flow of air that picks up moisture in the Bay of Bengal is formed. This air mass strikes the east coast of the southern peninsula (Tamil Nadu) and causes rainfall. Also, in this period, especially in November, severe tropical cyclones form in the Bay of Bengal and the Arabian sea. The cyclones formed in the Bay of Bengal are about twice as many as in the Arabian sea. These cyclones strike the coastal areas and cause intense rainfall and heavy damage to life and property.

Winter Season (December–February)

By about mid-December, disturbances of extra tropical origin travel eastwards across Afghanistan and Pakistan. Known as *western disturbances,* they cause moderate to heavy rain and snowfall (about 25 cm) in the Himalayas, and, Jammu and Kashmir. Some light rainfall also occurs in the northern plains. Low-pressure areas in the Bay of Bengal formed in these months cause 10–12 cm of rainfall in the southern parts of Tamil Nadu.

Summer (Pre-monsoon) (March-May)

There is very little rainfall in India in this season. Convective cells cause some thunderstorms mainly in Kerala, West Bengal and Assam. Some cyclone activity, dominantly on the east coast, also occurs.

Annual Rainfall

The annual rainfall over the country is shown in Fig. 2.4. Considerable areal variation exists for the annual rainfall in India with high rainfall of the magnitude of 200 cm in

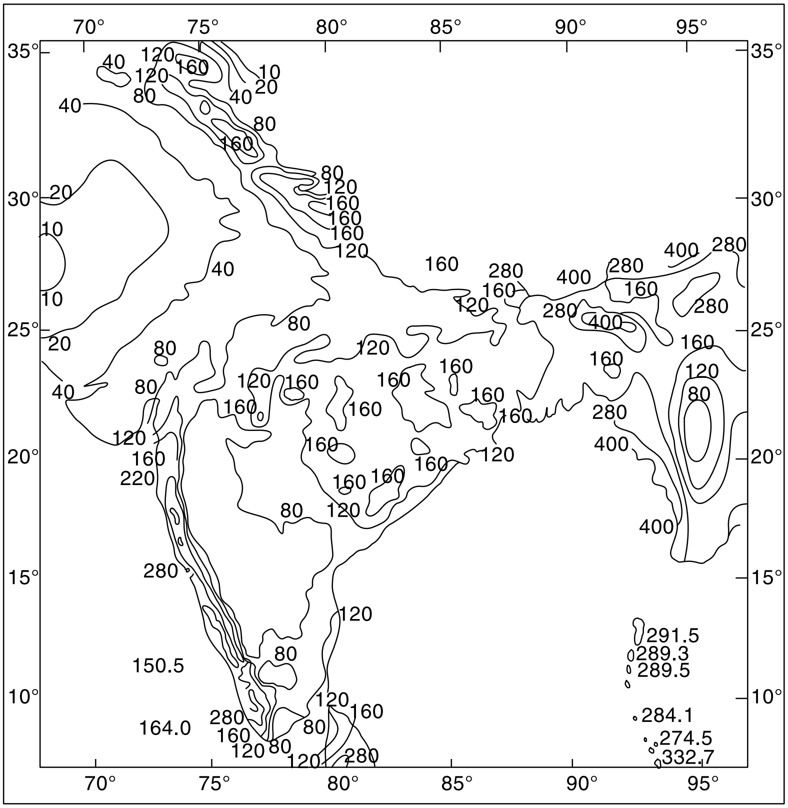

Fig. 2.4 Annual Rainfall (cm) over India and Neighbourhood (Reproduced from *Natural Resources of Humid Tropical Asia – Natural Resources Research, XII*. © UNESCO, 1974, with permission of UNESCO)

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The territorial waters of India extend into the sea to a distance of 200 nautical miles measured from the appropriate baseline

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Assam and north-eastern parts and the western ghats, and scanty rainfall in eastern Rajasthan and parts of Gujarat, Maharashtra and Karnataka. The average annual rainfall for the entire country is estimated as 117 cm.

It is well-known that there is considerable variation of annual rainfall in time at a place. The coefficient of variation,

$$C_v = \frac{100 \times \text{standard deviation}}{\text{mean}}$$

of the annual rainfall varies between 15 and 70, from place to place with an average value of about 30. Variability is least in regions of high rainfall and largest in regions of scanty rainfall. Gujarat, Haryana, Punjab and Rajasthan have large variability of rainfall.

Some of the interesting statistics relating to the variability of the seasonal and annual rainfall of India are as follows:

- A few heavy spells of rain contribute nearly 90% of total rainfall.
- While the average annual rainfall of the country is 117 cm, average annual rainfall varies from 10 cm in the western desert to 1100 cm in the North East region.
- More than 50% rain occurs within 15 days and less than 100 hours in a year.
- More than 80% of seasonal rainfall is produced in 10–20% rain events each lasting 1–3 days.

2.5 MEASUREMENT OF PRECIPITATION

A. Rainfall

Precipitation is expressed in terms of the depth to which rainfall water would stand on an area if all the rain were collected on it. Thus 1 cm of rainfall over a catchment area of 1 km^2 represents a volume of water equal to 10^4 m^3. In the case of snowfall, an equivalent depth of water is used as the depth of precipitation. The precipitation is collected and measured in a *raingauge.* Terms such as *pluviometer, ombrometer* and *hyetometer* are also sometimes used to designate a raingauge.

A raingauge essentially consists of a cylindrical-vessel assembly kept in the open to collect rain. The rainfall catch of the raingauge is affected by its exposure conditions. To enable the catch of raingauge to accurately represent the rainfall in the area surrounding the raingauge standard settings are adopted. For siting a raingauge the following considerations are important:

- The ground must be level and in the open and the instrument must present a horizontal catch surface.
- The gauge must be set as near the ground as possible to reduce wind effects but it must be sufficiently high to prevent splashing, flooding, etc.
- The instrument must be surrounded by an open fenced area of at least 5.5 m × 5.5 m. No object should be nearer to the instrument than 30 m or twice the height of the obstruction.

Raingauges can be broadly classified into two categories as (i) nonrecording raingauges and (ii) recording gauges.

Nonrecording Gauges

The nonrecording gauge extensively used in India is the *Symons' gauge.* It essentially consists of a circular collecting area of 12.7 cm (5.0 inch) diameter connected to a

Mass Curve of Rainfall

The mass curve of rainfall is a plot of the accumulated precipitation against time, plotted in chronological order. Records of float type and weighing bucket type gauges are of this form. A typical mass curve of rainfall at a station during a storm is shown in Fig. 2.9. Mass curves of rainfall are very useful in extracting the information on the duration and magnitude of a storm. Also, intensities at various time intervals in a storm can be obtained by the slope of the curve. For nonrecording raingauges, mass curves are prepared from a knowledge of the approximate beginning and end of a storm and by using the mass curves of adjacent recording gauge stations as a guide.

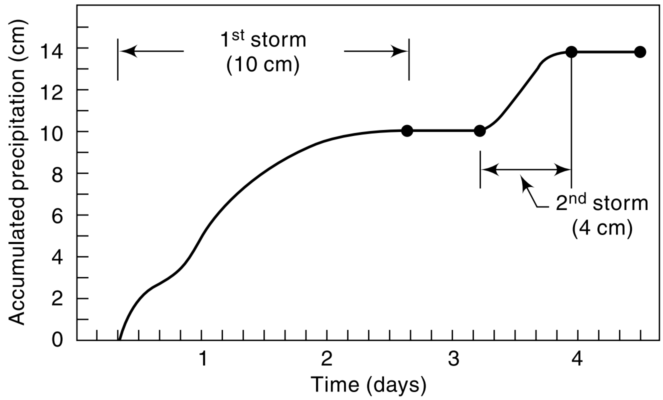


Fig. 2.9 Mass Curve of Rainfall

Hyetograph

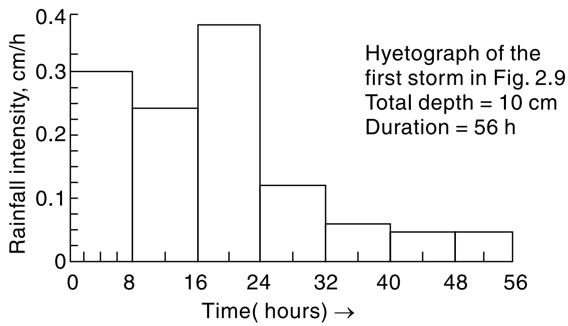


Fig. 2.10 Hyetograph of a Storm

A hyetograph is a plot of the intensity of rainfall against the time interval. The hyetograph is derived from the mass curve and is usually represented as a bar chart (Fig. 2.10). It is a very convenient way of representing the characteristics of a storm and is particularly important in the development of design storms to predict extreme floods. The area under a hyetograph represents the total precipitation received in the period. The time interval used depends on the purpose, in urban-drainage problems small durations are used while in flood-flow computations in larger catchments the intervals are of about 6 h.

Point Rainfall

Point rainfall, also known as *station rainfall* refers to the rainfall data of a station. Depending upon the need, data can be listed as daily, weekly, monthly, seasonal or annual values for various periods. Graphically these data are represented as plots of magnitude *vs* chronological time in the form of a bar diagram. Such a plot, however, is not convenient for discerning a trend in the rainfall as there will be considerable variations in the rainfall values leading to rapid changes in the plot. The trend is often discerned by the method of *moving averages*, also known as *moving means*.

Moving average Moving average is a technique for smoothening out the high frequency fluctuations of a time series and to enable the trend, if any, to be noticed. The basic principle is that a window of time range *m* years is selected. Starting from the first set of *m* years of data, the average of the data for *m* years is calculated and placed in the middle year of the range *m*. The window is next moved sequentially one time unit (year) at a time and the mean of the *m* terms in the window is determined at each window location. The value of *m* can be 3 or more years; usually an odd value. Generally, the larger the size of the range *m*, the greater is the smoothening. There are many ways of averaging (and consequently the plotting position of the mean) and the method described above is called Central Simple Moving Average. Example 2.4 describes the application of the method of moving averages.

EXAMPLE 2.4 *Annual rainfall values recorded at station M for the period 1950 to 1979 is given in Example 2.3. Represent this data as a bar diagram with time in chronological order. (i) Identify those years in which the annual rainfall is (a) less than 20% of the mean, and (b) more than the mean. (ii) Plot the three-year moving mean of the annual rainfall time series.*

SOLUTION: (i) Figure 2.11 shows the bar chart with height of the column representing the annual rainfall depth and the position of the column representing the year of occurrence. The time is arranged in chronological order.

The mean of the annual rainfall time series is 568.7 mm. As such, 20% less than the mean = 426.5 mm. Lines representing these values are shown in Fig. 2.11 as horizontal lines. It can be seen that in 6 years, viz. 1952, 1960, 1969, 1972, 1975 and 1978, the

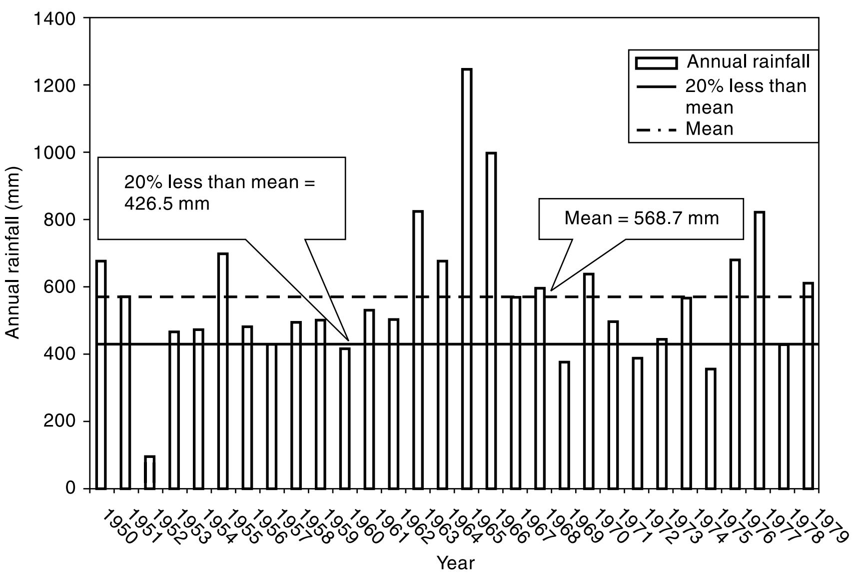


Fig. 2.11 Bar Chart of Annual Rainfall at Station *M*

annual rainfall values are less than 426.5 mm. In thirteen years, viz. 1950, 1951, 1955, 1963, 1964, 1965, 1966, 1967, 1968, 1970, 1976, 1977 and 1978, the annual rainfall was more than the mean.

(ii) Moving mean calculations are shown in Table 2.2. Three-year moving mean curve is shown plotted in Fig. 2.12 with the moving mean value as the ordinate and the time in chronological order as abscissa. Note that the curve starts from 1951 and ends in the year 1978. No apparent trend is indicated in this plot.

