

HYDROLOGY

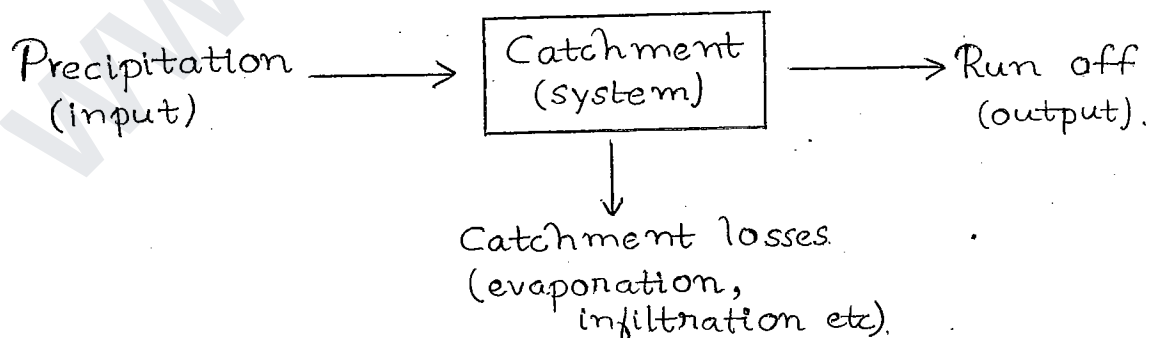
(5 marks - 6 marks)

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- Hydrology is a study of science of water.
- Hydrology deals with occurrence, movement, distribution and circulation of water above the ground, below the ground or even in the atmosphere.
- Hydrology deals with depletion and replenishment of water resource of earth.
- Objective:

To estimate yield (water) from drainage basin.

Drainage basin means watershed (or) catchment.



- Applications :

- (i) Design of hydraulic structures.
- (ii) Flood forecasting & management.

(iii) Irrigation.

(iv) Municipal and industrial water supply.

(v) Hydropower generation.

(vi) Pollution control.

(vii) Navigation.

(viii) Drought management.

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→ World's Water Resource:

Total water available — 1380 million km^3

Saline water — 97.2% available water

Fresh water — 2.8% available water.

Glaciers — 2.15% available water.
(located in polar ice caps)

Deep below the — 0.32% available water.
ground (depth of 800 m below
ground)

∴ 0.33% of total water available for human use and consumption.

$$= \frac{0.33}{100} \times 1380 \approx 4.5 \text{ million km}^3$$

— Average annual precipitation of world = 100 cm

→ Water Resource of India:

Average annual precipitation = 119.4 cm

Geographic area = $3.28 \times 10^6 \text{ km}^2$

Total volume of water = $3.28 \times 10^6 \times 119.4 \times 10^{-5}$

= 3916 km^3

Including snowfall, total water available = 4000 km^3

Evaporation loss = 700 km^3

Water soak into ground = 2150 km^3

Net water available = $4000 - 700 - 2150$
= 1150 km^3

% world's water available with India = $\frac{1150}{4.5 \times 10^6} \times 100$

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= 0.025 %

→ Hydrologic Cycle:

- Water circulatory cycle. which shows how water circulate from one place to other place and from one form to other form with time.

- Components of Hydrologic Cycle:

(i) Precipitation.

(ii) Evaporation.

(iii) Transpiration

(iv) Evapo-transpiration.

(v) Infiltration.

(vi) Run-off.

01. PRECIPITATION

Precipitation denotes all forms of moisture that reach ground from atmosphere.

→ Forms of Precipitation:

1. Rain :-

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Precipitation in the form of water droplets of size $> 0.5 \text{ mm}$ and intensity (rate of rain) $> 1 \text{ mm/hr}$.

$$\text{Intensity of rain (i)} = \frac{dP}{dt} = \frac{P}{t}$$

* Based on intensity, rains are classified into:

(i) Light rain :- $1 \text{ mm/hr} \leq i \leq 2.5 \text{ mm/hr}$.

(ii) Moderate rain :- $2.5 \text{ mm/hr} \leq i \leq 7.5 \text{ mm/hr}$.

(iii) Heavy rain :- $i > 7.5 \text{ mm/hr}$.

2. Drizzle :-

Precipitation in the form of water droplets of size $< 0.5 \text{ mm}$ and intensity $< 1 \text{ mm/hr}$.

