# *Engneering Hydrology*

## References:

1. ***Engineering Hydrology by Subramanya***
2. ***Advanced Hydrology by V.T. Chow***
3. ***Engineering Hydrology by Linsley***

## Contents:

# Chapter 1
# Introduction

## 1.1 Hydrology:

Hydrology means the science of water. It is the science that deals with the occurrence, circulation and distribution of water of the earth and earth's atmosphere. As a branch of earth science, it is concerned with the water in streams and lakes, rainfall and snow-fall, snow and ice on the land and water occurring below the earth's surface in the pores of the soil and rocks. In a general sense, hydrology is a very broad subject of an inter-disciplinary nature drawing support from allied sciences, such as meteorology, geology, statistics, chemistry, physics and fluid mechanics.

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

1. **Scientific hydrology**—the study which is concerned chiefly with academic aspects.
2. **Engineering or applied hydrology**—a study concerned with engineering applications.

In a general sense engineering hydrology deals with (i) estimation of water resources, (ii) the study of processes such as precipitation, runoff, evapotranspiration and their interaction and (iii) the study of problems such as floods and droughts, and strategies to combat them.

## 1.2. Hydrological Cycle

Hydrologic cycle (Fig. 1.1) is the water transfer cycle, which occurs continuously in nature; the three important phases of the hydrologic cycle are:

(*a*) Evaporation and evapotranspiration

(*b*) Precipitation and

(*c*) Runoff

The globe has one-third land and two thirds ocean. Evaporation from the surfaces of ponds, lakes, reservoirs. ocean surfaces, etc. and transpiration from surface vegetation i.e., from plant leaves of cropped land and forests, etc. take place. These vapours rise to the sky and are condensed at higher altitudes by condensation nuclei and form clouds, resulting in droplet growth. The clouds melt and sometimes burst resulting in precipitation of different forms like rain, snow, hail, sleet, mist, dew and frost. A part of this precipitation flows over the land called runoff and part infilters into the soil which builds up the ground water table. The surface runoff joins the streams and the water is stored in reservoirs. A portion of surface runoff and ground water flows back to ocean.

Again evaporation starts from the surfaces of lakes, reservoirs and ocean, and the cycle repeats. Of these three phases of the hydrologic cycle, namely, evaporation, precipitation and runoff, it is the 'runoff phase', which is important to a civil engineer since he is concerned with the storage of surface runoff in tanks and reservoirs for the purposes of irrigation, municipal water supply hydroelectric power etc.

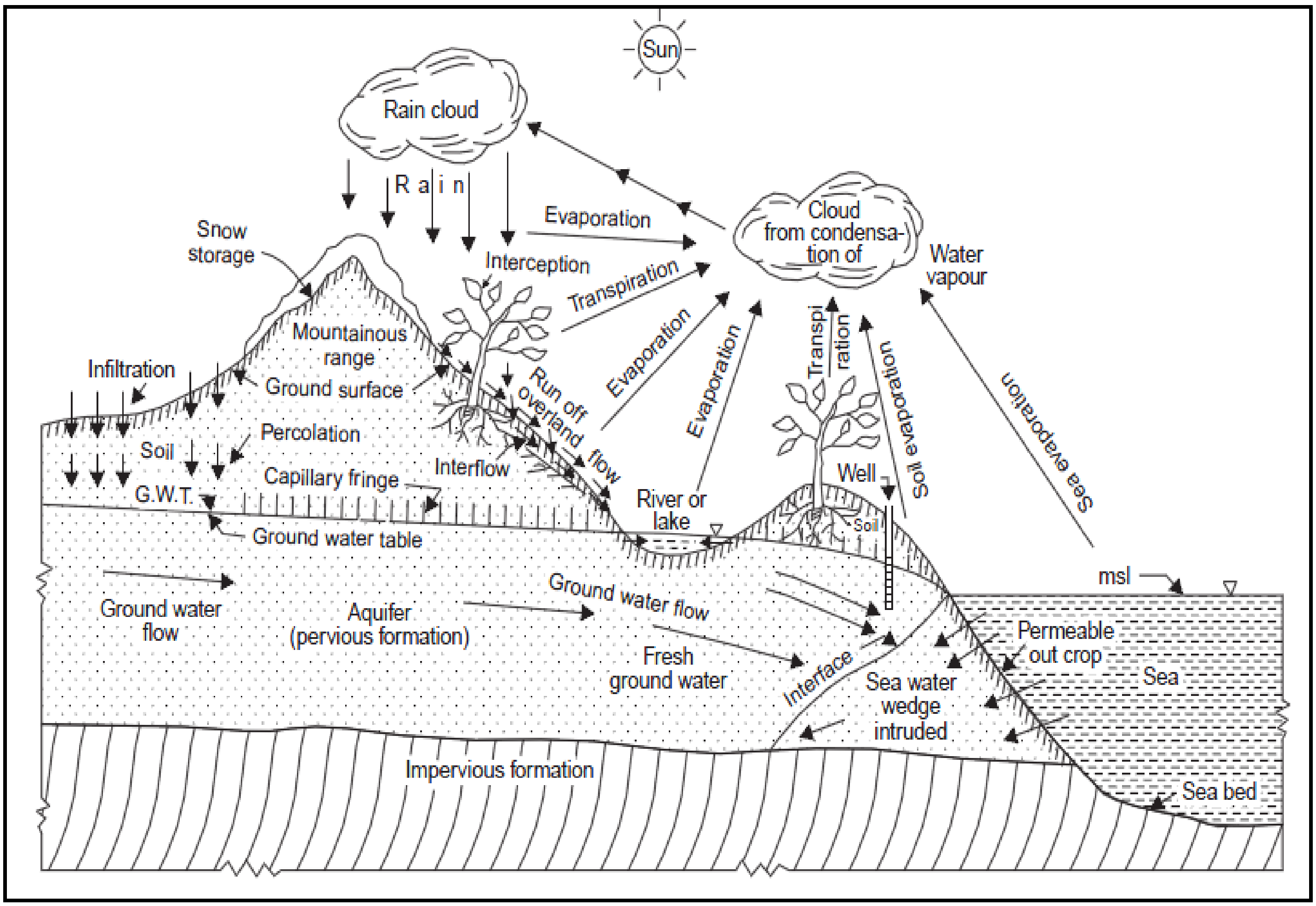
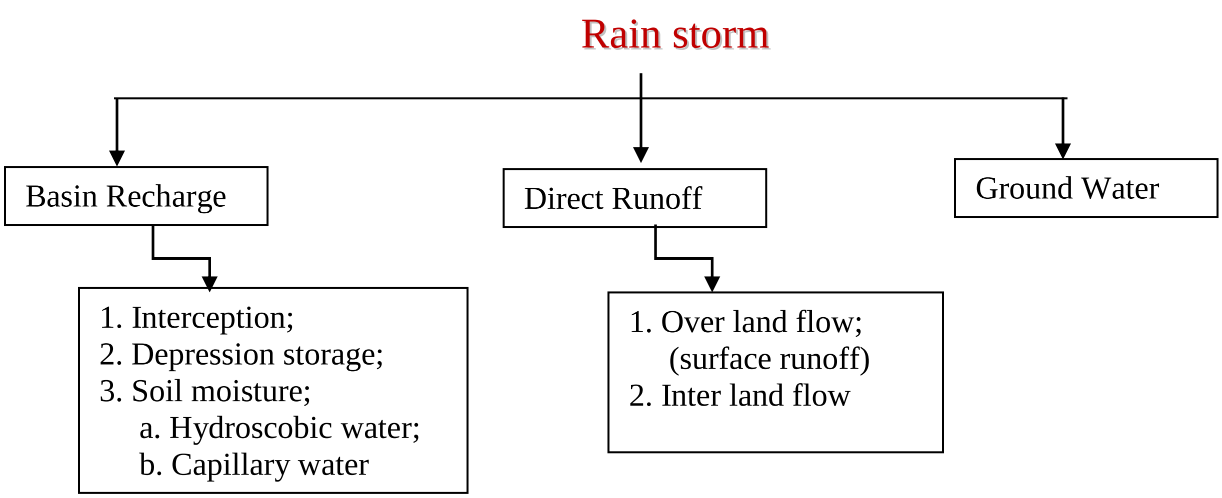



**Fig. 1.1** The hydrologic cycle

## N.B 1

Phases of the hydrological cycle are:

## N.B 2




## N.B 3

***The catchment (drainge area or river basin):*** the area which is drained by the river

# Chapter 1
# Introduction

## 1.3 Water Budget Equation

### 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.*

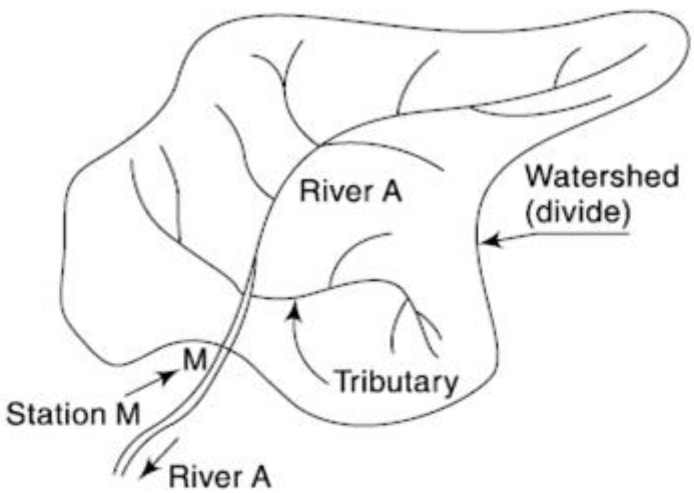



Fig. 1. 2 Schematic Sketch of Catchment of River A at Station M

### Water Budget Equation

For a given problem area, say a catchment, in an interval of time $\Delta t$, the continuity equation for water in its various phases is written as

Mass inflow – mass outflow = change in mass storage

If the density of the inflow, outflow and storage volumes are the same

$$V_i - V_0 = \Delta S \quad (1.1)$$

where $V_i$ = inflow volume of water into the problem area during the time period, $V_0$ = outflow volume of water from the problem area during the time period, and $\Delta S$ = change in the storage of the water volume over and under the given area during the given period. In applying this continuity equation [Eq. (1.1)] to the paths of the hydrologic cycle involving change of state, the volumes considered are the equivalent volumes of water at a reference temperature. 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 $\left(\frac{10^7}{10 \times 10^6}\right) = 1$ m $= 100$ cm. Rainfall, evaporation and often runoff volumes are expressed in units of depth over the catchment.

While realizing that all the terms in a hydrological water budget may not be known to the same degree of accuracy, an expression for the water budget of a catchment for a time interval $\Delta t$ is written as

$$P - R - G - E - T = \Delta S \quad (1.2\text{-a})$$

In this $P$ = precipitation, $R$ = surface runoff, $G$ = net groundwater flow out of the catchment, $E$ = evaporation, $T$ = transpiration and $\Delta S$ = change in storage.

The storage S consists of three components as

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

where $S_s$ = surface water storage
$S_{sm}$ = water in storage as soil moisture and
$S_g$ = water in storage as groundwater.

Thus in Eq. (1.2-a) $\Delta S = \Delta S_s + \Delta S_{sm} + \Delta S_g$

All terms in Eq. (1.2-a) have the dimensions of volume. Note that all these terms can be expressed as depth over the catchment area (e.g. in centimetres), and in fact this is a very common unit.

In terms of rainfall–runoff relationship, Eq. (1.2-a) can be represented as

$$R = P - L \quad (1.2\text{-b})$$

where $L$ = Losses = water not available to runoff due to infiltration (causing addition to soil moisture and groundwater storage), evaporation, transpiration and surface storage. Details of various components of the water budget equation are discussed in subsequent chapters. Note that in Eqs (1.2-a and b) the net import of water into the catchment, from sources outside the catchment, by action of man is assumed to be zero.

# 1 "Water Budget"

Hydrologic system

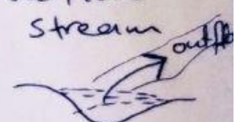
- Storage
- inputs (inflow)
- outputs (outflow)

**inputs** → **Storage "S"** → **outputs**

ex: (surface water)
1- precipitation
2- inflow stream


ex:
1- surface water ($S_s$)
2- ground water ($S_g$)
3- Home storage tank ($S_t$)
4- water storage in soil moisture ($S_{sm}$)

ex: (surface water)
1- evaporation rate
2- infiltration rate
3- outflow stream




$$\Delta S = \text{inputs} - \text{outputs}$$

chang in storage = inputs (inflow) − outputs (outflow)

* If Inputs > outputs → ΔS ⊕
* If inputs < outputs → ΔS ⊖
* if inputs = outputs → ΔS = zero (no change in storage).

## Note

All units must be the same in water budget equation, either we use depth unit or volume unit.

**EXAMPLE 1.1** *A lake had a water surface elevation of 103.200 m above datum at the beginning of a certain month. In that month the lake received an average inflow of 6.0 $m^3/s$ from surface runoff sources. In the same period the outflow from the lake had an average value of 6.5 $m^3/s$. Further, in that month, the lake received a rainfall of 145 mm and the evaporation from the lake surface was estimated as 6.10 cm. Write the water budget equation for the lake and calculate the water surface elevation of the lake at the end of the month. The average lake surface area can be taken as 5000 ha. Assume that there is no contribution to or from the groundwater storage.*

SOLUTION: In a time interval $\Delta t$ the water budget for the lake can be written as
Input volume – output volume = change in storage of the lake

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

where $\bar{I}$ = average rate of inflow of water into the lake, $\bar{Q}$ = average rate of outflow from the lake, $P$ = precipitation, $E$ = evaporation, $A$ = average surface area of the lake and $\Delta S$ = change in storage volume of the lake.

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

In one month:

$$\text{Inflow volume} = \bar{I}\,\Delta t = 6.0 \times 2.592 = 15.552 \text{ M m}^3$$

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

$$\text{Input due to precipitation} = PA = \frac{14.5 \times 5000 \times 100 \times 100}{100 \times 10^6} \text{ M m}^3 = 7.25 \text{ M m}^3$$

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

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

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

New water surface elevation at the end of the month = 103.200 + 0.058
= 103.258 m above the datum.

**EXAMPLE 1.2** *A small catchment of area 150 ha received a rainfall of 10.5 cm in 90 minutes due to a storm. At the outlet of the catchment, the stream draining the catchment was dry before the storm and experienced a runoff lasting for 10 hours with an average discharge of 1.5 $m^3$/s. The stream was again dry after the runoff event. (a) What is the amount of water which was not available to runoff due to combined effect of infiltration, evaporation and transpiration? What is the ratio of runoff to precipitation?*

Example 1.3

*Assume we have a lake with surface area of **1 $km^2$**, the rainfall is **2cm/hr** and average evaporation rate is 10 cm/day, if the infiltration volume is **1000000 $m^3$/day** calculate the change in storage for this lake after **5 days.** Assume the depth of water in this lake was **10m** after **5 days** the final depth will be …….. ?*

***Solution:***

***Input :*** *rainfall,* ***output :*** *evaporation +infiltration*

$$P = \frac{5cm}{hr} * 5day * \frac{24hr}{day} * \frac{m}{100cm} = 6m$$

$$E = \frac{10cm}{day} * 5day * \frac{m}{100cm} = 0.5m$$

$$I = \frac{1000000m^3}{day} * 5day * \frac{1}{10^6 m^2} = 5m^3$$

$$\Delta S = P - E - I = 5m$$

*Depth final =Depth initial± change in storage*

*= 10+0.5=10.5 m*

## 1.4 Meteorolgical Data

### 1.4.1 Temperature:

Air temperature is recorded by thermometers (Fig. 1.3) housed in open louvered boxes, known as Stevenson screens, about 1.25 m above ground. Protection is necessary from precipitation and the direct rays of the sun.

- ✓ *Maximum and minimum* temperature, *thermometers* are usually used.
- ✓ Temperature is measured in degrees Celsius.
- ✓ Temperature decreases with height at about **5.6 °C** per **1000 m** height increase

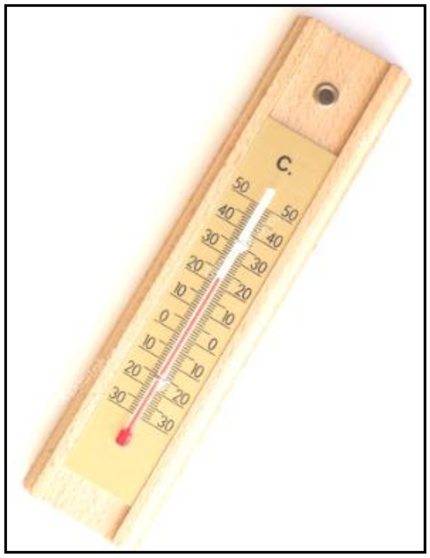


Fig. 1.3. Thermometer

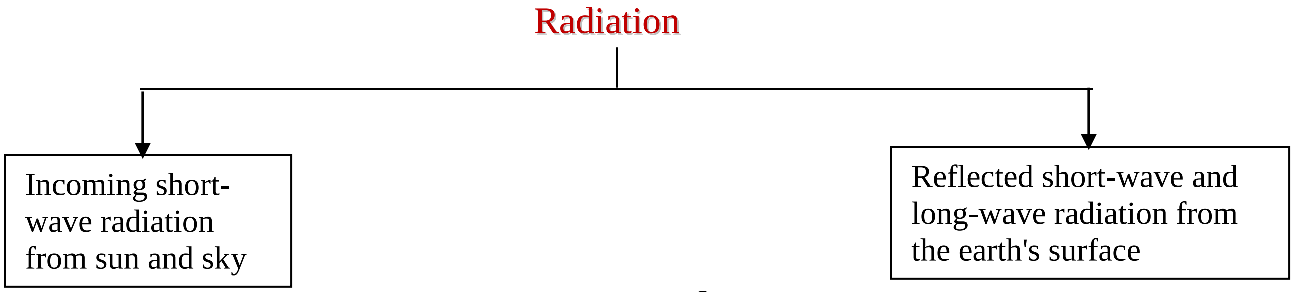
***Mean temperature of the day= (Maximum Temperature + minimum Temperature)/2*** (1.3)

***Mean temperature of the month= (∑ mean temperature of all days)/ No. of days)*** (1.4)

***Mean temperature of the year= (∑ mean temperature of all months)/ 12).*** (1.5)

### 1.4.2 Radiation:

It is a form of energy.



***Radiometers*** (Fig.1.4) are used to measure radiation.
The units of radiation is $kWh/m^2$

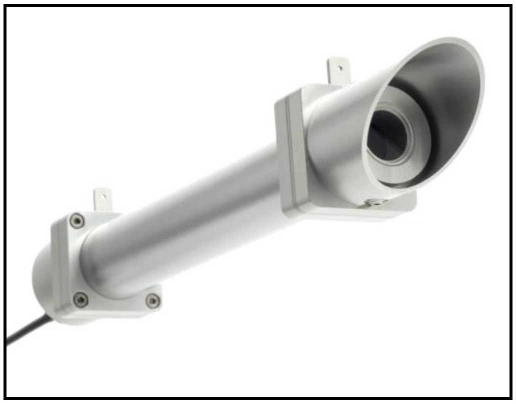


Fig. 1.4. Radiometer

## 1.4.3 Wind:

- ✓ Wind speed is measured by anemometer (Fig. 1.5).
- ✓ Wind direction is measured by wind vane (Fig. 1.5).

Because of the frictional effects of the ground or water surface over which the wind is blowing, it is important to specify in any observation of wind, the height above ground at which it was taken. An empirical relationship between wind speed and height has been commonly used

$$u/u_0 = (z/z_0)^{0.15} \qquad (1.6)$$

where $u_o$ = wind speed at anemometer at height $z_o$
u = wind speed at some higher-level z.


Fig. 1.5. Anemometer and wind van

# Chapter Two
# Precipitation

## 2.1 Introduction:

The term *precipitation* denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew. Of all these, only the first two contribute significant amounts of water.

For precipitation to form: (i) the atmosphere must have moisture, (ii) there must be sufficient nuclei present to aid condensation, (iii) weather conditions must be good for condensation of water vapour to take place, and (iv) the products of condensation must reach the earth.

## 2.2 Forms of Precipitation:

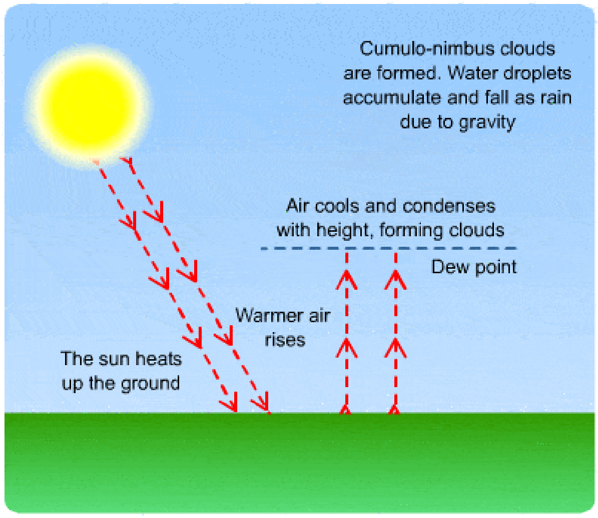
Some of the common forms of precipitation are: rain, snow, drizzle, glaze, sleet and hail.

**Rain** It is used to:
describe precipitations in the form of water drops of sizes larger than 0.5 mm. The maximum size of a raindrop is about 6 mm.