Table 2.2 Computation of Three-year Moving Mean

1	2	3	4
Year	**Annual Rainfall (mm) P_i**	**Three consecutive year total for moving mean ($P_{i-1} + P_i + P_{i+1}$)**	**3-year moving mean (Col. 3/3)***
1950	676		
1951	578	676 + 578 + 95 = 1349	449.7
1952	95	578 + 95 + 462 = 1135	378.3
1953	462	95 + 462 + 472 = 1029	343.0
1954	472	462 + 472 + 699 = 1633	544.3
1955	699	472 + 699 + 479 = 1650	550.0
1956	479	699 + 479 + 431 = 1609	536.3
1957	431	479 + 431 + 493 = 1403	467.7
1958	493	431 + 493 + 503 = 1427	475.7
1959	503	493 + 503 + 415 = 1411	470.3
1960	415	503 + 415 + 531 = 1449	483.0
1961	531	415 + 531 + 504 = 1450	483.3
1962	504	531 + 504 + 828 = 1863	621.0
1963	828	504 + 828 + 679 = 2011	670.3
1964	679	828 + 679 + 1244 = 2751	917.0
1965	1244	679 + 1244 + 999 = 2922	974.0
1966	999	1244 + 999 + 573 = 2816	938.7
1967	573	999 + 573 + 596 = 2168	722.7
1968	596	573 + 596 + 375 = 1544	514.7
1969	375	596 + 375 + 635 = 1606	535.3
1970	635	375 + 635 + 497 = 1507	502.3
1971	497	635 + 497 + 386 = 1518	506.0
1972	386	497 + 386 + 438 = 1321	440.3
1973	438	386 + 438 + 568 = 1392	464.0
1974	568	438 + 568 + 356 = 1362	454.0
1975	356	568 + 356 + 685 = 1609	536.3
1976	685	356 + 685 + 825 = 1866	622.0
1977	825	685 + 825 + 426 = 1936	645.3
1978	426	825 + 426 + 162 = 1863	621.0
1979	612		

*The moving mean is recorded at the mid span of 3 years.

2.9 MEAN PRECIPITATION OVER AN AREA

As indicated earlier, raingauges represent only point sampling of the areal

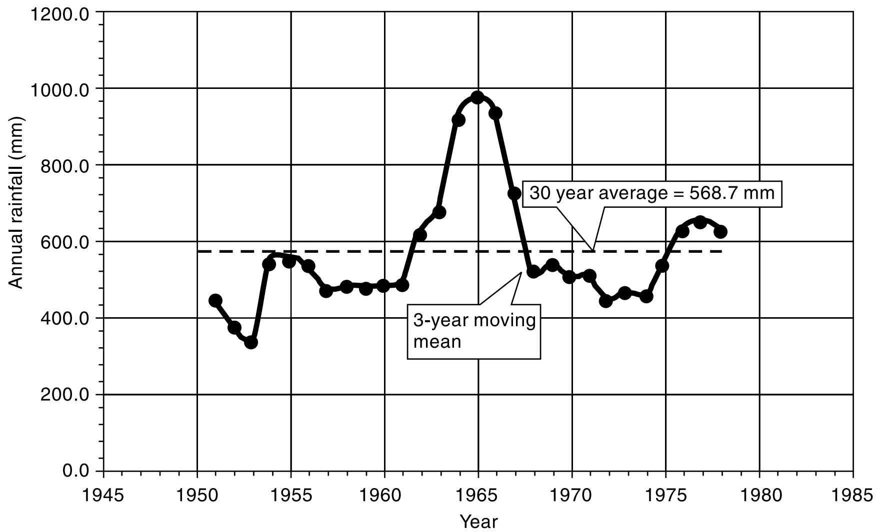


Fig. 2.12 Three-year Moving Mean

distribution of a storm. In practice, however, hydrological analysis requires a knowledge of the rainfall over an area, such as over a catchment.

To convert the point rainfall values at various stations into an average value over a catchment the following three methods are in use: (i) Arithmetical-mean method, (ii) Thiessen-polygon method, and (iii) Isohyetal method.

Arithmetical-Mean Method

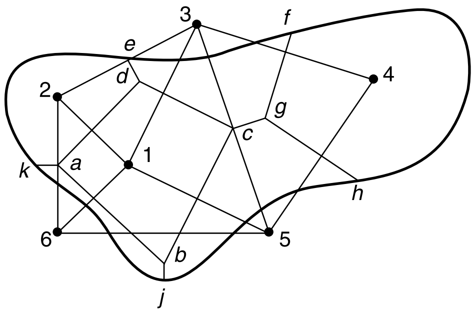
When the rainfall measured at various stations in a catchment show little variation, the average precipitation over the catchment area is taken as the arithmetic mean of the station values. Thus if $P_1, P_2, \ldots, P_i, \ldots P_n$ are the rainfall values in a given period in N stations within a catchment, then the value of the mean precipitation $\overline{P}$ over the catchment by the arithmetic-mean method is

$$\overline{P} = \frac{P_1 + P_2 + \ldots + P_i + \ldots + P_n}{N} = \frac{1}{N} \sum_{i=1}^{N} P_i \qquad (2.7)$$

In practice, this method is used very rarely.

Thiessen-Mean Method

In this method the rainfall recorded at each station is given a weightage on the basis of an area closest to the station. The procedure of determining the weighing area is as follows: Consider a catchment area as in Fig. 2.13 containing three raingauge stations. There are three stations outside the catchment but in its neighbourhood. The catchment area is drawn to scale and the positions of the six stations marked on it. Stations 1 to 6 are joined to form a network of triangles. Perpendicular bisectors for each of the sides of the triangle are drawn. These bisectors form a polygon around each station. The boundary of the catchment, if it cuts the bisectors is taken as the outer limit of the polygon. Thus for station 1, the bounding polygon is *abcd.* For station 2, *kade* is taken as the bounding polygon. These bounding polygons are called *Thiessen polygons.* The areas of these six Thiessen polygons are determined either with a planimeter or



A = total catchment area

Station	Bounded by	Area	Weightage
1	abcd	A_1	A_1/A
2	kade	A_2	A_2/A
3	edcgf	A_3	A_3/A
4	fgh	A_4	A_4/A
5	hgcbj	A_5	A_5/A
6	jbak	A_6	A_6/A

Fig. 2.13 Thiessen Polygons

by using an overlay grid. If P_1 P_2,… , P_6 are the rainfall magnitudes recorded by the stations 1, 2,…, 6 respectively, and A_1, A_2,…, A_6 are the respective areas of the Thiessen polygons, then the average rainfall over the catchment $\overline{P}$ is given by

$$\overline{P} = \frac{P_1 A_1 + P_2 A_2 + \ldots + P_6 A_6}{(A_1 + A_2 + \ldots + A_6)}$$

Thus in general for M stations,

$$\overline{P} = \frac{\sum_{i=1}^{M} P_i A_i}{A} = \sum_{i=1}^{M} P_i \frac{A_i}{A} \tag{2.8}$$

The ratio $\frac{A_i}{A}$ is called the *weightage factor* for each station.

The Thiessen-polygon method of calculating the average percipitation over an area is superior to the arithmetic-average method as some weightage is given to the various stations on a rational basis. Further, the raingauge stations outside the catchment are also used effectively. Once the weightage factors are determined, the calculation of $\overline{P}$ is relatively easy for a fixed network of stations.

Isohyetal Method

An *isohyet* is a line joining points of equal rainfall magnitude. In the isohyetal method, the catchment area is drawn to scale and the raingauge stations are marked. The recorded values for which areal average $\overline{P}$ is to be determined are then marked on the plot at appropriate stations. Neighbouring stations outside the catchment are also considered. The isohyets of various values are then drawn by considering point rain-

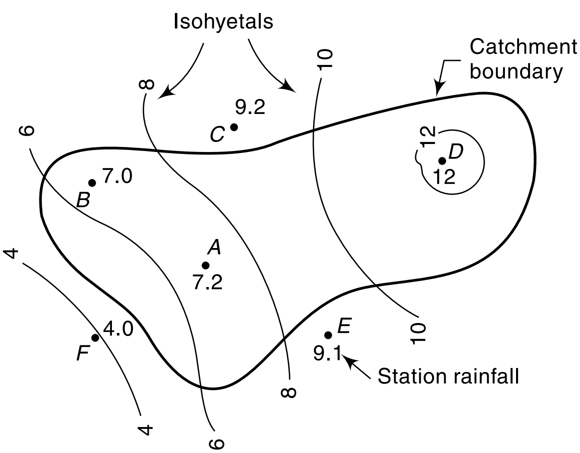


Fig. 2.14 Isohyetals of a Storm

falls as guides and interpolating between them by the eye (Fig. 2.14). The procedure is similar to the drawing of elevation contours based on spot levels.

The area between two adjacent isohyets are then determined with a planimeter. If the isohyets go out of catchment, the catchment boundary is used as the bounding line. The average value of the rainfall indicated by two isohyets is assumed to be acting over the inter-isohyet area. Thus $P_1, P_2, \ldots, P_n$ are the values of isohyets and if $a_1, a_2, \ldots, a_{n-1}$ are the inter-isohyet areas respectively, then the mean precipitation over the catchment of area A is given by

$$\bar{P} = \frac{a_1\left(\frac{P_1 + P_2}{2}\right) + a_2\left(\frac{P_2 + P_3}{2}\right) + \ldots + a_{n-1}\left(\frac{P_{n-1} + P_n}{2}\right)}{A} \tag{2.9}$$

The isohyet method is superior to the other two methods especially when the stations are large in number.

Example 2.5 *In a catchment area, approximated by a circle of diameter 100 km, four rainfall stations are situated inside the catchment and one station is outside in its neighbourhood. The coordinates of the centre of the catchment and of the five stations are given below. Also given are the annual precipitation recorded by the five stations in 1980. Determine the average annual precipitation by the Thiessen-mean method.*

Centre: (100, 100) Diameter: 100 km.
Distance are in km

Station	1	2	3	4	5
Coordinates	(30, 80)	(70, 100)	(100, 140)	(130, 100)	(100, 70)
Precipitation (cm)	85.0	135.2	95.3	146.4	102.2

Solution: The catchment area is drawn to scale and the stations are marked on it (Fig. 2.15). The stations are joined to form a set of triangles and the perpendicular bisector of each side is then drawn. The Thiessen-polygon area enclosing each station is then identified. It may be noted that station 1 in this problem does not have any area of influence in the catchment. The areas of various Thiessen polygons are determined either by a planimeter or by placing an overlay grid.

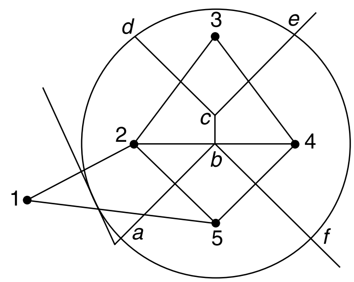


Fig. 2.15 Thiessen Polygons—Example 2.5

Station	Boundary of area	Area (km^2)	Fraction of total area	Rainfall	Weighted *P* (cm) (col. 4 × col. 5)
1	—	—	—	85.0	—
2	abcd	2141	0.2726	135.2	36.86
3	dce	1609	0.2049	95.3	19.53
4	ecbf	2141	0.2726	146.4	39.91
5	fba	1963	0.2499	102.2	25.54
Total		7854	1.000		121. 84

Mean precipitation = 121.84 cm.

EXAMPLE 2.6 *The isohyets due to a storm in a catchment were drawn (Fig. 2.14) and the area of the catchment bounded by isohyets were tabulated as below.*

Isohyets (cm)	Area (km^2)
Station–12.0	30
12.0–10.0	140
10.0–8.0	80
8.0–6.0	180
6.0–4.0	20

Estimate the mean precipitation due to the storm.

SOLUTION: For the first area consisting of a station surrounded by a closed isohyet, a precipitation value of 12.0 cm is taken. For all other areas, the mean of two bounding isohyets are taken.

Isohytes	Average value of P (cm)	Area (km^2)	Fraction of total area (col. 3/450)	Weighted *P* (cm) (col. 2 × col. 4)
1	2	3	4	5
12.0	12.0	30	0.0667	0.800
12.0–10.0	11.0	140	0.3111	3.422
10.0–8.0	9.0	80	0.1778	1.600
8.0–6.0	7.0	180	0.4000	2.800
6.0–4.0	5.0	20	0.0444	0.222
Total		450	1.0000	8.844

Mean precipitation $\bar{P}$ = 8.84 cm

2.10 DEPTH-AREA-DURATION RELATIONSHIPS

The areal distribution characteristics of a storm of given duration is reflected in its depth-area relationship. A few aspects of the interdependency of depth, area and duration of storms are discussed below.

DEPTH-AREA RELATION

For a rainfall of a given duration, the average depth decreases with the area in an exponential fashion given by

$$\bar{P} = P_0 \exp(-KA^n) \tag{2.10}$$

where $\bar{P}$ = average depth in cm over an area A km^2, P_0 = highest amount of rainfall in cm at the storm centre and K and n are constants for a given region. On the basis of 42 severemost storms in north India, Dhar and Bhattacharya[3] (1975) have obtained the following values for K and n for storms of different duration:

Duration	*K*	*n*
1 day	0.0008526	0.6614
2 days	0.0009877	0.6306
3 days	0.001745	0.5961

Since it is very unlikely that the storm centre coincides over a raingauge station, the exact determination of P_0 is not possible. Hence in the analysis of large area storms the highest station rainfall is taken as the average depth over an area of 25 km^2.

Equation (2.10) is useful in extrapolating an existing storm data over an area.

Maximum Depth-Area-Duration Curves

In many hydrological studies involving estimation of severe floods, it is necessary to have information on the maximum amount of rainfall of various durations occurring over various sizes of areas. The development of relationship, between maximum depth-area-duration for a region is known as DAD analysis and forms an important aspect of hydro-meteorological study. References 2 and 9 can be consulted for details on DAD analysis. A brief description of the analysis is given below.