3. Snow :-

Precipitation in the form of fine ice crystals of size $< 1 \text{ mm}$.

4. Sleet :- (Frozen rain).

Ice crystals of size 1 mm to 5 mm .

5. Hail :-

Ice crystals of size $> 8 \text{ mm}$

6. Dew :- vapour accumulated during day condenses during night and deposited on the ground as dew.

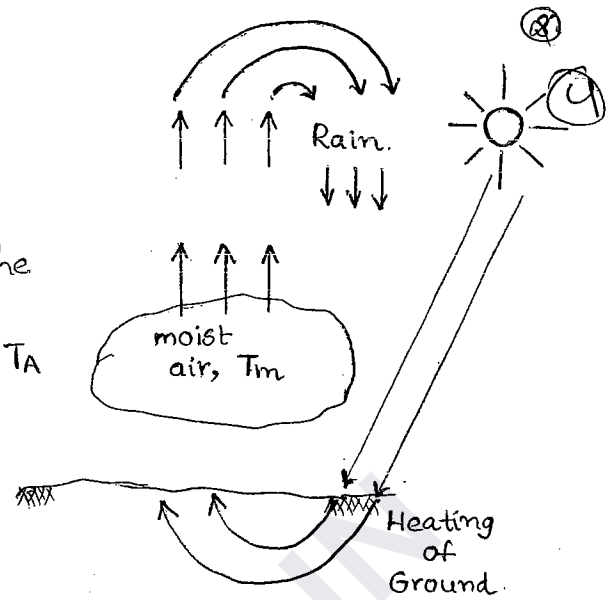
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→ Types of Precipitation:

1. Convective Precipitation -

This occurs due to heating of the ground and temperature difference b/w moist air and its surroundings T_A

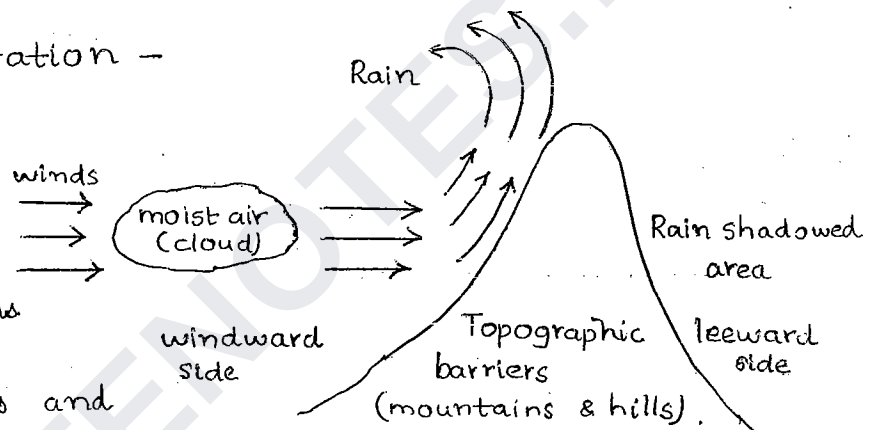
Eg:- Summer rains: high intensity rains occurring for short periods.



2. Orographic Precipitation -

It is caused by topographic barriers such as hills & mountains

Eg: Rains at Himalayas and Western ghats: moderate intensity rains for longer periods.



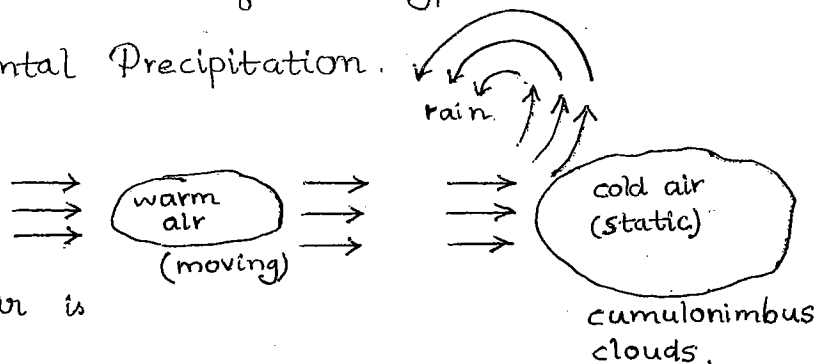
3. Frontal Precipitation -

Front air: It is an interface between two distinct air masses.

