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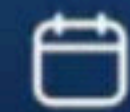


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- 1.19 Evapotranspiration
 - 1.19.1 Measurement of Evapotranspiration of Consumptive use
 - 1.19.2 Penman's Method
- 1.20 Infiltration
 - 1.20.1 Factors affecting Infiltration
 - 1.20.2 Infiltration Indices
 - 1.20.3 Measurement of Infiltration capacity
 - 1.20.4 Horton's equation of Infiltration
 - 1.20.5 Green-Ampt Method
- Examples
- Exercise
- Multiple Choice Questions

1.1 INTRODUCTION :

(April 2017)

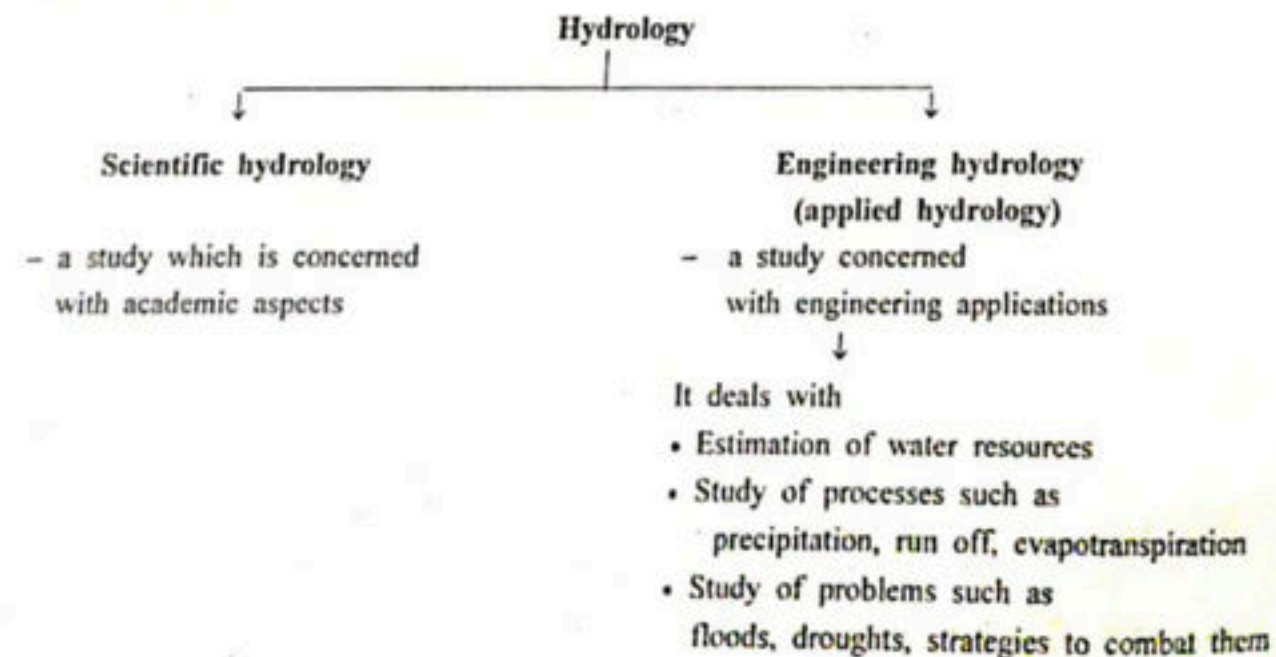
Hydrology is the science which deals with the occurrence, circulation and distribution of water upon, over and beneath the earth surface. It is the science concerned with the transportation of water vapour through the air, the precipitation occurring on the ground as rainfall or snowfall and the flow of water over the ground surface and through the underground strata of the earth.

It also deals with the evaporation from water surface and soil surface, transpiration from the plants, and the infiltration of water through the ground surface.

In a general sense, hydrology is a very broad subject of an interdisciplinary nature drawing support from allied sciences such as

- Meteorology
- Statistics
- Chemistry
- geology
- Physics
- Fluid mechanics, etc.

Hydrology is basically an applied science. To further emphasis the degree of applicability, the subject is sometimes classified as



Applications of hydrology

The study of hydrology helps us to know

- (i) The maximum probable flood that may occur at given site and its frequency.
 - This may required for the safe design of drains, culverts, dams, reservoirs, canals, etc.
- (ii) The water yield from basin-its occurrence, quantity and frequency, etc.
 - This is necessary for the design of dams, municipal water supply, water power, river navigation etc.
- (iii) Ground water development
 - For which a knowledge of the hydrogeology of the area i.e. formation of soil, recharge facilities, rainfall, patterns, climate, cropping pattern, etc. are required.
- (iv) The maximum intensity of storm and its frequency.
 - This is required for the design of a drainage project in the area.
- (v) Various methods of flood forecasting and flood control.
- (vi) Selection of suitable site for a dam, reservoir and hydroelectric power generation.
- (vii) The capacity of storage structures such as reservoirs.
- (viii) The interaction of the flood wave and hydraulic structures like levees, reservoirs, barrages and bridges.

1.2 HYDROLOGIC CYCLE :

(Nov. 2014)

The hydrologic cycle is a descriptive term applied to the circulation of water from the oceans to the atmosphere, to the ground and back to the oceans again. Thus, hydrologic cycle is the earth's water circulatory system.

Fig. 1.1 shows the schematic representation of the hydrologic cycle. The cycle may be considered to begin with the water of the oceans. Water from the ocean surface is evaporated into the atmosphere. The vapour

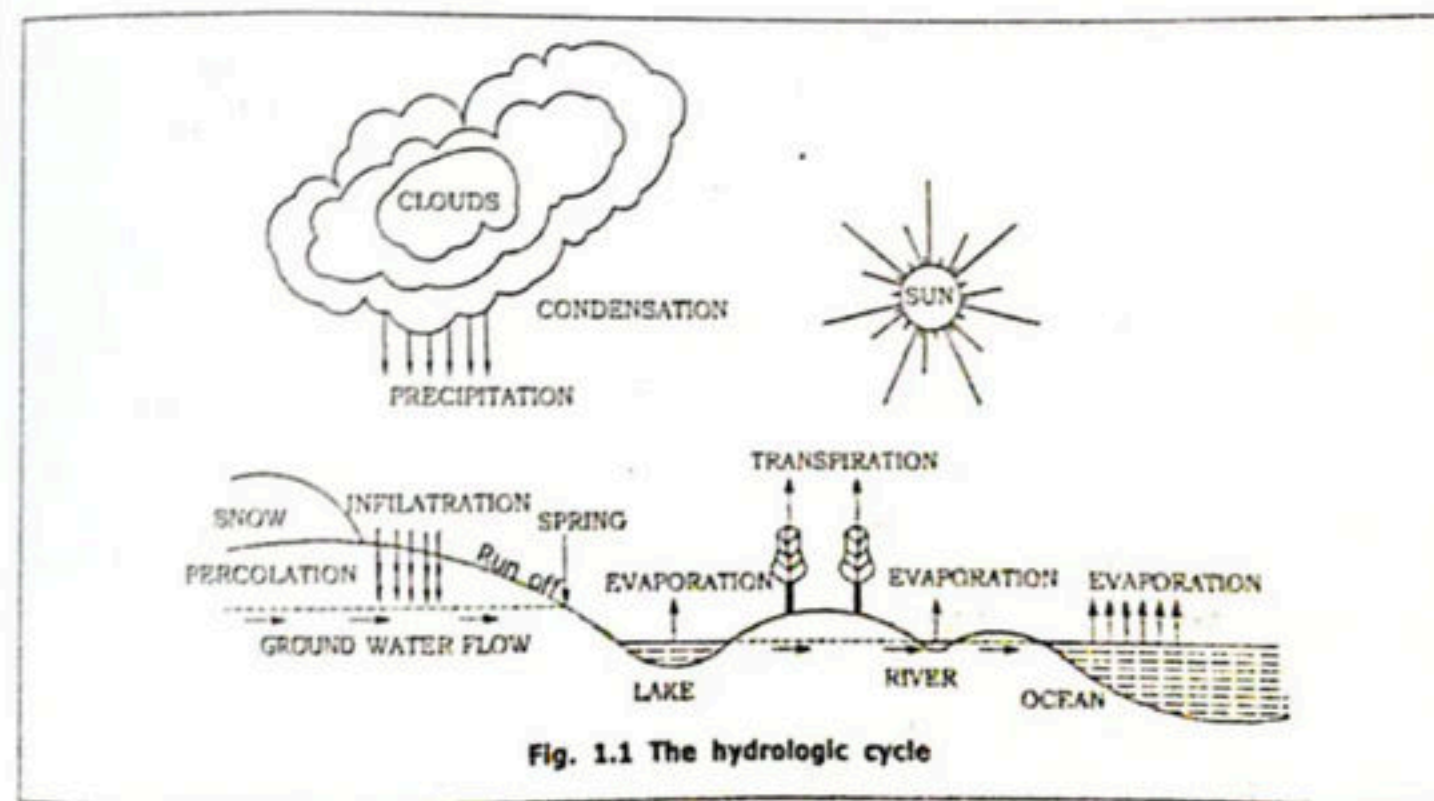


Fig. 1.1 The hydrologic cycle

is condensed by various processes and falls to the earth as precipitation. Some of this precipitation falls directly on the ocean, and some falls on the land surfaces. A portion of precipitation that falls on the land is retained temporarily in the soil, in surface depressions and on vegetation, until it returned to the atmosphere by evaporation and transpiration.

1.3 PROCESSES OF HYDROLOGIC CYCLE :

The hydrologic cycle consists of the following processes :

1. Evaporation and Transpiration
2. Precipitation
3. Runoff

1. Evaporation and Transpiration :

Due to heat of sun the water from the surfaces of ocean, rivers, lakes and from the moist ground surfaces evaporates. The vapour are carried over the land by air in the form of clouds. This process is called **evaporation**.

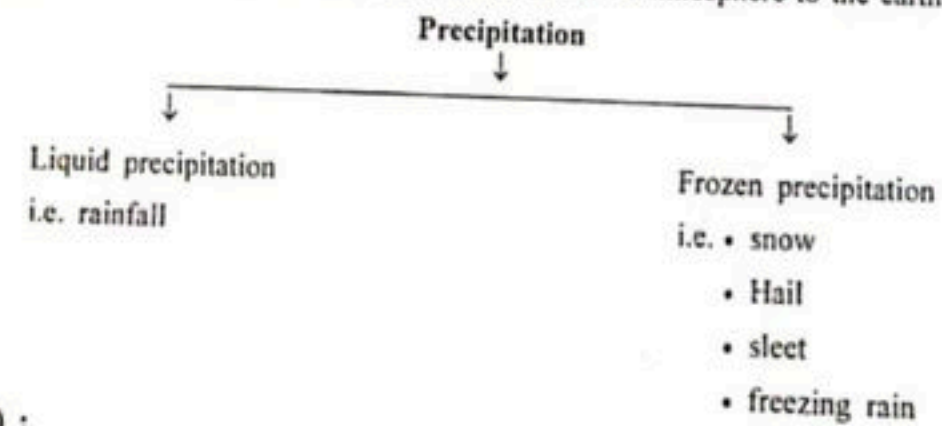
Transpiration is the process of water being lost from the leaves of the plants from their pores.

Thus, the total evaporation (E) is consists of,

$$\begin{aligned} \text{Evaporation (E)} &= \text{Surface evaporation} \\ &+ \text{water surface evaporation} \\ &+ \text{rivers, ponds surface evaporation} \\ &+ \text{ocean surface evaporation} \\ &+ \text{atmospheric evaporation} \\ &+ \text{transpiration} \end{aligned}$$

2. Precipitation (P) :

Precipitation may be defined as the fall of moisture from the atmosphere to the earth surface in any form. (June 2014)



3. Runoff (R) :

Runoff is that part of precipitation that is not evaporated.

When moisture falls to the earth's surface as precipitation, a part of it is evaporated from the water surface, soil and vegetation and through transpiration by plants, and the remainder precipitation is available as runoff. (June 2014)

There are three types of runoff.

- (i) Surface runoff
- (ii) Sub-surface runoff or interflow
- (iii) Ground water flow or base flow.

(i) Surface runoff :

A large portion of the precipitation, left after infiltration, flows over the ground into the streams and rivers, which ultimately discharge the water to the sea, is known as surface runoff.

(ii) Sub-surface runoff or interflow :

A portion of the precipitation infiltrates into surface soil runs as sub-surface runoff and reaches the streams and rivers. This water is known as sub-surface runoff or interflow.

(iii) Ground water flow or base flow :

It is that portion of precipitation which after infiltration, percolates down and joins the ground water reservoir, which is ultimately connected to the ocean.

$$\text{Precipitation} = \text{Evaporation} + \text{Runoff}$$

$$P = E + R$$

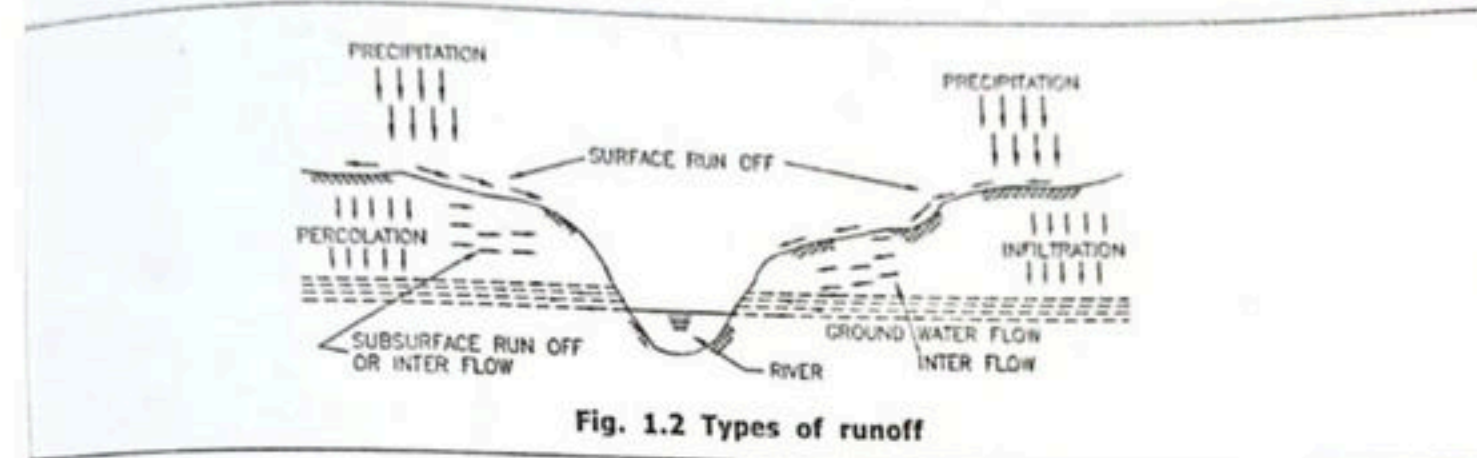


Fig. 1.2 Types of runoff

1.4 WATER BALANCES :

• Catchment area :

The area of land draining into a stream or a water course at a given location is known as **catchment area**.

It is also called as drainage area or **drainage basin**. In USA, it is known as **watershed**.

A catchment area is separated from its neighbouring areas by a ridge called **divide** in USA and **watershed** in UK.

Fig. 1.3

• Water budget equation :

(Nov. 2016)

The hydrologic equation is simply the statement of the law of conservation of matter and is given by

$$I = O + \Delta S$$

where,

I = Inflow

O = Outflow

ΔS = change in storage, in a given time interval.

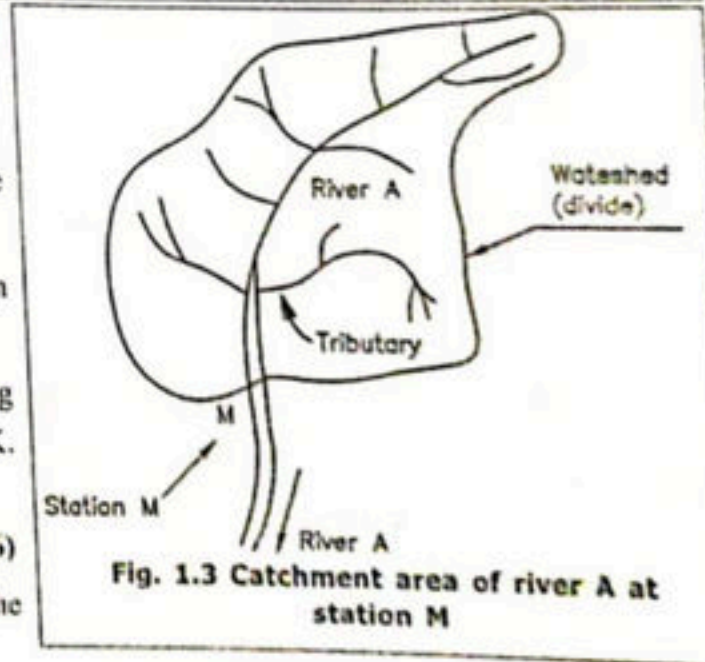


Fig. 1.3 Catchment area of river A at station M

..... (1.1)

In hydrologic calculations, the volumes are often expressed as average depths over the catchment area. Thus, for example, if the annual stream flow from a 10 km^2 catchment is 10^7 m^3 , it corresponds to a depth of $10^7 / (10 \times 10^6) = 1 \text{ m} = 100 \text{ cm}$ of water. Rainfall, evaporation and often runoff volumes are expressed in units of depth over the catchment.

The expression for the water budget of a catchment for a time interval Δt is written as,

$$P - R - G - E - T = \Delta S \quad \dots \dots \dots (1.2)$$

where,

- P = Precipitation
- R = Surface runoff
- G = Net groundwater flow out of the catchment
- E = Evaporation
- T = Transpiration,
- ΔS = change in storage

The inflow (I) in equation (1.1) consists of

- Precipitation
- Surface inflow
- Subsurface inflow
- Imported water or sewage through pipe or channel

The outflow (O) in equation (1.1) consists of

- Surface runoff
- Subsurface runoff
- Evaporation
- Transpiration
- Evapotranspiration
- Exported water or sewage out of basin

The change in storage (ΔS) in equation (1.2) consists of,

$$\Delta S = \Delta S_s + \Delta S_{sm} + \Delta S_g \quad \dots \dots \dots (1.3)$$

where,

- ΔS_s = Change in surface water storage
- ΔS_{sm} = change in soil moisture storage
- ΔS_g = change in ground water storage

In terms of rainfall - runoff relationship, eq. (1.2) can be represented as :

$$R = P - L$$

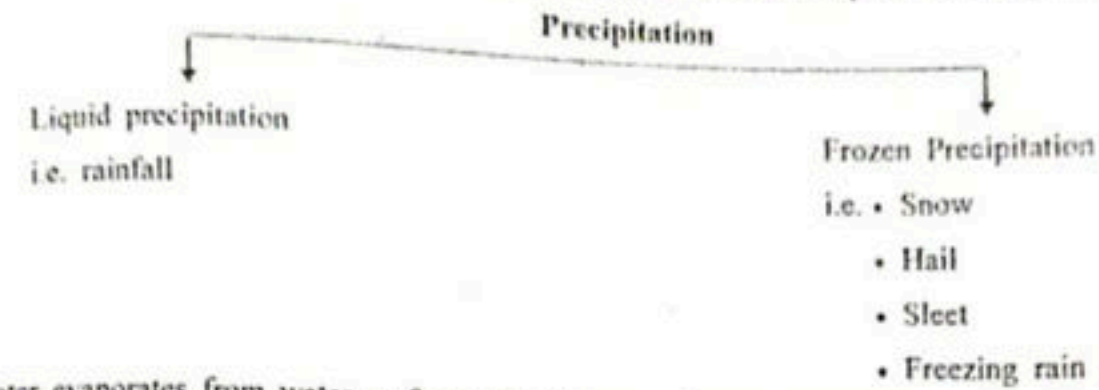
where,

- R = Runoff
- P = Precipitation (rainfall)
- L = Losses

1.5 PRECIPITATION :

(May 2014, Dec.2018)

Precipitation may be defined as the fall of moisture from the atmosphere to the earth surface in any form.



Water evaporates from water surfaces like streams, rivers, oceans, lakes, ponds, etc. and also from land and plants in the form of water vapour. These water vapour get collected in the atmosphere and behave like a gas. Under a normal range of temperature and pressure, the water vapour obey the various gas laws (like Boyle's law, Charles's law etc.) As the evaporation continues, the amount of atmospheric vapour go on increasing. But, since a space can hold only a certain fixed amount of water vapour in the presence of a solid or a liquid surface, a stage is reached when any further addition of vapour will get condensed on the surfaces. The vapour may get condensed in different forms, such as mist, rain, snow, hail, sleet, etc. The evaporated water, thus returns to the Earth's surface in any of these forms. **The water which comes back to the surface of the earth in its various forms like rain, hail, snow, sleet, etc. is known as precipitation.**

In India, major portion of precipitation is due to rainfall and small portion of snow fall in the himalayan region.

For precipitation to form, it therefore necessary to have the following favourable conditions in the environment :

- (i) The atmosphere must have moisture
- (ii) There must be sufficient nuclei (particles) present to aid condensation over them.
- (iii) Weather conditions must be favourable to condensation of water vapour.
- (iv) The products of condensation must reach to the earth.

1.6 FORMS OF PRECIPITATION :

(May 2015, Dec. 2018)

Some of the common forms of precipitation are :

- | | |
|----------|------------|
| 1. Rain | 2. Snow |
| 3. Hail | 4. Drizzle |
| 5. Glaze | 6. Sleet |
| 7. Rime | 8. Dew |

1. Rain :

Rain is the principal form of precipitation in India. When the size of water drop is larger than 0.5 mm, it is called rainfall. The maximum size of rain drop is about 6 mm. Any drop larger than this size tends to break down into drops of smaller sizes during its fall from the clouds.

On the basis of its intensity, a rainfall may be classified as light, moderate and heavy.

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

2. Snow :

Snow is the next important form of precipitation and consists of ice crystals, usually combining to form flakes. New fresh snow has an initial density of 0.06 to 0.15 g/cm^3 and the average value is assumed to be 0.10 g/cm^3 . Snowfall in India is usually confined only to the Himalayan region.

But, in countries like Canada, USA, Russia, China, etc. where snow occurs in abundance and, hence forms the major part of their precipitation.

3. Hail :

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

4. 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.

5. Glaze :

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

6. Sleet :

It is frozen rain drops of transparent grains which form when rain falls through air at subfreezing temperature.

7. Rime :

It is white opaque deposit of ice granules more or less separated by trapped air and formed by rapid freezing of super cooled water drops impinging on exposed objects. Specific gravity may be as low as 0.2 to 0.3 .

8. Dew :

Dew forms directly by condensation on the ground mainly during night when the surface has been cooled by outgoing radiation.

1.7 TYPES OF PRECIPITATION :

Precipitation is often classified according to the factors responsible for lifting. Broadly speaking, there are four types of precipitation.

1. Cyclonic precipitation
2. Convective precipitation
3. Orographic precipitation
4. Precipitation due to turbulent ascent

1. Cyclonic Precipitation :

Cyclonic precipitation is caused by the lifting of an air mass due to the pressure difference. If low pressure occurs in an area, air will flow horizontally from the surrounding area, causing the air in the low pressure area to lift.

Hydrological Parameters

The cyclonic precipitation may be divided into

- (a) Frontal Precipitation
- (b) Non-Frontal Precipitation

(a) Frontal Precipitation :

When two air masses due to contrasting temperatures and densities clash with each other, condensation and precipitation occur at the surface of contact. This surface of contact is called a 'Front' or 'Frontal Surface' and the precipitation is called frontal precipitation.

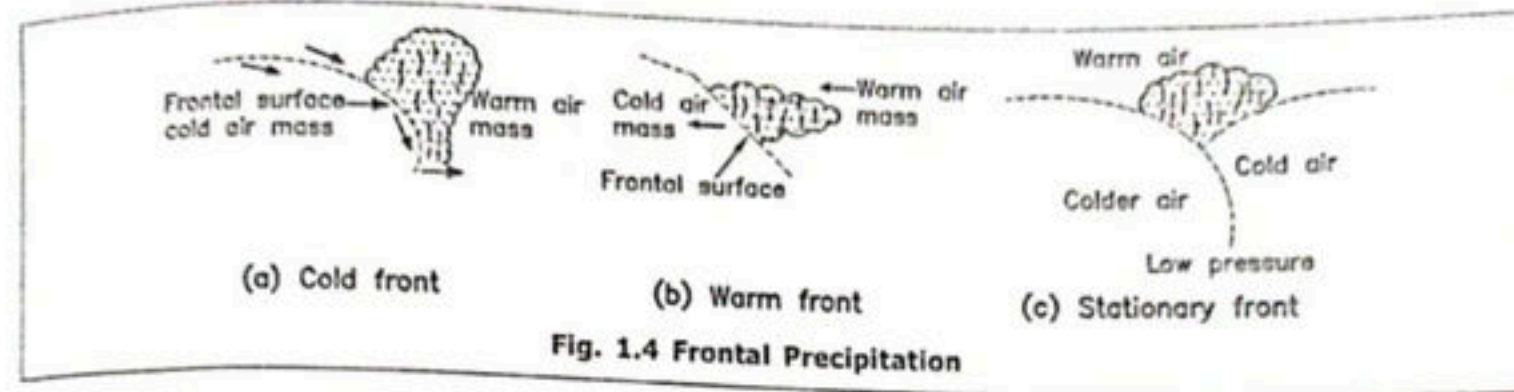


Fig. 1.4 Frontal Precipitation

If a cold air mass drives out a warm air mass, it is called a 'Cold Front' and if a warm air mass replaces the retreating cold air mass, it is called a 'Warm Front'. On the other hand, if the two air masses are drawn simultaneously towards a low pressure area, the front developed is stationary and is called a 'Stationary Front.' Cold Front causes intense precipitation on comparatively small areas, while the precipitation due to warm front is less intense but is spread over comparatively larger area. Cold fronts move faster than warm fronts.

(b) Non-Frontal Precipitation :

In case of non-frontal precipitation, the moist warm air mass is stationary and the moving cold air mass meets it. Thus, due to lightness of the warm air mass there is passive ascent of warm air over cold air owing to the active under cutting. When the lifted warm air cools down at higher altitude precipitation occurs.

2. Convective Precipitation :

Convective Precipitation is caused by natural rising of warmer lighter air in colder, denser surroundings. The difference in temperature may result from unequal heating at the surface, unequal cooling at the top of the air layer.

Generally, this kind of precipitation occurs in tropics, where on a hot day, the ground surface gets heated unequally, causing the warmer air to lift up, as the colder air comes to take its place. The vertical air currents develop tremendous velocities and are hazardous to aircrafts. Convective precipitation is spotty and its intensity vary from light showers to cloud bursts.

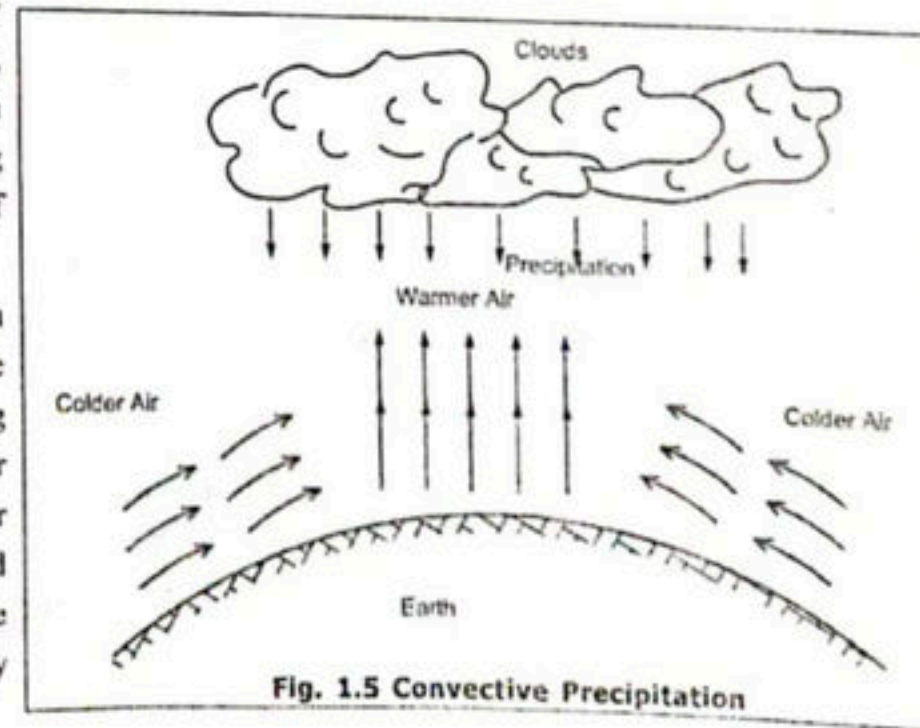


Fig. 1.5 Convective Precipitation

3. Orographic Precipitation :

Orographic precipitation is caused by moist air masses, which strike some natural topographic barriers like mountains, rise up causing condensation and precipitation. The greatest amount of precipitation falls on the windward side, and the leeward side often has very little precipitation. The rainfall is composed of showers and steady rainfall.

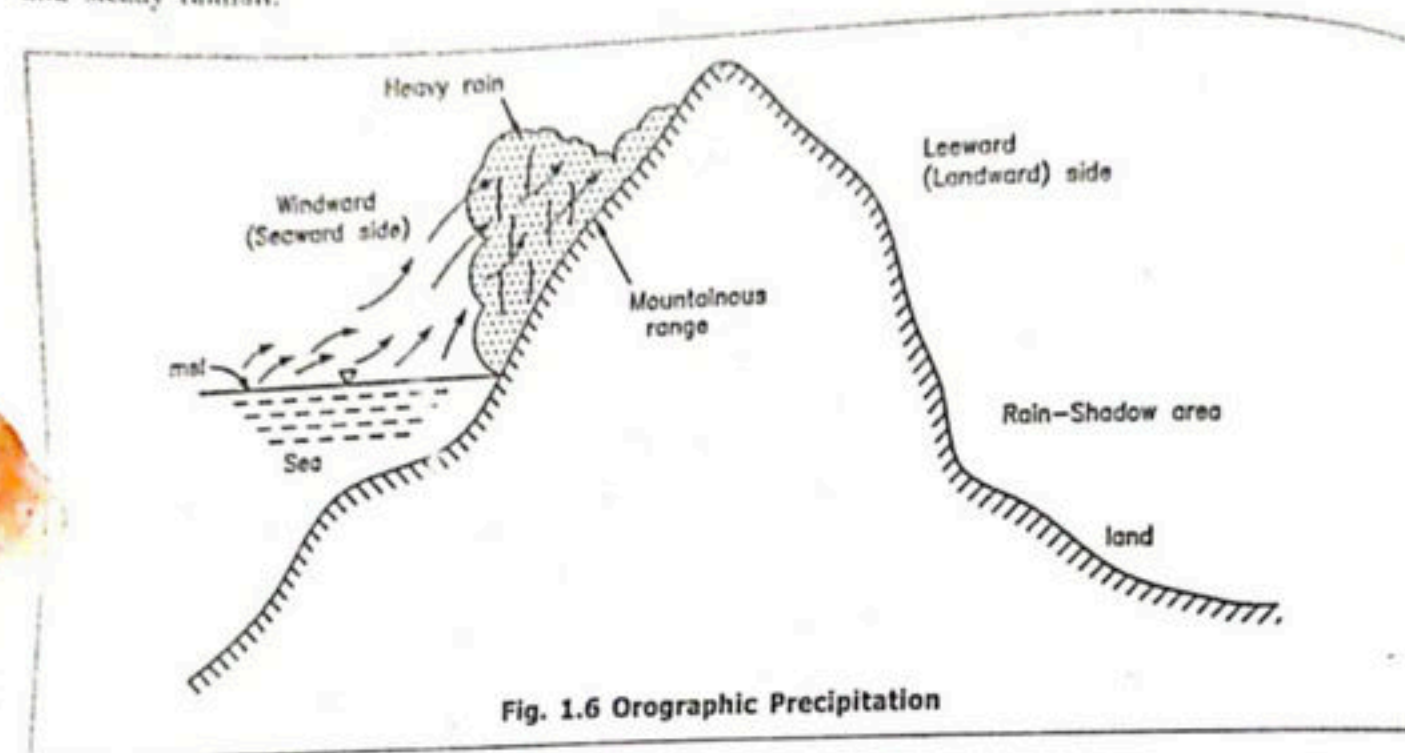


Fig. 1.6 Orographic Precipitation

The winds, heavily laden with moisture from the Bay of Bengal, strike the southern slope of Himalayas, causing intense rains so much so that a place known as Mawsynram near Cherrapunji in Meghalaya, gets the maximum average annual rainfall of the order of 1270 cm. Similarly, Agumbe in the Western Ghats of South India get very heavy orographic rainfall of 900 cm.

4. Precipitation due to turbulent ascent :

Air mass is forced to rise up due to greater friction of earth surface after its travel over ocean. The air mass rises up because of increased turbulence and friction, when it ultimately condenses and precipitation occurs.

Winter rainfall in Madras state is mainly due to this process.

• Artificial rainfall (Cloud seeding) :

A cloud is formed by the cooling and condensation of the rising water vapour (air) into some visible aggregates of minute particles. A cloud, therefore, generally contains ice particles and small droplets of water.

Sometimes the process of evaporation is smoothly carried and the air has sufficient amount of moisture (it is known as absolute humidity), but it does not reach the point of saturation because there is a deficiency of hygroscopic nuclei, which are necessary to form the raindrops. So artificial hygroscopic nuclei are provided in the following forms :

- Dry ice (solid CO_2)
- Silver dioxide
- frozen carbon dioxide
- Sodium chloride etc.

The process of artificial simulation of Precipitation by adding certain chemicals to cloud in atmosphere is known as cloud seeding.

It is accomplished by the following methods :

- (i) The seeding element such as dry ice is delivered into the cloud by aircrafts, balloons or rockets.
- (ii) Silver dioxide may be delivered into the cloud either by aircrafts or by ground based generator.
- (iii) Hygroscopic nuclei (freezing nuclei) can be emitted through the high-level chimneys.

The success of cloud seeding with economic value is still uncertain. It is still in experimental stage.

This method has the following disadvantages :

- The process of cloud seeding is very costly.
- The success rate is very limited.
- It may affect the process of natural rainfall in the adjoining areas.
- It may aggravate the flood disaster in certain areas.

1.5 VARIABILITY OF PRECIPITATION :

The distribution of precipitation is not uniform in a particular region. The precipitation regime for any region depends upon the following factors.

- (i) Location of the region in the general circulation pattern.
- (ii) The latitude.
- (iii) Distance from a moisture source
- (iv) Orography of a region

(i) Location of the region in the general circulation pattern :

The thermal circulation originates from the sun as a source of origin. About 40% of radiant energy of sun is reflected back from upper surface of clouds. The earth absorbs the remaining 60% with small losses. This in turn increases the heat of the surface. More solar energy is received at the equator and hence heated air at the equator zone rises up and flows towards the poles. To balance this, air in the lower layers must move towards the equator. Fig. 1.7 shows such thermal circulation.

But the actual circulation is different because of the following two factors :

- The earth's rotation
- The distribution of oceans and continents

(ii) The latitude :

Near the equator due to higher temperature evaporation is more. Thus, precipitation is heaviest near the equator and decreases towards higher latitudes (Poles).

(iii) Distance from a moisture source :

Near coastlines, precipitation tends to be heavier. With increase in distance from coastline, the moisture in the wind decreases and thus, precipitation also decreases.

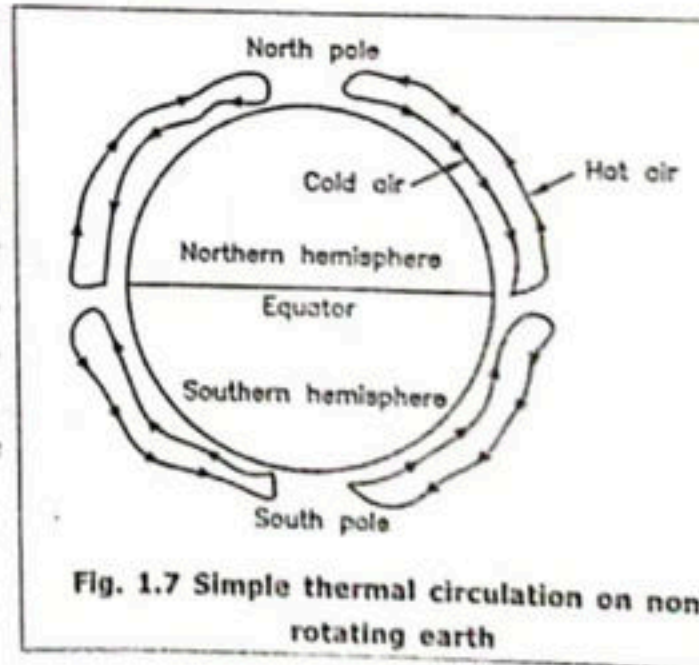


Fig. 1.7 Simple thermal circulation on non-rotating earth

The decrease of precipitation northward from the gulf coast is the most marked example of this effect. In general, the occurrence of precipitation is more frequent on the lee shore.

