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DDA – Junior Engineer

Civil Engineering

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Volume - 4

Junior Engineer (Civil)

Hydrology & Irrigation

SIERRA INNOVATIONS

Table of Content

1 CHAPTER General Aspects of Hydrology

THEORY

1.1 INTRODUCTION

Hydrology is the science of water which deals with

- Occurrence
- Circulation
- Distribution of water of the earth and earth's atmosphere.

It concerned with

- Water in streams and lakes
- Rainfall and snowfall
- Snow and ice on the land and water occurring below earth's surface in the pores of the soil and rocks.

1.1.1 Classification of Hydrology

- **Scientific Hydrology :** The study concerned chiefly with academic aspects.
- **Engineering or Applied Hydrology :** Study concerned with engineering applications
  - (i) Estimation of water resources.
  - (ii) The study of processes such as precipitation, runoff, evapotranspiration and their interaction.
  - (iii) The study of problems such as floods and droughts and strategies to combat them.

1.2 HYDROLOGIC CYCLE

The total water of earth, excluding deep ground water, is in constant circulation from the earth (including oceans) to atmosphere and back to the earth and oceans. This cycle of water amongst earth, oceans, and atmospheric systems is known as hydrologic cycle.

- The hydrologic cycle is a global sun-driven process. The processes in this cycle extends from an average depth of 1 km in the lithosphere (crust of the earth), to a height of about 15 km in the atmosphere.
- The hydrologic cycle does have beginning or end point. However oceans are considered as starting point for convenience of study.
- Because of heat energy provided by Sun evaporation in oceans takes place at very large scale. This water vapour moves upwards and forms clouds. Major part of these clouds condense and fall back to the oceans as in the form of rain. But some part of clouds is driven to the land areas by winds. Then they condense and precipitate onto the land mass as rain, snow, hail, sleet etc.
- A part of rainfall may evaporate book to atmosphere each while falling.

- Another part may be intercepted by vegetation, structures and other such surface modifications from which it may be either evaporated back to atmosphere or move down to the ground surface.
- A part of water that reaches ground, enters into earth's surface through infiltration, enhances the moisture content of soil and reaches to ground water.
- Through vegetation a part of water from under the ground surface to the atmosphere through the process of transpiration.
- Part of infiltrated water may to surface water bodies as interflow, while other part may become ground water flows.
- Ground water may ultimately be discharged into stream channel by a variety of paths above and below surface of the earth is called runoff.
- Once it enters a stream channel, runoff becomes stream flow.

The hydrologic cycle is usually described in terms of six major components as :

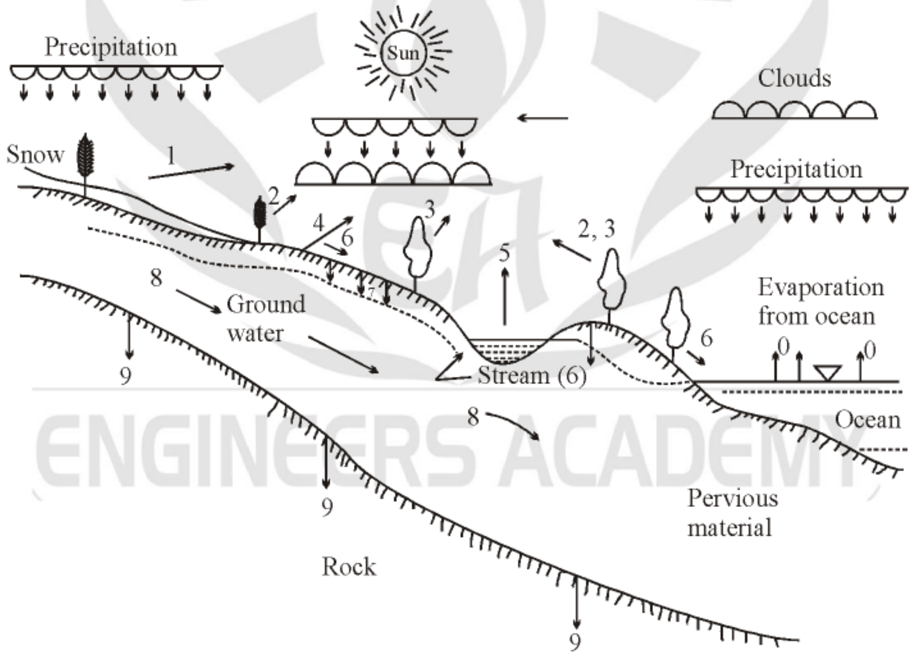
Precipitation (P), Infiltration (I)

Transpiration (T), Surface Runoff (R)

Evaporation (E), and ground water flow (G)

However for calculation purposes evaporation (E) and transpiration (T) are sometimes clubbed together as evapotranspiration (ET).

The figure given below show these components and illustrates the various paths they taken to complete hydrologic cycle.



0 = Evaporation from ocean
1 = Raindrop evaporation
2 = Interception
3 = Transpiration
4 = Evaporation from land
5 = Evaporation from water bodies
6 = Surface runoff
7 = Infiltration
8 = Groundwater
9 = Deep percolation

Fig. 1.1 : The Hydrologic Cycle

Note :

- **Evaporation** is conversion of water from liquid to gaseous state.
- **Precipitation** is the deposition of water on earth surface in the form of rain, snow, hail, frost and so on.
- **Infiltration** is the movement of water into the soil of earth's surface.
- **Percolation** is the movement of water from upper soil zone to a lower soil zone.
- **Transpiration** is the soil moisture taken up through the roots of a plant and discharged into atmosphere through the leaves of plants.
- **Storage** is the volume of water which gets stored in natural depression of a basin.
- **Runoff** is the volume of water drained by a river at the outlet of a catchment.