- Frontal precipitation are of two types:-

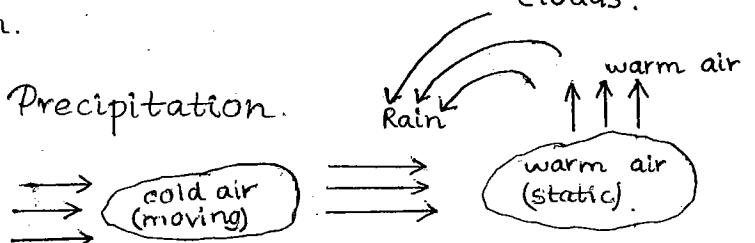
(i) Warm air frontal Precipitation.

Warm air is lighter, thinner and weaker whereas cold air is denser, thicker and stronger.



(ii) Cold air frontal Precipitation.

Cold air approaches warm air mass.



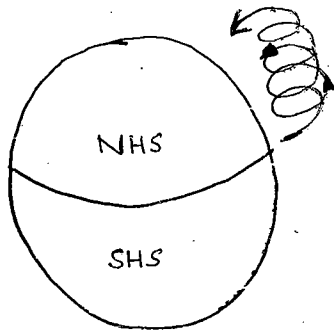
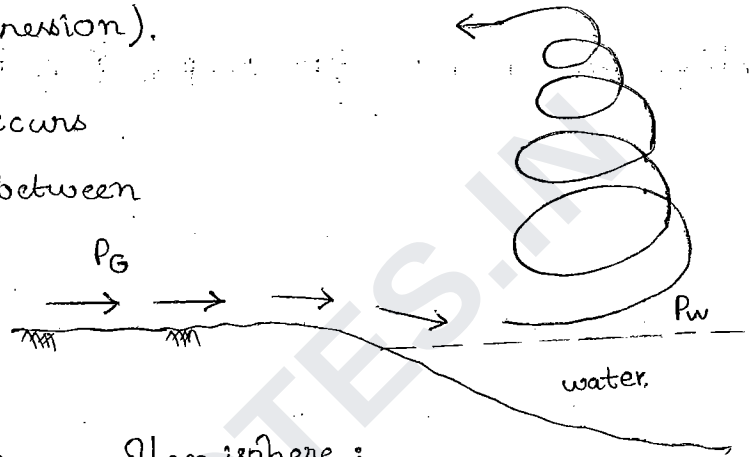
Eg: rains during rainy season.

4. Cyclonic Precipitation

- precipitation caused by cyclones.

cyclone:- large area of low pressure region with circular wind motion. (depression).

- cyclonic precipitation occurs due to pressure difference between ground and water bodies ($P_w \lll P_g$).



Northern Hemisphere:

Inward and anti-clockwise wind motion at northern hemisphere.

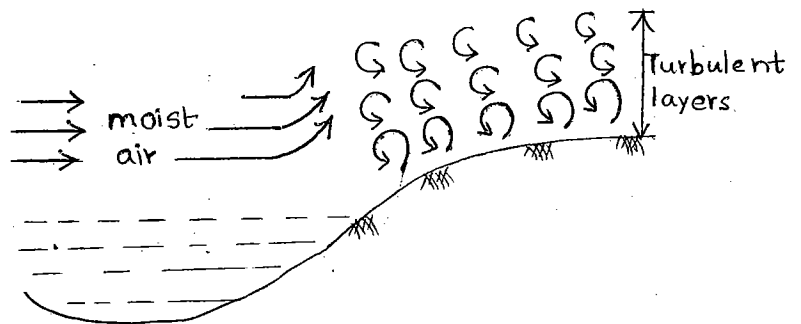
Southern Hemisphere:

Clockwise and outward.

- high intensity rains for longer period.

5. Precipitation due to Turbulent Ascent.

Eg:- winter rains along the coastal areas.



→ Rainfall Season

1. Monsoon period

- Principal rainy season.

- starts from May last week and lasts upto Oct 1st week.

- ~~North~~ ^{South} west winds cause rains during this period.

④
⑤
- Except Tamil Nadu & Jammu Kashmir, rest of the country receives rain during this period.

2. Post monsoon period.

- Nov 1st week to December 1st week.