First, the severemost rainstorms that have occurred in the region under question are considered. Isohyetal maps and mass curves of the storm are compiled. A depth-area curve of a given duration of the storm is prepared. Then from a study of the mass curve of rainfall, various durations and the maximum depth of rainfall in these durations are noted. The maximum depth-area curve for a given duration D is prepared by assuming the area distribution of rainfall for smaller duration to be similar to the total storm. The procedure is then repeated for different storms and the envelope curve of maximum depth-area for duration D is obtained. A similar procedure for various values of D results in a family of envelope curves of maximum depth *vs* area, with duration as the third parameter (Fig. 2.16). These curves are called *DAD curves*.

Figure 2.16 shows typical DAD curves for a catchment. In this the average depth denotes the depth averaged over the area under consideration. It may be seen that the maximum depth for a given storm decreases with the area; for a given area the maximum depth increases with the duration.

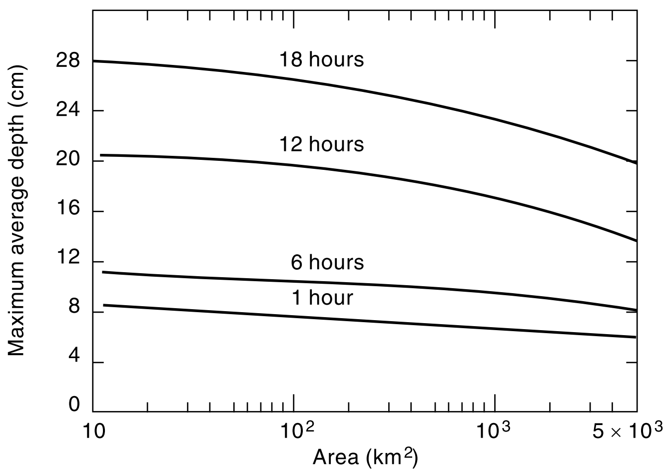


Fig. 2.16 Typical DAD Curves

Preparation of DAD curves involves considerable computational effort and requires meteorological and topographical information of the region. Detailed data on severemost storms in the past are needed. DAD curves are essential to develop design storms for use in computing the design flood in the hydrological design of major structures such as dams.

Table 2.3 Maximum (Observed) Rain Depths (cm) over Plains of North India[4, 5]

Duration	Area in km^2 × 10^4								
	.026	**0.13**	**0.26**	**1.3**	**2.6**	**5.2**	**7.8**	**10.5**	**13.0**
1 day	81.0*	76.5*	71.1	47.2*	37.1 *	26.4	20.3†	18.0†	16.0†
2 days	102.9*	97.5*	93.2*	73.4*	58.7*	42.4*	35.6†	31.5†	27.9†
3 days	121.9†	110.7†	103.1†	79.2†	67.1†	54.6†	48.3†	42.7†	38.9†

Note: *—Storm of 17–18 September 1880 over north-west U.P.
†—Storm of 28–30 July 1927 over north Gujarat.

Maximum rain depths observed over the plains of north India are indicated in Table 2.3. These were due to two storms, which are perhaps the few severe most recorded rainstorms over the world.

2.11 FREQUENCY OF POINT RAINFALL

In many hydraulic-engineering applications such as those concerned with floods, the probability of occurrence of a particular extreme rainfall, e.g. a 24-h maximum rainfall, will be of importance. Such information is obtained by the frequency analysis of the point-rainfall data. The rainfall at a place is a random hydrologic process and a sequence of rainfall data at a place when arranged in chronological order constitute a time series. One of the commonly used data series is the annual series composed of annual values such as annual rainfall. If the extreme values of a specified event occurring in each year is listed, it also constitutes an annual series. Thus for example, one may list the maximum 24-h rainfall occurring in a year at a station to prepare an annual series of 24-h maximum rainfall values. The probability of occurrence of an event in this series is studied by frequency analysis of this annual data series. A brief description of the terminology and a simple method of predicting the frequency of an event is described in this section and for details the reader is referred to standard works on probability and statistical methods. The analysis of annual series, even though described with rainfall as a reference is equally applicable to any other random hydrological process, e.g. stream flow.

First, it is necessary to correctly understand the terminology used in frequency analysis. The probability of occurrence of an event of a random variable (e.g. rainfall) whose magnitude is equal to or in excess of a specified magnitude X is denoted by P. The *recurrence interval* (also known as *return period*) is defined as

$$T = 1/P \tag{2.11}$$

This represents the average interval between the occurrence of a rainfall of magnitude equal to or greater than X. Thus if it is stated that the return period of rainfall of 20 cm in 24 h is 10 years at a certain station A, it implies that on an average rainfall magnitudes equal to or greater than 20 cm in 24 h occur once in 10 years, i.e. in a long period of say 100 years, 10 such events can be expected. However, it does not mean that every 10 years one such event is likely, i.e. periodicity is not implied. The probability of a rainfall of 20 cm in 24 h occurring in anyone year at station A is $1/T = 1/10 = 0.1$.

If the probability of an event occurring is P, the probability of the event *not occurring* in a given year is $q = (1 - P)$. The binomial distribution can be used to find the probability of occurrence of the event r times in n successive years. Thus

$$P_{r,n} = {}^nC_r P_r q^{n-r} = \frac{n!}{(n-r)!\,r!} P^r q^{n-r} \tag{2.12}$$

where $P_{r,n}$ = probability of a random hydrologic event (rainfall) of given magnitude and exceedence probability P occurring r times in n successive years. Thus, for example,

(a) The probability of an event of exceedence probability P occurring 2 times in n successive years is

$$P_{2,n} = \frac{n!}{(n-2)!\,2!} P^2 q^{n-2}$$

(b) The probability of the event not occurring at all in n successive years is

$$P_{0,n} = q^n = (1 - P)^n$$

(c) The probability of the event occurring at least once in n successive years

$$P_1 = 1 - q^n = 1 - (1 - P)^n \tag{2.13}$$

Example 2.7 *Analysis of data on maximum one-day rainfall depth at Madras indicated that a depth of 280 mm had a return period of 50 years. Determine the probability of a one-day rainfall depth equal to or greater than 280 mm at Madras occurring (a) once in 20 successive years, (b) two times in 15 successive years, and (c) at least once in 20 successive years.*

Solution: Here $P = \frac{1}{50} = 0.02$

By using Eq. (2.12):

(a) $n = 20$, $r = 1$

$$P_{1,20} = \frac{20!}{19!1!} \times 0.02 \times (0.98)^{19} = 20 \times 0.02 \times 0.68123 = 0.272$$

(b) $n = 15$, $r = 2$

$$P_{2,15} = \frac{15!}{13!2!} \times (0.02)^2 \times (0.98)^{13} = 15 \times \frac{14}{2} \times 0.0004 \times 0.769 = 0.323$$

(c) By Eq. (2.13)

$$P_1 = 1 - (1 - 0.02)^{20} = 0.332$$

Plotting Position

The purpose of the frequency analysis of an annual series is to obtain a relation between the magnitude of the event and its probability of exceedence. The probability analysis may be made either by empirical or by analytical methods.

A simple empirical technique is to arrange the given annual extreme series in descending order of magnitude and to assign an order number m. Thus for the first entry $m = 1$, for the second entry $m = 2$, and so on, till the last event for which $m = N$ = Number of years of record. The probability P of an event equalled to or exceeded is given by the *Weibull formula*

$$P = \left(\frac{m}{N+1}\right) \tag{2.14}$$

The recurrence interval $T = 1/P = (N + 1)/m$.

Equation (2.14) is an empirical formula and there are several other such empirical formulae available to calculate P (Table 2.4). The exceedence probability of the event obtained by the use of an empirical formula, such as Eq. (2.14) is called *plotting position.* Equation (2.14) is the most popular plotting position formula and hence only this formula is used in further sections of this book.

Table 2.4 Plotting Position Formulae

Method	P
California	m/N
Hazen	$(m - 0.5)/N$
Weibull	$m/(N + 1)$
Chegodayev	$(m - 0.3)/(N + 0.4)$
Blom	$(m - 0.44)/(N + 0.12)$
Gringorten	$(m - 3/8)/(N + 1/4)$

Having calculated P (and hence T) for all the events in the series, the variation of the rainfall magnitude is plotted against the corresponding T on a semi-log paper (Fig. 2.17) or log-log paper. By suitable extrapolation of this plot, the rainfall magnitude of specific duration for any recurrence interval can be estimated.

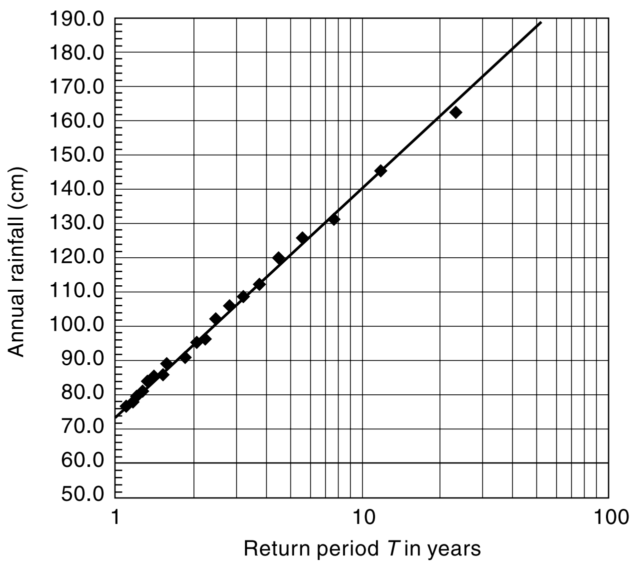


Fig. 2.17 Return Periods of Annual Rainfall at Station *A*

This simple empirical procedure can give good results for small extrapolations and the errors increase with the amount of extrapolation. For accurate work, various analytical calculation procedures using frequency factors are available. Gumbel's extreme value distribution and Log Pearson Type III method are two commonly used analytical methods and are described in Chap. 7 of this book.

If P is the probability of exceedence of a variable having a magnitude M, a common practice is to designate the magnitude M as having (100 P) percent dependability. For example, 75% dependable annual rainfall at a station means the value of annual rainfall at the station that can be expected to be equalled to or exceeded 75% times, (i.e., on an average 30 times out of 40 years). Thus 75% dependable annual rainfall means the value of rainfall in the annual rainfall time series that has $P = 0.75$, i.e., $T = 1/P = 1.333$ years.

Example 2.8 *The record of annual rainfall at Station A covering a period of 22 years is given below. (a) Estimate the annual rainfall with return periods of 10 years and 50 years. (b) What would be the probability of an annual rainfall of magnitude equal to or exceeding 100 cm occurring at Station A? (b) What is the 75% dependable annual rainfall at station A?*

Year	Annual rainfall (cm)	Year	Annual rainfall (cm)
1960	130.0	1971	90.0
1961	84.0	1972	102.0
1962	76.0	1973	108.0
1963	89.0	1974	60.0
1964	112.0	1975	75.0
1965	96.0	1976	120.0
1966	80.0	1977	160.0
1967	125.0	1978	85.0
1968	143.0	1979	106.0
1969	89.0	1980	83.0
1970	78.0	1981	95.0

Solution: The data are arranged in descending order and the rank number assigned to the recorded events. The probability P of the event being equalled to or exceeded is calculated by using Weibull formula (Eq. 2.14). Calculations are shown in Table 2.5. It may be noted that when two or more events have the same magnitude (as for m = 13 and 14 in Table 2.5) the probability P is calculated for the largest m value of the set. The return period T is calculated as $T = 1/P$.

Table 2.5 Calculation of Return Periods

N = 22 years

m	Annual Rainfall (cm)	Probability $= m/(N+1)$	Return Period $T = 1/P$ (years)	m	Annual Rainfall (cm)	Probability $P = m/(N+1)$	Return Period $T = 1/P$ (Years)
1	160.0	0.043	23.000	12	90.0	0.522	1.917
2	143.0	0.087	11.500	13	89.0	0.565	
3	130.0	0.130	7.667	14	89.0	0.609	1.643
4	125.0	0.174	5.750	15	85.0	0.652	1.533
5	120.0	0.217	4.600	16	84.0	0.696	1.438
6	112.0	0.261	3.833	17	83.0	0.739	1.353
7	108.0	0.304	3.286	18	80.0	0.783	1.278
8	106.0	0.348	2.875	19	78.0	0.826	1.211
9	102.0	0.391	2.556	20	76.0	0.870	1.150
10	96.0	0.435	2.300	21	75.0	0.913	1.095
11	95.0	0.478	2.091	22	60.0	0.957	1.045

A graph is plotted between the annual rainfall magnitude as the ordinate (on arithmetic scale) and the return period T as the abscissa (on logarithmic scale), (Fig. 2.17). It can be seen that excepting the point with the lowest T, a straight line could represent the trend of the rest of data.

(a) (i) For $T = 10$ years, the corresponding rainfall magnitude is obtained by interpolation between two appropriate successive values in Table 2.5, viz. those having $T = 11.5$ and 7.667 years respectively, as 137.9 cm

(ii) for $T = 50$ years the corresponding rainfall magnitude, by extrapolation of the best fit straight line, is 180.0 cm

(b) Return period of an annual rainfall of magnitude equal to or exceeding 100 cm, by interpolation, is 2.4 years. As such the exceedence probability $P = \frac{1}{2.4} = 0.417$

(c) 75% dependable annual rainfall at Station A = Annual rainfall with probability $P = 0.75$, i.e. $T = 1/0.75 = 1.33$ years. By interpolation between two successive values in Table 2.7 having $T = 1.28$ and 1.35 respectively, the 75% dependable annual rainfall at Station A is 82.3 cm.