1.3 HYDROLOGICAL BUDGET

For a given catchment area in a time internal Δt,

Total inflow – Total outflow = change is storage (continuity equation)

This continuity equation, expressed in terms of various phases of hydrological cycle is known as water budget equation/water budget equation.

Hydrological budget equation

$$P - R - E - T - G = \Delta S, \text{ water budget equation}$$

where
P = Precipitation
R = Net runoff
E = Net evaporation
T = Net Transpiration
G = Net Ground water flow
ΔS = Net storage change

The storage S consist of three components as

$$S = S_s + S_{sm} + S_g$$

where
S_{gs} = Surface water storage
S_{sm} = Water in storage as soil moisture
S_g = Water in storage as ground water

Thus, in above equation

$$\Delta S = \Delta S_s + \Delta S_{sm} + \Delta S_g$$

In terms of rainfall-runoff relationship water budget equation can be represented as

$$R = P - L$$

where
R = Runoff
P = Precipitation
L = Losses = water not available to runoff due to (I, E, T and depression storage)

All terms in above equations have the dimensions of volume however all these terms can be expressed as depth over the catchment area (e.g. in centimeters or millimeters). In fact this is a very common unit used.

Catchment Area

- The area of land draining into a stream or into a water course at a given location is called a catchment area.
- Other terms which are used to describe a catchment area are drainage basin, drainage area, catchment, catchment basin, river basins, water basin and watershed (in USA).
- The catchment area acts as a funnel by collecting all the water within the area covered by the catchment and channelling into a single point.

Watershed Divide

- Each catchment area in separated topographically from adjacent catchment areas by a natural barrier such as a ridge, hill, mountain this line is known as topographic water divide, or the watershed divide, or simply a divide.
- The divide follows ridge line around the catchment, crossing the stream only at the outlet point, it marks the highest points between the basins, but isolated peaks with in a basin may be at higher elevations than any point on the divide.

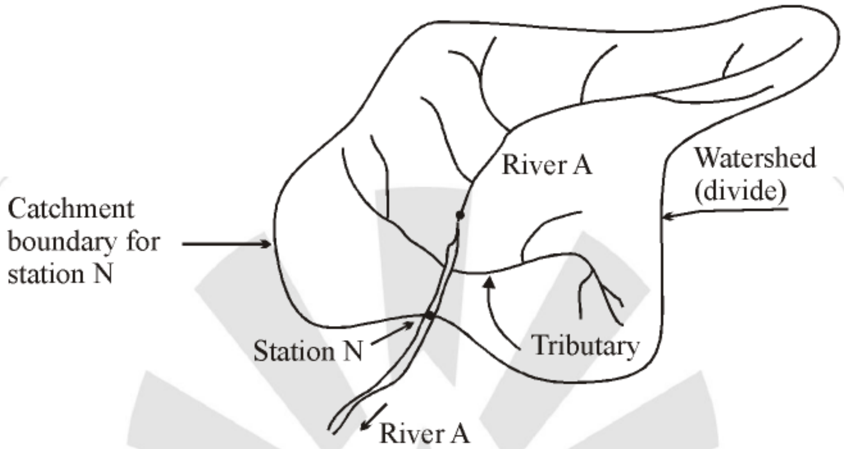


Fig. 1.2 : Schematic sketch of catchment of river A at station N.

Catchment Leakage

Sometimes the runoff measured at the outlet of a particular catchment may contain some contribution belonging to the precipitation fallen on a neighboring catchment by way of subsurface runoff. This is known as catchment leakage.

Catchment leakage also occurs when the ground water divide and catchment divide (watershed divide) are not coincident in plan as shown in figure below

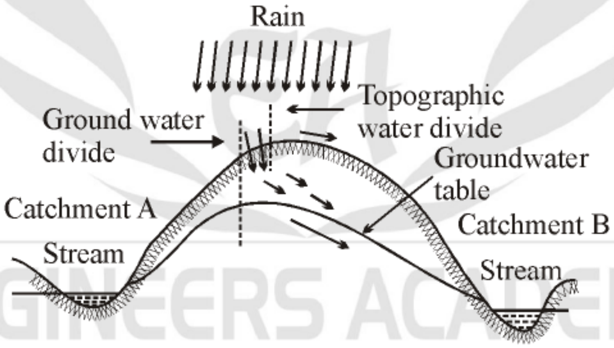


Fig. 1.3 : Topographical and ground water divide

Note :

- However for large catchments, ground water divide and topographical divide are assumed to coincide i.e. catchment leakages are neglected.
- Area between watershed shed divide on a topographic map is measured by an instrument called **Planimeter**.

Residence Time

Average duration of a particles of water to pass through a phase of the hydrological cycle is known as the residence time of that phase.

$$\text{Residence time} = \frac{\text{Volume of water in a phase}}{\text{Average flow rate in that phase}}$$

Average residence time of ocean is larger than that of global ground water.

Example 1 : A lake had a water surface elevation of 103.200 m above datum at the beginning of a certain month. In that month the lake received an average inflow of 6.0 m^3/s from surface runoff sources. In the same period the outflow from the lake had an average value of 6.5 m^3/s. Further, in that month, the lake received a rainfall of 145 mm and the evaporation from the lake surface was estimated as 6.10 cm. Write the water budget equation for the lake and calculate the water surface area can be taken as 5000 ha. Assume that there is no contribution to or from the groundwater storage.

