HYN-102: Lecture

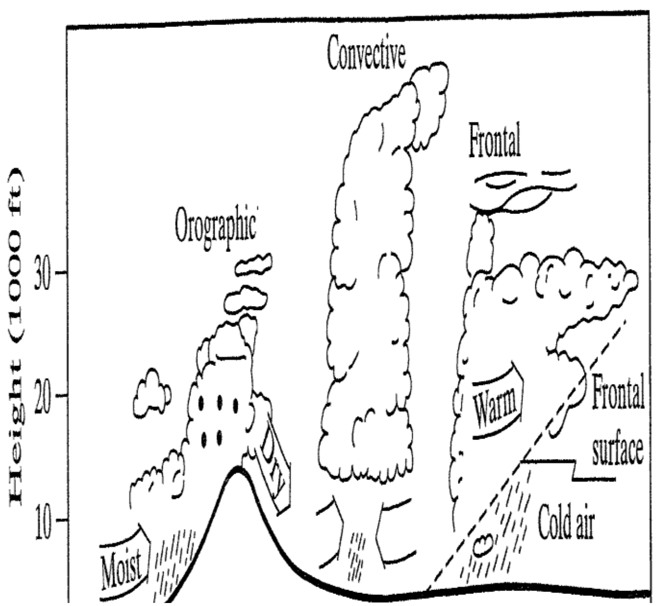
- Precipitation
  - Formation mechanisms
  - Types

Introduction

- All forms of water that reach the earth from the atmosphere is called Precipitation.
- Requires lifting of air mass so that it cools and condenses.
- In nature water is present in three aggregation states:
  - solid: snow and ice;
  - liquid: pure water and solutions;
  - gaseous: vapors under different grades of pressure and saturation
- The water exists in the atmosphere in these three aggregation states.

Mechanisms for air lifting

1. Frontal lifting
2. Orographic lifting
3. Convective lifting

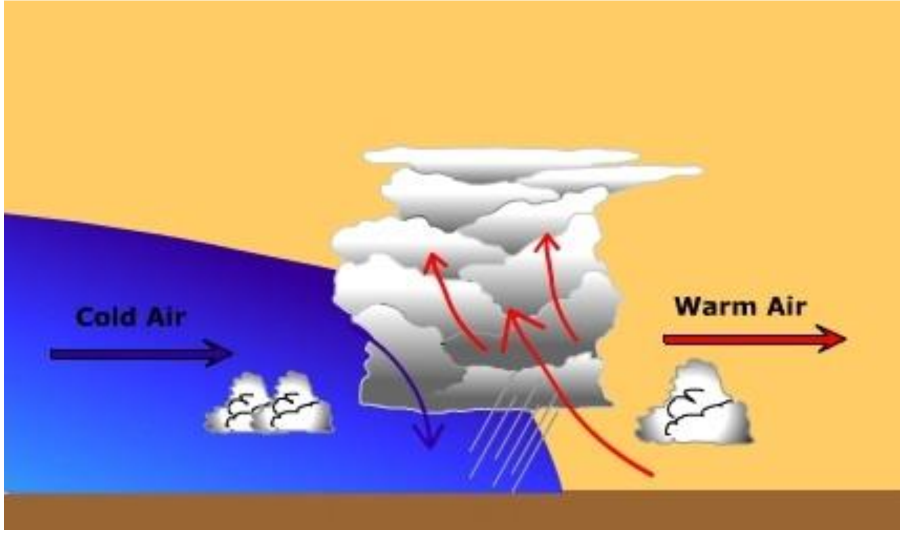


Definitions

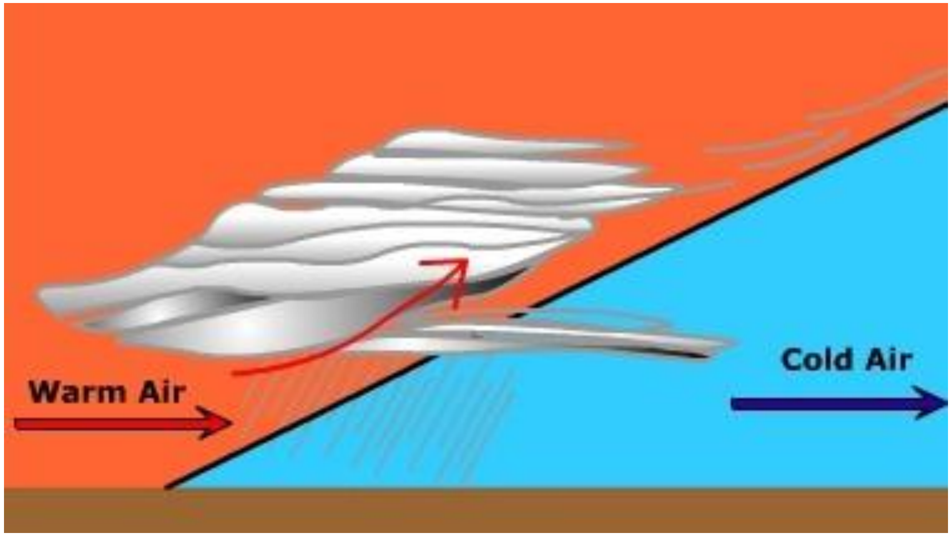
- **Air mass** : A large body of air with similar temperature and moisture characteristics over its horizontal extent.
- **Front**: Boundary between contrasting air masses.
  - **Cold front**: Leading edge of the cold air when it is advancing towards warm air.
  - **Warm front**: leading edge of the warm air when advancing towards cold air.

Frontal Lifting

- Boundary between air masses with different properties is called a *front*
- *Cold front* occurs when cold air advances towards warm air
- *Warm front* occurs when warm air overrides cold air



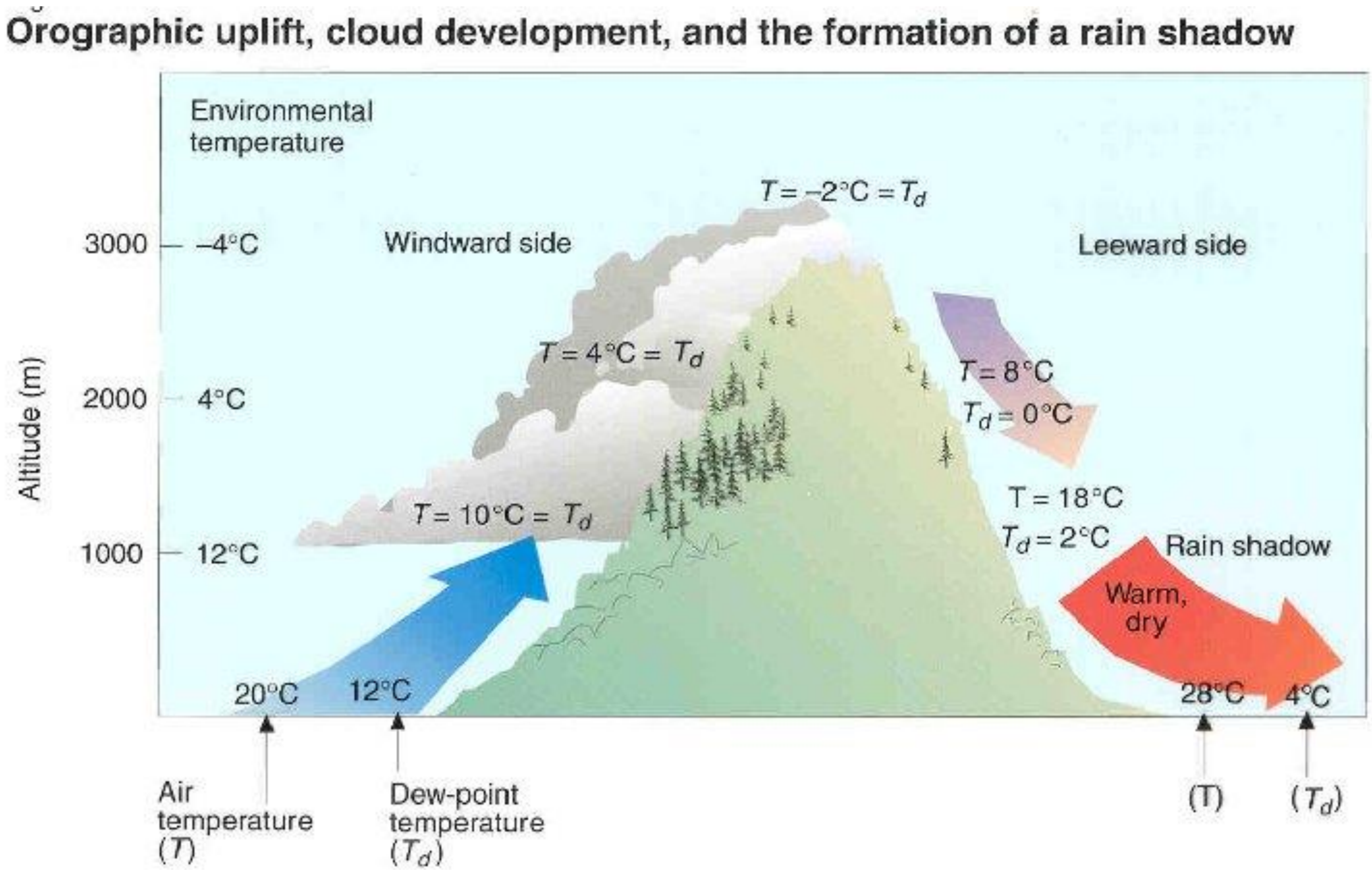
Cold front (produces cumulus cloud)



Cold front (produces stratus cloud)

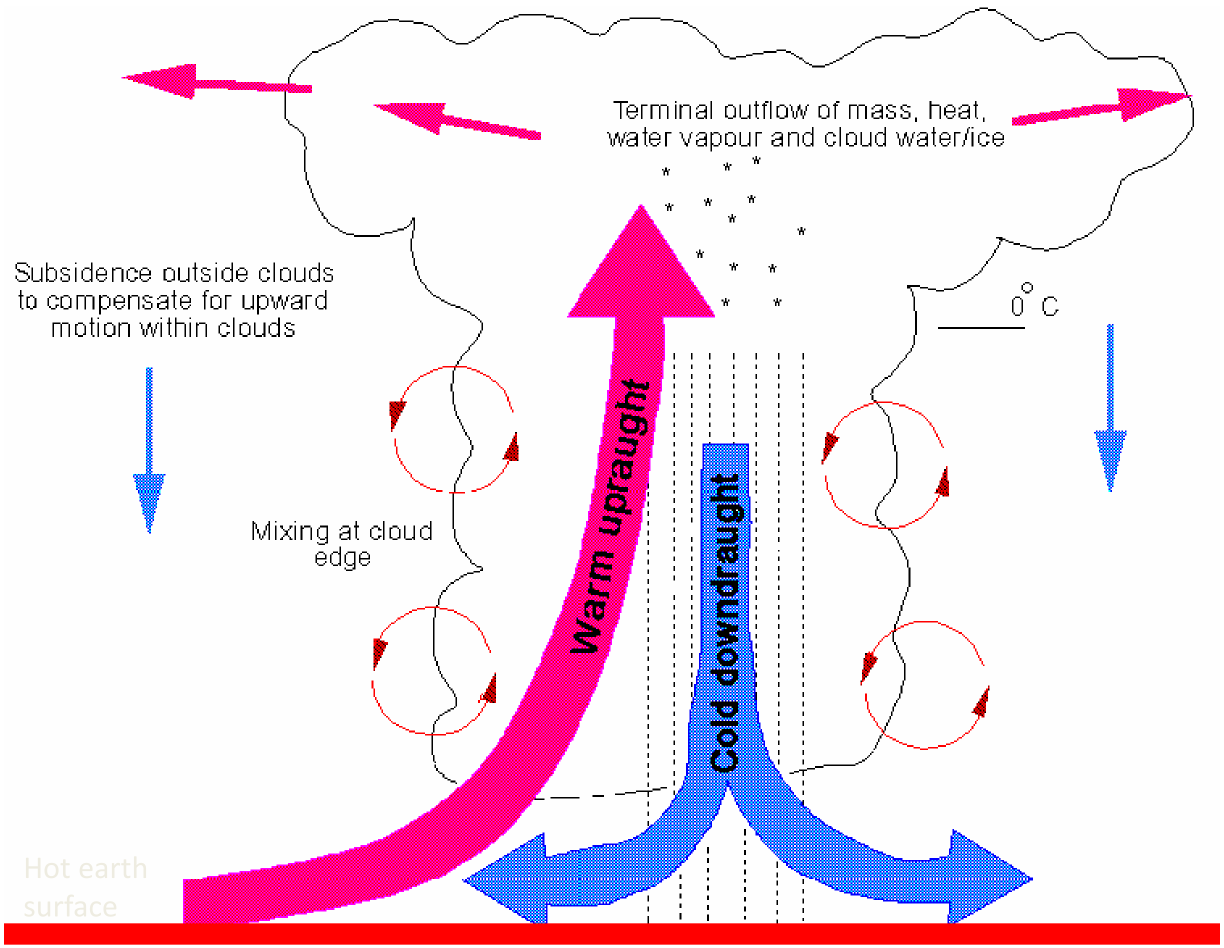
Orographic lifting

Orographic uplift occurs when air is forced to rise because of the physical presence of elevated land.



Convective lifting

Convective precipitation occurs when the air near the ground is heated by the earth's warm surface. This warm air rises, cools and creates precipitation.

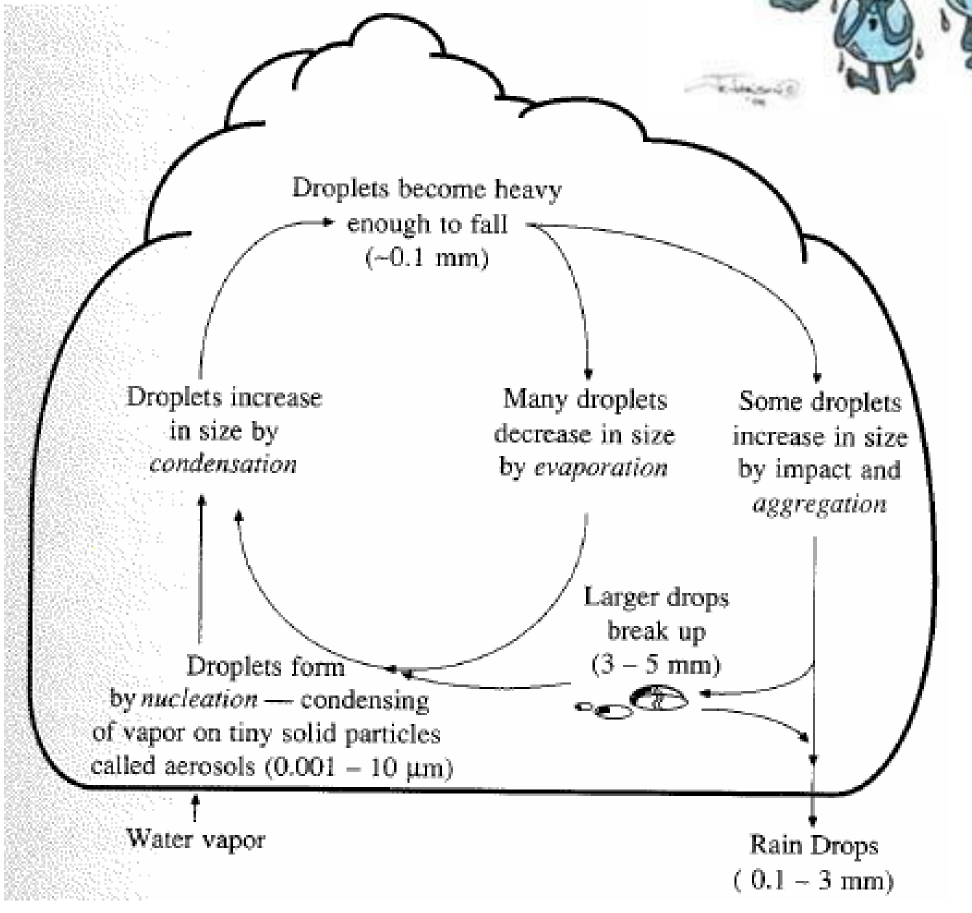


Condensation

- **Condensation** is the change of water vapor into a liquid. For condensation to occur, the air must be at or near saturation in the presence of condensation nuclei.
- **Condensation nuclei** are small particles or aerosol upon which water vapor attaches to initiate condensation. Dust particulates, sea salt, sulfur and nitrogen oxide aerosols serve as common condensation nuclei.
- Size of aerosols range from **10^{-3} to 10 μm**.