(iv) Orography of a region :

Topographic barriers like mountains affect the distribution of rainfall in the region. The greatest amount of precipitation falls on the windward side, and the leeward side often has very little precipitation.

For example, Mahabaleswar on the windward side, receive heavy rainfall in monsoon while Pune on leeward side gets very little rainfall.

• Characteristics of precipitation in India :

India is a tropical country, and its precipitation varies considerably in frequency, intensity and duration. The precipitation in India occurs mainly in the form of rainfall. Most of the precipitation occurs in the months of June to September during the period of the southwest monsoon. Snow fall occurs in the Himalayan regions during winter in the month of Dec.-Feb.

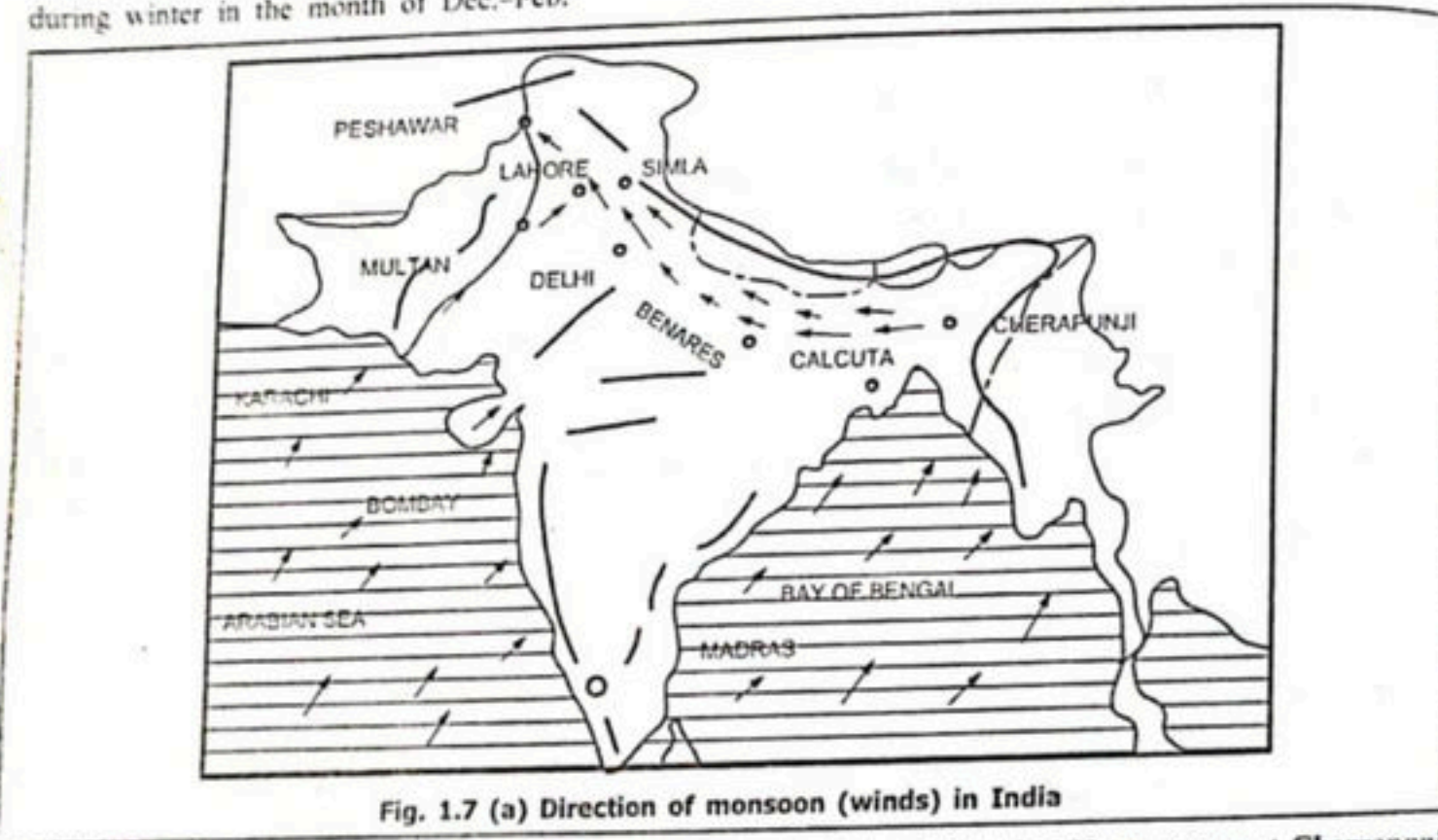


Fig. 1.7 (a) Direction of monsoon (winds) in India

There is a great variation of the rainfall. The maximum annual rainfall of 1270 cm occurs at Cherrapunji and Mawsynram in Meghalaya state and the minimum annual rainfall of 12 cm occurs in the desert of Rajasthan.

There are basically four rainfall seasons in India :

1. South-West monsoon season
2. North-East monsoon season
3. Winter season
4. Summer season

1. South-West monsoon season [June - September] :

The south-west monsoon causes about 75% of annual rainfall, covering almost entire country, except Jammu & Kashmir, and South-Eastern parts of South India.

The monsoon originates in the Indian Ocean and appears in the country in Kerala in the first week of June. It is the India Peninsula which rather deflects the monsoon, into the two branches :

- (i) the Arabian sea branch.
- (ii) the Bay of Bengal branch.

Hydrological Parameters

The Arabian sea branch touches Kerala in the end of May and moves towards north causing heavy precipitation in western ghats, Maharashtra, Gujarat, M.P. Rajasthan, Punjab, etc.

The Bay of Bengal branch moves westward, causing rain in West Bengal, Orissa, Bihar, U.P. etc.

2. North-East monsoon season : [Oct. - Nov.]

As the south-west monsoon retreats, a low pressure region is formed in the Bay of Bengal. Flow of air from North-East occurs during the period from October to November. This is known as North-East monsoon season. When the north-east monsoon strikes the eastern coast of the Southern Peninsula in and around Tamilnadu, rainfall occurs.

3. Winter season : [Dec. - Feb.]

By about mid December, Western disturbances of extra tropical origin travel eastward to India, crossing Afghanistan and Pakistan, causing heavy rainfall and snowfall in Himalayas and Jammu & Kashmir. Some light rainfall also occurs in the northern plains.

4. Summer season : [March - May]

Summer rainfall, also called premonsoon showers, occurs in parts of eastern coast and north-eastern states, due to localised convective currents. However, sometimes convective precipitation may occur in Kerala, West Bengal and Assam.

- Wind velocity - anemometer
- Humidity - Hygrometer
- Rainfall depth - ombrometer

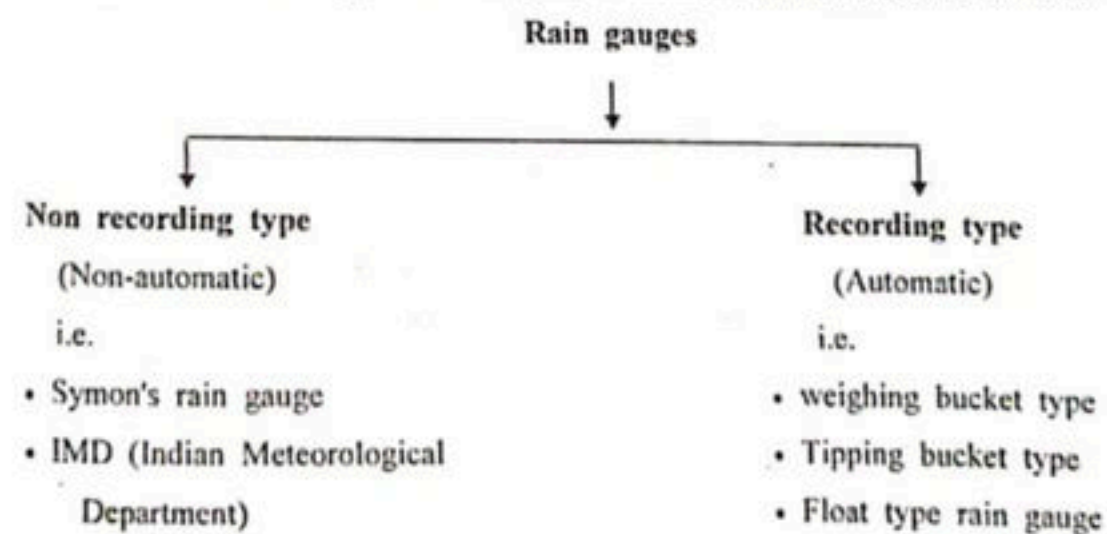
1.9 MEASUREMENT OF RAINFALL :

(May 2016)

Rainfall is the main source of water used for various purposes. The knowledge of amount of rainfall, intensity of rainfall and the distribution of rainfall is extremely useful for the irrigation engineers.

Rainfall at a place can be measured by a rain gauge, usually in cm.

The following are the main types of rain gauges used for measurement of rainfall. (Nov. 2017)



1. Symon's Rain gauge :

(Dec. 2015, Nov. 2016)

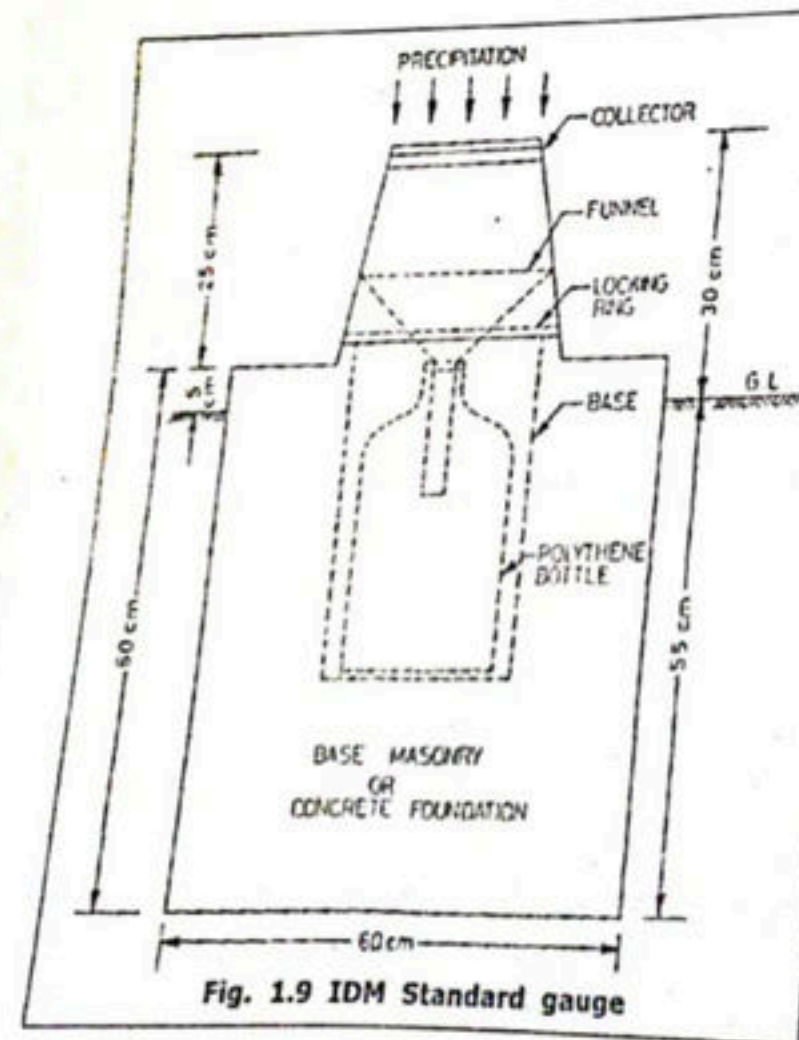
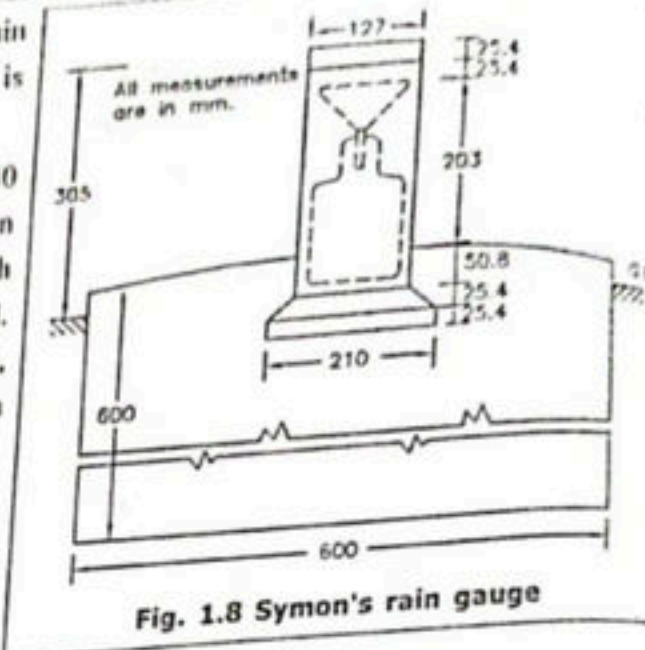
The Symon's rain gauge consists of a cylindrical metal case of internal diameter 127 mm and base enlarged to 210 mm. The metal casing is fixed vertically to a masonry foundation block of the size 600 × 600 × 600 mm. A funnel with a circular rim of 127 mm and a glass bottle are placed inside the metal casing. The height of the metal casing is so fixed that the rim is 305 mm above the ground level. The glass bottle, also called

the receiving bottle is of 75 to 100 mm diameter. The rain gauge is kept in open. The rain falling into the funnel is collected in the receiver.

The rainfall in India is measured every day at 08 :30 hours IST. The receiver with the rain water in it is taken out of the metal casing. The rainfall depth is measured with a special measuring glass jar graduated in mm of rainfall. It can measure upto 12.5 cm of rainfall. During heavy rains, the rainfall is measured 3-4 times in a day. It gives depth of rainfall.

The following points should be kept in mind while selecting the site for a rain-gauge station.

1. The rain gauge site should be an open place.
2. The distance between the rain gauge and the nearest object should be atleast twice the height of the object.
3. The rain gauge should be atleast 30 m away from the near by obstructions.
4. The rain gauge should never be situated on the side or top of a hill.
5. A fence, if erected to protect it from cattle etc. should be so located that the distance of the fence is not less than twice its height.



2. I.M.D. standard rain gauge :

The Symon's rain gauge was used by the Indian Meterological department (IMD) upto 1969 when the IMD standard rain gauge was adopted. It is a modified form of the Symon's rain gauge.

The IMD standrd rain gauge consists of a collector with a gun metal rim. The exposed top surface area of the collector is either 100 cm² or 200 cm². The collector is fitted over a base which is fixed to a concrete or masonry. Both the collector and the base are made of fibre glass reinforced polyester. The collector can be locked to the base by locking rings. The collector has a deep set funnel which discharges water into a polyethylene bottle kept inside the base. The capacity of bottle can be 2, 4 or 10 litres. The 200 cm² collector and 4 litre capacity bottle is the most commonly used rain gauge.

3. Weighing bucket type rain gauge :

This is a self recording type or automatic type rain gauge. In the weighing bucket type rain gauge, the rain water is collected by a receiver bucket. The bucket rest on a weighing pan of a spring or lever balance attached to the weighing mechanism. The increase in the weight of the bucket due to the addition of the rain water causes the platform (pan) to move. The movement of platform is transmitted through a system of levers to a pen. The pen makes a trace of the accumulated rainfall on a chart attached to a drum revolved by a clock-driven mechanism.

The rainfall record produced by this gauge is in the form of a mass curve of rainfall. The total rainfall is plotted with respect to time. The slope of the mass curve gives the intensity of rainfall.

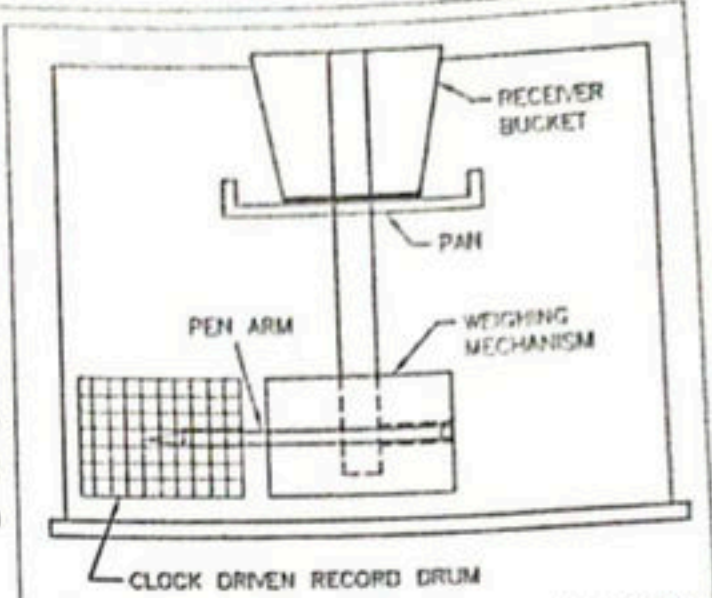


Fig. 1.10 Weighing bucket type rain gauge

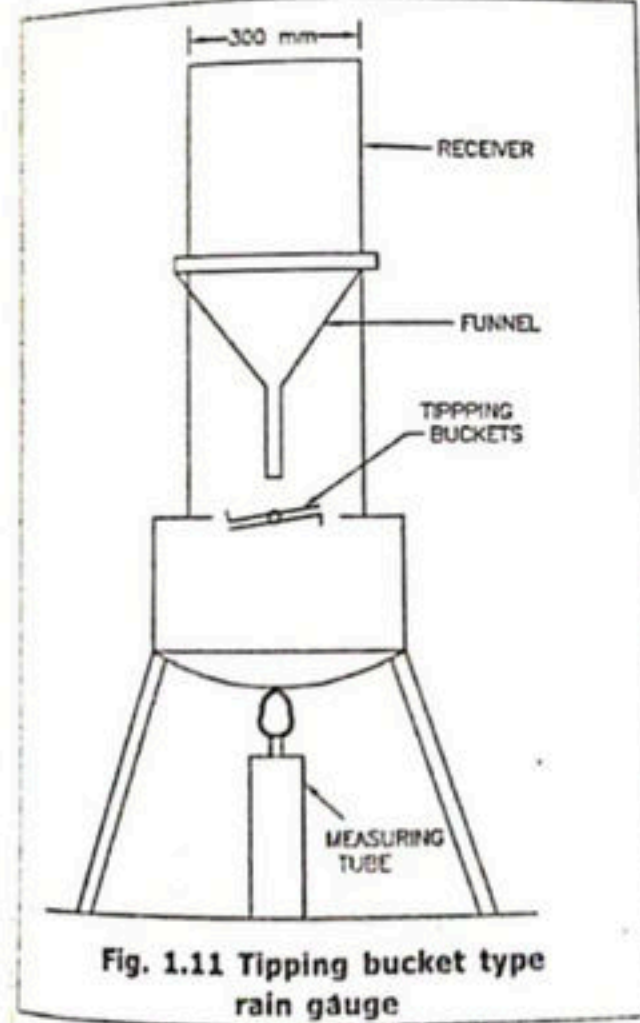


Fig. 1.11 Tipping bucket type rain gauge

4. Tipping Bucket type rain gauge :

(May 2015, Nov. 2016)

The tipping bucket type rain gauge consists of two small buckets placed below the funnel fitted in a 30 cm diameter receiver.

The buckets are so designed that when 0.25 mm of rainfall collects in one bucket, it tips and empties its water into the measuring tube below it, and at the same time the other bucket is brought under the funnel. The tipping of the bucket actuates an electric circuit which causes a pen to make a mark on a record sheet mounted on a clock driven revolving drum. Since each mark on the record sheet corresponds to 0.25 mm of rainfall, by counting the same the intensity of rainfall can be determined. The total rainfall as determine from the records at the end of the day may also be checked by measuring the rain water collected in the mesuring tube. It gives intensity of rainfall (cm/hr).

5. Float type rain gauge : [Natural Siphon type]

The working of a float type or syphon type rain gauge is similar to the weighing bucket type rain gauge. A funnel receives the rain water which is collected in a rectangular, float chamber. A float is provided at the bottom of the float chamber. The float is raised as the water level rises in the container, its movement being recorded by a pen moving on a recording drum actuated by a clock work.

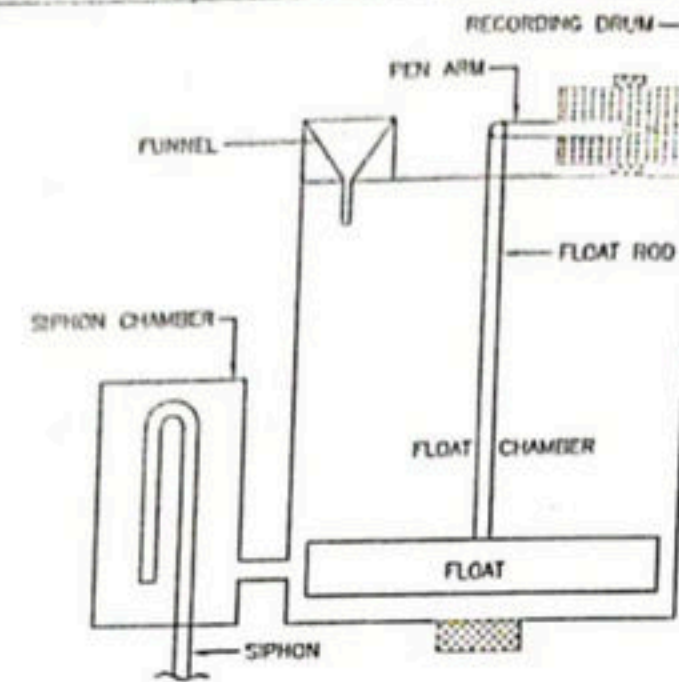


Fig. 1.12 Float type rain gauge

When the water level in the float chamber rises so that float touches the top, the syphon comes into operation and releases the water, thus all the water in the box is drained out.

It gives mass curve of rainfall (cumulative rainfall versus time). Indian standards have adopted float type rain gauge as the standard recording type gauge in India.

1.9.1 Advantages and Disadvantages of recording type rain gauges :

Advantages :

1. The rainfall is recorded automatically and therefore, no attendant is required.
2. As no attendant is required such rain gauge can be installed in remote places.
3. No possibility of human error.
4. The recording rain gauge also gives the intensity of rainfall at any time while the non-recording rain gauge gives only the total rainfall in any particular interval of time.

Disadvantages :

1. It is costly.
2. Fault may develop in electrical or mechanical mechanism.

1.10 METHODS OF CALCULATING AVERAGE RAINFALL OVER AN AREA :

(June 2014, Dec. 2015, April 2017, Nov. 2017, Dec. 2018)

The rainfall recorded by a rain gauge represents the rainfall at that station. In many hydrological studies, the average depth of rainfall over a specified area due to a storm is required. For determination of the average precipitation over an area, a large number of rain gauges are required.

The number of rain gauge stations required in a particular catchment area depends upon the size of the catchment as given in Table 1.1.

Table 1.1

Area of the catchment sq. km	Number of rain gauge stations required
0 to 80	1
80 to 160	2
160 to 320	3
320 to 560	4
560 to 800	5
800 to 1200	6

The average rainfall over an area can be computed by the following methods :

1. Arithmetic average method
2. Thiessen Polygen method
3. Isohyetal method

1. Arithmetic Average method :

In this method the average depth of rainfall over an area is obtained by dividing the sum of depths of rainfall recorded at the rain gauge stations located in the area by the number of stations.

Thus, if $P_1, P_2, P_3, \dots, P_n$ are the depths of rainfall recorded at various rain gauge stations,
 n = number of rain gauge stations

$$P = \frac{P_1 + P_2 + P_3 + \dots + P_n}{n}$$

$$= \frac{\sum P}{n}$$

For example

Table 1.2

Station No.	rainfall (mm)	Average rainfall (mm)
1.	150.4	$\therefore P = \frac{\sum P}{n}$ $= \frac{704.2}{5}$ $= 140.84 \text{ mm}$
2.	120.6	
3.	110.2	
4.	180.8	
5.	142.2	
	$\sum P = 704.2$	

• Merits and demerits of this method :

- (i) The method is very simple.
- (ii) It is used to determine the approximate rainfall.
- (iii) If the rainfall is uniformly distributed over the whole catchment, this method gives better results.
- (iv) In hilly terrains also, this method can yield fairly satisfactory results.

- (v) If the number of raingauge stations are more and the variation of the individual record is not far from the mean, method is taken to be accurate.
- (vi) The method is rapid and has got excellent adoptability for computer process.
- (vii) It is very costly and difficult to install maximum number of raingauge stations in the catchment for better results.

2. Thiessen Polygon method :

In the thiessen polygon method, the rainfall recorded at each rain gauge station is given a weightage on the basis of the area which it represents. This method is better than the arithmetic mean method which gives equal weightage to all the stations.

The following procedure is used.

Procedure :

- Join the adjacent rain gauge stations A, B, C, D etc. by straight lines, forming triangles.
- Construct the perpendicular bisectors of each of these sides of triangles.
- A thiessen network is thus created. The polygon formed by the perpendicular bisectors around a station encloses an area, which represents the area for that particular station.

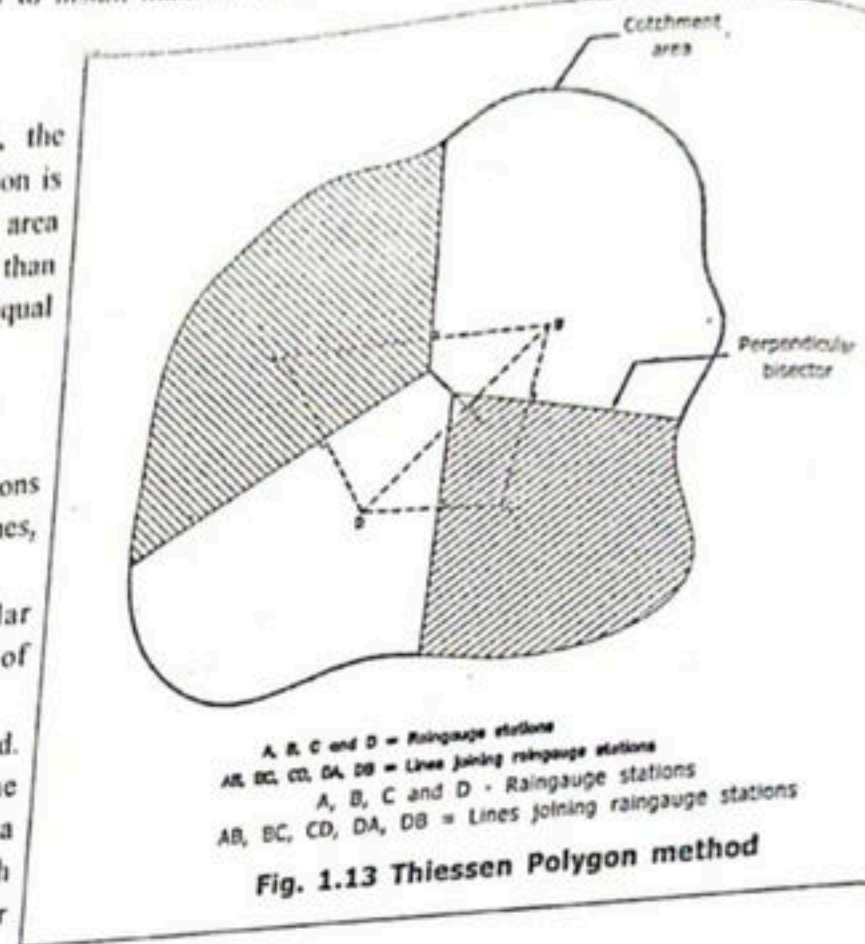


Fig. 1.13 Thiessen Polygon method

Let,

$P_1, P_2, P_3, \dots, P_n$ are the details of rainfall recorded at various rain gauge stations.

$A_1, A_2, A_3, \dots, A_n$ areas represented by various rain gauge stations.

$$\therefore P_{ave} = \frac{P_1 A_1 + P_2 A_2 + P_3 A_3 + \dots + P_n A_n}{A_1 + A_2 + A_3 + \dots + A_n}$$

$$= \frac{\sum PA}{\sum A}$$

For example,

Table 1.3

Station	Area of Thiessen Polygon (A)	rainfall (P) mm	A × P
A	45 sq.km	30.8	1386
B	28 sq.km	34.6	1314.8
C	30 sq.km	32.6	978
D	40 sq.km	24.6	984
	$\Sigma A = 153 \text{ sq.km}$		$\Sigma A \times P = 4662.8$

$$\begin{aligned}
 P_{ave} &= \frac{\sum PA}{\sum A} \\
 &= \frac{4662.8}{153} \\
 &= 30.47 \text{ mm}
 \end{aligned}$$

Merits and demerits of this method :

- (i) Results are accurate than arithmetic average method.
- (ii) Rainfall recorded at each raingauge station is given a weightage on the basis of area which it represents.
- (iii) This method eliminates error due to non-uniform distribution of raingauges.
- (iv) If catchment area is large and raingauge stations are also quite large in number, it is then adoptable to computer computation.
- (v) If gauging stations are few compared to the size of area, Thiessen polygon method should be used.
- (vi) A new Thiessen polygon diagram is to be drawn every time for the catchment if there is a change in the gauge network.
- (vii) This method does not consider the orographic influences.

Isonif : Line joining points of equal snowfall.

3. Isohyetal method :

Isohyets are the contours of equal rainfall. An isohyetal map showing contours of equal rainfall represent a more accurate picture of the rainfall distribution over the basin.

Procedure :

- (i) From the rainfall values recorded at various rain gauge stations, prepare the isohyetal map for the rainfall over the area.
- (ii) Measure the areas enclosed between the successive isohyets with the help of planimeter.
- (iii) Multiply each of these areas by the average rainfall between the isohyets.
- (iv) The average rainfall is then computed as below :

$$P_{ave} = \frac{\sum \left[A \times \left(\frac{P_1 + P_2}{2} \right) \right]}{\sum A}$$

For example,

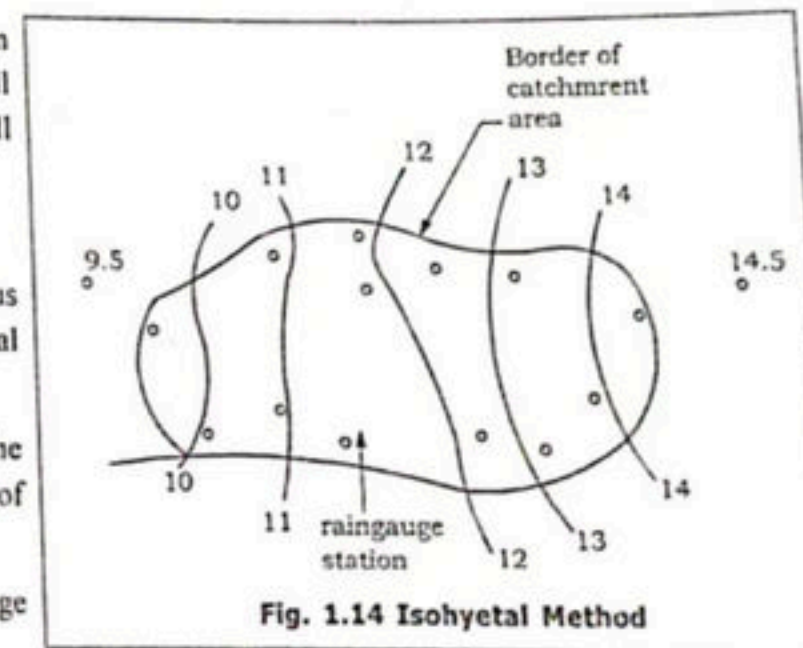


Fig. 1.14 Isohyetal Method

Table 1.4

Isohyets (cm)	Area between isohyets (A)	Average rainfall $\left(\frac{P_1 + P_2}{2}\right)$ Sq. km.	Product $A \times \left(\frac{P_1 + P_2}{2}\right)$
		9.5	209
9	22	10.5	840
10	80	11.5	1208
11	105	12.5	1225
12	98	13.5	1053
13	78	14.5	232
14	16		$\Sigma = 4767$
	$\Sigma A = 399$		

$$P_{ave} = \frac{\Sigma \left[A \times \left(\frac{P_1 + P_2}{2} \right) \right]}{\Sigma A} = \frac{4767}{399} = 11.95 \text{ cm}$$

• **Merits and demerits of this method :**

- (i) This method is most suitable for hilly and rugged basin.
- (ii) If the analyst has the knowledge of orographic effect, he can use it in constructing the isohyetal map for better results.
- (iii) This method permits the use of all available data.
- (iv) Overall, this method is superior to the other two methods.

1.11 DESIGN OF RAINGAUGE NETWORK :

Rainfall records constitute the most important and fundamental data required for hydrological investigations.

They are required for,

- analysing storms
- Fixing design flood
- Forecasting floods in a river
- Reservoir regulation, etc.

For all such studies and investigations, a well distributed network of rain gauge stations within the catchment is essential.

The rain-gauge density or network density is defined as the ratio of total area of the catchment to the total number of raingauges in the catchment. To obtain reliable results, the various rain gauges should be evenly and uniformly distributed within a given catchment. More-over, the total number of rain gauges installed within a given catchment area should neither be too many as to be costly nor should be too less as to give unreliable results.

The World Meteorological Organisation (WMO) has laid down the following norms for the minimum network density.

Table 1.5 Minimum raingauge density (as per WMO)

Region	Description	Network density	
		Minimum	tolerable
I	Flat regions of temperate, mediterranean and tropical zones	1 gauge for 600 to 900 km ²	1 gauge for 900 to 3000 km ²
II	Mountainous areas of temperate, mediterranean and tropical zones	1 gauge for 100 to 250 km ²	1 gauge for 250 to 1000 km ²
III	Arid and polar zones	1 gauge for 1500 to 10,000 km ²	-

• IS code Recommendations :

IS : 4987 - 1968 recommends the following raingauge densities :

- (i) In plains, 1 station/520 km²
- (ii) In regions of average elevation of 1000 m, 1 station/260 to 390 km²
- (iii) In hilly areas, 1 station/130 km².

It is recommended that 10% of the gauges are of recording type.

• Optimum number of Raingauges :

Statistics has been used in determining the optimum number of raingauge stations required to be installed in a given catchment. The basis behind such statistical considerations is that a certain number of rain gauges stations are required to give average rainfall with a certain percentage of error. If the allowable percentage error is more, lesser number of gauges would be required.

Based on this statistical principal principle the optimum number of raingauges (N) can be obtained by the following equation :

$$N = \left(\frac{C_v}{E} \right)^2 \quad \dots \dots \dots (1.4)$$

where,

N = Optimum number of raingauges

C_v = Coefficient of variation of rainfall

E = Allowable percentage error in estimate of mean rainfall.

C_v can be computed as follows :

- (i) Calculate mean average annual rainfall

$$\bar{P} = \frac{\Sigma P}{n}$$

where,

ΣP = total rainfall

= P₁ + P₂ + P₃ + ... P_n

n = number of raingauges existing

- (ii) Calculate $\Sigma (P - \bar{P})^2$
- (iii) Calculate sample standard deviation

$$\sigma = \sqrt{\frac{\Sigma (P - \bar{P})^2}{(n - 1)}}$$

- (iv) Calculate the coefficient of variation

$$C_v = \frac{100 \times \sigma}{\bar{P}}$$

1.12 INTENSITY OF RAINFALL, MEAN ANNUAL RAINFALL :

1. Intensity of rainfall :

The amount of rainfall in a unit duration is called **intensity of rainfall**. It is usually expressed in cm/hour, or mm/hour. It is the rate at which rainfall occurs.