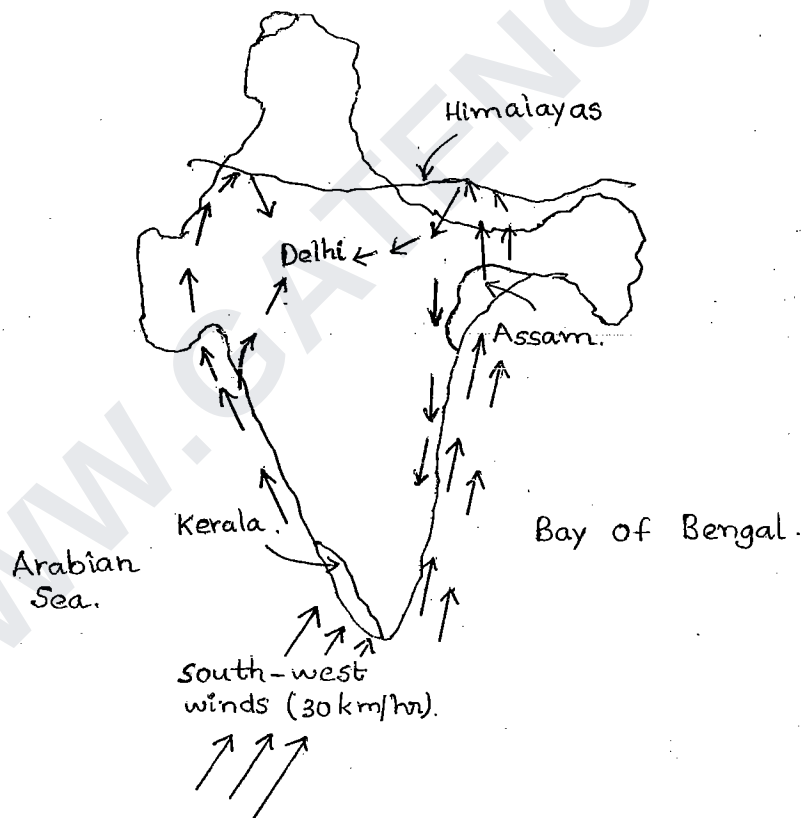
- TN and its surroundings receives rains (Southern Peninsular region)

- North East winds cause rains during this period.

3. Winter Rains

- Dec last week to Feb last week

- J & K receive rainfall and snowfall.



- Kerala & Assam receive first rainfall, from South-west winds.

- Assam records the highest rainfall in the country

- Arabian branch reaches upto Punjab in the North and sent back to Delhi by Himalayan Ranges.

→ Measurement of Rainfall.

- Precipitation is measured as a vertical depth of water that would accumulate over a level ground if precipitation is retained where it fell.

- It is expressed in mm or cm.

- Precipitation is measured by using devices known as 'rain gauges' (also known as Ombrometers, Pluviometers or Hyetometers)

- There are two types of rain gauges:

(i) Non Recording type Rain gauges

a) Symon's Raingauge.

b) IS (IMD) raingauge.

(ii) Recording type Raingauge.

a) Weighing Bucket type raingauge.

b) Tipping Bucket type raingauge.

c) Siphon raingauge (float type raingauge)

d). Radar measurement.

* Symon's Raingauge :

- universal gauge.

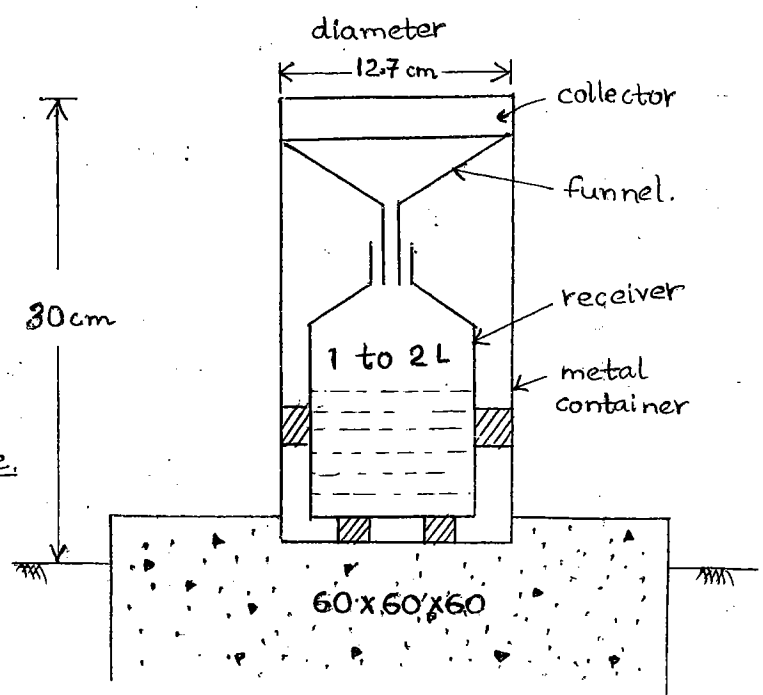
- Diameter of collector
= 12.7 cm.