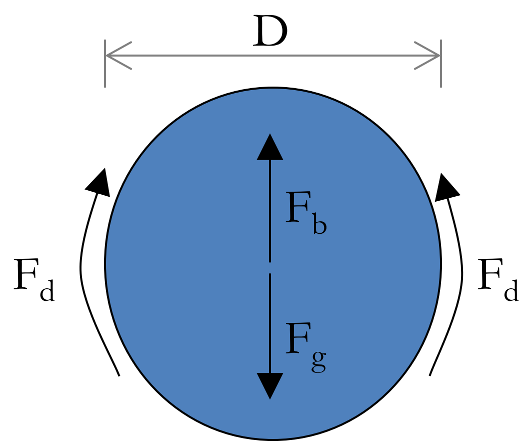
Precipitation formation

- Lifting cools air masses so moisture condenses
- Condensation nuclei
  - Aerosols
  - water molecules attach
- Rising & growing
  - 0.5 cm/s sufficient to carry 10 μm droplet
  - Critical size (~0.1 mm)
  - Gravity overcomes and drop falls



Forces acting on rain drop

- Three forces acting on rain drop
  - **Gravity force** due to weight
  - **Buoyancy force** due to displacement of air
  - **Drag force** due to friction with surrounding air



$$Volume = \frac{\pi}{6} D^3$$

$$Area = \frac{\pi}{4} D^2$$

$$F_g = \rho_w g \frac{\pi}{6} D^3 \qquad F_b = \rho_a g \frac{\pi}{6} D^3$$

$$F_d = C_d \rho_a A \frac{V^2}{2} = C_d \rho_a D^2 \frac{\pi}{4} \frac{V^2}{2}$$

Terminal Velocity

- Terminal velocity: velocity at which the forces acting on the raindrop are in equilibrium.
- If released from rest, the raindrop will accelerate until it reaches its terminal velocity

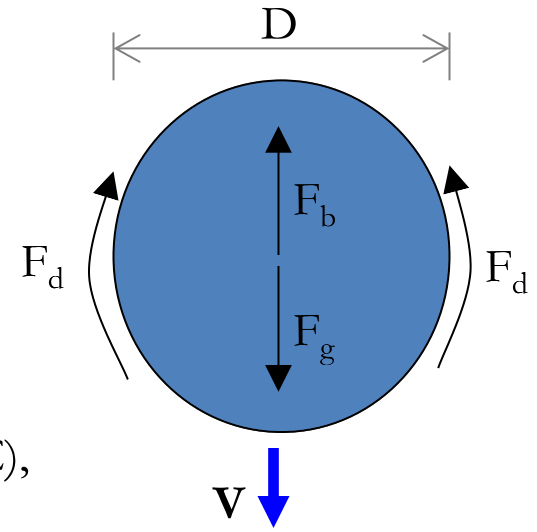
$$\sum F_{vert} = 0 = F_B + F_D - W$$

$$= \rho_a g \frac{\pi}{6} D^3 + C_d \rho_a \frac{\pi}{4} D^2 \frac{V^2}{2} - \rho_w g \frac{\pi}{6} D^3$$

$$F_D = F_B - W$$

$$C_d \rho_a \frac{\pi}{4} D^2 \frac{V_t^2}{2} = \rho_a g \frac{\pi}{6} D^3 - \rho_w g \frac{\pi}{6} D^3$$

$$\boxed{V_t = \sqrt{\frac{4gD}{3C_d}\left(\frac{\rho_w}{\rho_a} - 1\right)}}$$



At standard atmospheric pressure (101.3 kpa) and temperature (20°C), ρ_w = 998 kg/m3 and ρ_a = 1.20 kg/m3

- Raindrops are spherical up to a diameter of 1 mm
- For tiny drops up to 0.1 mm diameter, the drag force is specified by Stokes law

$$C_d = \frac{24}{\text{Re}} \qquad \text{Re} = \frac{\rho_a V D}{\mu_a}$$

Can you name the different types of precipitation?

- Rain
- Snow
- Hail
- Sleet
- Freezing Rain

Introduction….

- Rainfall being the predominant form of precipitation causing stream flow, especially the flood flow in majority of rivers. Thus, in this context, rainfall is used synonymously with precipitation.

Introduction….

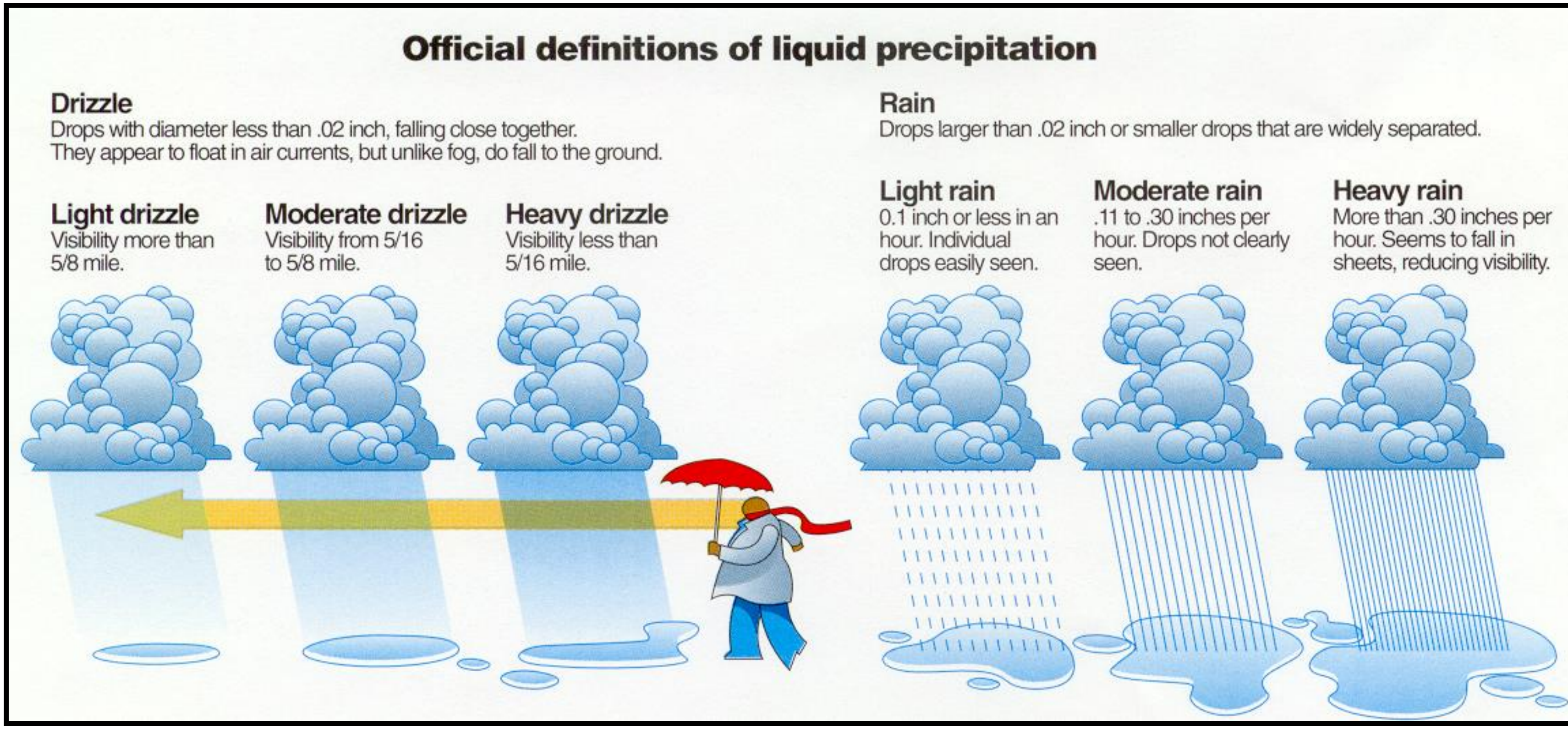
- The type of precipitation that falls to the ground depends upon the formation process and the temperatures of the environment between the cloud and the surface

Introduction….

- Rain:
  - Is precipitation in the form of water drops of size larger than 0.5 mm to 6mm
  - The rainfall is classified in to
    - Light rain – if intensity is trace to 2.5 mm/h
    - Moderate – if intensity is 2.5 mm/hr to 7.5 mm/hr
    - Heavy rain – above 7.5 mm/hr

Precipitation Types

Type	**Size**	**Description**
Drizzle	**<0.5 mm**	**Small drops of relatively uniform size that fall from stratus**
Rain	**0.5 – 5 mm**	**Size of drops vary depending on time and place**
Freezing rain	**0.5 – 5 mm**	**Rain that freezes on contact**
Sleet	**0.5 – 5 mm**	**Ice particles that melt and then re-freeze on decent**
Snow	**1 – 2 mm**	**Aggregated ice crystals that remain frozen during decent**
Hail	**5 to 10 cm or larger**	**Hard pellets of ice from cumulonimbus**



Williams, *The Weather Book*

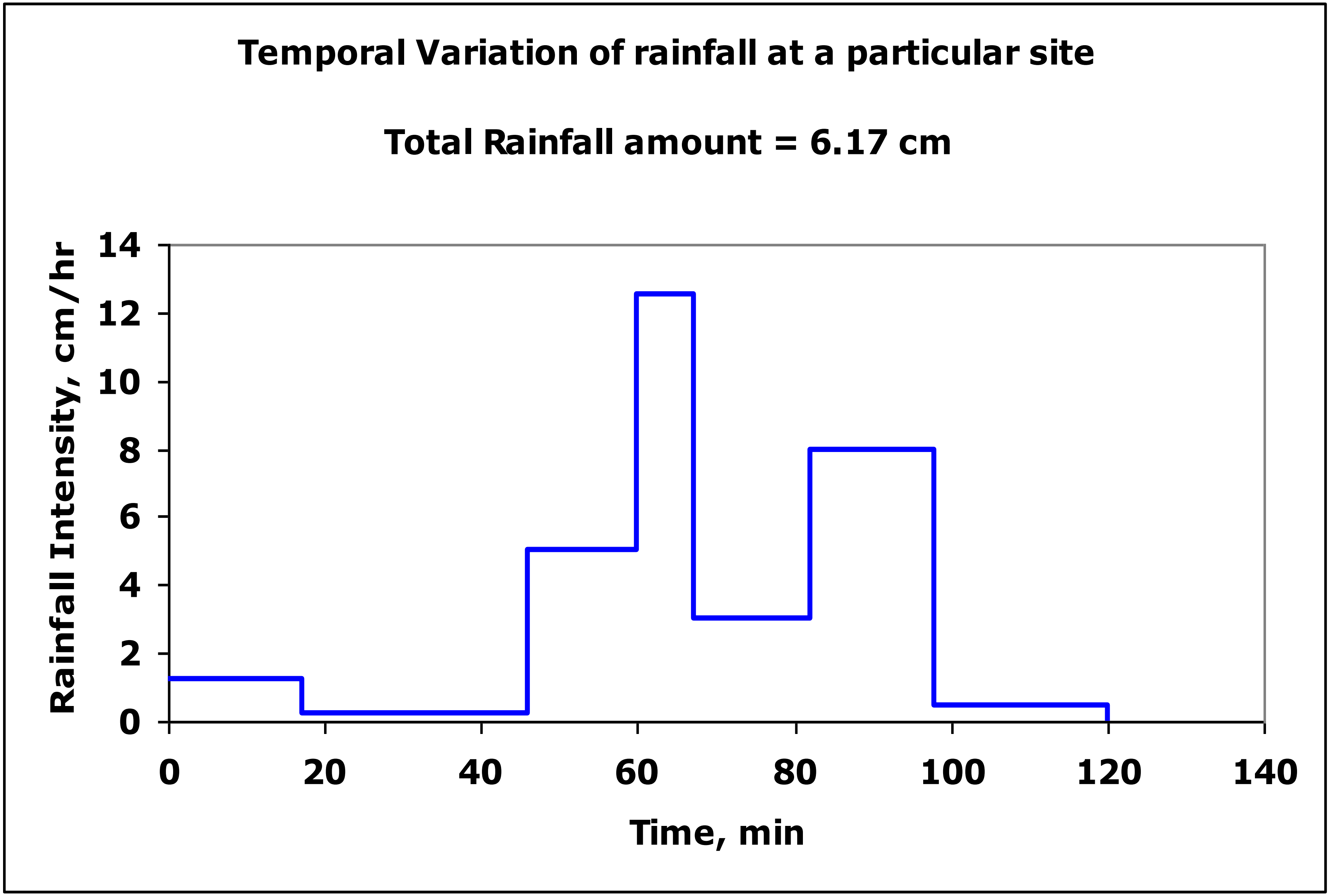
Introduction….

- Snow:
  - Snow is formed from ice crystal masses, which usually combine to form flakes
- Hail (violent thunderstorm)
  - precipitation in the form of small balls or lumps usually consisting of concentric layers of clear ice and compact snow.
  - Hail varies from 0.5 to 5 cm in diameter and can be damaging crops and small buildings.

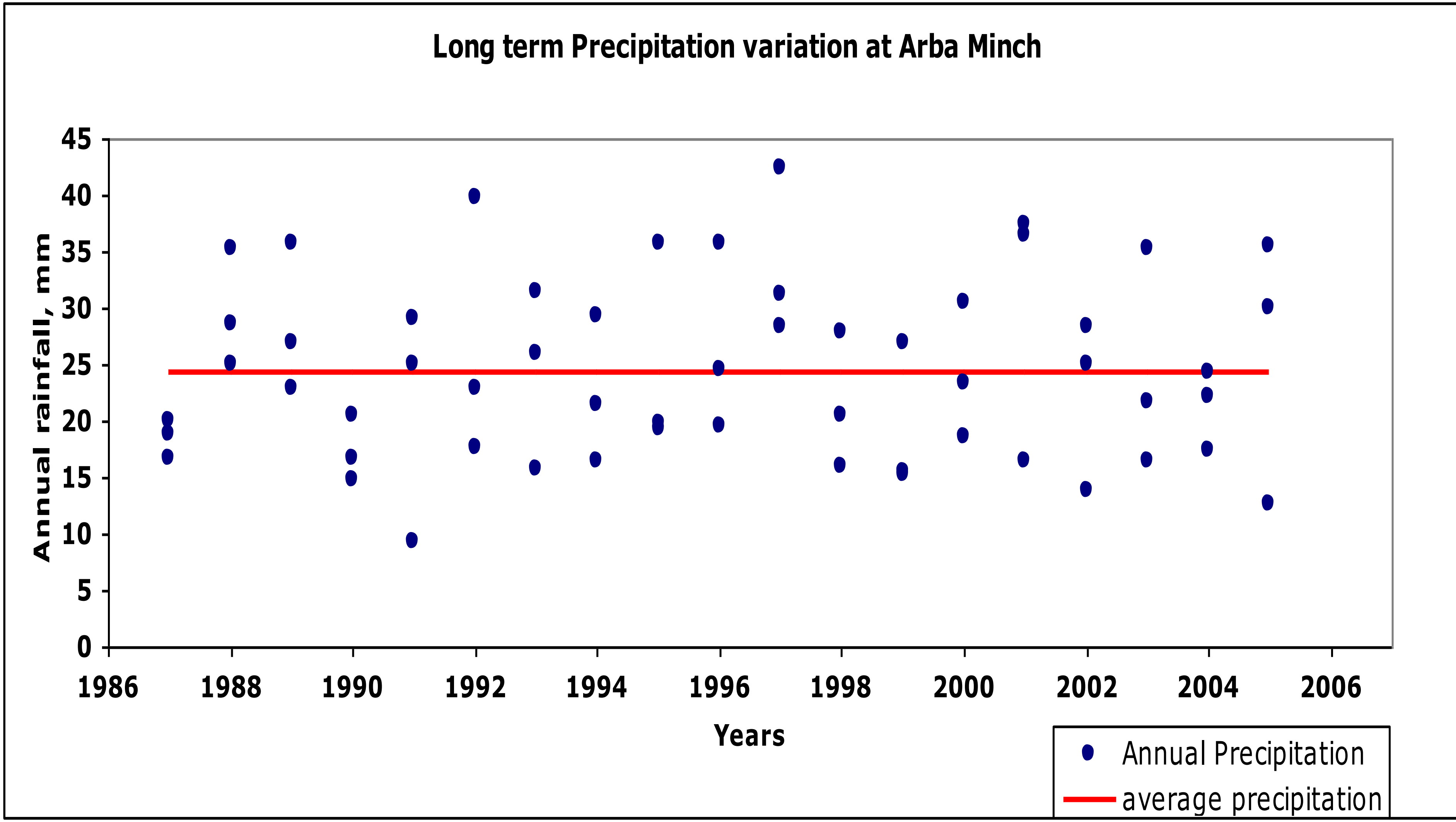
2.2 Temporal and Spatial Variation of Rainfall

- **Rainfall varies greatly both in time and space**
  - **With respect to time – temporal variation**
  - **With space – Spatial variation**

- **The temporal variation may be defined as hourly, daily, monthly, seasonal variations and annual variation (long-term variation of precipitation)**



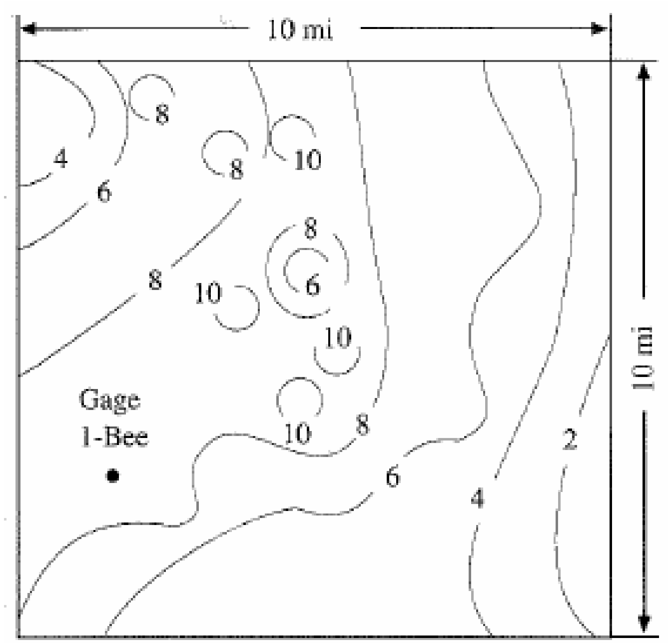
Temporal Variation of rainfall at a particular site
Total Rainfall amount = 6.17 cm
Rainfall Intensity, cm/hr
Time, min
0
2
4
6
8
10
12
14
20
40
60
80
100
120
140



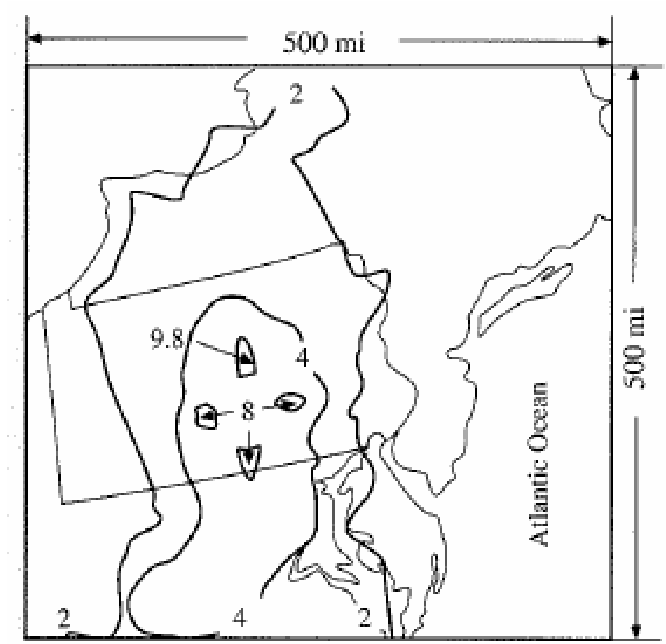
Long term Precipitation variation at Arba Minch
Annual rainfall, mm
45
40
35
30
25
20
15
10
5
0
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
Years
Annual Precipitation
average precipitation

Spatial Representation

- Isohyet – contour of constant rainfall
- Isohyetal maps are prepared by interpolating rainfall data at gaged points.