If there is 18 cm rainfall in 3 hours duration, the intensity of rainfall is $\frac{18}{3} = 6$ cm/hour.

The greater the intensity of rainfall the shorter is the duration of rainfall.

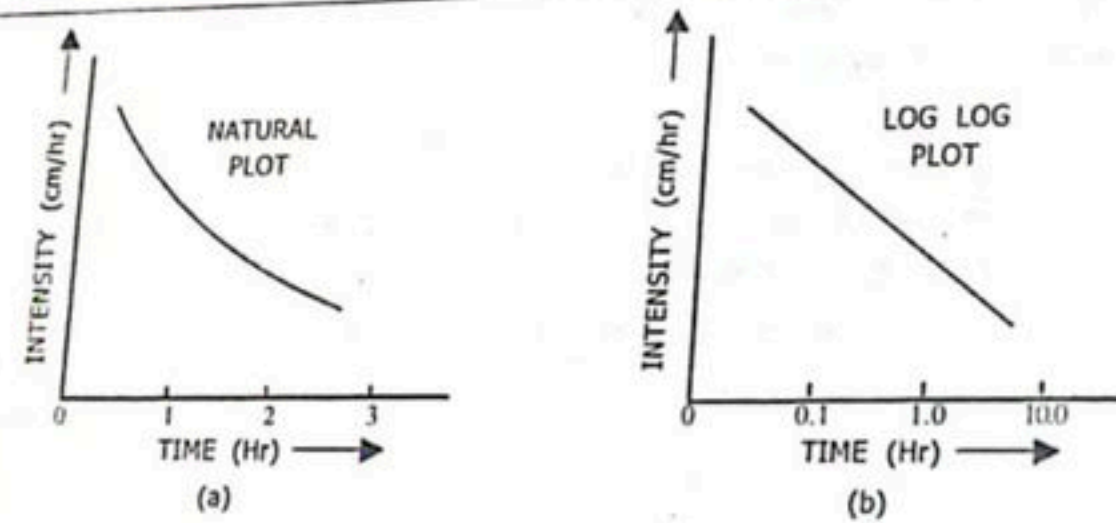


Fig. 1.15 Intensity duration curve

2. Mean Annual Rainfall :

Daily rainfall :

The rainfall collected at any raingauge station in a duration of 24 hours is called **daily rainfall**.

Mean annual rainfall :

The daily rainfall collected from a raingauge station is totalled to obtain the yearly rainfall of that year. The mean annual rainfall is equal to the average of the total yearly rainfalls of several consecutive years.

The mean annual rainfall is also known as the **average annual rainfall (AAR)**.

In India precipitation cycle repeats roughly after 35 years.

Hydrological Parameters

3. Index of wetness :

Whenever we talk of the rainfall at any given place, we generally refer to the average annual rainfall of that place. Thus, when we speak that Cherrapunji gets 1270 cm of yearly rain, it means that this figure has been averaged over a long period of about 35 years. This is known as average rainfall. But, in any given particular year, the rain may not fall equal to this amount. It may be less than this average value or may exceed this average value.

The index of wetness is given by,

$$\text{Index of wetness} = \frac{\text{Actual rainfall in a given year at a given place}}{\text{average annual rainfall of that place}} \times 100 \%$$

Index of wetness, thus, gives us an idea of the wetness of the year, and hence indicates the deficiency of rain. 60% wetness index means a rain deficiency of 40%.

- rain deficiency
- 30 to 45% Large deficiency
 - 45 to 60 % serious deficiency
 - more than 60% disastrous deficiency

Rainy day : When the total amount of rainfall collected by a raingauge is 2.5 mm or more in a period of 24 hours, it is called a rainy day.

1.13 ESTIMATING MISSING RAINFALL DATA :

(Dec. 2015)

Sometimes, it may not be possible to measure the rainfall at a particular raingauge station due to absence of the observer or instrument failure or any other reason. In that case, the prediction of the missing data can be made with the help of available data of nearby measuring stations, using the following methods :

1. Arithmetic mean method
2. Normal ratio method
3. Inverse distance method
4. Station-year method

1. Arithmetic Mean Method :

According to this method, the missing rainfall P_x of the station X is computed by simple arithmetic average of the rainfall at the nearby stations (index stations).

$$P_x = \frac{P_1 + P_2 + P_3 + \dots + P_n}{n} \quad \dots \dots \dots (1.5)$$

where, n = number of index stations

$P_1, P_2, P_3 \dots P_n$ = rainfall at the index stations 1, 2, 3, n

This method is used only under the following conditions :

- (i) data of atleast three index stations should be available.
- (ii) The average annual rainfall of the missing station is within 10% of the average annual rainfall of the index stations.
- (iii) The index stations should be evenly distributed around the missing station and should be as close as possible.

2. Normal Ratio Method :

This method is used, when the average annual rainfall at any of the index stations differs from that at the station in question by more than 10%.

In this method, the rainfall (P_i) of the index stations are weighted by the ratio of their average annual rainfall. Missing rainfall P_x is given by

$$P_x = \frac{1}{n} \left[P_1 \frac{N_x}{N_1} + P_2 \frac{N_x}{N_2} + P_3 \frac{N_x}{N_3} + \dots + P_n \frac{N_x}{N_n} \right] \dots \dots \dots (1.6)$$

$$= \frac{N_x}{n} \left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \dots + \frac{P_n}{N_n} \right]$$

where,

- $N_1, N_2, N_3 \dots N_n$ = average annual rainfall of index stations
- N_x = average annual rainfall of missing station
- n = Number of index stations

3. Inverse distance method :

In this method a set of rectangular co-ordinate axes are passed through the missing station so that its co-ordinates are (0, 0). The co-ordinates (x_i, y_i) of each index station surrounding the missing station are found. The weightage (W_i) of each index station is represented by the inverse of the square of its distance from the missing station, given by :

$$W_i = \frac{1}{D_i^2} = \frac{1}{x_i^2 + y_i^2} \dots \dots \dots (1.7)$$

The missing rainfall data of station X is then computed from the relation :

$$P_x = \frac{\sum_{i=1}^n P_i W_i}{\sum_{i=1}^n W_i} \dots \dots \dots (1.8)$$

This method gives good results and is therefore acceptable for scientific analysis. However, the limitation of the method is that it estimates missing rainfall between the highest and the lowest values of the index stations.

4. Station year method :

In this method, the records of two or more raingauge stations are combined into one long record provided station's record are independent and areas of stations are climatologically the same. The missing record at a certain station in a particular year may be found out by the ratio of the average or by graphical comparison. For example, in a certain year total rainfall of sation A is 78 cm and for the neighbouring station B, no record is available. But, if average annual rainfall at A and B in previous year record are 72 and 82 cm respectively, the missing year's rainfall at B, i.e. P_B may be obtained by simple proportion as :

$$\frac{78}{72} = \frac{P_B}{82}$$

$$\therefore P_B = 88.833 \text{ cm}$$

This result must be checked by another station C for better results. If the new P_B is slightly different, average of the two will provide a bit accurate P_B .

1.14 PRESENTATION OF RAINFALL DATA :

There are three methods of presentation of rainfall data collected through measurements at a given station.

1. Hyetograph method
2. Mass curve of rainfall method
3. Point rainfall method

1. Hyetograph Method :

A hyetograph is a bar graph showing the intensity of rainfall with respect to time. The hyetograph can be prepared either from the mass curve of rainfall, or directly from the data obtained from automatic raingauges.

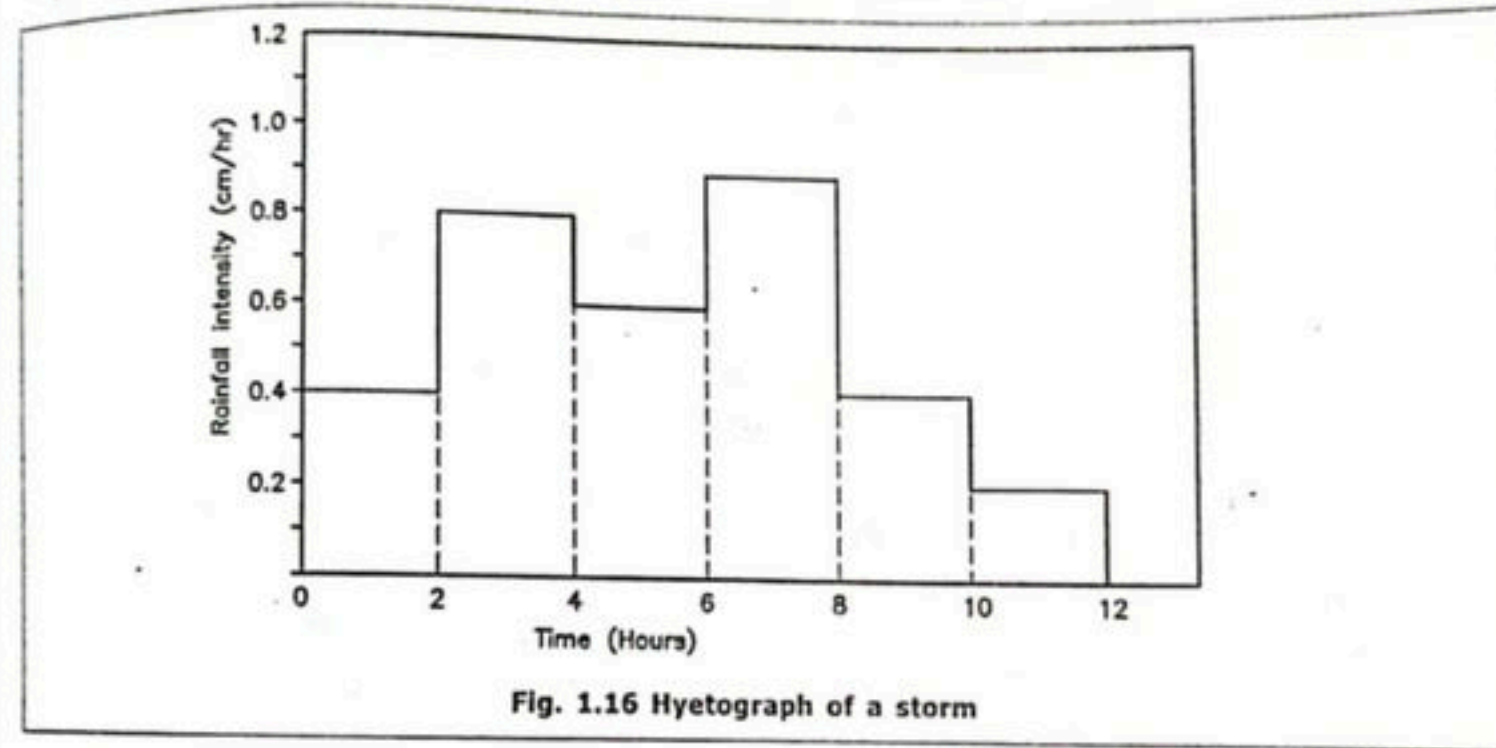


Fig. 1.16 Hyetograph of a storm

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 rainfall received in that period.

The time interval used depends on the purpose, in urban drainage problems small durations are used while in flood-flow computations in large catchments the intervals are of about 6 hour.

2. Mass curve of rainfall :

(Nov. 2016)

A mass curve of rainfall is a plot of cumulative depth of rainfall against time. The steepness of the curve indicates the intensity of rainfall. A horizontal portion of the curve indicates that there was no rainfall during that period.

Thus, in Fig. 1.17, A to B is the first period of rainfall. There was no rainfall from B to C and therefore the curve is horizontal. C to D shows the second period of rainfall, while E to F shows the third period of rainfall. The mass curve of rainfall is a rising curve.

The intensity of rainfall during any period is given by

$$i = \frac{\Delta p}{\Delta t}$$

From the mass curve of rainfall, the total depth of rainfall and intensity of rainfall at any instant of time can be found. A mass curve of rainfall is very useful in extracting the information of the duration and magnitude of a storm. The mass curve of a design storm can be obtained by maximising the mass curves of the severe storms in the basin.

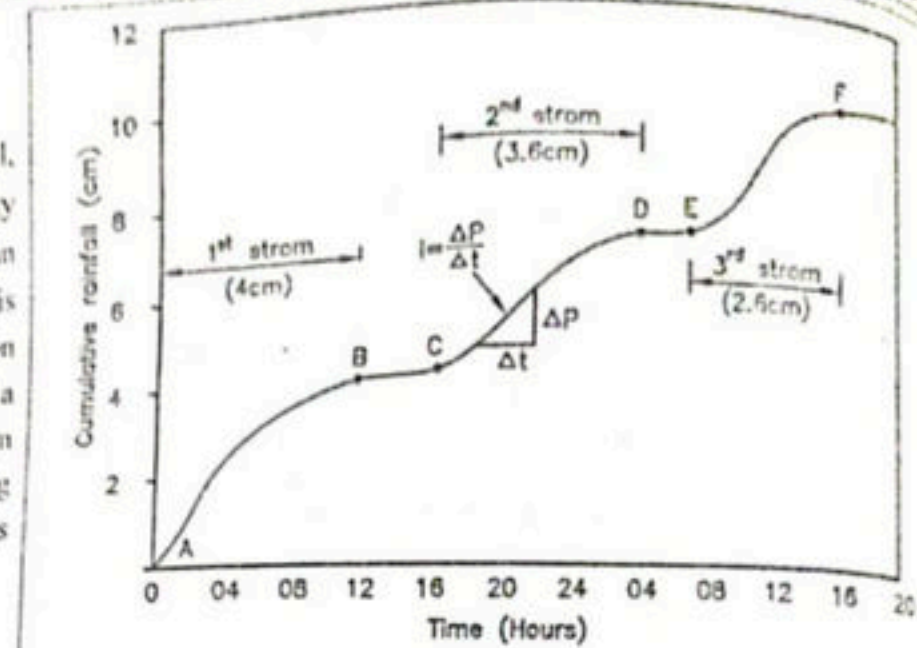


Fig. 1.17 Mass curve of rainfall

3. Point rainfall method :

The rainfall data of a station is known point rainfall or station rainfall. This data can be presented as daily, weekly, monthly, seasonal or annual values. The point rainfall data is presented graphically as plots of magnitude V , chronological time in the form of a bar diagram.

Point rainfall data are used collectively to estimate the areal variability of rainfall. It is also used in deriving the intensity - duration - frequency curves.

However, the point rainfall data bar graph does not reflect any clear trends or patterns in the rainfall due to abrupt variations in individual years. In order to suppress these and to bring out the general trend of the rainfall, moving average curve is used.

• Moving average curve :

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 rainfall averages of the three (or five) consecutive years, are computed, and then plotted. For a three year moving mean, the various values of rainfall to be plotted against time (mean of three years) shall be calculated as :

$$P_1' = \frac{P_1 + P_2 + P_3}{3}$$

$$P_2' = \frac{P_2 + P_3 + P_4}{3}$$

$$P_3' = \frac{P_3 + P_4 + P_5}{3}$$

The values P_1', P_2', P_3', \dots are then plotted against the corresponding time. The plot so obtained will be known as 3-year moving average curve of annual rainfall, and will indicate the general trends regarding increase or decrease of annual rainfall with time.

1.15 ANALYSIS OF RAINFALL DATA :

Rainfall during a year (or a number of years) consists of several storms. The characteristics of a rainstorm are :

- (i) Intensity (cm/hr)
- (ii) Duration (min, hr or days)
- (iii) Frequency (once in 5 years, or once in 10, 20, 40, 60 or 100 years)
- (iv) Areal extent (area over which it is distributed)

(i) Intensity of rainfall :

The intensity of rainfall (i) is defined as the rate at which rainfall occurs, and is expressed as cm/hr or mm/h. The non-recording type raingauge however, measures/records only rainfall depth (P) in a day, or in a duration (t) of the rainfall. In that case, the intensity of rainfall is given by

$$i = \frac{P}{t}$$

where,

i = intensity of rainfall

p = rainfall amount

t = duration of rainfall

However, in the case of recording type raingauge, the duration and depth of rainfall both are recorded simultaneously in the form of mass curve on the raingauge recording chart.

The intensity of rainfall is classified into the following three types :

Rainfall	intensity in mm/h
1. Light intensity rainfall	1 - 2.5 mm/h
2. Moderate intensity rainfall	2.5 - 7.5 mm/h
3. Heavy intensity	> 7.5 mm/h

(ii) Frequency of point rainfall :

The frequency of a rainfall is the number of time that a given magnitude of rainfall may occur in a given period.

The study of the probability of occurrence of a particular extreme rainfall (such as 24-h maximum rainfall) is of extreme importance to the determination of design flood. This is determined with the help of frequency analysis. For such an analysis the point rainfall data at a place are arranged in a chronological order to constitute a time series. For example, let us assume that we have maximum 24-h rainfall data for 30 years, recorded at a station. The highest value of 24-h rainfall depth in the series occurs once in 30-years, or its frequency of occurrence is 30 years. Again, the second highest 24-h rainfall depth occurs twice in the record of 30 years, and hence, it has a frequency of 15 years, and so on for other data.

The **recurrence interval** is the interval in years for occurrence of the event of the same magnitude and is the reciprocal of the frequency.

Thus, the recurrence interval, also known as return period, is given by

$$T = \frac{1}{P_{10}}$$

where,

T = recurrence interval

P₁₀ = Probability of occurrence

If there are rainfall records for 30 to 40 years, the various storms during the period of record may be arranged in the descending order of their magnitude (of maximum depth or intensity). When arranged like this in the descending order, if there are a total number of n items and the order number or rank of any particular storm (maximum depth or intensity) is m, then the recurrence interval (T) of the storm magnitude is given by one of the following equations :

(a) California Formula :

$$T = \frac{n}{m} \text{ or } P_{10} = \frac{m}{n} \quad \dots \dots \dots (1.10)$$

(b) Hazen's Formula :

$$T = \frac{2n}{2m-1} \text{ or } P_{10} = \frac{2m-1}{2n} \quad \dots \dots \dots (1.11)$$

(c) Weibull Formula :

$$T = \frac{n+1}{m} \text{ or } P_{10} = \frac{m}{n+1} \quad \dots \dots \dots (1.12)$$

where,

m = order number of any particular storm

n = total number of items (years of record or rank)

Frequency of storm is given by

$$f = \frac{1}{T} \times 100\%$$

Out of these, Weibull formula is most widely used.

Isopluvial : Lines connecting points of equal depths of rainfall of a particular duration with a particular return period.

We shall discuss the following :

1. Intensity - duration analysis
2. Intensity - duration - frequency relationship
3. Depth - area relationship
4. Depth - area - duration relationship

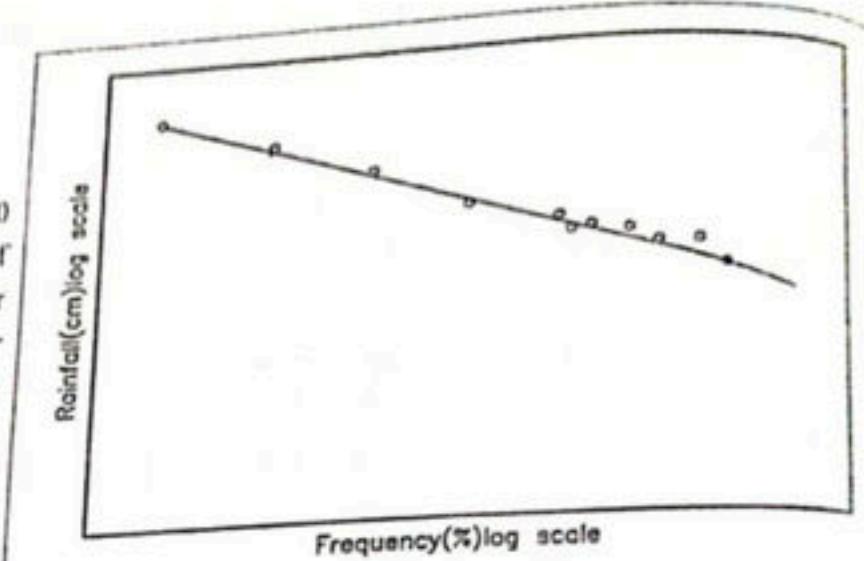


Fig. 1.18 Rainfall frequency curve

1.15.1 Intensity - duration curve :

It has been observed in practice that the greater is the intensity of rainfall, the shorter is the duration of the rainfall. In other words, very intense storms occur for a short duration and as the duration of a storm increases, its intensity decreases.

The intensity duration curve can be obtained by plotting the rainfall intensity (cm/hr) against duration of storm Fig. 1.19 (a). The rainfall intensity is usually expressed in cm/hr and the duration in minutes (or hours). The curve is usually drawn on a natural graph paper. Sometimes, it is drawn on a log-log paper. Fig. 1.19 (b) For plotting the intensity-duration curve, the observed maximum rainfall intensities at a place for storms of different durations are obtained from the available rainfall record. While selecting the storms of different maximum intensity, the following points should be kept in mind.

1. The severest storm of longer duration need not include the severest storm of shorter duration. For example, the storm in which the maximum rainfall intensity for 10 minute duration occurs may not be the same storm in which the maximum rainfall intensity for 5 minute duration occurs.

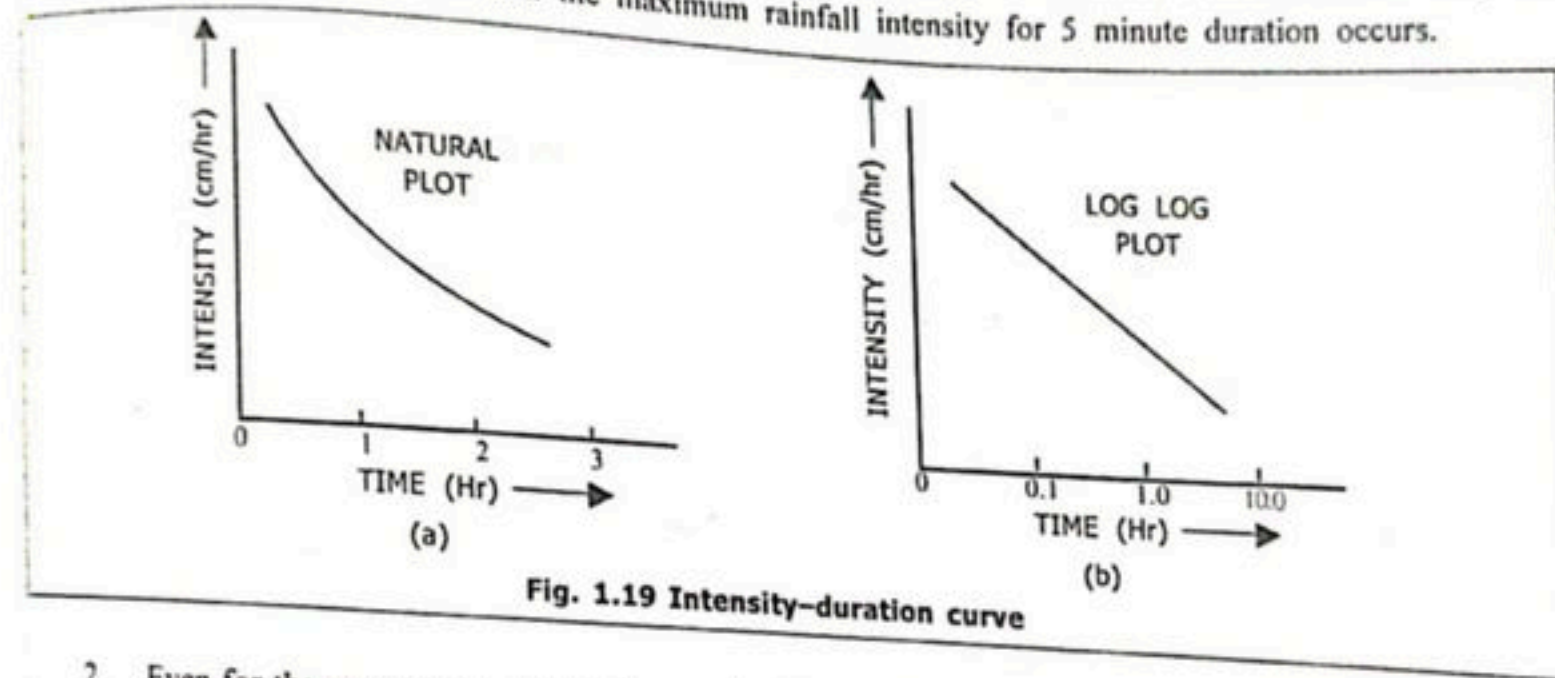


Fig. 1.19 Intensity-duration curve

2. Even for the same storm, the maximum rainfall intensity for 5 minute duration and that for 10 minute duration may not be successive. For example, the maximum rainfall intensity for 5 minute duration may be from 8.00 AM to 8.05 AM, whereas that for 10 minute duration may be from 8.20 to 8.30 AM.

As the rainfall intensity (i) varies inversely with the duration (t), the relation between the two can be expressed by Talbot's Formula :

$$i = \frac{a}{t + b} \quad \dots \dots \dots (1.13)$$

where,

a and b are constants.

The Talbot formula is applicable for storms of duration 5 to 120 minutes.

For storms of duration longer than 120 minutes (2 hours), Sherman formula is commonly used. According to this formula

$$i = \frac{a}{(t + b)^n} \quad \dots \dots \dots (1.14)$$

where, n is a constant.

The curve represented by eq. (1.14) will be hyperbolic as shown in Fig. 1.19 (a).

Paulhus suggests that if rainfall is plotted against duration in a log-log scale, the world's greatest recorded rainfalls lie on or just under a straight line whose equation is

$$R = 16.6 D^{0.475} \quad \dots \dots \dots (1.15)$$

where,

R = rainfall (inches)

D = duration (hours)

The world's highest recorded intensities are of the order of

40 mm in a minute

200 mm in 20 minutes

26 m in a year

1.15.2 Intensity-duration-frequency curves (IDF curves) :

Rainfall of a place can be completely defined if the intensities, duration and frequencies of the various storms occurring at that place are known. Whenever, an intense rain occurs, its magnitude and duration is generally known from the meteorological readings. Thus, at a given station, the magnitudes of the isolated rains of various durations, such as 5 minutes, 10 minutes, 15 minutes, 30 minutes, 60 minutes, 120 minutes etc., are generally known. This available data can be used to determine the frequencies of the various rains, using the equation,

$$T = \frac{n}{m} \dots \text{California formula}$$

$$\therefore f = \frac{1}{T}$$

where, f = frequency

The frequency data for storms of various durations, so obtained, can be represented by intensity-duration-frequency curves. An intensity duration frequency curve is a plot of average rainfall intensity (cm/hr) and the duration in hours.

The intensity-duration curves for storms of different recurrence intervals are different. A storm of any given duration will have higher intensity if its recurrence interval is large or the frequency is low. In other words, for a given duration, the storms of higher intensity are rarer than the storm of smaller intensity.

Fig. 1.20 shows the intensity-duration-frequency curves for three different recurrence intervals. The storms of different recurrence intervals such as 5 years, 10 years and 20 years are determined. The intensity-duration curve for a storm of a particular recurrence interval (T) is then drawn.

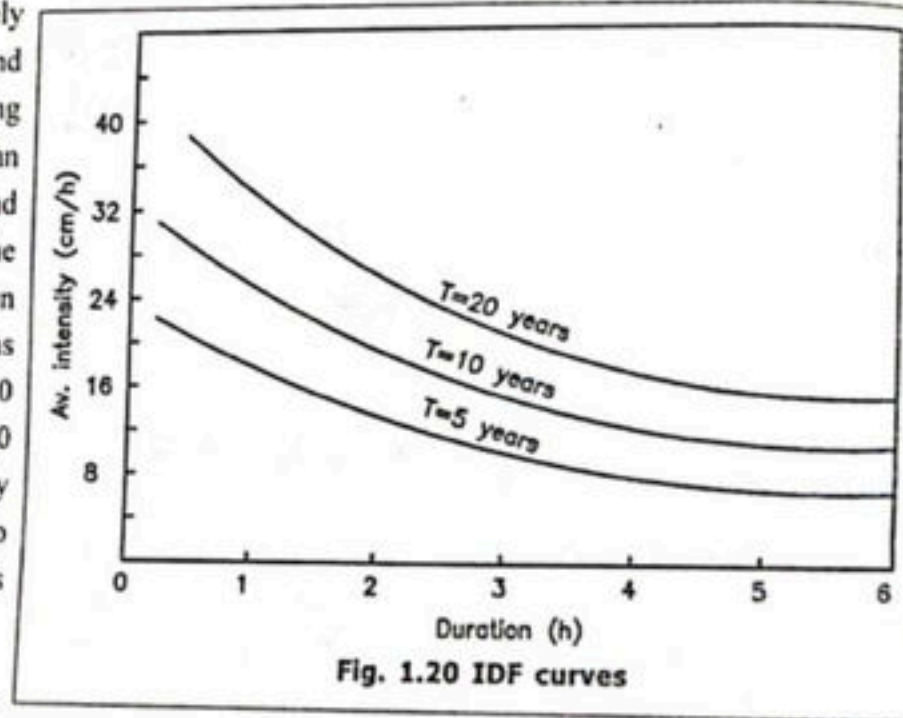


Fig. 1.20 IDF curves

The relationship between the rainfall intensity (i), duration (t) and the recurrence interval (T) can be expressed

$$i = \frac{k T^x}{(t + b)^n} \dots \dots \dots (1.16)$$

where,
 k, x, b, and n = constants of the catchment
 T = recurrence interval

1.15.3 Depth - duration frequency Curves (DDF curves) :

The depth-duration-frequency curves are similar to the intensity-duration curves with one basic difference that the ordinate represents the total depth of the rainfall instead of the intensity of rainfall. Fig. 1.21.

Storms of different recurrence intervals are found from the record by the probability analysis. For the storms of recurrence intervals of say, 5, 10, 50, 100 years, etc. Separate curves are drawn between the total depth of rainfall (cm) and duration (hr).

As the total depth of rainfall increases with the duration of the rainfall, the curves are rising curves. Moreover, the total depth of rainfall for a particular duration increases with an increase in recurrence interval.

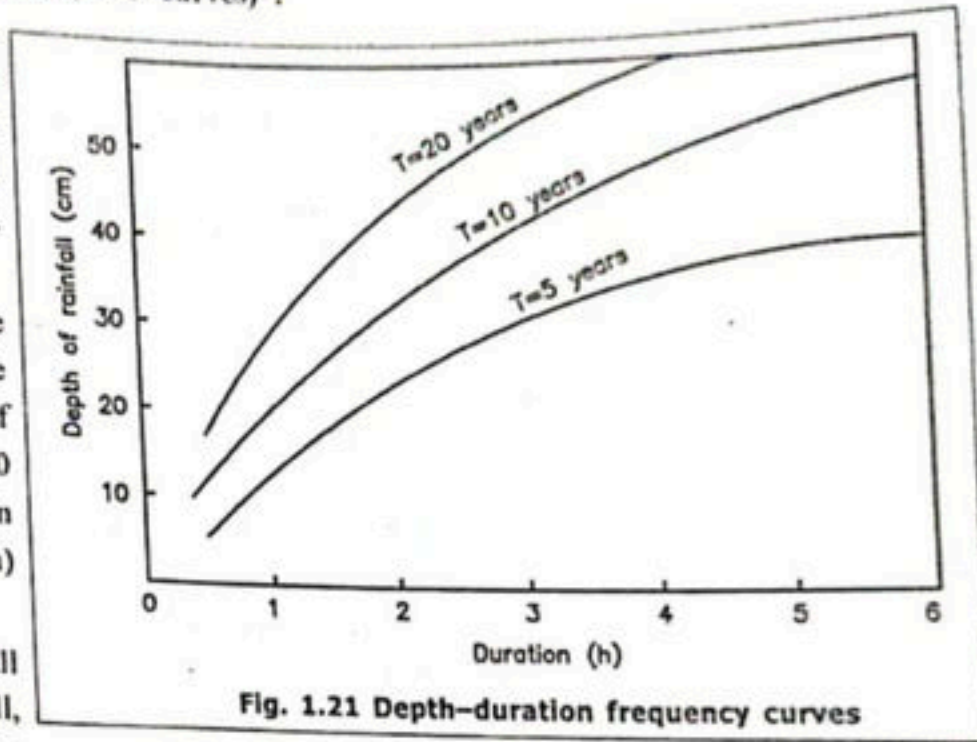


Fig. 1.21 Depth-duration frequency curves

1.15.4 Depth-area curves :

A storm over a particular catchment does not produce uniform rainfall depth over the entire catchment. Each storm usually has its centre called the eye where the rainfall is maximum. As the distance of a point from the eye increases, the rainfall decreases. Thus, the average depth of rainfall decreases as the area of the catchment increases (Fig. 1.22). The average depth of rainfall decreases exponentially with an increase in area. The relationship is usually expressed as :

$$\bar{P} = P_n \cdot e^{-kA^n} \dots \dots \dots (1.17)$$

where, \bar{P} = average depth in cm, over the area
 A = Area (km²)
 P_n = highest amount of rainfall observed at the storm centre
 k, n = constants of the catchment

Because it is very unlikely that the storm centre will be located at the raingauge station, it is not possible to determine the exact value of P₀ from the rainfall record. It is the usual practice to take P₀ as the average depth of precipitation over an area of 25 km² near the storm centre.

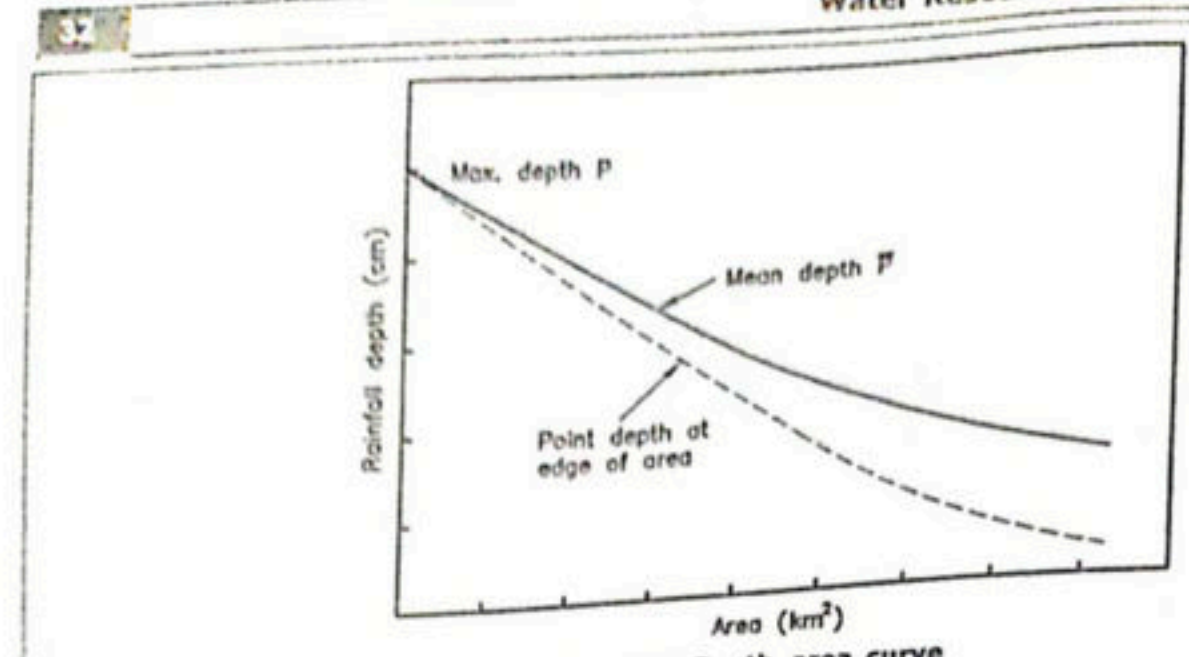


Fig. 1.22 Depth-area curve

1.15.5 Depth-area-duration curves (DAD Curves) :

The depth-area relationships for storms of different durations are different. The depth-area duration curves for storms of different durations can be obtained from the rainfall record. These curves are drawn on semi-log paper. The average precipitation depth (\bar{P}) is plotted on natural scale as ordinate and the area is plotted on the log scale as abscissa. These curves are abbreviated as DAD curves. Fig. 1.23 shows DAD curves.