Solution :

Given data,

$$\bar{I} = 6.0 \text{ m}^3/\text{s}$$

$$\bar{Q} = 6.5 \text{ m}^3/\text{s}$$

$$P = 145 \text{ mm}$$

$$E = 61.0 \text{ mm}$$

$$A = 5000 \times 10^4 \text{ m}^2$$

In a time interval Δt the water budget for the lake can be written as Input volume-output volume = change in storage of the lake

$$(\bar{I}\Delta t + PA) - (\bar{Q}\Delta t + EA) = \Delta S$$

where, $\bar{I}$ = average rate of inflow of water into the lake

$\bar{Q}$ = average rate of outflow from the lake

P = precipitation

E = evaporation

A = average surface area of the lake

ΔS = change in storage volume of the lake.

Here $\Delta t = 1 \text{ month} = 30 \times 24 \times 60 \times 60 = 2.592 \times 10^6 \text{ s} = 2.592 \text{ Ms}$

In one month Inflow volume = $\bar{I}\,\Delta t = 6.0 \times 2.592 = 15.552 \text{ Mm}^3$

Outflow volume = $\bar{Q}\,\Delta t = 6.5 \times 2.592 = 16.848 \text{ Mm}^3$

Input due to precipitation = $PA = \dfrac{145 \times 5000 \times 100 \times 100}{1000 \times 10^6} \text{ Mm}^3 = 7.25 \text{ Mm}^3$

Outflow due to evaporation = $EA = \dfrac{6.10}{100} \times \dfrac{5000 \times 100 \times 100}{10^6} = 3.05 \text{ Mm}^3$

Hence $\Delta S = 15.552 + 7.25 - 16.848 - 3.05 = 2.904 \text{ Mm}^3$

Change in elevation $\Delta z = \dfrac{\Delta S}{A} = \dfrac{2.904 \times 10^6}{5000 \times 100 \times 100} = 0.058 \text{m}$

New water surface elevation at the end of the month = 103.200 + 0.058

= 103.258 m above the datum

Example 2 : A small catchment of area 150 ha received a rainfall of 10.5 cm in 90 minutes due to a storm. At the outlet of the catchment, the stream draining the catchment was dry before the storm and experienced a runoff lasting for 10 hours with an average discharge of 1.5 m^3/s. the stream was again dry after the runoff event.

(a) What is the amount of water which was not available to runoff due to combined effect of infiltration, evaporation and transpiration?

(b) What is the ratio of runoff to precipitation?

Solution : The water budget equation for the catchment in a time Δt is

$$R = P - L$$

where L = Losses = water not available to runoff due to infiltration (causing addition to soil moisture and groundwater storage), evaporation, transpiration and surface storage. In the present case Δt = duration of the runoff = 10 hours.

Note that the rainfall occurred in the first 90 minutes and the rest 8.5 hours the precipitation was zero.

(a) P = Input due to precipitation in 10 hours

$= 150 \times 100 \times 100 \times (10.5/100) = 157{,}500 \text{ m}^3$

R = runoff volume = outflow volume at the catchment outlet in 10 hours

$= 1.5 \times 10 \times 60 \times 60 = 54{,}000 \text{ m}^3$

Hence losses $L = 157{,}500 - 54{,}000 = 103{,}500 \text{ m}^3$

(b) Runoff/rainfall = 54,000/157,500 = 0.343

1.4 CONVERSION OF PRECIPITATION INTO STREAM FLOW

- In hydrological studies in engineering hydrology the precipitation (rainfall) is taken as input mathematically in the form of hyetograph (Hyetograph is a plot of rainfall intensity against time).
- Output in obtain as stream flow runoff mathematically in the form of hydrograph (Hydrograph in a plot of discharge (flow) against time).

The figure given below shows the conversion of rainfall (input) to stream flow (output)