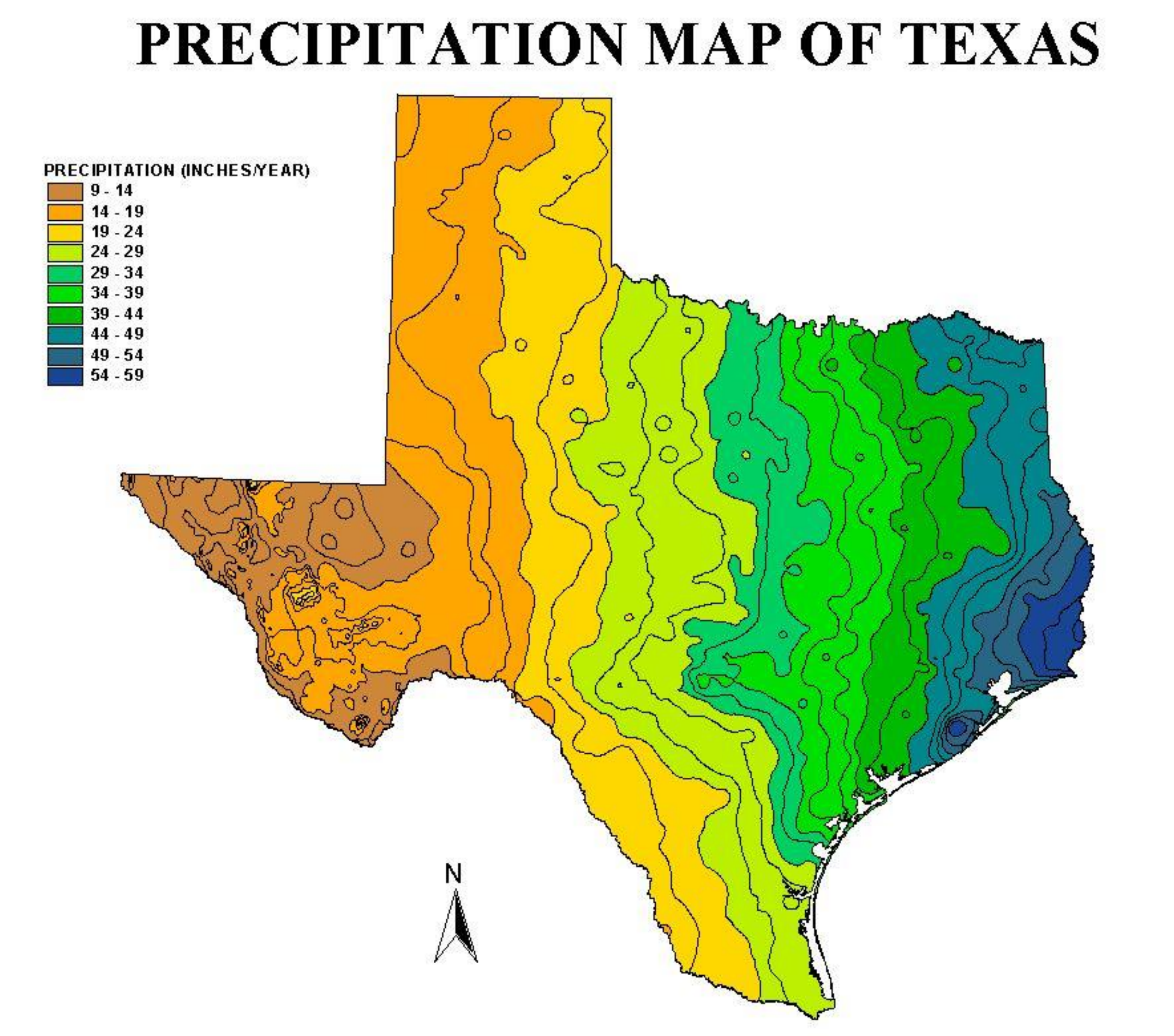


Austin, May 1981



Wellsboro, PA 1889

Texas Rainfall Maps



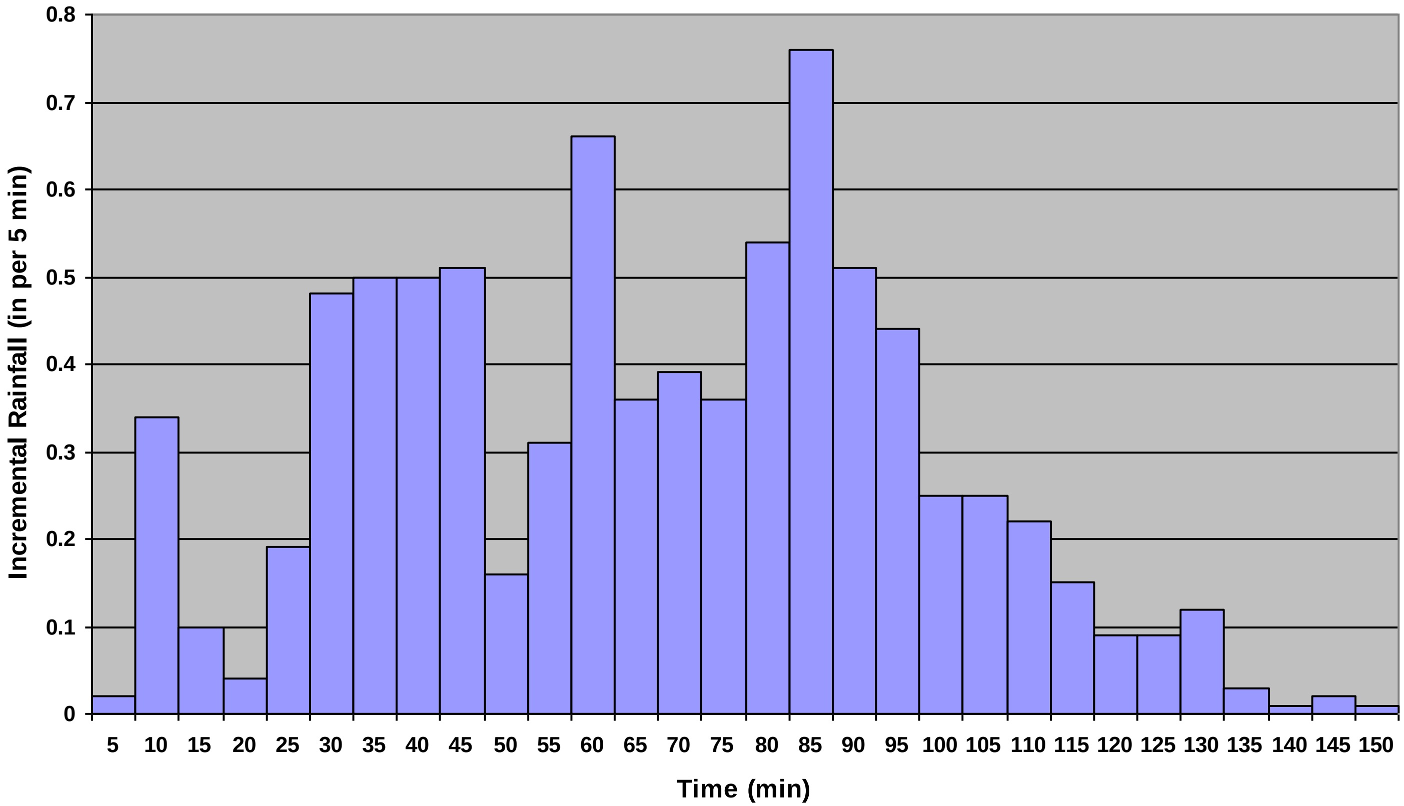
Temporal Representation

- **Rainfall hyetograph** – plot of rainfall depth or intensity as a function of time
- **Cumulative rainfall hyetograph or rainfall mass curve** – plot of summation of rainfall increments as a function of time
- **Rainfall intensity** – depth of rainfall per unit time

Rainfall Depth and Intensity

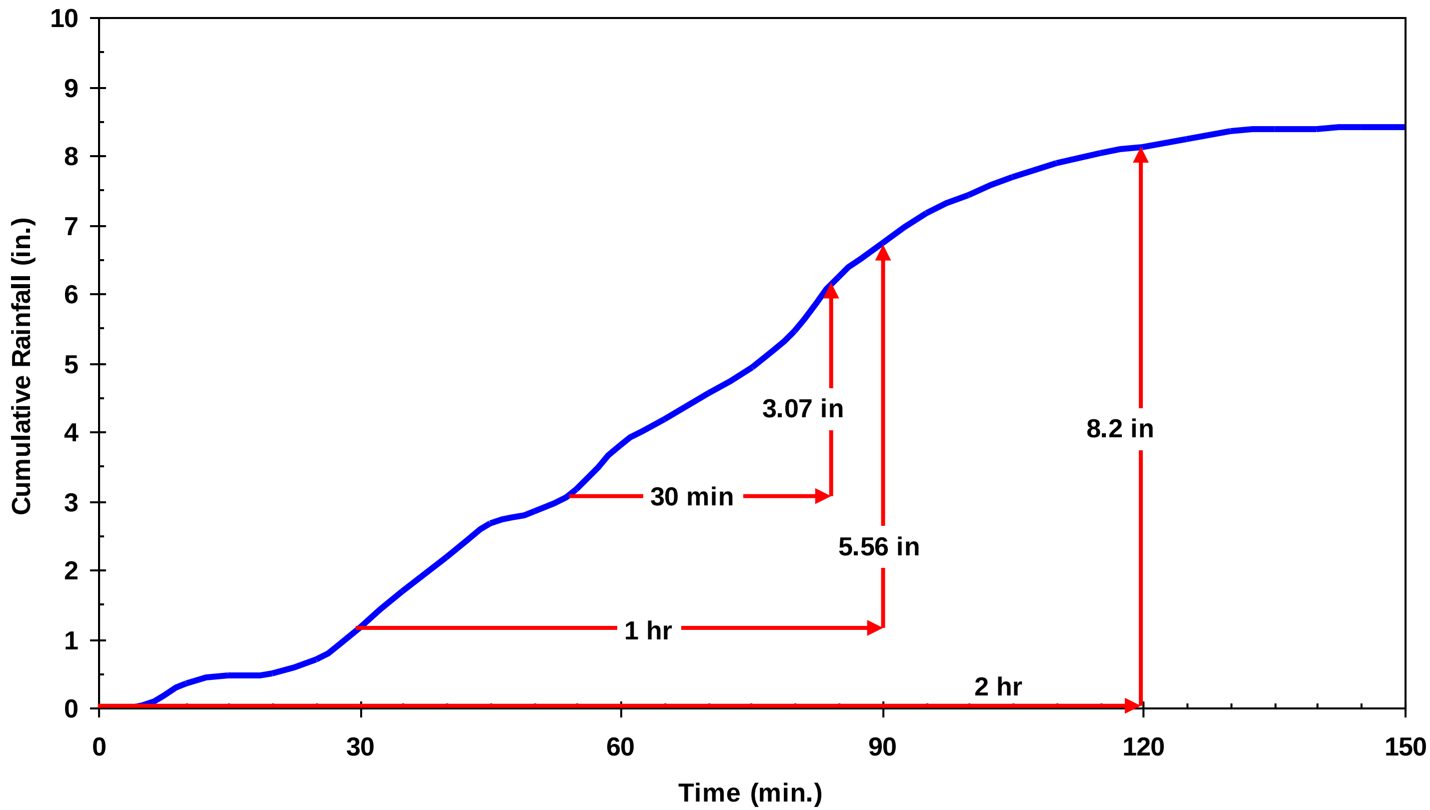
			Running Totals		
Time (min)	**Rainfall (in)**	**Cumulative Rainfall (in)**	**30 min**	**1 h**	**2 h**
0		0			
5	0.02	0.02			
10	0.34	0.36			
15	0.1	0.46			
20	0.04	0.5			
25	0.19	0.69			
30	0.48	1.17	1.17		
35	0.5	1.67	1.65		
40	0.5	2.17	1.81		
45	0.51	2.68	2.22		
50	0.16	2.84	2.34		
55	0.31	3.15	2.46		
60	0.66	3.81	2.64	3.81	
65	0.36	4.17	2.5	4.15	
70	0.39	4.56	2.39	4.2	
75	0.36	4.92	2.24	4.46	
80	0.54	5.46	2.62	4.96	
85	0.76	6.22	3.07	5.53	
90	0.51	6.73	2.92	5.56	
95	0.44	7.17	3	5.5	
100	0.25	7.42	2.86	5.25	
105	0.25	7.67	2.75	4.99	
110	0.22	7.89	2.43	5.05	
115	0.15	8.04	1.82	4.89	
120	0.09	8.13	1.4	4.32	8.13
125	0.09	8.22	1.05	4.05	8.2
130	0.12	8.34	0.92	3.78	7.98
135	0.03	8.37	0.7	3.45	7.91
140	0.01	8.38	0.49	2.92	7.88
145	0.02	8.4	0.36	2.18	7.71
150	0.01	8.41	0.28	1.68	7.24
Max. Depth	**0.76**		**3.07**	**5.56**	**8.2**
Max. Intensity	**9.12364946**		**6.14**	**5.56**	**4.1**

Incremental Rainfall



Rainfall Hyetograph

Cumulative Rainfall



Rainfall Mass Curve

2.3. Measurement of Rainfall

- Rainfall and other forms of precipitation are measured in terms of depth, the values being expressed in millimeters.
- One millimeter of precipitation represents the quantity of water needed to cover the land with a 1mm layer of water, taking into account that nothing is lost through drainage, evaporation or absorption.
- Instrument used to collect and measure the precipitation is called raingauge.

Ready?

1. Nuclei for the formation of rain drops can be small particles of: A) salt, B) smoke, C) dust, D) all the above
2. This form of precipitation is supercooled: A) rain, B) snow, C) sleet, D) freezing rain
3. This form of precipitation stays frozen all the way to the ground: A) rain, B) snow, C) sleet, D) freezing rain

The Answers!

1. D
2. D
3. B

Measurement of precipitation

- Precipitation is expressed in terms of the depth to which water would stand on an area if all the rain were collected in it.
- In case of snowfall, an equivalent depth of water is used as the depth of precipitation.
- The rainfall is collected and measured in a raingauge.

Pluviometer, Ombrometer and hyetometer are all synonymous names for raingauge.

- The exposure conditions affect the catch of the raingauge. For sitting a raingauge the following considerations are important:
  - ✓ The ground must be level and in the open area and instrument must present a horizontal catch.
  - ✓ The gauge must be set near the ground as possible to reduce wind effect, but it must be sufficiently high to prevent splashing.
  - ✓ The instrument should be surrounded by an open fenced area of atleast 5.5m*5.5m. No object should be nearer to the instrument than 30m or twice the height of obstruction.