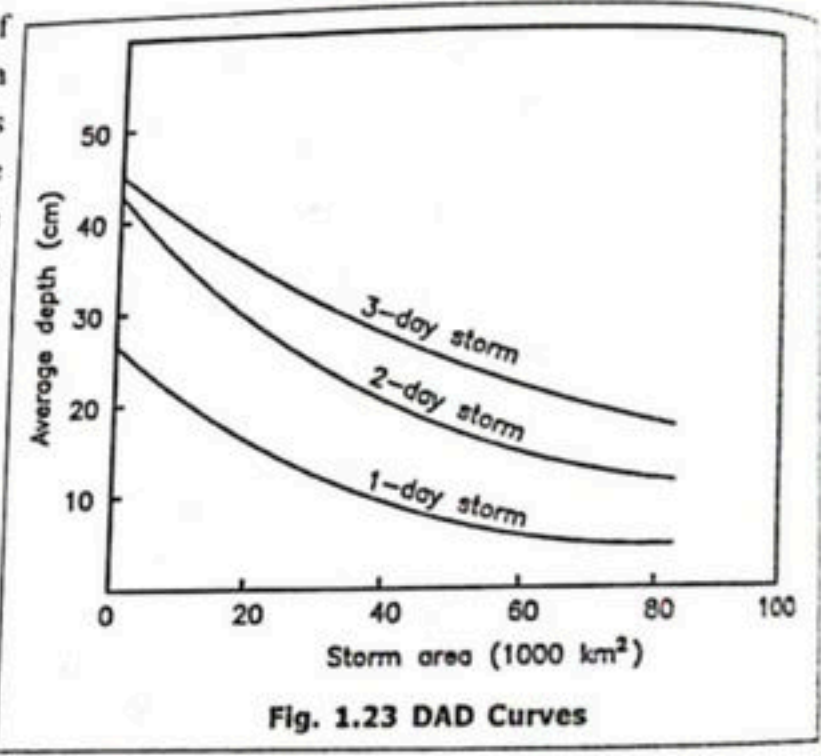


Fig. 1.23 DAD Curves

The following points may be noted for DAD curves :

- (i) The maximum average depth of precipitation for a storm of given duration decreases as the area increases.
- (ii) The maximum average depth increases with the duration of the storm.

DAD curves are extremely useful for the development of design storms required for computing the design flood for the design of spillways and other hydraulic structures.

1.15.6 Double-Mass Curve :

(Nov. 2016, April 2017)

Double mass curve is a technique used for checking the consistency of a rainfall record of a particular raingauge station. If the conditions at a particular raingauge station change significantly during the period of record, the rainfall data of that station is inconsistent.

Some of the common causes of the changes in conditions are as follows :

1. Shifting of the raingauge station from one place to the other.
2. Replacement of the old instrument with a new one.

Hydrological Parameters

3. Change of the observer or change in the method of observation.
4. Changes in the ecosystem near the station, such as forest fire, land slide, new construction, etc.
5. Raingauge may be faulty from a certain period.
6. Change in the vicinity of the station due to growth of trees, building, fencing, cutting of trees, etc.

A double mass curve is a graph plotted between the accumulated annual rainfall at a given station X (test station) versus accumulated annual values of the average of group of base stations, for various consecutive time periods as shown in Fig. 1.24. A break in the slope of the resulting plot indicates a change in the precipitation regime of station X. The precipitation values at the station X, beyond the period of break are corrected by the following relation :

$$P_{rc} = P_x \cdot \frac{C'}{C} \quad \dots \dots \dots (1.18)$$

where,

P_{rc} = corrected precipitation at the test station X, at any time period t

P_x = recorded precipitation at the test station X, at time period t.

As shown in Fig. 1.24, the change in the regime is indicated in 1953 corresponding to point B. Hence

data beyond point B are to be corrected in the ratio $\left(\frac{C'}{C}\right)$.

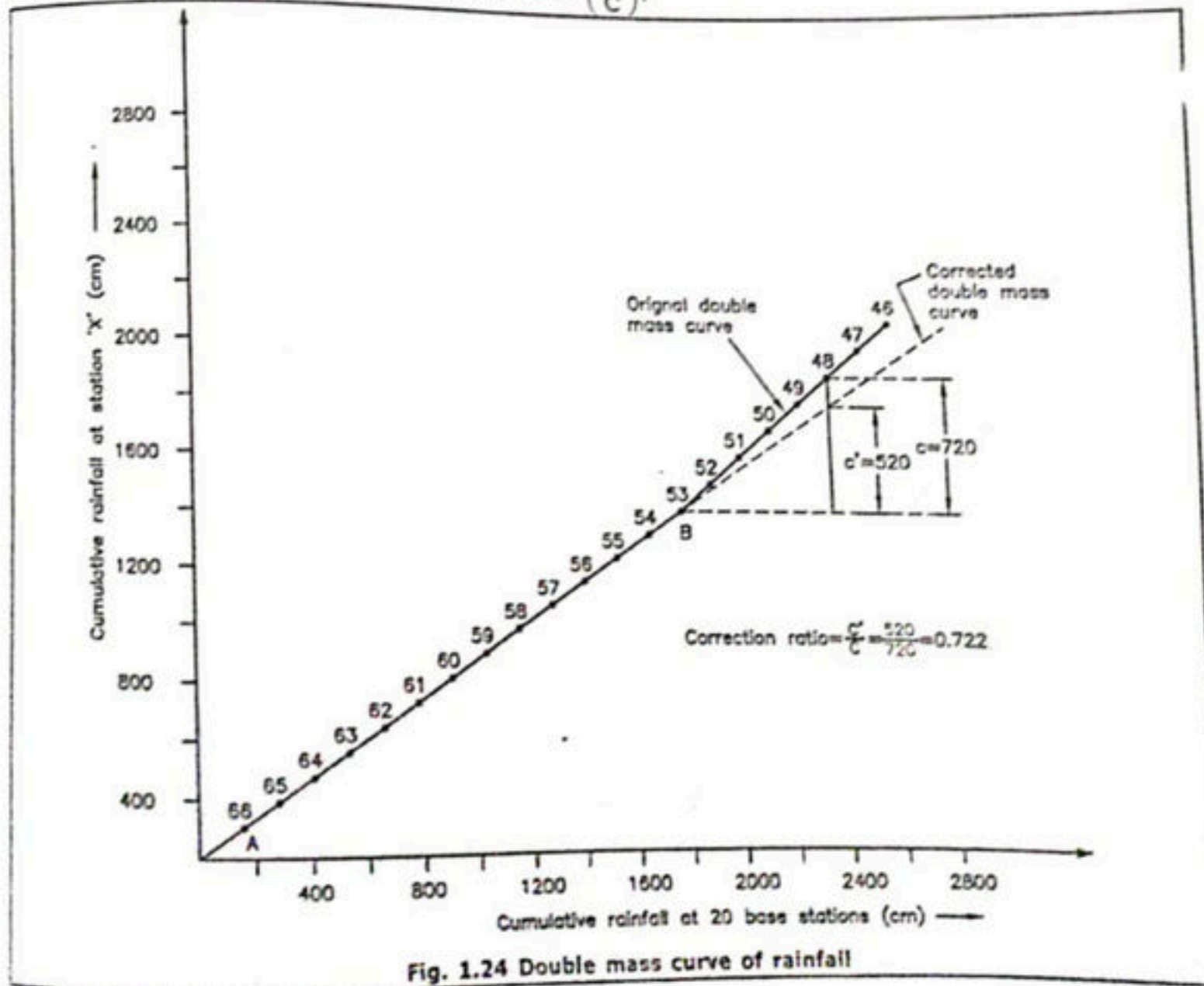


Fig. 1.24 Double mass curve of rainfall

1.15.7 Probable Maximum Precipitation (PMP) :

The probable maximum precipitation (PMP) may be defined as the maximum depth of precipitation for a given duration that may possibly occur on a given catchment at any time of the year. It is the critical Depth-area-duration (DAD) relation for a given basin, which would result from a storm due to the most critical meteorological conditions that are possible of occurrence.

The PMP is usually estimated by maximising the effect of various meteorological factors such as humidity, temperature and wind.

There are two approaches for estimating PMP :

1. Meteorological approach
2. Statistical approach

1. Meteorological approach :

In this approach, PMP is derived from the depth-area-duration (DAD) analysis of precipitation that have occurred in the basin. These DAD curves are adjusted for maximum moisture changes which are possible. The DAD curves of PMP are then obtained by enveloping curves of the adjusted values for all storms.

As discussed earlier, world's greatest observed point rainfall lie on or just under a straight line whose equation is

$$R = 16.6 D^{0.475}$$

where,

R = rainfall (inches)

D = Duration (hours)

2. Statistical approach :

PMP of a basin can be estimated by the statistical approach if data is available for a long period.

PMP is estimated from the relation :

$$PMP = \bar{p} + k \cdot \sigma$$

where,

\bar{p} = mean of annual maximum rainfall

σ = standard deviation

k = frequency factor (usually taken as 15).

Use of PMP :

PMP is required for the estimation of probable maximum flood (PMF) for the design of spillways of large dams. To keep the failure probability of dam as low as possible, the designer selects PMP for its design.

EXAMPLES

Example-1 : In a certain river basin, There are four raingauge stations, with their normal annual precipitation amounting to 800, 520, 450 and 390 mm, respectively. Determine the optimum number of raingauges in the catchment if it is desired to limit the error in the mean value of rainfall in the catchment to 10 %.

(Dec. 2015, Similar May 2018)

Solution :

Step - 1 : Average annual rainfall (\bar{P})

$$\begin{aligned}\bar{P} &= \frac{P_1 + P_2 + P_3 + \dots + P_n}{n} \\ &= \frac{800 + 520 + 450 + 390}{4} \\ &= \frac{2160}{4} \\ &= 540 \text{ mm}\end{aligned}$$

Step - 2 : Calculate

$$\begin{aligned}\Sigma (P - \bar{P})^2 &= (800 - 540)^2 + (520 - 540)^2 + (450 - 540)^2 + (390 - 540)^2 \\ &= 98,600\end{aligned}$$

Step - 3 : Standard deviation (σ)

$$\begin{aligned}\sigma &= \sqrt{\frac{\Sigma (P - \bar{P})^2}{(n - 1)}} \\ &= \sqrt{\frac{98,600}{(4 - 1)}} \\ &= 181.29 \text{ mm}\end{aligned}$$

Step - 4 : Coefficient of variation (C_v)

$$\begin{aligned}C_v &= \frac{100 \times \sigma}{\bar{P}} \\ &= \frac{100 \times 181.29}{540} \\ &= 33.57\end{aligned}$$

Step - 5 : Optimum number of raingauges (N)

$$\begin{aligned}N &= \left[\frac{C_v}{E} \right]^2 & E = 10 \% \\ &= \left[\frac{33.57}{10} \right]^2 \\ &= 11.26 \\ &\approx 12 \text{ Nos}\end{aligned}$$

∴ Additional number of raingauges required

$$= 12 - 4$$

$$= 8 \text{ nos.}$$

Example-2 : A water shed has four raingauge stations, A, B, C and D. During a storm, raingauge station A was inoperative, while stations B, C and D, surrounding station A, recorded rainfall of 36 mm, 42 mm and 50 mm respectively. Estimate the missing storm precipitation of station A, using arithmetic mean method.

Solution :

$$P_A = \frac{P_B + P_C + P_D}{3}$$

$$= \frac{36 + 42 + 50}{3}$$

$$= 42.67 \text{ mm}$$

Example-3 : A raingauge 'D' was inoperative during a specific storm. The rainfall recorded at three surrounding stations A, B and C during that storm were 52, 85 and 70 mm respectively. If the average annual rainfall of stations A, B, C and D are 650, 900, 820 and 700 mm respectively, estimate the storm rainfall of station D. (May 2015, April 2017)

Solution :

$$P_A = 52 \text{ mm}, \quad P_B = 85 \text{ mm}, \quad P_C = 70 \text{ mm}, \quad P_D = \dots\dots\dots$$

$$N_A = 650 \text{ mm}, \quad N_B = 900 \text{ mm}, \quad N_C = 820 \text{ mm}, \quad N_D = 700 \text{ mm}$$

$$n = 3$$

$$\therefore P_D = \frac{N_D}{n} \left[\frac{P_A}{N_A} + \frac{P_B}{N_B} + \frac{P_C}{N_C} \right] \dots\dots\dots \text{Normal ratio method}$$

$$= \frac{700}{3} \times \left[\frac{52}{650} + \frac{85}{900} + \frac{70}{820} \right]$$

$$= \frac{700}{3} \times (0.2598)$$

$$= 60.62 \text{ mm}$$

Example-4 : In a certain year the total rainfall of station A is 75 cm and for the neighbouring station B there is no record. But if the average annual rainfall (a.a.r) at A and B are 70 and 80 cm, respectively, estimate the missing year's rainfall at B.

Solution :

$$P_A = 75 \text{ cm}$$

$$P_B = \text{---}$$

$$N_A = 70 \text{ cm}$$

$$N_B = 80 \text{ cm}$$

Using station year method,

$$\frac{P_B}{N_B} = \frac{P_A}{N_A}$$

$$\therefore \frac{P_B}{80} = \frac{75}{70}$$

$$\therefore P_B = 85.71 \text{ cm}$$

Example-5 : Find average rainfall from following data by (i) Arithmetical average method (ii) Thiessen polygon method

Raingauge station	1	2	3	4	5
Precipitation in cm	13	18	29	25	15
Area of polygon in cm ²	160	172	165	205	185

Solution :

(i) Arithmetical average method

$$P_{ave} = \frac{P_1 + P_2 + P_3 + \dots + P_n}{n}$$

$$= \frac{13 + 18 + 29 + 25 + 15}{5}$$

$$= \frac{100}{5}$$

$$= 20 \text{ cm}$$

(ii) Thiessen polygon method

$$P_{ave} = \frac{P_1A_1 + P_2A_2 + P_3A_3 + \dots + P_nA_n}{A_1 + A_2 + A_3 + \dots + A_n}$$

$$= \frac{(13 \times 160) + (18 \times 172) + (29 \times 165) + (25 \times 205) + (15 \times 185)}{(160 + 172 + 165 + 205 + 185)}$$

$$= \frac{17,861}{887}$$

$$= 20.13 \text{ cm}$$

Example-6 : The rainfall values at gauging stations and corresponding areas of Thiessen's polygons for a drainage basin are as follows : (May 2015)

Station	A	B	C	D	E	F	G
Area of Thiessen's polygon (km ²)	160	135	92	110	68	70	35
Rainfall (cm)	10.0	13.5	9.1	12.6	11.2	14.0	10.8

Compute the average rainfall over the basin.

Solution :

(Similar April 2017)

Thiessen's polygon method :

Station	Area of Thiessen's polygon, A (km ²)	Rainfall P (cm)	A × P
A	160	10.0	1600.0
B	135	13.5	1822.5
C	92	9.1	837.2
D	110	12.6	1386.0
E	68	11.2	761.6
F	70	14.0	980.0
G	35	10.8	378.0
	ΣA = 670		ΣA × P = 7765.3

$$P_{ave} = \frac{\sum P \times A}{\sum A}$$

$$= \frac{7765.3}{670}$$

$$= 11.59 \text{ cm}$$

Example-7 : The isohyets for annual rainfall over a catchment basin were drawn. The areas of strips between the isohyets are indicated below in the table. Find the average depth of annual precipitation over the basin.

Isohyets cm	Area in sq.km	Isohyets cm	Area in sq.km
75 - 85	580	105 - 115	1,000
85 - 95	2,960	115 - 135	610
95 - 105	2,850	135 - 155	160

Solution :

$$P_{ave} = \frac{\sum \left[A \cdot \left(\frac{P_1 + P_2}{2} \right) \right]}{\sum A}$$

Isohyets cm	Area between isohyets (A) km ²	average rainfall $\left(\frac{P_1 + P_2}{2} \right)$	product $A \times \left(\frac{P_1 + P_2}{2} \right)$
75 - 85	580	80	46,400
85 - 95	2,960	90	266,400
95 - 105	2,850	100	285,000
105 - 115	1,000	110	110,000
115 - 135	610	125	76,250
135 - 155	160	145	23,200
	$\Sigma A = 8160 \text{ km}^2$		$\Sigma = 807,250$

$$P_{ave} = \frac{807,250}{8160}$$

$$= 98.92 \text{ cm}$$

Example-8 : For a drainage basin of 600 km², isohyets drawn for a storm gave the following data :

Isohyets (cm)	40	35	30	25	20	15	10
catchment area enclosed (km ²)	-	35	90	150	310	430	600

Estimate the average depth of precipitation over the basin.

Solution : Total area of the catchment = 600 km²

Isohyets (cm)	catchment area enclosed (km ²)	area between two isohyets A (km ²)	average rainfall $\left(\frac{P_1 + P_2}{2}\right)$	product $A \times \left(\frac{P_1 + P_2}{2}\right)$
40	-	-	-	-
35	35	35	37.5	1312.5
30	90	55	32.5	1787.5
25	150	60	27.5	1650.0
20	310	160	22.5	3600.0
15	430	120	17.5	2100.0
10	600	170	12.5	2125.0
		$\Sigma A = 600 \text{ km}^2$		$\Sigma = 12,575$

$$P_{ave} = \frac{\Sigma \left[A \times \left(\frac{P_1 + P_2}{2} \right) \right]}{\Sigma A}$$

$$= \frac{12,575}{600}$$

$$= 20.96 \text{ cm}$$

Example-9 : Calculate average rainfall for the catchment area shown in figure by :

- (1) Arithmetic mean method
- (2) Thiessen's polygon method
- (3) draw isohyets at 1 cm interval in the catchment.

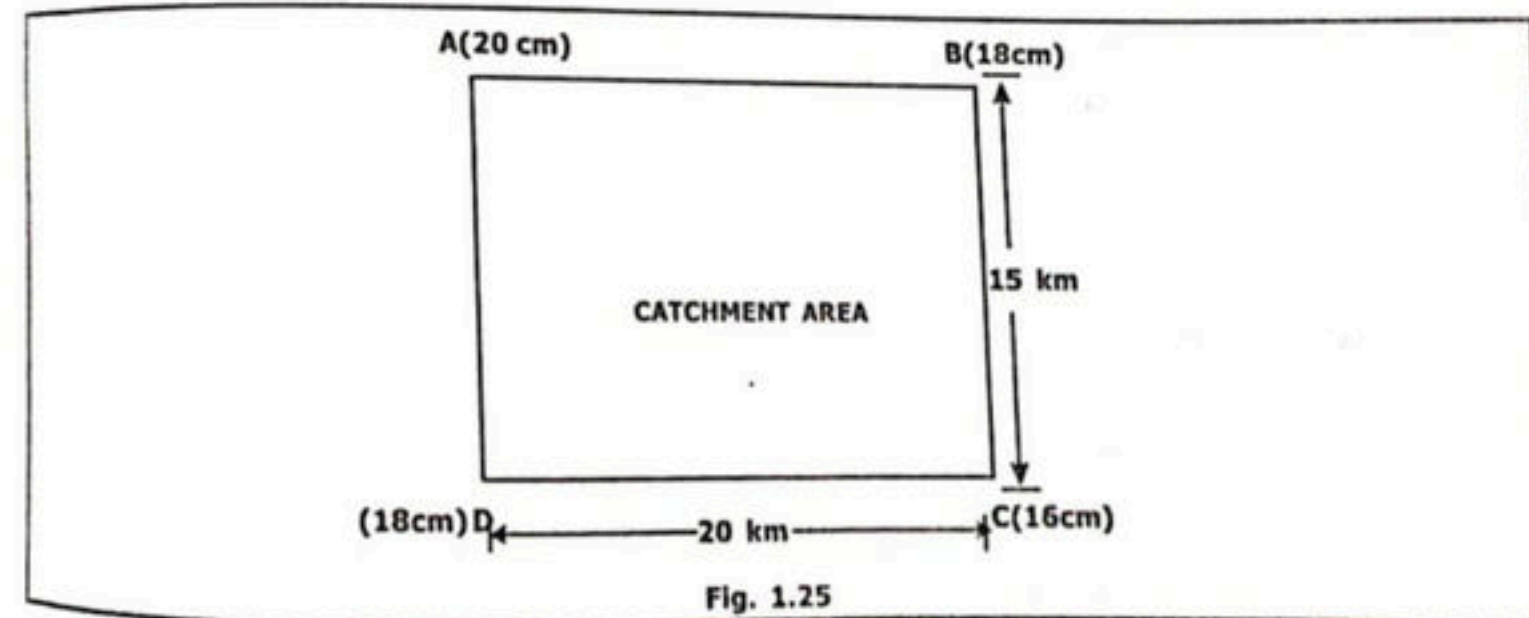


Fig. 1.25

Solution :

- (1) Arithmetic mean method :

$$P_{ave} = \frac{P_A + P_B + P_C + P_D}{4}$$

$$\begin{aligned}
 &= \frac{20 + 18 + 16 + 18}{4} \\
 &= \frac{72}{4} \\
 &= 18 \text{ cm}
 \end{aligned}$$

(2) Thiessen's Polygon method :

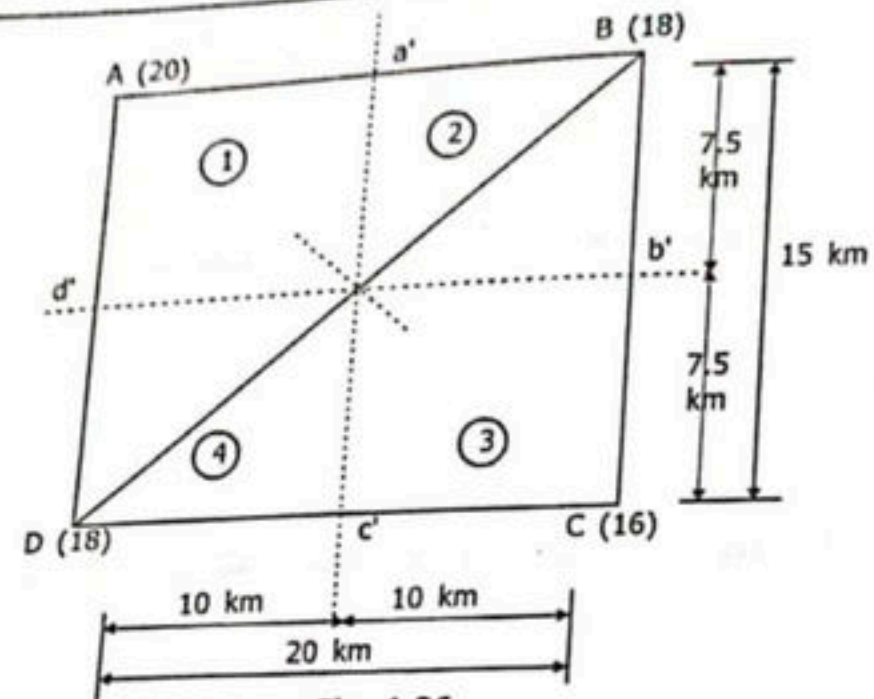


Fig. 1.26

ABCD = catchment area

Polygon (1) = a'e'd'A

Polygon (2) = a'e'b'B

Polygon (3) = b'e'c'C

Polygon (4) = d'e'c'D

Area of each polygon

$$= 10 \times 7.5$$

$$= 75 \text{ sq.km}$$

$$\therefore A_1 = A_2 = A_3 = A_4 = 75 \text{ sq.km}$$

$$\therefore P_{ave} = \frac{P_1 A_1 + P_2 A_2 + P_3 A_3 + P_4 A_4}{A_1 + A_2 + A_3 + A_4}$$

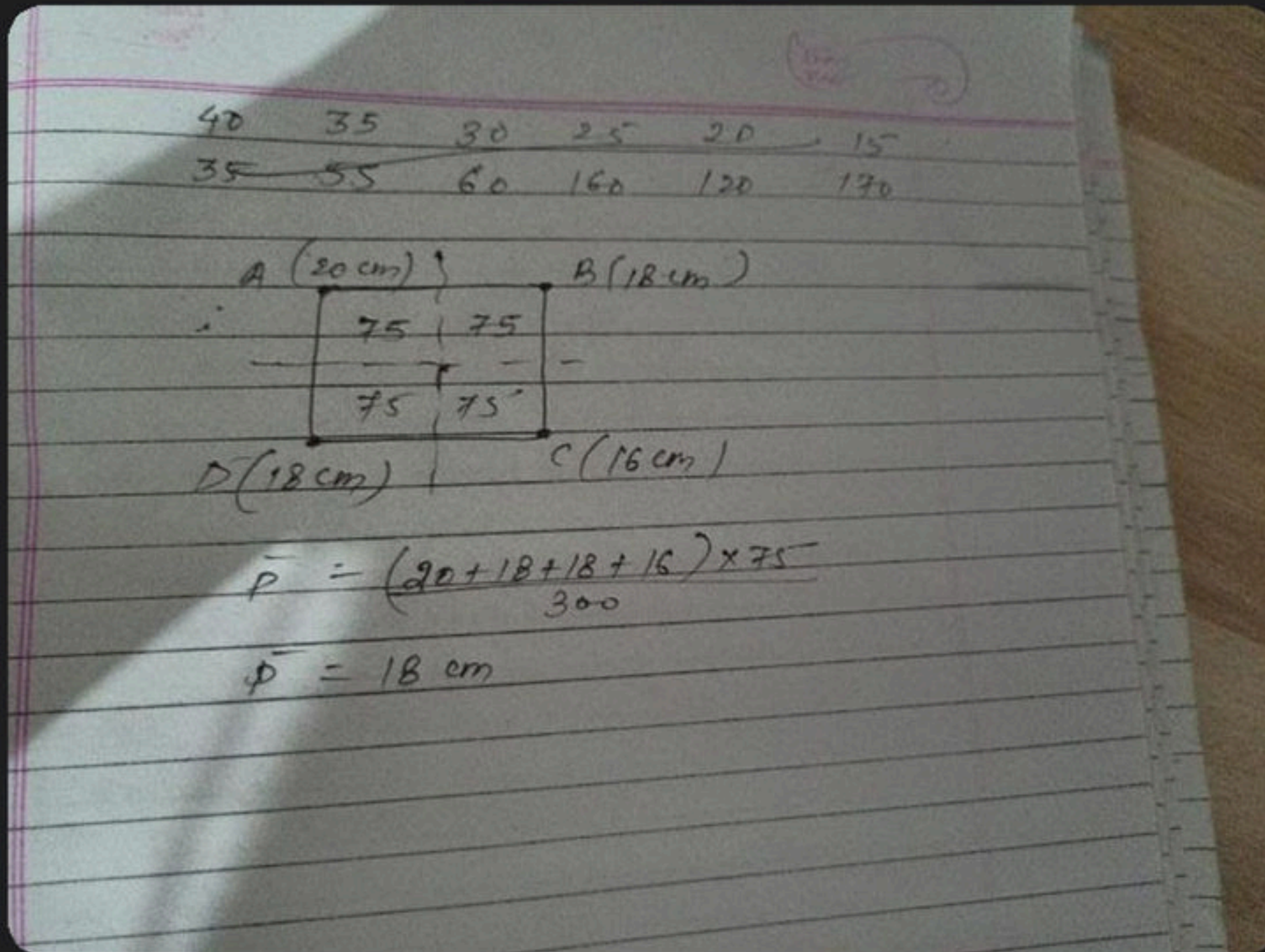
$$= \frac{(20 \times 75) + (18 \times 75) + (16 \times 75) + (18 \times 75)}{(75 + 75 + 75 + 75)}$$

$$= \frac{5400}{300}$$

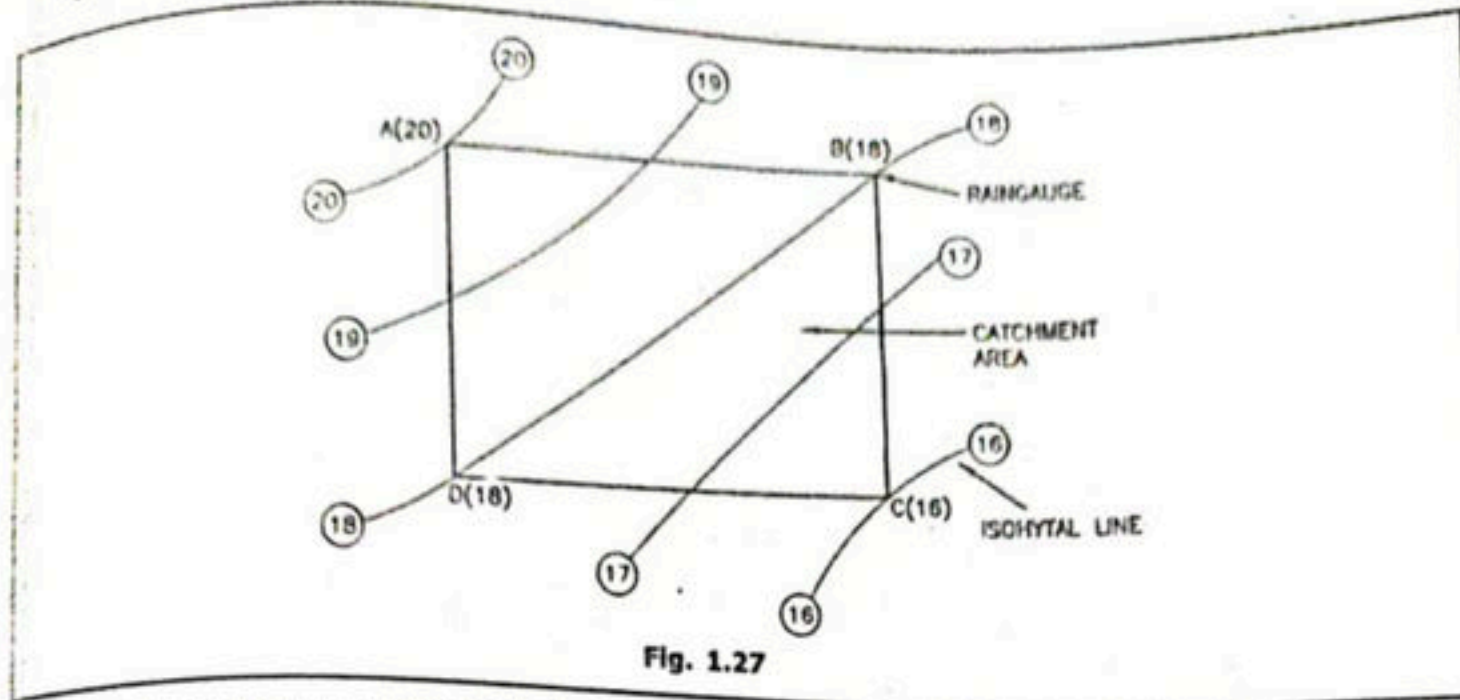
$$= 18 \text{ cm}$$

▲ 1 • Asked by Vivek

Please help me with this doubt



(3) To draw isohyets in the catchment area



Example-10 : The annual precipitation in cm of a certain raingauge station from 1966 to 1978 is given as follows :

38.5, 31, 58.2, 85, 29.8, 25.8, 74.2, 50.5, 33.8, 21.2, 33, 68.4.

Estimate the value of precipitation having recurrence interval of 5 years using probability or statistical method.

Solution :

Arranging the precipitation values in the decreasing order.

Rank	1	2	3	4	5	6	7	8	9	10	11	12
Preci. (cm)	85	74.2	68.4	58.2	50.5	38.5	33.8	33	31	29.8	25.8	21.2

n = total number of years of record
= 12

T = recurrence interval
= 5 years

using California formula

$$T = \frac{n}{m} \quad \therefore m = \frac{n}{T} = \frac{12}{5} = 2.4$$

m = order number of particular storm (Rank)

Since m = rank of storm = 2.4

Choose the second severest storm, i.e. 74.2 cm

\therefore Precipitation having a recurrence interval of 5 years will be 74.2 cm.

Example-11 : The ordinates of a rainfall mass curve for a storm commenced at 6.30 hours, recorded by self recording raingauge at 15 minutes interval are as follows :

0, 12.4, 22.1, 35.1, 52.7, 63.7, 81.9, 109.2, 123.5, 132.6, 143.3, 146 and 146 (mm)

Computations for cumulative rainfalls at X and at average of 20 base stations are arranged in table as under, starting from data of most recent year.

Year	Rainfall at stn. X (cm)	Cumulative rainfall at stn. X (cm)	Rainfall at 20 base stn. (cm)	cumulative rainfall at 20 base st. (cm)
(1)	(2)	(3)	(4)	(5)
1966	88	88	111	111
1965	80	168	97	208
1964	112	280	104	312
1963	116	396	131	443
1962	81	477	91	534
1961	106	583	92	626
1960	95	678	142	768
1959	112	790	123	891
1958	88	878	142	1033
1957	68	946	92	1125
1956	111	1057	131	1256
1955	86	1143	93	1349
1954	97	1240	99	1448
1953	112	1352	112	1560
1952	190	1542	142	1702
1951	126	1668	111	1813
1950	108	1776	107	1920
1949	127	1903	108	2028
1948	172	2075	119	2147
1947	153	2228	138	2285
1946	120	2348	90	2375

A graph is plotted between the values of col. (3) and (5) as shown in Fig. 1.29. Corresponding years from col. (1) are also marked on the corresponding plotted points, as shown in this figure.

A perusal of this figure shows that the inconsistency has occurred from 1953. Hence the present data, since 1953 to 1966 will be treated as correct, and the previous data prior to the year 1953 will be corrected. In other words the rainfall values of years 1952 to 1946 will be corrected.

Take suitable value BC and determine C' and C values from the graph.

$$\therefore \text{Correction ratio} = \frac{C'}{C} = \frac{520}{720} = 0.722$$

Hydrological Parameters

The rainfall values of station 'X' between the years 1952 to 1946 are corrected by multiplying the original values by 0.722 as below.

year (1)	Rainfall at station 'X' P_x (cm) (2)	Corrected rainfall values at stn. X = $P_x \times 0.722$ P_{xc} (cm) (3)
1952	190	137
1951	126	91
1950	108	78
1949	127	92
1948	172	124
1947	153	110
1946	120	87

The final adjusted values of annual rainfall at station 'X' are serialled in table below and mean annual precipitation is determined equal to 98.62 cm.

year	corrected/adjusted annual rainfall at stn. X (cm)	year	corrected/adjusted annual rainfall at stn. X (cm)
1946	87	1957	68
1947	110	1958	88
1948	124	1959	112
1949	92	1960	95
1950	78	1961	106
1951	91	1962	81
1952	137	1963	116
1953	112	1964	112
1954	97	1965	80
1955	86	1966	88
1956	111		

$$\Sigma = 2071$$

$$\therefore P_{av} = \frac{2071}{21} = \boxed{98.62 \text{ cm}}$$

Example-13 : Thiessen polygons constructed for a network of 10 raingauges in river basin yielded thiessen weights of 0.10, 0.16, 0.12, 0.11, 0.09, 0.08, 0.07, 0.11, 0.06 and 0.10. If the rainfalls recorded at these gauges during a cyclonic storm are 132, 114, 162, 138, 207, 156, 135, 158, 168 and 150 mm respectively determine the average depth of rainfall by thiessen mean and arithmetic mean methods. Also determine the volume of surface runoff at the basin outlet if 35 % of the rainfall is lost as infiltration. Take the area of the basin as 5800 km² and express your answer in million cubic metres. (May 2013)

Solution :

(a) Thiessen mean method :

$$\Sigma A = 5800 \text{ km}^2$$

Raingauge station	rainfall P (mm)	weighted area A (km ²)	P × A
1	132	5800 × 0.10 = 580	76560
2	114	5800 × 0.16 = 928	105792
3	162	5800 × 0.12 = 696	112752
4	138	5800 × 0.11 = 638	88044
5	207	5800 × 0.09 = 522	108054
6	156	5800 × 0.08 = 464	72384
7	135	5800 × 0.07 = 406	54810
8	158	5800 × 0.11 = 638	100804
9	168	5800 × 0.06 = 348	58464
10	150	5800 × 0.10 = 580	87000

$$\Sigma P \times A = 864664$$

$$\begin{aligned} \therefore P_{ave} &= \frac{\Sigma P \times A}{\Sigma A} \\ &= \frac{864664}{5800} \\ &= \boxed{149.08 \text{ mm}} \end{aligned}$$

(b) Arithmetic mean method :

$$\begin{aligned} P_{ave} &= \frac{P_1 + P_2 + P_3 + \dots + P_n}{n} \\ &= \frac{(132 + 114 + 162 + 138 + 207 + 156 + 135 + 158 + 168 + 150)}{10} \\ &= \frac{1520}{10} \\ &= \boxed{152 \text{ mm}} \end{aligned}$$

(c) Volume of surface runoff :

$$\text{Area of basin} = 5800 \times 10^6 \text{ m}^2$$

$$\text{Average rainfall} = 152 \text{ mm} = 0.152 \text{ m}$$

$$\therefore \text{Total volume of water} = 5800 \times 10^6 \times 0.152$$

$$= 881.6 \times 10^6 \text{ m}^3$$

$$= 881.6 \text{ million cubic metres.}$$

$$\text{Infiltration loss} = 0.35 \times 881.6$$

$$= 308.56 \text{ million cubic metres}$$

Hydrological Parameters

$$\begin{aligned} \text{Volume of surface runoff} &= 881.6 - 308.56 \\ &= 573.04 \text{ million cubic metres} \end{aligned}$$

Example-14 : A lake has an area of 15 km².