- Depth of rain =
(cm or mm)

$$\frac{\text{volume of water collected by gauge.}}{\text{c/s area of collector.}}$$

- measures 100 mm to

175 mm rain at a time.



* IS raingauge

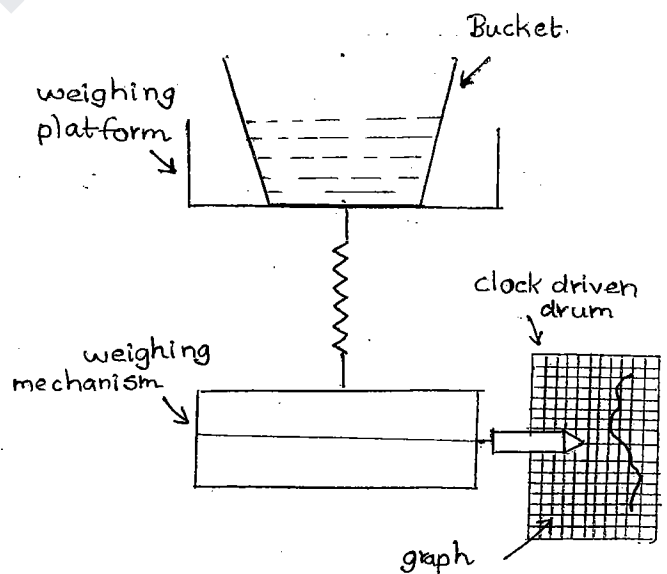
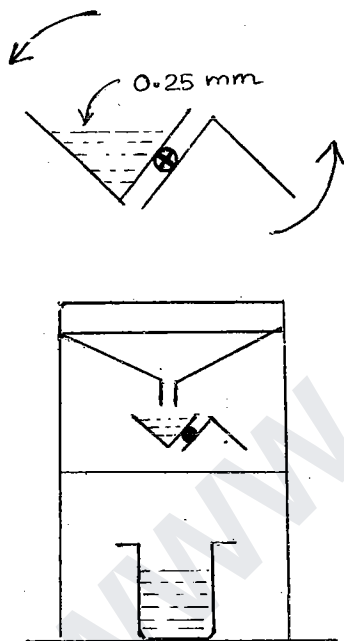
- Indian Standard raingauge to match Indian conditions.
- Similar to Symon's gauge with following modifications.
 - (i) c/s area of collector : 100 cm^2 to 200 cm^2
 - (ii) Receiver capacity : 2 to 10 L
 - (iii) Metal container replaced with Fibre Reinforced Plastic, FRP, container.

FRP, container.

- Measures 100 mm to 1000 mm rain at a time.
- Measurement is recorded at IST 8:30 manually.

* Weighing Bucket type Raingauge

- used to measure both rainfall and snowfall.