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

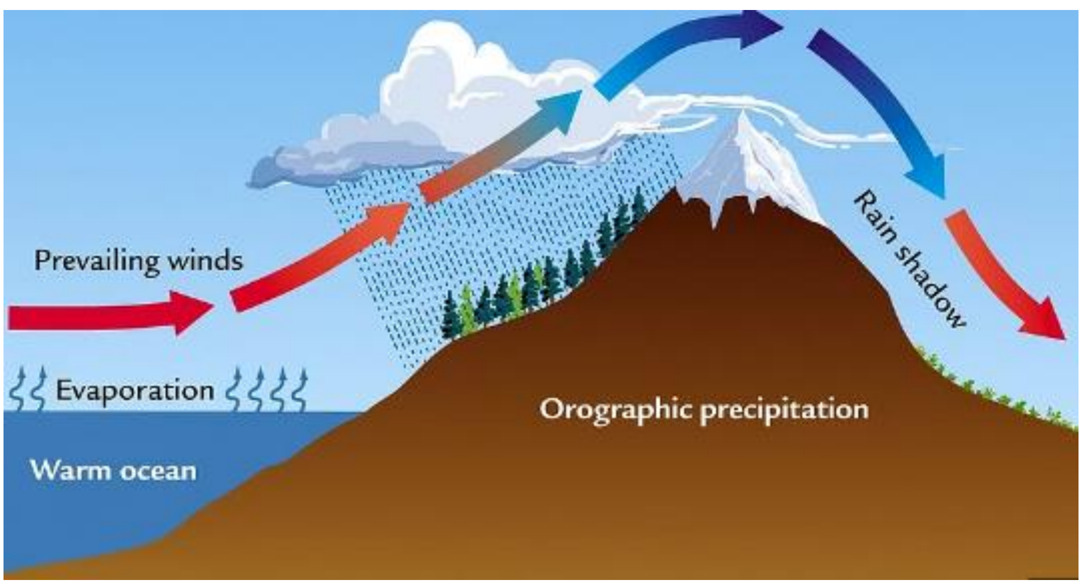
## 2.3 Type of rain:

***Conventional Rain:***
The cause of the fall in temperature of an air mass may be due to convection, the warm moist air rising and cooling to form cloud and subsequently to precipitate rain. This is called *convective precipitation.*



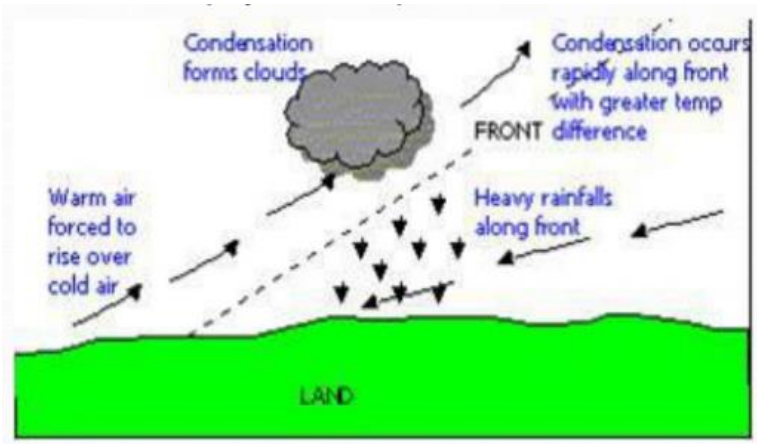

## *Orographic (Relif) Rain:*

*Orographic precipitation* results from ocean air streams passing over land and being deflected upward by coastal mountains, thus cooling below saturation temperature and spilling moisture. Most orographic rain is deposited on the windward slopes.



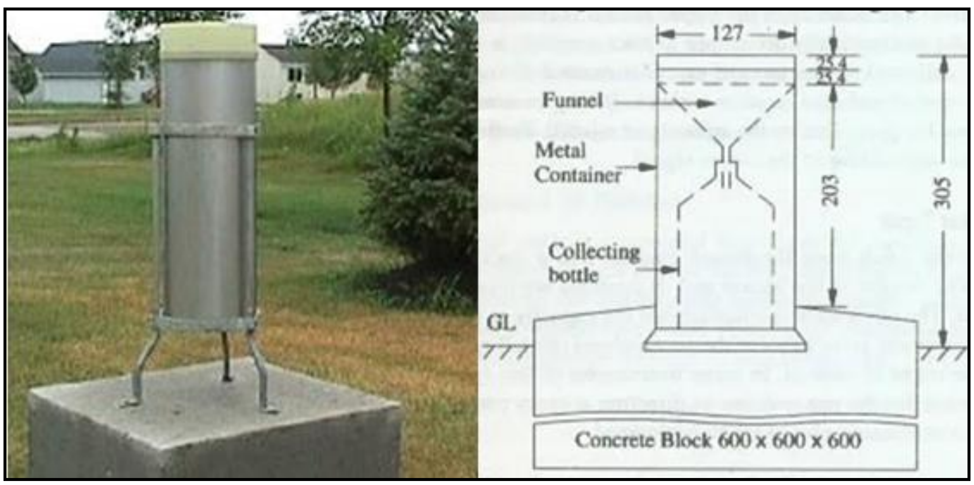

## *Frontal (cyclonic ) Rain:*

The third general classification of rainfall is *cyclonic and frontal precipitation.* When low-pressure areas exist, air tends to move into them from surrounding areas and in so doing displaces low-pressure air upward, to cool and precipitate rain.

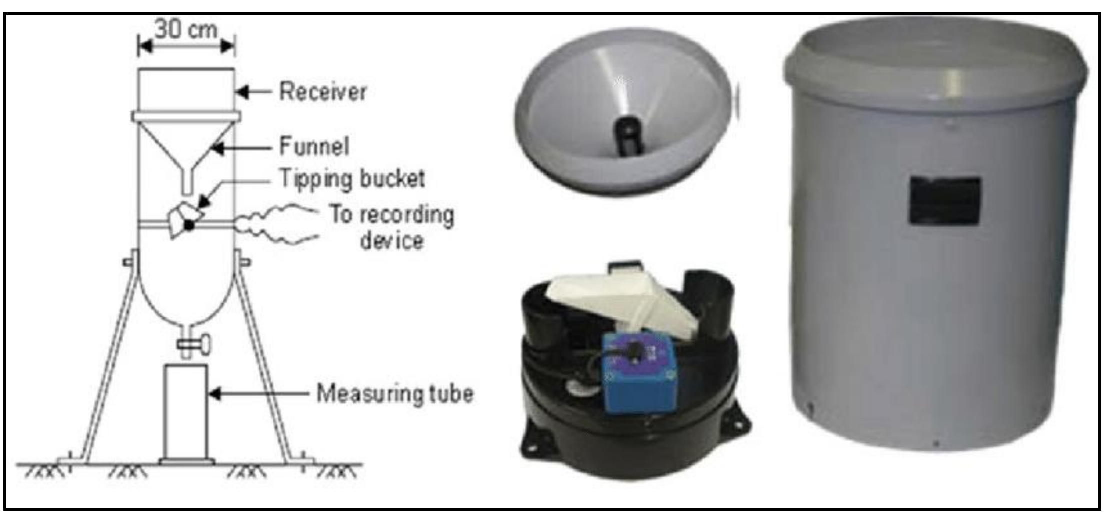



## 2.4 Rain Measurements:

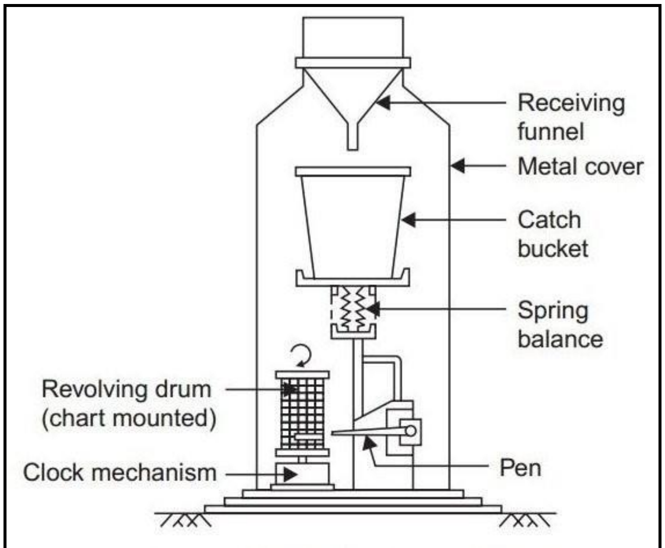
***1. Non Recording (Manual) Gauge***




***2. Tipping Bucket Rain Gauge***

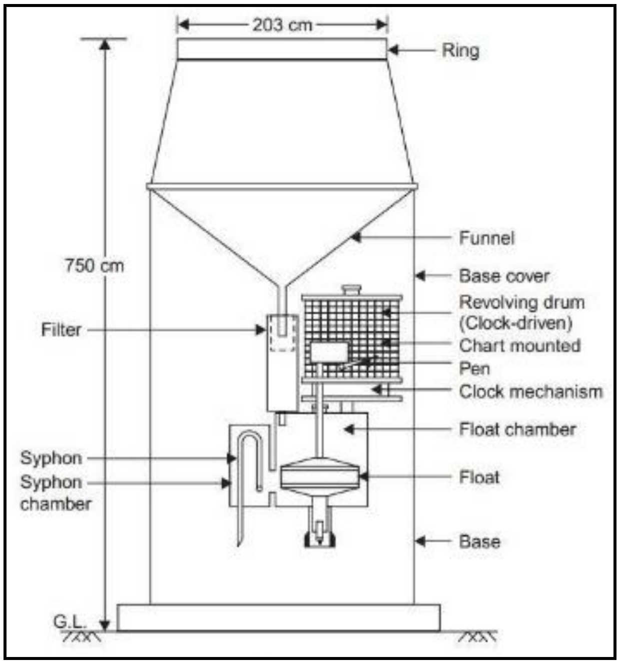


***3. Recording gauge (weighing type gauge):***




Weighing type rain gauge

***4. Float Recording Gauge:***




## 2.5 Definitions.

- ✓ *Intensity.(i,mm/hr)* This is a measure of the quantity of rain falling in a given time; for example, mm per hour.
- ✓ *Duration.(t,hr)* This is the period of time during which rain falls.

- ✓ *Frequency (T,year).*This refers to the expectation that a given depth of rainfall will fall in a given time. Such an amount may be equaled or exceeded in a given number of days or years.

Precipitation varies in ➡ Space
➡ Time

According to ➡ The general pattern of atmospheric circulation

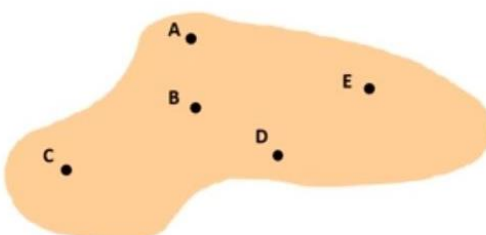
➡ Local factors

The average over a number of years of observations of a weather variable is called **its normal value**.

## 2.7 Adequate of raingauge stations:

- **Assume we have the following basin & stations network:**

| Station | Rainfall (cm) |
|---|---|
| A | 10 |
| B | 12 |
| C | 8 |
| D | 14 |
| E | 9 |




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

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

$$\sigma_{m-1} = \sqrt{\frac{\sum_1^m p_i^2 - \frac{\sum_1^m p_i^2}{m}}{m-1}}$$

$$\bar{P} = \frac{1}{m}\left(\sum_{1}^{m} p_i\right)$$

## Where:

N= optimal number of rain gauge stations
$C_v$ =coefficient of variation
∈= allowable degree of error
σ= Standard deviation
$\bar{p}$ = Mean precipitation
M=number of precipitation value

**Example:** A catchment that contains (6) stations for measuring rainfall, and in one year the annual rain is recorded as follows:

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

Assuming a 10% error in the estimating of the mean rain, calculate the optimal number of stations in this catchment.

## Solution:

$m = 6$ ; $\sigma_{m-1} = 35.04$ ; $\epsilon = 10\%$ $\bar{P} = 118.6$

$C_v = 100 * 35.04 / 118.6 = 29.54$

N = 8.7 = 9 stations , three more additional stations are needed

H.W:
Calculate the optimal number of stations if the allowable error 5%

| Station | A | B | C | D | E |
|---|---|---|---|---|---|
| Rainfall rate (cm) | 26 | 17 | 20 | 22 | 18 |

## 2.8 Preparation of Data

- **Sometimes rainfall gauge station become inoperative due to many reasons, for example:**
  - **Mechanical/Electronic error**
  - **Station is damaged by heavy wind**
  - **Absence of observer (for manual stations)**

- **If we have a missing rainfall data we need to estimate it, there are several methods for estimation but in this lesson we will learn how to estimate missing rainfall data using Normal Ratio Method.**

## 2.9 Estimating of Missing Rainfall Data

The point observation from a precipitation gage may have a short break in the record because of instrument failure or absence of the observer. Thus, it is often necessary to estimate the missing record using data from the neighboring station. The following methods are most commonly used for estimating the missing records.

1. Simple Arithmetic Method
2. Normal Ratio Method

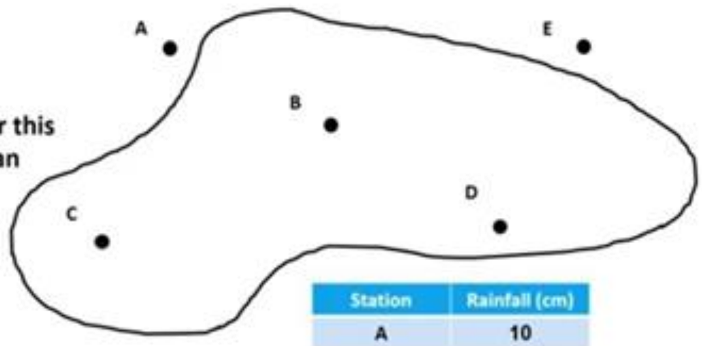
**2.9.1 Simple Arithmetic Average -** The missing precipitation Px can be determined using simple arithmetic average, if the normal annual precipitation at various stations are within 10% of the normal precipitation at station, x, as follows:

$$Px = \frac{1}{m}[P1 + P2 + \cdots + Pm]$$

*P*x = precipitation at the missing location
*P*i = precipitation at index station *I*
*m* = number of rain gauges

***Used when*** $N_1 = N_2 = \ldots\ldots N_m = N_x, \ \pm 10\% N_x$

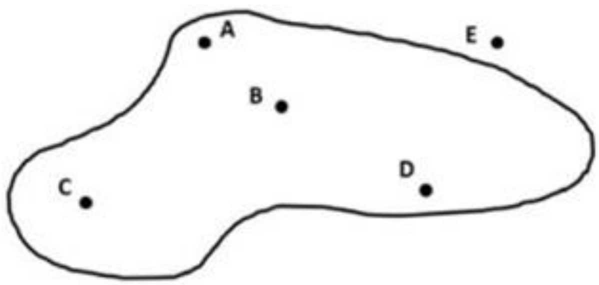
**Example:**
**Calculate the average rainfall for this catchment using arithmetic mean method.**




| Station | Rainfall (cm) |
|---|---|
| A | 10 |
| B | 14 |
| C | 8 |
| D | 17 |
| E | 20 |

**H.W:** Calculate the average rainfall of this cathment:

| Station | Rainfall (cm) |
|---|---|
| A | 20 |
| B | 40 |
| C | 35 |
| D | 15 |
| E | 27 |




**2.9.2 Normal Ratio Method -** If the normal precipitations vary considerably then Px is estimated by weighting the precipitation at various stations by the ratios of normal annual precipitation. The normal ration method gives Px as:

$$Px = \frac{Nx}{m}\left[\frac{P1}{N1} + \frac{P2}{N2} + \cdots + \frac{Pm}{Nm}\right]$$

Where:
$P$x = missing rainfall value
$m$ = number of surrounding stations
Pi = recorded rainfall value of surrounding stations 1,2….m
Ni=Normal rainfall value of surrounding stations 1,2….m
Nx= Normal rainfall value for inoperative station

***Used when*** $N_1=N_2=\ldots\ldots N_m \neq N_x$, $\pm 10\% N_x$

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

***Solution:*** As the normal rainfall values vary by more than 10%, the ration method is adopted.

$$Px = \frac{Nx}{m}\left[\frac{P1}{N1} + \frac{P2}{N2} + \cdots + \frac{Pm}{Nm}\right]$$

$$Pd = \frac{92.01}{3}\left[\frac{91.11}{80.97} + \frac{72.23}{67.59} + \frac{79.89}{76.28}\right] = 99.41 cm$$

***H.W***

Find out the missing storm precipitation of station 'C' given in the following table:

| Station | A | B | C | D | E |
|---|---|---|---|---|---|
| Storm precipitation (cm) | 9.7 | 8.3 | ---- | 11.7 | 8.0 |
| Normal Annual precipitation (cm) | 100.3 | 109.5 | 93.5 | 125.7 | 117.5 |

## 2.10 Consistency of Rainfall Record

Many studies require long term rainfall data, therefore, a test must be conducted to check homogeneity or self consistency of the rainfall record. This is necessary because over a period of time, it may happen that there be a some obstructions (trees, buildings) may have emerged after the installation of gage or its location might have changed or observational procedure might have changed. The inconsistency of rainfall record can be checked by graphical or statistical methods including double mass curve, the von Neumann ratio test, cumulative deviation, run test. Double mass curve method described below is one of the most common and widely accepted methods for checking the consistency of rainfall record.

### Double-mass Curve

This method is based on the assumption that the mean accumulated precipitation for a large group of stations is not significantly affected by a change or changes in individual stations. If we plot the mean accumulated precipitation for several stations against the accumulated precipitation of the record for the station that needs to be adjusted, any change in slope will indicate a "break" in the station record.

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

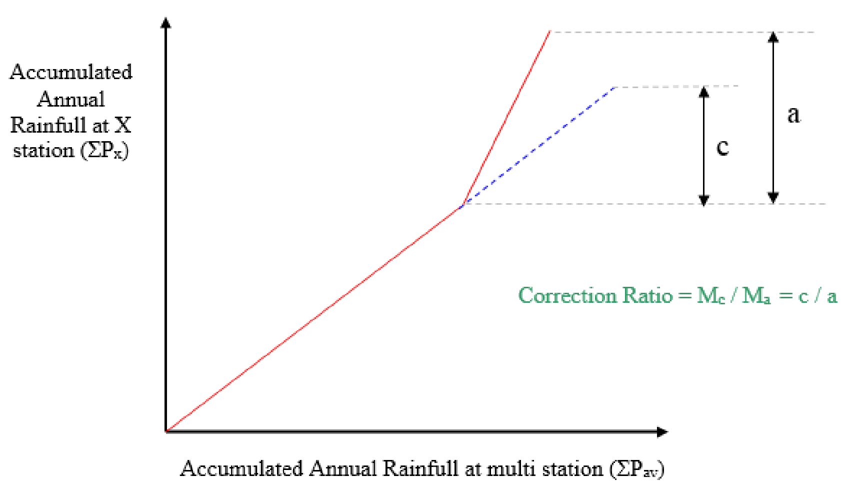
***A double-mass curve is used to check the consistency of a rain gauge record:***

- compute cumulative rainfall amounts for suspect gauge and check gauges ( $\Sigma P_{av}$)
- plot cumulative rainfall amounts against each other ($\Sigma P_x$) and ($\Sigma P_{av}$) (divergence from a straight line indicates error)
- multiplying erroneous data after change by a correction factor k ($M_e / M_a$) where:

$$k = \frac{\text{gradient of line before change}}{\text{gradient of line after change}}$$

$$P_{cx} = P_x \frac{M_e}{M_a}$$

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



## *Example*

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

| Year | Annual Rainfall of Station A (mm) | Average Annual Rainfall (AAR) of 8 Station Group (mm) |
|---|---|---|
| 1946 | 177 | 143 |
| 1947 | 144 | 132 |
| 1948 | 178 | 146 |
| 1949 | 162 | 147 |
| 1950 | 194 | 161 |
| 1951 | 168 | 155 |
| 1952 | 196 | 152 |
| 1953 | 144 | 117 |
| 1954 | 150 | 130 |
| 1955 | 130 | 190 |
| 1956 | 141 | 170 |
| 1957 | 160 | 190 |
| 1958 | 155 | 166 |

| | | |
|---|---|---|
| 1959 | 140 | 150 |
| 1960 | 120 | 125 |
| 1961 | 148 | 140 |
| 1962 | 142 | 163 |
| 1963 | 140 | 145 |
| 1964 | 130 | 143 |
| 1965 | 137 | 135 |
| 1966 | 130 | 150 |
| 1967 | 163 | 165 |

a) In what year is a change in regime indicated?

b) Adjust the record data at a station A and determine the mean annual precipitation.