Observation of hydrological variables during a certain year has shown that :

$$P = 700 \text{ mm / year}$$

$$\text{Average inflow, } Q_{in} = 1.4 \text{ m}^3/\text{s}$$

$$\text{Average outflow, } Q_{out} = 1.6 \text{ m}^3/\text{s}$$

Assume that there is no net water exchange between the lake and the ground water. Determine the evaporation during this year.

Solution :

$$\begin{aligned} P &= 700 \text{ mm/year, area of lake} = 15 \text{ km}^2 \\ &= 15 \times 10^6 \text{ m}^2 \end{aligned}$$

$$Q_{in} = \frac{1.4 \times 365 \times 24 \times 3600}{15 \times 10^6} = 2.943 \text{ m} = 2943 \text{ mm}$$

$$Q_{out} = \frac{1.6 \times 365 \times 24 \times 3600}{15 \times 10^6} = 3.364 \text{ m} = 3364 \text{ mm}$$

$I - O = \Delta S$ water balance equation

$\Sigma \text{ in flow} - \Sigma \text{ out flow} = \text{change in volume}$

$$\therefore (P + Q_{in}) - (E + Q_{out}) = \Delta S$$

Assume storage change during an year is zero.

$$\therefore \Delta S = 0$$

$$\therefore (P + Q_{in}) - (E + Q_{out}) = 0$$

$$\therefore E = P + Q_{in} - Q_{out}$$

$$\therefore E = 700 + 2943 - 3364$$

$$= \boxed{279 \text{ mm}}$$

Example-15 : The evaporation from a lake is to be calculated by the water balance method. Inflow to the lake occurs through three small rivers A, B and C. The outflow occurs through river D.

Calculate the evaporation from the lake surface during the period May-August, if the water level was at +264.30 m on May 1 and +264.37 m on August 31. The lake surface area is 100 km². The precipitation during the period was 100 mm. Average inflow and outflow are as under.

River	Catchment (km ²)	Q, average, m ³ /s
A	120	20.0
B	150	15.0
C	130	17.0
D	-	45.0

Solution :

Assume that there is no ground water exchange.

The water balance equation is :

$$(Q_{in} + P) - (Q_{out} + E) = \Delta S$$

time in days from 1st May to 31st August

$$= 31 + 30 + 31 + 31 = 123 \text{ days}$$

$$Q_{in} = \frac{(20 + 15 + 17) \times 123 \times 24 \times 3600}{100 \times 10^6}$$

$$= 5.526 \text{ m}$$

$$Q_{out} = \frac{45 \times 123 \times 24 \times 3600}{100 \times 10^6}$$

$$= 4.782 \text{ m}$$

$$P = 100 \text{ mm} = 0.10 \text{ m}$$

$$\Delta S = 264.37 - 264.30$$

$$= 0.07 \text{ m}$$

$$\therefore (Q_{in} + P) - (Q_{out} + E) = \Delta S$$

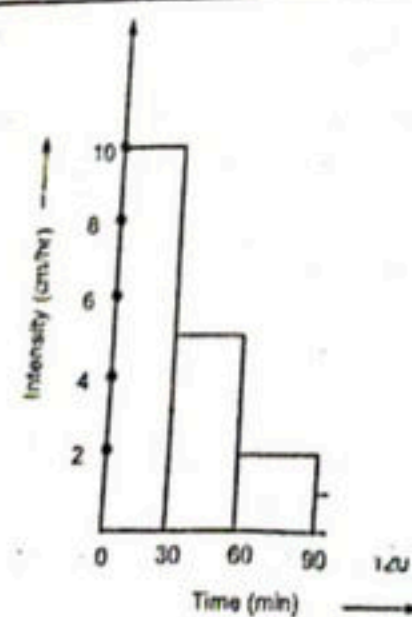
$$(5.526 + 0.10) - (4.782 + E) = 0.07$$

$$\therefore E = 5.526 + 0.10 - 4.782 - 0.07$$

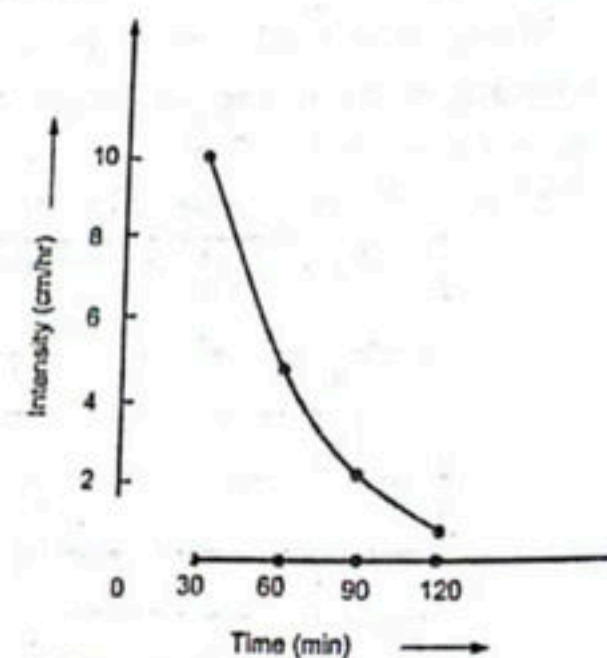
$$= 0.774 \text{ m}$$

Example-16 : Compute and draw the storm hyetograph and the intensity duration curve for the following storm (of a given frequency) on a drainage basin :

Duration (minute)	Accumulated Precipitation (cm)
0	-
30	5.0
60	7.5
90	8.5
120	9.0



(a) Rainfall hyetograph



(b) Intensity duration curve

Fig. Example-16

Solution :

The computations are done in tabular form below :

Time (min)	Accumulated Precipitation(cm)	Recipitation in Successive 30 min. interval (cm)	Rainfall intensity (cm/hr)
(1)	(2)	(3)	(4) = (3) × 60/30
0	-	-	-
30	5.0	5.0	10.0
60	7.5	2.5	5.0
90	8.5	1.0	2.0
120	9.0	0.5	1.0

The storm hietograph and Intensity duration curve are shown below :

Example-17 : In a watershed, the average annual precipitation for four sub-basins was recorded as follows : 100.84, 112.27, 84.84 & 73.406 cm, the areas of the sub-basins were : 93264.3, 71243.5, 108808.2 & 168393.8 ha. calculate the average precipitation of the total watershed using the Thiessen method. (Nov. 2014)

Solution :

Thiessen polygon method

$$P_{ave} = \frac{P_1 A_1 + P_2 A_2 + P_3 A_3 + P_4 A_4}{A_1 + A_2 + A_3 + A_4} = \frac{\sum P \times A}{\sum A}$$

$$= \frac{(100.84 \times 93264.3) + (112.27 \times 71243.6) + (84.84 \times 108808.2) + (73.406 \times 168393.8)}{(93264.3 + 71243.5 + 103808.2 + 168393.8)}$$

$$= \frac{38.995 \times 10^6}{441,709.8}$$

$$= 88.28 \text{ cm}$$

Example-18 : Calculate the average annual rainfall using thiessen polygon method for the following data : (Nov. 2016)

Raingauge station	1	2	3	4	5	6	7	8
Annual rainfall (cm)	34	35	36	37	38	39	40	41
Area (km ²)	55	50	45	33	69	49	55	39

Solution :

Thiessen polygon method

$$P_{ave} = \frac{P_1 A_1 + P_2 A_2 + \dots + P_n A_n}{A_1 + A_2 + \dots + A_n} = \frac{\sum PA}{\sum A}$$

$$= \frac{(34 \times 55) + (35 \times 50) + (36 \times 45) + (37 \times 33) + (38 \times 69) + (39 \times 49) + (40 \times 55) + (41 \times 39)}{(55 + 50 + 45 + 33 + 69 + 49 + 55 + 39)}$$

$$= \frac{14793}{395}$$

$$= 37.45 \text{ cm}$$

1.16 EVAPORATION :

Due to heat of sun the water from the surfaces of ocean, rivers, lakes and from the moist ground surfaces evaporates. The vapour are carried over the land by air in the form of clouds. This process is called **evaporation**. It is expressed in mm/day or mm/hour.

Transpiration is the process of water being lost from the leaves of the plants from their pores.

Thus, the total evaporation (E) is consists of,

$$\begin{aligned} \text{Evaporation (E)} &= \text{Surface evaporation} \\ &+ \text{water surface evaporation} \\ &+ \text{rivers, ponds surface evaporation} \\ &+ \text{ocean surface evaporation} \\ &+ \text{atmospheric evaporation} \\ &+ \text{transpiration} \end{aligned}$$

Evaporation is the process in which water is changed to vapours (the gaseous state) at the free surface, below the boiling point of water, through the transfer of heat energy. It is a continuous natural process by which a substance changes from liquid to gaseous state. The main source of evaporation is the solar radiation. For arid regions, the loss due to evaporation may be as high as 90% of the annual precipitation.

During the process of evaporation, water molecules, continuously leave the water surface. The motion of these molecules produce a pressure on the water surface, which is known as '**Vapour pressure**'. Thus the vapour pressure is due to vapour molecules present in air. If there is continuous supply of heat energy, more and more molecules accumulate, and finally a stage is reached when the air above the free surface becomes saturated with vapours and it cannot accommodate more vapours. The partial pressure exerted by the water vapours at that stage is called the "**Saturation vapour pressure (e_s)**". The saturation pressure increases with an increase in temperature. If the vapour pressure in the air above the water surface remains less than that of the water surface, evaporation continues. As soon as the vapour pressure reaches the saturation vapour pressure, evaporation stops.

Dalton's Law of Evaporation :

According to Dalton's law,

"the rate of evaporation depends upon the difference between the saturation vapour pressure and the vapour pressure in the air above".

$$E = C (e_s - e_2) \quad \dots \dots \dots (1.19)$$

where,

E = evaporation loss (mm/day)

e_s = saturation vapour pressure

e_2 = vapour pressure in the air at about 2 m above the water surface

C = coefficient, that depends upon barometric pressure, wind velocity, etc.

For evaporation to continue, the following three conditions should be satisfied :

1. There should be a constant supply of water.
2. There should be a constant supply of heat.
3. There should be a vapour deficit.

Evaporation loss continue till $e_a = e_s$. On the other hand, if $e_a > e_s$, condensation will take place. In that case, more molecules return to the water surface than those leave it.

Factors Affecting Evaporation :

(May 2015)

The rate of evaporation depends upon a number of factors, as given below :

1. Temperature of air
2. Wind velocity
3. Atmospheric pressure
4. Nature of evaporating surface
5. Area of water surface
6. Depth of water body
7. Humidity
8. Impurities in water

1. Temperature of air :

The evaporation increases with an increase in air temperature. Thus, in summer season or in hot countries, the evaporation will be more as compared to that in the winter season or in cold countries.

2. Wind velocity :

The process of evaporation also depends upon the prevailing turbulence in the air. If the velocity of air is more, the saturated film of air containing the water vapour will move easily, causing more evaporation. However, the effect of an increase in the wind velocity decreases as some limiting high velocity is reached. A further increase beyond limiting wind velocity does not increase the evaporation appreciably because all the molecules escaping from the water surface have been removed at the limiting velocity.

3. Atmospheric pressure :

A decrease in the atmospheric pressure increases the rate of evaporation because there are fewer molecules in the air above the free surface to cause interference. Consequently, evaporation is more at high altitudes provided other factors remain the same.

4. Nature of evaporating surface :

Different evaporating surfaces like soil, barren land, forest area, houses, lakes affect evaporation to the extent they have the potential.

Black cotton soil help to evaporate the soil water faster than red soil because such soils have the potential to absorb incoming radiation more effectively. Evaporation from wet soil is faster and it reduces gradually as the soil becomes drier.

The evaporation from a snow surface is less as compared to that from a water surface. Moreover, evaporation from snow takes place only when the dew point is below 0°C .

Area of water surface :

The amount of evaporation is directly proportional to the area of evaporation. If the exposed area is large, the evaporation will be more and vice-versa.

6. Depth of water body :

The depth of water influences the evaporation considerably. Deep water bodies evaporate slower than shallow water bodies in summer, while in winter season, they evaporate faster.

7. Humidity :

Evaporation is inversely proportional to humidity. If the humidity in the atmosphere is more, evaporation will be less.

8. Impurities in water :

Any dissolved salts in water reduces the saturated vapour pressure of water (e_s), which consequently reduces the rate of evaporation. The evaporation decreases by 1% for every 1% increase in the salinity of a water body. Turbidity of water may also affect the rate of evaporation by affecting the heat transfer within the depth of the water body.

(Nov. 2014, May 2015)

1.17 MEASUREMENT OF EVAPORATION :

The rate of evaporation from large water surfaces, such as rivers, ponds, reservoirs, etc. can be determined by the following methods :

1. Pan Measurement method
2. Using Empirical formulae
3. Water budget method
4. Energy budget method

1.17.1 Pan measurement method :

The most reliable method for the estimation of evaporation from large water bodies is that by measurements from evaporation pans.

In this method, a pan of certain standard dimensions is taken, and the water is filled in this pan up to a certain range of level. The depth of water evaporated from this pan of given area and in a given time is measured with the help of a micrometer; from which the rate of evaporation per unit time per unit area is calculated. The rate of evaporation so obtained is multiplied by a suitable pan coefficient, so as to obtain the evaporation rate from the given water body. This is necessary because it is found that the evaporation, from a large surface source is not the same as that from a small pan.

Different shapes of pans have been designed by different designers, and different values of pan coefficients have been suggested. The more important of these pans are described below.

- (a) U.S. Weather Bureau class A pan
- (b) Colorado Sunken pan
- (c) U.S. Geological Survey Floating pan
- (d) I.S. Standard pan

(a) U.S. Weather Bureau class A pan :

This is perhaps the most commonly used evaporation pan. The pan consists of a shallow vessel 1.2 m in diameter and 25 cm deep. The pan is made of unpainted galvanised iron sheet. Where there is corrosion problem, it is made of monel sheet. The water in the pan is filled to a depth of 20 cm. When the depth of water reduces to 18 cm, it is refilled. Water surface level is measured daily.

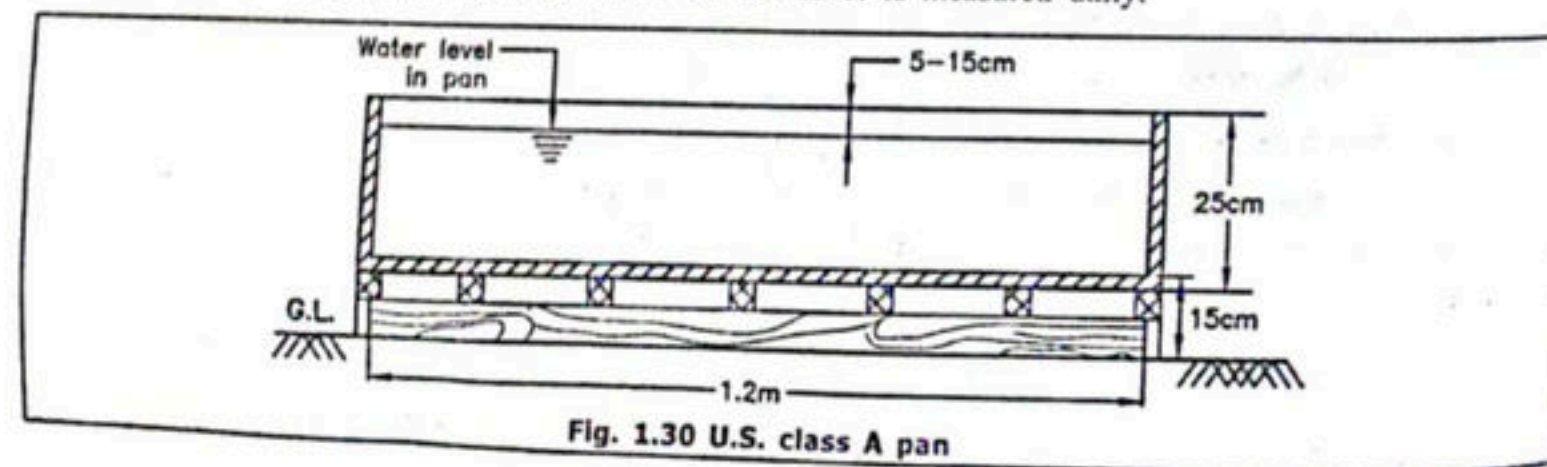


Fig. 1.30 U.S. class A pan

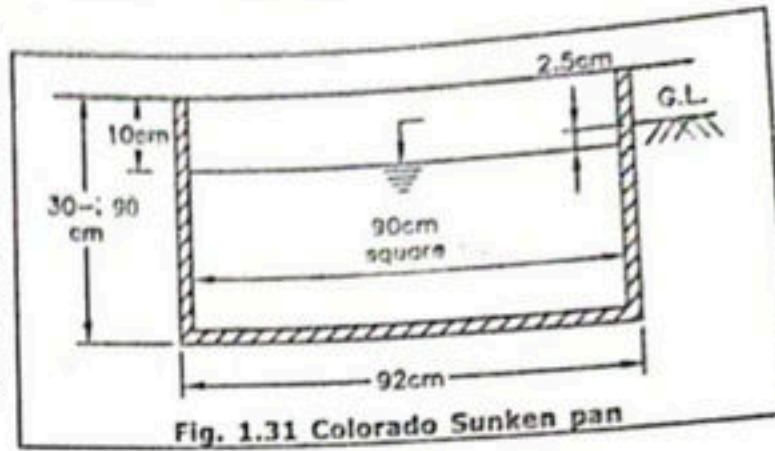
Hydrological Parameters

The pan is placed on a wooden platform such that its base is 15 cm above the ground surface to allow free circulation of air below the pan.

Evaporation is computed as the difference between observed water levels on two consecutive days. Pan coefficient is about 0.6 to 0.8, generally taken as 0.7.

(b) Colorado Sunken pan :

It is 90 cm x 90 cm square with a depth ranging from 30 to 90 cm and buried in the ground within about 10 cm of the top. The water should be within 2.5 cm of ground level. It is made of unpainted galvanised iron sheet. The main advantage of the Sunken pan over the class A evaporation pan is that its radiation and aerodynamic characteristics are closer to those of a reservoir.



Pan coefficient is 0.75 to 0.86, generally taken as 0.78.

Disadvantages :

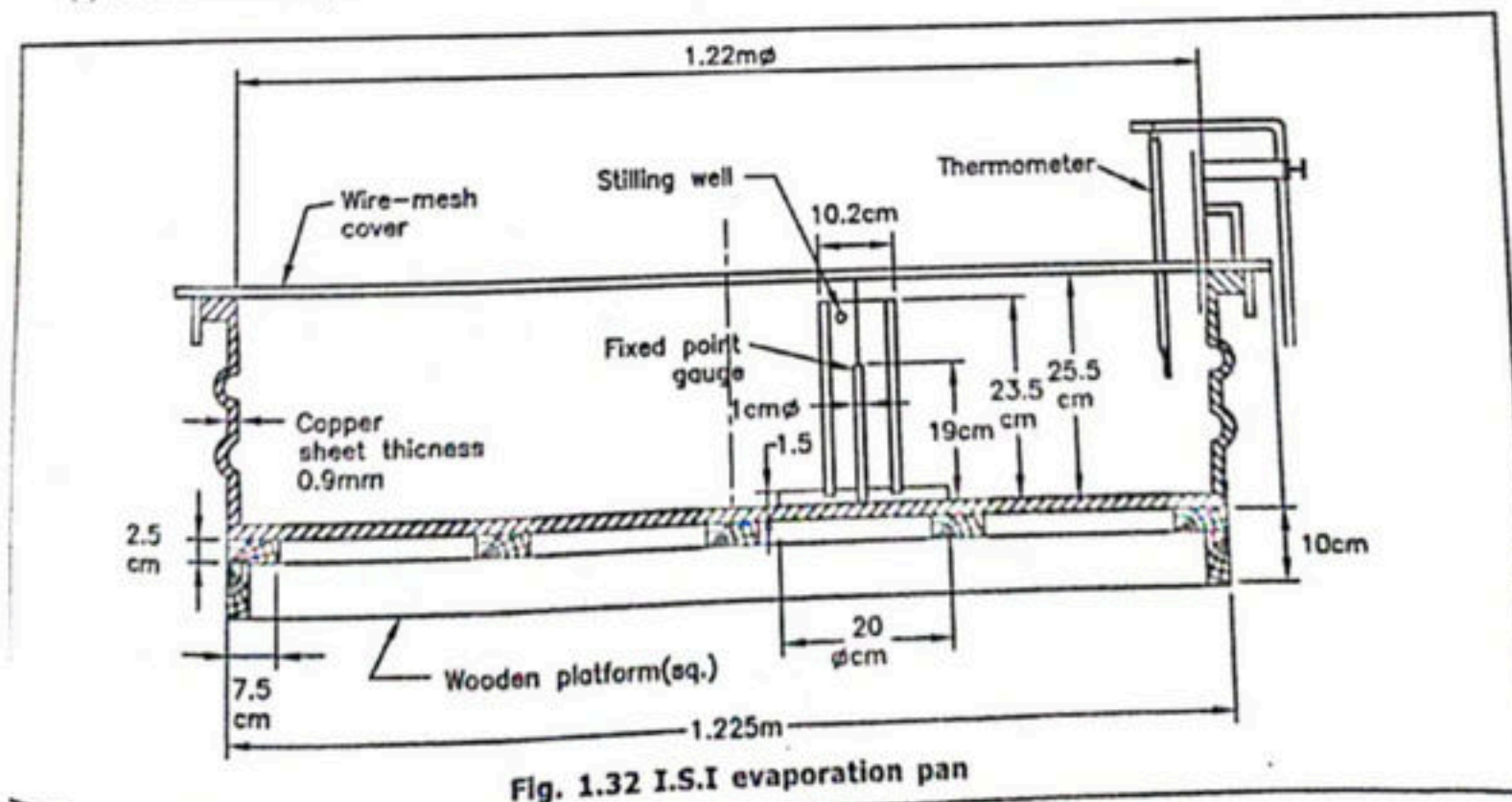
- (i) It is more expensive.
- (ii) It is more difficult to detect leaks.
- (iii) It needs more care to keep the surrounding area free from grass, dust, etc.

(c) U.S. Geological Survey Floating pan :

This is 90 cm square in plan and 45 cm deep pan floating in a large body of water supported by drum floats in the centre of a raft 14' x 16'. The water level in the pan is to be at the same level as that of the surrounding body of the water, with the sides of the pan projecting 7.5 cm above.

The pan coefficient is generally taken as 0.80.

(d) I.S. Standard pan :



IS : 5973 - 1970 gives the specifications of I.S. standard pan, which is a modified form of the U.S. class A evaporation pan. It consists of a shallow vessel made of copper sheet of 0.9 mm thickness, tinned inside and painted outside. The pan is 1.22 m in diameter and 25.5 cm in depth. It is installed on a wooden grillage platform 10 cm above the ground surface. The pan has a small stilling well in which a fixed point gauge with a vernier is installed to measure the level of water. The water surface is initially kept 5 cm below the top of pan. The daily evaporation is computed as the difference between the observed water levels in the pan.

The pan coefficient is about 0.8.

• **Estimation of evaporation :**

The evaporation measured with an evaporation pan is more than that from a reservoir or a lake because of the following reasons :

- (i) A reservoir is of very large size as compared to an evaporation pan and is exposed to different patterns of winds.
- (ii) The pan is made of metal and contains a smaller quantity of water which is greatly affected by temperature fluctuations and solar radiations as compared to a reservoir.

Pan coefficient :

The pan coefficient is defined as the ratio of the lake evaporation to the pan evaporation.

$$\therefore \text{Pan coefficient} = \frac{\text{lake evaporation}}{\text{pan evaporation}}$$

Lake evaporation is estimated as,

$$\text{Lake evaporation} = \text{Pan coefficient} \times \text{pan evaporation}$$

In India, there are about 200 pan evaporimeter stations maintained by the IMD.

• **Methods to reduce evaporation losses :**

Various methods available for reduction of evaporation losses are :

- (i) Reduction of surface area
- (ii) Mechanical covers
- (iii) Chemical films

(i) **Reduction of surface area :**

Since the volume of water lost by evaporation is directly proportional to the surface area of the water body, the reduction of surface area wherever feasible reduces evaporation losses. The measures like having deep reservoirs in place of wider ones and elimination of shallow areas can be adopted.

(ii) **Mechanical covers :**

These may be in the form of :

- Permanent roofs over the reservoir
- temporary roofs
- floating roofs such as rafts

These measures are limited to very small water bodies such as ponds, etc.

(iii) Chemical films :

This method consists of applying a thin chemical film on the water surface to reduce evaporation. Currently this is the only feasible method available for reduction of evaporation of reservoirs up to moderate size. Certain chemicals like cetyl alcohol and stearyl alcohol are used. The thin film has the following desirable characteristics.

- The film is strong and durable and does not break easily due to wave action.
- If punctured due to the impact of raindrops, birds, insects, etc. the film closes back soon after.
- It is pervious to oxygen and carbon dioxide, the water quality is not affected by its presence.
- It is colourless, odourless and non-toxic.

1.1.2 Using Empirical Formulae :

Evaporation from lakes and reservoirs is usually estimated by empirical methods based on meteorological data. There are a large number of empirical formulae available in the literature. Most of these equations are based on Dalton's law of evaporation.

Some of the common empirical formulae are given below :

1. Mayer formula :

It states that

$$E = k_m (e_s - e_a) \left[1 + \frac{V_9}{16} \right] \dots \dots \dots (1.20)$$

where,

- E = evaporation (mm/day)
- e_s = saturation vapour pressure at the water surface temperature (in mm of mercury)
- e_a = actual vapour pressure (in mm of mercury) at 9 m above water surface.
- V_9 = Mean wind velocity (km/h) at 9 m above ground level.
- K_m = a coefficient, 0.36 for large deep water
0.50 for small shallow water

2. Rohwer's Formula :

It states that

$$E = 0.771 (1.465 - 0.000732 P_a) (0.44 + 0.0733 V_{0.6}) (e_s - e_a) \dots (1.21)$$

where,

- E, e_s and e_a have the same meaning as in eq. (1.21)
- P_a = Mean atmospheric pressure, barometric reading in mm of mercury.
- $V_{0.6}$ = Mean wind velocity in km/h, at 0.6 m above the ground.

The wind velocity (V) will usually be measured at some other height above the ground and wind velocity at required height Z can be computed as,

$$V_z = C.Z^{1/7} \dots \dots \dots (1.22)$$

or $\frac{V_{z_1}}{V_{z_2}} = \left[\frac{Z_1}{Z_2} \right]^{1/7}$

where,

- V_z = wind velocity at height z.

3. Lake Hefner formula :

It states that

$$E = 0.097 (e_s - e_a) V_8 \quad \dots \dots \dots (1.23)$$

where,

- E = evaporation (cm/day)
- e_s = Saturated vapour pressure at the temperature of the water surface (mb)
- e_a = actual vapour pressure at 8 m above water surface (mb)
- V_8 = wind velocity at 8 m above the water surface (m/s).

(Nov. 2010)

1.17.3 Water budget method (storage equation) :

This method balances all the incoming, outgoing and stored water in a lake or reservoir over a period of time using the following equation.

$$P + Q_i \pm Q_u = E + Q_o \pm \Delta Q_s \quad \dots \dots \dots (1.24)$$

where,

- P = total precipitation on the water surface
- Q_i = total surface inflow
- Q_u = total underground inflow or outflow (+Ve for inflow and -Ve for outflow)
- E = Evaporation from the water surface
- Q_o = Surface outflow
- ΔQ_s = Change in storage (+Ve value for increase in storage and -Ve value for a decrease)

All these factors are taken in the same unit, usually expressed as the depth of water. This method is very useful, as various quantities cannot be easily worked out.

1.17.4 Energy Budget method :

This method is based on the principle of conservation of heat energy and the cooling produced by evaporation. Thus, the energy available for evaporation is determined by considering the incoming energy, stored energy and outgoing energy, from a water body over a known time interval.

Let us consider a water body as shown in Fig. 1.33. The energy balance at the evaporating surface in a period of one day is given by :

(i) Net incoming energy :

$$H_n = H_c (1 - r) - H_b \quad \dots \dots \dots (1.25)$$

where, $H_c (1 - r)$ = the incoming solar radiation into a surface of reflection coefficient (albedo) r .

the value of r ,

for water surface, $r = 0.05$

For newly laid snow, $r = 0.90$

H_b = back radiation (long wave) from water

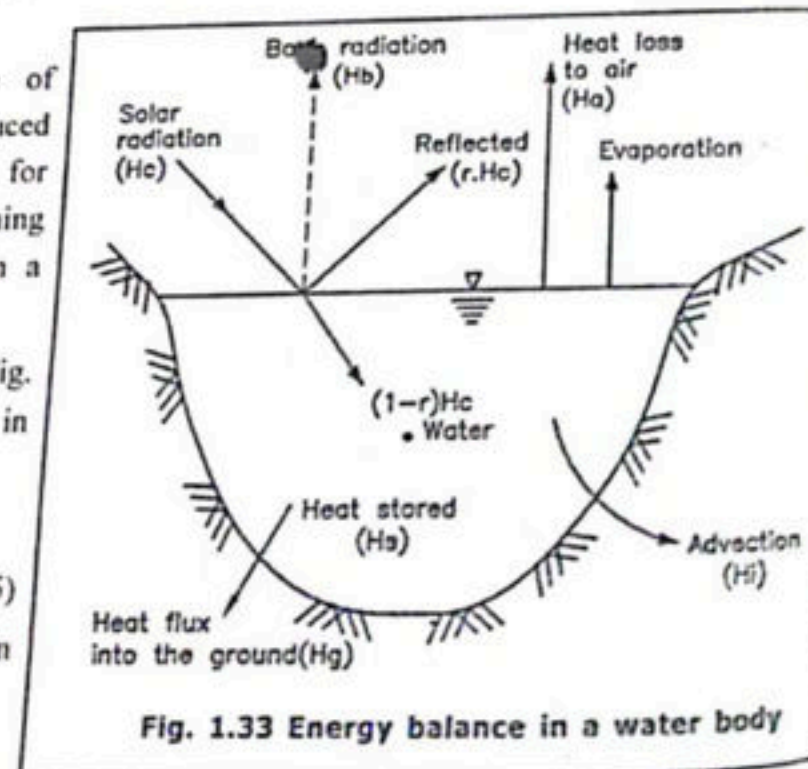


Fig. 1.33 Energy balance in a water body

(ii) Outgoing energy :
 Outgoing energy = $H_a + H_g + H_i$

where,
 H_a = sensible heat loss to air
 H_g = Heat loss to ground
 H_i = net heat conducted out of the system by water flow.

(iii) Heat stored in the water body :
 H_s = heat stored in the water body

(iv) Heat used in evaporation :
 $H_e = \rho \cdot L_a \cdot E$

where,
 ρ = density of water
 L_a = Latent heat of vaporisation of water
 E = Evaporation in mm.

Using energy conservation law, we have

Total incoming energy = outgoing energy + energy stored + energy used in evaporation
 $H_n = (H_a + H_g + H_i) + (H_s) + (H_e)$ (1.26)

All the energy terms in the above equation are in calories/mm²/day.

All the terms except H_a can either be measured or evaluated. The sensible heat transfer to air (H_a) can, however be estimated by using Bowen's ratio (β) by the following equation :

$$\beta = \frac{H_a}{H_e} = 6.1 \times 10^{-4} P_a \left[\frac{T_w - T_a}{e_s - e_a} \right]$$
 (1.27)

where,
 P_a = atmospheric pressure in mm of mercury
 T_w = Temperature of water in °C
 T_a = Temperature of air in °C
 e_s = saturation vapour pressure at T_w °C
 e_a = Vapour pressure of air in mm of mercury

Combining eq. (1.26) and (1.27), we get

$$E = \frac{H_n - H_g - H_i - H_s}{\rho \cdot L_a (1 + \beta)}$$
 (1.28)

For short periods, H_i and H_s can be neglected.

$$\therefore E = \frac{H_n - H_g}{\rho \cdot L_a (1 + \beta)}$$
 (1.29)

1.18 TRANSPIRATION :

Transpiration is the process by which plants dissipate water from the surface of their leaves, stalks and trunks in the process of their growth. As much as 99% of the total water received by a plant through its roots is lost to the atmosphere by this process. Transpiration mainly occurs during daylight hours.

Transpiration, in fact occurs, when the plant manufactures carbohydrates for its growth, by the process of **photosynthesis**. What actually happens, is that the water extracted by the plant-root system from the soil, is transferred to the plant leaves. In the photosynthesis process, air enters the **stomata** openings in the leaf surface, and the chloroplasts within the leaf utilise carbon dioxide from the air along with a very small amount of moisture to manufacture carbohydrates. As air enters the leaf, the water escapes through the stomata.

$$\text{Transpiration ratio (T.R)} = \frac{\text{weight of water transpired}}{\text{weight of dry matter produced}}$$

The transpiration ratio for most crops varies from 300 to 800.

All the factors that affect the evaporation from the free water surface also affect transpiration. The factors affecting transpiration may be summarised as follows :

- | | |
|-------------------------|------------------|
| 1. Temperature of air | 2. Wind velocity |
| 3. Atmospheric pressure | 4. Humidity |
| 5. Solar radiation | 6. Soil moisture |
| 7. Physiologic factors | |

1. Temperature of air :

The transpiration increases with increase in air temperature. As the temperature increases, there is an increase in aqueous vapour pressure of leaves and the transpiration increases. Thus, in summer season or in hot countries, the transpiration will be more as compared to that in the winter or in cold countries.

2. Wind velocity :

As the wind velocity increases, the water vapours in the leaf surface are quickly remove and the rate of transpiration increases.

3. Atmospheric pressure :

A decrease in the atmospheric pressure increases the rate of transpiration. At high altitudes, the rate of transpiration is more.

4. Humidity :

Transpiration is inversely proportional to humidity. If the humidity in the atmosphere is more, transpiration will be less.

5. Solar radiation :

Transpiration increases as the solar radiation increases. Transpiration can be decreased by reducing solar radiation. About 95% of the total transpiration occurs in day-light hours.

6. Soil Moisture :

Transpiration also depends upon the soil moisture content. The water content of the soil after the gravitational water has drained out is called the field capacity. The water in the soil between the field capacity and wilting coefficient is available for transpiration. The rate of transpiration decreases as the soil water content decreases.

7. Physiological Factors :

Transpiration depends upon the physiological factors of the plants, such as density and characteristics of the stomata, extent and character of protective coatings and leave structure.

Stomato contains numerous pores water escapes through stomata as air enters and it results in transpiration. Stomato open with day light, and close with darkness or when the moisture supply is insufficient. When stomato are fully opened, the transpire is a maximum.

Measurement of transpiration :

In order to measure the transpiration, various methods are used by botanists. Phytometer method, which is generally adopted by engineers is discussed here :

Phytometer method :

This is the most important and widely used method. The phytometer consists of a closed and water tight tank, containing sufficient earth to nourish the plant. It is sealed so as to prevent any automatic inflow or outflow of water. Water is applied, only artificially, till the plant growth is completed. The instrument is weighed in the beginning as well as at the end of the experiment. Water required during the growth is measured and the loss due to transpiration can be calculated by the following equation.

$$T = (W_1 + W) - W_2 \quad \dots \dots \dots (1.30)$$

where,

- T = loss due to transpiration
- W₁ = Initial weight of the instrument
- W = Total weight of water applied during full growth of the plant.
- W₂ = Final weight of the instrument

The transpiration loss calculated above is not the actual value of the field, but is only of the laboratory. So the values obtained by the above test must be multiplied by a suitable factor to obtain the possible field results.