2.12 MAXIMUM INTENSITY-DURATION-FREQUENCY RELATIONSHIP

Maximum Intensity-Duration Relationship

In any storm, the actual intensity as reflected by the slope of the mass curve of rainfall varies over a wide range during the course of the rainfall. If the mass curve is considered divided into N segments of time interval Δt such that the total duration of the storm $D = N\,\Delta t$, then the intensity of the storm for various sub-durations $t_j = (1.\,\Delta t)$, $(2.\,\Delta t)$, $(3.\,\Delta t)$,…$(j.\,\Delta t)$… and $(N.\,\Delta t)$ could be calculated. It will be found that for each duration (say t_j), the intensity will have a maximum value and this could be analysed to obtain a relationship for the variation of the maximum intensity with duration for the storm. This process is basic to the development of maximum intensity duration frequency relationship for the station discussed later on.

Briefly, the procedure for analysis of a mass curve of rainfall for developing maximum intensity-duration relationship of the storm is as follows.

- Select a convenient time step Δt such that duration of the storm $D = N.\,\Delta t$.
- For each duration (say $t_j = j.\Delta t$) the mass curve of rainfall is considered to be divided into consecutive segments of duration t_j . For each segment the incremental rainfall d_j in duration t_j is noted and intensity $I_j = d_j/t_j$ obtained.
- Maximum value of the intensity (I_{mj}) for the chosen t_j is noted.
- The procedure is repeated for all values of $j = 1$ to N to obtain a data set of I_{mj} as a function of duration t_j. Plot the maximum intensity I_m as function of duration t.
- It is common to express the variation of I_m with t as

$$I_m = \frac{c}{(t+a)^b}$$

where a, b and c are coefficients obtained through regression analysis. Example 2.9 describes the procedure in detail.

Maximum Depth-Duration Relationship

Instead of the maximum intensity I_m in a duration t, the product $(I_m.\ t) = d_m$ = maximum depth of precipitation in the duration t could be used to relate it to the duration.

Such a relationship is known as the maximum depth-duration relationship of the storm. The procedure of developing this relationship is essentially same as that for maximum intensity-duration relationship described earlier.

Example 2.9 describes the procedure in detail

Maximum Intensity-Duration-Frequency Relationship

If the rainfall data from a self-recording raingauge is available for a long period, the frequency of occurrence of maximum intensity occurring over a specified duration can be determined. A knowledge of maximum intensity of rainfall of specified return period and of duration equal to the critical time of concentration is of considerable practical importance in evaluating peak flows related to hydraulic structures.

Briefly, the procedure to calculate the intensity-duration-frequency relationship for a given station is as follows.

- M numbers of significant and heavy storms in a particular year Y_1 are selected for analysis. Each of these storms are analysed for maximum intensity duration relationship as described in Sec. 2.12.1
- This gives the set of maximum intensity I_m as a function of duration for the year Y_1.
- The procedure is repeated for all the N years of record to obtain the maximum intensity $I_m\ (D_j)_k$ for all $j = 1$ to M and $k = 1$ to N.
- Each record of $I_m\ (D_j)_k$ for $k = 1$ to N constitutes a time series which can be analysed to obtain frequencies of occurrence of various $I_m\ (D_j)$ values. Thus there will be M time series generated.
- The results are plotted as maximum intensity *vs* return period with the *Duration* as the third parameter (Fig. 2.18). Alternatively, maximum intensity *vs* duration with frequency as the third variable can also be adopted (Fig. 2.19).

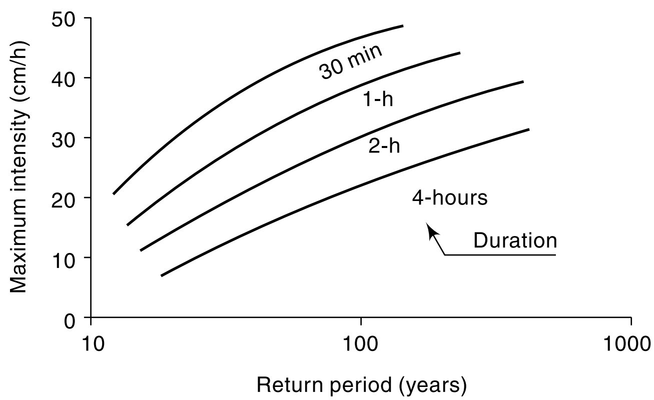


Fig. 2.18 Maximum Intensity-Return Period-Duration Curves

Analytically, these relationships are commonly expressed in a condensed form by general form

$$i = \frac{KT^x}{(D + a)^n} \tag{2.15}$$

where i = maximum intensity (cm/h), T = return period (years), D = duration (hours) K, x, a and n are coefficients for the area represented by the station.

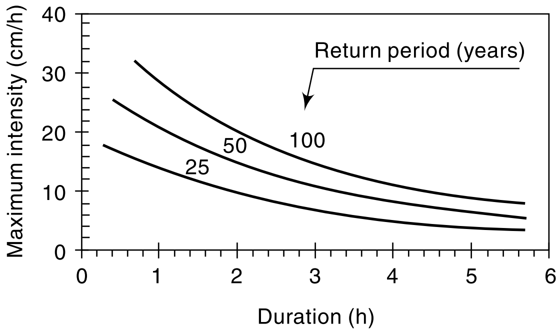


Fig. 2.19 Maximum Intensity-Duration-Frequency Curves

Sometimes, instead of maximum intensity, maximum depth is used as a parameter and the results are represented as a plot of maximum depth *vs* duration with return period as the third variable (Fig. 2.20).

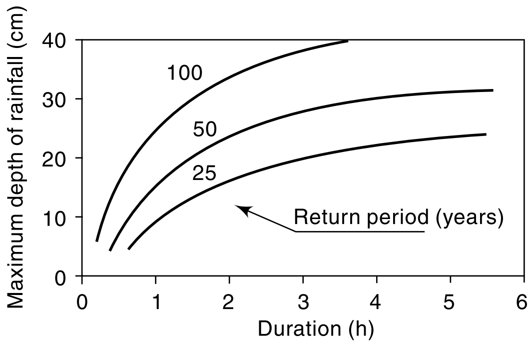


Fig. 2.20 Maximum Depth-Duration-Frequency Curves

[*Note:* While maximum intensity is expressed as a function of duration and return period, it is customary to refer this function as intensity-duration-frequency relationship. Similarly, in the depth-duration-frequency relationship deals with maximum depth in a given duration.]

Rambabu et al. (1979)[10] have analysed the self-recording rain gauge rainfall records of 42 stations in the country and have obtained the values of coefficients *K*, *x*, *a*, and *n* of Eq. 2.15. Some typical values of the coefficients for a few places in India are given in Table 2.6.

Table 2.6 Typical values of Coefficients *K, x, a* and *n* in Eq. (2.15)

[Ref. 10]

Zone	Place	K	*x*	*a*	*n*
Northern Zone	Allahabad	4.911	0.1667	0.25	0.6293
	Amritsar	14.41	0.1304	1.40	1.2963
	Dehradun	6.00	0.22	0.50	0.8000
	Jodhpur	4.098	0.1677	0.50	1.0369
	Srinagar	1.503	0.2730	0.25	1.0636
	Average for the zone	5.914	0.1623	0.50	1.0127
Central Zone	Bhopal	6.9296	0.1892	0.50	0.8767
	Nagpur	11.45	0.1560	1.25	1.0324
	Raipur	4.683	0. 1389	0.15	0.9284
	Average for the zone	7.4645	0.1712	0.75	0.9599
Western Zone	Aurangabad	6.081	0.1459	0.50	1.0923
	Bhuj	3.823	0.1919	0.25	0.9902

(*Contd.*)

(*Contd.*)

	Veraval	7.787	0.2087	0.50	0.8908
	Average for the zone	3.974	0.1647	0.15	0.7327
Eastern Zone	Agarthala	8.097	0.1177	0.50	0.8191
	Kolkata (Dumdum)	5.940	0.1150	0.15	0.9241
	Gauhati	7.206	0.1157	0.75	0.9401
	Jarsuguda	8.596	0.1392	0.75	0.8740
	Average for the zone	6.933	0.1353	0.50	0.8801
Southern Zone	Bangalore	6.275	0.1262	0.50	1.1280
	Hyderabad	5.250	0.1354	0.50	1.0295
	Chennai	6.126	0.1664	0.50	0.8027
	Trivandrum	6.762	0.1536	0.50	0.8158
	Average for the zone	6.311	0.1523	0.50	0.9465

Extreme point rainfall values of different durations and for different return periods have been evaluated by IMD and the *iso-pluvial* (lines connecting equal depths of rainfall) maps covering the entire country have been prepared. These are available for rainfall durations of 15 min, 30 min, 45 min, 1 h, 3 h, 6 h, 9 h, 15 h and 24 h for return periods of 2, 5, 10, 25, 50 and 100 years. A typical 50 year–24 h maximum rainfall map of the southern peninsula is given in Fig. 2.21. The 50 year-l h maximum rainfall

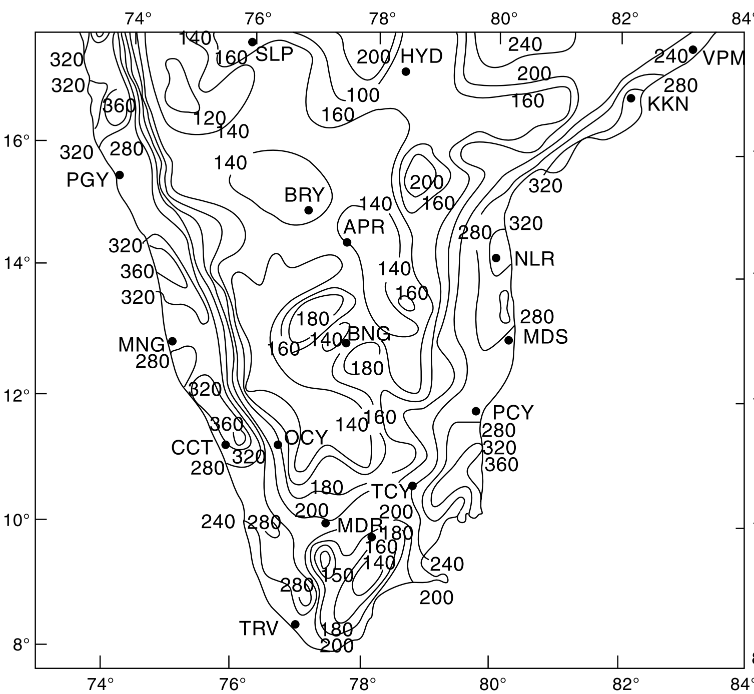


Fig. 2.21 Isopluvial Map of 50 yr-24 h Maximum Rainfall (mm) (Reproduced with permission from India Meteorological Department)

Based upon Survey of India map with the permission of the Surveyor General of India, © Government of India Copyright 1984

The territorial waters of India extend into the sea to a distance of 200 nautical miles measured from the appropriate baseline

Responsibility for the correctness of the internal details on the map rests with the publisher.

depths over India and the neighbourhood are shown in Fig. 2.22. Isopluvial maps of the maximum rainfall of various durations and of 50-year return periods covering the entire country are available in Ref. 1.

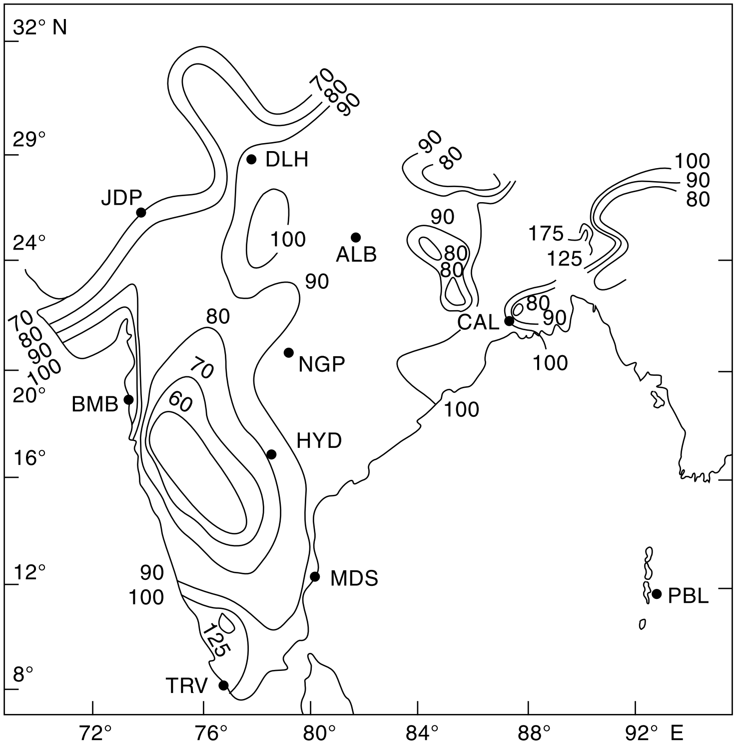


Fig. 2.22 Isopluvial Map of 50 yr-l h Maximum Rainfall (mm) (Reproduced from *Natural Resources of Humid Tropical Asia—Natural Resources Research,* XII. © UNESCO, 1974, with permission of UNESCO)