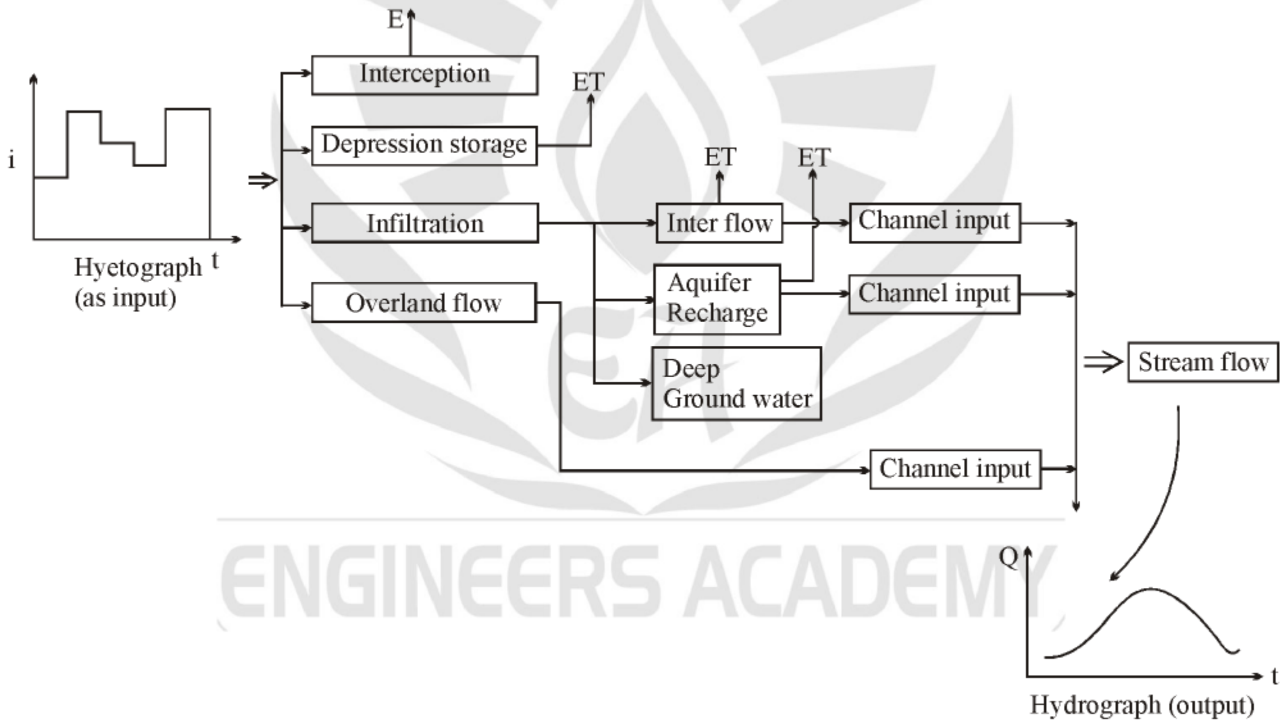


Fig. 1.4 : Distribution of precipitation

Interesting Facts

- Runoff is minimum in Africa and maximum in Europe and North America.
- In India the long term estimates of average runoff = 46%.
- In the ocean about 9% more water evaporates that falls back as precipitation.
- World's largest river, the Amazon, has an annual average discharge of 200,000 m^3/s.
- In India largest rivers, the Brahmaputra – 16,200 m^3/s the Ganga : 15,600 m^3/s.

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2 CHAPTER

Precipitation and Its Measurements

THEORY

2.1 PRECIPITATION

The term precipitation denotes the all forms of water that reaches the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew.

2.2 FORMS OF PRECIPITATION

1. **Rain :** In form of water drops of sizes larger than 0.5 mm and smaller than 6 mm
   (i) Light rain – trace to 2.5 mm/hr
   (ii) Moderate rain – 2.5 mm/h to 7.5 mm/h
   (iii) Heavy rain - > 7.5 mm/hr
2. **Snowfall :** The fall of larger snowflakes from the clouds on the ground surface is called snowfall. In fact snowfall is "Precipitation of white and opaque grains of ice. The average density of snow fall is 0.1 gm/cc.
3. **Drizzle :** A fine sprinkle of numerous water droplets of size less than 0.5 mm and intensity having less than 1 mm/hr.
4. **Glaze :** Water drops freeze to form an ice coating also called freezing rain.
5. **Sleet :** Frozen raindrops of transparent grains (when rain falls through air at subfreezing temperature) of raindrops size dia of 5 mm or lesser.
6. **Hail :** Showery precipitation in the form of irregular pellets or lumps of ice of size between 5 mm to 50 mm.

Two important processes in precipitation

ice crystal process	coalescence process
ice crystal exists with water droplets at subfreezing temp.(-40°c)	small cloud droplets increase their size due to contact with other through collisions
the dust particles (clay minerals, organic and ordinary ocean salts) serves as the freezing nuclei	fall velocity at equilibrium are proportional to the square of radius of droplets
the ice crystal grow in size	hence large size fall at greater velocity and results in collisions
with increase in size they tend to fall down due to gravity	very large droplets > 7mm diameter tend to break into small droplets
this is basis for artificial rain or cloud seeding	Very important in tropical regions.

Characteristics of precipitation in India : The Indian sub continent 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)

Facts about Rainfall in India

- Average annual rainfall – 117 cm.
- Average annual rainfall varies from 10 cm in the western Thar desert to 110 cm in North East region.
- C_V varies from 15 to 70 (standard deviation/mean).
- A few heavy spells of rain contributes almost 90% of total rainfall in India.
- More than 50% rain occurs within 15 days less than 100 hours in a year.
- At an average the number of rainy days are 52 in a year.

2.3 MEASUREMENT OF PRECIPITATION

One of the most crucial and least known components of the global hydrologic cycle is the precipitation that is the basic data required to estimate any hydrologic quantity (such as runoff, flood discharge *etc*.). Therefore, measurement of precipitation is an important component of all hydrologic studies. Weather and water-balance studies too require information on precipitation.

2.3.1 Precipitation Gauges

Precipitation (of all kinds) is measured in terms of depth of water (in mm or cm) that would accumulate on a level surface if the precipitation remained where it fall.

A variety of instruments has been developed for measuring precipitation (or precipitation rate) and are known as precipitation gauges or simply rain gauge which are classified as either recording or non-recording rain gauges.

The terms such as pulviometer, ombrometer and hyetometer are also sometimes used to designate a rain gauge.

Types of rainfall gauges

1. Non-recording gauges
2. Recording gauges

Non-Recording Gauges

- Non-recording rain gauges only collect rain water which, when measured suitably, gives the total amount of rainfall at the rain gauge station during the measuring interval.
- The Indian Meteorological Department has adopted Symon's rain gauge.
- A glass bottle and funnel with brass rim are put in a metallic cylinder such that the top of the cylinder is 305 mm above the ground level.
- Rain water falls into the glass bottle through the funnel. The water collected in the bottle is measured with the help of a standard measuring glass jar which is supplied with the rain gauge.
- The jar measures rainfall in millimeters.

- For uniformity, the rainfall observations are taken everyday at 8 : 30 AM (IST) and is recorded as the rainfall of that day.