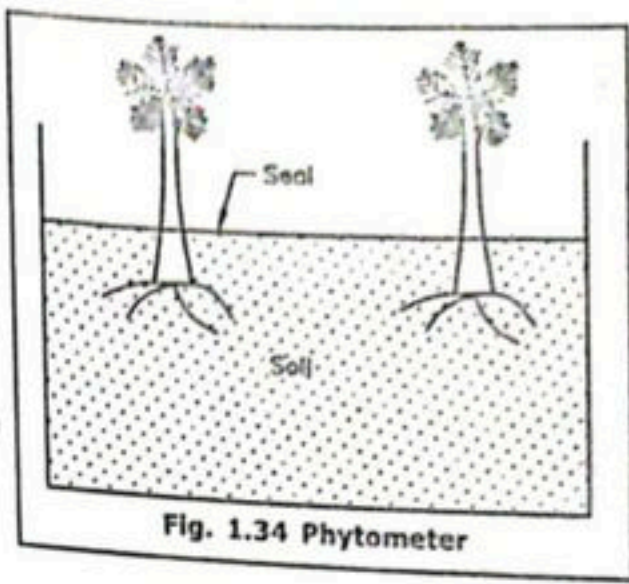


Fig. 1.34 Phytometer

1.19 EVAPOTRANSPIRATION :

Evaporation : In addition to escape of water to the atmosphere through leaves of plants. (i.e. transpiration) water is also lost during the growth of the plant from soil body surrounding the plant is called evaporation. (Nov. 2016, April 2017, Dec. 2018)

Evapotranspiration :

Evapotranspiration is the sum of the water lost to the atmosphere by the plants through transpiration, and the water evaporated from the soil or water body surrounding the plant. (June 2014)

$$\therefore \text{evapotranspiration} = \text{evaporation} + \text{transpiration}$$

Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET) :

If sufficient moisture is always available to completely meet the needs of the plants, the resulting evapotranspiration is called **potential evapotranspiration (PET)**.

The real evapotranspiration occurring in a specific situation is called the **actual evapotranspiration (AET)**.

At the moisture content in the soil corresponding to field capacity (F.C.), the water supply to the plant is adequate and hence AET will be equal to PET, or in other words, the ratio AET/PET will be equal to 1. With the reduction in the available moisture in the soil, the ratio AET/PET decreases and finally AET will be

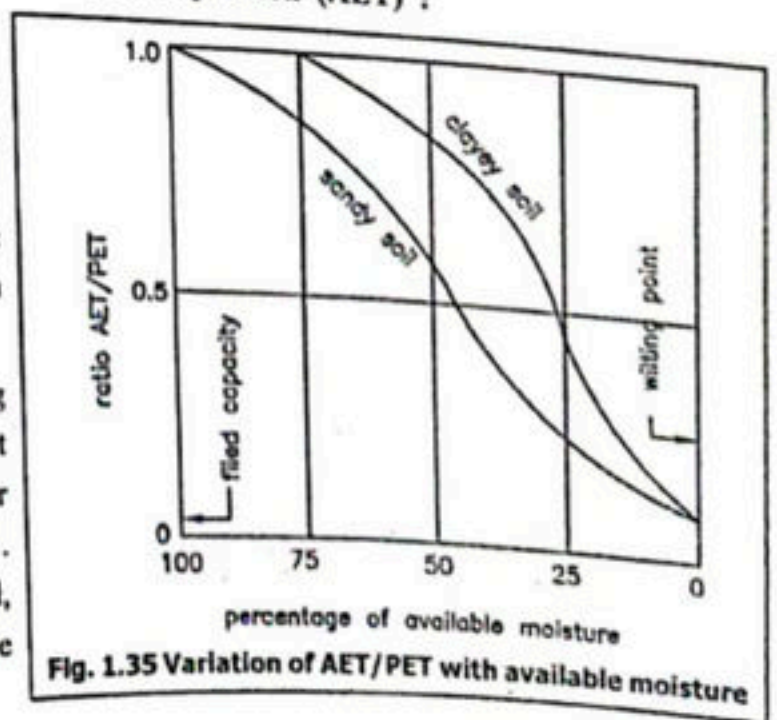


Fig. 1.35 Variation of AET/PET with available moisture

zero at permanent wilting point. Fig. 1.35 shows the relation between AET/PET ratio and percentage of available moisture for sandy soil and clayey soil. For the same percent of available moisture, the AET/PET ratio will be less for sandy soil than for clayey soil.

(Dec. 2010, April 2017)

Factors affecting evapotranspiration :

The factors affecting evapotranspiration are the same that affect evaporation and transpiration. Some of these are described below.

- 1. Meteorological factors
- 2. Density of vegetation
- 3. Soil moisture
- 4. Stage of plant growth
- 5. Adjoining land
- 6. Surface of leaves

1. Meteorological factors :

Meteorological factors like temperature, sunshine, wind velocity and humidity affect the evapotranspiration. Evapotranspiration increases with increase in temperature, sunshine and wind velocity but decreases with increase in humidity.

2. Density of vegetation :

The greater is the density of vegetation, the greater is the evapotranspiration.

3. Soil moisture :

When the vegetative surface becomes dry and the soil moisture decreases, the evapotranspiration decreases. However, the decrease of evapotranspiration depends upon the type of soil and the rate of drying .

4. Stage of plant growth :

Evapotranspiration also depends upon the stage of plant growth. In general, the evapotranspiration is higher in the seedling stage and it decreases after the ripening of grains.

5. Adjoining land :

If the adjoining land is also cropped, the air becomes cool and more humid, and thus, evapotranspiration is less.

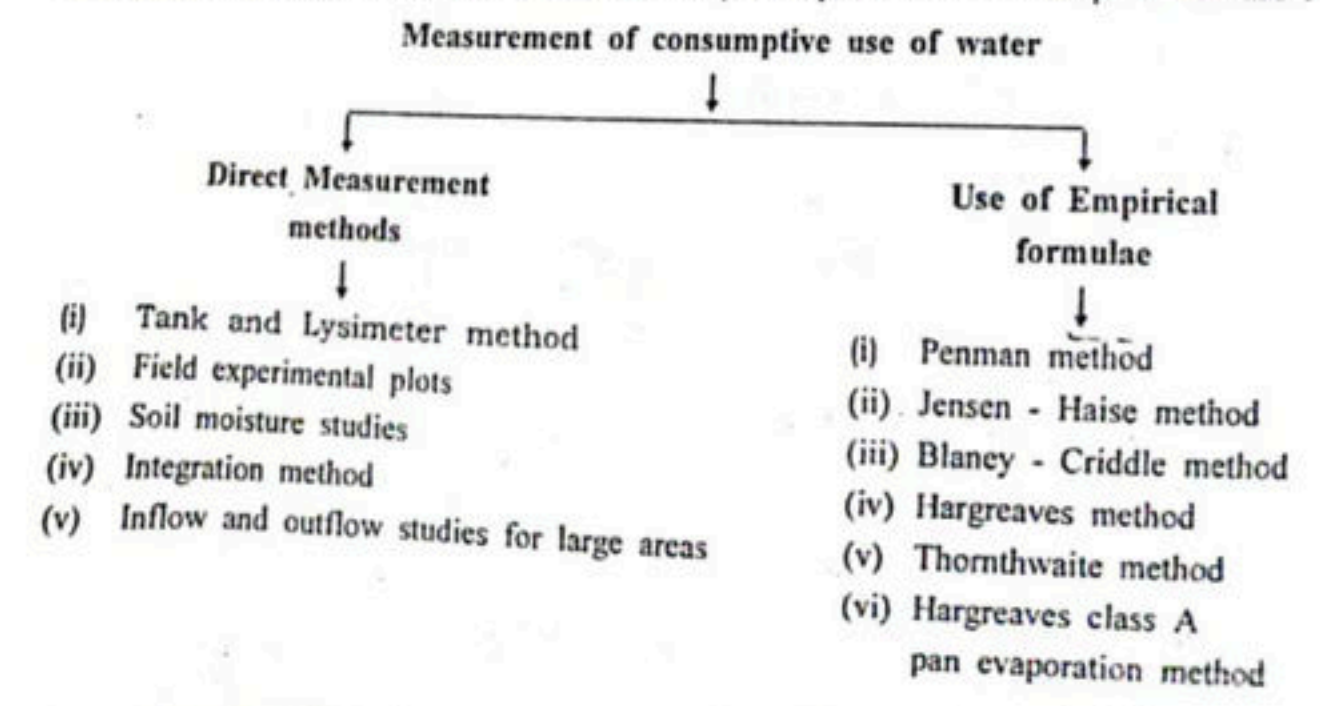
6. Surface leaves :

Evapotranspiration is less in a light coloured surface of leaves than that in a dark coloured surface because a light coloured surface reflects more radiation.

1.19.1 Measurement of Evapotranspiration or Consumptive use :

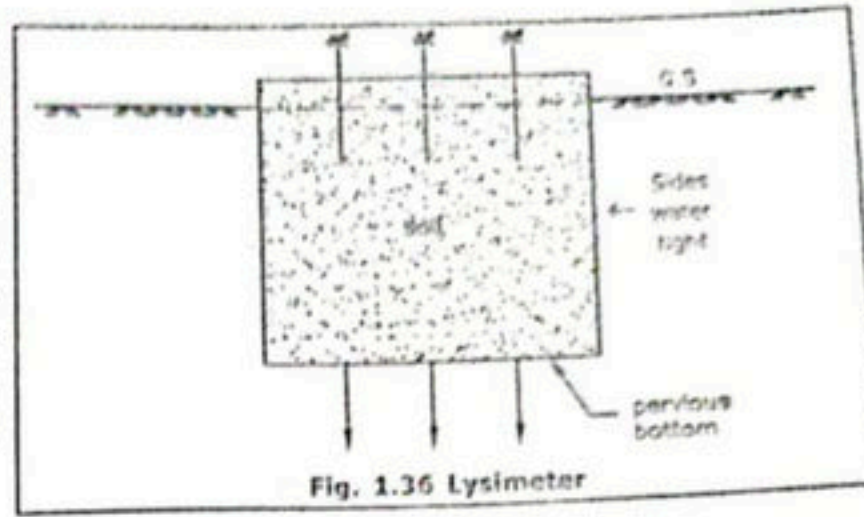
(Nov. 2013)

The various methods of the determination of evapotranspiration or consumptive use are :



(i) Tank and Lysimeter method :

Tanks are watertight cylindrical containers which are open at one end and are set into the ground with their rim approximately flush with the surface. The tanks are 1 to 3 m in diameter and 2 to 3 m deep. Usually larger tanks are preferred because they permit more nearly natural root development for the plants grown in the tanks. The consumptive use of water is determined by measuring the quantity of water required to be supplied to maintain satisfactory growth of the plants within the tank.



Lysimeters are similar to tanks with the difference that Lysimeters have pervious bottoms. The plants are grown in the Lysimeters filled with soil and placed in the ground such that their rims are approximately flush with the ground surface. Because the bottoms of the Lysimeters are pervious, a part of water applied to the plants is drained through it and the same is collected in a pan placed below it. The consumptive use is equal to the difference between the water applied and that collected in the pan. In case of Lysimeter, the flow conditions are more closely simulated with the actual field conditions and natural gravity flow occurs in it.

(ii) Field experimental plots :

In this method, an experimental plot is selected for growing plants. Irrigation water is applied in measured quantity to the selected plot in such a way that there is neither run-off nor deep percolation. However, the quantity of water should be sufficient for satisfactory growth of the plants. The consumptive use is equal to the quantity of water applied.

However, if some run-off occurs, it should be measured by adopting a suitable method and its quantity should be subtracted from the quantity of water applied.

(iii) Soil moisture studies :

This method is specially suited to those areas where soil is fairly uniform and ground water is deep enough so that it does not affect the fluctuation in soil moisture within the root zone of the soil. Soil moisture measurements are done before and after each watering. The quantity of water extracted per day from soil is computed for each period. A curve is plotted for rate of use against time and from this curve consumptive use can be determined.

(iv) Integration method :

In this method, a large area of the land is selected for studies. The total area (A) is divided into sub-area under crops (A₁), natural vegetation (A₂), water ponds (A₃) and bare land (A₄). The consumptive use of water is then computed as,

$$dw \times A = dw_1 \times A_1 + dw_2 \times A_2 + dw_3 \times A_3 + dw_4 \times A_4$$

where,

dw₁ = Consumptive use of water for crop

dw₂ = consumptive use of water for natural vegetation

dw₃ = evaporation from the water surface

dw₄ = evaporation from the bare land.

Thus, the consumptive use of water dw for the entire area is found in the volume units (hect - m) in terms of the depth of water, it can be found by dividing the volume of water by the total area of the land.

(v) **Inflow and outflow studies from large areas :**

In this method, annual consumptive use of water is found for large areas. The annual consumptive use (U) is given by :

$$U = (I + P) + (G_s - G_e) - R$$

where,

U = consumptive use of water in hectare - metre

I = Total inflow during 12 - months year

P = Yearly precipitation on the area

G_s = Ground water storage of the area at the beginning of the year

G_e = Ground water storage of the area at the end of the year.

R = Yearly outflow from the area

All the above volumes are measured in hectare - metre.

• **Use of Empirical Formulae :**

Due to difficulty in measuring evapotranspiration in the field, various investigators suggested empirical equations for the estimation of evapotranspiration. These equations relate the evapotranspiration to meteorological conditions such as temperature, wind velocity, humidity sunshine, day length etc. Various formulae are discussed below :

(a) **Blaney - criddle equation :**

The Blaney - criddle equation is based on the data collected from the arid western zone of the United States, and is commonly used all over the world. In this equation it is assumed that the potential evapotranspiration, or the consumptive use, depends only on the mean monthly temperature and the monthly sunshine hours. The monthly sunshine hours are also called the monthly daylight hours.

The monthly consumptive use or evapotranspiration (ET) is given by

$$C_u \text{ or } ET = k.f \dots (\text{cm})$$

where,

ET = monthly evapotranspiration in cm

k = empirical constant of the crop

f = monthly consumptive use factor

The monthly consumptive use factor (f) is computed as :

$$f = \frac{p(4.6 T_m + 81.3)}{100}$$

where,

p = monthly daylight hours expressed as % of total daylight hours.

T_m = mean monthly temperature (°C)

..... (1.31)

..... (1.32)

(b) Thornthwaite equation :

According to this equation, the monthly consumptive use (or potential evapotranspiration) is given by :

$$PET = 1.6 b \left[\frac{10 T_m}{1} \right]^a \text{ cm/month} \dots \dots \dots (1.33)$$

where,

T_m = mean monthly temperature ($^{\circ}C$)

1 = annual heat index, which is obtained from the monthly heat index i of the year

$$i = \left[\frac{T_m}{5} \right]^{1.514}$$

$$1 = \sum_{n=1}^{12} i = \sum_{n=1}^{12} \left[\frac{T_m}{5} \right]^{1.514}$$

$$a = (67.5 \times 10^{-8})i^3 - (77.1 \times 10^{-6})i^2 + (0.01791)i + 0.492$$

$$b = \frac{\text{maximum number of sunshine hours in the month}}{12 \times 30}$$

The Thornthwaite equation has been derived from the data obtained from the eastern U.S.A.

1.19.2 Penman's method :

(Nov. 2016, May 2018)

For shorter periods, it is necessary to use calculation methods to estimate evapotranspiration. This can be done by Penman's method. This method was developed to determine the potential evapotranspiration (PET) of a specific area, depending on its climate and meteorological conditions.

The Penman's equation is a combination of energy balance and wind transfer approach, which reads :

$$PET = \frac{A \cdot H_n + E_a \cdot \gamma}{(A + \gamma)} \dots \dots \dots (1.34)$$

where,

PET = daily potential evapotranspiration

A = slope of the saturation pressure versus temperature curve at mean air temperature as given in Fig. 1.37 (mm Hg/ $^{\circ}C$)

H_n = net incoming solar radiation (mm/day)

E_a = A parameter including wind velocity and saturation deficit.

γ = psychrometric constant (0.49 mm Hg/ $^{\circ}C$)

The net radiation is the same as used in the energy budget equation (1.26) and is estimated by the following equation :

$$H_n = H_c (1 - r) \left(a + b \cdot \frac{n}{N} \right) - \sigma T_a^4 (0.56 - 0.092 \sqrt{e_a}) \times \left(0.10 + 0.90 \frac{n}{N} \right) \dots \dots \dots (1.35)$$

where,

H_c = mean incident solar radiation outside the atmosphere on a horizontal surface (mm/day)

τ = reflection coefficient (albedo) of the given area

a = a constant depending upon the latitude (ϕ)

$$= 0.29 \cos \phi$$

b = a constant having average value = 0.52

n = actual duration of bright sunshine in hours

N = Maximum possible hours of bright sunshine (mean value).

σ = Stefan - Boltzman constant

$$= 2.01 \times 10^{-9} \text{ mm/day}$$

T_a = mean air temperature in K

$$= 273 + ^\circ\text{C}$$

e_a = actual mean vapour pressure in the air in mm of Hg

The parameter E_a is estimated as

$$E_a = 0.35 \left[1 + \frac{v_2}{160} \right] (e_s - e_a) \text{ mm/day} \quad \dots \dots \dots (1.36)$$

where,

v_2 = mean wind velocity at 2 m above ground in km/day

e_s = saturation vapour pressure at mean air temperature in mm of Hg

e_a = actual mean vapour pressure of air in mm of Hg.

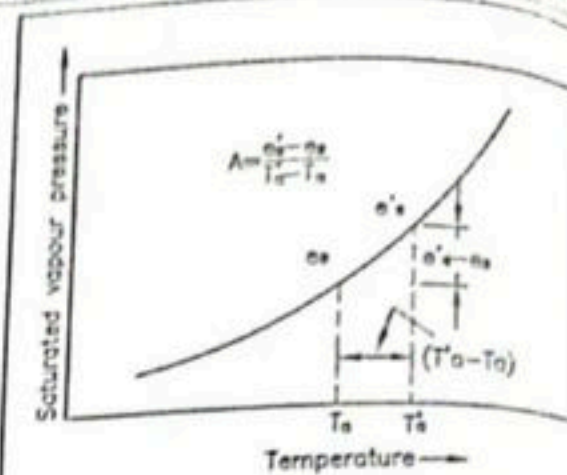


Fig. 1.37 Saturation vapour pressure versus temperature curve

1.20 INFILTRATION :

(Dec. 2018)

Infiltration may be defined as the entry of water into the soil surface and its movement. When rain water falls on the ground, a small part of it is initially absorbed by the top thin layer of soil so as to replenish the soil-moisture deficiency. The excess water moves downwards by the force of gravity to join ground water table.

The downward movement of water under gravity, into soil is known as percolation (or seepage).

The two terms infiltration and percolation are closely related. Infiltration refers to the entry of water in to the soil surface, while percolation refers to the downward movement of water under gravity into the soil. Percolation starts after infiltration.

Abstraction may be defined as the part of precipitation that is not available as surface runoff. It indicates loss in precipitation.

The abstractions (initial losses) include :

- (i) **Interception** : That part of precipitation which is caught by the plant leaves and evaporates later is called interception.

- (ii) **Evaporation** : Loss of water occurs from water surfaces like reservoirs, lakes, ponds, etc. is called evaporation.
- (iii) **Depression storage** : Part of rainfall water get stored in depressions like ditches, small ponds, etc. before the river starts flowing is known as depression storage.
- (iv) **Infiltration** : That part of water which enter into the soil surface is called infiltration.

The evaluation of infiltration helps us in computing the runoff obtained from a given rainfall. The infiltration, as a matter of fact, affects the short time runoff caused by a single rainfall, as well as the long - time runoff evolving over a long period, such as the yearly runoff of a catchment.

Infiltration capacity (f) :

The maximum rate at which a soil in any given condition is capable of absorbing water is called its infiltration capacity. It is also defined as the maximum rate at which water will enter the soil in a given condition.

The ground water stored in the under ground soil depends mainly upon the number of voids present in the soil, which, in turn, does not depend upon the size of the soil particles but rather upon the arrangement, sorting, shape and degree of compaction. Therefore, different soils will have different number of voids, and hence, different capacities to absorb water.

Infiltration rate : The **infiltration rate** at any instant is the rate at which water actually enters the soil during a storm and is equal to the infiltration capacity (f) or the rainfall rate, whichever is less.

- If intensity of rainfall > infiltration capacity of soil, then, infiltration rate = infiltration capacity of soil.
- If intensity of rainfall < infiltration capacity of soil, then, infiltration rate = intensity of rainfall
- **Effects of Infiltration :**
 1. It reduces the magnitude of the flood.
 2. It delays the time of arrival of water to the channel.
 3. It recharges the ground water reservoir.
 4. It reduces soil erosion.
 5. It fills the soil pores to its capacity, thus making water available to plants.
 6. It sustains green vegetation cover on the ground surface and thus helps in reducing dust storms.

1.20.1 Factors affecting infiltration :

(May 2013, June 2014, May 2016, Nov. 2017, May 2018)

The various factors affecting infiltration are :

1. Thickness of saturated layer and depth of surface detention
2. Permeability/percolation characteristics of soil formation
3. Soil moisture
4. Temperature
5. Intensity and duration of rainfall

(June 2014, April 2017, May 2016)

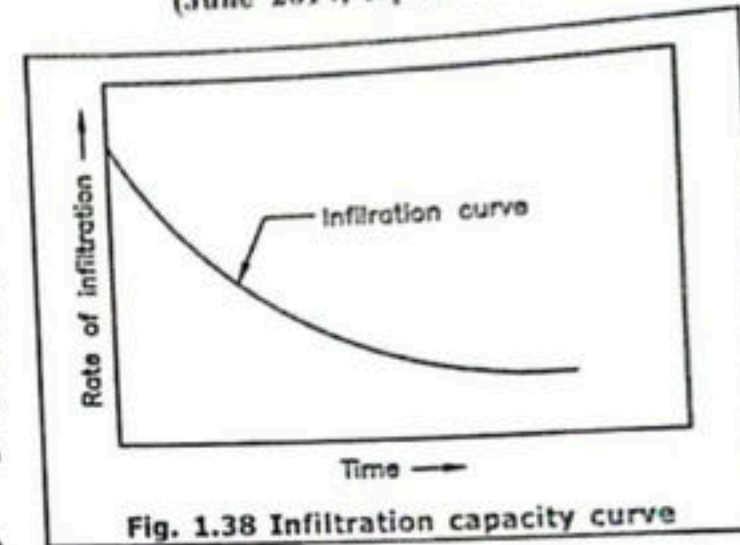


Fig. 1.38 Infiltration capacity curve

6. Vegetation cover
7. Compaction due to men and animals
8. Washing of fines
9. Human activities
10. Quality of water
11. Size and characteristics of soil particles
12. Pressure of ground water table

1. Thickness of saturated layer and depth of surface detention :

The water infiltrates into the ground under the force of gravity, and there exist a layer of soil near the surface having its interstitial spaces saturated. If the thickness of this layer is more rate of infiltration will be more in the beginning.

After satisfying the interception and depression storage loss, the rain water collects over the ground surface as surface detention. The rate of infiltration increases as the depth of surface detention increases because the head causing flow is increased.

2. Permeability/percolation characteristics of soil formation :

The infiltration will continue only when percolation continues. The infiltrated water must be transmitted down by the force of gravity and capillary action. Percolation depends upon several factors such as soil type and its composition, permeability, porosity, stratification, presence of salts and organic matter.

3. Soil moisture :

The amount a soil moisture has an important effect on the infiltration capacity. The effect of soil moisture on infiltration capacity (f) are two folds.

In early winter, the soil moisture content is high and the value of f is low, while in summer the soil moisture content is low, and so the value of f goes up.

On the other hand when the soil becomes wet, the colloids present in the soil swell immediately and hence reduce the infiltration capacity during the initial period of rainfall.

4. Temperature :

The viscosity of water changes with temperature. The flow of water within the body of soil is laminar and the flow is directly proportional to viscosity.

In summer, therefore, infiltration will be higher due to less viscous water, in comparison to winter.

5. Intensity and duration of rainfall :

When the precipitation takes place with heavy intensity, the impact of water causes mechanical compaction and in-wash of fine particles resulting in faster decrease in the rate of infiltration. However, rainfall of lesser intensity result in higher infiltration rate.

6. Vegetation cover :

The presence of dense vegetation cover over a soil, increases the infiltration capacity of that soil to a considerable extent. In the presence of a vegetation cover, the rain will not be able to compact the soil. Further, the vegetation cover provides a layer of decaying organic matter which promotes the activity of burrowing animals and insects which in turn produces permeable soil structure.

Further, transpiration by vegetation cover removes soil moisture and thus tends to increase infiltration capacity (I) during initial periods of rain.

7. **Compaction due to men and animals :**

When there is heavy movement of men and animals, the soil gets compacted resulting in reduction in the infiltration rate.

8. **Washing of fines :**

When a soil becomes very dry, the surface often contains many fine particles. When the rain falls, and the infiltration begins, these fines are taken down into the soil, and are deposited in the voids, thus reducing the infiltration capacity.

9. **Human activities :**

Cultivation of barren land by growing crops and grass cover, results in increased rate of filtration. On the other hand, construction of roads, houses, factories, play ground, results in reduction in infiltration capacity.

10. **Quality of water :**

Silts and other impurities present in incoming water result in retardation of infiltration rate due to clogging of soil pores.

The salts present in water affect the viscosity of water and may react with soil to form complex compounds which reduce the porosity of soil.

11. **Size and characteristics of soil particles :**

The infiltration rate is directly proportional to the grain size/diameter for granular soils. However, if the soil has swelling minerals like illite and montmorillonite, the infiltration rate will reduce drastically. Infiltration rate will be higher in sandy soils as compared to clayey soils.

12. **Presence of ground water table :**

Presence of ground water table reduces infiltration. For infiltration to continue, the position of ground water table should not be very close.

1.20.2 Infiltration indices :

(June 2014)

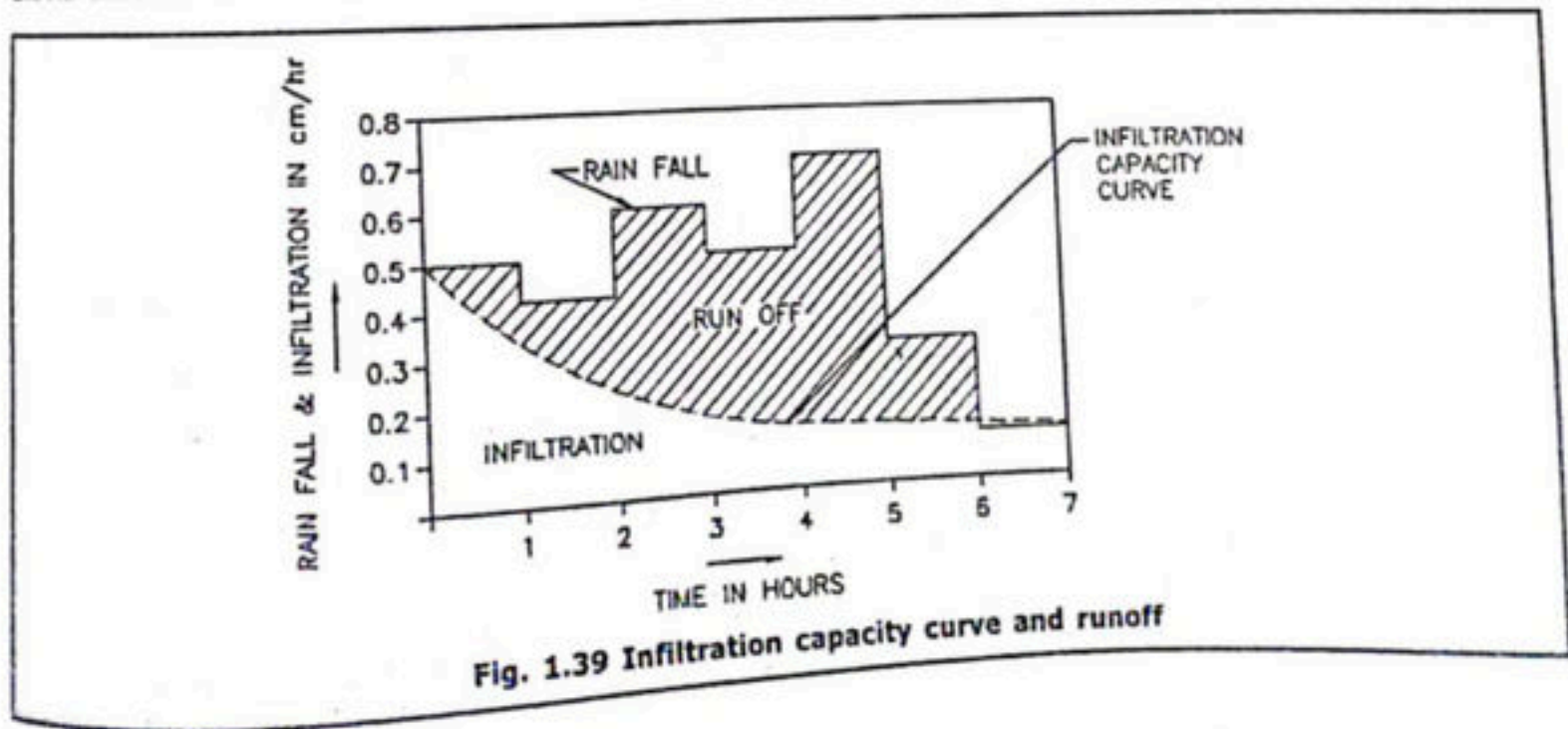


Fig. 1.39 Infiltration capacity curve and runoff

The infiltration capacity of a soil can be determined experimentally by subjecting an experimental plot to rain fall rates in excess of infiltration capacity and by measuring the surface runoff. For small areas having uniform infiltration characteristics, the run-off volume can be estimated by subtracting the infiltration from the design rainfall.

Infiltration index :

Infiltration index is the average rate of loss such that the volume of rainfall in excess of that rate will be equal to direct runoff. Thus, the average constant value of infiltration rate is called infiltration index. (Nov. 2017)

There are two types of infiltration rate which are commonly used.

1. W - index
2. ϕ - index

1. W - index :

It is the average of infiltration during the period when the rainfall intensity exceeds the infiltration rate. It is given by,

$$W - \text{index} = \frac{P - R - S_R}{t_r} \quad \dots \dots \dots (1.37)$$

where,

W = rate of infiltration (cm/hr)

P = Total precipitation (cm)

R = total runoff (cm)

S_R = surface retention (cm)

t_r = duration of rainfall (hr)

The W-index is more accurate than the ϕ -index because it excludes the interception and depression losses which are considered as a part of infiltration in latter. Thus, W-index is always less than ϕ -index. Because it is difficult to estimate depression and interception losses, W-index is not commonly used in practice. W-index can be used to estimate the runoff coefficient (k) from the relation,

$$k = \frac{i - W}{i} \quad \text{where, } i = \text{rainfall intensity cm/hr.}$$

• W_{\min} - index :

The minimum values of W-index is called W_{\min} -index. The value of W_{\min} index is obtained when the soil is very wet. At that stage, because the effect of the depression storage and interception losses is negligible, W-index and ϕ -index are approximately equal.

2. ϕ -index :

(Nov. 2016)

It is the average rate of rainfall such that the volume of rainfall in excess of that rate is equal to the volume of surface runoff. The value of ϕ -index can be derived from the rainfall hyetograph and the resulting surface runoff volume by trial and error.

It is given by,

$$\phi = \frac{P - R}{t_r} \text{ cm/hr} \quad \dots \dots \dots (1.38)$$

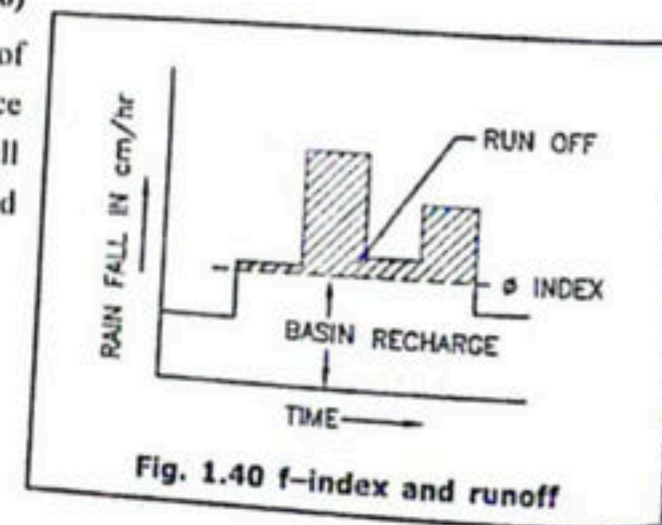


Fig. 1.40 ϕ -index and runoff

For the determination of ϕ -index, a horizontal line is drawn on the hyetograph such that the shaded area above that line is equal to the volume of surface runoff. The unshaded area below the horizontal line actually represents all losses including interception, depression storage and infiltration, but it is assumed that these losses are due to infiltration only. If the shaded area is not equal to the volume of measured surface runoff, the horizontal line is shifted upwards or downwards till this condition is satisfied. Therefore, the determination of ϕ -index needs a few trials. The ϕ -index can be determined for each storm for which the surface runoff volume has been measured.

The amount of rainfall in excess of ϕ -index is called rainfall excess. The ϕ -index is useful for the unit hydrograph analysis to determine the pattern of rainfall excess. Because, the ϕ -index accounts for the total abstractions (interception, depression and infiltration losses), it can also be used to estimate surface runoff from a given hyetograph. It is specially useful for predicting the infiltration from a storm occurring over a very large basin for which the infiltration capacity curve cannot be easily determined.

If there is uniform rainfall over a basin, W-index and ϕ -index are equal.

Infiltration index (ϕ) can also be determined by the equation suggested by the Central Water Commission (CWC) as under :

$$\phi\text{-index} = \frac{i - R}{24}$$

where,

i = intensity of rainfall (cm/day)

R = Runoff in cm from 24 hour rainfall.

$R = \alpha (i)^{1.2}$

where,

α = coefficient depending upon type of soil.

1.20.3 Measurement of Infiltration capacity :

Infiltration capacity of a soil can be measured in the field by conducting controlled experiments on a small area, using infiltratimeters, and rain simulators.

The following two types of infiltratometer are commonly used in practice.

(a) Flooding type infiltratimeters

(i) Simple infiltratometer

(ii) Double ring infiltratometer

(b) Rain simulators

(a) Flooding type infiltratometer :

1. Simple infiltratometer :

A simple infiltratometer consists of a metal cylinder of 30 cm diameter and 60 cm long, open at both ends as shown in Fig. 1.41. This cylinder is driven into the ground to a depth of 50 cm. Water is poured into the cylinder to fill a depth of 55 cm (i.e. 5 cm vacant from top). A pointer is set to mark the water level. As the infiltration takes place, the water level goes down. The water level is maintained constant by adding more water from a burette. The volumes of water added at different time intervals are noted. the volume of

capacity. The infiltration capacity versus time curve can, hence be drawn. The experiment is in fact, continued till a uniform rate of infiltration is obtained, which may take 2 to 3 hours.

The major drawback of the simple infiltrometer lies in the fact that the infiltrated water spreads at the bottom of the cylinder, and hence, the effective area of flow is considerably greater than the base area. It results in low accuracy.

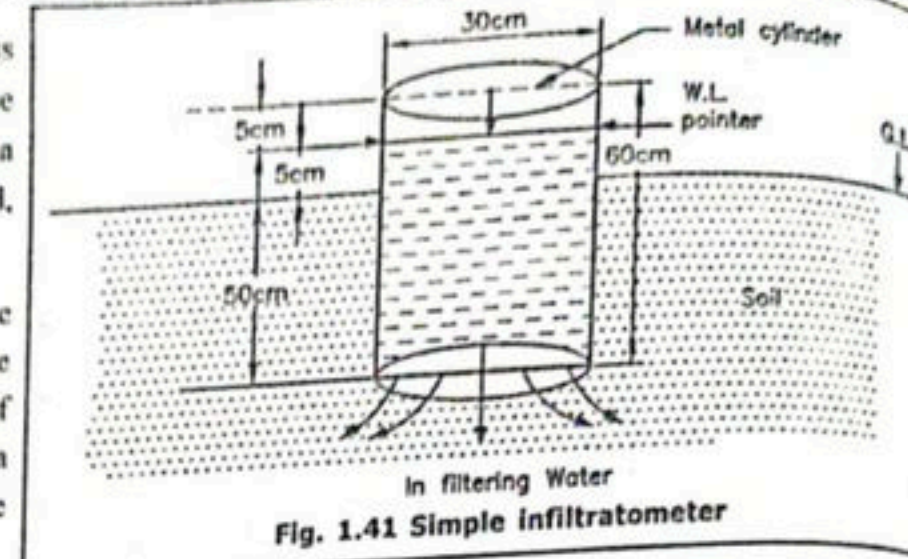


Fig. 1.41 Simple infiltrometer

(Nov. 2016)

2. Double ring infiltrometer :

Double ring infiltrometer is the modified form of simple infiltrometer, used to increase the accuracy of the results.