***Solution:***

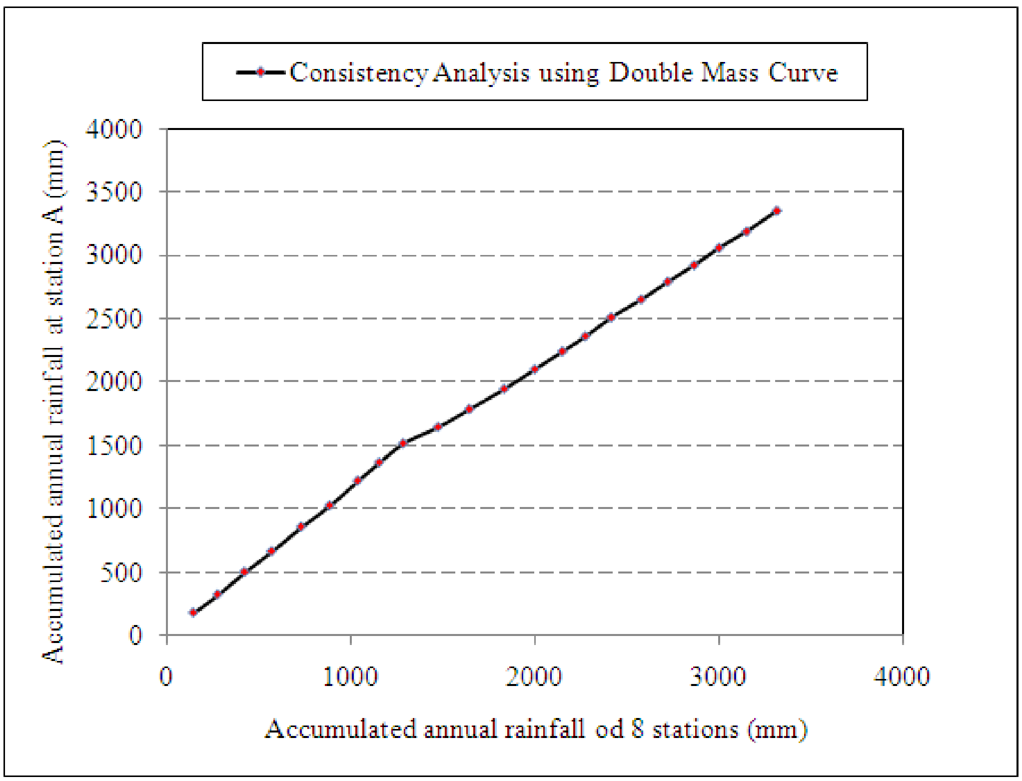
| Year | Annual Rainfall of Station A(mm) | Average Annual Rainfall (AAR) of 8 Station groups (mm) | Cumulative Station A rainfall (mm) | Cumulative of 8 Station A.A.R. (mm) | Correction factor | Adjusted rainfall at station A |
|---|---|---|---|---|---|---|
| 1946 | 177 | 143 | 177 | 143 | | 140.8471 |
| 1947 | 144 | 132 | 321 | 275 | 1.18 | 114.5875 |
| 1948 | 178 | 146 | 499 | 421 | | 141.6428 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1949 | 162 | 147 | 661 | 568 | | 128.9109 |
| 1950 | 194 | 161 | 855 | 729 | | 154.3748 |
| 1951 | 168 | 155 | 1023 | 884 | | 133.6854 |
| 1952 | 196 | 152 | 1219 | 1036 | | 155.9663 |
| 1953 | 144 | 117 | 1363 | 1153 | | 114.5875 |
| 1954 | 150 | 130 | 1513 | 1283 | | 119.3619 |
| 1955 | 130 | 190 | 1643 | 1473 | | 196 |
| 1956 | 141 | 170 | 1784 | 1643 | | 141 |
| 1957 | 160 | 190 | 1944 | 1833 | | 158 |
| 1958 | 155 | 166 | 2099 | 1999 | | 145 |
| 1959 | 140 | 150 | 2239 | 2149 | | 132 |
| 1960 | 120 | 125 | 2359 | 2274 | 0.94 | 95 |
| 1961 | 148 | 140 | 2507 | 2414 | | 148 |
| 1962 | 142 | 163 | 2649 | 2577 | | 142 |
| 1963 | 140 | 145 | 2789 | 2722 | | 140 |
| 1964 | 130 | 143 | 2919 | 2865 | | 130 |
| 1965 | 137 | 135 | 3056 | 3000 | | 137 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 1966 | 130 | 150 | 3186 | 3150 | | 130 |
| 1967 | 163 | 165 | 3349 | 3315 | | 163 |
| | | | | | | 139.134 |

Correction factor: (0.935/1.175)= 0.7957= 0.796 or 0.8

Mean Annual Precipitation =139.134



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

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

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

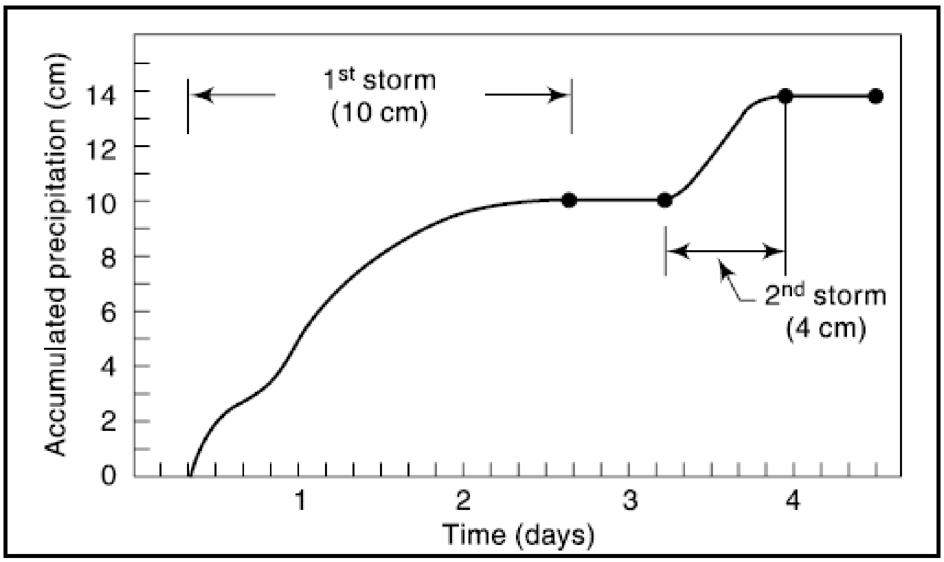
## 2.11 Presentation of Rainfall Data

The rainfall data are usually presented in the following form:

1) Mass curve of rainfall
2) Hyetograph

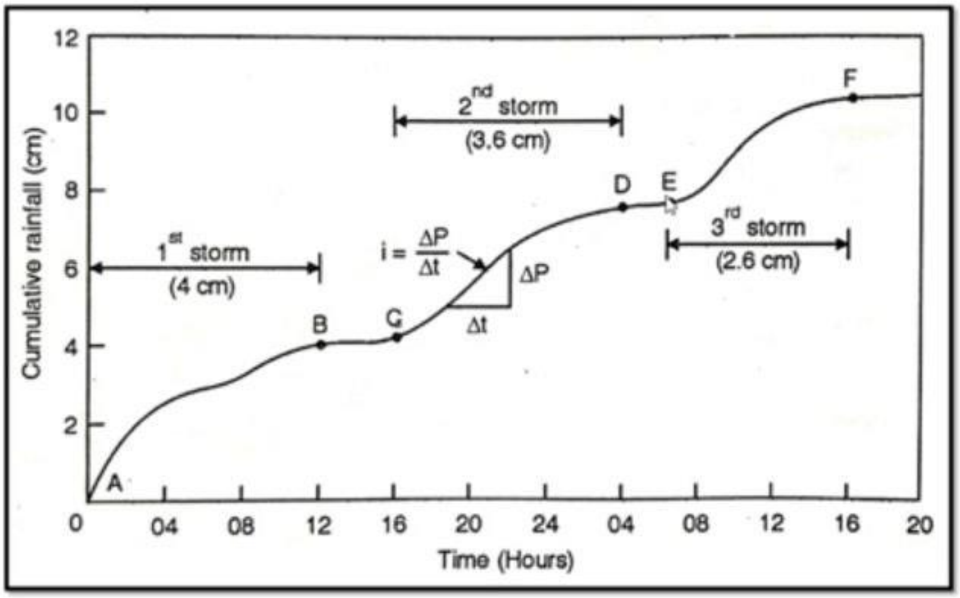
## 1) Mass curve of rainfall

The mass curve of rainfall is a plot of the accumulated precipitation against time, plotted in chronological order.



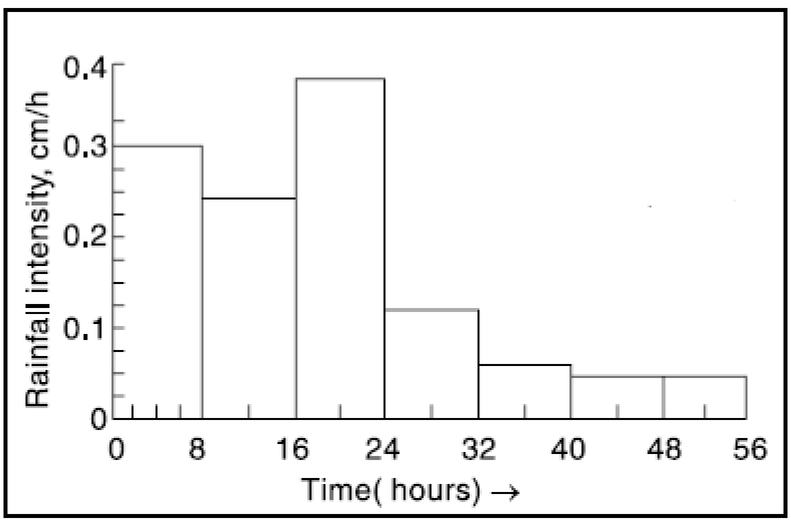

***Important notes:***

- ✓ The mass curve of rainfall is arising curve.
- ✓ A horizontal portion of the curve indicates that there was norainfall during that period.
- ✓ Slope of the cuve will give the intensity during that period.
- ✓ It is useful in extracting duration and magnitude of the storm.
- ✓ Records of automic rain gauges are of this type (for non-recording gauges,the beginning and end of the rainfall is not known, so only an approximate mass curve can be prepared).




## 2) Hyetograph

Hyetograph is abar diagram plotted between the intensity of rainfall and time




***Important notes:***

- ✓ The hyetograph can be prepared either from a mass curve or directly from the data obtained from atomic rian gauges.
- ✓ Area under the graph represents the total rainfall occurred in that period.
- ✓ The intensity is taken as the average intensity for a constant time interval (Δt).
- ✓ The time interval chosen depends upon the required accuracy and the storm duration.

**Example:**

## 2.12 Average Precipitation over Area:

**The recorded value for any rainfall gauge station is called "Point value" which means that the recorded rainfall value represents the location of the station not the whole watershed or catchment area, so if we need a value that represents the rainfall value all over the watershed we need to calculate the Average Precipitation or Average Rainfall.**

**There are many methods to calculate the average rainfall; we will demonstrate the following methods:**
**Arithmetic Mean 2- Thiessen Polygon 3- Isohyets**

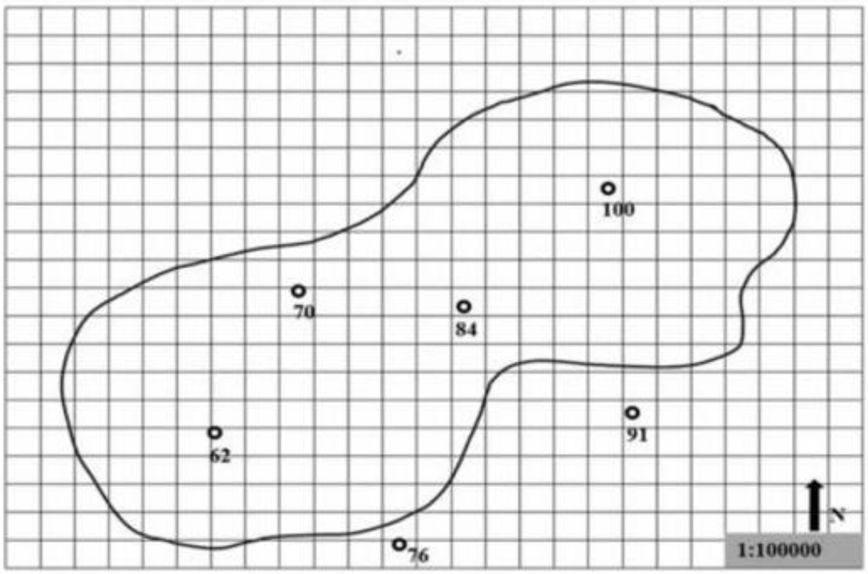
### 1. Arithmetic Mean Method

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

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

In practice, this method is used very rarely.

***Example:*** Calculate the average precipitation for this catchment (as figure below) using arithmetic mean method.




***Solution:***

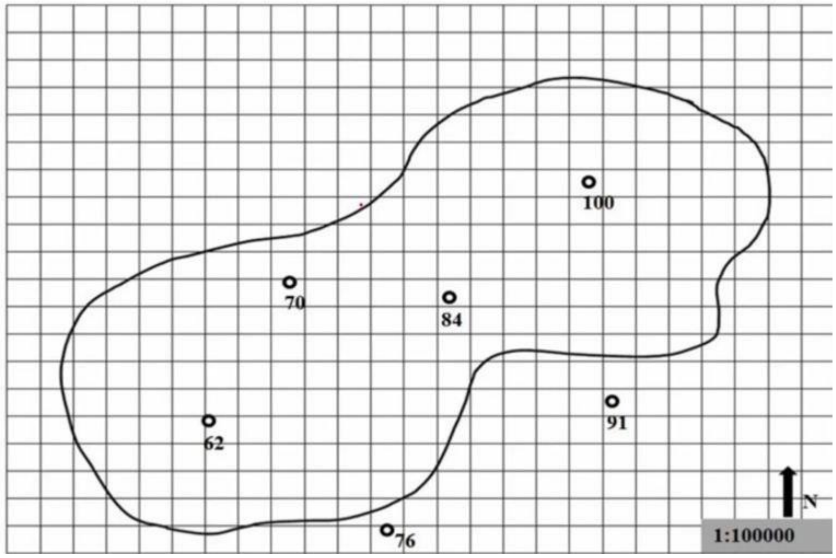
$$\bar{P} = \frac{P_1 + P_2 + \ldots + P_i + \ldots + P_n}{N} = \frac{1}{N}\sum_{i=1}^{N} P_i$$

$P_{av.}$= (62+70+84+100)/4 = 79 cm

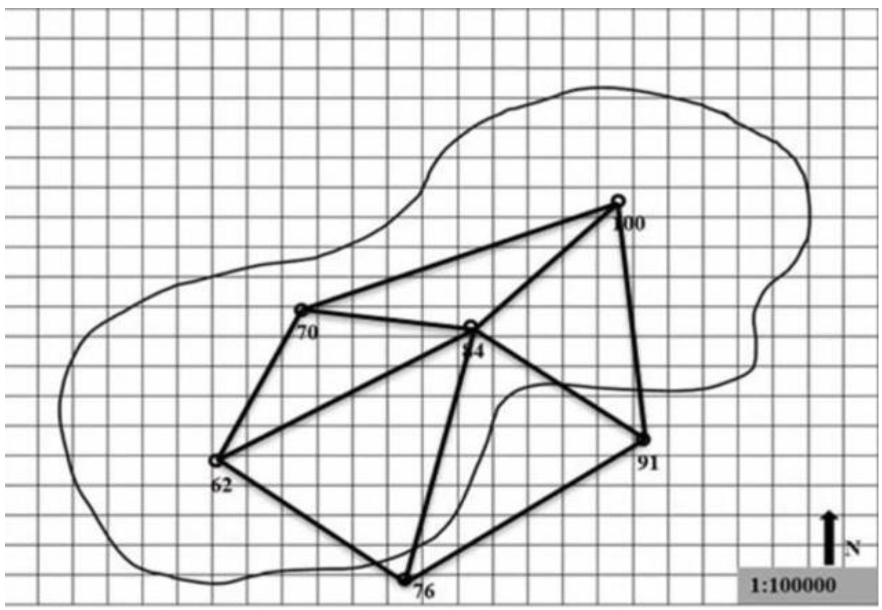
## 2. Thissen Polygons Method

To calculate the average precipitation using thiessen polygon method we need to prepare the thiessen polygon map first, the following steps are showing how to prepare the map:

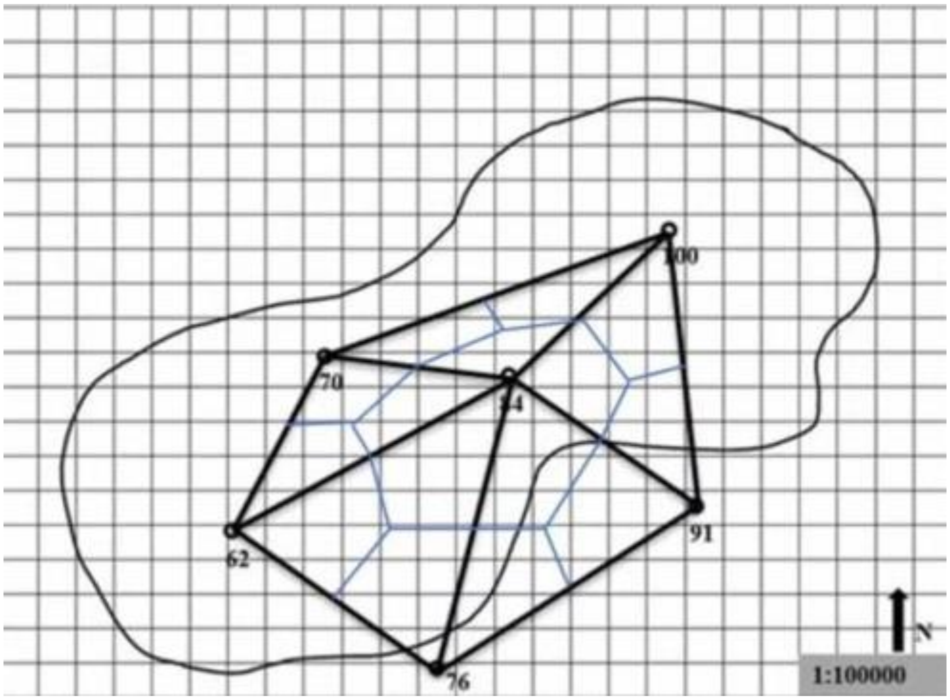
1.



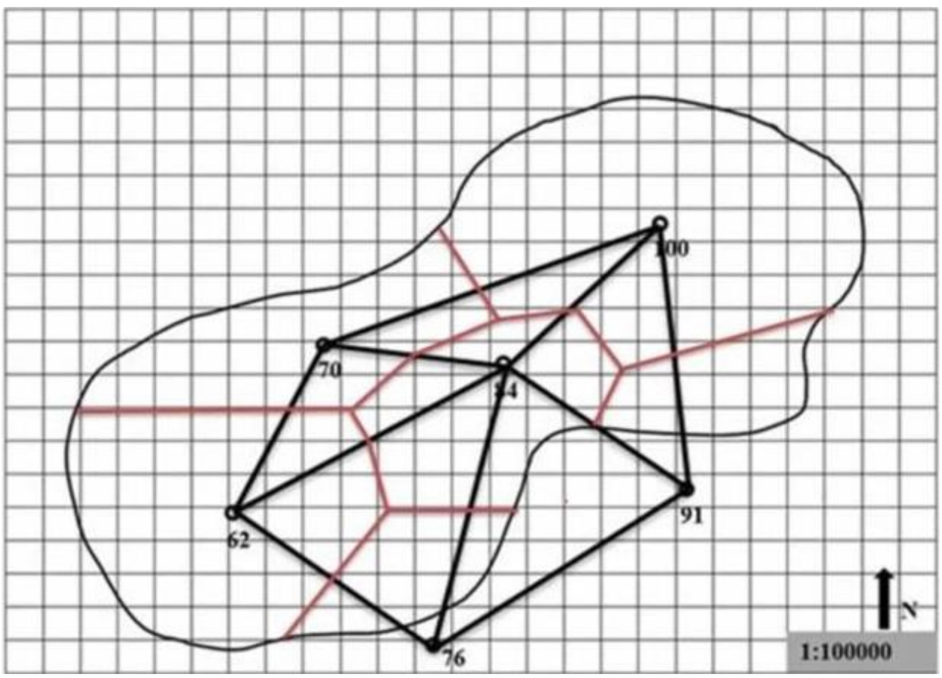

2.




3.