Nonrecording

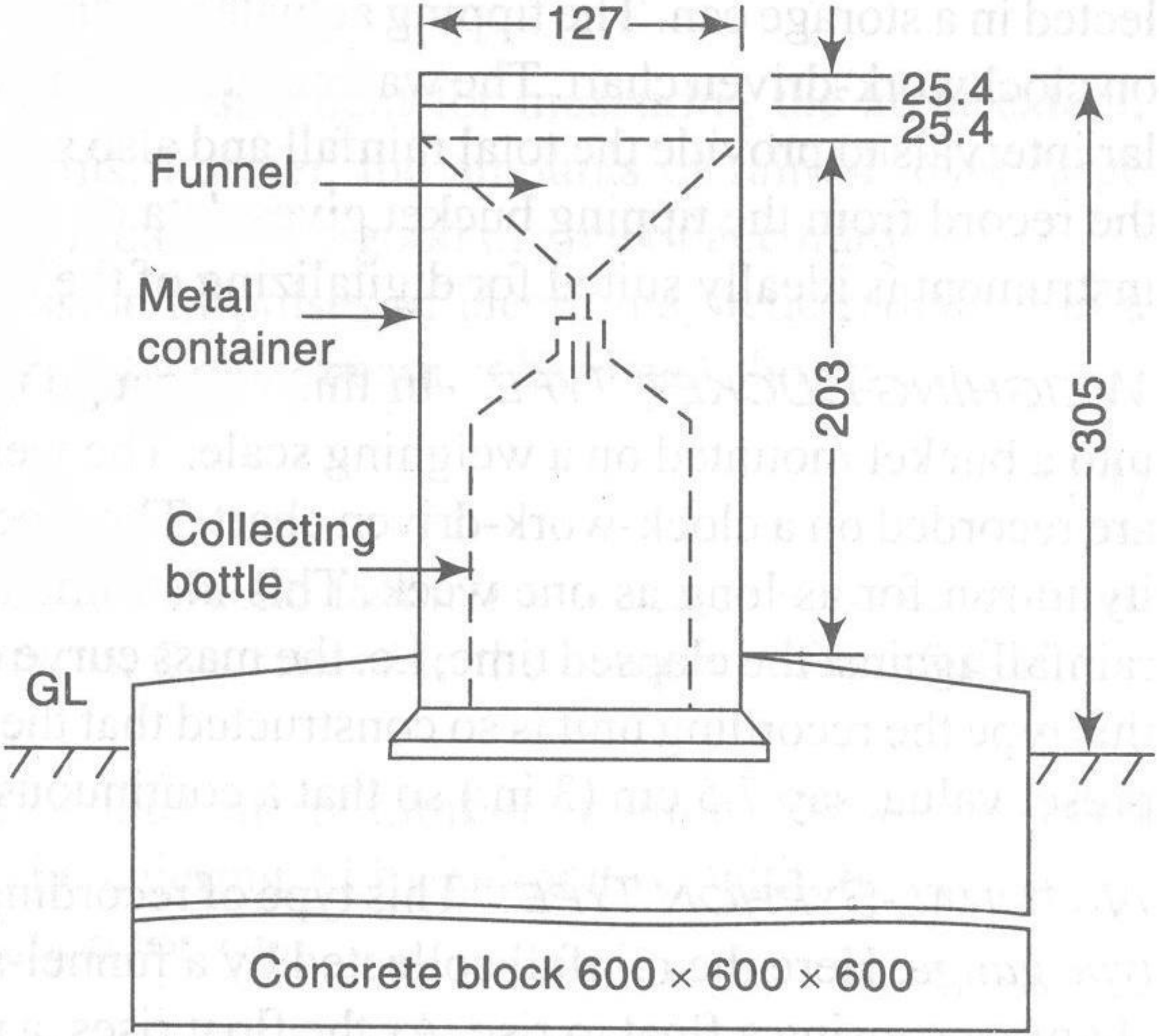
Types

Recording

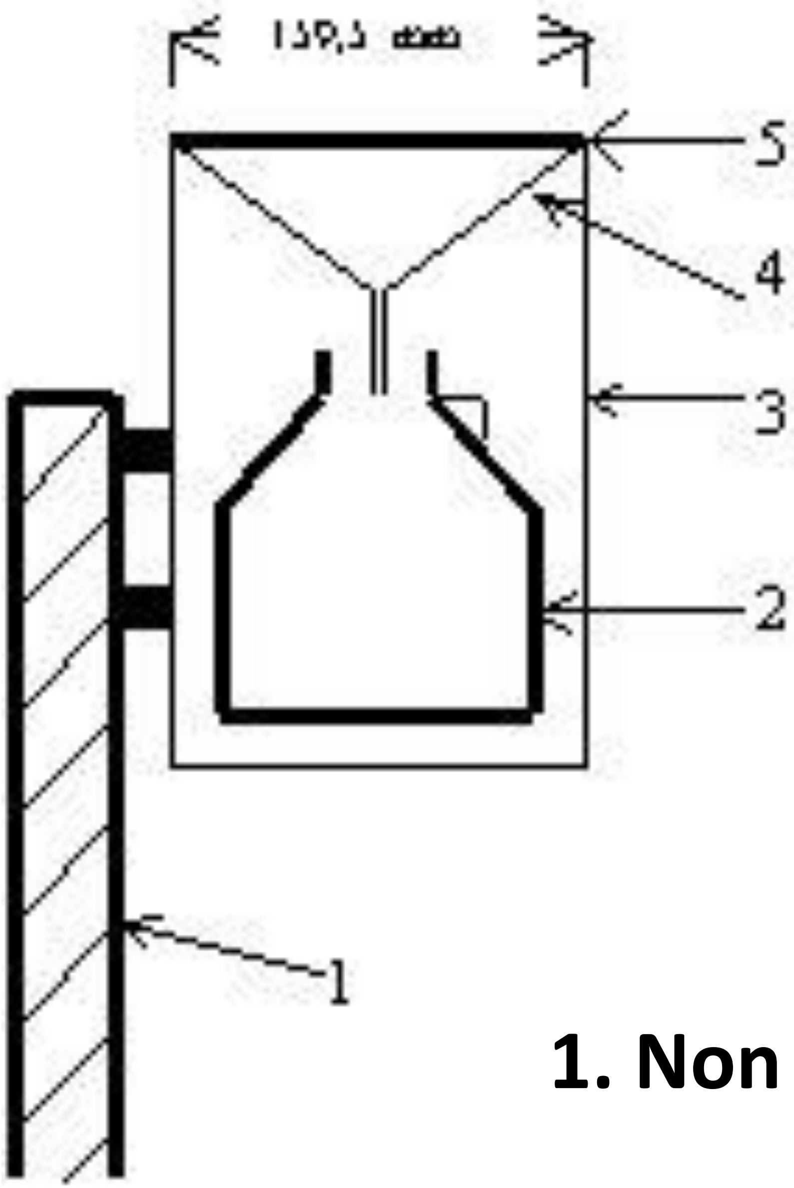
Nonrecording gauge (Symons' gauge)

Recording gauges

1. Tipping–bucket type
2. Weighing-bucket type
3. Natural-Syphon type (float type gauge)
4. Telemetering raingauge



Nonrecording Raingauge (Symons' Gauge)



Precipitation gauge

1 - pole

2 - collector

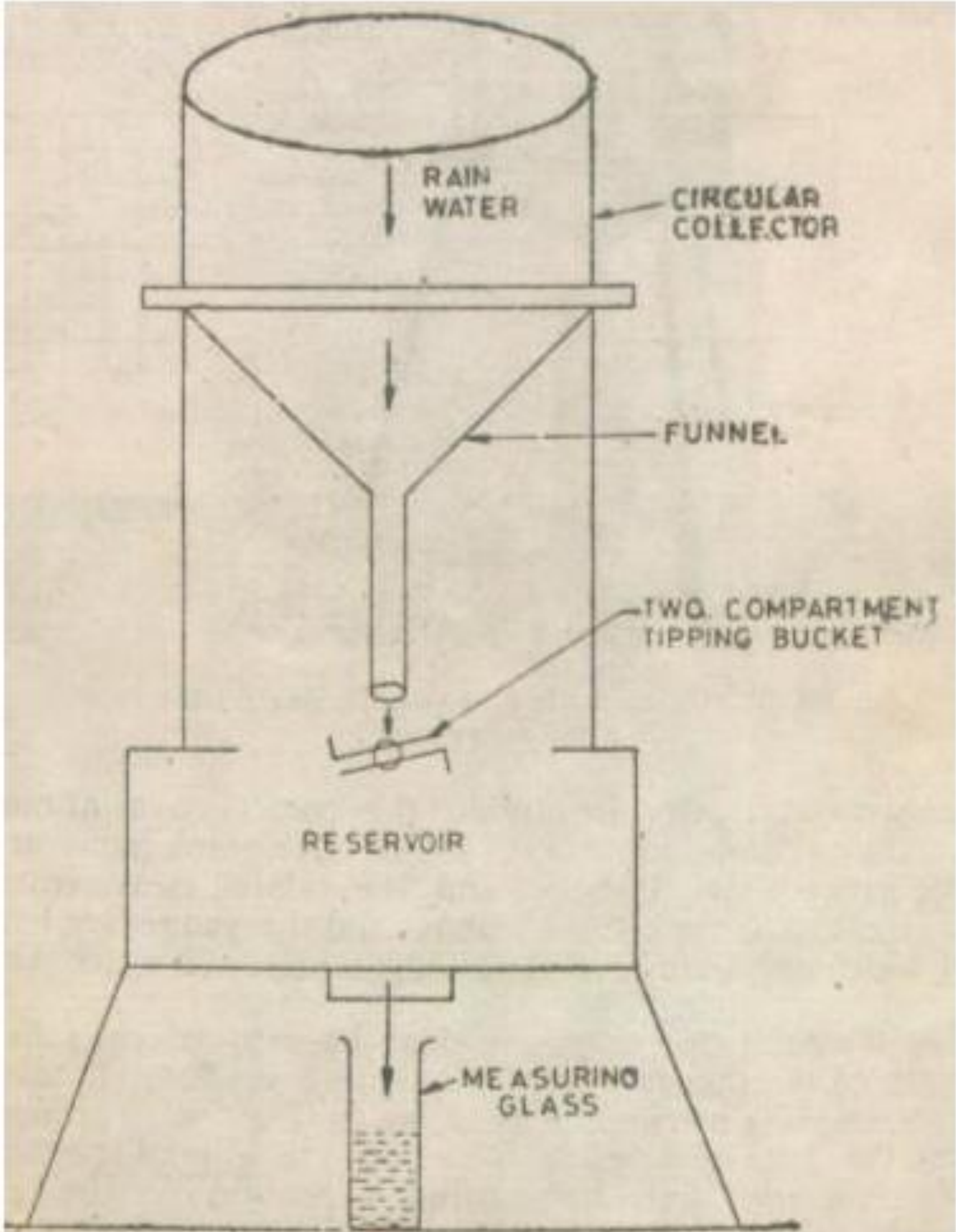
3 - support- galvanized metal sheet

4 – funnel

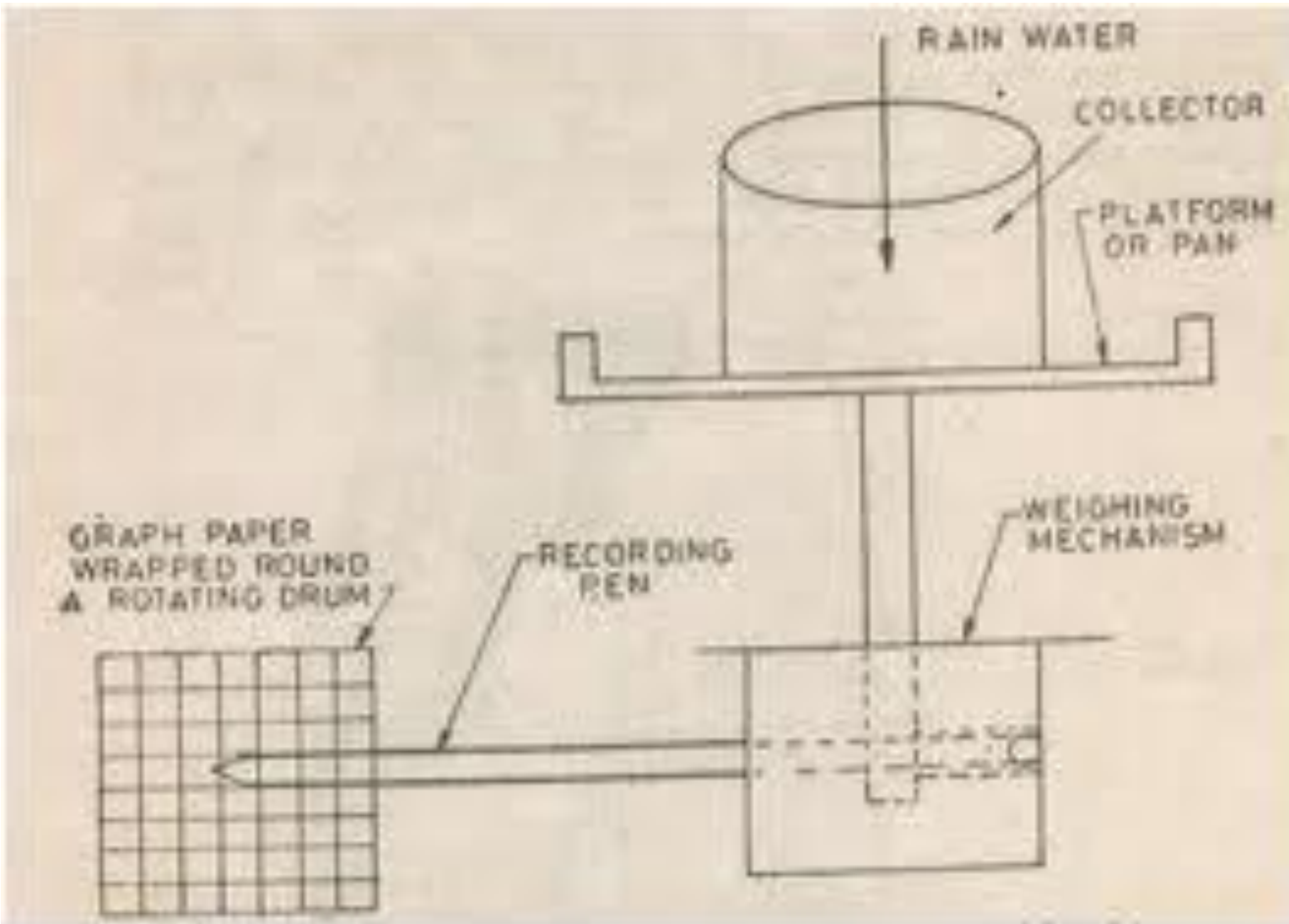
5 - steel ring

1. Non recording gauge

Tipping–bucket Raingauge

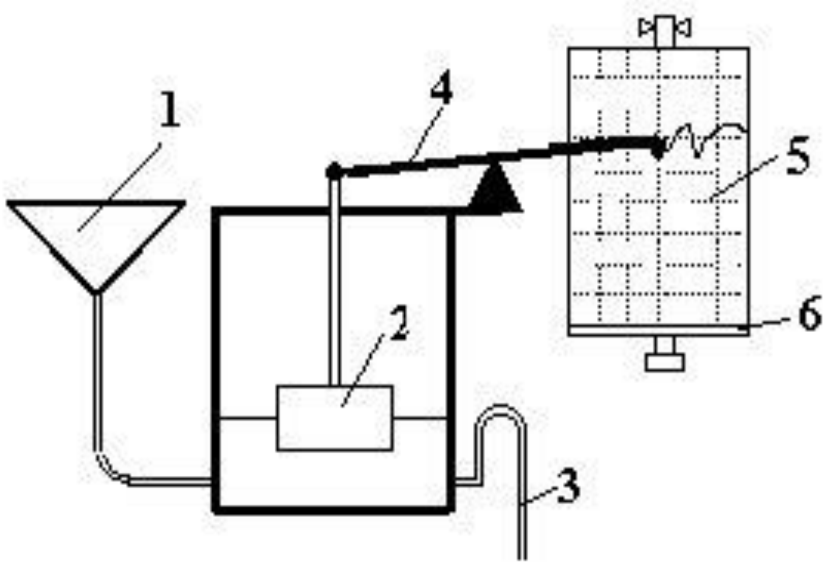


Weighing-bucket Raingauge

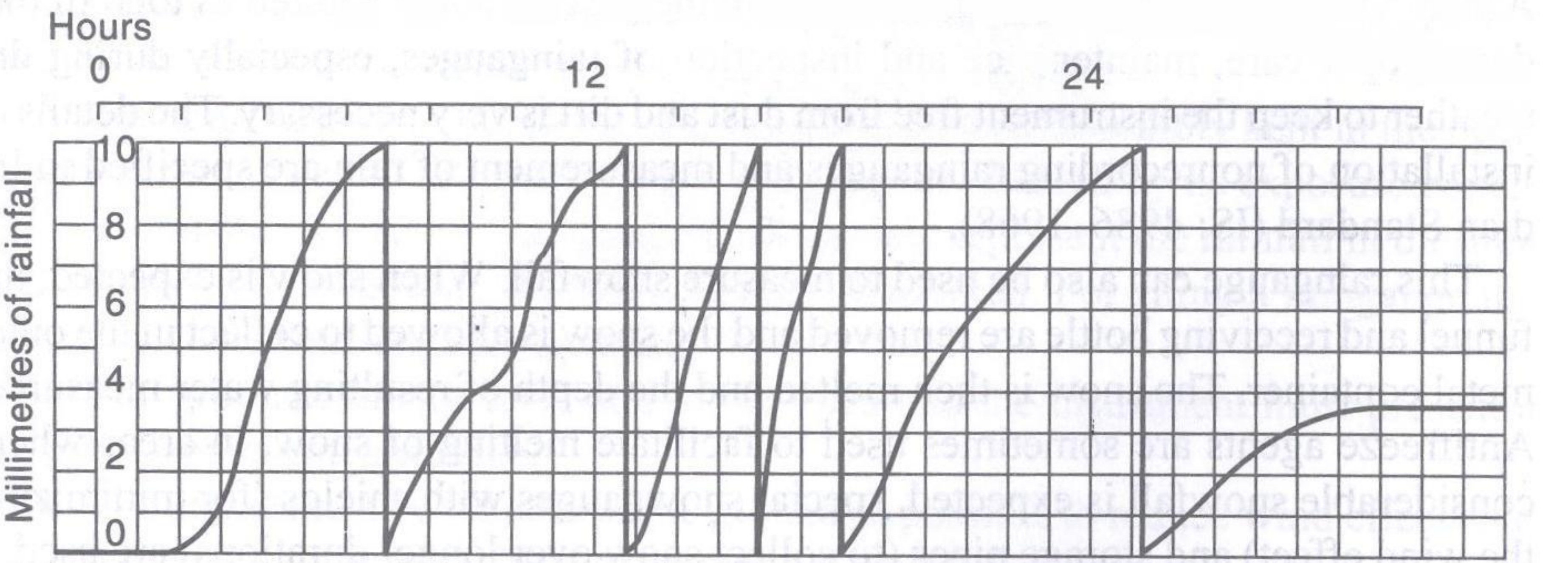


2. Recording gauge / graphic raingauge

- The instrument records the graphical variation of the fallen precipitation, the total fallen quantity in a certain time interval and the intensity of the rainfall (mm/hour).
- It allows continuous measurement of the rainfall.