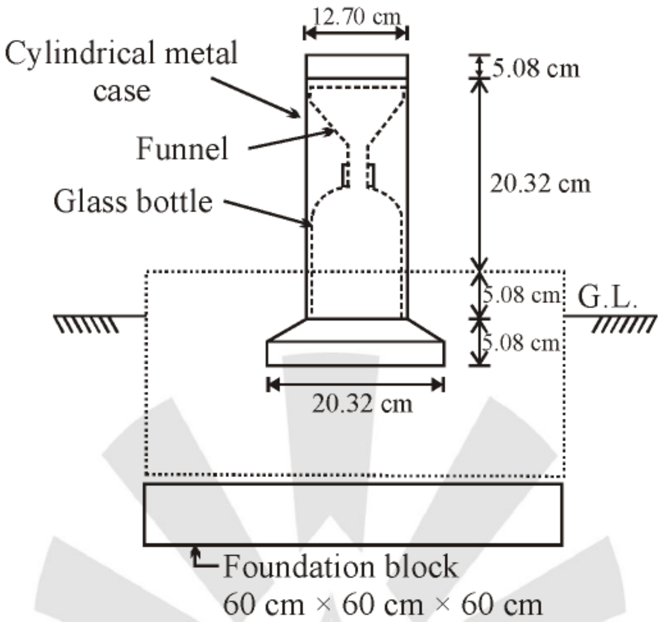

Fig. 2.1 : Symon's rain gauge

Recording Rain Gauges

Recording rain gauges automatically record the intensity of rainfall and the time of its occurrence in the form of a trace (or graph) marked on a graph paper wrapped round a revolving drum. Following three types are the most widely used recording rain gauges :

(a) Tipping Bucket Type :

- This is 30.5 cm size rain gauge.
- The catch from funnel falls onto one of a pair of small buckets.
- These buckets are so balanced that when 0.25 mm rainfall collects in one bucket, it tips and brings other one in position.
- The water from these buckets connected in storage can.
- The tipping actuates an electrically driven pen to trace a record from tipping bucket gives data as intensity of rainfall.
- Output can be recorded at a distance from the rain gauge as output obtained is in electronic form.

(b) Weighing Bucket Type

- The catch from funnel empties into a bucket fixed on a weighing scale.
- The weight of bucket and its contents are recorded on a clock-work-driven chart.
- This type of rain gauge gives mass curve of rainfall i.e. plot of accumulated rainfall against elasped time.

(c) Natural Syphon type (or float type gauge)

- In this rain gauge 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 clock-work mechanism.

- A Syphon arrangement empties the float chamber when the float has reached a pre-set maximum level which resets the pen to its zero level.
- This type of rain gauge in adopted as the standard recording type rain gauge in India.
- This rain gauge gives a mass curve of rainfall.

2.3.2 Snowfall Water Equivalent

- Water equivalent of snow is the depth of water that would result in melting of a unit of snow.
- It can be find either by weighing or melting.
- Generally density of fresh snow in assumed to be 0.10 gm/cc.
- Snow collected in a non recording raingauge in melted immediately and measured by means of a graduated cylinder.
- The weighting type recording gauge is also used to determine the water content of snowfall.

2.4 RAIN GAUGE NETWORK

Bureau of Indian Standards has laid down the following guidelines for selecting the site for rain gauges (IS : 4897-1968) :

(a) The rain gauge shall be placed on a level ground, not upon a slope or a terrace and never upon a wall or roof.

(b) On no account the rain gauge shall be placed on a slope such that the ground falls away steeply in the direction of the prevailing wind.

(c) The distance of the rain gauge from any object shall not be less than 30 m or twice the height of the object above the rim of the gauge.

(d) Great care shall be taken at mountain and coast stations so that the gauges are not unduly exposed to the sweep of the wind. A belt of trees or a wall on the side of the prevailing wind at a distance exceeding twice its height shall form an efficient shelter.

(e) In hills where it is difficult to find a level space, the site for the rain gauge shall be chosen where it is best shielded from high winds and where the wind does not cause eddies.

(f) The location of the gauge should not be changed without taking suitable precautions.

As per world meteorological organization (WMO) the raingauges should be placed as :

- 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.
- 10% of raingauge stations should be equipped with self recording gauges to know the intensities of rainfall.

From practical considerations in Indian conditions, the Indian standard (IS : 4987-1968) recommends the following densities as sufficient.

- In plains : 1 station per 250 km^2.
- In regions of average elevation 1000 m : 1 station per 260-390 km^2.
- In hilly areas with heavy rainfall : 1 station per 130 km^2.

2.4.1 Adequacy of Rain Gauge Stations

For an existing network of raingauge stations, one may need to know the adequacy of the raingauge stations and therefore the optimal number of raingauge stations N required for a desired accuracy (or maximum error in per cent, $\in$) in the estimation of the mean rainfall.

$$\overline{P} = \frac{1}{m}\left(\sum_{1}^{m} P_i\right)$$

Where, $\overline{P}$ = mean precipitation

$$\sigma_{m-1} = \text{standard deviation} = \sqrt{\left[\frac{\sum_{i=1}^{m}(p_i - \overline{P})^2}{m-1}\right]}$$

Where, P_i = precipitation measured at i^{th} station

m = number of raingauge station

The optimal number of raingauge stations N is given as

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

Where, N = Optimal number of stations

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

C_v = the coefficient of variation of the rainfall values at the existing *m* stations (in percent) and C_v calculated as

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

- For calculating N, $\in$ is usually taken as 10%. Obviously, the number N would increase with the decrease in allowable error, $\in$.
- The coefficient of variation of the annual rainfall for different places may vary between 15 (for regions of high rainfall) and 70 (for regions of scanty rainfall) with an average value of about 30.