4.



| station | P (cm) | Area (m²) | Pi*Ai |
|---|---|---|---|
| 1 | 62 | 51 cells/4 = 12.75 cm² = 12.75*10⁶ m² | 790.5*10⁶ |
| 2 | 70 | 31 cells/4 = 7.75 cm² = 7.75*10⁶ m² | 542.5*10⁶ |
| 3 | 76 | 15 cells/4 = 3.75 cm² = 3.75*10⁶ m² | 285*10⁶ |
| 4 | 84 | 29 cells/4 = 7.25 cm² = 7.25*10⁶ m² | 609*10⁶ |
| 5 | 91 | 15 cells/4 = 3.75 cm² = 12.75*10⁶ m² | 341.25*10⁶ |
| 6 | 100 | 66 cells/4 = 16.5 cm² = 16.5*10⁶ m² | 1650*10⁶ |

$P_{average} = \sum Pi*Ai$ / Total Area
$= 4218.25*10^6/60.75*10^6$
$= 69.43$ cm

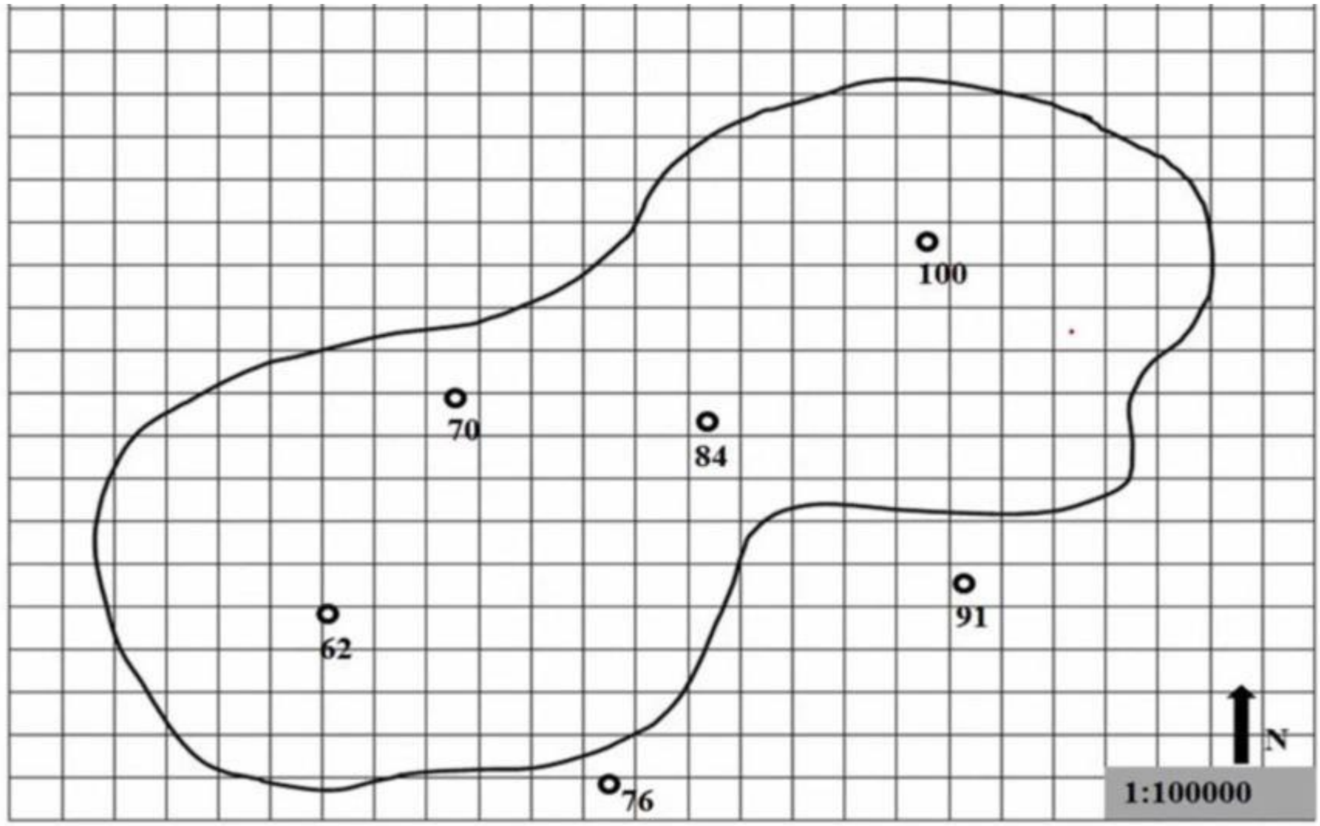
## 3. Isohyets Method

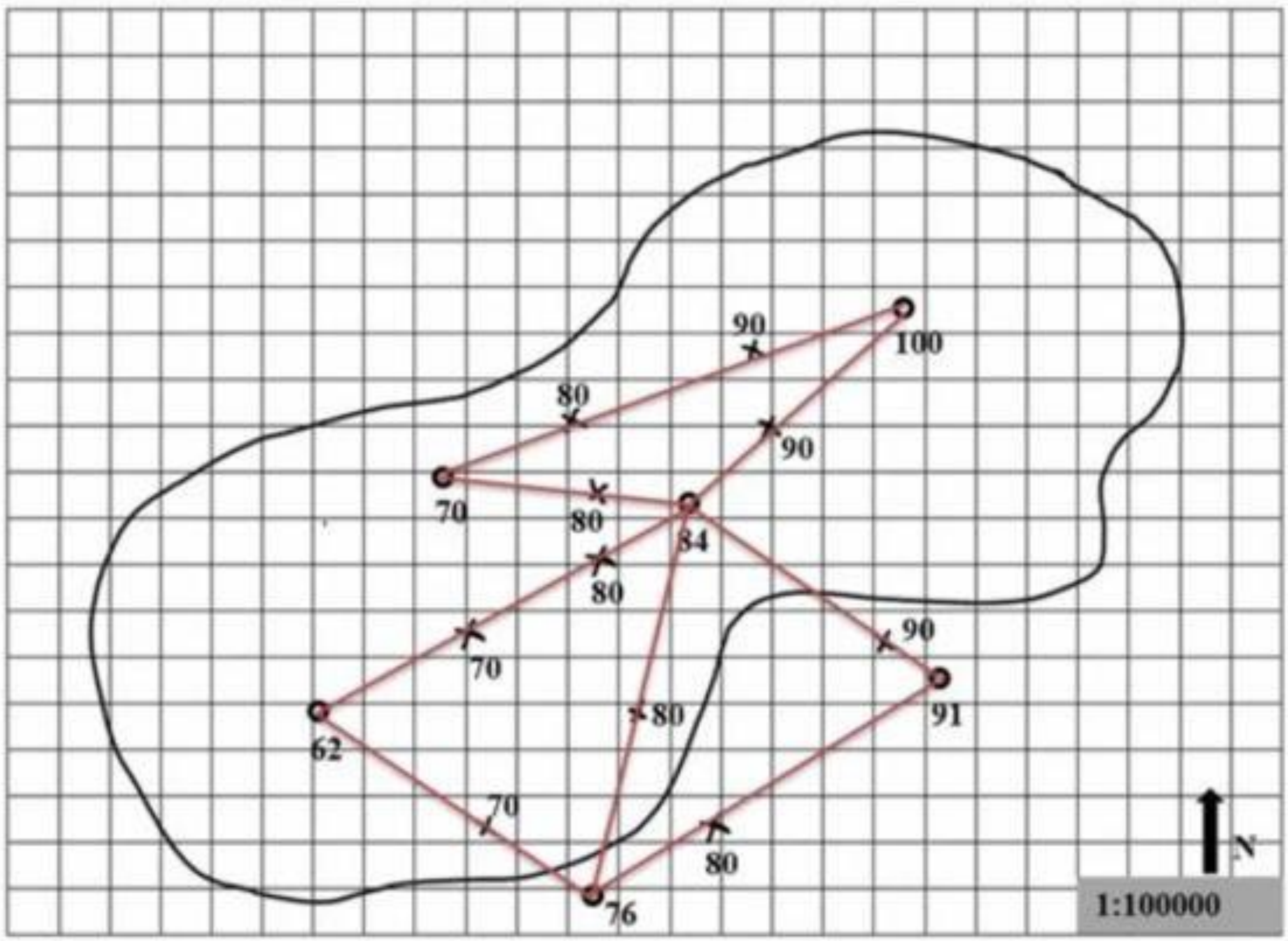
- In thiessen polygon method, the average precipitation value is more accurate than the arithmetic mean method but here in isohyets method we use the elevation factor in the calculations to get more accurate value of rainfall average.

- Contour lines: lines connecting between equal elevations.
- Isohyet lines: lines connecting between equal precipitation values.

- Contour lines never intersect
- They have the same value all over the line
- The contour interval is constant between each 2 consequent lines.

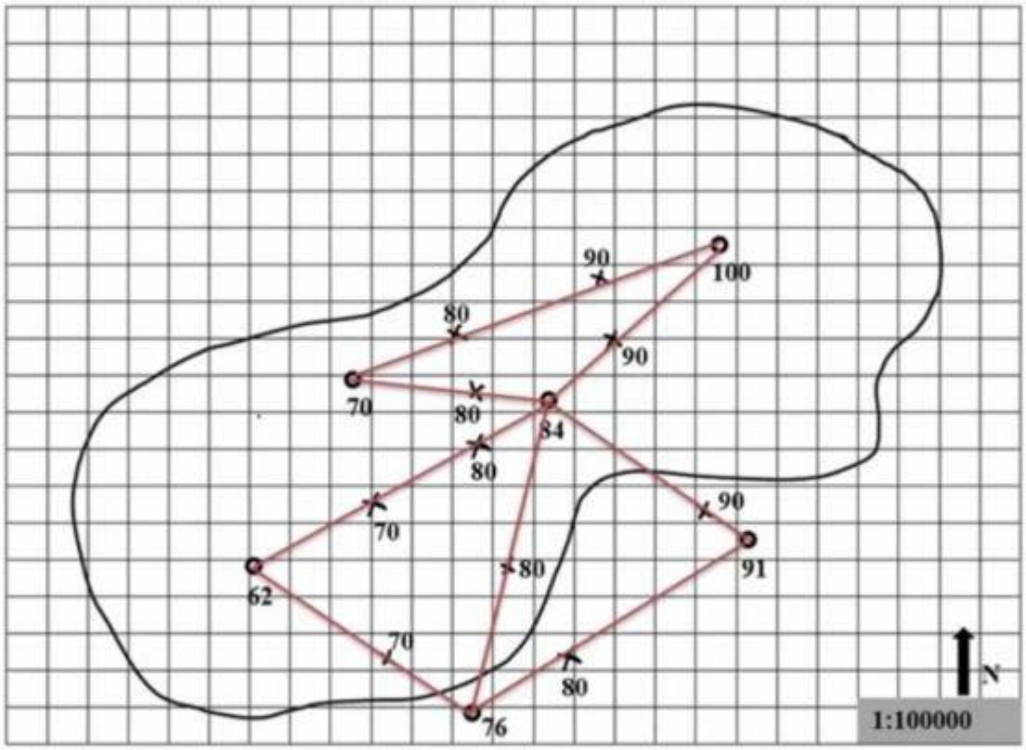
$$\bar{P} = \frac{a_1\left(\frac{P_1+P_2}{2}\right)+a_2\left(\frac{P_2+P_3}{2}\right)+.......+a_n\left(\frac{P_{n-1}+P_n}{2}\right)}{A}$$

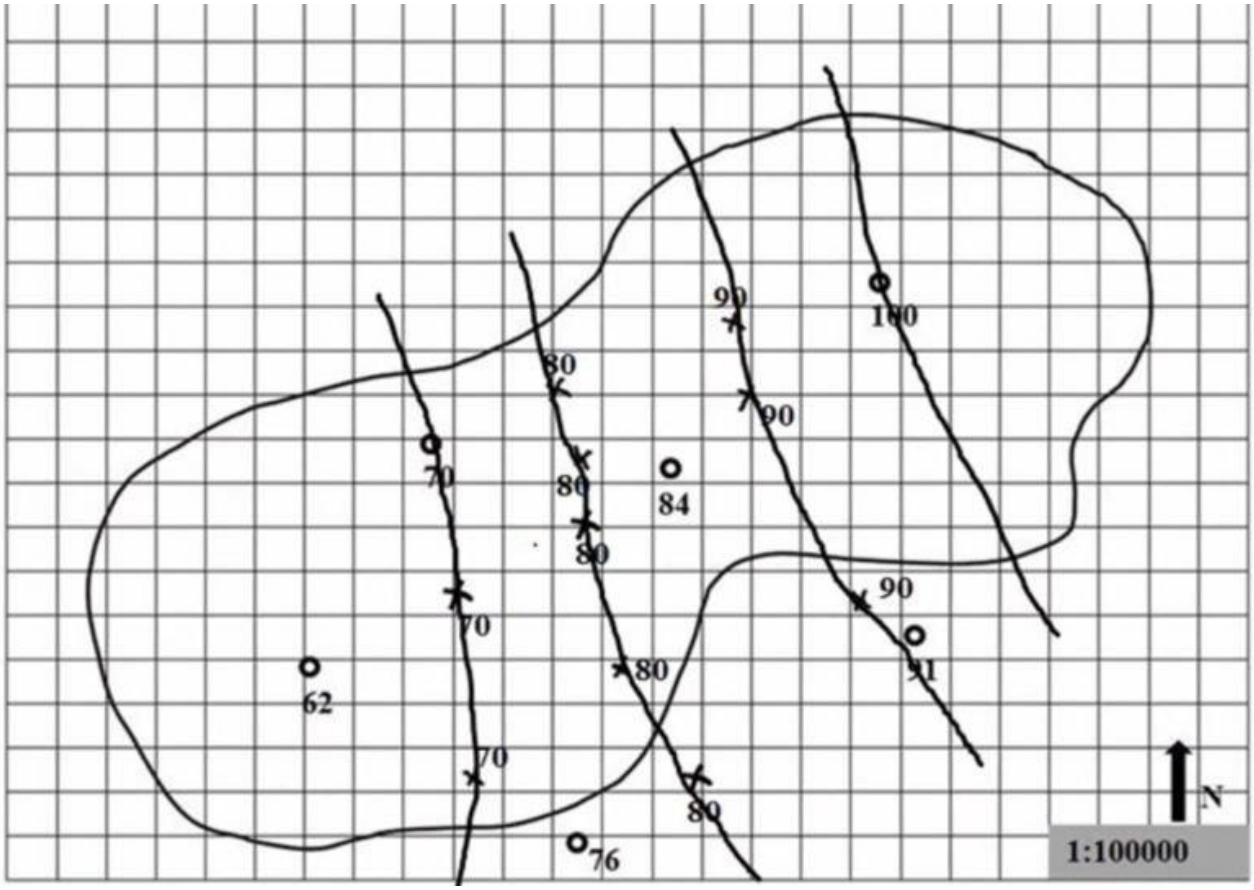

100
70
84
91
62
76
N
1:100000


90
100
80
90
70
80
84
80
90
70
80
62
91
70
80
76
N
1:100000

→ If we assume the contour interval 5 then the possible contour values will be:
60, 65,70,75,80,85,90,95,100

→ If we assume the contour interval 10 then the possible contour values will be:
60,70,80,90,100






Now the calculations process will be according to the following equation:

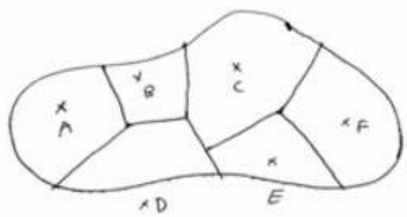
$$P_{average} = \frac{\sum \text{Average Contour} * A_i}{\text{Total Area}}$$

We will prepare the following table:

| Average Contour Line | Zone Area | Average contour * Area |
|---|---|---|
| 65 | 69 cells/4 = 17.75 cm2 = $17.75*10^6$ $m^2$ | 1153.75 |
| 75 | 33 cells/4 = 8.25 $cm^2$ = $8.25*10^6$ $m^2$ | 618.75 |
| 85 | 38 cells/4 = 9.5 $cm^2$ = $9.5*10^6$ $m^2$ | 807.5 |
| 95 | 37 cells/4 = 9.25 $cm^2$ = $9.25*10^6$ $m^2$ | 878.75 |
| 105 | 39 cells/4 = 9.75 $cm^2$ = $9.75*10^6$ $m^2$ | 1023.75 |

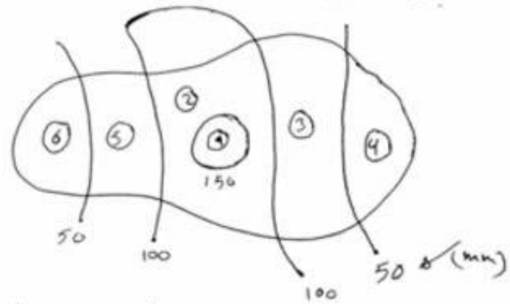
$P_{average} = 4482.5*10^6/54.5*10^6$

$= 82.24$ cm




| | P (mm) | A (km²) |
|---|---|---|
| A | 180 | 220 |
| B | 220 | 50 |
| C | 90 | 30 |
| D | 60 | 120 |
| E | 170 | 250 |
| F | 160 | 170 |

Calculate Average P ?



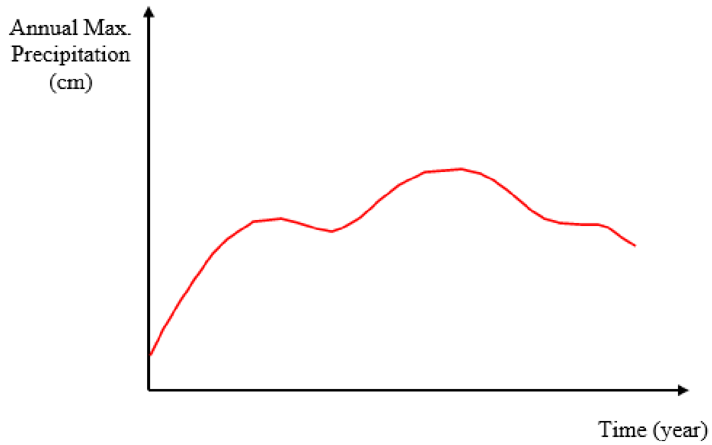

| Zone | Area (km²) |
|---|---|
| 1 | 210 |
| 2 | 170 |
| 3 | 95 |
| 4 | 135 |
| 5 | 195 |
| 6 | 200 |

Calculate average P ?

## 2.13 Frequency of point rainfall

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

$$T = 1/P$$




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

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

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

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

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

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

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

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

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

$$P_1 = 1 - q^n = 1 - (1 - P)^n$$

## Example:

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

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

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

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

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

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

(c) By Eq. (2.13)

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

## 2.14 Plotting Position Criterea

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

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

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

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

## Example:

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

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

## Solution:

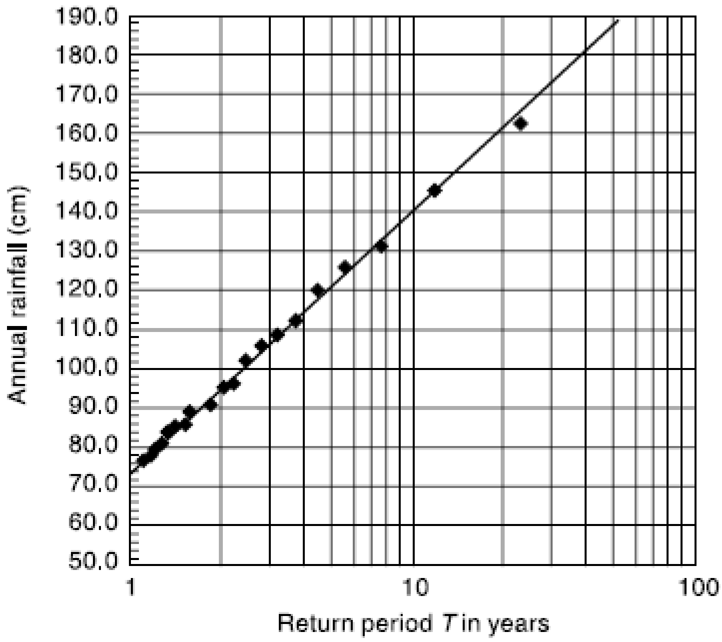
$N = 22$ years

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

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

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

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




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

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

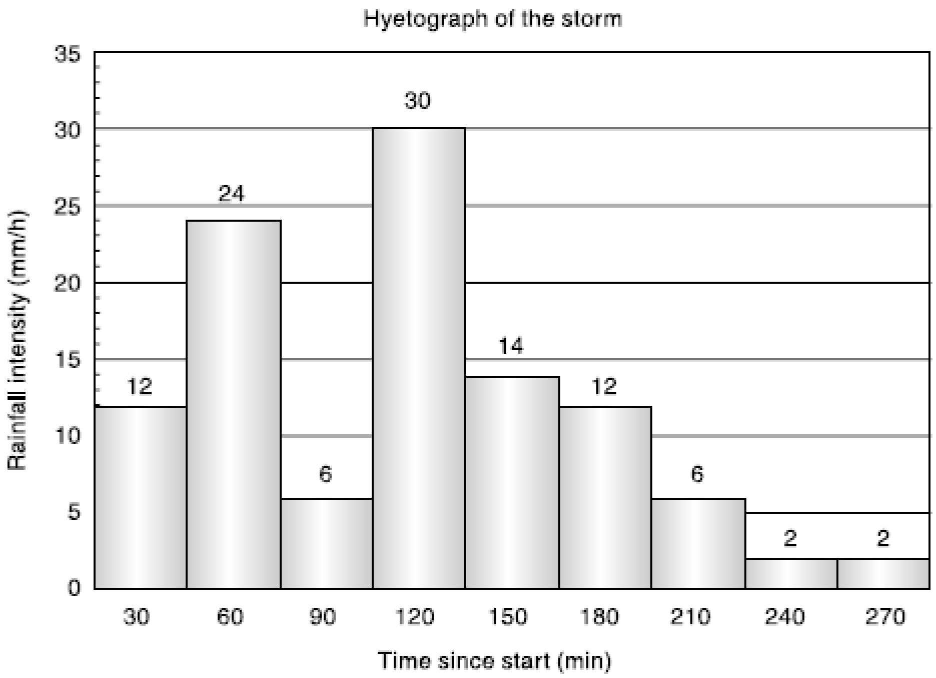
## Example:

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

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

## Solution:

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

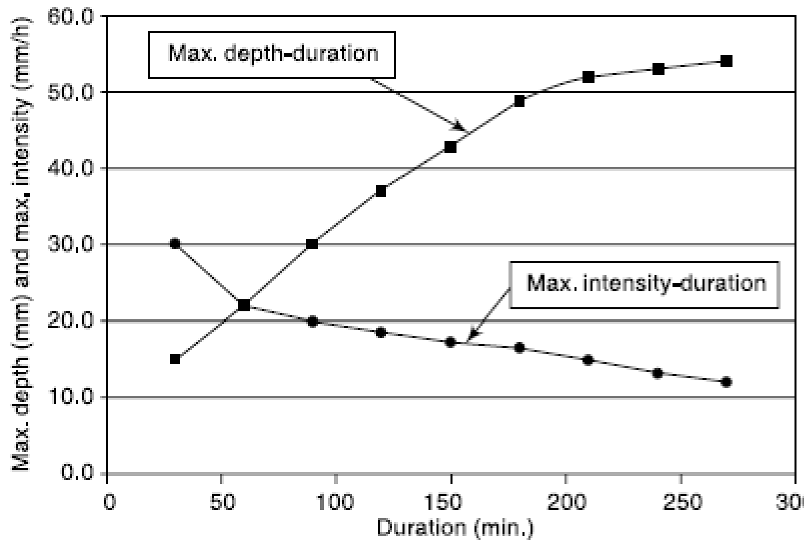


Maximum Intensity-Duration Relation

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

Maximum Intensity-Maximum Depth-Duration Relation

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




Maximum Intensity-Duration and Maximum Depth-Duration Curves for the Storm of Example

# Chapter Three
# Abstraction from Precipitation

## 3.1 Evaporationprocess

*Evaporation* is the process in which a liquid changes to the gaseous state at the free surface, below the boiling point through the transfer of heat energy.