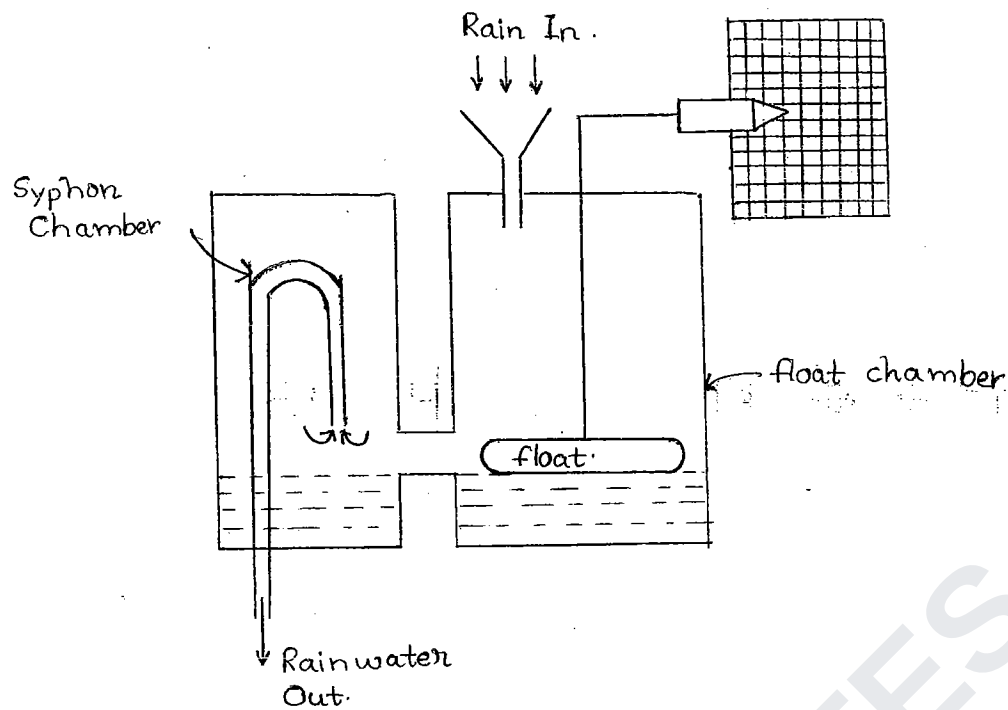
* Tipping Bucket Type Raingauge:

- to measure rainfall at remote and inaccessible location
- tips for every 0.25 mm rainwater collection.

* Syphon's Rain gauge.

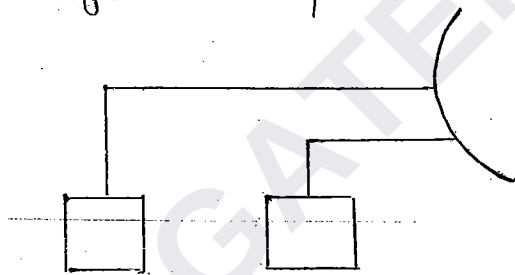
- under normal conditions
- Syphon raingauges are preferred to other gauges as per

IS code.



* Radar Measurement (Radio Detection And Ranging).

- measures rainfall over an area, whereas other gauges measure rainfall at a point.

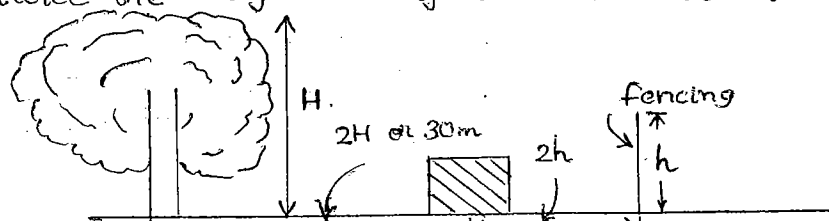


- Range = 200 km^2

2nd Dec, → Rain Gauge Station
WEDSDAY

The place where rain gauge is installed and rainfall measurement is carried out is called Rain gauge Station.

- To install rain gauge, min. plot of size $5.5 \text{ m} \times 5.5 \text{ m}$ required.
- Level ground open to sky is required.
- Minimum distance b/w the gauge and the nearest tall object is 30 m (or) twice the height of object whichever is more.



→ Density of Raingauge Network :

⑧
⑦

Number of rain gauges per given area is called Raingauge Density (or) density of raingauge network.

- For plain and flat catchment : 1 raingauge for 520 km²
- Areas elevated above 1000 m : 1 raingauge for 260-390 km²
- Mountains and hilly regions : 1 raingauge for 130 km²

→ Optimum number of Raingauges, 'n'

Let $P_1, P_2, \dots, P_m$ be the rainfall values recorded at the existing raingauge stations, 1, 2, ..., m respectively.

By subjecting the rainfall data recorded at 'm' no. of existing raingauge stations to statistical analysis, optimum no. of raingauges 'n' can be determined for a given percentage of allowable or admissible error 'E'

Step 1: Find mean of rainfall data.

$$\bar{P} = \frac{P_1 + P_2 + \dots + P_m}{m} = \frac{\sum P_i}{m}$$

Step 2: Find standard deviation of rainfall data.

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

Step 3: Find coefficient of variation.