It consists of two cylinders, called rings. The inner ring is 22.5 cm in diameter and the outer ring is 35 cm diameter. The inner tube is used to determine the infiltration rate as in the case of a simple infiltrometer. The water level in the annular space between the two rings is kept at the same level as that in the inner ring to reduce the border effects due to water coming out of the inner tube. Thus the outer ring provides a sort of water jacket to the inner ring and the water in the inner ring infiltrates vertically downward without spreading.

The water volume being added to the inner ring at different time intervals are noted. The experiment is continued till a uniform rate of infiltration is achieved.

$$\text{Infiltration capacity} = \frac{\text{Volume of water added}}{\text{Area of inner ring} \times \text{time interval}}$$

Disadvantages of flooding type infiltrometers :

- (i) It does not simulate the effect of the rain drop impact.
- (ii) The soil gets disturbed when cylinder is driven.
- (iii) The results depends upon the size of the cylinder.
- (iv) Water spreads at the bottom in case of simple infiltrometer.

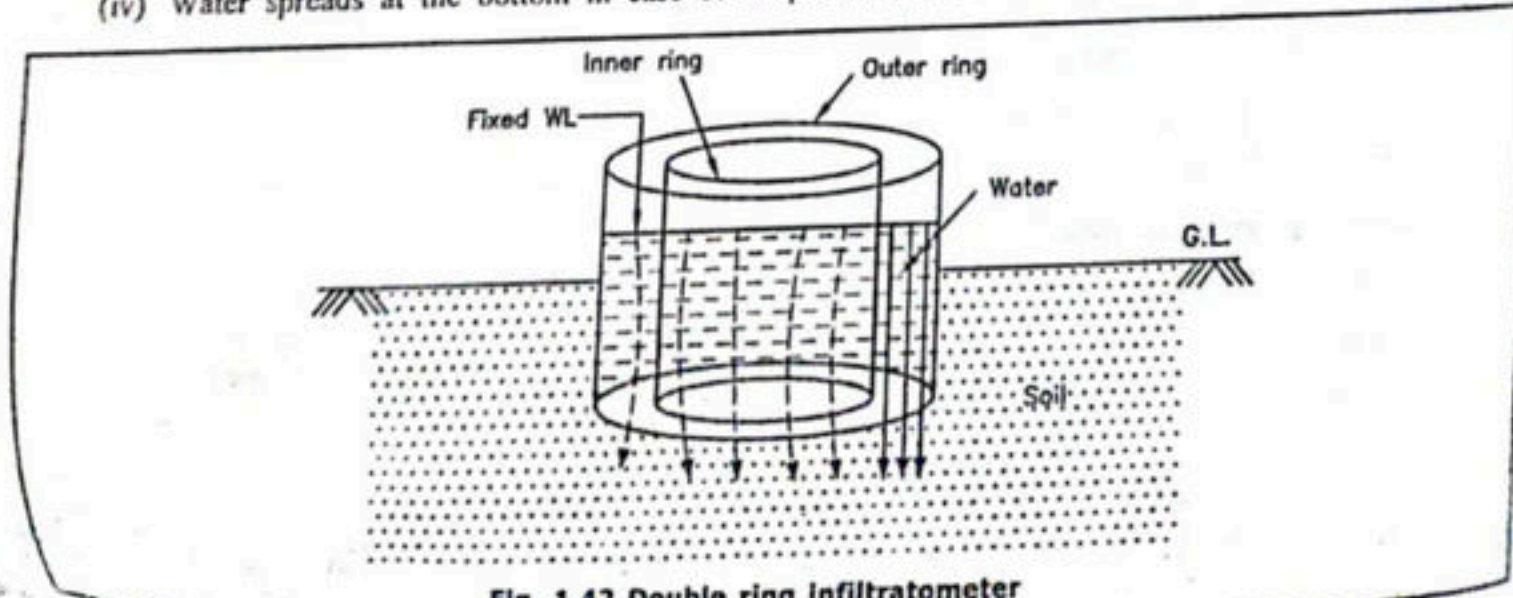


Fig. 1.42 Double ring infiltrometer

Hydrological Parameters

(b) Rain simulators :

A rain simulator is a type of infiltratometer in which, water is applied in the form of spray or artificial rain. A plot of about 2 m x 4 m is selected, and water is applied to it in the form of artificial rain at a uniform rate. For applying the water two rows of special types of nozzles are installed, one along each long side of the plot. The nozzles are so adjusted that they direct spray upwards and slightly inwards. The drops of water reach a height of about 2 m above the ground surface before falling on the plot. Various intensities of rainfall can be simulated by changing the nozzle openings. Experiments are conducted under controlled conditions and the surface runoff is measured.

The amount of infiltration is determined from the water budget equation as,
 Infiltration = Rainfall - surface runoff

All the terms are expressed as the depth of water over the plot or as the volume of water. The rate of infiltration is determined from the total infiltration depth and the duration of the experiment.

The rain simulators gives lower values of the infiltration index than a flooding type infiltratometer. This is due to the effect of rainfall impact and the turbidity of water which decrease the permeability.

(Nov. 2016)

1.20.4 Horton's equation of infiltration :

The maximum rate at which the soil in any given condition is capable of absorbing water is called its infiltration capacity (f_p). Infiltration (f) often begins at a high rate (20 to 25 cm/hr) and decreases to a fairly steady state rate (f_c) as the rain continues, called the ultimate f_p (= 1.25 to 2.0 cm/hr) Fig. 1.43.

The infiltration rate (f) at any time t is given by Horton's equation as,

$$f = f_c + (f_0 - f_c) e^{-kt} \quad \dots \dots \dots (1.40)$$

where,

- f_0 = initial rate of infiltration capacity
- f_c = final constant rate of infiltration at saturation
- k = a constant depending primarily upon soil and vegetation

$$k = \frac{f_0 - f_c}{F_c}$$

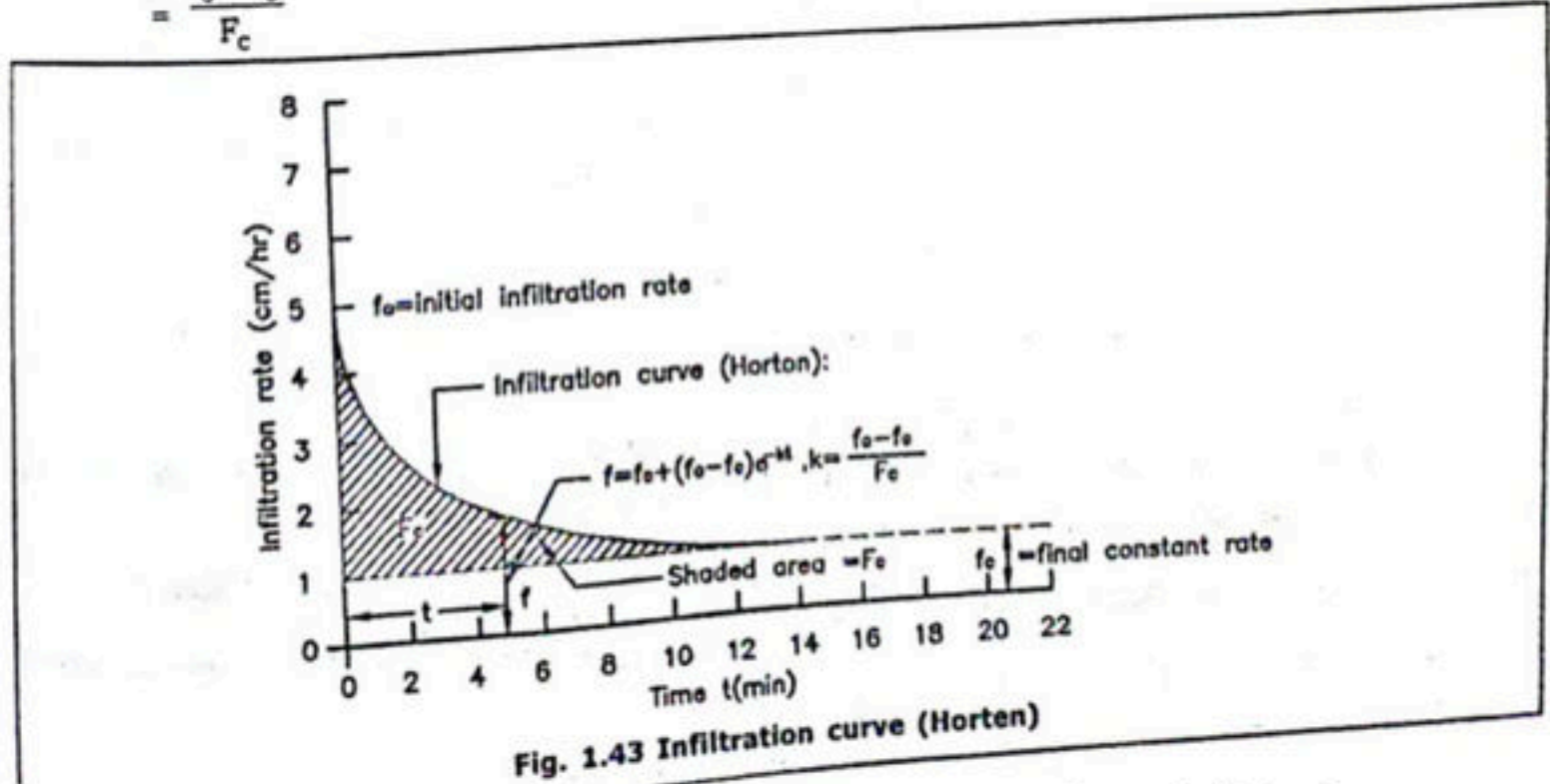


Fig. 1.43 Infiltration curve (Horton)

F_c = shaded area below infiltration curve in Fig. 1.43.

e = base of the Napierian logarithm

t = time from beginning of the storm

The infiltration takes place at capacity rates only when the intensity of rain fall equals or exceeds f_p

i.e. $f = f_p$ when $i \geq f_p$

but when, $i < f_p$ i = intensity of rainfall

$f > f_p$ and the actual infiltration rates are approximately equal to the rainfall $f > f_p$ and the actual infiltration rates are approximately equal to the rainfall rates.

• Solution of Horton's equation :

The Horton's equation is given by

$$f = f_c + (f_o - f_c) e^{-kt}$$

transposing,

$$f - f_c = (f_o - f_c) e^{-kt}$$

Taking log on both sides,

$$\log_{10} (f - f_c) = \log_{10} (f_o - f_c) - kt \log_{10} e$$

$$\log_{10} (f - f_c) - \log_{10} (f_o - f_c) = -kt \log_{10} e$$

$$\therefore t = \frac{-1}{k \log_{10} e} [\log_{10} (f - f_c) - \log_{10} (f_o - f_c)]$$

$$\therefore t = \frac{-1}{k \log_{10} e} \log_{10} (f - f_c) + \frac{1}{k \log_{10} e} \log_{10} (f_o - f_c)$$

The above equation is of the form

$$y = mx + c$$

where, $y = t$

$$m = \frac{-1}{k \log_{10} e}$$

$$x = \log_{10} (f - f_c)$$

$$c = \frac{1}{k \log_{10} e} \log_{10} (f_o - f_c)$$

and hence represents a straight line having a slope, $m = \frac{-1}{k \log_{10} e}$ (1.41)

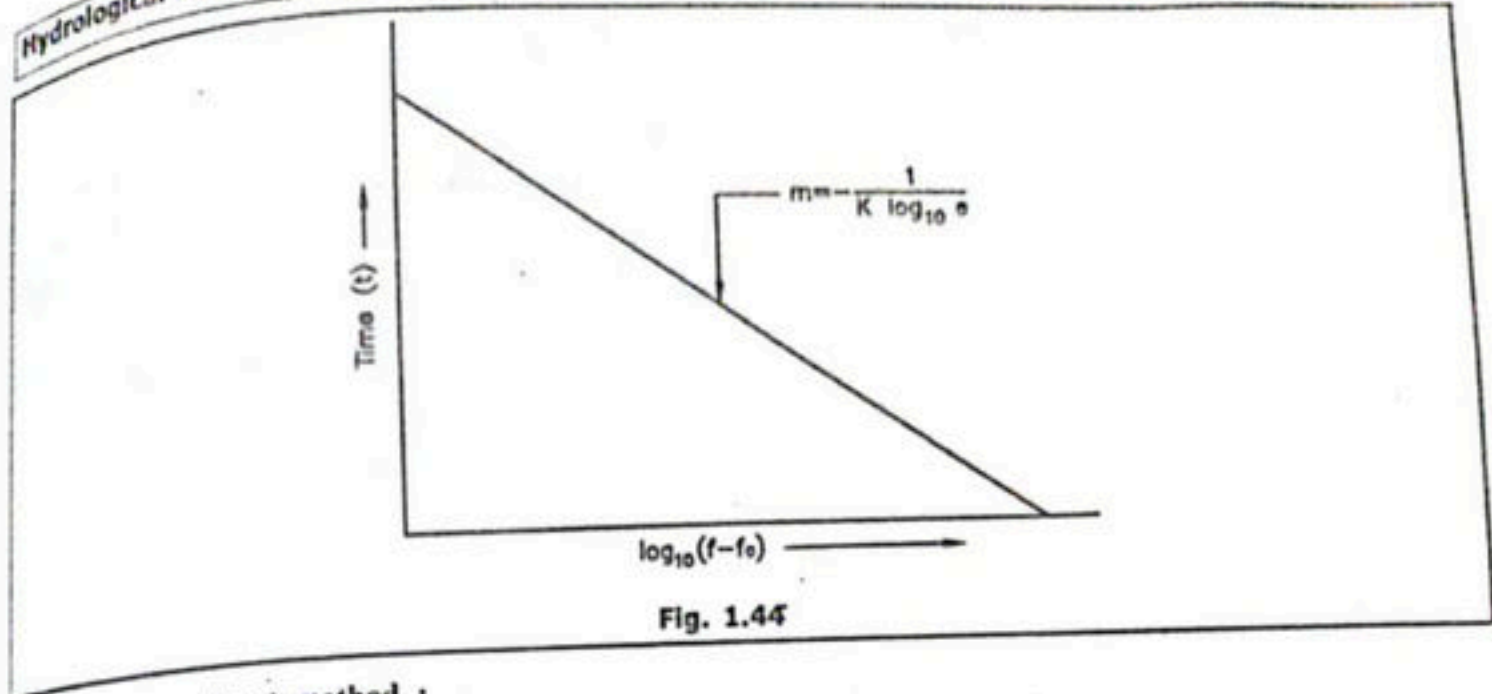
The negative sign shows that as t increase f decreases, and therefore $(f - f_c)$ decreases, and hence $\log (f - f_c)$ decreases. This straight line graph is of the form shown in Fig. 1.44.

If two values of f at two known times are known, the straight line can be drawn through these two points and the slope of the line measured; and then equating it to $\frac{-1}{k \log_{10} e}$, k can be determined, and hence, an equation for the I.C. curve can be written easily.

Total infiltration

$$F = \int_0^t f \cdot dt$$

$$= f_c \cdot t + (f_o - f_c) \times \frac{1}{k}$$



1.20.5 Green - Ampt method :

Green and Ampt proposed a model for infiltration capacity based on Darcy's law as,

$$f_p = K \left[1 + \frac{\eta S_c}{F_p} \right] \dots \dots \dots (1.42)$$

where,

- f_p = infiltration capacity
- η = porosity of the soil
- S_c = capillary suction at the wetting front
- K = Darcy's hydraulic conductivity

Equation (1.42) could be considered as,

$$f_p = m + \frac{n}{F_p}$$

where, m and n are Green - Ampt parameters

F_p = Cumulative infiltration capacity

Values of f_p are plotted against $1/F_p$ on a simple arithmetic graph paper and the best fit straight line is drawn through the plotted points.

From the graph,

m = intercept of straight line

n = slope of the line

EXAMPLES

Example-1 : The rates of rainfall for successive 30 minute period of a 3-hour storm are 1.5, 3.2, 4.3, 2.7, 2.1 and 1.2 cm/hr. The surface runoff in response to the storm is estimated to be 3.0 cm. Determine ϕ -index and w-index. Consider a total of depression and interception losses of 1.0 cm. (May 2015)

Solution :

(i) ϕ -index :

Let, i = rate of rainfall (cm/hr)

t = time in hours

Let us assume that, ϕ_i is greater than 1.5 cm/hr.

\therefore Surface runoff, $R = \Sigma (i - \phi_i) t$

$$R = 3.0 \text{ cm}$$

$$\therefore R = [(3.2 - \phi_i) + (4.3 - \phi_i) + (2.7 - \phi_i) + (2.1 - \phi_i)] \times \frac{30}{60}$$

$$3.0 = (12.3 - 4 \times \phi_i) \times 0.5$$

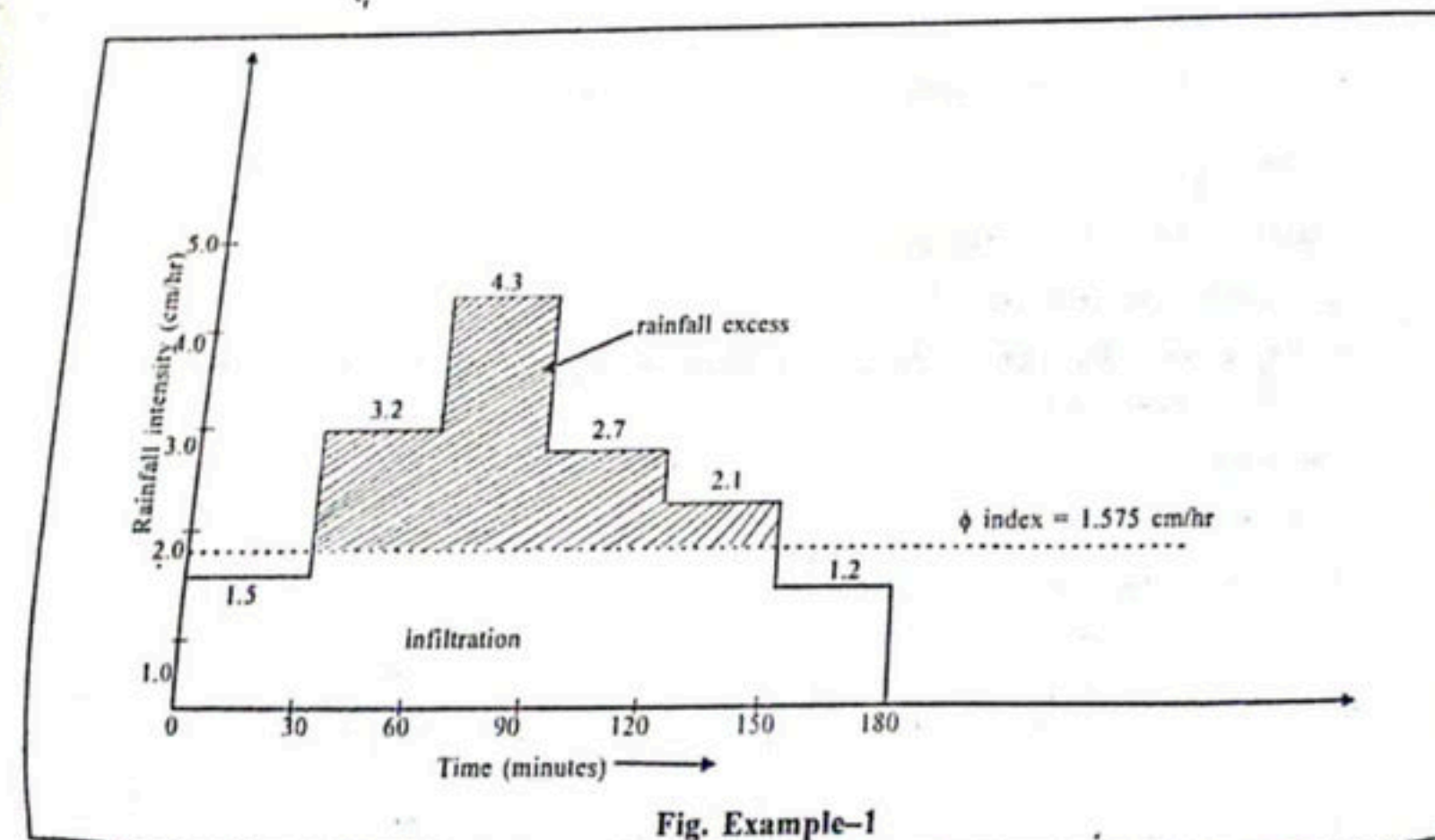
$$\therefore 6.0 = 12.3 - 4 \times \phi_i$$

$$\therefore \phi_i = 1.575 \text{ cm/hr} > 1.5 \text{ cm/hr} \therefore \text{assumption is correct.}$$

Note : Had, ϕ_i been less than 1.5, term 1.5 would have been included on the R.H.S. of the equation.

(ii) W-index :

$$W_i = \frac{P - R - S_p}{t_r}$$



we have,

$$P = [1.5 + 3.2 + 4.3 + 2.7 + 2.1 + 1.2] \times \frac{30}{60}$$

$$= 15 \times 0.5$$

$$= 7.5 \text{ cm}$$

S_R = surface retention (cm)
 = depression and interception losses
 = 1.0 cm

t_r = 3 hours (rainfall duration)

$$W_i = \frac{P - R - S_R}{t_r}$$

$$= \frac{7.5 - 3.0 - 1.0}{3.0}$$

$$= 1.166 \text{ cm/hr}$$

Example-2 : The rate of rainfall for successive 30 minutes periods of a 4-hour storm are given below

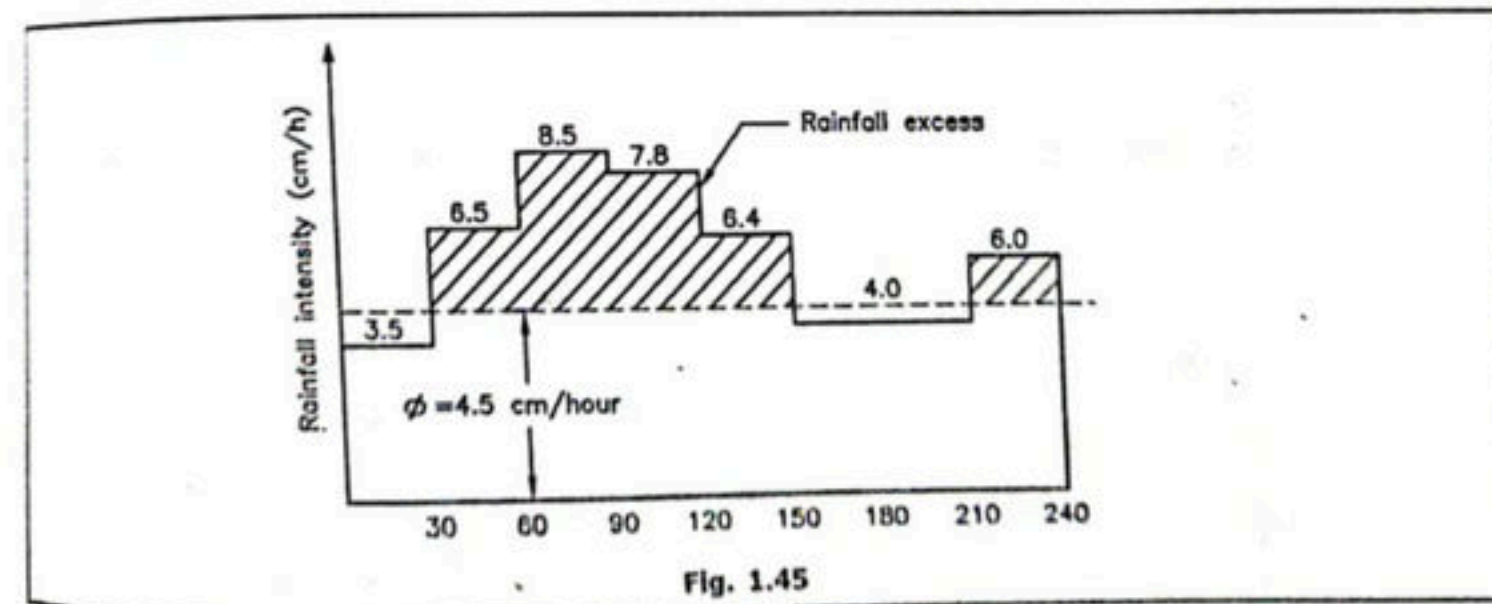
3.5, 6.5, 8.5, 7.8, 6.4, 4.0, 4.0, 6.0 cm/hr.

Taking a value of ϕ -index 4.5 cm/hr compute :

- (i) total rainfall
- (ii) total rainfall excess
- (iii) W-index

Solution :

The rainfall hyetograph is shown in Fig. 1.45 ϕ -index is also shown in it.



(i) Total rainfall :

$$P = (3.5 + 6.5 + 8.5 + 7.8 + 6.4 + 4.0 + 4.0 + 6.0) \times \frac{30}{60}$$

$$= (46.7) \times 0.5$$

$$= 23.35 \text{ cm}$$

(ii) total rainfall excess :

The hatched area above ϕ -index gives the total rainfall excess.

total rainfall excess

$$= [(6.5 - 4.5) + (8.5 - 4.5) + (7.8 - 4.5) + (6.4 - 4.5) + (6 - 4.5)] \times \frac{30}{60}$$

$$= (12.7) \times 0.5$$

$$= \boxed{6.35 \text{ cm}}$$

For values of P less than ϕ -index, there is no excess rainfall.

(iii) W-index

$$W_i = \frac{P - R}{t_r}$$

$$= \frac{23.35 - 6.35}{4}$$

$$= \boxed{4.25 \text{ cm/hr}}$$

Example-3 : A storm with a 15.0 cm precipitation produced a direct runoff of 8.7 cm. The time distribution of the storm is as follows :

Time from start in hr.	1	2	3	4	5	6	7	8
Incremental rainfall (cm)	0.6	1.35	2.25	3.45	2.7	2.4	1.5	0.75

Estimate ϕ -index of the storm.

(June 2014, April 2017, Dec. 2018)

Solution :

The hietograph of rainfall is drawn as shown in Fig. 1.46.

total precipitation, P = 15.0 cm

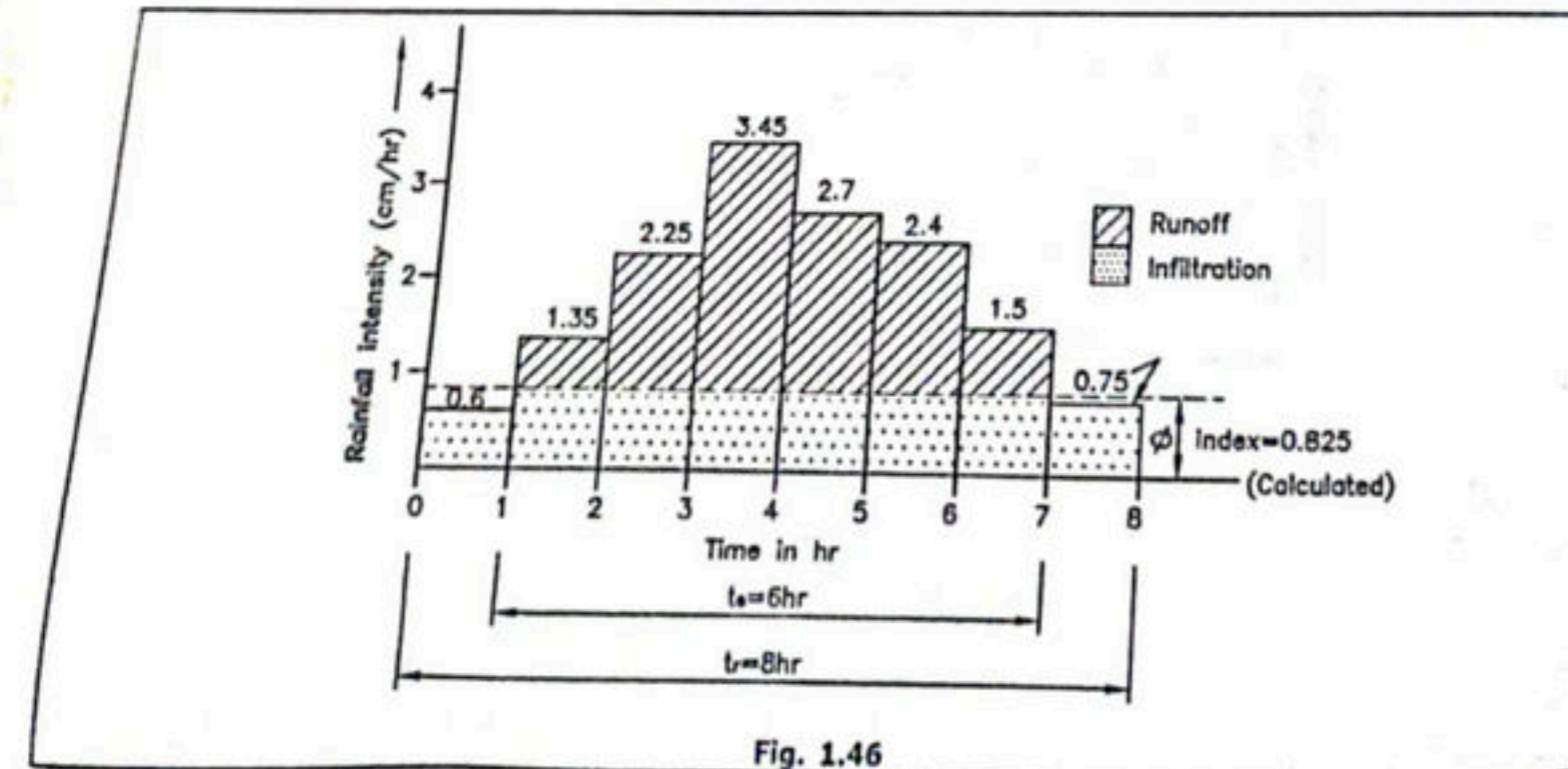


Fig. 1.46

Hydrological Parameters

total runoff, $R = 8.7 \text{ cm}$, $S_R = 0$

$$W_i = \frac{P - R - S_R}{t_r}$$

$$= \frac{15 - 8.7 - 0}{8}$$

$$= 0.7875 \text{ cm/hr}$$

Since ϕ -index has to be somewhat more than W -index, ϕ -index would be a little more than 0.7875 cm/hr .
 When this is so, evidently, the first hour rainfall 0.6 cm and 8^{th} hour rainfall 0.75 cm would become ineffective in producing excess rainfall, because the rainfall intensity in those two hours would be less than ϕ -index.

∴ the period during excess rain occurs would be only,

$$8 - 2 = 6 \text{ hours}$$

$$\therefore t_e = 6 \text{ hours}$$

$$\phi - \text{index} = \frac{\text{total infiltration during period of excess rainfall}}{\text{period of excess rainfall } (t_e)}$$

$$= \frac{\text{total infiltration} - \text{Infiltration during the period when no excess rainfall occurs}}{t_e}$$

$$\text{total infiltration} = P - R$$

$$= 15 - 8.7$$

$$= 6.3 \text{ cm}$$

$$\text{Infiltration during the period when no excess rain occurs}$$

$$= 0.6 + 0.75$$

$$= 1.35 \text{ cm}$$

$$\therefore \phi - \text{index} = \frac{(6.3 - 1.35)}{6}$$

$$= \frac{(6.3 - 1.35)}{6}$$

$$= 0.825 \text{ cm/hr}$$

Check : Hatched portion in Fig. 1.50 gives runoff.

$$\text{Runoff } (R) = \sum (i - \phi_i)t$$

$$= [(1.35 - 0.825) + (2.25 - 0.825) + (3.45 - 0.825) + (2.7 - 0.825) + (2.4 - 0.825) + (1.5 - 0.825)] \times 1$$

$$= 8.7 \text{ cm} \dots \text{ which is as given in data. } \therefore \text{OK}$$

Example-4 : A catchment area 30 km^2 has one recording gauge. During a storm, the following mass curve of rainfall was recorded.

Time from start of storm (hr)	0	2	4	6	8	10	12	14
Accumulated rainfall (mm)	0	6	17	57	70	81	87	90

If the volume of the runoff due to the storm measured is $1.2 \times 10^6 \text{ m}^3$, estimate the ϕ -index of the catchment.
(Similar May 2016)

Solution :

Total runoff volume = $1.2 \times 10^6 \text{ m}^3$

catchment area = 30 km^2

$$\therefore \text{Total runoff (depth)} = \frac{\text{total runoff volume}}{\text{catchment area}}$$

$$R = \frac{1.2 \times 10^6 \text{ m}^3}{30 \times 10^6 \text{ m}^2}$$

$$= 0.04 \text{ m}$$

$$= 40 \text{ mm}$$

Total rainfall, $P = 90 \text{ mm}$

$$\therefore \text{Total infiltration} = P - R$$

$$= 90 - 40$$

$$= 50 \text{ mm}$$

$$\therefore \text{W-index} = \frac{P - R}{t_r}$$

$$= \frac{90 - 40}{14} = 3.57 \text{ mm/hr}$$

Since ϕ -index has to be somewhat more than W-index, ϕ -index would be a little more than 3.57 mm/hr . Thus, infiltration for every 2-hour interval would be little more than $2 \times 3.57 = 7.14 \text{ mm}$.

The incremental rainfalls in different 2 hr intervals are now worked out as below.

Time from start of storm in (hr)	Accumulated rainfall in (mm)	Incremental rainfall during each interval in mm
0	0	-
2	6	6
4	17	11
6	57	40
8	70	13
10	81	11
12	87	6
14	90	3
		$\Sigma P = 90 \text{ mm}$

$$\text{W-index (infiltration)} = 2 \times 3.57$$

$$= 7.14 \text{ mm for every 2-hours}$$

Thus, by the observation of table, it is evident that incremental rainfall during first interval and last two intervals is less than 7.14 mm , thus it would be ineffective in producing excess rainfall.

\therefore the period during excess rain occurs would be only,

$$14 - 3 \times 2 = 8 \text{ hours}$$

$$\therefore t_c = 8 \text{ hours}$$

Hydrological Parameters

$$\phi - \text{index} = \frac{\text{total infiltration during period of excess rainfall}}{\text{period of excess rainfall } (t_e)}$$

$$= \frac{\text{total infiltration} - \text{Infiltration during the period when no excess rain occurs}}{t_e}$$

$$\text{total infiltration} = P - R$$

$$= 90 - 40 = 50 \text{ mm}$$

$$\text{infiltration during the period when no excess rain occurs} = 6 + 6 + 3$$

$$= 15 \text{ mm}$$

$$\phi - \text{index} = \frac{50 - 15}{8}$$

$$= 4.375 \text{ mm/hr}$$

Example-5 : Hourly rainfalls of 2.5, 6 and 3 cm occur over a 20-ha area consisting 4 ha of $\phi = 5 \text{ cm/hr}$, 10 ha of $\phi = 3 \text{ cm/hr}$ and 6 ha of $\phi = 1 \text{ cm/hr}$.
Derive hourly values of net rain.