The rate of evaporation is dependent on (i) the vapour pressures at the water surface and air above, (ii) air and water temperatures, (iii) wind speed, (iv) atmospheric pressure, (v) quality of water, and (vi) size of the water body.

VAPOUR PRESSURE

The rate of evaporation is proportional to the difference between the saturation vapour pressure at the water temperature, $e_w$ and the actual vapour pressure in the air, $e_a$. Thus

$$E_L = C(e_w - e_a) \qquad (3.1)$$

where $E_L$ = rate of evaporation (mm/day) and $C$ = a constant; $e_w$ and $e_a$ are in mm of mercury. Equation (3.1) is known as *Dalton's law of evaporation* after John Dalton (1802) who first recognised this law. Evaporation continues till $e_w = e_a$. If $e_w > e_a$ condensation takes place.

TEMPERATURE Other factors remaining the same, the rate of evaporation increases with an increase in the water temperature.

WIND Wind aids in removing the evaporated water vapour from the zone of evaporation and consequently creates greater scope for evaporation.

ATMOSPHERIC PRESSURE Other factors remaining same, a decrease in the barometric pressure, as in high altitudes, increases evaporation.

SOLUBLE SALTS When a solute is dissolved in water, the vapour pressure of the solution is less than that of pure water and hence causes reduction in the rate of evaporation.

## 3.2 Evaporimeter

The amount of water evaporated from a water surface is estimated by the following methods: (i) using evaporimeter data, (ii) empirical evaporation equations, and (iii) analytical methods.

## 3.3 Evaporation Measurement Stations

EVAPORATION STATIONS It is usual to instal evaporation pans in such locations where other meteorological data are also simultaneously collected. The WMO recommends the minimum network of evaporimeter stations as below:

1. Arid zones—One station for every 30,000 $km^2$,
2. Humid temperate climates—One station for every 50,000 $km^2$, and
3. Cold regions—One station for every 100,000 $km^2$.

## 3.4 Empirical Evaporation Equations.

A large number of empirical equations are available to estimate lake evaporation using commonly available meteorological data. Most formulae are based on the Dalton-type equation and can be expressed in the general form

$$E_L = K f(u)(e_w - e_a) \tag{3.2}$$

where $E_L$ = lake evaporation in mm/day, $e_w$ = saturated vapour pressure at the water-surface temperature in mm of mercury, $e_a$ = actual vapour pressure of over-lying air at a specified height in mm of mercury, $f(u)$ = wind-speed correction function and $K$ = a coefficient. The term $e_a$ is measured at the same height at which wind speed is measured. Two commonly used empirical evaporation formulae are:

## Meyer's Equation

MEYER'S FORMULA (1915)

$$E_L = K_M(e_w - e_a)\left(1 + \frac{u_9}{16}\right) \tag{3.3}$$

in which $E_L$, $e_w$, $e_a$ are as defined in Eq. (3.2), $u_9$ = monthly mean wind velocity in km/h at about 9 m above ground and $K_M$ = coefficient accounting for various other factors with a value of 0.36 for large deep waters and 0.50 for small, shallow waters.

## Rohwer's Equation

ROHWER'S FORMULA (1931) Rohwer's formula considers a correction for the effect of pressure in addition to the wind-speed effect and is given by

$$E_L = 0.771(1.465 - 0.000732\, p_a)(0.44 + 0.0733\, u_0)\,(e_w - e_a) \tag{3.4}$$

in which $E_L$, $e_w$, and $e_a$ are as defined earlier in Eq. (3.2),

$p_a$ = mean barometric reading in mm of mercury

$u_0$ = mean wind velocity in km/h at ground level, which can be taken to be the velocity at 0.6 m height above ground.

$e_w$ from table (3.1)

$U_h = U\,(\,h\,)^{1/7}$

where $u_h$ = wind velocity at a height $h$ above the ground and $C$ = constant. This equation can be used to determine the velocity at any desired level if $u_h$ is known.

**Table** Saturation Vapour Pressure of Water

| Temperature (°C) | Saturation vapour pressure $e_w$ (mm of Hg) | A (mm/°C) |
|---|---|---|
| 0 | 4.58 | 0.30 |
| 5.0 | 6.54 | 0.45 |
| 7.5 | 7.78 | 0.54 |
| 10.0 | 9.21 | 0.60 |
| 12.5 | 10.87 | 0.71 |
| 15.0 | 12.79 | 0.80 |
| 17.5 | 15.00 | 0.95 |
| 20.0 | 17.54 | 1.05 |
| 22.5 | 20.44 | 1.24 |
| 25.0 | 23.76 | 1.40 |
| 27.5 | 27.54 | 1.61 |
| 30.0 | 31.82 | 1.85 |
| 32.5 | 36.68 | 2.07 |
| 35.0 | 42.81 | 2.35 |
| 37.5 | 48.36 | 2.62 |
| 40.0 | 55.32 | 2.95 |
| 45.0 | 71.20 | 3.66 |

$e_w = 4.584 \exp\left(\frac{17.27\,t}{237.3 + t}\right)$ mm of Hg, where $t$ = temperature in °C.

**EXAMPLE 3.1**

*(a) A reservoir with a surface area of 250 hectares had the following average values of climate parameters during a week: Water temperature = 20°C, Relative humidity = 40%, Wind velocity at 1.0 m above ground surface = 16 km/h. Estimate the average daily evaporation from the lake by using Meyer's formula.*

*(b) An ISI Standard evaporation pan at the site indicated a pan coefficient of 0.80 on the basis of calibration against controlled water budgeting method. If this pan indicated an evaporation of 72 mm in the week under question, (i) estimate the accuracy if Meyer's method relative to the pan evaporation measurements. (ii) Also, estimate the volume of water evaporated from the lake in that week.*

## 3.5 Analytical methods for estimating Evaporation

The analytical methods for the determination of lake evaporation can be broadly classified into three categories as:

1. Water-budget method,
2. Energy-balance method, and
3. Mass-transfer method.

## Water Budget Method

$$P + V_{is} + V_{ig} = V_{os} + V_{og} + E_L + \Delta S + T_L \qquad (3.6)$$

where $P$ = daily precipitation

$V_{is}$ = daily surface inflow into the lake
$V_{ig}$ = daily groundwater inflow
$V_{os}$ = daily surface outflow from the lake
$V_{og}$ = daily seepage outflow
$E_L$ = daily lake evaporation
$\Delta S$ = increase in lake storage in a day
$T_L$ = daily transpiration loss

All quantities are in units of volume ($m^3$) or depth (mm) over a reference area. Equation (3.6) can be written as

$$E_L = P + (V_{is} - V_{os}) + (V_{ig} - V_{og}) - T_L - \Delta S \qquad (3.7)$$

## 3.6 EvapotranspirationEquations

*Transpiration* is the process by which water leaves the body of a living plant and reaches the atmosphere as water vapour.

## Penman's Equation

Penman's equation is based on sound theoretical reasoning and is obtained by a combination of the energy-balance and mass-transfer approach. Penman's equation, incorporating some of the modifications suggested by other investigators is

$$\text{PET} = \frac{AH_n + E_a\gamma}{A + \gamma} \qquad (3.13)$$

where PET = daily potential evapotranspiration in mm per day
$A$ = slope of the saturation vapour pressure *vs* temperature curve at the mean air temperature, in mm of mercury per °C (Table 3.3)
$H_n$ = net radiation in mm of evaporable water per day
$E_a$ = parameter including wind velocity and saturation deficit
$\gamma$ = psychrometric constant = 0.49 mm of mercury/°C

The net radiation is the same as used in the energy budget [Eq. (3.8)] and is estimated by the following equation:

$$H_n = H_a(1-r)\left(a + b\frac{n}{N}\right) - \sigma T_a^4 (0.56 - 0.092\sqrt{e_a})\left(0.10 + 0.90\frac{n}{N}\right) \quad (3.14)$$

where $H_a$ = incident solar radiation outside the atmosphere on a horizontal surface, expressed in mm of evaporable water per day (it is a function of the latitude and period of the year as indicated in Table 3.4)
$a$ = a constant depending upon the latitude $\phi$ and is given by $a = 0.29 \cos \phi$
$b$ = a constant with an average value of 0.52
$n$ = actual duration of bright sunshine in hours
$N$ = maximum possible hours of bright sunshine (it is a function of latitude as indicated in Table 3.5)
$r$ = reflection coefficient (albedo). Usual ranges of values of $r$ are given below.

| Surface | Range of $r$ values |
|---|---|
| Close ground corps | 0.15–0.25 |
| Bare lands | 0.05–0.45 |
| Water surface | 0.05 |
| Snow | 0.45–0.95 |

$\sigma$ = Stefan-Boltzman constant = $2.01 \times 10^{-9}$ mm/day
$T_a$ = mean air temperature in degrees kelvin = 273 + °C
$e_a$ = actual mean vapour pressure in the air in mm of mercury

The parameter $E_a$ is estimated as

$$E_a = 0.35\left(1 + \frac{u_2}{160}\right)(e_w - e_a) \quad (3.15)$$

in which
$u_2$ = mean wind speed at 2 m above ground in km/day
$e_w$ = saturation vapour pressure at mean air temperature in mm of mercury (Table 3.3)
$e_a$ = actual vapour pressure, defined earlier

**Table 3.** Mean Monthly Solar Radiation at Top of Atmosphere, $H_a$ in mm of Evaporable Water/Day

| North latitude | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 14.5 | 15.0 | 15.2 | 14.7 | 13.9 | 13.4 | 13.5 | 14.2 | 14.9 | 15.0 | 14.6 | 14.3 |
| 10° | 12.8 | 13.9 | 14.8 | 15.2 | 15.0 | 14.8 | 14.8 | 15.0 | 14.9 | 14.1 | 13.1 | 12.4 |
| 20° | 10.8 | 12.3 | 13.9 | 15.2 | 15.7 | 15.8 | 15.7 | 15.3 | 14.4 | 12.9 | 11.2 | 10.3 |
| 30° | 8.5 | 10.5 | 12.7 | 14.8 | 16.0 | 16.5 | 16.2 | 15.3 | 13.5 | 11.3 | 9.1 | 7.9 |
| 40° | 6.0 | 8.3 | 11.0 | 13.9 | 15.9 | 16.7 | 16.3 | 14.8 | 12.2 | 9.3 | 6.7 | 5.4 |
| 50° | 3.6 | 5.9 | 9.1 | 12.7 | 15.4 | 16.7 | 16.1 | 13.9 | 10.5 | 7.1 | 4.3 | 3.0 |

**Table 3.** Mean Monthly Values of Possible Sunshine Hours, $N$

| North latitude | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0° | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 | 12.1 |
| 10° | 11.6 | 11.8 | 12.1 | 12.4 | 12.6 | 12.7 | 12.6 | 12.4 | 12.9 | 11.9 | 11.7 | 11.5 |
| 20° | 11.1 | 11.5 | 12.0 | 12.6 | 13.1 | 13.3 | 13.2 | 12.8 | 12.3 | 11.7 | 11.2 | 10.9 |
| 30° | 10.4 | 11.1 | 12.0 | 12.9 | 13.7 | 14.1 | 13.9 | 13.2 | 12.4 | 11.5 | 10.6 | 10.2 |
| 40° | 9.6 | 10.7 | 11.9 | 13.2 | 14.4 | 15.0 | 14.7 | 13.8 | 12.5 | 11.2 | 10.0 | 9.4 |
| 50° | 8.6 | 10.1 | 11.8 | 13.8 | 15.4 | 16.4 | 16.0 | 14.5 | 12.7 | 10.8 | 9.1 | 8.1 |

| | | |
|---|---|---|
| *Mean monthly temperature* | : | *19° C* |
| *Mean relative humidity* | : | *75%* |
| *Mean observed sunshine hours* | : | *9 h* |
| *Wind velocity at 2 m height* | : | *85 km/day* |
| *Nature of surface cover* | : | *Close-ground green crop* |

**EXAMPLE 3.2** *Calculate the potential evapotranspiration from an area near New Delhi in the month of November by Penman's fomula. The following data are available:*

| | | |
|---|---|---|
| *Latitude* | : | *28°4′N* |
| *Elevation* | : | *230 m (above sea level)* |

SOLUTION: From Table 3. ,

$A = 1.00$ mm/°C $\qquad e_w = 16.50$ mm of Hg

From Table 3.4

$H_a = 9.506$ mm of water/day

From Table 3.5

$N = 10.716$ h $\qquad n/N = 9/10.716 = 0.84$

From given data

$$e_a = 16.50 \times 0.75 = 12.38 \text{ mm of Hg}$$
$$a = 0.29 \cos 28° \, 4' = 0.2559$$
$$b = 0.52$$
$$\sigma = 2.01 \times 10^{-9} \text{ mm/day}$$
$$T_a = 273 + 19 = 292 \text{ K}$$
$$\sigma T_a^4 = 14.613$$

$r$ = albedo fer close-ground green crop is taken as 0.25

From Eq. (3.14),

$$H_n = 9.506 \times (1 - 0.25) \times (0.2559 + (0.52 \times 0.84)) - 14.613 \times (0.56 - 0.092\sqrt{12.38}) \times (0.10 + (0.9 \times 0.84))$$
$$= 4.936 - 2.946 = 1.990 \text{ mm of water/day}$$

From Eq. (3.15),

$$E_a = 0.35 \times \left(1 + \frac{85}{160}\right) \times (16.50 - 12.38) = 2.208 \text{ mm/day}$$

From Eq. (3.13), noting the value of $\gamma = 0.49$.

$$\text{PET} = \frac{(1 \times 1.990) + (2.208 \times 0.49)}{(1.00 + 0.49)} = 2.06 \text{ mm/day}$$

**EXAMPLE 3.3** *Using the data of Example 3.2, estimate the daily evaporation from a lake situated in that place.*

SOLUTION: For estimating the daily evaporation from a lake, Penman's equation is used with the albedo $r = 0.05$.

Hence

$$H_n = 4.936 \times \frac{(1.0 - 0.05)}{(1.0 - 0.25)} - 2.946 = 6.252 - 2.946 = 3.306 \text{ mm of water/day}$$
$$E_a = 2.208 \text{ mm/day}$$

From Eq. (3.13),

$$\text{PET} = \text{Lake evaporation}$$

$$= \frac{(1.0 \times 3.306) + (2.208 \times 0.49)}{(1.0 - 0.49)} = 2.95 \text{ mm/day}$$

## 3.4 Empirical EvapotranspirationEquations.

### Blaney – Criddle formula

$$E_T = 2.54\ KF$$

and $$F = \Sigma P_h \bar{T}_f / 100 \qquad (3.1\ \ )$$

where $E_T$ = PET in a crop season in cm

$K$ = an empirical coefficient, depends on the type of the crop and stage of growth

$F$ = sum of monthly consumptive use factors for the period

$P_h$ = monthly percent of annual day-time hours, depends on the latitude of the place (Table 3.6)

and $\bar{T}_f$ = mean monthly temperature in °F

**Table 3.** Monthly Daytime Hours Percentages, $P_h$, for use in Blaney-Criddle Formula (Eq. 3.1  )

| North latitude (deg) | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 8.50 | 7.66 | 8.49 | 8.21 | 8.50 | 8.22 | 8.50 | 8.49 | 8.21 | 8.50 | 8.22 | 8.50 |
| 10 | 8.13 | 7.47 | 8.45 | 8.37 | 8.81 | 8.60 | 8.86 | 8.71 | 8.25 | 8.34 | 7.91 | 8.10 |
| 15 | 7.94 | 7.36 | 8.43 | 8.44 | 8.98 | 8.80 | 9.05 | 8.83 | 8.28 | 8.26 | 7.75 | 7.88 |
| 20 | 7.74 | 7.25 | 8.41 | 8.52 | 9.15 | 9.00 | 9.25 | 8.96 | 8.30 | 8.18 | 7.58 | 7.66 |
| 25 | 7.53 | 7.14 | 8.39 | 8.61 | 9.33 | 9.23 | 9.45 | 9.09 | 8.32 | 8.09 | 7.40 | 7.42 |
| 30 | 7.30 | 7.03 | 8.38 | 8.72 | 9.53 | 9.49 | 9.67 | 9.22 | 8.33 | 7.99 | 7.19 | 7.15 |
| 35 | 7.05 | 6.88 | 8.35 | 8.83 | 9.76 | 9.77 | 9.93 | 9.37 | 8.36 | 7.87 | 6.97 | 6.86 |
| 40 | 6.76 | 6.72 | 8.33 | 8.95 | 10.02 | 10.08 | 10.22 | 9.54 | 8.39 | 7.75 | 6.72 | 6.52 |

**Table 3.** Values of $K$ for Selected Crops

| Crop | Average value of $K$ | Range of monthly values |
|---|---|---|
| Rice | 1.10 | 0.85–1.30 |
| Wheat | 0.65 | 0.50–0.75 |
| Maize | 0.65 | 0.50–0.80 |
| Sugarcane | 0.90 | 0.75–1.00 |
| Cotton | 0.65 | 0.50–0.90 |
| Potatoes | 0.70 | 0.65–0.75 |
| Natural Vegetation: | | |
| (a) Very dense | 1.30 | |
| (b) Dense | 1.20 | |
| (c) Medium | 1.00 | |
| (d) Light | 0.80 | |

**Example 3.4** *Estimate the PET of an area for the season November to February in which wheat is grown. The area is in North India at a latitude of 30° N with mean monthly temperatures as below:*

| Month | Nov. | Dec. | Jan. | Feb. |
|---|---|---|---|---|
| Temp. (°C) | 16.5 | 13.0 | 11.0 | 14.5 |

*Use the Blaney-Criddle formula.*

**Solution:** From Table 3. , for wheat $K = 0.65$. Values of $P_h$ for 30° N is read from Table 3. , the temperatures are converted to Fahrenheit and the calculations are performed in the following table.

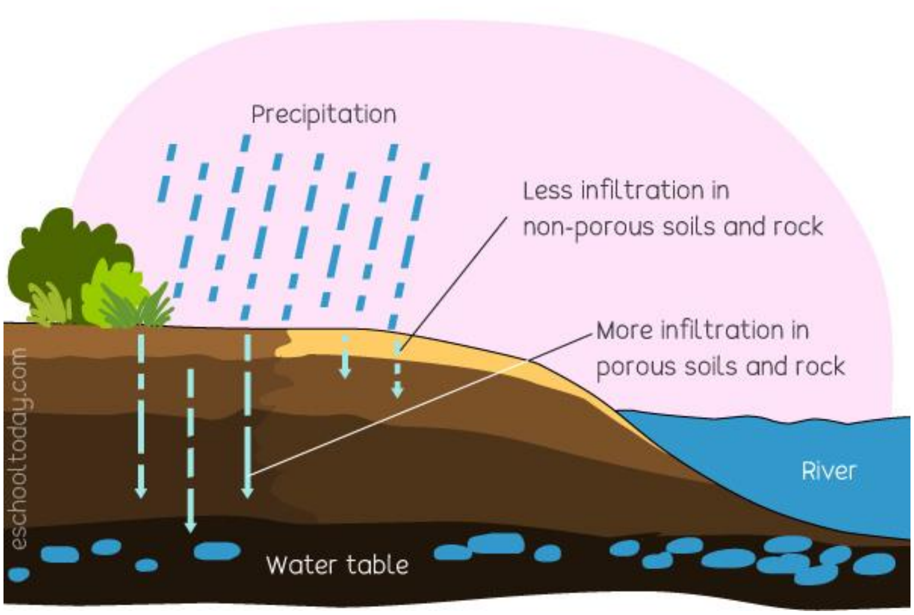
| Month | $\bar{T}_f$ | $P_h$ | $P_h\bar{T}_f/100$ |
|---|---|---|---|
| Nov. | 61.7 | 7.19 | 4.44 |
| Dec. | 55.4 | 7.15 | 3.96 |
| Jan. | 51.8 | 7.30 | 3.78 |
| Feb. | 58.1 | 7.03 | 4.08 |
| | | $\Sigma P_h\bar{T}_f/100 =$ | 16.26 |

By Eq. (3.17),

$$E_T = 2.54 \times 16.26 \times 0.65 = 26.85 \text{ cm.}$$

## 3.8 Infiltration

**Infiltration** is the process by which water on the ground surface enters the soil. It is commonly used in both hydrology and soil sciences. The **infiltration** capacity is defined as the maximum rate of **infiltration**.