Example 2.9 *The mass curve of rainfall in a storm of total duration 270 minutes is given below. (a) Draw the hyetograph of the storm at 30 minutes time step. (b) Plot the maximum intensity-duration curve for this storm. (c) Plot the maximum depth-duration curve for the storm.*

Times since Start in Minutes	0	30	60	90	120	150	180	210	240	270
Cumulative Rainfall (mm)	0	6	18	21	36	43	49	52	53	54

Solution: (a) Hyetograph: The intensity of rainfall at various time durations is calculated as shown below:

Time since Start (min)	30	60	90	120	150	180	210	240	270
Cumulative Rainfall (mm)	6.0	18.0	21.0	36.0	43.0	49.0	52.0	53.0	54.0
Incremental depth of rainfall in the interval (mm)	6.0	12.0	3.0	15.0	7.0	6.0	3.0	1.0	1.0
Intensity (mm/h)	12.0	24.0	6.0	30.0	14.0	12.0	6.0	2.0	2.0

The hyetograph of the storm is shown in Fig. 2.23

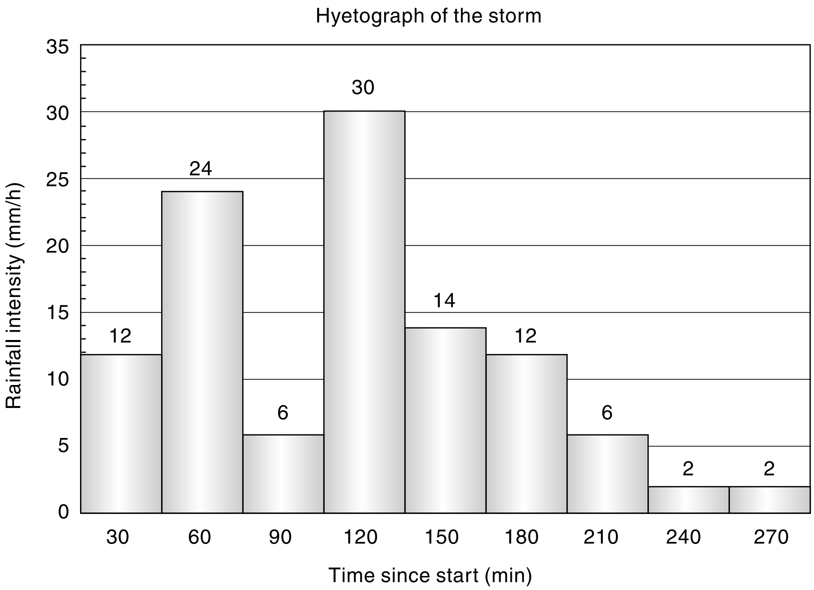


Fig. 2.23 Hyetograph of the Storm—Example 2.9

(b) Various durations Δt = 30, 60, 90 … 240, 270 minutes are chosen. For each duration Δt a series of running totals of rainfall depth is obtained by starting from various points of the mass curve. This can be done systematically as shown in Table 2.7(a & b). By inspection the maximum depth for each t_j is identified and corresponding maximum intensity is calculated. In Table 2.7(a) the maximum depth is marked by bold letter and maximum intensity corresponding to a specified duration is shown in Row No. 3 of Table 2.7(b). The data obtained from the above analysis is plotted as maximum depth *vs* duration and maximum intensity *vs* duration as shown in Fig. 2.24.

2.13 PROBABLE MAXIMUM PRECIPITATION (PMP)

In the design of major hydraulic structures such as spillways in large dams, the hydrologist and hydraulic engineer would like to keep the failure probability as low as possible, i.e. virtually zero. This is because the failure of such a major structure will cause very heavy damages to life, property, economy and national morale. In the design and analysis of such structures, the maximum possible precipitation that can reasonably be expected at a given location is used. This stems from the recognition that there is a physical upper limit to the amount of precipitation that can fall over a specified area in a given time.

Table 2.7(a) Maximum Intensity-Duration Relation

Time (min.)	Cumulative Rainfall (mm)	Incremental depth of rainfall (mm) in various durations — Durations(min) 30	60	90	120	150	180	210	240	270
0	0									
30	6	6								
60	18	12	18							
90	21	3	15	21						
120	36	**15**	18	**30**	36					
150	43	7	**22**	25	**37**	43				
180	49	6	13	28	31	**43**	**49**			
210	52	3	9	16	31	34	46	**52**		
240	53	1	4	10	17	32	35	47	**53**	
270	54	1	2	5	11	18	33	36	48	**54**

Table 2.7(b) Maximum Intensity-Maximum Depth-Duration Relation

Maximum Intensity (mm/h)	30.0	22.0	20.0	18.5	17.2	16.3	14.9	13.3	12.0
Duration in min.	30	60	90	120	150	180	210	240	270
Maximum Depth (mm)	15.0	22.0	30.0	37.0	43.0	49.0	52.0	53.0	54.0

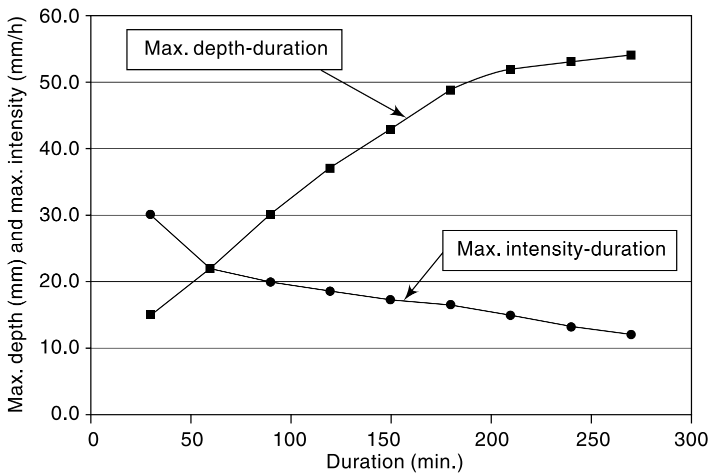


Fig. 2.24 Maximum Intensity-Duration and Maximum Depth-Duration Curves for the Storm of Example 2.9

The probable maximum precipitation (PMP) is defined as the greatest or extreme rainfall for a given duration that is physically possible over a station or basin. From the operational point of view, PMP can be defined as that rainfall over a basin which would produce a flood flow with virtually no risk of being exceeded. The development of PMP for a given region is an involved procedure and requires the knowledge of an experienced hydrometeorologist. Basically two approaches are used (i) Meteorological methods and (ii) the statistical study of rainfall data. Details of meteorological methods that use storm models are available in published literature.[8]

Statistical studies indicate that PMP can be estimated as

$$\text{PMP} = \bar{P} + K\sigma \tag{2.16}$$

where $\bar{P}$ = mean of annual maximum rainfall series, σ = standard deviation of the series and K = a frequency factor which depends upon the statistical distribution of the series, number of years of record and the return period. The value of K is usually in the neighbourhood of 15. Generalised charts for one-day PMP prepared on the basis of the statistical analysis of 60 to 70 years of rainfall data in the North-Indian plain area (Lat. 20° N to 32° N, Long. 68° E to 89° E) are available in Refs 4 and 5. It is found that PMP estimates for North-Indian plains vary from 37 to 100 cm for one-day rainfall. Maps depicting isolines of 1-day PMP over different parts of India are available in the PMP atlas published by the Indian Institute of Tropical Meteorology.[6]

World's Greatest Observed Rainfall

Based upon the rainfall records available all over the world, a list of world's greatest recorded rainfalls of various duration can be assembled. When this data is plotted on a log-log paper, an enveloping straight line drawn to the plotted points obeys the equation.

$$P_m = 42.16\, D^{0.475} \tag{2.17}$$

where P_m = extreme rainfall depth in cm and D = duration in hours. The values obtained from this Eq. (2.17) are of use in PMP estimations.

2.14 RAINFALL DATA IN INDIA

Rainfall measurement in India began in the eighteenth century. The first recorded data were obtained at Calcutta (1784) and it was followed by observations at Madras (1792), Bombay (1823) and Simla (1840). The India Meteorological Department (IMD) was established in 1875 and the rainfall resolution of the Government of India in 1930 empowered IMD to have overall technical control of rainfall registration in the country. According to this resolution, which is still the basis, the recording, collection and publication of rainfall data is the responsibility of the state government whereas the technical control is under IMD. The state government have the obligation to supply daily, monthly and annual rainfall data to IMD for compilation of its two important annual publications entitled *Daily Rainfall of India* and *Monthly Rainfall of India.*

India has a network of observatories and rain gauges maintained by IMD. Currently (2005), IMD has 701 hydrometeorological observatories and 201 agrometeorological observatories. In addition there are 8579 rain gauge stations out of which 3540 stations report their data to IMD. A fair amount of these gauges are of self-recording type and IMD operates nearly 400 self-recording rain gauges.

A set of 21 snow gauges, 10 ordinary rain gauges and 6 seasonal snow poles form part of glaciological observatories of the country.

In addition to the above, a large number of rain gauges are maintained by different governmental agencies such as Railways, State departments of Agriculture, Forestry and Irrigation and also by private agencies like coffee and tea plantations. Data from these stations though recorded regularly are not published and as such are not easily available for hydrological studies.

funnel. The rim of the collector is set in a horizontal plane at a height of 30.5 cm above the ground level. The funnel discharges the rainfall catch into a receiving vessel. The funnel and receiving vessel are housed in a metallic container. Figure 2.5 shows the details of the installation. Water contained in the receiving vessel is measured by a suitably graduated measuring glass, with an accuracy up to 0.1 mm.

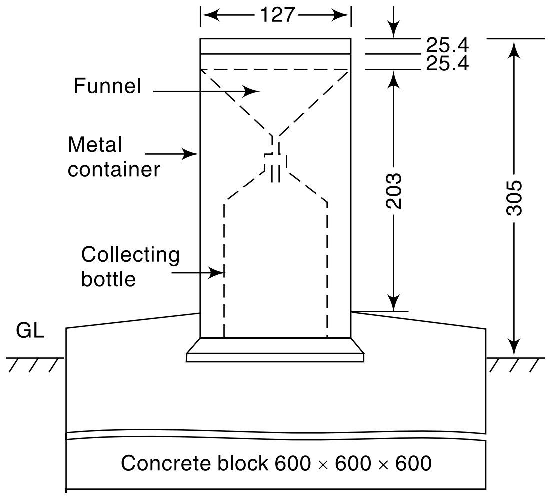


Fig. 2.5 Nonrecording Raingauge (Symons' Gauge)

Recently, the India Meteorological Department (IMD) has changed over to the use of fibreglass reinforced polyester raingauges, which is an improvement over the *Symons' gauge*. These come in different combinations of collector and bottle. The collector is in two sizes having areas of 200 and 100 cm^2 respectively. Indian standard (IS: 5225–1969) gives details of these new raingauges.

For uniformity, the rainfall is measured every day at 8.30 AM (IST) and is recorded as the rainfall of that day. The receiving bottle normally does not hold more than 10 cm of rain and as such in the case of heavy rainfall the measurements must be done more frequently and entered. However, the last reading must be taken at 8.30 AM and the sum of the previous readings in the past 24 hours entered as total of that day. Proper care, maintenance and inspection of raingauges, especially during dry weather to keep the instrument free from dust and dirt is very necessary. The details of installation of nonrecording raingauges and measurement of rain are specified in Indian Standard (IS: 4986–1968).

This raingauge can also be used to measure snowfall. When snow is expected, the funnel and receiving bottle are removed and the snow is allowed to collect in the outer metal container. The snow is then melted and the depth of resulting water measured. Antifreeze agents are sometimes used to facilitate melting of snow. In areas where considerable snowfall is expected, special snowgauges with shields (for minimizing the wind effect) and storage pipes (to collect snow over longer durations) are used.

Recording Gauges

Recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis of storms. The following are some of the commonly used recording raingauges.

Tipping-Bucket Type This is a 30.5 cm size raingauge adopted for use by the US Weather Bureau. The catch from the funnel falls onto one of a pair of small buckets. These buckets are so balanced that when 0.25 mm of rainfall collects in one bucket, it tips and brings the other one in position. The water from the tipped bucket is collected in a storage can. The tipping actuates an electrically driven pen to trace a record on clockwork-driven chart. The water collected in the storage can is measured at regular intervals to provide the total rainfall and also serve as a check. It may be noted that the record from the tipping bucket gives data on the intensity of rainfall. Further, the instrument is ideally suited for digitalizing of the output signal.

Weighing-Bucket Type In this raingauge the catch from the funnel empties into a bucket mounted on a weighing scale. The weight of the bucket and its contents are recorded on a clock-work-driven chart. The clockwork mechanism has the capacity to run for as long as one week. This instrument gives a plot of the accumulated rainfall against the elapsed time, i.e. the mass curve of rainfall. In some instruments of this type the recording unit is so constructed that the pen reverses its direction at every preset value, say 7.5 cm (3 in.) so that a continuous plot of storm is obtained.

Natural-Syphon Type This type of recording raingauge is also known as *float-type gauge.* Here the rainfall collected by a funnel-shaped collector is led into a float chamber causing a float to rise. As the float rises, a pen attached to the float through a lever system records the elevation of the float on a rotating drum driven by a clockwork mechanism. A syphon arrangement empties the float chamber when the float has reached a pre-set maximum level. This type of raingauge is adopted as the standard recording-type raingauge in India and its details are described in Indian Standard (IS: 5235–1969).