Solution :

1st hour $P = 2.5 \text{ cm}$

$$P_{\text{net-mean}} = \frac{4(0) + 10(0) + 6(2.5 - 1)}{20}$$

$$= 0.45 \text{ cm}$$

2nd hour $P = 6 \text{ cm}$

$$P_{\text{net-mean}} = \frac{4(6 - 5) + 10(6 - 3) + 6(6 - 1)}{20}$$

$$= 3.20 \text{ cm}$$

3rd hour $P = 3 \text{ cm}$

$$P_{\text{net-mean}} = \frac{4(0) + 10(3 - 3) + 6(3 - 1)}{20}$$

$$= 0.6 \text{ cm}$$

$$\text{total net rain for the 3-hour storm} = 0.45 + 3.20 + 0.6$$

$$= 4.25 \text{ cm}$$

Example-6 : A catchment has an area $A = 2.26 \text{ km}^2$, gives direct runoff volume of $5.6 \times 10^4 \text{ m}^3$. Find ϕ -index from the following data :

Time (hr)	Rainfall intensity (mm/hr)
0 - 2	7.1
2 - 5	11.7
5 - 7	5.6
7 - 10	3.6
10 - 12	1.5

Solution :

$$\text{Total runoff volume} = 5.6 \times 10^4 \text{ m}^3$$

$$\begin{aligned} \text{Catchment area} &= 2.26 \text{ km}^2 \\ &= 2.26 \times 10^6 \text{ m}^2 \end{aligned}$$

$$\therefore \text{Total runoff depth} = \frac{\text{total runoff volume}}{\text{catchment area}}$$

$$\begin{aligned} R &= \frac{5.6 \times 10^4 \text{ m}^3}{2.26 \times 10^6 \text{ m}^2} \\ &= 0.0248 \text{ m} \\ &= 24.8 \text{ mm} \end{aligned}$$

Total rainfall,

$$\begin{aligned} P &= (2 \times 7.1) + (3 \times 11.7) + (2 \times 5.6) + (3 \times 3.6) + (2 \times 1.5) \\ &= 74.3 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{The losses are} &= P - R \\ &= 74.3 - 24.8 \\ &= 49.5 \text{ mm} \end{aligned}$$

$$t_r = 12 \text{ hours}$$

$$\begin{aligned} \therefore \text{average loss rate (W-index)} &= \frac{49.5}{12} \\ &= 4.125 \text{ mm/hr} \end{aligned}$$

However during the time period 7 - 10 and 10 - 12 hours, the rainfall intensity is less than 4.125 mm/hr, which implies that it would be ineffective in producing excess rainfall.

$$\begin{aligned} \therefore \text{The period during excess rain occurs would be only} &= 12 - 5 \\ &= 7 \text{ hours} \end{aligned}$$

$$\therefore t_e = 7 \text{ hours}$$

$$\therefore \phi - \text{index} = \frac{\left[\text{total infiltration} - \text{infiltration during the period when no excess rain occurs} \right]}{t_e}$$

$$\begin{aligned} \text{total infiltration} &= P - R \\ &= 49.5 \text{ mm} \end{aligned}$$

$$\begin{aligned} \text{infiltration during period when no excess rain} & \\ &= (3 \times 3.6) + (2 \times 1.5) \\ &= 13.8 \text{ mm} \end{aligned}$$

$$\begin{aligned} \therefore \phi - \text{index} &= \frac{(49.5 - 13.8)}{7} \\ &= \frac{35.7}{7} = 5.10 \text{ mm/hr} \end{aligned}$$

Example-7 : For a particular place in November the P.C. of sunshine hours is 7.2 and mean temperature is 18°C. If the consumptive use coefficient of the crop is 0.7 for that month, find the evapotranspiration (Consumptive use) for the crop in mm/day using Balney-Criddle method.

Meteorological Parameters

Solution :

Rainey - Criddle equation is,

$$C_e = ET = \frac{kp (4.6 T_m + 81.3)}{100} \text{ cm/month}$$

$$k = 0.7$$

$$p = 7.2$$

$$T_m = 18^\circ\text{C}$$

$$C_e = ET = 0.7 \times 7.2 \left[\frac{4.6 \times 18 + 81.3}{100} \right]$$

$$= 8.27 \text{ cm/month}$$

$$= \frac{8.27 \times 10}{30}$$

$$= \boxed{2.756 \text{ mm/day}}$$

Example-8 : A reservoir with a surface area 400 hectares has the following average meteorological values during a given week.

water temperature = 30°C

relative humidity = 50%

wind velocity 1 m above ground = 12 km/h

Mean barometer reading = 750 mm of mercury

Estimate the average daily evaporation from the lake reservoir and the volume of water evaporated from the lake during this week. Use

(a) Meyer's method (b) Rohwer's method

Take saturation vapour pressure at $30^\circ\text{C} = 31.82 \text{ mm of Hg}$

Solution :

(a) Meyer's method :

$$\text{Evaporation, } E = k_m (e_s - e_a) \left[1 + \frac{V_w}{16} \right] \dots (a)$$

where,

$k_m = 0.36$ for large deep water

$e_s =$ saturation vapour pressure at 30°C

$= 31.82 \text{ mm of Hg}$

$e_a =$ actual vapour pressure

$= \dots ?$

Also,

$$\frac{e_a}{e_s} = 50\% \text{ (R.H.)}$$

$$\therefore e_a = 0.5 e_s$$

$$= 0.5 \times 31.82$$

$$= 15.91 \text{ mm of Hg}$$

$$V_1 = 12 \text{ km/h}$$

$$\frac{v_0}{v_1} = \left[\frac{9}{1} \right]^{1/7} = 1.368$$

$$\begin{aligned} \therefore V_0 &= V_1 \times 1.368 \\ &= 12 \times 1.368 \\ &= 16.43 \text{ km/h} \end{aligned}$$

substituting these values in eq. (a).

$$\begin{aligned} \therefore E &= 0.36 (31.82 - 15.91) \times \left[1 + \frac{16.43}{16} \right] \\ &= 11.61 \text{ mm/day} \end{aligned}$$

\therefore Total evaporation volume in 7 days (1 week) from 400 hectares of surface area :

$$\begin{aligned} &= \frac{11.61 \text{ m}}{1000 \text{ day}} \times 7 \text{ days} \times (400 \times 10^4 \text{ m}^2) \\ &= \boxed{3,25,080 \text{ m}^3} \end{aligned}$$

(b) Rohwer's method

$$E = 0.771 (1.465 - 0.000732 P_a) \times (0.44 + 0.0733 V_{0.6}) \times (e_s - e_a) \quad \dots (b)$$

where,

$$e_s = 31.82 \text{ mm of Hg}$$

$$e_a = 15.91 \text{ mm of Hg}$$

$$P_a = 750 \text{ mm of Hg}$$

$$\frac{V_{0.6}}{V_1} = \left[\frac{0.6}{1} \right]^{1/7} = 0.9296$$

$$\begin{aligned} \therefore V_{0.6} &= 0.9296 V_1 \\ &= 0.9296 \times 12 \\ &= 11.15 \text{ km/h} \end{aligned}$$

Substituting these values in eq. (b)

$$\begin{aligned} \therefore E &= 0.771 (1.465 - 0.000732 \times 750) \times (0.44 + 0.0733 \times 11.15) \times (31.82 - 15.91) \\ &= 14.13 \text{ mm/day} \end{aligned}$$

\therefore total evaporation volume in 7 days (1 week) from 400 hectares of surface area :

$$\begin{aligned} &= \frac{14.13 \text{ m}}{1000 \text{ day}} \times 7 \text{ days} \times (400 \times 10^4 \text{ m}^2) \\ &= \boxed{395,640 \text{ m}^3} \end{aligned}$$

Example-9 : The following observations were taken from a double ring infiltrometer with inner ring plot have towards the end. Also compute the average infiltration rate for the first 10 and first 30 minutes.

Hydrological Parameters

Time (min.)	0	2	5	10	20	30	45	60	80	100	120	150	180
Cumulative volume (cm ³)	0	200	470	840	1405	1840	2245	2510	2745	2885	2990	3130	3270

Solution :

$$\text{Area of infiltratometer } A = \frac{\pi}{4} \times (30)^2 = 706.86 \text{ cm}^2$$

The computations are given in the table.

Time (min)	Time increment Δt hours	Cumulative volume of water added V (cm ³)	Cumulative infiltration $F = V/A$ (cm)	Incremental infiltration ΔF (cm)	Infiltration rate $f_t = \Delta F/\Delta t$ (cm)
(1)	(2)	(3)	(4)	(5)	(6)
0	0	0	0	-	-
2	0.0333	200	0.283	0.283	8.5
5	0.0500	470	0.665	0.382	7.64
10	0.0833	840	1.188	0.523	6.28
20	0.1667	1405	1.988	0.800	4.80
30	0.1667	1840	2.603	0.615	3.69
45	0.2500	2245	3.176	0.573	2.29
60	0.2500	2510	3.551	0.375	1.50
80	0.3333	2745	3.883	0.332	1.00
100	0.3333	2885	4.081	0.198	0.59
120	0.3333	2990	4.230	0.149	0.45
150	0.5000	3130	4.428	0.198	0.40
180	0.5000	3270	4.626	0.198	0.40

Calculations in table

$$\text{For column (2)} \rightarrow 0 - 2 = 2 \text{ min} = \frac{2}{60} = 0.0333 \text{ hr}$$

$$2 - 5 = 3 \text{ min} = \frac{3}{60} = 0.0500 \text{ hr}$$

$$5 - 10 = 5 \text{ min} = \frac{5}{60} = 0.0833 \text{ hr}$$

$$\text{For column (4)} \rightarrow F = \frac{V}{A} = \frac{200}{706.85} = 0.283 \text{ cm}$$

$$F = \frac{V}{A} = \frac{470}{706.85} = 0.665 \text{ cm}$$

$$\begin{aligned} \text{For column (5)} \rightarrow & 0.283 - 0 = 0.283 \\ & 0.665 - 0.283 = 0.382 \\ & 1.188 - 0.665 = 0.523 \end{aligned}$$

A graph between rate of infiltration (f_t) versus time in minutes is drawn, which called infiltration capacity curve.

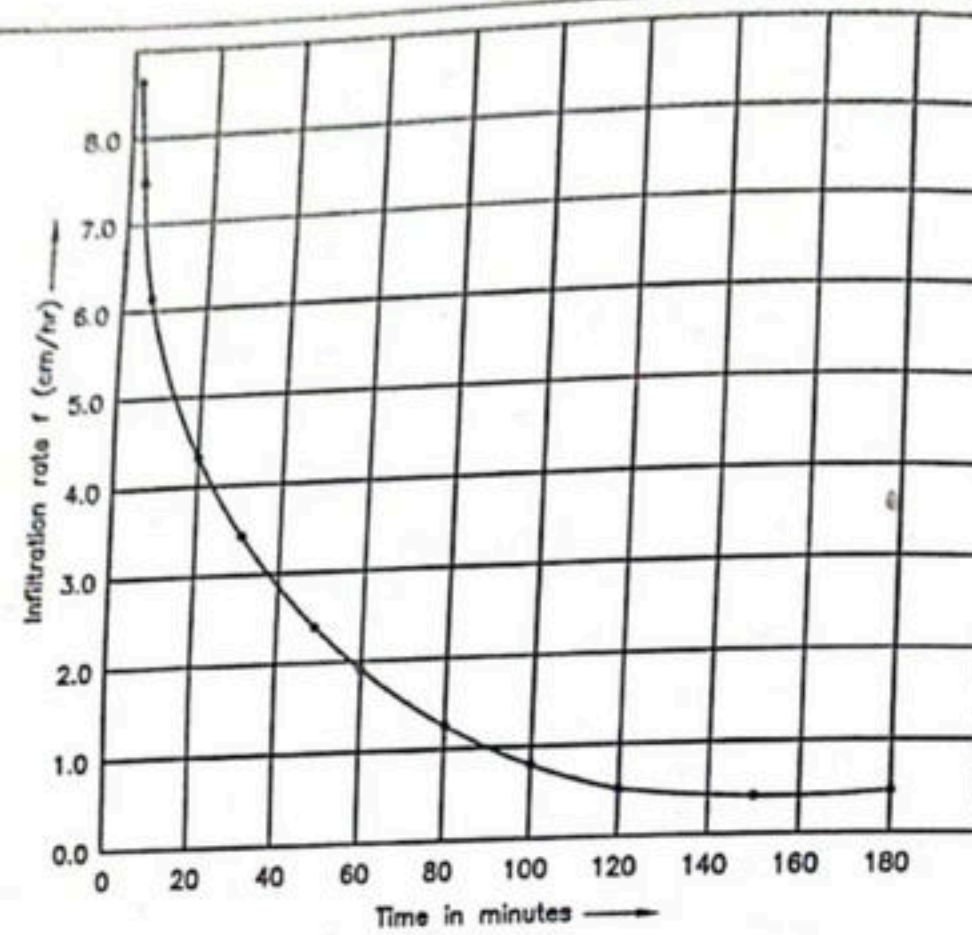


Fig. 1.47 Infiltration capacity curve

From the table as well as from the graph, constant rate of infiltration is,

$$f_c = 0.40 \text{ cm/hr}$$

which is also the minimum infiltration capacity.

Average rate of infiltration for the first 10 minutes

$$= \frac{1.188}{(10/60)} = 7.13 \text{ cm/hr}$$

Average rate of infiltration for the first 30 minutes

$$= \frac{2.603}{(30/60)} = 5.21 \text{ cm/hr}$$

Example-10 : The Horton's infiltration equation $f(t)$ describe how the infiltration capacity (mm/hr) for the soil is changing with time as the soil becomes wetter. In a specific soil, the following parameters are known :

$$f_0 = 35 \text{ mm/hr}$$

$$f_c = 6 \text{ mm/hr}$$

$$k = 2 \text{ per hour}$$

- (a) What is the infiltration capacity after 15, 30 and 60 min ?
 (b) How much water has infiltrated after 15, 30 and 60 min ?

Solution : (a) Infiltration capacity

The infiltration rate (f) at any instant of time is given by Horton's equation as,

$$f(t) = f_c + (f_0 - f_c) e^{-kt} \dots \text{mm/hr}$$

$$\text{after } t = 15 \text{ min} = \frac{15}{60} = 0.25 \text{ hr}$$

$$f(0.25) = 6 + (35 - 6)e^{-2 \times 0.25} \\ = 23.58 \text{ mm/hr}$$

$$\text{after } t = 30 \text{ min} = \frac{30}{60} = 0.50 \text{ hr}$$

$$f(0.50) = 6 + (35 - 6)e^{-2 \times 0.50} \\ = 16.66 \text{ mm/hr}$$

$$\text{after } t = 60 \text{ min} = 1 \text{ hr}$$

$$f(1.0) = 6 + (35 - 6)e^{-2 \times 1.0} \\ = 9.92 \text{ mm/hr}$$

(b) Accumulated infiltrated water :

We know that,

$$f(t) = f_c + (f_0 - f_c) e^{-kt}$$

The accumulated infiltrated water can be calculated using the integral of $f(t)$.

$$\therefore F(t) = f_c t + \frac{(f_0 - f_c)}{k} (1 - e^{-kt})$$

$$\text{after } t = 15 \text{ min} = \frac{15}{60} = 0.25 \text{ hr}$$

$$F(0.25) = 6 \times 0.25 + \frac{(35 - 6)}{2} \times (1 - e^{-2 \times 0.25}) \\ = 1.5 + 14.5 \times 0.3934 \\ = 7.205 \text{ mm}$$

$$\text{after } t = 30 \text{ min} = 30/60 = 0.50 \text{ hr}$$

$$\therefore F(0.50) = 6 \times 0.5 + \left(\frac{35 - 6}{2} \right) (1 - e^{-2 \times 0.50}) \\ = 3 + 14.5 \times 0.6321 = 12.16 \text{ mm}$$

$$\text{after } t = 60 \text{ min} = 1 \text{ hr}$$

$$F(1) = 6 \times 1 + \left(\frac{35 - 6}{2} \right) (1 - e^{-2 \times 1}) \\ = 6 + 14.5 \times 0.8646 \\ = 18.54 \text{ mm}$$

Example-11 : Calculate the potential evapotranspiration (PET) using Penman's method, for a location with the following meteorological data :

Latitude of place : $28^{\circ}4'$

saturation vapour pressure (e_s) = 17.54 mm of Hg

mean solar radiation (H_c) = 9.506 mm water per day

Average monthly temperature = 20°C

Average relative humidity = 75%

$A = 1.05 \text{ mm}^{\circ}\text{C}$

Average sunshine hours per day = 9 hrs

Maximum possible hours of bright sunshine = 10.7 hours per day

Average wind velocity at 2 m above ground = 85 km/day

Surface cover : close grained crops

Solution :

The Penman's equation is given by,

$$\text{PET} = \frac{A \cdot H_n + E_a \cdot \gamma}{(A + \gamma)}$$

where,

$$H_n = H_c (1 - r) \left(a + b \frac{n}{N} \right) - \sigma T_a^4 (0.56 - 0.092 \sqrt{e_a})$$

$$\times (0.10 + 0.90 \frac{n}{N})$$

$$e_s = 17.54 \text{ mm of Hg}$$

$$\frac{e_a}{e_s} = 75\% \text{ (R.H.)}$$

$$\therefore e_a = 0.75 e_s$$

$$= 0.75 \times 17.54$$

$$= 13.16 \text{ mm of Hg}$$

$$n = 9 \text{ hours/day}$$

$$N = 10.7 \text{ hours/day}$$

$$\phi = \text{Latitude} = 28^{\circ}4'$$

$$\therefore a = 0.29 \cos \phi$$

$$= 0.29 \cos 28^{\circ}4'$$

$$= 0.2559$$

$$b = 0.52 \text{ (assume average value)}$$

$$\sigma = 2.01 \times 10^{-9} \text{ mm/day}$$

$$T_a = 273^{\circ} + 20^{\circ}\text{C} = 293 \text{ K}$$

$$r = 0.25 \text{ (For close grained crops)}$$

$$H_c = 9.506 \text{ mm water per day}$$

$$H_e = H_e (1 - r) \left(a + b \frac{n}{N} \right) - \sigma T_a^4 (0.56 - 0.092 \sqrt{e_a}) \times (0.10 + 0.90 \frac{n}{N})$$

$$= 0.506 (1 - 0.25) \times (0.2559 + 0.52 \frac{9}{10.7}) - 2.01 \times 10^{-9} \times$$

$$(293)^4 \times (0.56 - 0.092 \times \sqrt{13.16}) \times (0.10 + 0.9 \times \frac{9}{10.7})$$

$$= 4.043 - 3.351 \times 0.857$$

$$= 2.07 \text{ mm H}_2\text{O (water) per day}$$

$$E_p = 0.35 \left[1 + \frac{V_z}{160} \right] (e_x - e_a)$$

$$= 0.35 \left[1 + \frac{85}{160} \right] (17.54 - 13.16)$$

$$= 2.347 \text{ mm of H}_2\text{O per day}$$

Now,

$$ETP = \frac{A \cdot H_e + E_p \cdot \gamma}{(A + \gamma)}$$

$$= \frac{1.05 \times 2.07 + 2.347 \times 0.49}{1.05 + 0.49}$$

$$= \boxed{2.158 \text{ mm of H}_2\text{O per day}}$$

Example-12 : The average rainfall over a basin of area 50 ha during a storm was as follows :

Time (hr)	0	1	2	3	4	5	6	7
Rainfall (cm)	0	6	11	34	28	12	6	0

If volume of runoff from this storm was measured as 25000 m³, determine the ϕ -index for the storm.

Solution :

Total runoff volume = 25000 m³

Catchment area = 50 ha = 50 × 10⁴ m²

∴ Total runoff depth = $\frac{\text{total runoff volume}}{\text{catchment area}}$

$$R = \frac{25000 \text{ m}^3}{50 \times 10^4 \text{ m}^2}$$

$$= 0.05 \text{ m}$$

$$= 5 \text{ cm}$$

Total rainfall, P = 6 + 11 + 34 + 28 + 12 + 6

$$= 97 \text{ cm}$$

Total infiltration = P - R

$$= 97 - 5$$

$$= 92 \text{ cm}$$

$t_r = 7 \text{ hr}$

$$\begin{aligned} \therefore W\text{-index} &= \frac{P - R}{t_r} \\ &= \frac{92}{7} \\ &= 13.14 \text{ cm/hr} \end{aligned}$$

Since ϕ -index has to be somewhat more than W-index, ϕ -index would be little more than 13.14 cm/hr. When it is so, evidently, the first 0 - 2 hours rainfall, and last 5 - 7 hours rainfall would become ineffective in producing excess rainfall, because the rainfall intensity in those hours would be less than ϕ -index.

\therefore the period during excess rain occurs would be only, $7 - 5 = 2$ hours

$$\therefore t_e = 2 \text{ hours}$$

$$\text{total infiltration} = P - R = 92 \text{ cm}$$

infiltration during the period when no excess rain occurs

$$= 6 + 11 + 12 + 6 + 0$$

$$= 35 \text{ cm}$$

$$\begin{aligned} \therefore \phi\text{-index} &= \frac{92 - 35}{t_e} \\ &= \frac{92 - 35}{2} \\ &= \boxed{28.5 \text{ cm/hr}} \end{aligned}$$

Example-13 : Results to determine Horton's infiltration capacity (f_{ct}) in the exponential form are tabulated below :

Time (hr)	0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0
f_{ct} (cm/hr)	5.60	3.20	2.10	1.50	1.20	1.10	1.0	1.0

Determine the infiltration capacity exponential equation.

Solution : The infiltration capacity (f_{ct}) at any instant of time is given by Horton's equation.

$$(f_{ct}) = f_c + (f_0 - f_c) e^{-kt} \quad \dots (a) \quad \left| \quad f_{ct} = f \right.$$

From the data it is evident that the infiltration capacity (f_c) reaches a constant value equal to $f_c = 1.0$ cm/hr.

The values of $(f_{ct} - f_c)$ are tabulated below :

Time (hr)	0.25	0.50	0.75	1.0	1.25	1.50	1.75	2.0
f_{ct} (cm/hr)	5.60	3.20	2.10	1.50	1.20	1.10	1.0	1.0
$(f_{ct} - f_c)$ cm/hr	4.60	2.20	1.10	0.50	0.20	0.10	0	0
$\log_{10} (f_{ct} - f_c)$	0.663	0.342	0.042	-0.301	-0.699	-1.0	-	-

Now a graph is plotted with $\log_{10} (f_{ct} - f_c)$ as abscissa and time t (hours) as ordinate on ordinary graph paper.

The slope of Horton's curve is given by,

$$m = \text{slope} = \frac{-1}{k \log_{10} e} \dots \text{-ve sign shows that as } t \text{ increases } (f_{ct} - f_c) \text{ decreases.}$$

Measure the slope of line from the graph.

$$m = \frac{-0.76}{1} = \frac{-1}{1.32}$$

$$\frac{-1}{k \log_{10} e} = \frac{-1}{1.32}$$

$$1.32 = k \log_{10} e$$

$$1.32 = k \log_{10}^{2.718} = k \times 0.4342$$

$$k = 3.04$$

Hence the equation of the infiltration capacity curve (I.C.C.) is given by

$$f_{ct} = f_c + (f_0 - f_c) e^{-kt}$$

$$f_{ct} = 1.0 + (5.6 - 1.0) e^{-3.04t} \quad | \quad f_0 = 5.6$$

$$f_{ct} = f = 1.0 + 4.6 e^{-3.04t}$$

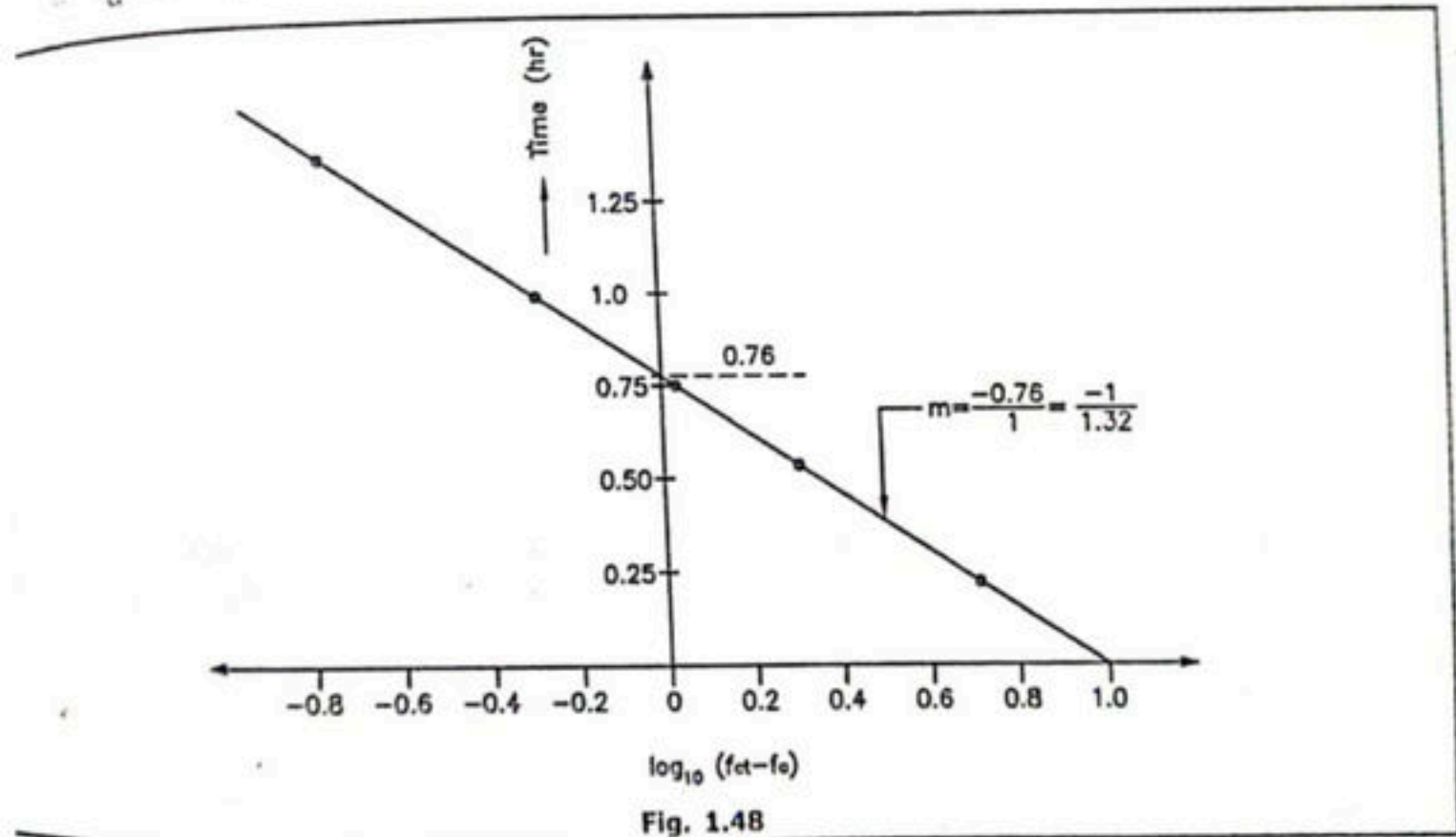


Fig. 1.48

Example-14 : Assuming the initial infiltration rate of 10 mm/h, final infiltration rate of 5 mm/h and constant rate of decay 0.95 h^{-1} , calculate the total infiltration depth for a storm lasting 6 hours.

Solution :

- $f_0 = 10 \text{ mm/h}$
- $f_c = 5 \text{ mm/h}$
- $f = \text{infiltration rate at any time } t$

The equation of infiltration capacity curve is given by :

$$f = f_c + (f_0 - f_c) e^{-kt}$$

$$k = 0.95 \text{ h}^{-1} \text{ (rate of decay of infiltration rate)}$$

Substituting values,

$$f = 5 + (10 - 5) e^{-0.95t}$$

$$= 5 + 5 e^{-0.95t}$$

To find the total infiltration, Σf in mm during 6 hour storm, integrate the above equation between 0 to 6 hour as,

$$\begin{aligned} \sum_0^{6\text{hr}} f &= \int_0^6 5 + 5 e^{-0.95t} \\ &= \int_0^6 5 + \int_0^6 5 e^{-0.95t} \\ &= 5[t]_0^6 + 5 \left[\frac{e^{-0.95t}}{-0.95} \right]_0^6 \\ &= 5(6 - 0) + 5 \left[-\frac{e^{-0.95 \times 6}}{0.95} - \frac{e^0}{0.95} \right] \\ &= 30 + \frac{5}{0.95} [e^0 - e^{5.7}] \\ &= 30 + \frac{5}{0.95} (1 - 3.346 \times 10^{-3}) \\ &= 30 + 5.245 \\ &= 35.245 \text{ mm} \end{aligned}$$

Example-15 : The infiltration capacity in a basin is represented by Horton's equation as $f = 3.0 + e^{-2t}$ where f is in cm/h and t is in hours. Assuming the infiltration to take place at capacity rates in a storm of 60 minutes duration, estimate the depth of infiltration in

- first 30 minutes
- second 30 minutes of the storm.

Solution :

$$f = 3.0 + e^{-2t}$$

$$\therefore F = \int_0^t f \cdot dt$$

(i) Infiltration in first 30 minutes :

$$t = 30 \text{ minutes} = \frac{30}{60} = 0.5 \text{ hr}$$

$$\begin{aligned}
 F(0.5) &= \int_0^{0.5} (3 + e^{-2t}) dt \\
 &= [3t]_0^{0.5} + \left[\frac{e^{-2t}}{-2} \right]_0^{0.5} \\
 &= 1.5 - \frac{1}{2} (e^{-2 \cdot 0.5} - e^0) \\
 &= 1.5 - \frac{1}{2} (0.3678 - 1.0) \\
 &= \boxed{1.184 \text{ cm}}
 \end{aligned}$$

(ii) Infiltration in second 30 minutes :

$$t = 30 \text{ minutes} = 0.5 \text{ hr.}$$

$$\begin{aligned}
 F(0.5) &= \int_{0.50}^{1.0} (3 + e^{-2t}) dt \\
 &= [3t]_{0.5}^{1.0} + \left[\frac{e^{-2t}}{-2} \right]_{0.5}^{1.0} \\
 &= (3 - 1.5) - \frac{1}{2} (e^{-2 \cdot 1} - e^{-2 \cdot 0.5}) \\
 &= 1.5 - \frac{1}{2} (0.1353 - 0.3678) \\
 &= 1.5 - (-0.1162) \\
 &= \boxed{1.616 \text{ cm}}
 \end{aligned}$$

Example-16 : The infiltration capacity of soil in a small watershed was found to be 6 cm/hr before a rainfall event. It was found to be 1.2 cm/hr at the end of 8 hours of storm. If the total infiltration during the 8 hours period of storm was 15 cm, estimate the value of the decay coefficient k , in Horton's infiltration capacity equation.

Solution :

Horton's equation,

$$f = f_c + (f_0 - f_c) e^{-kt}$$

$$\text{and } F = \int_0^t f \cdot dt$$

$$= \int_0^t [f_c + (f_0 - f_c) e^{-kt}] dt$$

$$= f_c t + (f_0 - f_c) \int_0^t e^{-kt} \cdot dt$$

$$\text{As } t \rightarrow \infty, \int_0^{\infty} e^{-kt} dt \rightarrow \frac{1}{k}$$

total precipitation, $P = 10$ cm

total runoff, $R = 6.0$ cm, $t_r = 8$ hours

$$\begin{aligned} \therefore W_i &= \frac{P - R}{t_r} \\ &= \frac{10 - 6.0}{8} = 0.5 \text{ cm/hr} \end{aligned}$$

Since ϕ -index has to be some what more than W -index, ϕ -index would be a little more than 0.5 cm/hr.

When this is so, evidently, the first hour rainfall 0.1 cm and 8th hour rainfall 0.4 cm would become ineffective in producing excess rainfall, because the rainfall intensity in those two hours would be less than ϕ -index.

\therefore The period during excess rain occurs would be only

$$8 - 2 = 6 \text{ hours}$$

$$\therefore t_e = 6 \text{ hours}$$

$$\begin{aligned} \phi\text{-index} &= \frac{\text{total infiltration during period of excess rainfall}}{t_e} \\ &= \frac{[\text{total infiltration} - \text{infiltration during the period when no excess rainfall occurs}]}{t_e} \end{aligned}$$

$$\begin{aligned} \text{total infiltration} &= P - R \\ &= 10 - 6 = 4 \text{ cm} \end{aligned}$$

$$\begin{aligned} \text{Infiltration during the period when no excess rain occurs} \\ &= 0.1 + 0.4 \\ &= 0.5 \text{ cm} \end{aligned}$$

$$\begin{aligned} \therefore \phi\text{-index} &= \frac{(4.0 - 0.5)}{t_e} \\ &= \frac{(4.0 - 0.5)}{6} = 0.583 \text{ cm/hr} \end{aligned}$$

Hatched portion in the figure gives runoff.

Check :

$$\begin{aligned} \text{Runoff (R)} &= \sum (i - \phi_i) t \\ &= [(1 - 0.583) + (1.4 - 0.583) + (2.6 - 0.583) + (2.0 - 0.583) \\ &\quad + (1.5 - 0.583) + (1 - 0.583)] \times 1 \\ &= 6.0 \text{ cm which is as given in the data} \quad \therefore \text{OK.} \end{aligned}$$

Example-20 : Calculate the rainfall excess from the rainfall hyetograph data given below. Assume ϕ -index = 0.25 cm/hr. (Nov. 2016)

Time	8 am to 9 am	9 am to 10 am	10 am to 11 am	11 am to 12 noon	12 noon to 1 pm	1 pm to 2 pm	2 pm to 3 pm	3 pm to 4 pm	4 pm to 5 pm
Rainfall intensity(cm/hr)	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8

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Solution :

Since all values of rainfall intensity are more than ϕ -index, all rainfall will produce rainfall excess.

$$\begin{aligned} \text{Total rainfall excess} &= [(1 - 0.25) + (1.1 - 0.25) + (1.2 - 0.25) + (1.3 - 0.25) + (1.4 - 0.25) \\ &+ (1.5 - 0.25) + (1.6 - 0.25) + (1.7 - 0.25) + (1.8 - 0.25)] \times \frac{60}{60} \\ &= 10.35 \text{ cm} \end{aligned}$$

Example-21 : A storm of 10 cm precipitation produced a direct runoff of 5.8 cm, the duration of rainfall was 16 hours and its distribution is given below. Estimate the infiltration index of the storm. (Nov. 2017)

Time from start (hour)	0	2	4	6	8	10	12	14	16
Cumulative rainfall (cm)	0	0.4	1.3	2.8	5.1	6.9	8.5	9.5	10.0

Solution :

Time from start (hour)	0	2	4	6	8	10	12	14	16
Cumulative rainfall (cm)	0	0.4	1.3	2.8	5.1	6.9	8.5	9.5	10.0
Incremental rainfall (cm)	0	0.4	0.9	1.5	2.3	1.8	1.6	1.0	0.5

Total precipitation, $P = 10 \text{ cm}$

Total runoff, $R = 5.8 \text{ cm}$, $S_R = 0$

$t_r = 16 \text{ hours}$

$$W_s = \frac{P - R}{t_r} = \frac{10 - 5.8}{16} = 0.2625 \text{ cm/hr.}$$

Since ϕ -index has to be somewhat more than W_s -index, ϕ -index would be little more than 0.2625 cm/hr.

When this is so, evidently, all incremental rainfall values are higher than 0.2625 cm/hr. Hence, all rainfall values would be effective in producing excess rainfall.

\therefore effective period of excess rainfall, $t_e = 16 \text{ hours}$.

$$\begin{aligned} \phi\text{-index} &= \frac{\text{total infiltration during period of excess rainfall}}{\text{Period of excess rainfall}} \\ &= \frac{(\text{total infiltration} - \text{infiltration during the period when no excess rainfall})}{t_e} \end{aligned}$$

$$\begin{aligned} \text{Total infiltration} &= P - R \\ &= 10 - 5.8 \\ &= 4.2 \text{ cm} \end{aligned}$$

Infiltration during the period when no excess rain occurs = 0

$$\therefore \phi\text{-index} = \frac{(4.2 - 0)}{16}$$

$$= 0.2625 \text{ cm/hr.}$$

Note : When all incremental values of rainfall are higher than w-index, ϕ -index will be equal to w-index.

EXERCISE

- Describe recording and non-recording type of rain gauge stations. (April 2017)
- Discuss factors affecting evapo-transpiration. (Nov. 2014)
- What is hydrological cycle ? Give a brief description of different components of a hydrological cycle. (Nov. 2014)
- Explain the terms :
 - ϕ -index
 - W - index
 - W_{\min} index
- What is transpiration ? What are the various factors that affect transpiration ? How would you measure transpiration ? What is transpiration ratio ?
- Differentiate between the infiltration capacity and the infiltration index. How would you measure the infiltration capacity ?
- Enlist different types of raingauges and explain the use of a non-recording rain gauge in the measurement of rainfall.
- Explain 'evapotranspiration'. Enlist different methods of measurement of evapotranspiration and describe any one of them. (April 2017)
- What is evaporation ? Mention the factors affecting evaporation. (May 2015)
- Discuss Dalton's law for evaporation from water surfaces. For a large water surface, explain the influence of depth on the rate of evaporation.
- Explain the terms :
 - Infiltration capacity
 - Infiltration rate
 - Rainfall excess
- Write the form of an equation, expressing the relation between infiltration capacity and time, as suggested by Horton.
- List various methods to measure evaporation from large water surface.