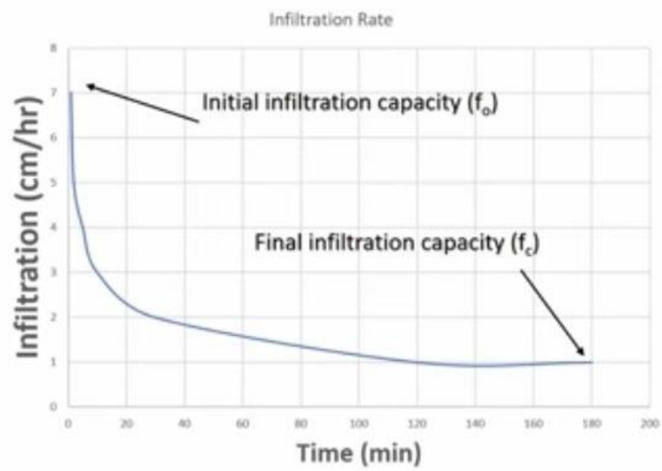

## Infiltration Measurement:

The **infiltration** rate is the velocity or speed at which water enters into the soil. It is usually **measured** by the depth (in mm) of the water layer that can enter the soil in one hour. An **infiltration** rate of 15 mm/hour means that a water layer of 15 mm on the soil

.

Infiltrometer is a device used to measure the rate of water infiltration into soil or other porous media. Commonly used infiltrometers are single ring or double ring infiltrometer.

| Time (min) | Infiltration (cm) |
| --- | --- |
| 1 | 7 |
| 2 | 5 |
| 5 | 4 |
| 10 | 3 |
| 30 | 2 |
| 120 | 1 |
| 180 | 1 |



## Horton Infiltration Model

* Infiltration rate (capacity)

$$\underset{cm/hr}{f(t)} = \underset{cm/hr}{f_c} + (f_o - f_c)\, e^{-k \cdot t} \quad \text{(k: } hr^{-1}\text{, t: hr, } f_o\text{: cm/hr)} \qquad \text{—— (1)}$$

* Infiltration depth

$$f_d = f_c * t + \frac{f_o - f_c}{k} \left(1 - e^{-k \cdot t}\right) \Big|_{t_o}^{t=n} \qquad \text{—— (2)}$$

$$\Rightarrow f_{volume} = f_d * Area \qquad \text{—— (3)}$$

Example (1): $f_o = 5 \frac{cm}{hr}$, $f_c = 2 \frac{cm}{hr}$

$k = 6\ day^{-1}$ calculate the infiltration rate at $t = 4\ hrs$ ?

sol :-

$$f(4) = f_c + (f_o - f_c)\, e^{-kt}$$

$$f(4) = 2 + (5-2)\, e^{-\frac{6}{24} * 4}$$

$$f(4) = 2 + 1.1$$

$$f(4) = 3.1\ cm/hr$$

**A soil sample has an initial infiltration capacity of 10.0 mm/hr and a final infiltration capacity of 4.0 mm/hr, the recession constant is 0.02 $min^{-1}$, calculate:**

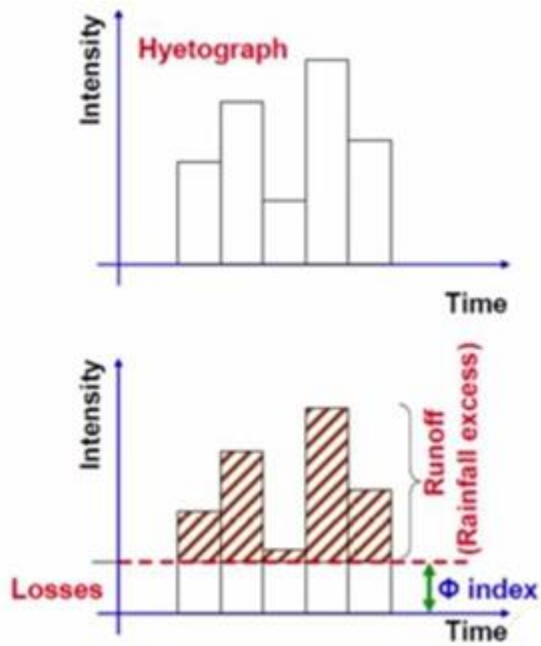
**A) Infiltration capacity after 6 hours from the beginning of the storm.**
**B) Infiltration volume after 8 hours from the beginning of the storm (assuming the area is 100 $km^2$).**

A soil sample has an initial infiltration capacity of 95 mm/hr and a final infiltration capacity of 52 mm/hr, the recession constant is 0.15 $hr^{-1}$, calculate:

A) Infiltration capacity after 3 hours from the beginning of the storm.
B) Infiltration volume from 3rd hour to the 10th hour of the storm (assuming the area is 32 $km^2$).

During a storm the recorded rainfall was 12 cm, at the same location the soil has initial infiltration capacity of 6 cm/hr and final infiltration capacity of 2 cm/hr with a decay constant of 0.22 $hr^{-1}$ , if the storm duration is 12 hours calculate the run-off volume of this storm (assume area = 10 $km^2$)

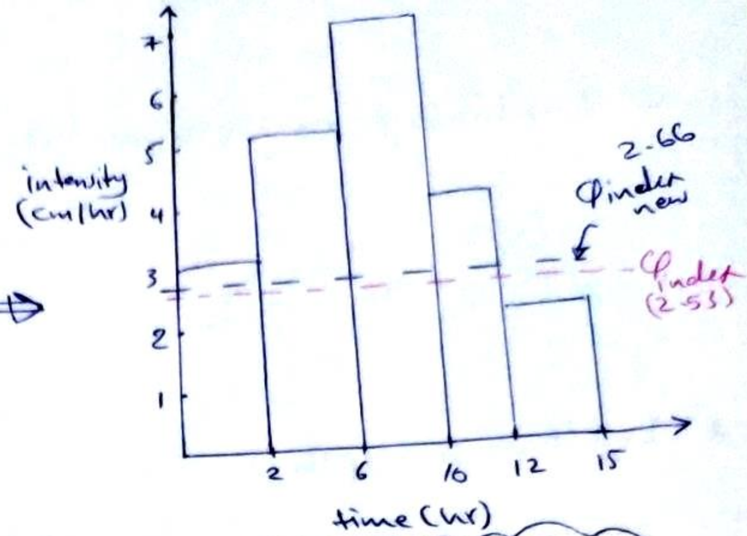
<u>ϕ index</u>: is defined as the average rainfall above which the rainfall volume equals the runoff volume.



Example:

| time (hr) | Intensity (cm/hr) |
|---|---|
| 2 | 3 |
| 6 | 5 |
| 10 | 7 |
| 12 | 4 |
| 15 | 2 |

⟹




$$\underset{cm/hr}{\varphi} = \frac{\overset{cm}{P} - \overset{cm}{R}}{D_{hr}}$$

solution:

$$P = \sum \Delta t * i$$

$$= (2*3) + (4*5) + (4*7) + (2*4) + (3*2)$$

$$\boxed{P = 68\ cm}$$

R assume 30cm

$$\varphi = \frac{68\,cm - 30\,cm}{15\,hr} = 2.53\ cm/hr$$

$$\varphi_{new} = \frac{P_{new} - R}{D_{new}}$$

$$= \frac{62 - 30}{12} = 2.66\ cm/hr$$

# Chapter Four
# Stream Flow Measurement

## 4.1 Introduction:

Streamflow, or channel runoff, is the flow of water in streams, rivers, and other channels, and is a major element of the water cycle. It is one component of the runoff of water from the land to waterbodies, the other component being surface runoff. Water flowing in channels comes from surface runoff from adjacent hillslopes, from groundwater flow out of the ground, and from water discharged from pipes. The discharge of water flowing in a channel is measured using stream gauges or can be estimated by the Manning equation. The record of flow over time is called a hydrograph. Flooding occurs when the volume of water exceeds the capacity of the channel.

Streamflow measurement techniques can be broadly classified into two cate-gories as (i) direct determination and (ii) indirect determination. Under each category there are a host of methods, the important ones are listed below:

1. Direct determination of stream discharge:
   - (a) Area-velocity methods,
   - (b) Dilution techniques,
   - (c) Electromagnetic method, and
   - (d) Ultrasonic method.
2. Indirect determination of streamflow:
   - (a) Hydraulic structures, such as weirs, flumes and gated structures, and
   - (b) Slope-area method.

### *1. The velocity-area method*

The velocity-area method is the most common method of estimating river flow. As the term implies, the flow is the product of the average velocity in the cross-section and the cross-sectional area of flow.

## Example :

| Section | $V_{0.2}$ | | $V_{0.8}$ | | $A(m^2)$ |
|---|---|---|---|---|---|
| | # revolulion | Time | # revolulion | Time | |
| 1 | 39 | 55 | --- | --- | 20 |
| 2 | 57 | 50 | 76 | 40 | 35 |
| 3 | 65 | 48 | 81 | 54 | 44 |
| 4 | 43 | 51 | --- | --- | 15 |

**H.W:**

the data pertaining to a stream-gauging operation at a gauging site are given below.
The rating equation of the current meter is $v = 0.51\ Ns + 0.03\ m/s$ Calculate the discharge in the stream.

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Distance from left water dege (m) | 0 | 1.0 | 3.0 | 5.0 | 7.0 | 9.0 | 11.0 | 12.0 |
| Depth (m) | 0 | 1.1 | 2.0 | 2.5 | 2.0 | 1.7 | 1.0 | 0 |
| Revolutions of a current meter kept at 0.6 depth | 0 | 39 | 58 | 112 | 90 | 45 | 30 | 0 |
| Duration of observation (s) | 0 | 100 | 100 | 150 | 100 | 100 | 100 | 0 |

*Ans. Total discharge $Q$ = 6.457m3 /s*

# Chapter Four
# Stream Flow Measurement

## 2. Dilution method:

The tracer-dilution method consists of adding a known amount of concentrated tracer at a constant rate to the flow stream. Chemical analysis is used to determine the dilution of the uniformly mixed concentrate at some downstream point. It is important that the tracer be added at a known and constant discharge rate.

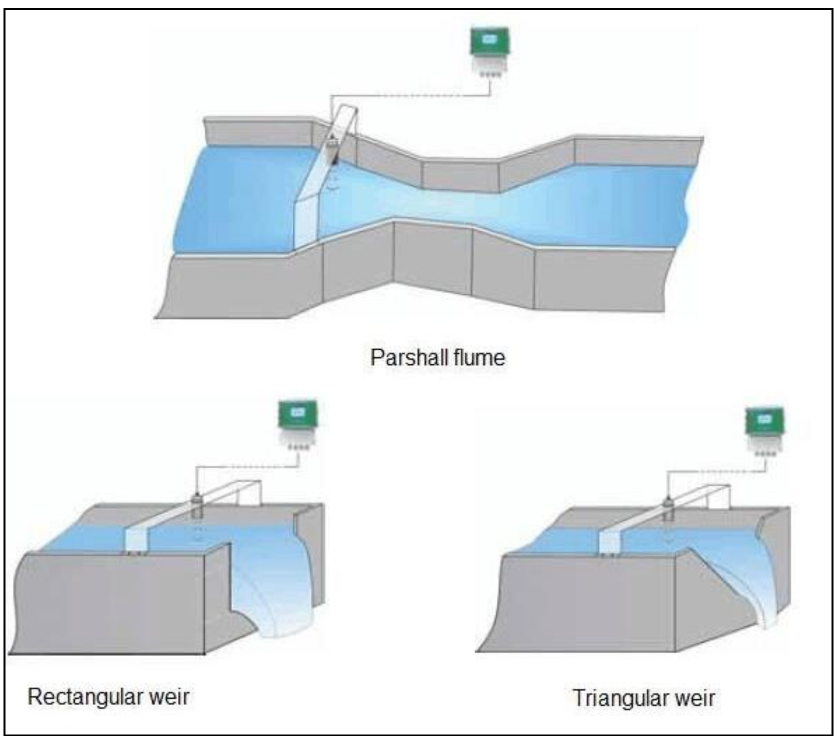
An advantage of the tracer-dilution method is that no measurements of the flow channel geometry are required.

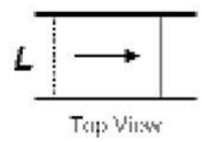
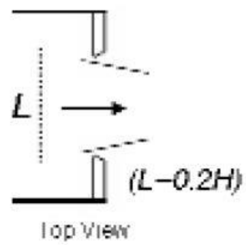
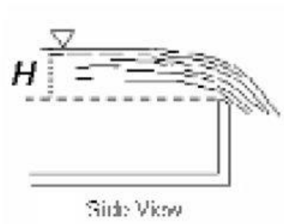
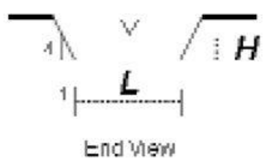
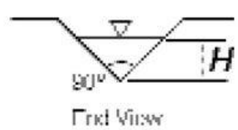
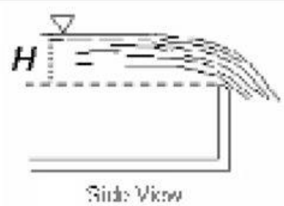
Tracers may be color-dilution or salt-dilution, with the former suitable for measuring small to large flows (the cost of the dye being relatively low) and the latter suitable for turbulent streams of small to medium size where other methods of flow measurement are impractical.

Tracer-dilution methods can vary considerably in accuracy, from +/- 1% to over 30%, depending upon the equipment used, experience of the personnel, and the accuracy of the measuring equipment.

## 3. Flow measurement using hydraulic structures

Flow measurement using hydraulic structures involves the placement of a selected hydraulic structure such as weirs or flumes across a river channel. This is to generate flow properties that can be used to develop relationships between flow rate and water levels at certain section along the stream. This method uses a hydraulic structure constructed across a channel to produce flow properties that are characterized by relationships between the water level measurement at some location and the flow rate of the stream. The streamflow is estimated by taking measurement of the water surface level in or near the restriction of the hydraulic structure.

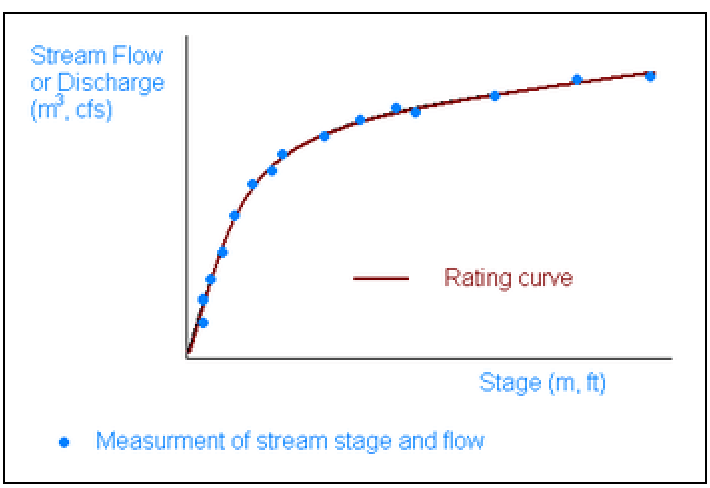


| Weir Type | Views | | Formula |
|---|---|---|---|
| Rectangular (without contraction) |   | | $Q = 0.0184\ LH^{1.5}$ |
| Rectangular (with contraction) |   |   | $Q = 0.0184\ (L - 0.2H)\ H^{1.5}$ |
| Trapezoidal |   | | $Q = 0.0184\ LH^{1.5}$ |
| Triangular V notch |   |   | $Q = 0.0138\ H^{2.5}$ |

Q = Discharge (l/second), L = Crest width (cm), H = Head (cm)

## 4. Rating Curve

A *rating curve* is a plot of the stage of the water versus the flow that the stream had at that stage. An example of a rating curve is shown in the following figure.



The *stage* is the height of the water surface above some datum point, which is usually taken as the deepest point in the stream channel. (Difference between Stage and Depth)

***Importance of Rating Curve***

Hydrologists very often need to know flow rates in streams under many different conditions but they do not have the time or resources to go into the field and measure these flow rates continually. Instead, they often rely on rating curves to give them this information. When the time and energy is taken to directly measure stream flow (using sections) at a given point in a stream, the stage of the water is usually recorded at the same time. Using these data points of the water elevation (stage) and the measured flow rate, hydrologists can produce a rating curve.

**Surface Run- off:**

When water does not soak into the ground, it runs-off into gullies, streams and rivers. Nearly 40 per cent of all precipitation flows back across the land to rivers, lakes, seas and oceans.

**Baseflow** is a portion of streamflow that is not directly generated from the excess rainfall during a storm event. In other words, this is the flow that would exist **in the** stream without the contribution of **direct runoff** from the rainfall.

But runoff which is also called Surface **runoff** is **water**, from rain, snowmelt, or other sources, that flows over the land surface, and is a major component of the **water cycle**. ... When **runoff** flows along the ground, it can pick up soil contaminants such as petroleum, pesticides, or fertilizers that become discharge or overland flow.

## Natural Flow

Runoff representing the response of a catchment to precipitation reflects the integrated effects of a wide range of catchment, climate and rainfall characteristics. True runoff is therefore stream flow in its natural condition, i.e. without human intervention. Such a stream flow unaffected by works of man, such as reservoirs and diversion structures on a stream, is called *natural flow* or *virgin flow*. When there exists storage or diversion works on a stream, the flow on the downstream channel is affected by the operational and hydraulic characteristics of these structures and hence does not represent the true runoff, unless corrected for the diversion of flow and return flow.

The natural flow (virgin flow) volume in time $\Delta t$ at the terminal point of a catchment is expressed by water balance equation as

$$R_N = (R_o - V_r) + V_d + E + E_X + \Delta S$$

where $R_N$ = Natural flow volume in time $\Delta t$

$R_o$ = Observed flow volume in time $\Delta t$ at the terminal site

$V_r$ = Volume of return flow from irrigation, domestic water supply and industrial use

$V_d$ = Volume diverted out of the stream for irrigation, domestic water supply and industrial use

$E$ = net evaporation losses from reservoirs on the stream

$E_X$ = Net export of water from the basin

$\Delta S$ = Change in the storage volumes of water storage bodies on the stream

*The following table gives values of measured discharges at a stream–gauging site in a year. Upstream of the gauging site a weir built across the stream diverts 3.0 $Mm^3$ and 0.50 $Mm^3$ of water per month for irrigation and for use in an industry respectively. The return flows from the irrigation is estimated as 0.8 $Mm^3$ and from the industry at 0.30 $Mm^3$ reaching the stream upstream of the gauging site. Estimate the natural flow. If the catchment area is 180 $km^2$ and the average annual rainfall is 185 cm, determine the runoff-rainfall ratio.*

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gauged flow ($Mm^3$) | 2.0 | 1.5 | 0.8 | 0.6 | 2.1 | 8.0 | 18.0 | 22.0 | 14.0 | 9.0 | 7.0 | 3.0 |

SOLUTION: In a month the natural flow volume $R_N$ is obtained from

$$R_N = (R_o - V_r) + V_d + E + E_X + \Delta S$$

Here $E$, $E_X$ and $\Delta S$ are assumed to be insignificant and of zero value.

$V_r$ = Volume of return flow from irrigation, domestic water supply and industrial use = 0.80 + 0.30 = 1.10 $Mm^3$

$V_d$ = Volume diverted out of the stream for irrigation, domestic water supply and industrial use = 3.0 + 0.5 = 3.5 $Mm^3$

The calculations are shown in the following Table:

| **Month** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $R_o$($Mm^3$) | 2.0 | 1.5 | 0.8 | 0.6 | 2.1 | 8.0 | 18.0 | 22.0 | 14.0 | 9.0 | 7.0 | 3.0 |
| $V_d$($Mm^3$) | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 | 3.5 |
| $V_r$($Mm^3$) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| $R_N$($Mm^3$) | 4.4 | 3.9 | 3.2 | 3.0 | 4.5 | 10.4 | 20.4 | 24.4 | 16.4 | 11.4 | 9.4 | 5.4 |

Total $R_N$ = 116.8 $Mm^3$

Annual natural flow volume = Annual runoff volume = 116.8 $Mm^3$

Area of the catchment = 180 $km^2$ = $1.80 \times 10^8$

$$\text{Annual runoff depth} = \frac{1.168 \times 10^8}{1.80 \times 10^8} = 0.649 \text{ m} = 64.9 \text{ cm}$$

Annual rainfall = 185 cm (Runoff/Rainfall) = 64.9/185 = 0.35

# Stream Flow and Its Measurement Methods

stream flow is usually defined as visible water on the ground, i.e., the surface water. This may include ponds, brooks, creeks, rivers, lakes, reservoirs, etc. Surface water is valuable for water supply and environmental concerns. For example, a lake is a natural water reservoir that can be used for water supply as well as irrigation.

### *STREAM FLOW MEASUREMENTS*

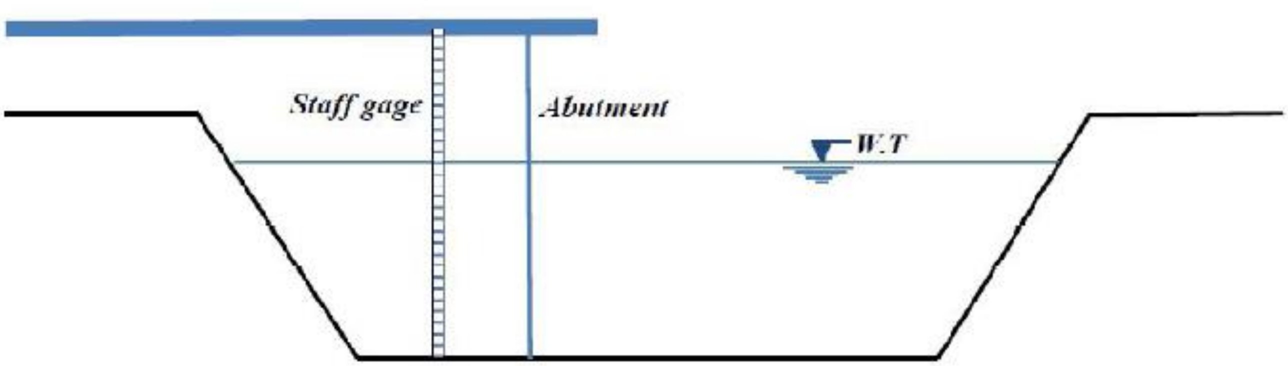
1- Water stage measurements.
2- Discharge measurements.