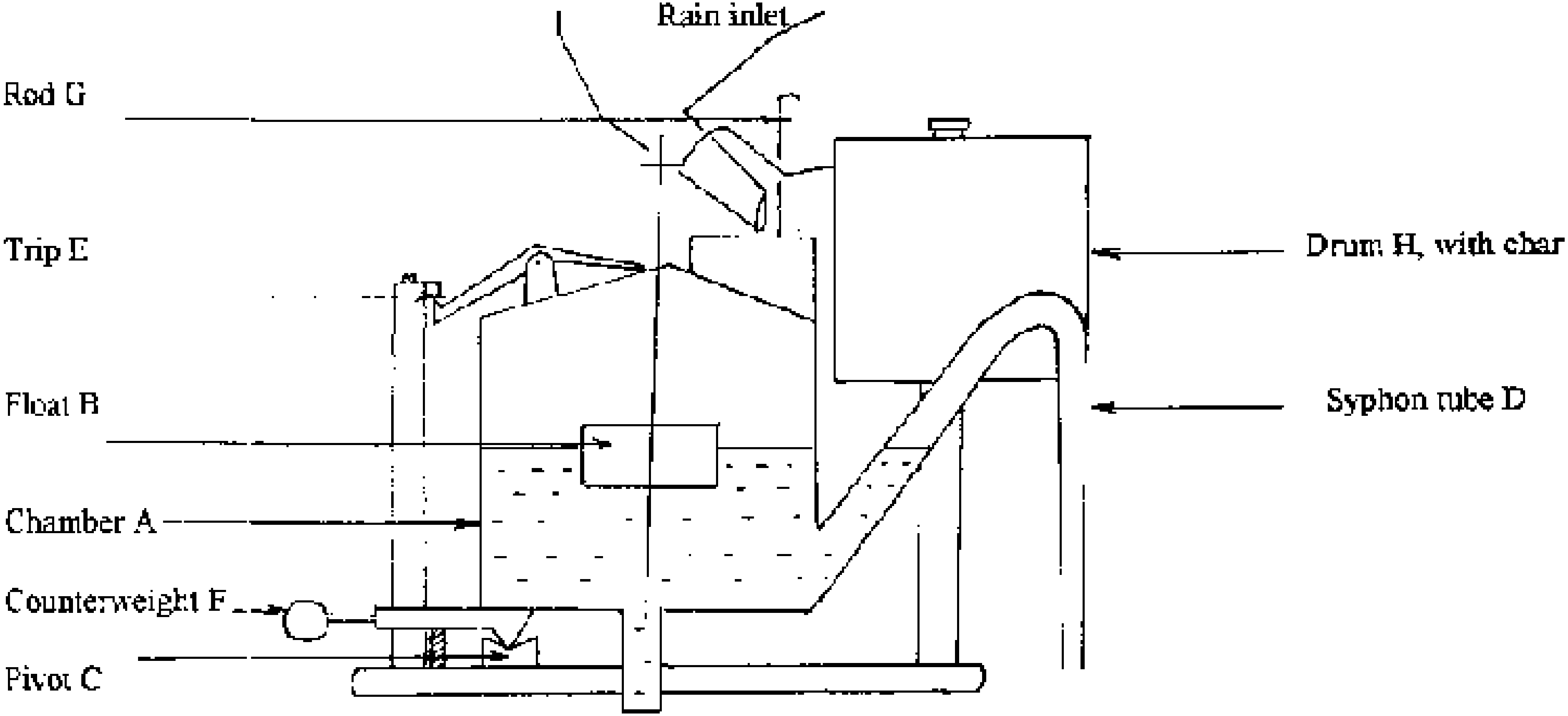


The graphic rain gauge
1-receiver
2-floater
3-siphon
4-recording needle
5-drum with diagram
6-clock mechanism



Recording from a Natural Syphon-type Gauge (Schematic)

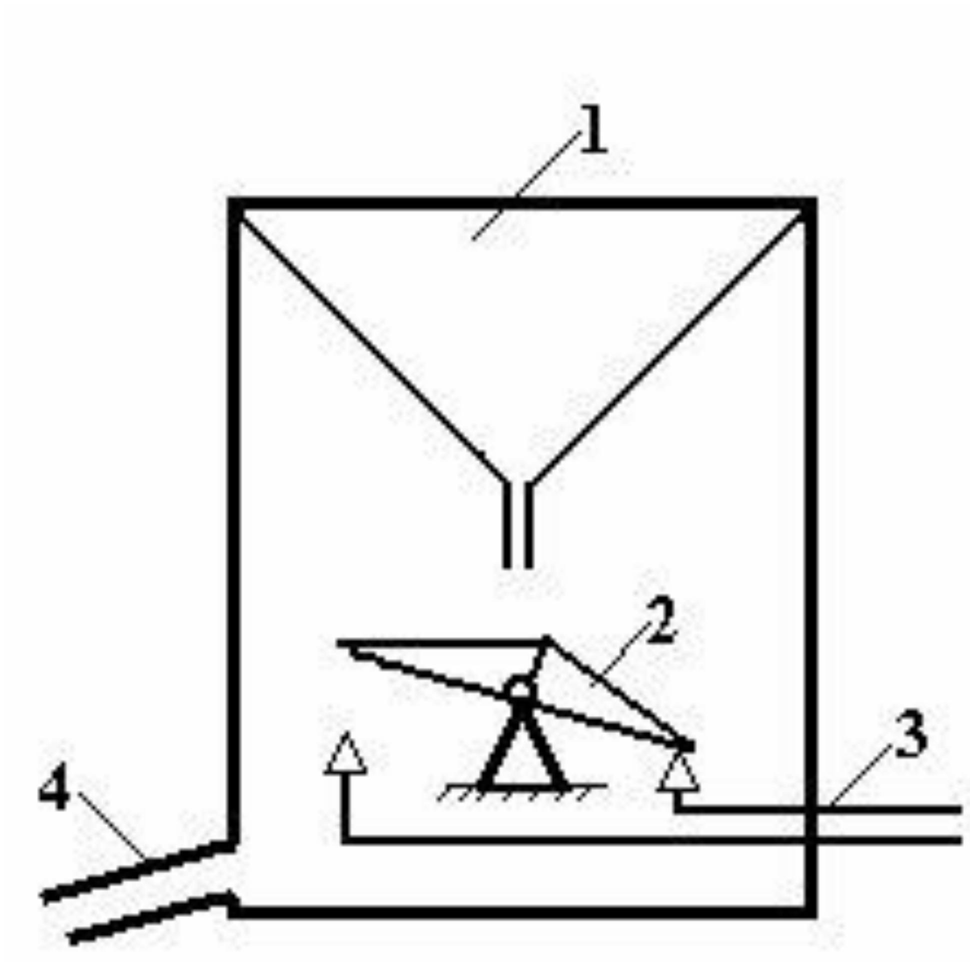
Natural-Syphon type (float type raingauge)



3. Tele-rain gauge with tilting baskets

- The tele-rain gauge is used to transmit measurements of precipitation through electric or radio signals.
- The sensor device consists of a system with two tilting baskets, which fill alternatively with water from the collecting funnel, establishing the electric contact.
- The number of tilting is proportional to the quantity of precipitation *hp*

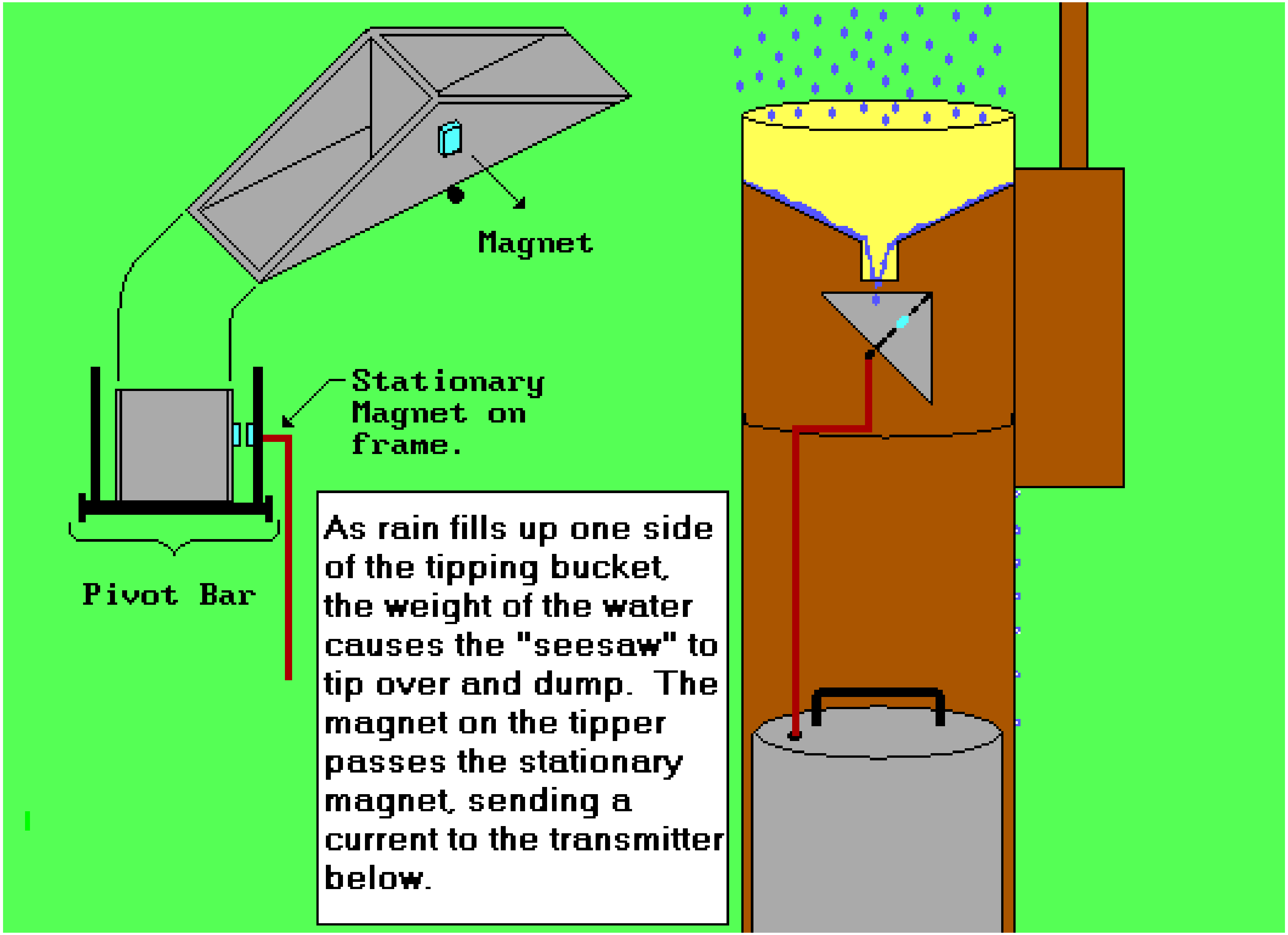
Tele-rain gauge ……



The tele-rain-gauge

1 - collecting funnel 2 - tilting baskets
3 - electric signal
4 - evacuation

Telemetering raingauge



4. Radar measurement of rainfall

- The meteorological radar is the powerful instrument for measuring the area extent, location and movement of rainstorm.
- The amount of rainfall overlarge area can be determined through the radar with a good degree of accuracy
- The radar emits a regular succession of pulse of electromagnetic radiation in a narrow beam so that when the raindrops intercept a radar beam, its intensity can easily be known.

Radar (RAdio Detection And Ranging) Measurement

$$P_r = \frac{cz}{r^2}$$

P_r= average echopower

z = radar echo factor

r = distance to target volume

c = a constant

$z = aI^b$ a and b are coefficients,

I = intensity (mm/hr)

a and b determined by calibration with the help of recording raingauge

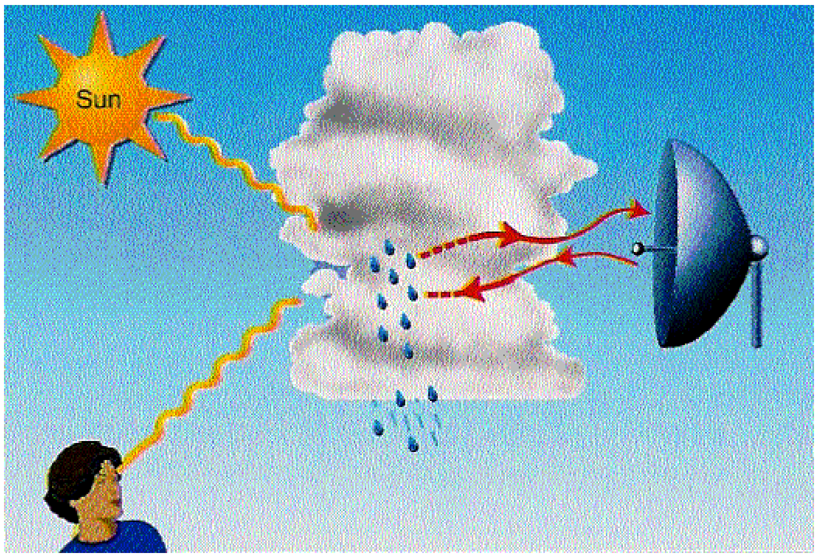
$z = 200\ I^{1.6}$

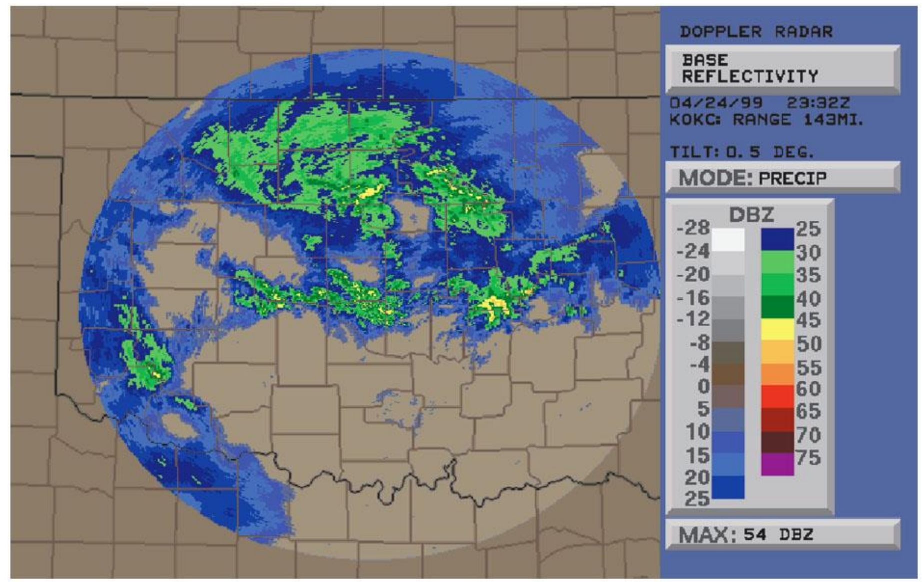
10cm wave length radar is used for heavy-flood producing rains

5cm wave length radar is used for light rain & snow

r = 200 km. Areal extent upto 100,000 km^2

RADAR
(RAdio Detection And Ranging)





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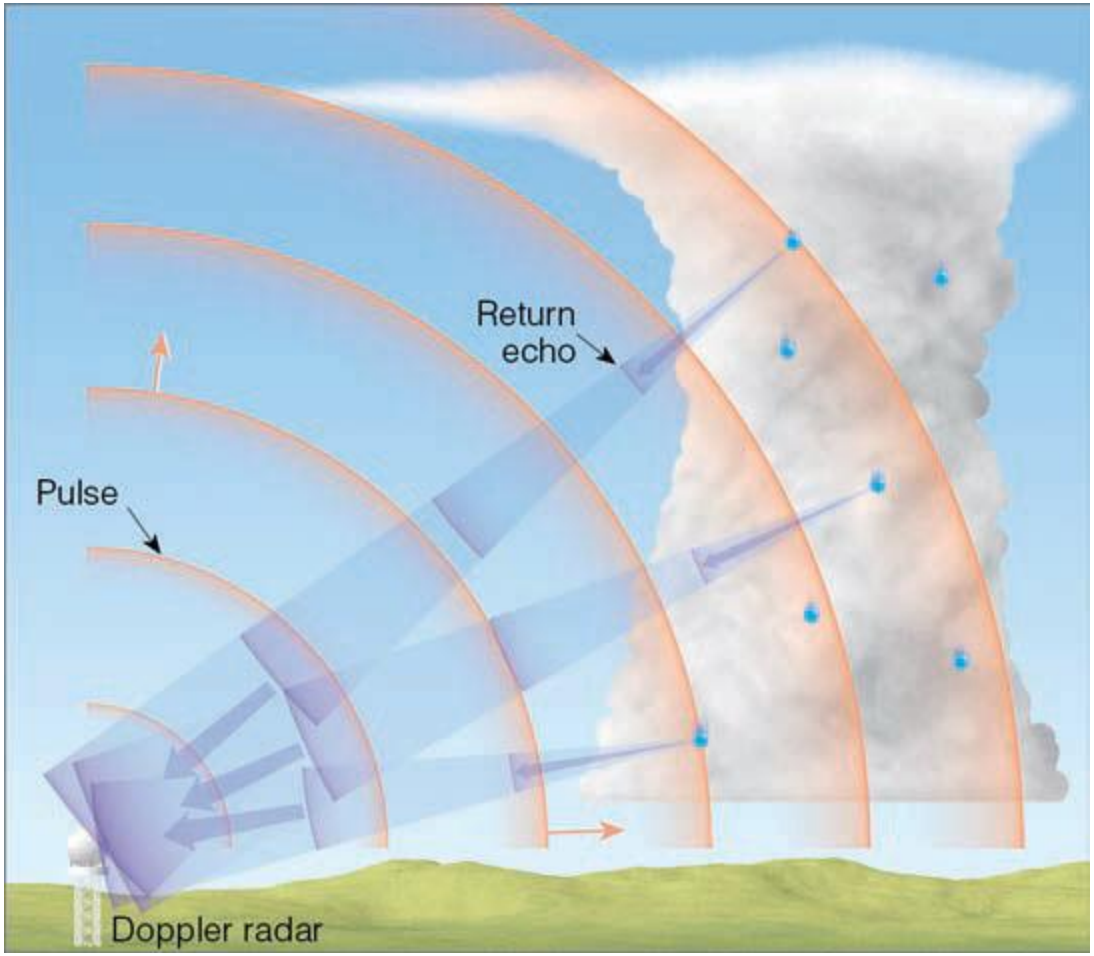
<u>Principle</u>: Detects reflected radiation emitted for short wavelength radio waves. The degree of reflectivity corresponds with the intensity of precipitation (or what ever else in the beam path).

- A microwave pulse is sent out from the radar transmitter. The pulse strikes raindrops and a fraction of its energy is reflected back to the radar unit, where it is detected and displayed



Snow Measurement

- The depth of snow can be determined by measuring its depth at three or more representative areas using **graduated stick or staff**.
  - **Snow stakes and snow boards (40 cm side square board)**
  - The amount of snowfall is defined as the average of these measurements.
  - Since snow often blows around and accumulates into drifts, finding a representative area can be a problem. Determining the actual depth of snow can include considerable educated guesswork.
- Snow depth may also be measured using a standard rain gauge
  - Turbulent air often blows flakes away from the gauge
  - Makes the amount of snow collected less than the actual snowfall.
  - Remedy: Slatted windshields are placed around the cylinder to block the wind and ensure a more correct catch.

Raingauge Network

- Since the catching area of the raingauge is very small as compared to the areal extent of the storm, to get 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.
- There are several factors to be considered to restrict the number of gauge:
  - Like economic considerations to a large extent
  - Topographic & accessibility to some extent.

- Raingauge Network

WMO recommendations:

In flat regions of tropical regions:

Ideal – 1 station for 600-900 km^2

Acceptable- 1 station for 900-3000 km^2

Mountainous regions of tropical zones:

Ideal – 1 station for 100-250 km^2

Acceptable – 1 station for 25-1000 km^2

Arid & Polar zone : 1 station for 1500-10,000km^2

10% of raingauge should be equipped with self-recording raingauge.