Example 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 given data, m = 6, $\in$ = 10% = 0.1

Now calculation of $\overline{P}$, σ_{m-1} and C_v is required

Step 1 : Calculation of mean rainfall $(\overline{P})$

$$\overline{P} = \frac{82.6 + 102.9 + 180.3 + 110.3 + 98.8 + 136.7}{6}$$

$$= 118.6 \text{ cm}$$

Step 2 : Calculation of σ_{m-1}, (Standard deviation)

$$\sigma_{m-1} = \sqrt{\frac{\sum_{1}^{m}(P_i - \overline{P})^2}{m-1}} \text{ or } \sigma_{m-1}^2 = \frac{\sum_{1}^{m}(P_i - \overline{P})^2}{(m-1)}$$

$$\sigma_{m-1}^2 = \frac{(118.6-82.6)^2+(118.6-102.9)^2+(118.6-180.3)^2+(118.6-110.3)^2+(118.6-98.8)^2+(118.6-136.7)^2}{6-1}$$

or $\sigma_{m-1}^2 = 1227.80$

or $\sigma_{m-1} = 35.04$

Step 3 : Calculation of coefficient of variation (C_v)

$$C_v = \frac{\sigma_{m-1}}{\overline{P}} \times 100 = \frac{35.04}{118.6} \times 100 = 29.54$$

Step 4 : Optimal number of stations (N)

$$N = \left(\frac{C_v}{\in}\right)^2 = \left(\frac{29.54}{0.1}\right)^2 = 8.7, \text{ say 9 stations}$$

Hence optimum number of raingauge stations for the catchment is 9.

Hence three more stations are required.

Normal Precipitation

- The normal precipitation (rain fall) is the average value of rain fall of a particular date, month or year over a specified 30 year period (for e.g. normal rainfall of 7th July or normal rainfall of August or yearly rain fall).
- The 30 year normal rainfall are recomputed every decade to account for change in environment and land use, because these factors may affect the amount of rainfall on that area.
- Normal rainfall is used to estimate missing data of certain raingauges.

Average Annual Rainfall

- The amount of rain fall collected by a rain gauge in the last 24 hours is called as daily rainfall and the total amount collected in 1 year in called annual rainfall.
- Average annual rainfall is the average value of annual rainfall values for the last 35 years.

2.5 PREPARATION OF PRECIPITATION DATA

Precipitation data must be checked for the continuity and consistency before they are analyzed for any significant purpose. This is essential when it is suspected that the gauge site (or its surroundings) might have changed appreciably during the period for which the average is being computed.

2.5.1 Estimation of Missing Data

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.

Assuming the annual precipitations values P_1, P_2, P_3, P_4 .... P_m at neighboring M stations 1, 2, 3 .... m respectively.

Now we have to find missing annual precipitation P_x at a station X not included in the above M stations. Further, normal annual precipitations N_1, N_2 .... N_i at each of the above (M + 1) stations including station X are known then two cases arises :

(A) Arithmetic mean method : If the normal annual precipitations at various stations are within 10% of the normal annual precipitation at station X, then a simple arithmetic average procedure in followed to estimate P_X. Thus

$$P_x = \frac{1}{M}\left[P_1 + P_2 + ... + P_n\right]$$

(B) Normal ratio method : It normal precipitations vary considerably then normal ratio method is used (i.e. normal precipitation at any of these stations in more than 10% of that for station with missing data). Then

$$P_x = \frac{N_n}{M}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + ... + \frac{P_m}{N_m}\right]$$

Where, P_x = precipitation (missing data)

N_x = normal precipitation of the station at which data is missing

Example 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.

Normal ratio method $$P_x = \frac{N_x}{M}\left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + ... + \frac{P_m}{N_m}\right]$$

So, here $N_x = N_D = 92.01$ cm normal precipitation at station D

$M = 3$,

So $$P_D = \frac{92.01}{3}\left[\frac{91.11}{80.79} + \frac{72.23}{67.59} + \frac{79.89}{76.28}\right] = 99.48 \text{ cm}$$

Example 3 : The normal annual rainfall of stations A, B, C and D in a catchment is 80 mm, 91 mm, 85 mm and 87 mm respectively.

In the year 2007, the station D was inoperative when stations A, B and C recorded annual rainfall of 91.11, 72.23 and 78.29 mm. Estimate the missing data at station D in the year 2007.

Solution : First to check weather Normal precipitation of all the station A, B and C are within 10% of that at station D.

So, 87 $\begin{cases} \rightarrow 87 \times 1.1 = 95.7 \\ \rightarrow 87 \times 0.9 = 78.3 \end{cases}$ Hence there are within 10%

So, Arithmetic mean method is used.

$$\Rightarrow \qquad P_D = \frac{P_1 + P_2 + P_3 + ... + P_m}{m}$$

$$\Rightarrow \qquad \frac{91.11 + 72.23 + 79.89}{3} = 81.08 \text{ mm}$$

2.5.2 Test of Consistency of Records

Changes in relevant conditions of a rain gauge (such as gauge location, exposure, instrumentation or observation techniques and surroundings) may cause a relative change in the precipitation catchment of the rain gauge. The consistency of the precipitation data of such rain gauges needs to be examined.

Factors affect the consistency of the record at a given station are

- damage and replacement of a raingauge
- change in the gauge location or elevation
- growth of high vegetation or construction of a building
- change in measurement procedure
- human, mechanical or electrical error in taking readings

A method called **Double Mass Curve** is used for adjusting inconsistent data.

Double-mass curve technique (to find missing data)

Double-mass curve technique, compares the accumulated annual or seasonal precipitation at a given station with the concurrent accumulated values of mean precipitation for a group of the surrounding stations (i.e., base stations).