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

Step 4: For a given allowable (or) admissible % error, E

$$\text{Optimum no: of } \left. \begin{array}{l} \text{raingauges} \end{array} \right\} n = \left(\frac{C_v}{E} \right)^2$$

$$\left. \begin{array}{l} n \propto \frac{1}{E} \\ E \propto \frac{1}{\% \text{ accuracy}} \end{array} \right\} \Rightarrow n \propto \% \text{ accuracy}$$

$$\left. \begin{array}{l} C_v \propto \sigma \\ n \propto C_v \\ \sigma \propto \frac{1}{m} \end{array} \right\} \Rightarrow n \propto \frac{1}{m}$$

- If $n < m$, gauges installed are sufficient in number.

- If $n > m$, gauges installed are deficient in number

$\therefore$ additional number of raingauges = $n - m$

% accuracy = $100 - E$

P-6

1. $\bar{p} = 92.8 \text{ cm}$ $C_v = \frac{100 \sigma}{\bar{p}} = \underline{\underline{33.08\%}}$

$\sigma = 30.7 \text{ cm}$

$E = 10\%$

$n = \left(\frac{C_v}{E} \right)^2 = \left(\frac{33.08}{10} \right)^2 = 10.94 \sim \underline{\underline{11}}$

2. $C_v = 33\%$, $n = 5$

$n = \left(\frac{C_v}{E} \right)^2$

$\therefore E = \frac{33}{\sqrt{5}} = 14.76\%$

% accuracy = 85.24%

3. $C_v = 29.54\%$, $E = 10\%$

$\therefore n = \left(\frac{C_v}{E} \right)^2 = \left(\frac{29.54}{10} \right)^2 = 8.73 \sim \underline{\underline{9}}$

Q. There are 4 rain gauges in a catchment recorded 3 cm, 5 cm, 6 cm & 8 cm rainfall values resply. Find optimum number for 90% accuracy. Also recommend no. of additional raingauges required.

$$\sigma = 1.443^2, C_v = \frac{100 \times 2.08}{5.5} = 37.82\%$$

$$\bar{x} = 5.5,$$

$$n = \left(\frac{37.82}{100-90} \right)^2 = 14.3 \sim \underline{\underline{15}}$$

$$\text{Additional rain gauges required} = 15 - 4 = \underline{\underline{11}}$$

→ Preparation of Rainfall Data

Before using the rainfall data in hydrological analysis, data is verified with following two conditions:

- (i) Continuity - data should be continuous without any broken information.
- (ii) Consistency - data should be truly representative of the region.

* Missing Rainfall Data:

Let $P_1, P_2, \dots, P_m$ be the rainfall values recorded by the adjacent raingauge stations during the period, station 'X' was missed in recording rainfall. & $N_1, N_2, \dots, N_x \dots N_m$ be the normal annual rainfall values (min 30 years, ^{latest} average rainfall data) of raingauge stations $1, 2, \dots, x, \dots, m$, then missing rainfall data at station X is worked out by:

(i) Simple Mean Method.

- used when $N_1 = N_2 = \dots = N_m = N_x \pm 10\%$

$$P_x = \frac{P_1 + P_2 + \dots + P_m}{m}; P_x \rightarrow \text{missing rainfall data at station X}$$

(ii) Normal Ratio Method.

- used when $N_1 = N_2 = \dots = N_m \neq N_x \pm 10\% N_x$

$$P_x = \frac{N_x}{m} \left[\frac{P_1}{N_1} + \frac{P_2}{N_2} + \dots + \frac{P_m}{N_m} \right]$$

While working, missing rainfall data at any station, rainfall data of all adjacent stations lying in same climatic zone is considered.

04.

A	B	C
$N_A = 170.6 \text{ cm}$	$N_B = 180.3 \text{ cm}$	$N_C = 165.3$
$P_A = 153 \text{ cm}$	$P_B = ?$	$P_C = 145.1$

$$N_B \pm 10\% N_B \begin{cases} 198.33 \\ 162.27 \end{cases} \quad N_A = N_C = N_B \pm 10\% N_B.$$

$\therefore$ Simple mean method is used.

$$P_B = \frac{P_A + P_C}{2} = \frac{153 + 145.1}{2} = \underline{\underline{149.1 \text{ cm}}}$$

05.