- **Indian conditions**

(Recommended by Indian Standards: IS 4987-1268)

Plains - 1 station for 520 km^2

Average elevation of 1000 m- 1 station for 260-290 km^2

Predominant hilly areas with heavy rainfall- 1 station for 130 km^2

Considerable variation of annual rainfall in time at a place

$$C_v = \frac{\sigma}{\mu} * 100$$

$C_v \longrightarrow$ 15 to 70 from place to place

Variability is least in regions of high rainfall and large in regions of scanty rainfall.

Gujarat. Haryana, Punjab and Rajasthan have large variability of rainfall.

Adequacy of raingauge stations

Optimal no. of stations, $N = \left(\frac{C_v}{\epsilon}\right)^2$

Ɛ = Allowable degree of error in the estimate of mean rainfall

C_v = C_v of rainfall values at the existing m station in %.

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

$$\sigma_m = \sqrt{\frac{\sum(P_i - \bar{P})^2}{(m-1)}}$$

$$\bar{P} = \frac{1}{m}\sum P_i$$

Example: Optimum no. of raingauges

A catchment has six raingauge stations. In an year, the annual rainfall recorded by the gauges are as below:

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 no. of stations in the catchment.

$$m = 6, \overline{P} = 118.6, \ \sigma_m = 35.04, \varepsilon = 10$$

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

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

Preparation of data

- Before use of rainfall records of a station , preliminary check of rainfall data is necessary.
  - Continuity of a record may be broken with missing data – damage, fault in raingauge.
  - Missing data can be estimated using neighboring stations.
- If Normal annual precipitation of stations within 10% of the N_x, then

$$P_x = \frac{1}{M}[P_1 + P_2 \ldots . + P_M]$$

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

Example: Estimation of missing data

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

$$P_D = \frac{92.01}{3}\left[\frac{91.11}{80.79} + \frac{72.23}{67.59} + \frac{79.89}{76.28}\right]$$

$= 99.48$ cm

Test for inconsistency of rainfall record

Why inconsistency in rainfall record of a station occurs ?

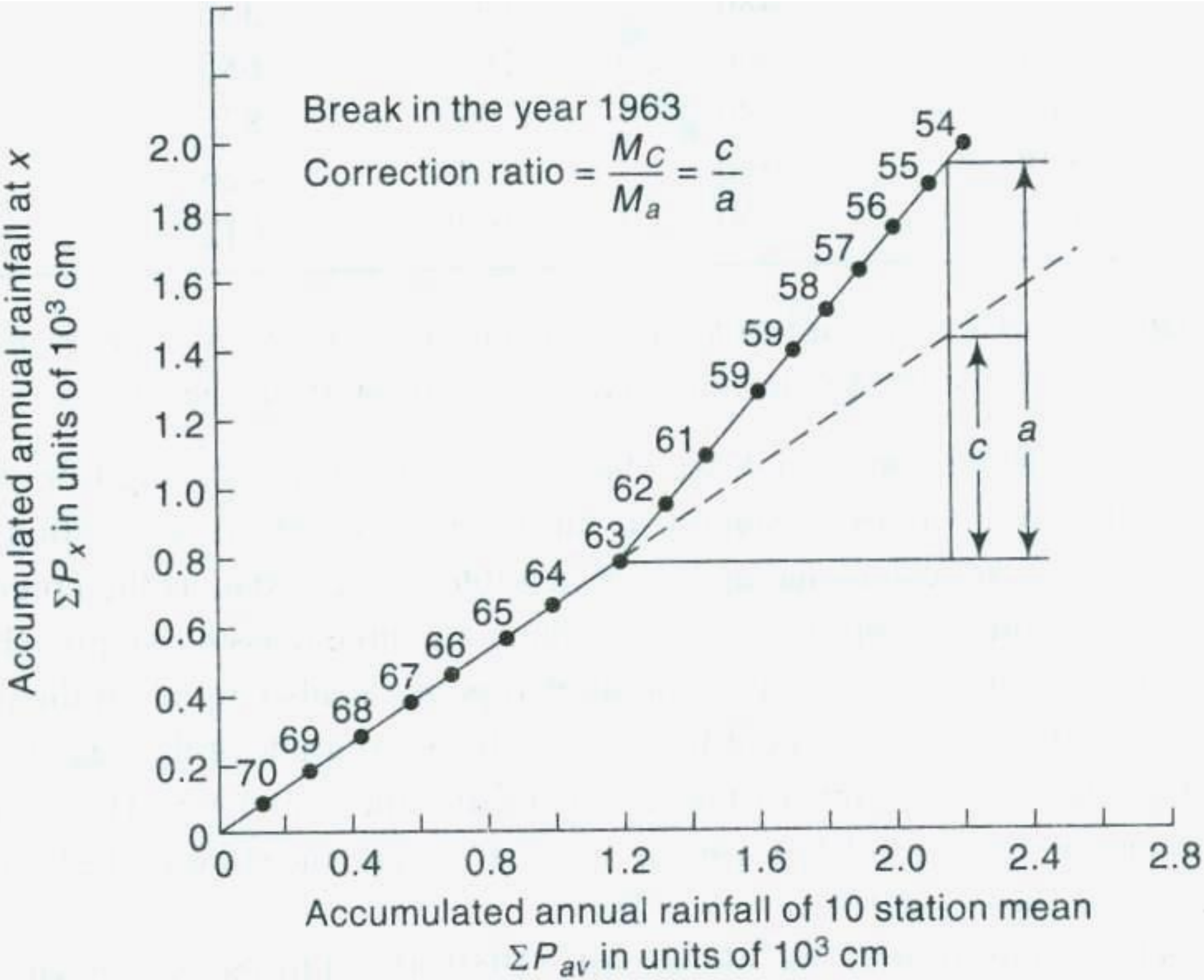
i. Shifting of the raingauge station to a new location

ii. Neighborhood of the station undergoing a marked change

iii. Change in the nearby environment like forest fire, land slides

iv. Instrumental and observational error.

- A change in slope is normally taken as significant only when it persist for more than 5 years.



Break in the year 1963
Correction ratio = $\frac{M_C}{M_a} = \frac{c}{a}$
54
55
56
57
58
59
59
61
62
63
64
65
66
67
68
69
70
c
a
0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
0
0.4
0.8
1.2
1.6
2.0
2.4
2.8
Accumulated annual rainfall at x
ΣP_x in units of 10^3 cm
Accumulated annual rainfall of 10 station mean
ΣP_{av} in units of 10^3 cm

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 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 $\sum P_{av}$ (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	793

Total of P_m = 19004 mm

Mean of P_m = 633.5 mm

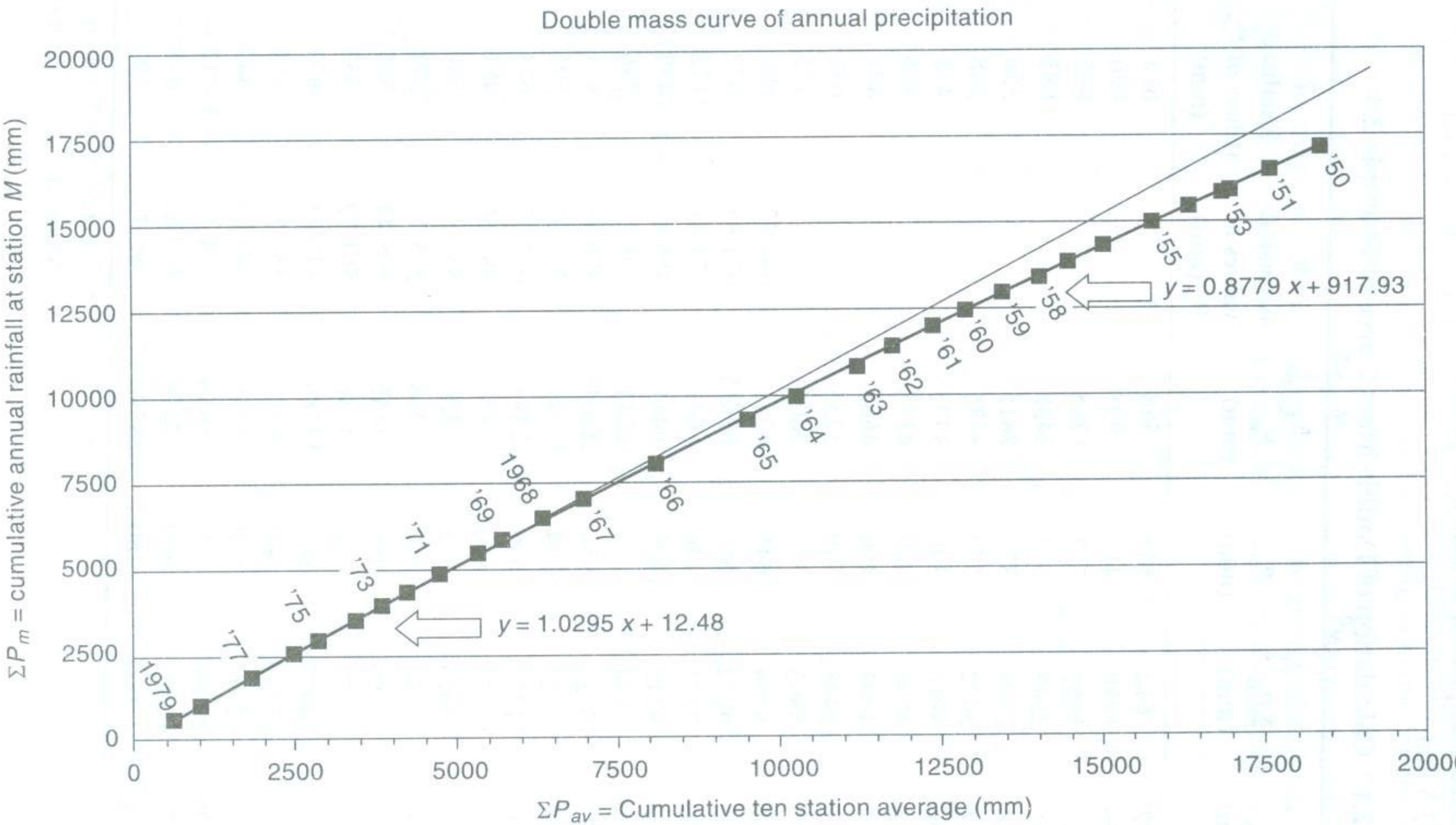
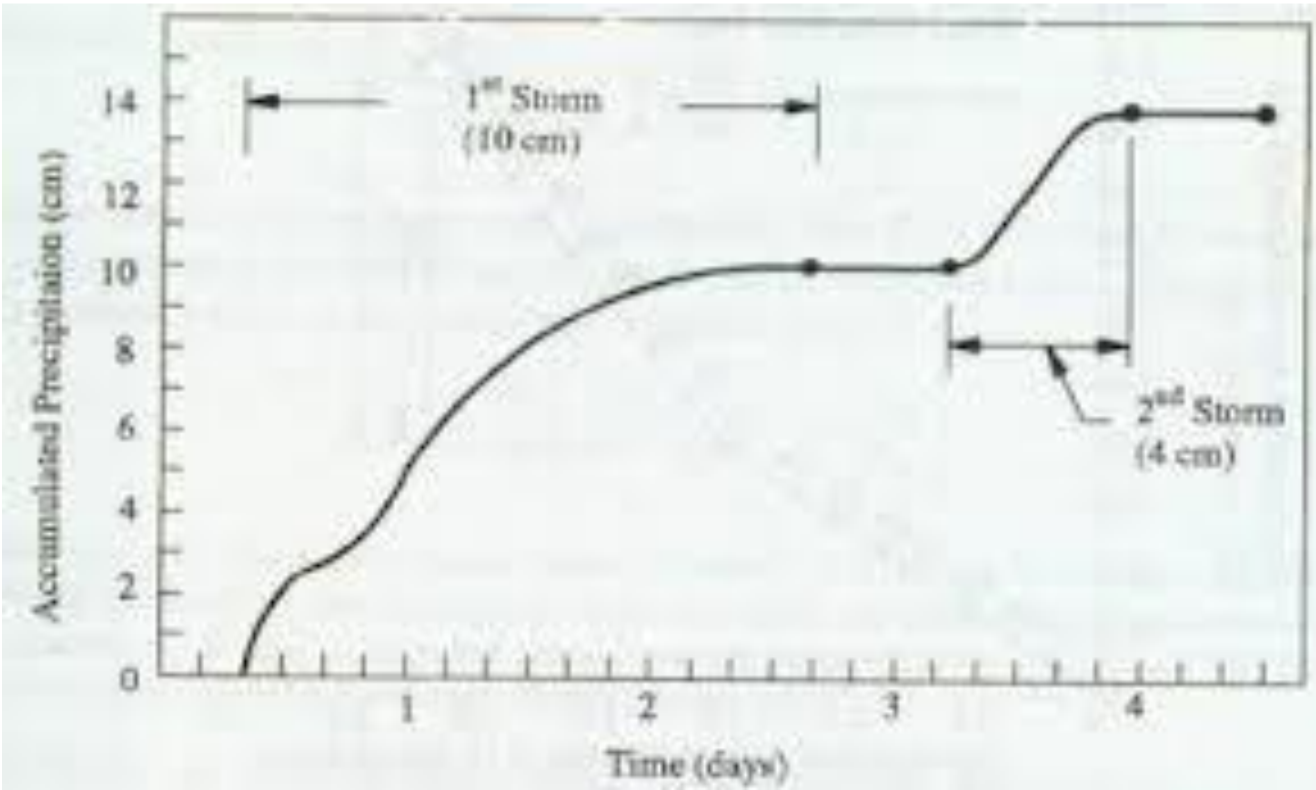


Fig. 2.8 Double Mass Curve of Annual Rainfall at Station M

PRESENTATION OF RAINFALL DATA

1. Mass curve of rainfall
2. Hyetograph
3. Moving average

1. Mass curve of rainfall

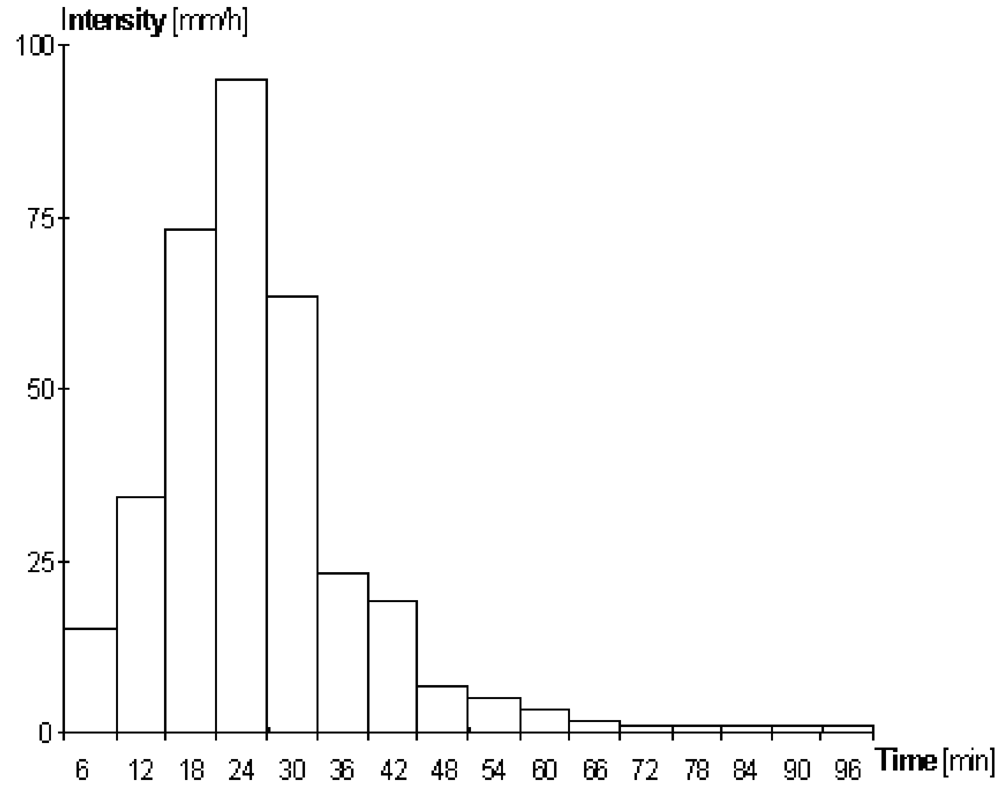


→ in extracting the information on the duration and magnitude of storm.

→ The slope of the curve gives the intensity.

- For non-recording 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 raingauge stations as a guide.

2. Hyetograph



- It is a plot of the intensity of rainfall against the time interval.
- It is prepared from the mass curve and is usually represented as a bar chart.
- Useful for the development of design storms to estimate extreme floods.

- Area under the hyetograph gives total precipitation .
- Δt used for hyetograph preparation depends on the purpose of its use.

1) Urban design flood estimation ‘Δt’ needs to be small.

2) Larger catchment flood estimation $\longrightarrow$ $\Delta t = 6$ hrs.

3. **Moving Average**

It is a technique for smoothening out the high frequency fluctuations of a time series and to enable the trend, if any, to be noticed.

Procedure:

- Select a window of time range in years, say 3 year.
- Start from the first set of 3 years of data, the average of 3 years is calculated and placed in the middle year of range m.
- Move to the next window, shifting by one time unit (year) at a time, and the mean of this new window is computed in its middle position of time.

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

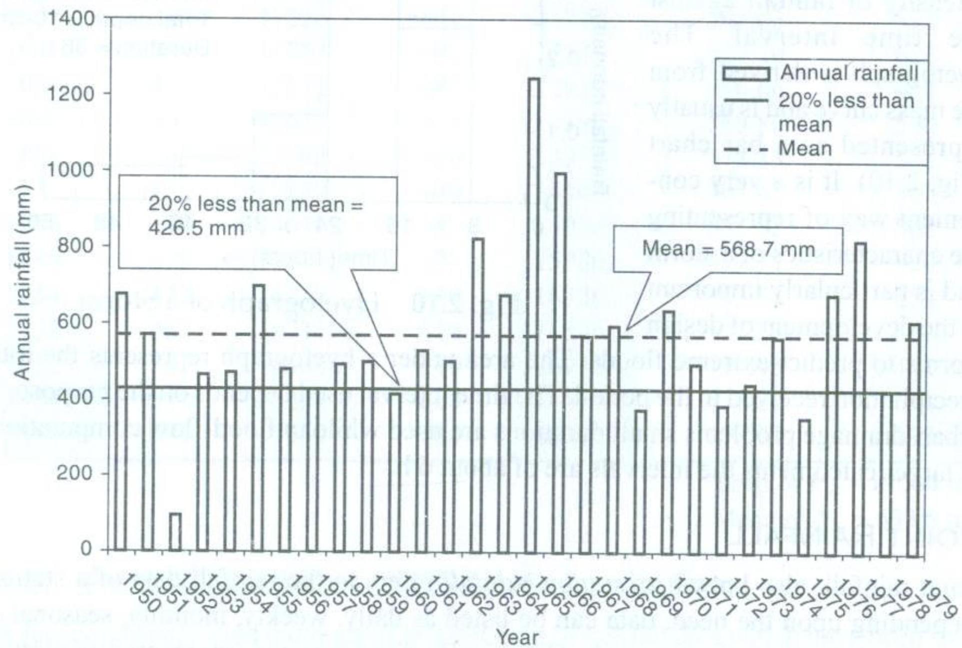


Fig. 2.11 Bar Chart of Annual Rainfall at Station *M*

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.