## *1- Water stage measurements*

The stage of a river is defined as its water-surface elevation measured above a datum. This datum can be the mean-sea level (MSL) or any arbitrary datum connected independently to the MSL.
The simplest way to measure river stage is by means of staff gage. The stage measurements are made by noting the elevation of the water surface in contact with a fixed graduated.

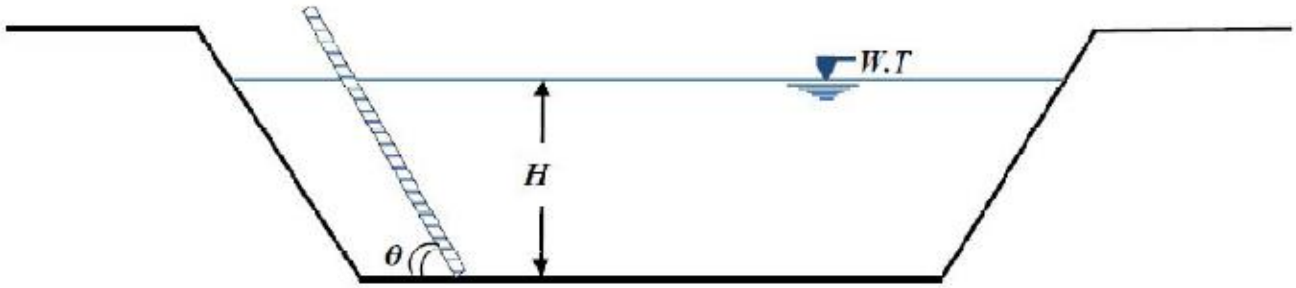
***TYPES OF STAFF GAGE***

1- Simple vertical staff gage

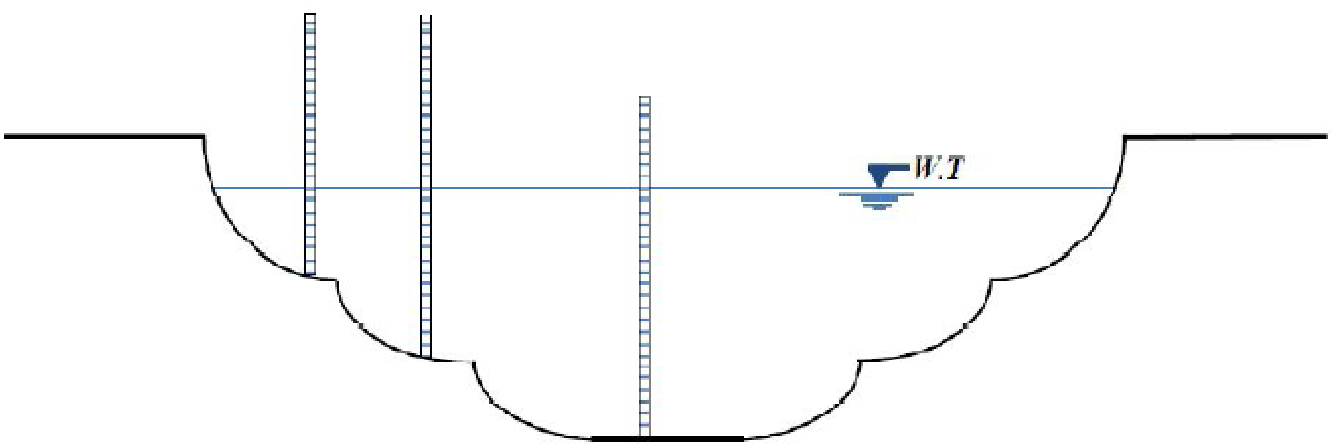


2- Inclined staff gage

$$H - L\,.\,sin\theta$$




3- Sectional staff gage




## *2- Water discharge measurements*

Q = v * A

***First:*** *Direct methods (stream gaging)* **(Area Velocity method)**

**(a):- Current-meter method**
**(b):- Ultrasonic method (ADCP)**
**(c):- Floats**
(d):- Pitot tube
(e):- Venture meter
(f):- Orifice meter

***Second:*** - Hydraulic Devices **(Area Velocity method)**
(a):- Weirs and notches
(b):- Orifices
(c):- Flumes

***Third:*** - Indirect Techniques
(a):- Slope-area method
(b):- Rating Curve

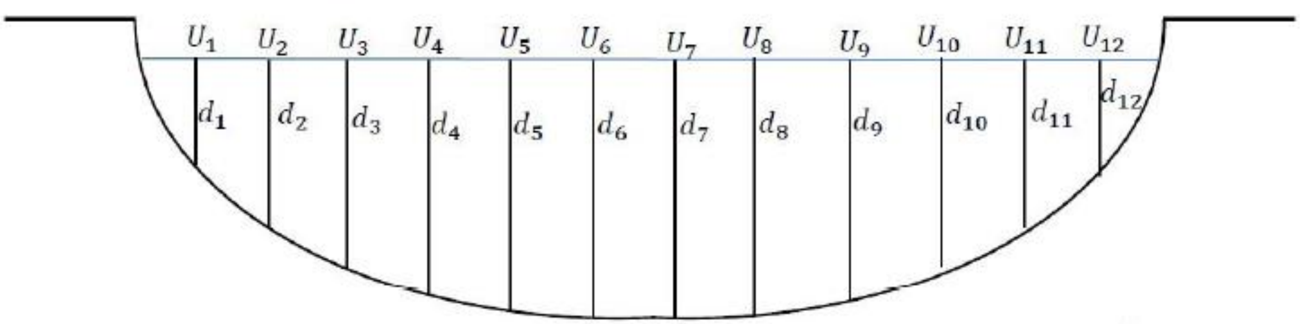
***First: Direct methods (stream gaging)***
**(a):- Current-meter method (Area Velocity method)**

$Q = V * A$

*Q : Discharge or flow.*

*V : Velocity of water (m/sec).*

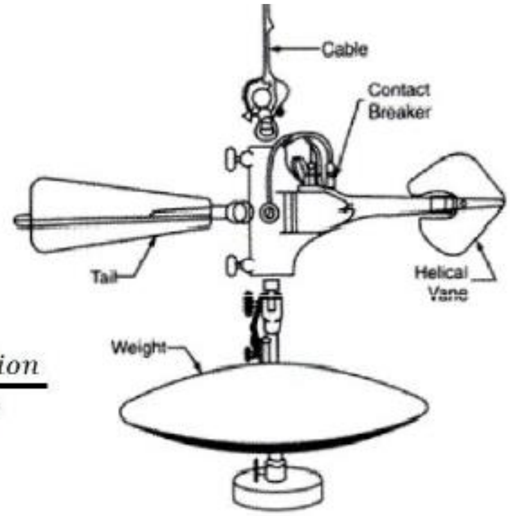
*A : Cross – Section area of river(m).*



$V = a + b * N \quad (\frac{m}{sec})$

*a & b are constants.*

*N : Number of revolution with respect to time* $= \frac{Revolution}{time}$




Curentmeters

$A\ (m^2) = Average\ width * Depth$

$A = \Delta w * d$

$\Delta w = \frac{w_1 + w_2}{2}$

**Ex:-** *Given the data below and the constants:*

$a = 0.01$

$b = 2.4$

*Compute the stream discharge?*

| Distance from the bank (m) | Depth (m) | Observation depth (m) | Revolution | Time (sec) |
|---|---|---|---|---|
| 1 | 0.95 | 0 | 0 | 0 |
| 4 | 1.2 | 0.6 | 5 | 40 |
| 7 | 2 | 0.6 | 7 | 43 |
| 10 | 2.1 | 0.2<br>0.8 | 15<br>10 | 50<br>50 |
| 13 | 2.3 | 0.2<br>0.8 | 10<br>15 | 52<br>40 |
| 15 | 2 | 0.2<br>0.8 | 10<br>15 | 55<br>54 |
| 16 | 1.5 | 0.6 | 15 | 40 |
| 17 | 0 | 0 | 0 | 0 |

**Solution :-**

$$Q = V * A$$

$$V = a + b * N$$

$$N = \frac{Revolution}{Time}$$

$$A = \Delta w * d$$

| $N$ | $V$ (m/sec) | $\Delta w$ (m) | $A$ ($m^2$) | $Q$ ($m^3$/sec) |
|---|---|---|---|---|
| 0 | $0.01 + 2.4 * 0 = 0.01$ | $\frac{1-0}{2} + \frac{4-1}{2} = 2$ | $2*0.95 = 1.9$ | 0.019 |
| $\frac{5}{40} = 0.125$ | $0.01 + 2.4 * 0.125 = 0.31$ | $\frac{4-1}{2} + \frac{7-4}{2} = 3$ | $3*1.2 = 3.6$ | 1.116 |
| $\frac{7}{43} = 0.162$ | $0.01 + 2.4 * 0.162 = 0.398$ | $\frac{7-4}{2} + \frac{10-7}{2} = 3$ | $3*2 = 6$ | 2.388 |
| $\frac{15}{50} = 0.333$<br>$\frac{10}{50} = 0.2$ | $0.01 + 2.4 * 0.333 = 0.809$<br>0.649<br>$0.01 + 2.4 * 0.2 = 0.49$ | $\frac{10-7}{2} + \frac{13-10}{2} = 3$ | $3*2.1 = 6.3$ | 4.091 |
| $\frac{10}{52} = 0.192$<br>$\frac{15}{40} = 0.375$ | $0.01 + 2.4 * 0.192 = 0.47$<br>0.69<br>$0.01 + 2.4 * 0.375 = 0.91$ | $\frac{13-10}{2} + \frac{15-13}{2} = 2.5$ | $2.5 * 2.3 = 5.75$ | 3.967 |
| $\frac{10}{55} = 0.181$<br>$\frac{15}{54} = 0.277$ | $0.01 + 2.4 * 0.181 = 0.444$<br>0.559<br>$0.01 + 2.4 * 0.277 = 0.674$ | $\frac{15-13}{2} + \frac{16-15}{2} = 1.5$ | $1.5 * 2 = 3$ | 1.677 |
| $\frac{15}{40} = 0.375$ | $0.01 + 2.4 * 0.375 = 0.91$ | $\frac{16-15}{2} + \frac{17-16}{2} = 1$ | $1 * 1.5 = 1.5$ | 1.365 |
| 0 | 0.01 | $\frac{17-16}{2} + \frac{0-0}{2} = 0.5$ | $0.5 * 0 = 0$ | 0 |
| | | | $Q_{total}$ ($m^3$/sec) | **14.623** |

***Ex:-*** *The following are data in a stream gaging operation a current meters with equation $V = 0.7\,N + 0.03$ is used to measure the velocity at following depths. Calculate the discharge in the stream?*

| *Distance from bank (m)* | 1 | | 3 | | 6 | | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| *Depth (m)* | 2 | | 3 | | 3 | | 2 | 0 |
| *Meter depth (m)* | 1.2 | 1.6 | 1.8 | 2.4 | 1.8 | 2.4 | 1.2 | 0 |
| *Revolution* | 22 | 35 | 28 | 40 | 28 | 40 | 22 | 0 |
| *Time (sec)* | 55 | 57 | 53 | 58 | 53 | 58 | 55 | 0 |

***Solution:-***

***Velocity calculations***

$V_1 - 0.03 + 0.7\,(\frac{22}{55}) = 0.31\ m/sec$

$V_2 = 0.03 + 0.7\,(\frac{28}{53}) = 0.399\ m/sec$

$V_3 = 0.03 + 0.7\,(\frac{28}{53}) = 0.399\ m/sec$

$V_4 = 0.03 + 0.7\,(\frac{22}{55}) = 0.31\ m/sec$

$V_5 = 0.03 + 0.7\ (\frac{0}{0}) = 0.03\ m/sec$

***Area calculations***

$A = \Delta w * d$

$\Delta w_1 = \frac{1-0}{2} + \frac{3-1}{2} = 1.5\ m \quad \Rightarrow A = 1.5 * 2 = 3\ m^2$

$\Delta w_2 = \frac{3-1}{2} + \frac{6-3}{2} = 2.5\ m \quad \Rightarrow A = 2.5 * 3 = 7.5\ m^2$

$\Delta w_3 = \frac{6-3}{2} + \frac{8-6}{2} = 2.5\ m \quad \rightarrow A = 2.5 * 3 = 7.5\ m^2$

$\Delta w_4 - \frac{8-6}{2} + \frac{9-8}{2} - 1.5\ m \quad \Rightarrow A - 1.5 * 2 - 3\ m^2$

$$\Delta w_5 = \frac{9-8}{2} + \frac{0-0}{2} = 0.5\ m \quad \Longrightarrow A = 0.5 * 0 = 0$$

## Discharge calculations

$$Q_1 = 0.31 * 3 = 0.93 \frac{m^3}{sec}$$

$$Q_2 = 0.399 * 7.5 = 2.992\ \frac{m^3}{sec}$$

$$Q_3 = 0.399 * 7.5 = 2.992\ \frac{m^3}{sec}$$

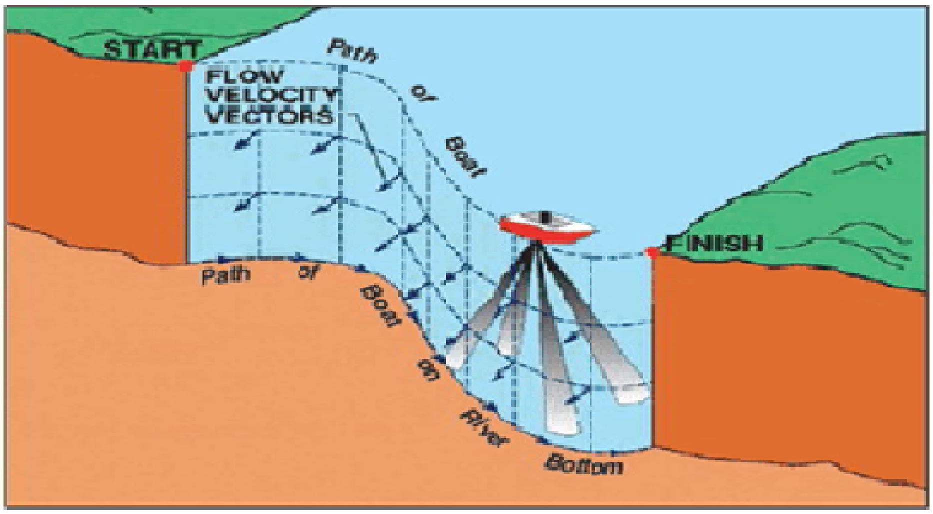
$$Q_4 = 0.31 * 3 = 0.93\ \frac{m^3}{sec}$$

$$Q_5 = 0.03 * 0 = 0$$

$$Discharge\ of\ stream = \sum Q = 7.845\ \frac{m^3}{sec}$$

## (b):- Ultrasonic method- *Acoustic Doppler Current Profiler* (ADCP)

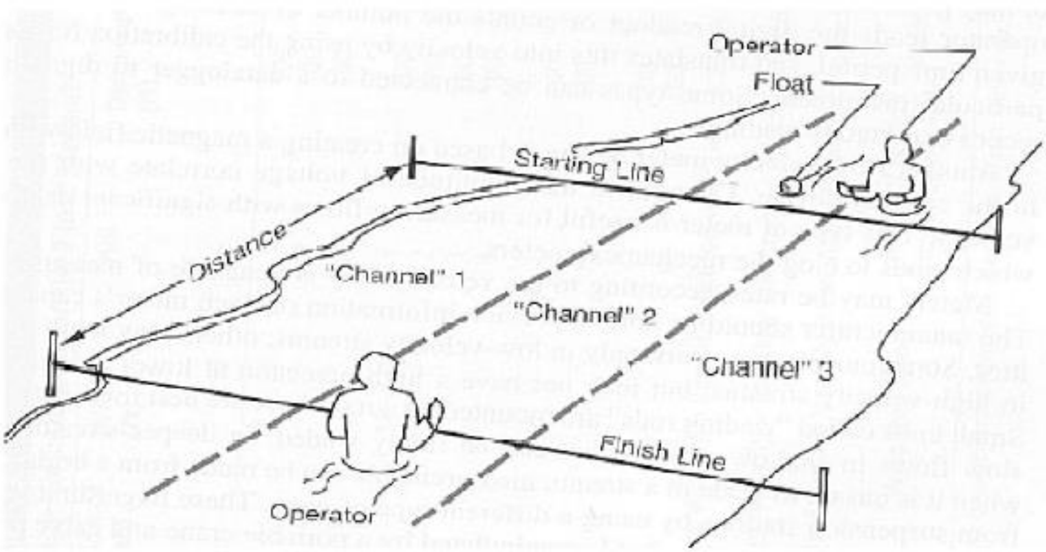
The ADCP uses the Doppler Effect to determine water velocity by sending a sound pulse into the water and measuring the change in frequency of that sound pulse reflected back to the ADCP by sediment or other particulates being transported in the water. The change in frequency, or Doppler Shift, that is measured by the ADCP is translated into water velocity.




Acoustic Doppler Current Profiler (ADCP) mounted in a small watercraft, is used for measuring the discharge of a river. The ADCP acoustic beams are directed down into the water as it is guided across a river channel.

## (c):- Floats

Inexpensive and simple Measures surface velocitymean velocity obtained using a correction factorBasic idea: measure the time that it takes an object to float a specified distance downstream.




Surface velocity = distance / time,
Average velocity = (0.85*surface velocity)

## Third: Indirect Techniques

### (a):- Slope-area method

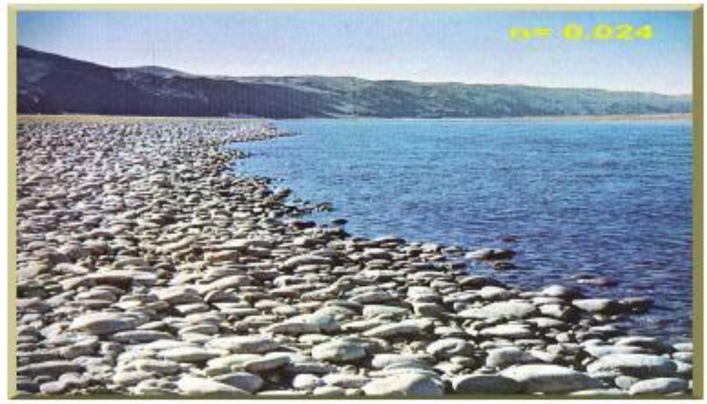
***Manning's formula***

$$V = \frac{1}{n} R^{\frac{2}{3}} S^{\frac{1}{2}}$$


$$Q = \frac{1}{n} A R^{\frac{2}{3}} S^{\frac{1}{2}}$$ ............... *Manning's formula*

$$R = \frac{A}{P}$$

*Where :-*




*Q : discharge of channel* $(\frac{m^3}{sec})$.

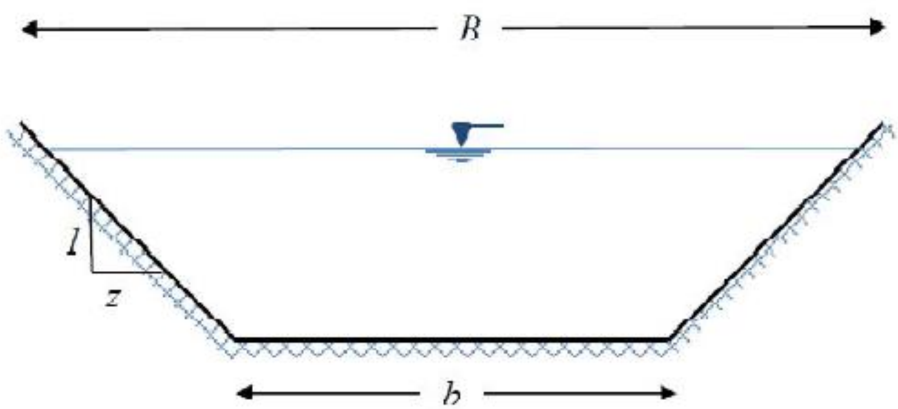
*n : The roughness coefficient.*

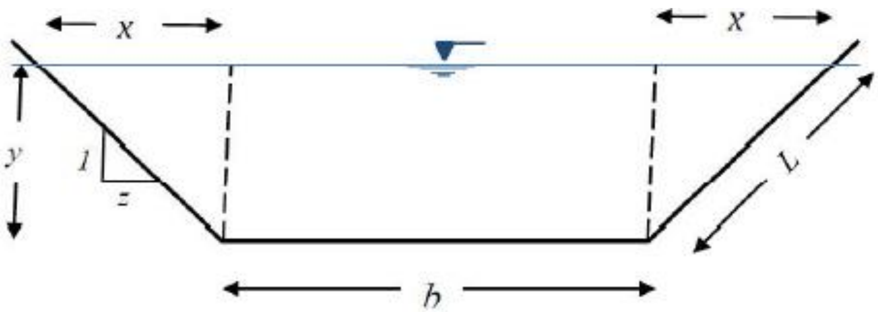
*S : Slop of the bed.*

*R : Hydraulic radius (m).*

*A: Cross section area* ($m^2$).