A typical chart from this type of raingauge is shown in Fig. 2.6. This chart shows a rainfall of 53.8 mm in 30 h. The vertical lines in the pen-trace correspond to the sudden emptying of the float chamber by syphon action which resets the pen to zero level. It is obvious that the natural syphon-type recording raingauge gives a plot of the mass curve of rainfall.

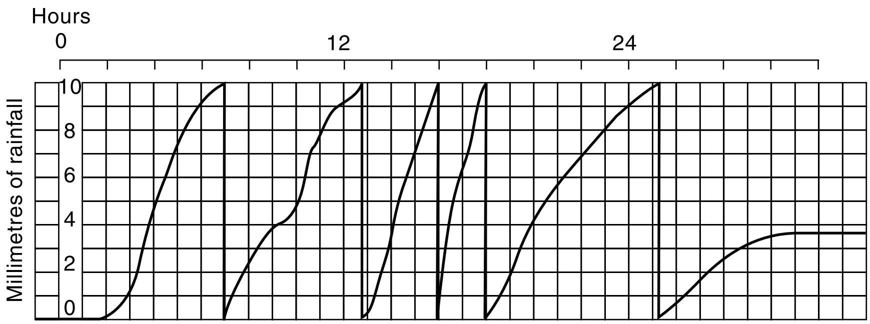


Fig. 2.6 Recording from a Natural Syphon-type Gauge (Schematic)

Telemetering Raingauges

These raingauges are of the recording type and contain electronic units to transmit the data on rainfall to a base station both at regular intervals and on interrogation. The tipping-bucket type raingauge, being ideally suited, is usually adopted for this purpose. Any of the other types of recording raingauges can also be used equally effectively. Telemetering gauges are of utmost use in gathering rainfall data from mountainous and generally inaccessible places.

Radar Measurement of Rainfall

The meteorological radar is a powerful instrument for measuring the areal extent, location and movement of rain storms. Further, the amounts of rainfall over large areas can be determined through the radar with a good degree of accuracy.

The radar emits a regular succession of pulses of electromagnetic radiation in a narrow beam. When raindrops intercept a radar beam, it has been shown that

$$P_r = \frac{CZ}{r^2} \tag{2.1}$$

where P_r = average echopower, Z = radar-echo factor, r = distance to target volume and C = a constant. Generally the factor Z is related to the intensity of rainfall as

$$Z = aI^b \tag{2.2}$$

where a and b are coefficients and I = intensity of rainfall in mm/h. The values a and b for a given radar station have to be determined by calibration with the help of recording raingauges. A typical equation for Z is

$$Z = 200\, I^{1.60}$$

Meteorological radars operate with wavelengths ranging from 3 to 10 cm, the common values being 5 and 10 cm. For observing details of heavy flood-producing rains, a 10-cm radar is used while for light rain and snow a 5-cm radar is used. The hydrological range of the radar is about 200 km. Thus a radar can be considered to be a remote-sensing super gauge covering an areal extent of as much as 100,000 km^2. Radar measurement is continuous in time and space. Present-day developments in the field include (i) On-line processing of radar data on a computer and (ii) Doppler-type radars for measuring the velocity and distribution of raindrops.

B. Snowfall

Snowfall as a form of precipitation differs from rainfall in that it may accumulate over a surface for some time before it melts and causes runoff. Further, evaporation from the surface of accumulated snow surface is a factor to be considered in analysis dealing with snow. Water equivalent of snowfall is included in the total precipitation amounts of a station to prepare seasonal and annual precipitation records.

Depth of Snowfall Depth of snowfall is an important indicator for many engineering applications and in hydrology it is useful for seasonal precipitation and long-term runoff forecasts. A graduated stick or staff is used to measure the depth of snow at a selected place. Average of several measurements in an area is taken as the depth of snow in a snowfall event. *Snow stakes* are permanent graduated posts used to measure total depth of accumulated snow at a place.

Snow boards are 40 cm side square boards used to collect snow samples. These boards are placed horizontally on a previous accumulation of snow and after a snowfall event the snow samples are cut off from the board and depth of snow and water equivalent of snow are derived and recorded.

Water Equivalent of Snow Water equivalent of snow is the depth of water that would result in melting of a unit of snow. This parameter is important in assessing the seasonal water resources of a catchment as well as in estimates of stream flow and floods due to melting of snow.

The amount of water present in a known depth of snow could be estimated if the information about the density of snow is available. The density of snow, however, varies quite considerably. Freshly fallen snow may have a density in the range of 0.07 to 0.15 with an average value of about 0.10. The accumulated snow however causes compaction and in regions of high accumulation densities as high as 0.4 to 0.6 is not uncommon. Where specific data is not available, it is usual to assume the density of fresh snow as 0.10.

Water equivalent of snow is obtained in two ways:

Snow Gauges Like rain gauges, *snow gauges* are receptacles to catch precipitation as it falls in a specified sampling area. Here, a large cylindrical receiver 203 mm in diameter is used to collect the snow as it falls. The height of the cylinder depends upon the snow storage needed at the spot as a consequence of accessibility etc. and may range from 60 cm to several metres. The receiver is mounted on a tower to keep the rim of the gauge above the anticipated maximum depth of accumulated snow in the area. The top of the cylinder is usually a funnel like fulcrum of cone with side slopes not less than 1 H: 6 V, to minimize deposits of ice on the exterior of the gauge. Also, a windshield is provided at the top. Melting agents or heating systems are sometimes provided in the remote snow gauges to reduce the size of the containers. The snow collected in the cylinder is brought in to a warm room and the snow melted by adding a pre-measured quantity of hot water. Through weighing or by volume measurements, the water equivalent of snow is ascertained and recorded.

Snow Tubes Water equivalent of accumulated snow is measured by means of *snow tubes* which are essentially a set of telescopic metal tubes. While a tube size of 40 mm diameter is in normal use, higher sizes up to 90 mm diameter are also in use. The main tube is provided with a cutter edge for easy penetration as well as to enable extracting of core sample. Additional lengths of tube can be attached to the main tube depending upon the depth of snow.

To extract a sample, the tube is driven into the snow deposit till it reaches the bottom of the deposit and then twisted and turned to cut a core. The core is extracted carefully and studied for its physical properties and then melted to obtain water equivalent of the snow core. Obviously, a large number of samples are needed to obtain representative values for a large area deposit. Usually, the sampling is done along an established route with specified locations called *snow course.*

2.6 RAINGAUGE NETWORK

Since the catching area of a raingauge is very small compared to the areal extent of a storm, it is obvious that to get a representative picture of a storm over a catchment the number of raingauges should be as large as possible, i.e. the catchment area per gauge should be small. On the other hand, economic considerations to a large extent and other considerations, such as topography, accessibility, etc. to some extent restrict the number of gauges to be maintained. Hence one aims at an optimum density of gauges from which reasonably accurate information about the storms can be obtained. Towards this the World Meteorological Organisation (WMO) recommends the following densities.

- In flat regions of temperate, Mediterranean and tropical zones
  Ideal—1 station for 600–900 km^2
  Acceptable—1 station for 900–3000 km^2

- In mountainous regions of temperate, Mediterranean and topical zones
  Ideal—1 station for 100–250 km^2
  Acceptable—1 station for 25–1000 km^2
- In arid and polar zones: 1 station for 1500–10,000 km^2 depending on the feasibility.

Ten per cent of raingauge stations should be equipped with self-recording gauges to know the intensities of rainfall.

From practical considerations of Indian conditions, the Indian Standard (IS: 4987–1968) recommends the following densities as sufficient.

- In plains: 1 station per 520 km^2;
- In regions of average elevation 1000 m: 1 station per 260–390 km^2; and
- In predominantly hilly areas with heavy rainfall: 1 station per 130 km^2.

Adequacy of Raingauge Stations

If there are already some raingauge stations in a catchment, the optimal number of stations that should exist to have an assigned percentage of error in the estimation of mean rainfall is obtained by statistical analysis as

$$N = \left(\frac{C_v}{\varepsilon}\right)^2 \tag{2.3}$$

where N = optimal number of stations, ε = allowable degree of error in the estimate of the mean rainfall and C_v = coefficient of variation of the rainfall values at the existing m stations (in per cent). If there are m stations in the catchment each recording rainfall values $P_1, P_2, \ldots, P_i, \ldots P_m$ in a known time, the coefficient of variation C_v is calculated as:

$$C_v = \frac{100 \times \sigma_{m-1}}{\bar{P}}$$

where $$\sigma_{m-1} = \sqrt{\left[\frac{\sum_1^m (P_i - \bar{P})^2}{m-1}\right]} = \text{standard deviation}$$

P_i = precipitation magnitude in the i^{th} station

$$\bar{P} = \frac{1}{m}\left(\sum_1^m P_i\right) = \text{mean precipitation}$$

In calculating N from Eq. (2.3) it is usual to take $\varepsilon = 10\%$. It is seen that if the value of ε is small, the number of raingauge stations will be more.

According to WMO recommendations, at least 10% of the total raingauges should be of self-recording type.

Example 2.1 *A catchment has six raingauge stations. In a year, the annual rainfall recorded by the gauges are as follows:*

Station	A	B	C	D	E	F
Rainfall (cm)	82.6	102.9	180.3	110.3	98.8	136.7

For a 10% error in the estimation of the mean rainfall, calculate the optimum number of stations in the catchment.

Solution: For this data,

$$m = 6 \qquad \bar{P} = 118.6 \qquad \sigma_{m-1} = 35.04 \qquad \varepsilon = 10$$

$$C_v = \frac{100 \times 35.04}{118.6} = 29.54$$

$$N = \left(\frac{29.54}{10}\right)^2 = 8.7, \text{ say 9 stations}$$

The optimal number of stations for the catchment is 9. Hence three more additional stations are needed.

2.7 PREPARATION OF DATA

Before using the rainfall records of a station, it is necessary to first check the data for continuity and consistency. The continuity of a record may be broken with missing data due to many reasons such as damage or fault in a raingauge during a period. The missing data can be estimated by using the data of the neighbouring stations. In these calculations the *normal rainfall* is used as a standard of comparison. The normal rainfall is the average value of rainfall at a particular date, month or year over a specified 30-year period. The 30-year normals are recomputed every decade. Thus the term *normal annual percipitation* at station A means the average annual precipitation at A based on a specified 30-years of record.

Estimation of Missing Data

Given the annual precipitation values, P_1 P_2, P_3, … P_m at neighbouring M stations 1,2, 3, …, M respectively, it is required to find the missing annual precipitation P_x at a station X not included in the above M stations. Further, the normal annual precipitations N_1 N_2, …, N_i … at each of the above (M + 1) stations including station X are known.

If the normal annual precipitations at various stations are within about 10% of the normal annual precipitation at station X, then a simple arithmetic average procedure is followed to estimate P_x. Thus

$$P_x = \frac{1}{M}\,[P_1 + P_2 + \ldots + P_m] \tag{2.4}$$

If the normal precipitations vary considerably, then P_x is estimated by weighing the precipitation at the various stations by the ratios of normal annual precipitations. This method, known as the *normal ratio method,* gives P_x as

$$P_x = \frac{N_x}{M}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \ldots + \frac{P_m}{N_m}\right] \tag{2.5}$$

Example 2.2 *The normal annual rainfall at stations A, B, C, and D in a basin are 80.97, 67.59, 76.28 and 92.01 cm respectively. In the year 1975, the station D was inoperative and the stations A, B and C recorded annual precipitations of 91.11, 72.23 and 79.89 cm respectively. Estimate the rainfall at station D in that year.*

Solution: As the normal rainfall values vary more than 10%, the normal ratio method is adopted. Using Eq. (2.5),

$$P_D = \frac{92.01}{3} \times \left(\frac{91.11}{80.79} + \frac{72.23}{67.59} + \frac{79.89}{76.28}\right) = 99.48 \text{ cm}$$

Test for Consistency of Record

If the conditions relevant to the recording of a raingauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. This inconsistency would be felt from the time the significant change took place. Some of the common causes for inconsistency of record are: (i) shifting of a raingauge station to a new location, (ii) the neighbourhood of the station undergoing a marked change, (iii) change in the ecosystem due to calamities, such as forest fires, land slides, and (iv) occurrence of observational error from a certain date. The checking for inconsistency of a record is done by the *double-mass curve technique.* This technique is based on the principle that when each recorded data comes from the same parent population, they are consistent.