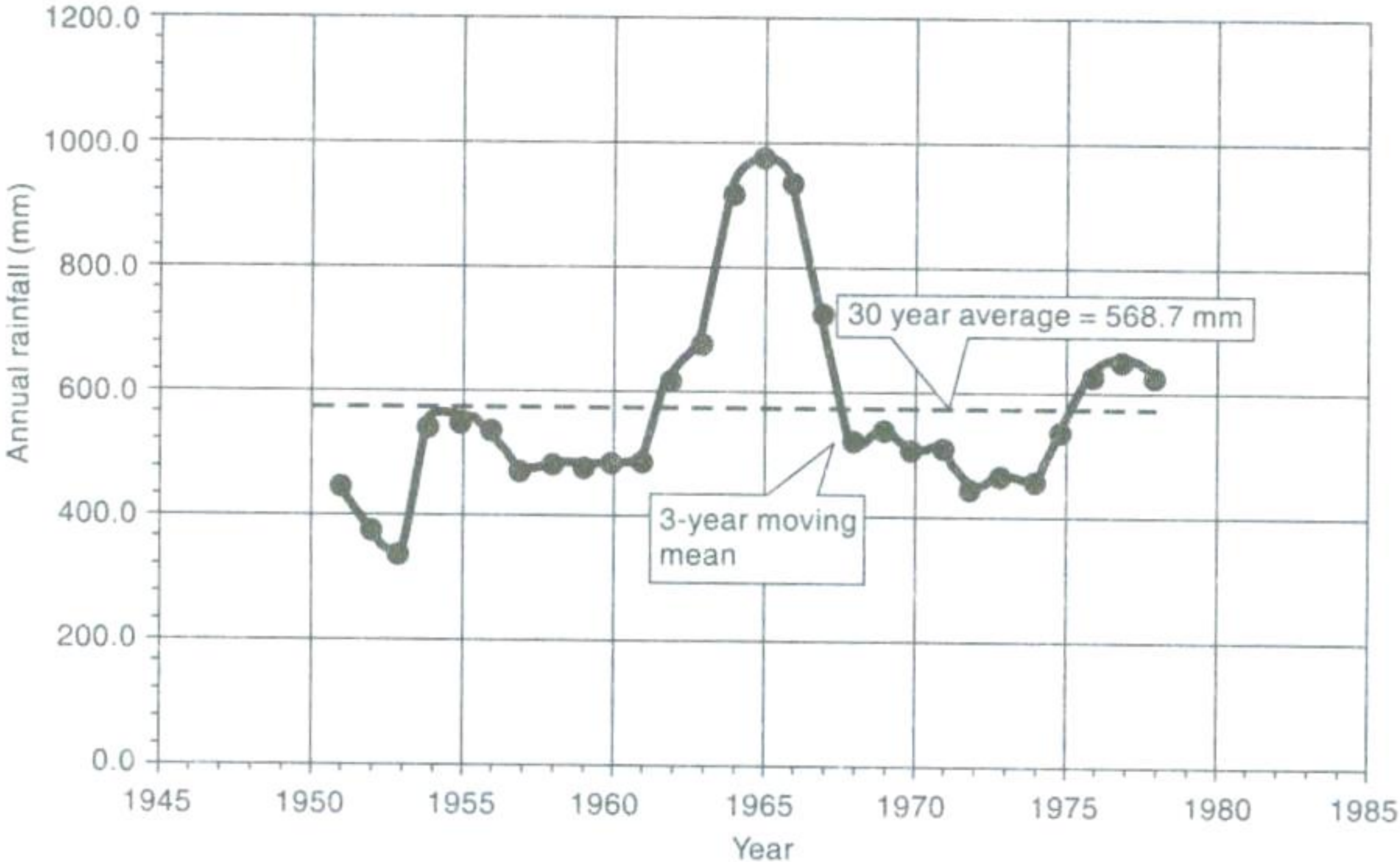


Fig. 2.12 Three-year Moving Mean

Mean precipitation over an area

Raingauge records represent only point sampling of the areal distribution of a storm.

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

To convert point rainfall values of various stations into an average values over a catchment the following three methods are in use:

1) Arithmetical-mean method

2) Thiesson-Polygon method, and

3) Isohyetal method.

1. Arithmetical-mean method

- When the rainfall measured at various stations in a catchment shows little variation, the average precipitation over the catchment area is taken as the arithmetic mean of the station values

$$\bar{P} = \frac{P_1 + P_2 + \cdots + P_i + \cdots + P_n}{N} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

- In practice this method is used very rarely.

Arithmetic Mean Method

- Simplest method for determining areal average

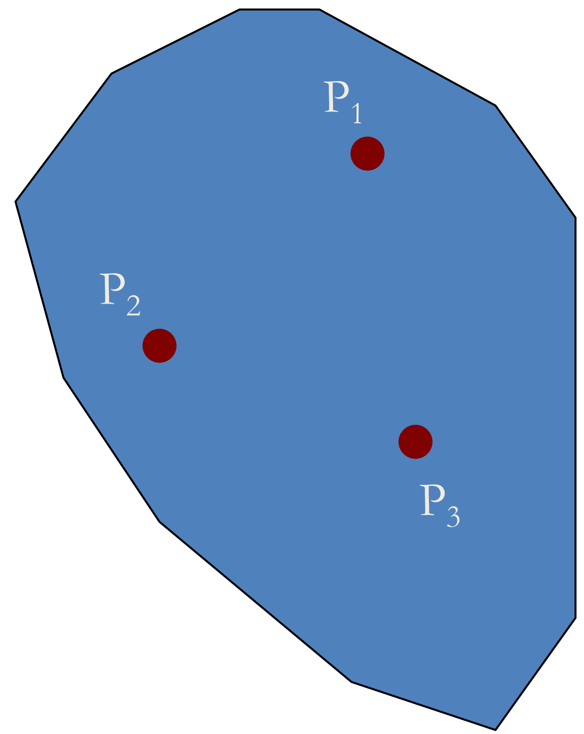
$P_1 = 10$ mm

$P_2 = 20$ mm

$P_3 = 30$ mm

$$\overline{P} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

$$\overline{P} = \frac{10+20+30}{3} = 20 \; mm$$



- Gages must be uniformly distributed
- Gage measurements should not vary greatly about the mean

2. Thiesson-Polygon method

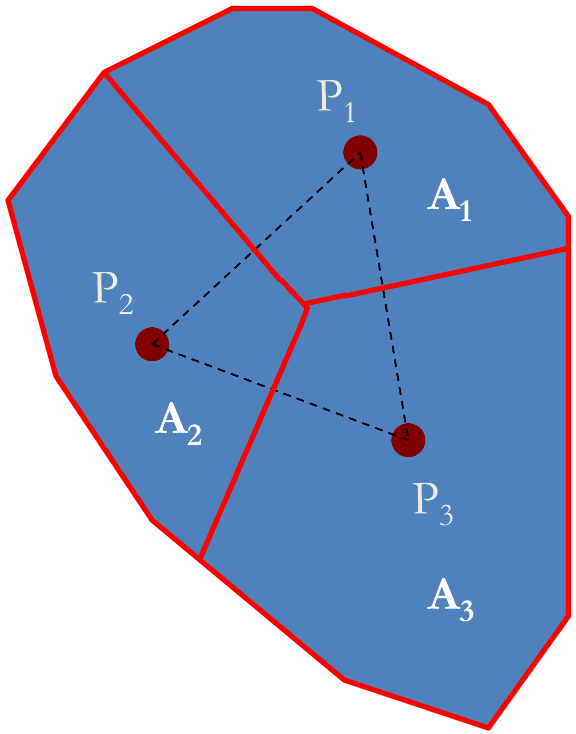
- Rainfall recorded at each station is given a weightage on the basis of an area closest to the station.

$$\bar{P} = \frac{\sum_{i=1}^{M} P_i A_i}{A} = \sum_{i=1}^{M} P_i \frac{A_i}{A}$$

- Ratio $\frac{A_i}{A}$ is called weightage factor for each station.
- Superior to the Arithmetical-mean method as some weightage is given to the various stations on a rational basis.
- Raingauge stations outside the catchment are used effectively.

Thiessen polygon method

- Any point in the watershed receives the same amount of rainfall as that at the nearest gage
- Rainfall recorded at a gage can be applied to any point at a distance halfway to the next station in any direction
- Steps in Thiessen polygon method
  1. Draw lines joining adjacent gages
  2. Draw perpendicular bisectors to the lines created in step 1
  3. Extend the lines created in step 2 in both directions to form representative areas for gages
  4. Compute representative area for each gage
  5. Compute the areal average using the following formula

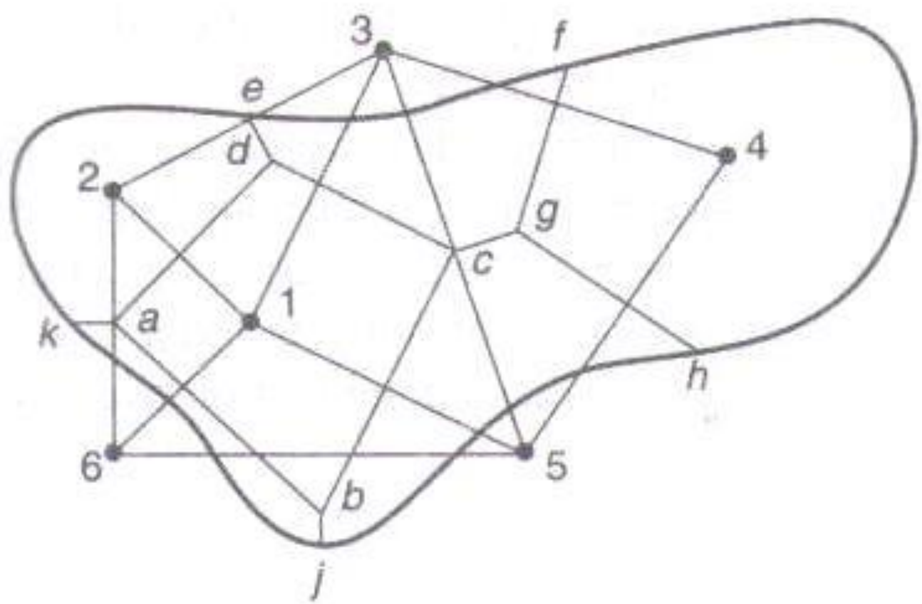


$$\overline{P} = \frac{1}{A}\sum_{i=1}^{N} A_i P_i \qquad \overline{P} = \frac{12\times 10 + 15\times 20 + 20\times 30}{47} = 20.7\ mm$$

$P_1 = 10\ \mathrm{mm},\ A_1 = 12\ \mathrm{Km}^2$

$P_2 = 20\ \mathrm{mm},\ A_2 = 15\ \mathrm{Km}^2$

$P_3 = 30\ \mathrm{mm},\ A_3 = 20\ \mathrm{km}^2$



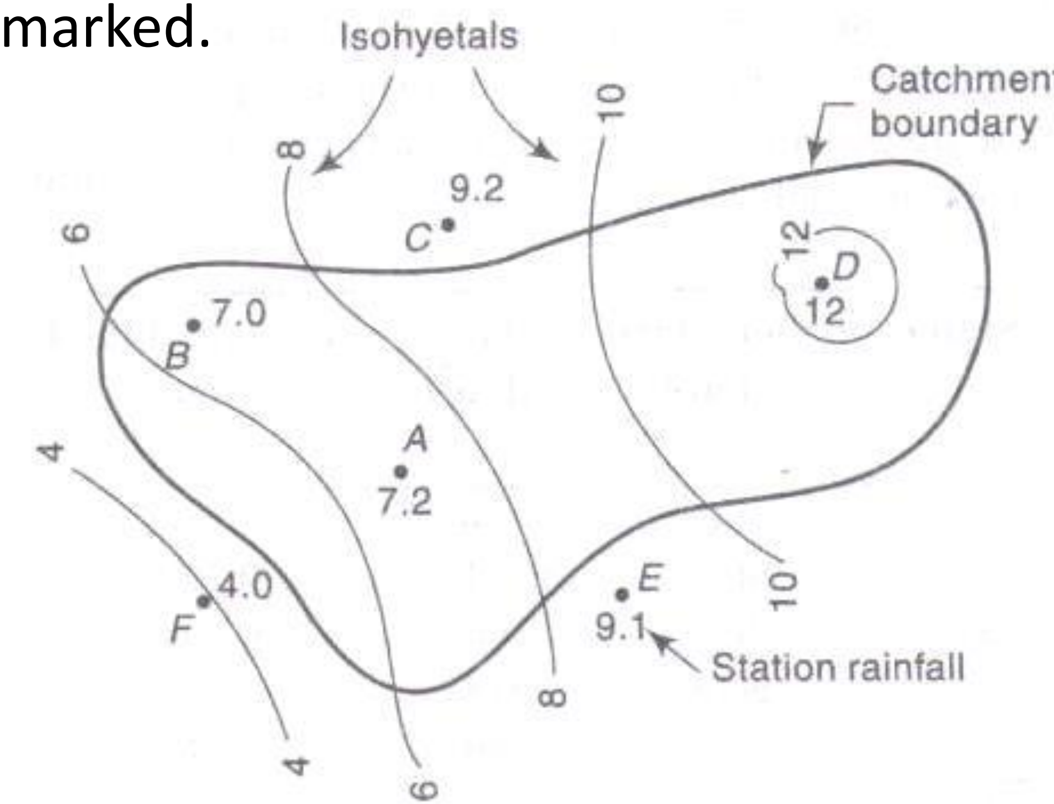
A = total catchment area

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

Thiessen Polygons

3. Isohyetal method

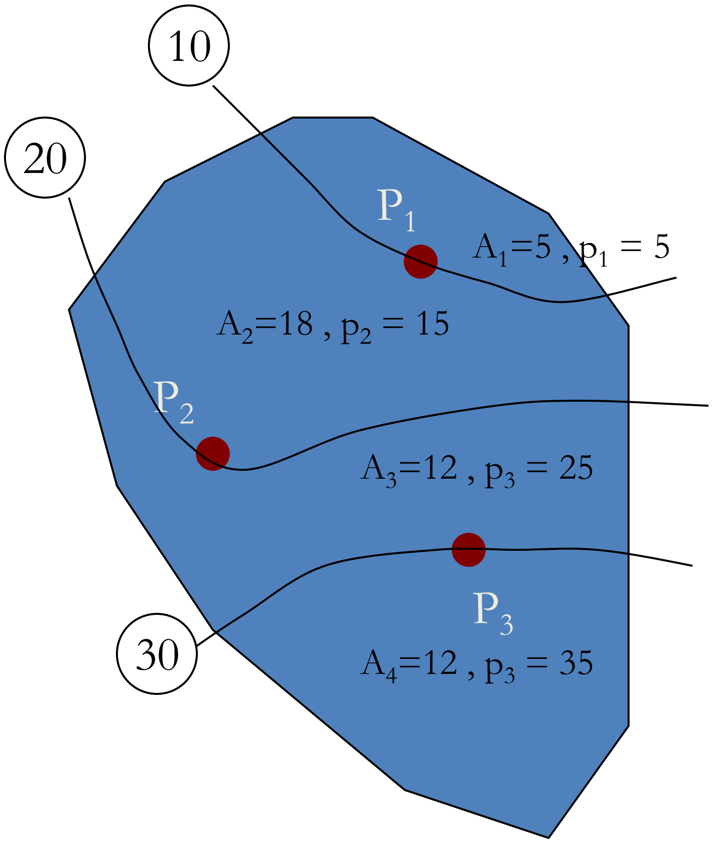
- Isohyet -line joining points of equal rainfall magnitude.
- In this method, the catchment area is drawn to scale and the raingauge stations are marked.



Isohyetals of a Storm

Isohyetal method

- Steps
  - Construct isohyets (rainfall contours)
  - Compute area between each pair of adjacent isohyets (A_i)
  - Compute average precipitation for each pair of adjacent isohyets (p_i)
  - Compute areal average using the following formula



$$\overline{P} = \frac{1}{A}\sum_{i=1}^{N} A_i P_i$$

$$\overline{P} = \frac{5\times 5 + 18\times 15 + 12\times 25 + 12\times 35}{47} = 21.6\ mm$$

- The recorded values for which areal average $\bar{P}$ is to be determined are marked on the plot at appropriate stations.
- Neighboring stations outside the catchment are also considered.
- Isohyets of various values are drawn by considering point rainfall as guides and interpolating between them by the eye.
- Area between 2 adjacent isohyets are then determined with a planimeter.
- If the isohyets go out of the catchment, the catchment boundary is used as the bounding line.
- The average value of the rainfall indicated by 2 isohyet is assumed to be acting over the inter-isohyet area.