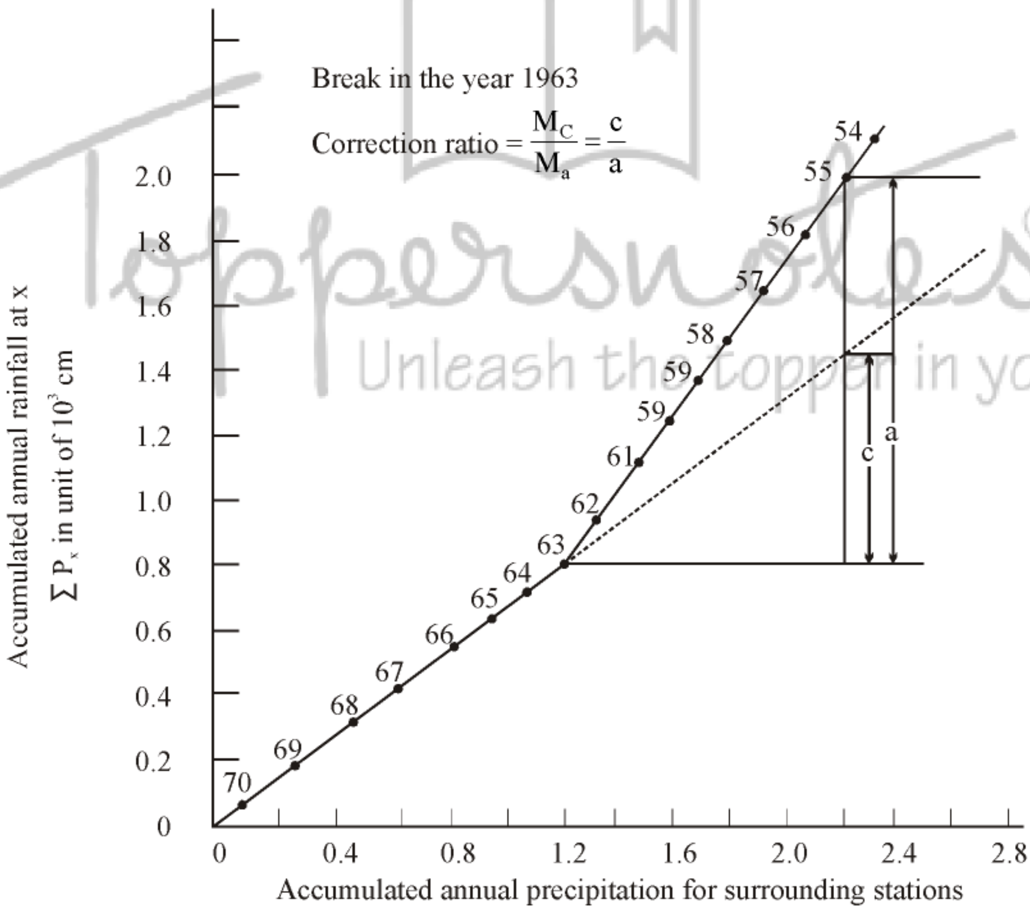

Fig. 2.2 : Double-mass curve

Steps to draw double-mass curve

1. Arrange the data in chronologically descending order.
2. Find cumulative rainfall of station x (given).
3. Find cumulative average rainfall of other stations.
4. Plot the graph of accumulated rainfall at station x as y-axis against cumulative average rain fall of other stations as x-axis.

   Plot the graph station A (given) in Y axis and others in X axis.
5. Locate the points and mark the year on it.
6. Join the points.
7. Find where the line changes its slope (if so).
8. Adjust the old records so that they form the current straight line trend.

A change in slope in normally taken as significant only where it persists for more than 5 years.

$$P_{corr}\,x = P_x \times \frac{M_C}{M_a}$$

Where M_C = corrected slope of double mass curve

M_a = original slope of double mass curve

and correction factor $= \frac{M_C}{M_a} = \frac{c}{s}$

$P_{corr}\,x$ = Corrected precipitation at any time period t_1 at station x.

P_x = original recorded precipitation at any time period t_1 at station x.

Example 4 : Annual rainfall data for station M as well as the average annual rainfall values for a group of ten neighboring stations located in meteorologically homogeneous region are given below.

Year	Annual Rainfall of Station M (mm)	Average Annual Ranfall of the group (mm)	Year	Annual Rainfall of Station M (mm)	Average Annual Ranfall 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	579	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	825	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 :

Step 1 : The given data are arranged in a reverse chronological order starting from latest year 1979 as shown in column 1 of table given below.

Step 2 : Cumulative values of station M rain fall (ΣP_m) and the average rainfall values (ΣP_{av}) are calculated as shown in table given.

Step 3 : The data is then plotted to obtain a double mass curve plot as ΣP_m on y-axis and ΣP_{av} on x-axis.

Step 4 : Then the break in slope is found out. It exists after the year 1968. The slope of the straight line for period 1979-1969 in M_C = 1.0295

and for the period 1968-1950 in

$$m_a = \frac{17060 - 6399}{18396 - 6251} = 0.87781$$

So the correction ratio $= \dfrac{M_C}{m_a} = \dfrac{1.02965}{0.8779} = 1.173$

Now each of the pre 1969 annual rain fall value in multiplied by the correction ratio of 1.173 to get the adjusted value as in column 6 of given table.

Now mean annual precipitation at station M (Based on finalized corrected data) $= \dfrac{19004}{30} = 633.5\text{mm}$