A group of 5 to 10 base stations in the neighbourhood of the problem station *X* is selected. The data of the annual (or monthly or seasonal mean) rainfall of the station *X* and also the average rainfall of the group of base stations covering a long period is arranged in the reverse chronological order (i.e. the latest record as the first entry and the oldest record as the last entry in the list). The accumulated precipitation of the station *X* (i.e. ΣP_x) and the accumulated values of the average of the group of base stations (i.e. ΣP_{av}) are calculated starting from the latest record. Values of ΣP_x are plotted against ΣP_{av} for various consecutive time periods (Fig. 2.7). A decided break in the slope of the resulting plot indicates a change in the precipitation regime of station *X*. The precipitation values at station *X* beyond the period of change of regime (point 63 in Fig. 2.7) is corrected by using the relation

$$P_{cx} = P_x \frac{M_e}{M_a} \qquad (2.6)$$

where P_{cx} = corrected precipitation at any time period t_1 at station *X*
P_x = original recorded precipitation at time period t_1 at station *X*

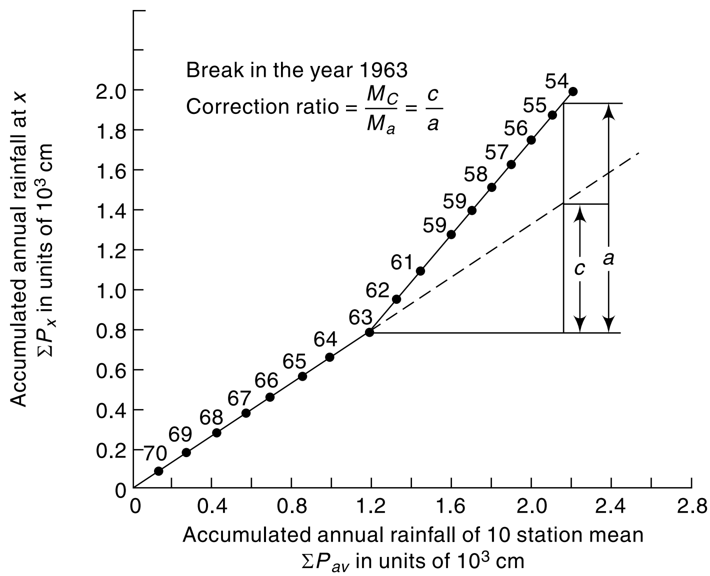


Fig. 2.7 Double-mass Curve

M_c = corrected slope of the double-mass curve
M_a = original slope of the double-mass curve

In this way the older records are brought to the new regime of the station. It is apparent that the more homogeneous the base station records are, the more accurate will be the corrected values at station *X*. A change in the slope is normally taken as significant only where it persists for more than five years. The double-mass curve is also helpful in checking systematic arithmetical errors in transferring rainfall data from one record to another.

Example 2.3 *Annual rainfall data for station M as well as the average annual rainfall values for a group of ten neighbouring stations located in a meteorologically homogeneous region are given below.*

Year	Annual Rainfall of Station M (mm)	Average Annual Rainfall of the group (mm)	Year	Annual Rainfall of Station M (mm)	Average Annual Rainfall of the group (mm)
1950	676	780	1965	1244	1400
1951	578	660	1966	999	1140
1952	95	110	1967	573	650
1953	462	520	1968	596	646
1954	472	540	1969	375	350
1955	699	800	1970	635	590
1956	479	540	1971	497	490
1957	431	490	1972	386	400
1958	493	560	1973	438	390
1959	503	575	1974	568	570
1960	415	480	1975	356	377
1961	531	600	1976	685	653
1962	504	580	1977	825	787
1963	828	950	1978	426	410
1964	679	770	1979	612	588

Test the consistency of the annual rainfall data of station M and correct the record if there is any discrepancy. Estimate the mean annual precipitation at station M.

Solution: The data is sorted in descending order of the year, starting from the latest year 1979. Cumulative values of station *M* rainfall (ΣP_m) and the ten station average rainfall values (ΣP_{av}) are calculated as shown in Table 2.1. The data is then plotted with ΣP_m on the Y-axis and ΣP_{av} on the X-axis to obtain a double mass curve plot (Fig. 2.8). The value of the year corresponding to the plotted points is also noted on the plot. It is seen that the data plots as two straight lines with a break of grade at the year 1969. This represents a change in the regime of the station *M* after the year 1968. The slope of the best straight line for the period 1979–1969 is $M_c = 1.0295$ and the slope of the best straight line for the period 1968–1950 is $M_a = 0.8779$.

The correction ratio to bring the old records (1950–1968) to the current (post 1968) regime is $= M_c/M_a = 1.0295/0.8779 = 1.173$. Each of the pre 1969 annual rainfall value is

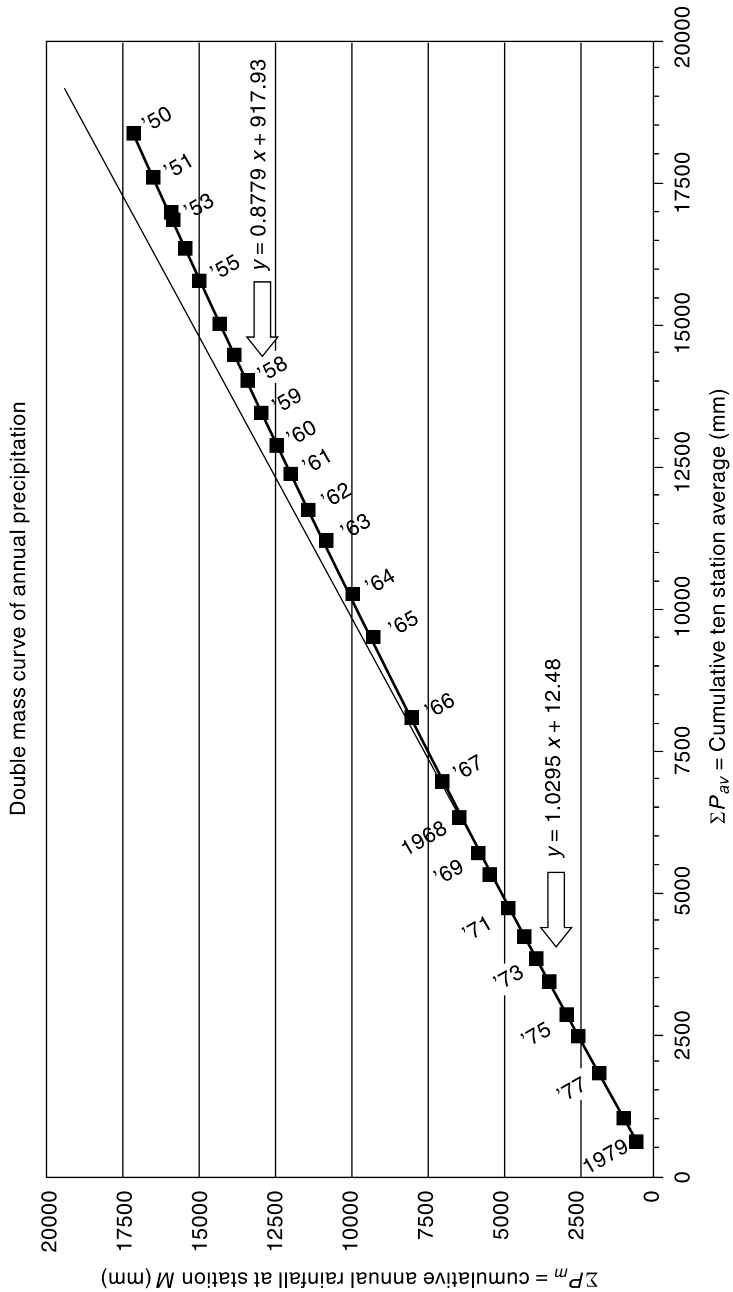


Fig. 2.8 Double Mass Curve of Annual Rainfall at Station *M*

multiplied by the correction ratio of 1.173 to get the adjusted value. The adjusted values at station *M* are shown in Col. 5 of Table. The finalized values of P_m (rounded off to nearest mm) for all the 30 years of record are shown in Col. 7.

The mean annual precipitation at station *M* (based on the corrected time series) = (19004/30) = 633.5 mm

Table 2.1 Calculation of Double Mass Curve of Example 2.3

1 Year	2 P_m (mm)	3 ΣP_m (mm)	4 P_{av} (mm)	5 P_{av} (mm)	6 Adjusted values of P_m (mm)	7 Finalised values of P_m (mm)
1979	612	612	588	588		612
1978	426	1038	410	998		426
1977	825	1863	787	1785		825
1976	685	2548	653	2438		685
1975	356	2904	377	2815		356
1974	568	3472	570	3385		568
1973	438	3910	390	3775		438
1972	386	4296	400	4175		386
1971	497	4793	490	4665		497
1970	635	5428	590	5255		635
1969	375	5803	350	5605		375
1968	596	6399	646	6251	698.92	699
1967	573	6972	650	6901	671.95	672
1966	999	7971	1140	8041	1171.51	1172
1965	1244	9215	1400	9441	1458.82	1459
1964	679	9894	770	10211	796.25	796
1963	828	10722	950	11161	970.98	971
1962	504	11226	5801	11741	591.03	591
1961	531	11757	600	12341	622.70	623
1960	415	12172	480	12821	486.66	487
1959	503	12675	575	13396	589.86	590
1958	493	13168	560	13956	578.13	578
1957	431	13599	490	14446	505.43	505
1956	479	14078	540	14986	561.72	562
1955	699	14777	800	15786	819.71	820
1954	472	15249	540	16326	553.51	554
1953	462	15711	520	16846	541.78	542
1952	95	15806	110	16956	111.41	111
1951	578	16384	660	17616	677.81	678
1950	676	17060	780	18396	792.73	193

Total of P_m = 19004 mm
Mean of P_m = 633.5 mm

2.8 PRESENTATION OF RAINFALL DATA

A few commonly used methods of presentation of rainfall data which have been found to be useful in interpretation and analysis of such data are given as follows:

References

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Revision Questions

2.1 Describe the different methods of recording of rainfall.

2.2 Discuss the current practice and status of rainfall recording in India.

2.3 Describe the salient characteristics of precipitation on India.

2.4 Explain the different methods of determining the average rainfall over a catchment due to a storm. Discuss the relative merits and demerits of the various methods.

2.5 Explain a procedure for checking a rainfall data for consistency.

2.6 Explain a procedure for supplementing the missing rainfall data.

2.7 Explain briefly the following relationships relating to the precipitation over a basin:
(a) Depth-Area Relationship
(b) Maximum Depth-Area-Duration Curves
(c) Intensity Duration Frequency Relationship.

2.8 What is meant by Probable Maximum Precipitation (PMP) over a basin? Explain how PMP is estimated.

2.9 Consider the statement: The 50 year-24 hour maximum rainfall at Bangalore is 160 mm. What do you understand by this statement?

Problems

2.1 A catchment area has seven raingauge stations. In a year the annual rainfall recorded by the gauges are as follows:

Station	*P*	*Q*	*R*	*S*	*T*	*U*	*V*
Rainfall (cm)	130.0	142.1	118.2	108.5	165.2	102.1	146.9

For a 5% error in the estimation of the mean rainfall, calculate the minimum number of additional stations required to be established in the catchment.

2.2 The normal annual precipitation of five raingauge stations *P, Q, R, S* and *T* are respectively 125, 102, 76, 113 and 137 cm. During a particular storm the precipitation recorded by stations *P*, *Q*, *R*, and *S* are 13.2, 9.2, 6.8 and 10.2 cm respectively. The instrument at station *T* was inoperative during that storm. Estimate the rainfall at station *T* during that storm.

2.3 Test the consistency of the 22 years of data of the annual precipitation measured at station *A*. Rainfall data for station *A* as well as the average annual rainfall measured at a group of eight neighbouring stations located in a meteorologically homogeneous region are given as follows.

Year	Annual Rainfall of Station A (mm)	Average Annual Rainfall of 8 Station groups (mm)	Year	Annual Rainfall of Station A (mm)	Average Annual Rainfall of 8 Station groups (mm)
1946	177	143	1957	158	164
1947	144	132	1958	145	155
1948	178	146	1959	132	143
1949	162	147	1960	95	115
1950	194	161	1961	148	135
1951	168	155	1962	142	163
1952	196	152	1963	140	135
1953	144	117	1964	130	143
1954	160	128	1965	137	130
1955	196	193	1966	130	146
1956	141	156	1967	163	161

(a) In what year is a change in regime indicated?
(b) Adjust the recorded data at station *A* and determine the mean annual precipitation.

2.4 In a storm of 210 minutes duration, the incremental rainfall at various time intervals is given below.

Time since start of the storm (minutes)	30	60	90	120	150	180	210
Incremental rainfall in the time interval (cm)	1.75	2.25	6.00	4.50	2.50	1.50	0.75

(a) Obtain the ordinates of the hyetograph and represent the hyetograph as a bar chart with time in chronological order in the *x*-axis.
(b) Obtain the ordinates of the mass curve of rainfall for this storm and plot the same. What is the average intensity of storm over the duration of the storm?

2.5 Assuming the density of water as 998 kg/m^3, determine the internal diameter of a tubular snow sample such that 0.1 *N* of snow in the sample represents 10 mm of water equivalent.

2.6 Represent the annual rainfall data of station *A* given below as a bar chart with time in chronological order. If the annual rainfall less than 75% of long term mean is taken to signify meteorological drought, identify the drought years and suitably display the same in the bar chart.

Year	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970
Annual rain (mm)	760	750	427	380	480	620	550	640	624	500
Year	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980
Annual rain (mm)	400	356	700	580	520	102	525	900	600	400

2.7 For a drainage basin of 600 km^2, isohyetals drawn for a storm gave the following data:

Isohyetals (interval) (cm)	15–12	12–9	9–6	6–3	3–1
Inter-isohyetal area (km^2)	92	128	120	175	85

Estimate the average depth of precipitation over the catchment.

2.8 There are 10 raingauge stations available to calculate the rainfall characteristics of a catchment whose shape can be approximately described by straight lines joining the following coordinates (distances in kilometres):
(30, 0), (80, 10), (110, 30), (140, 90), (130, 115), (40, 110), (15, 60). Coordinates of the raingauge stations and the annual rainfall recorded in them in the year 1981 are given below.

Station	**1**	**2**	**3**	**4**	**5**
Co-ordinates	(0, 40)	(50, 0)	(140, 30)	(140, 80)	(90, 140)
Annual Rainfall (cm)	132	136	93	81	85
Station	**6**	**7**	**8**	**9**	**10**
Co-ordinates	(0, 80)	(40, 50)	(90, 30)	(90, 90)	(40, 80)
Annual Rainfall (cm)	124	156	128	102	128

Determine the average annual rainfall over the catchment.