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

- $P_1, P_2, \ldots P_n$ are the values of isohyets and if a_1, $a_2, \ldots$ a_{n-1} are the inter isohyet areas respectively, catchment area A

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

Computation of rainfall depth and intensity at a point

Time (min)	Rainfall (in)	Cumulative rainfall	Running Totals		
			30 min	1 h	2 h
0		0.00			
5	0.02	0.02			
10	0.34	0.36			
15	0.10	0.46			
20	0.04	0.50			
25	0.19	0.69			
30	0.48	1.17	1.17		
35	0.50	1.67	1.65		
40	0.50	2.17	1.81		
45	0.51	2.68	2.22		
50	0.16	2.84	2.34		
55	0.31	3.15	2.46		
60	0.66	3.81	2.64	3.81	
65	0.36	4.17	2.50	4.15	
70	0.39	4.56	2.39	4.20	
75	0.36	4.92	2.24	4.46	
80	0.54	5.46	2.62	4.96	
85	0.76	6.22	***3.07***	5.53	
90	0.51	6.73	2.92	***5.56***	
95	0.44	7.17	3.00	5.50	
100	0.25	7.42	2.86	5.25	
105	0.25	7.67	2.75	4.99	
110	0.22	7.89	2.43	5.05	
115	0.15	8.04	1.82	4.89	
120	0.09	8.13	1.40	4.32	8.13
125	0.09	8.22	1.05	4.05	***8.20***
130	0.12	8.34	0.92	3.78	7.98
135	0.03	8.37	0.70	3.45	7.91
140	0.01	8.38	0.49	2.92	7.88
145	0.02	8.40	0.36	2.18	7.71
150	0.01	8.41	0.28	1.68	7.24
Max. depth	0.76		3.07	5.56	8.20
Max. intensity (in/h)	9.12		6.14	5.56	4.10

2.5 Mean Precipitation over an area

- Raingauges rainfall represent only point sampling of the areal distribution of a storm
- The important rainfall for hydrological analysis is a rainfall over an area, such as over the catchment
- To convert the point rainfall values at various stations to in to average value over a catchment, the following methods are used:
  - arithmetic mean
  - the method of the Thiessen polygons
  - the isohyets method

Arithmetic Mean Method

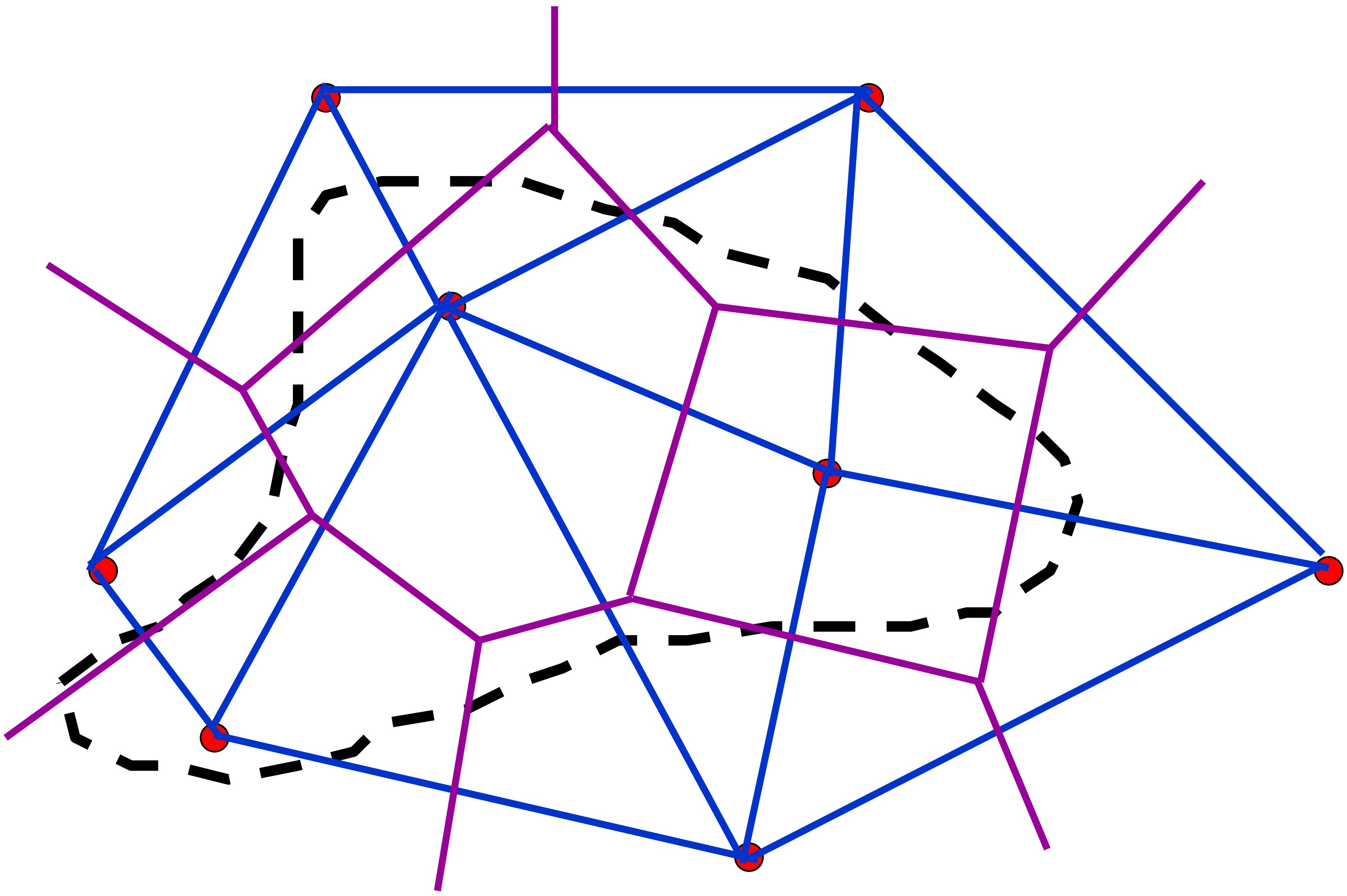
- When the area is physically and climatically homogenous and the required accuracy is small, the average rainfall ($\overline{P}$) for a basin can be obtained as the arithmetic mean of the h_i values recorded at various stations.
- Applicable rarely for practical purpose

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

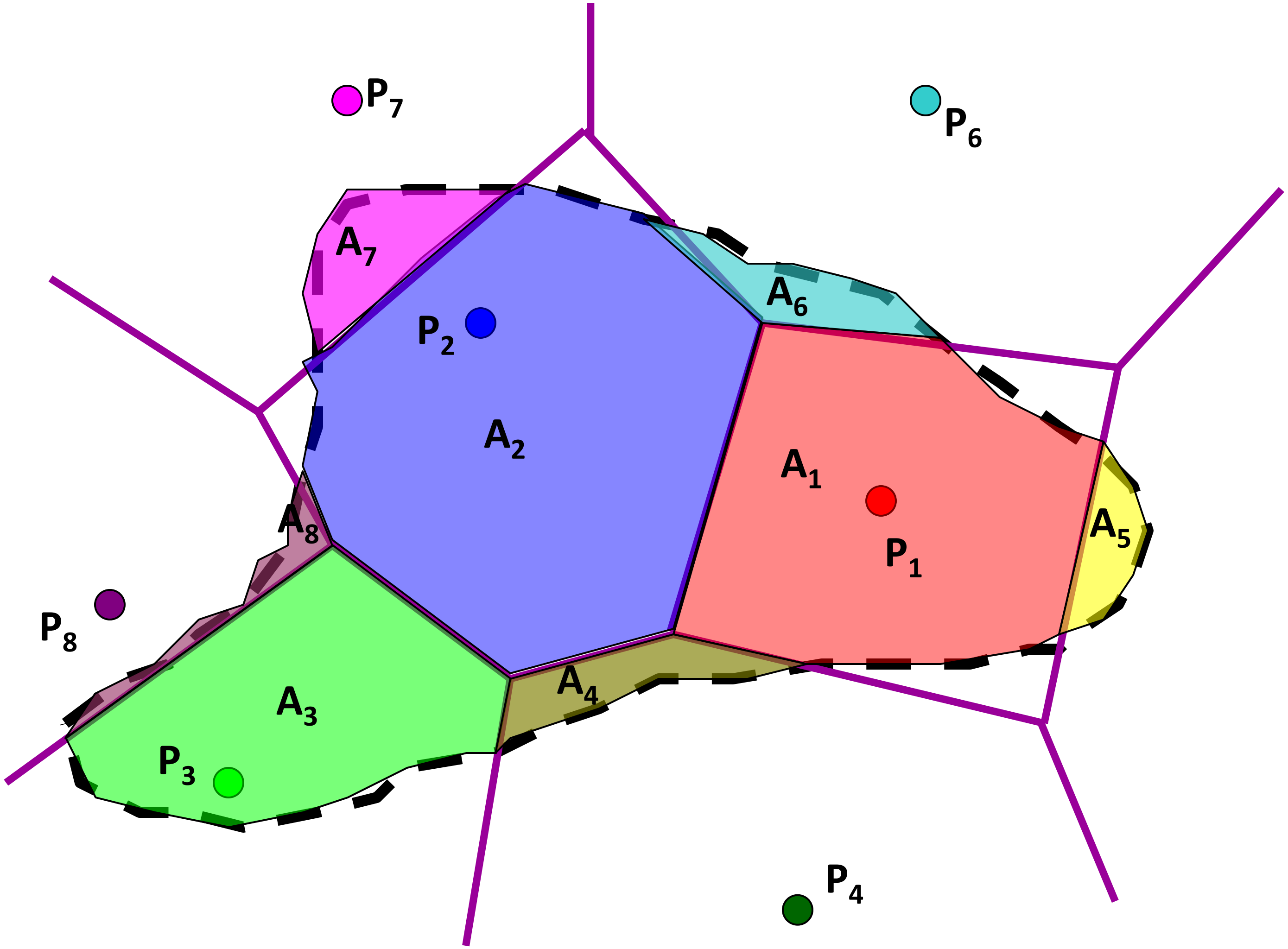
Method of Thiessen polygons

- The method of Thiessen polygons consists of attributing to each station an influence zone in which it is considered that the rainfall is equivalent to that of the station.
- The influence zones are represented by convex polygons.
- These polygons are obtained using the mediators of the segments which link each station to the closest neighbouring stations

Thiessen polygons ……….



Thiessen polygons ……….



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

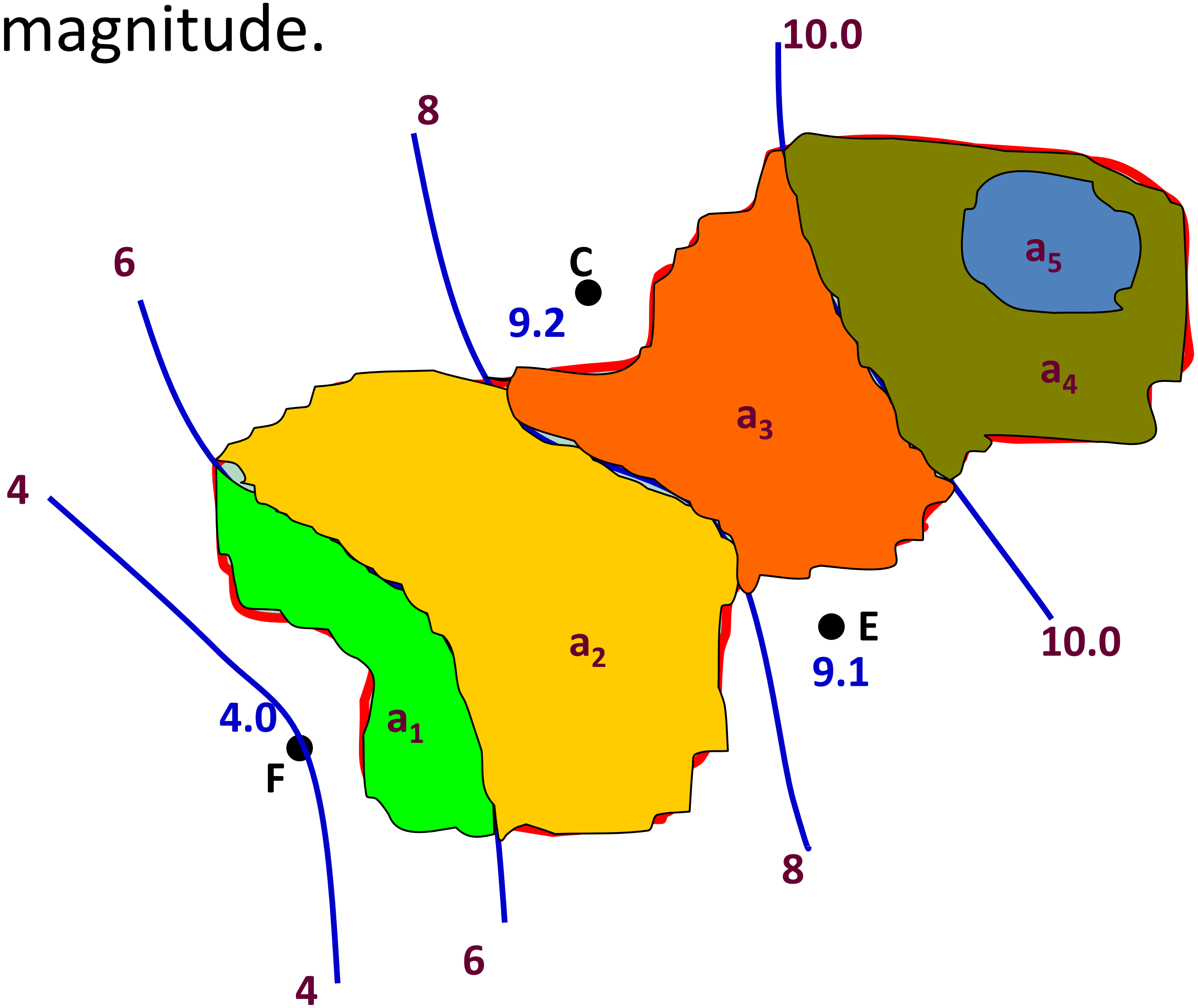
Generally for M station

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

The ratio $\frac{A_i}{A}$ **is called the weightage factor of station i**

Isohyetal Method

- An isohyet is a line joining points of equal rainfall magnitude.



Isohyetal Method

- $P_1, P_2, P_3, \ldots, P_n$ – the values of the isohytes
- $a_1, a_2, a_3, \ldots, a_4$ – are the inter isohytes area respectively
- A – the total catchment area
- $\overline{P}$ - the mean precipitation over the catchment

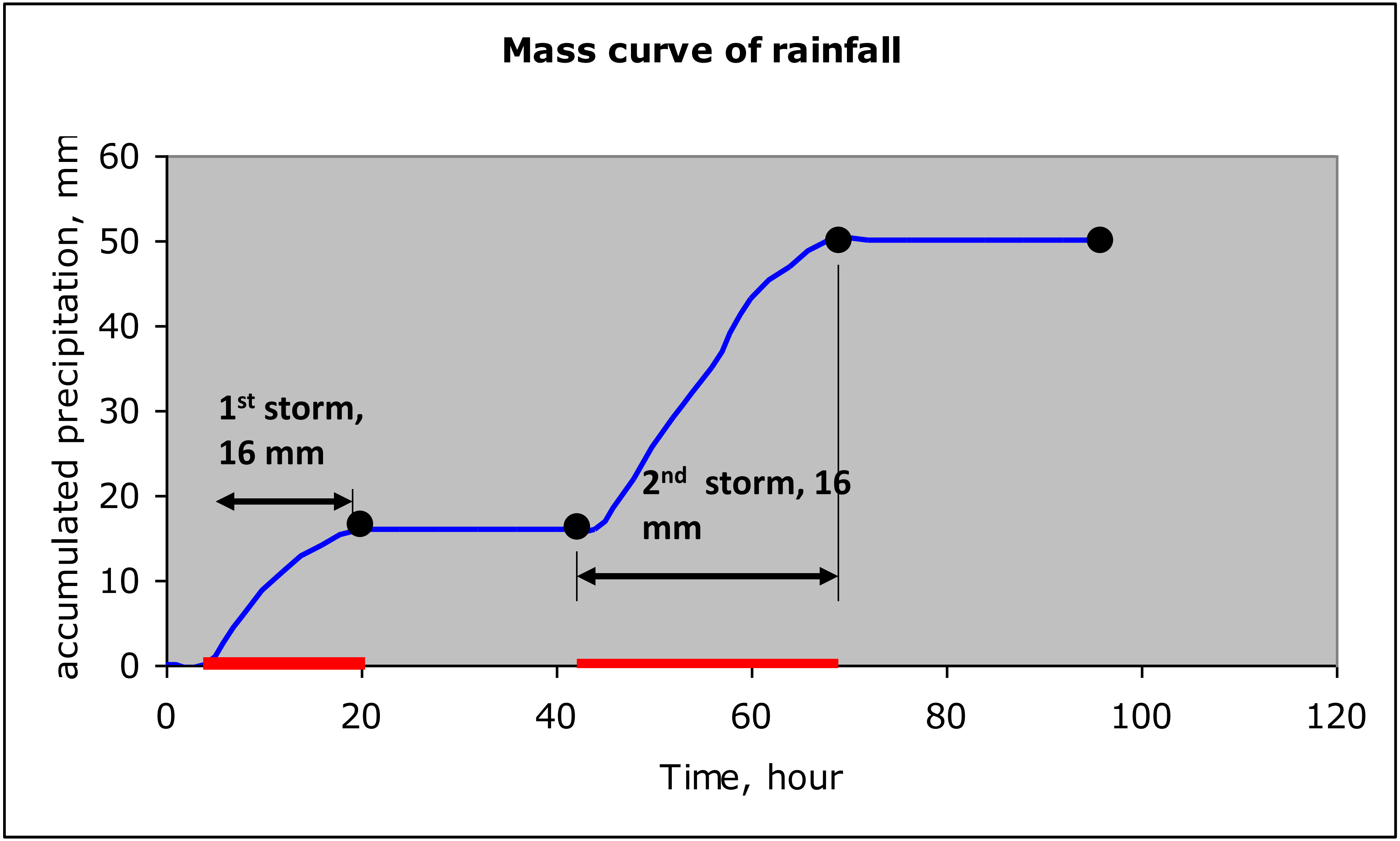
$$\overline{P} = \frac{a_1\left(\frac{P_1 + P_2}{2}\right) + a_2\left(\frac{P_2 + P_3}{2}\right) + \ldots + a_{n-1}\left(\frac{P_{n-1} + P_n}{2}\right)}{A}$$

NOTE

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

2.6 Intensity – Duration – Frequency (IDF) Relationship

Mass Curve of Rainfall



Hyetograph

- is a plot of the accumulated precipitation against time, plotted in chronological order