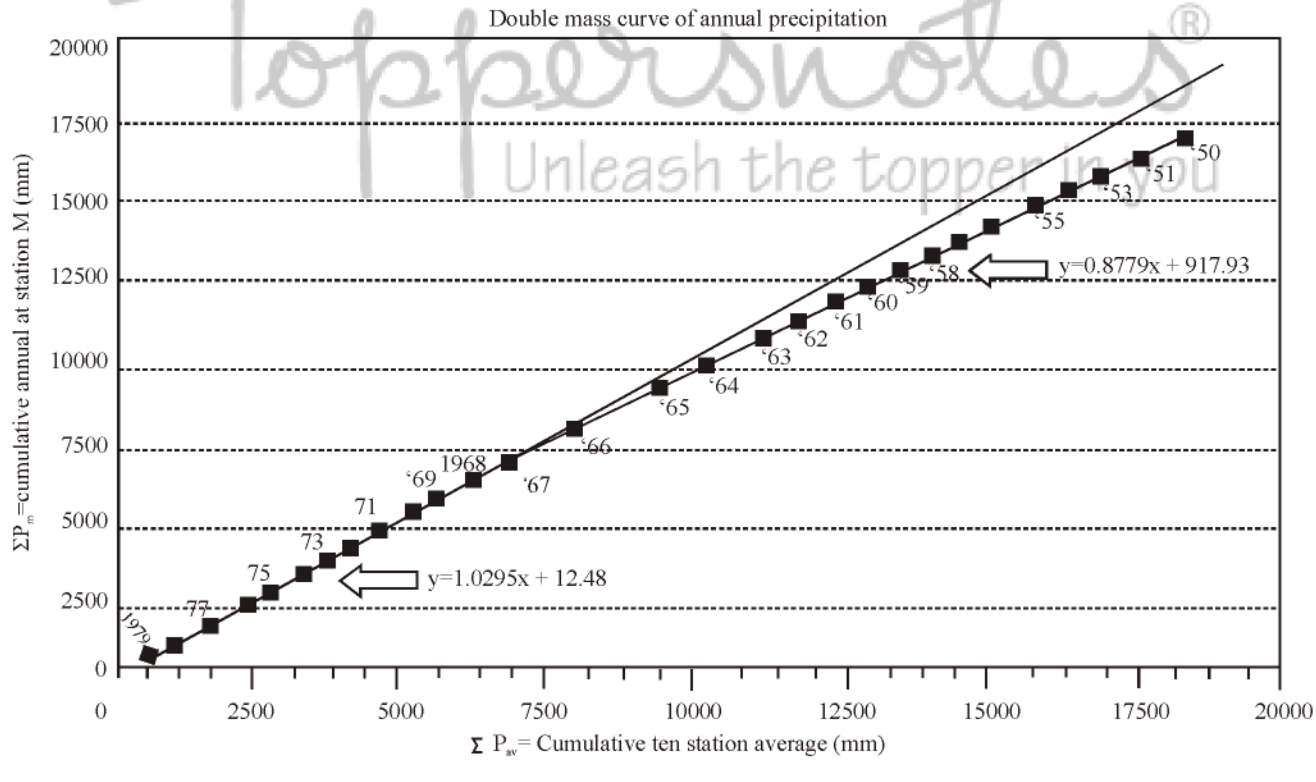

Fig. 2.3 : Double mass curve of annual rainfall at station M

Table : Calculation of double mass curve of example

1	2	3	4	5	6	7
Year	P_m (mm)	ΣP_m (mm)	P_{av} (mm)	ΣP_{av} (mm)	Adjusted values of P_m (mm)	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	580	11741	591.03	591
1961	531	11757	600	12341	622.7	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

2.6 PRESENTATION OF RAINFALL DATA

After preparation of rainfall data its presentation is to be required and subsequently interpretation and analysis of such data can be done. Three most common methods are as follows :

2.6.1 Mass Curve of Rainfall

- The mass curve of rainfall is a plot of the accumulated precipitation against time plotted in chronological order.
- Records obtained from float type and weighing bucket type gauges are in this form.
- Mass curve of rainfall are very useful in extracting the information on the duration and magnitude of storm.
- Slope of mass curve gives intensity of rainfall at that point.

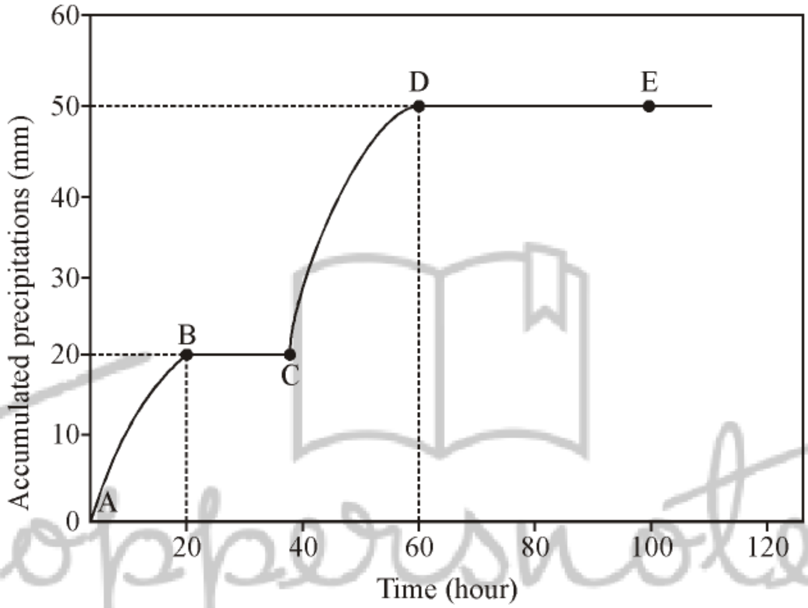

Fig. 2.4 : Mass curve of rainfall

Average intensity in 1st storm (B – A) = $\frac{20}{20} = 1 \text{ mm / hr}$

No rain fall during BC

Average intensity in 2nd storm (D – C) = $\frac{50-20}{20} = 1.5 \text{ mm / hr}$

No rainfall during DE

2.6.2 Hyetograph

- A hyetograph is a plot of the intensity of rainfall against the time internal.
- The hyetograph is derived from the mass curve and is usually represented as a bar chart.
- The area under a hyetograph represents the total precipitation received in the particular time period.
- Hyetograph is more convenient than mass curve since it is easier to determine the area of hyetograph.