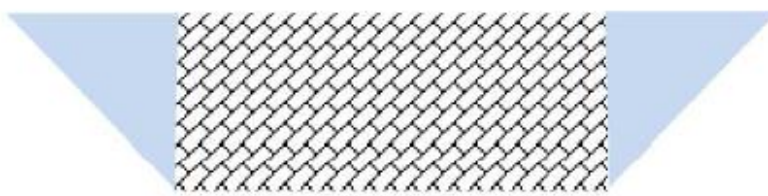
*P : Wetted perimeter (m).*






- *Area of cross-section = Area of trapezoidal*

  *= Area of rectangular + 2 * Area of triangular*



$Area\ of\ rectangular = b * y$

$Area\ of\ triangular = \frac{1}{2} x * y$

$\frac{1}{z} = \frac{y}{x} \implies x = z * y$

$Area\ of\ triangular = \frac{1}{2} z * y * y$

$= \frac{1}{2} z * y^2$

$Area\ of\ trapezoidal = b * y + \frac{1}{2}\ z * y^2 * 2$

$= y\ (b + z * y)$

- *Wetted perimeter of channel*

$$P = b + 2 * L$$

$$L^2 = x^2 + y^2$$

$$x = z * y \implies L^2 = z^2 * y^2 + y^2$$

$$= y^2 (z^2 + 1)$$

$$L = y \sqrt{(z^2 + 1)}$$

$$P = b + 2\, y \sqrt{(z^2 + 1)}$$

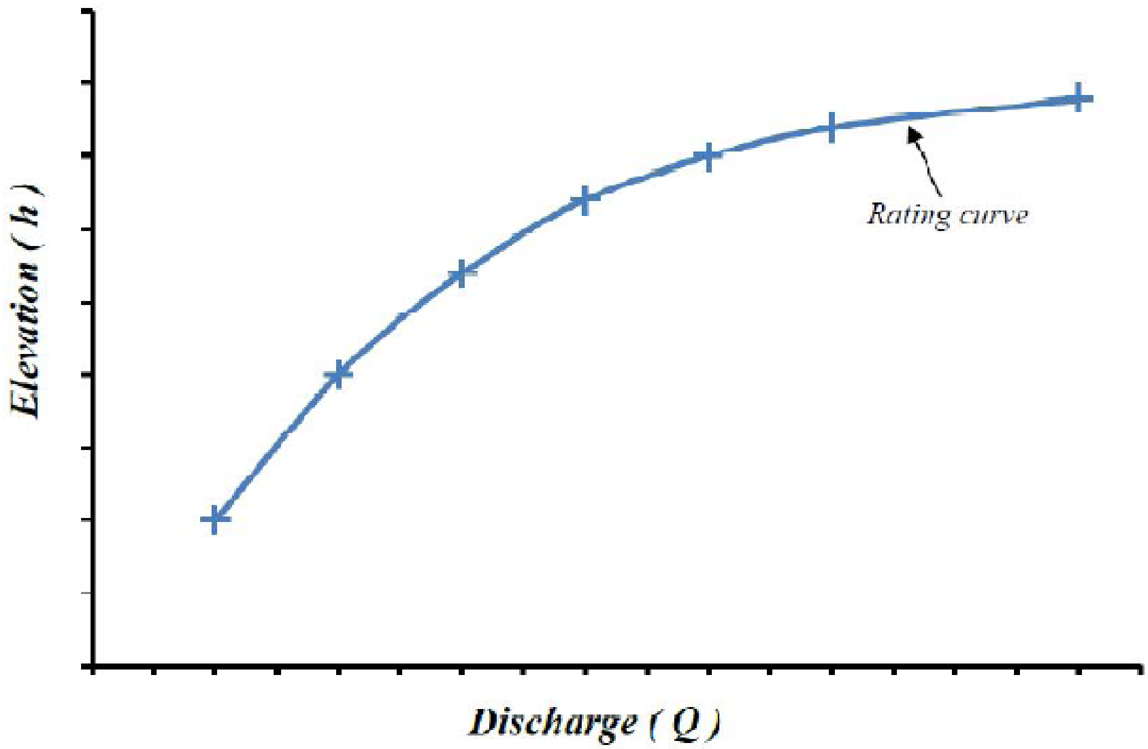
- *Hydraulic radius*

$$R = \frac{A}{P}$$

$$R = \frac{y\,(b + z * y)}{b + 2\,y \sqrt{(z^2 + 1)}}$$

## (b):- Rating Curve *(Stage-discharge relation*)

*Rating curve:- Is the relationship between discharge and stage of elevation of point inter the steam of river.*



$Q - K\,(h - a\,)^b$

$Q$ : *Discharge of stream* $(\frac{m^3}{sec})$.

$h$ :*Elevation (m).*

$a, b, K$ : *Constant of rating curve.*

***<u>To find ( a )</u>:-***

*We have to plot the rating curve and choose three random values of discharge.*

$$\frac{Q_1}{Q_2} = \frac{Q_2}{Q_3}$$

$Q = K\,(h - a\,)^b$

$$\frac{K\,(h_1 - a)^b}{K\,(h_2 - a)^b} = \frac{K\,(h_2 - a)^b}{K\,(h_3 - a)^b}$$

$$\frac{(h_1 - a)}{(h_2 - a)} - \frac{(h_2 - a)}{(h_3 - a)}$$

$$(h_1 - a)(h_3 - a) = (h_2 - a)(h_2 - a)$$

$$h_1 h_3 - h_1 a - h_3 a + a^2 = h_2^{\,2} - h_2 a - h_2 a + a^2$$

$$a - \frac{h_1 h_3 - h_2^{\,2}}{h_1 + h_3 - 2h_2}$$

$$If\ Q = 0\ \&\ h \neq 0\ \ then$$

$$0 = K\,(h - a)^b$$

$$a = h$$

**To find K and b:-**

$$Log\ (Q) = Log\ K\ (h - a)^b$$

$$Log\ (Q) = Log\ K + b\ Log\ (h - a)$$

*Assume that :-*

$$Log(Q) - y$$

$$Log\ K - A$$

$$Log\ (h - a) = x$$

$$\Rightarrow y = A + b * x$$

$$A = \frac{\sum y * \sum x^2 - \sum x y \sum x}{n \sum x^2 - (\sum x)^2}$$

*n :Number of points.*

$$A = Log\ K \Rightarrow K = 10^A$$

$$b = \frac{n \sum x\ y - \sum y\ \sum x}{n \sum x^2 - (\sum x)^2}$$

*Ex:- The following table representing the relation between the recorded discharges with water levels. Find the stage corresponding to the discharge 500* $\frac{m^3}{sec}$ *from the equation of the form* $\boldsymbol{Q = K\,(h - 20)^b}$ *?*

| Water level (m) | 20.8 | 21.3 | 21.95 | 22.4 | 23 | 23.52 | 23.9 |
|---|---|---|---|---|---|---|---|
| Discharge $\frac{m^3}{sec}$ | 20 | 40 | 60 | 80 | 120 | 160 | 200 |

*Solution:-*

$Q = K\,(h - 20)^b$

*From the equation a − 20*

*Find K & b*

$\underbrace{\log Q}_{y} = \underbrace{\log K}_{A} + \underbrace{b \log (h-20)}_{x}$

$$A = \frac{\sum y * \sum x^2 - \sum x\, y \sum x}{n \sum x^2 - (\sum x)^2}$$

$$b = \frac{n \sum x\, y - \sum y \sum x}{n \sum x^2 - (\sum x)^2}$$

| $h\ (m)$ | $Q\ (\frac{m^3}{sec})$ | $Y$ | $X$ | $xy$ | $x^2$ |
|---|---|---|---|---|---|
| 20.8 | 20 | 1.301 | -0.097 | -0.126 | 0.0093 |
| 21.3 | 40 | 1.602 | 0.114 | 0.182 | 0.013 |
| 21.95 | 60 | 1.778 | 0.290 | 0.515 | 0.084 |
| 22.4 | 80 | 1.903 | 0.380 | 0.723 | 0.144 |
| 23 | 120 | 2.08 | 0.477 | 0.992 | 0.227 |
| 23.52 | 160 | 2.204 | 0.546 | 1.204 | 0.298 |
| 23.9 | 200 | 2.301 | 0.591 | 1.360 | 0.349 |
| | $\sum$ | 13.17 | 2.30 | 4.852 | 1.126 |

$$A = \frac{(13.17)*(1.126)-(2.3)*(4.852)}{7*(1.126)-(2.3)^2} = 1.417$$

$$b = \frac{7*(4.85)-(2.3)(13.17)}{7*(1.126)-(2.3)^2} = 1.417$$

$$K = 10^A$$

$$= 10^{1.417}$$

$$K = 26.121$$

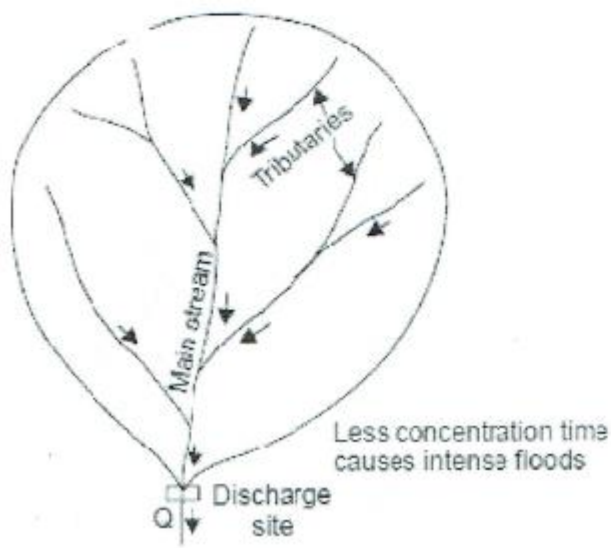
$$Q = 26.121\ (h - 20)^{1.417}$$

$$500 = 26.121\ (h - 20)^{1.417}$$

$$h = \qquad m$$

## *Runoff:*

Runoff is that balance of rain water, which flows or runs over the natural ground surface after losses by evaporation, interception and infiltration.




## <u>*FACTORS AFFECTING RUNOFF*</u>

The various factors, which affect the runoff from a drainage basin depend upon the following characteristics:-

(*i*) Storm characteristics

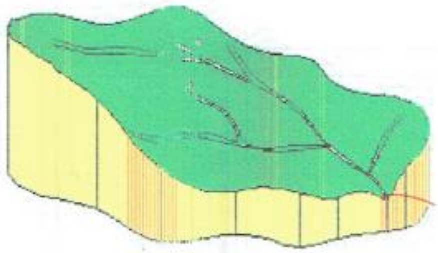
(ii) Meteorological characteristics

(iii) Basin characteristics

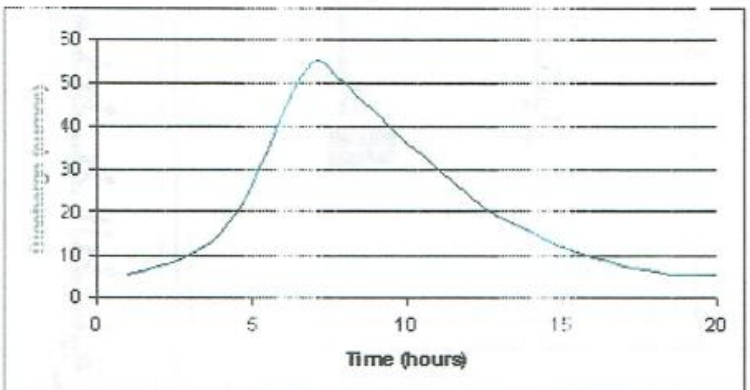
(iv) Storage characteristics

Peak runoff decreases as the catchment area increases due to higher time of concentration. A fan-shaped catchment produces greater flood intensity than fern-shaped catchment.

Steep rocky catchments with less vegetation will produce more runoff compared to flat tracts with more vegetation

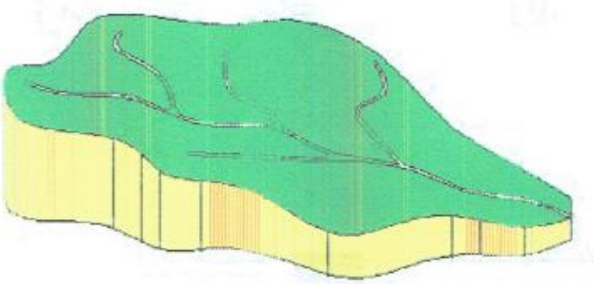


(a)

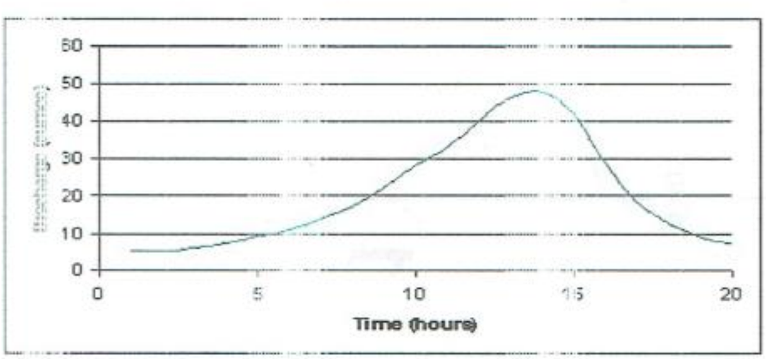



(b)

A catchment that is shaped in the form of a pear, with the narrow end towards the upstream and the broader end nearer the catchment outlet (Figure 1a) shall have a hydrograph that is fast rising and has a rather concentrated high peak (Figure 1b).



(a)




(b)

A catchment with the same area as in Figure 1 but shaped with its narrow end towards the outlet has a hydrograph that is slow rising and with a somewhat lower peak (Figure 2) for the same amount of rainfall.

## ESTIMATION OF RUNOFF

The yield of a catchment (usually means annual yield) is the net quantity of water available for storage, after all losses, for the purposes of water resources utilization and planning, like irrigation, water supply, etc.

The time required for the rain falling at the most distant pointing a drainage area (i.e., on the fringe of the catchment) to reach the concentration point is called *the concentration time*. This is a very significant variable since only such storms of duration greater than the time of concentration will be able to produce runoff from the entrance at catchment area and cause high intensity floods.

### *The runoff from rainfall may be estimated by the following methods:*

i) Empirical formulae, curves and tables

ii) Infiltration method

iii) Rational method

iv) Overland flow hydrograph

v) Unit hydrograph method

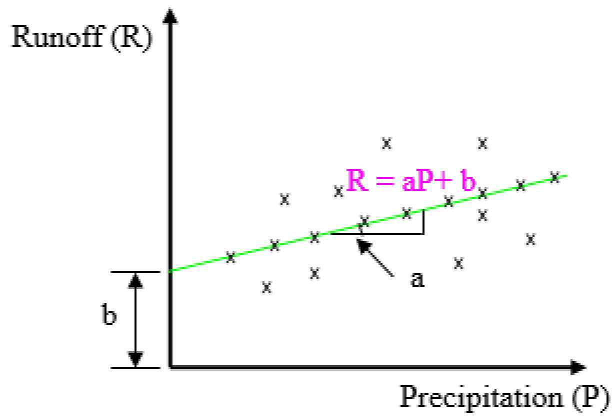
**i) *Empirical formulae*,** curves and tables. Several empirical formulae, curves and tablesrelating to the rainfall and runoff have been developed as follows:

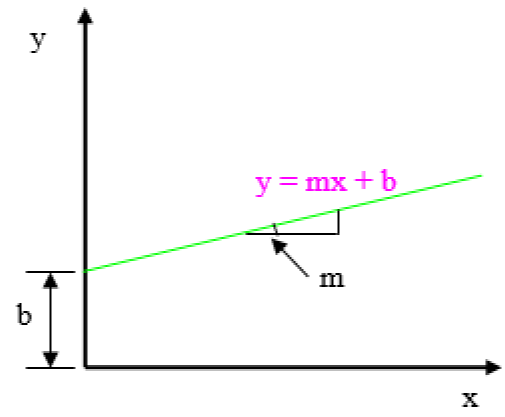
Usually, $R = a P + b$

Sometimes, $R = a P^n$

Where R = runoff, P = rainfall, a, b, and n, are constants

$$a = \frac{N(\sum PR) - (\sum P)(\sum R)}{N(\sum P^2) - (\sum P)^2}$$




$$R = a\,P + b \quad \text{.......... (1)}$$

$$a = \frac{N\left(\sum PR\right) - \left(\sum P\right)\left(\sum R\right)}{N\left(\sum P^2\right) - \left(\sum P\right)^2} \quad \text{.......... (2)}$$

$$b = \frac{\sum R - a\sum P}{N} \quad \text{................ (3)}$$

$$r = \frac{N\left(\sum PR\right) - \left(\sum P\right)\left(\sum R\right)}{\sqrt{\left[N\left(\sum P^2\right) - \left(\sum P\right)^2\right] * \left[N\left(\sum R^2\right) - \left(\sum R\right)^2\right]}} \quad \text{........ (4)}$$

$0 \leq r \leq 1$

$0.6 < r < 1$

$$R = \beta P^m \quad \text{..... (5)}$$

$$\ln R = m \ln P + \ln \beta \quad \text{...... (6)}$$

Example:

| R(cm) | P(cm) | month | R(cm) | P(cm) | month |
|---|---|---|---|---|---|
| 8 | 30 | 10 | 0.5 | 5 | 1 |
| 2.3 | 10 | 11 | 10 | 35 | 2 |
| 1.6 | 8 | 12 | 13.8 | 40 | 3 |
| 0 | 2 | 13 | 8.2 | 30 | 4 |
| 6.5 | 22 | 14 | 3.1 | 15 | 5 |
| 9.4 | 30 | 15 | 3.2 | 10 | 6 |
| 7.6 | 25 | 16 | 0.1 | 5 | 7 |
| 1.5 | 8 | 17 | 12 | 31 | 8 |
| 0.5 | 6 | 18 | 16 | 36 | 9 |

$N = 18$ , $\Sigma P = 348$ , $\Sigma R = 104.3$ , $\Sigma P^2 = 9534$ , $\Sigma R^2 = 1040.51$ , $\Sigma PR = 3083.3$

$(\Sigma P)^2 = 121104$ , $(\Sigma R)^2 = 10878.49$

$a = 0.38$ , $b =- 1.55$ , $R = 0.38\,P - 1.55$

$r = 0.964$

Imperical formula:

$R_m = P_m - L_m$

$L_m = 0.48\,T_m$

| **T(°C)** | 4.5 | -1 | - 6.5 |
|---|---|---|---|
| **$L_m$ (cm)** | 2.77 | 1.78 | 1.52 |

Example:

| 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | month |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | 19 | 29 | 28 | 29 | 31 | 34 | 31 | 27 | 21 | 16 | 12 | T(°C) |
| 2 | 1 | 2 | 16 | 29 | 32 | 12 | 2 | 0 | 2 | 4 | 4 | (cm ) P |

Sol:

$L_m = 0.48\ T_m$

| 12 | 11 | 10 | 9 | 8 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | month |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 6.72 | 9.12 | 13.92 | 13.44 | 13.92 | 14.88 | 16.32 | 14.88 | 12.96 | 10.08 | 7.68 | 5.76 | $L_m$ |
| 0 | 0 | 0 | 2.56 | 15.08 | 17.12 | 0 | 0 | 0 | 0 | 0 | 0 | $R_m$ |

**ii)** ***Infiltration Method***. By deducting the infiltration loss, i.e., the areas under the infiltration curve, from the total precipitation or by the use of infiltration indices.

**iii)** ***Rational Method***. A rational approach is to obtain the yield of a catchment by assuming a suitable runoff coefficient

$Q = CIA$

Where A = area of catchment

I = intensity

C = runoff coefficient .The value of the runoff coefficient C varies depending upon the soil type, vegetation Geologies.

Table 4.3 Runoff coefficients for various types of catchments

| *Type of catchment* | *Value of C* |
|---|---|
| Rocky and impermeable | 0.8–1.0 |
| Slightly permeable, bare | 0.6–0.8 |
| Cultivated or covered with vegetation | 0.4–0.6 |
| Cultivated absorbent soil | 0.3–0.4 |
| Sandy soil | 0.2–0.3 |
| Heavy forest | 0.1–0.2 |

In the rational method, the drainage area is divided into a number of sub-areas and with the known times of concentration for different subareas the runoff contribution from each area is determined. The choice of the value of the runoff coefficient C for the different sub-areas is an important factor in the runoff computation by this method. This method of dividing the area into different zones by drawing lines of time contour, i.e., isochrones, is illustrated in the following example.
The time of concentration of a watershed is the time required for water to flow from the most remote (in time of flow) point to the outlet once the soil has become saturated and minor depressions filled. It is assumed that, when the duration of a storm equals the time of concentration, all parts of the watershed are contributing simultaneously to the discharge at the outlet. One of the formulas often used in the US for computing the time of concentration is

where $Tc = 0.02\, L^{0.8}\, S^{-0.4}$

Tc=time of concentration in min,

L=maximum length of flow in ft., and

S=the watershed gradient in feet per foot (the difference in elevation between the outlet and the most remote point divided by the length, L.

$T_c = (0.87 * L^3/H)^{0.885}$

L ,in (km) and H , in (m)

Where H= difference in level for upper point of flow and outlet

***Example /*** A 4-hour rain of average intensity 1 cm/hr. falls over the fern leaf type catchments shown in Fig. below . The time of concentration from the lines AA, BB, CC and DD are 1, 2, 3and 4 hours, respectively, to the site 0 where the discharge measurements are made. The value of the runoff coefficient C are 0.5, 0.6, and 0.7 for the 1st, 2nd and 3rd hours of rainfall respectively and attains a constant value of 0.8 after 3 hours. Determine the discharge at site O and draw the discharge hydrograph at O?