2.9 Figure 2.25 shows a catchment with seven raingauge stations inside it and three stations outside. The rainfall recorded by each of these stations are indicated in the figure. Draw the figure to an enlarged scale and calculate the mean precipitation by (a) Thiessen-mean method, (b) Isohyetal method and by (c) Arithmetic-mean method.

2.10 Annual rainfall at a point M is needed. At five points surrounding the point M the values of recorded rainfall together with the coordinates of these stations with respect to a set of axes at point M are given below. Estimate the annual rainfall at point M by using the USNWS method.

Station	**Rainfall P (cm)**	**Coordinates of station (in units)**	
		X	***Y***
A	102	2.0	1.0
B	120	2.0	2.0
C	126	3.0	1.0
D	108	1.5	1.0
E	131	4.5	1.5

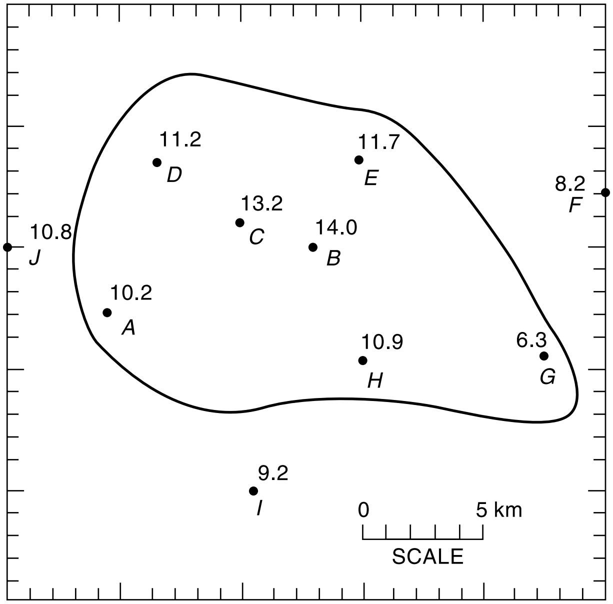

Fig. 2.25 Problem 2.9

[**Hint:** In the US National Weather Service (USNWS) method the weightage to the stations are inversely proportional to the square of the distance of the station from the station *M*. If the co-ordinate of any station is (x, y) then $D^2 = x^2 + y^2$ and weightage $W = 1/D^2$. Then rainfall at $M = P_m = \dfrac{\Sigma PW}{\Sigma W}$].

2.11 Estimate from depth-area curve, the average depth of precipitation that may be expected over an area of 2400 Sq. km due to the storm of 27th September 1978 which lasted for 24 hours. Assume the storm centre to be located at the centre of the area. The isohyetal map for the storm gave the areas enclosed between different isohyetes as follows:

Isohyet (mm)	21	20	19	18	17	16	15	14	13	12
Enclosed	54	134	203	254	295	328	353	371	388	391
area (km^2)	3	5	0	5	5	0	5	0	0	5

2.12 Following are the data of a storm as recorded in a self-recording rain gauge at a station:

Time from the beginning of storm (minutes)	10	20	30	40	50	60	70	80	90
Cumulative rainfall (mm)	19	41	48	68	91	124	152	160	166

(a) Plot the hyetograph of the storm.
(b) Plot the maximum intensity-duration curve of the storm.

2.13 Prepare the Maximum depth-duration curve for the 90 minute storm given below:

Time (minutes)	0	10	20	30	40	50	60	70	80	90
Cumulative rainfall (mm)	0	8	15	25	30	46	55	60	64	67

2.14 The mass curve of rainfall in a storm of total duration 90 minutes is given below. (a) Draw the hyetograph of the storm at 10 minutes time step. (b) Plot the Maximum intensity-duration curve for this storm. (c) Plot the Maximum depth-duration curve for the storm.

Time (Minutes)	0	10	20	30	40	50	60	70	80	90
Cumulative rainfall (mm)	0	2.1	6.3	14.5	21.7	27.9	33.0	35.1	36.2	37.0

2.15 The record of annual rainfall at a place is available for 25 years. Plot the curve of recurrence interval *vs* annual rainfall magnitude and by suitable interpolation estimate the magnitude of rainfall at the station that would correspond to a recurrence interval of (a) 50 years and (b) 100 years.

Year	Annual Rainfall (cm)	Year	Annual Rainfall (cm)
1950	113.0	1963	68.6
1951	94.5	1964	82.5
1952	76.0	1965	90.7
1953	87.5	1966	99.8
1954	92.7	1967	74.4
1955	71.3	1968	66.6
1956	77.3	1969	65.0
1957	85.1	1970	91.0
1958	122.8	1971	106.8
1959	69.4	1972	102.2
1960	81.0	1973	87.0
1961	94.5	1974	84.0
1962	86.3		

2.16 The annual rainfall values at a station *P* for a period of 20 years are as follows:

Year	Annual Rainfall (cm)	Year	Annual Rainfall (cm)
1975	120.0	1985	101.0
1976	84.0	1986	109.0
1977	68.0	1987	106.0
1978	92.0	1988	115.0
1979	102.0	1989	95.0
1980	92.0	1990	90.0
1981	95.0	1991	70.0
1982	88.0	1992	89.0
1983	76.0	1993	80.0
1984	84.0	1994	90.0

Determine

(a) The value of annual rainfall at *P* with a recurrence interval of 15 years.

(b) The probability of occurrence of an annual rainfall of magnitude 100 cm at station *P*.

(c) 75% dependable annual rainfall at the station.

[**Hint:** If an event (rainfall magnitude in the present case) occurs more than once, the rank *m* = number of times the event is equalled + number of times it is exceeded.]

2.17 Plot the three-year and the five-year moving means for the data of Problem 2.15. Comment on the effect of increase in the period of the moving mean. Is there any apparent trend in the data?

2.18 On the basis of isopluvial maps the 50 year-24 hour maximum rainfall at Bangalore is found to be 16.0 cm. Determine the probability of a 24 h rainfall of magnitude 16.0 cm occurring at Bangalore:
(a) Once in ten successive years.
(b) Twice in ten successive years.
(c) At least once in ten successive years.

2.19 A one-day rainfall of 20.0 cm at a place *X* was found to have a period of 100 years. Calculate the probability that a one-day rainfall of magnitude equal to or larger than 20.0 cm:
(a) Will not occur at station *X* during the next 50 years.
(b) Will occur in the next year.

2.20 When long records are not available, records at two or more stations are combined to get one long record for the purposes of recurrence interval calculation. This method is known as *Station-year method.*
The number of times a storm of intensity 6 cm/h was equalled or exceeded in three different rain gauge stations in a region were 4, 2 and 5 for periods of records of 36, 25 and 48 years. Find the recurrence interval of the 6 cm/h storm in that area by the *station–year method*.

2.21 Annual precipitation values at a place having 70 years of record can be tabulated as follows:

Range (cm)	Number of years
< 60.0	6
60.0–79.9	6
80.0–99.9	22
100.0–119.9	25
120.0–139.9	8
> 140.0	3

Calculate the probability of having:
(a) an annual rainfall equal to or larger than 120 cm,
(b) two successive years in which the annual rainfall is equal to or greater than 140 cm,
(c) an annual rainfall less than 60 cm.

Objective Questions

2.1 A tropical cyclone is a
(a) low-pressure zone that occurs in the northern hemisphere only
(b) high-pressure zone with high winds
(c) zone of low pressure with clockwise winds in the northern hemisphere
(d) zone of low pressure with anticlockwise winds in the northern hemisphere.

2.2 A tropical cyclone in the northern hemisphere is a zone of
(a) low pressure with clockwise wind
(b) low pressure with anticlockwise wind
(c) high pressure with clockwise wind
(d) high pressure with anticlockwise wind.

2.3 Orographic precipitation occurs due to air masses being lifted to higher altitudes by
(a) the density difference of air masses
(b) a frontal action
(c) the presence of mountain barriers
(d) extratropical cyclones.

2.4 The average annual rainfall over the whole of India is estimated as
(a) 189 cm (b) 319 cm (c) 89 cm (d) 117 cm.

2.5 Variability of annual rainfall in India is
(a) least in regions of scanty rainfall (b) largest in regions of high rainfall
(c) least in regions of high rainfall (d) largest in coastal areas.

2.6 The standard Symons' type raingauge has a collecting area of diameter
(a) 12.7 cm (b) 10 cm (c) 5.08 cm (d) 25.4 cm.

2.7 The standard recording raingauge adopted in India is of
(a) weighing bucket type (b) natural siphon type
(c) tipping bucket type (d) telemetry type

2.8 The following recording raingauges does not produce the mass curve of precipitation as record:
(a) Symons' raingauge (b) tipping-bucket type gauge
(c) weighing-bucket type gauge (d) natural siphon gauge.

2.9 When specific information about the density of snowfall is not available, the water equivalent of snowfall is taken as
(a) 50% (b) 30% (c) 10% (d) 90%

2.10 The normal annual rainfall at stations *A*, *B* and *C* situated in meteorologically homogeneous region are 175 cm, 180 cm and 150 cm respectively. In the year 2000, station *B* was inoperative and stations *A* and *C* recorded annual precipitations of 150 cm and 135 cm respectively. The annual rainfall at station *B* in that year could be estimated to be nearly
(a) 150 cm (b) 143 cm (c) 158 cm (d) 168 cm

2.11 The monthly rainfall at a place *A* during September 1982 was recorded as 55 mm above normal. Here the term *normal* means
(a) the rainfall in the same month in the previous year
(b) the rainfall was normally expected based on previous month's data
(c) the average rainfall computed from past 12 months' record
(d) The average monthly rainfall for September computed from a specific 30 years of past record.

2.12 The Double mass curve technique is adopted to
(a) check the consistency of raingauge records
(b) to find the average rainfall over a number of years
(c) to find the number of rainguages required
(d) to estimate the missing rainfall data

2.13 The mass curve of rainfall of a storm is a plot of
(a) rainfall depths for various equal durations plotted in decreasing order
(b) rainfall intensity *vs* time in chronological order
(c) accumulated rainfall intensity *vs* time
(d) accumulated precipitation *vs* time in chronological order.

2.14 A plot between rainfall intensity *vs* time is called as
(a) hydrograph (b) mass curve (c) hyetograph (d) isohyet

2.15 A hyetograph is a plot of
(a) Cumulative rainfall *vs* time (b) rainfall intensity *vs* time
(c) rainfall depth *vs* duration (d) discharge *vs* time

2.16 The Thiessen polygon is
(a) a polygon obtained by joining adjoining raingauge stations
(b) a representative area used for weighing the observed station precipitation
(c) an area used in the construction of depth-area curves
(d) the descriptive term for the shape of a hydrograph.

2.17 An isohyet is a line joining points having
(a) equal evaporation value (b) equal barometric pressure
(c) equal height above the MSL (d) equal rainfall depth in a given duration.

2.18 By DAD analysis the maximum average depth over an area of 10^4 km^2 due to one-day storm is found to be 47 cm. For the same area the maximum average depth for a three day storm can be expected to be
(a) < 47 cm (b) > 47 cm (c) = 47 cm
(d) inadequate information to conclude.

2.19 Depth-Area-Duration curves of precipitation are drawn as
(a) minimizing envelopes through the appropriate data points
(b) maximising envelopes through the appropriate data point
(c) best fit mean curves through the appropriate data points
(d) best fit straight lines through the appropriate data points

2.20 Depth-Area-Duration curves of precipitation at a station would normally be
(a) curves, concave upwards, with duration increasing outward
(b) curves, concave downwards, with duration increasing outward
(c) curves, concave upwards, with duration decreasing outward
(d) curves, concave downwards, with duration decreasing outward

2.21 A study of the isopluvial maps revealed that at Calcutta a maximum rainfall depth of 200 mm in 12 h has a return period of 50 years. The probability of a 12 h rainfall equal to or greater than 200 mm occurring at Calcutta at least once in 30 years is
(a) 0.45 (b) 0.60 (c) 0.56 (d) 1.0

2.22 A 6-h rainfall of 6 cm at a place *A* was found to have a return period of 40 years. The probability that at *A* a 6-h rainfall of this or larger magnitude will occur at least once in 20 successive years is
(a) 0.397 (b) 0.603 (c) 0.309 (d) 0.025

2.23 The probability of a 10 cm rain in 1 hour occurring at a station *B* is found to be 1/60. What is the probability that a 1 hour rain of magnitude 10 cm or larger will occur in station *B* once in 30 successive years is
(a) 0.396 (b) 0.307 (c) 0.604 (d) 0.500

2.24 A one day rainfall of 18 hours at Station *C* was found to have a return period of 50 years. The probability that a one-day rainfall of this or larger magnitude will not occur at station *C* during next 50 years is
(a) 0.636 (b) 0.020 (c) 0.364 (d) 0.371

2.25 If the maximum depth of a 50 years-15 h-rainfall depth at Bhubaneshwar is 260 mm, the 50 year-3 h-maximum rainfall depth at the same place is
(a) < 260 mm (b) > 260 mm (c) = 260 mm
(d) inadequate date to conclude anything.

2.26 The probable maximum depth of precipitation over a catchment is given by the relation PMP =
(a) $\bar{P} + KA^n$ (b) $\bar{P} + K\sigma$ (c) $\bar{P}\ \exp(-K A^n)$ (d) $m\bar{P}$