I	II	III	IV
$N_I = 60 \text{ cm}$	$N_{II} = 75 \text{ cm}$	$N_{III} = 80 \text{ cm}$	$N_{IV} = 100 \text{ cm}$
$P_I = 90 \text{ cm}$	$P_{III} = 60 \text{ cm}$	$P_{III} = ?$	$P_{IV} = 70 \text{ cm}$

$$80 \pm 10\% (80) \begin{cases} 88 \\ 72 \end{cases} \quad N_I = N_{IV} \neq N_{III} \pm 10\% N_{III}$$

$\therefore$ Normal ratio method used

$$P_{III} = \frac{N_{III}}{m} \left(\frac{P_I}{N_I} + \frac{P_{IV}}{N_{IV}} \right) = \frac{80}{3} \left(\frac{90}{60} + \frac{70}{100} \right) = \underline{\underline{80 \text{ cm}}}$$

06.

A	$N_A = 75 \text{ cm}$	$P_A = 8.5 \text{ cm}$	$90 \pm 10\% (90) \begin{cases} \rightarrow 99 \\ \rightarrow 81 \end{cases}$
B	$N_B = 84 \text{ cm}$	$P_B = 6.7 \text{ cm}$	
C	$N_C = 70 \text{ cm}$	$P_C = 9 \text{ cm}$	
D	$N_D = 90 \text{ cm}$	$P_D = ?$	

Normal ratio method is used.

$$P_D = \frac{N_D}{m} \left(\frac{P_A}{N_A} + \frac{P_B}{N_B} + \frac{P_C}{N_C} \right)$$

$$= \frac{90}{3} \left(\frac{8.5}{75} + \frac{6.7}{84} + \frac{9}{70} \right) = \underline{\underline{9.65 \text{ cm}}}$$

* Consistency of Rainfall Data : (true representation)

Consistency of rainfall data is verified by plotting "Double Mass Curve".

Base Stations:-

Adjacent rain gauge station's whose data is consistent.

Connected consistent rainfall at station 'X',

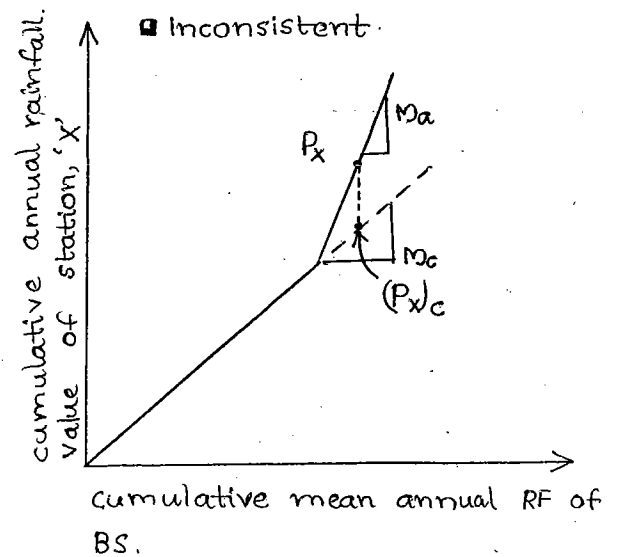
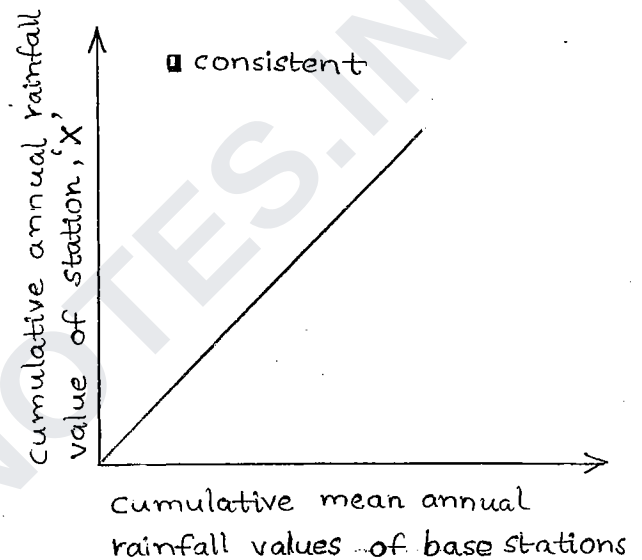
$$(P_x)_c = P_x * \frac{M_c}{M_a}$$

→ Presentation of Rainfall Data:

- (i) Rainfall Mass curve.
- (ii) Rainfall Hyetograph
- (iii) Depth-area-duration curves.
- (iv) Intensity-duration-Frequency curves.
- (v) Depth-duration-Frequency curves.

* Rainfall mass curve:

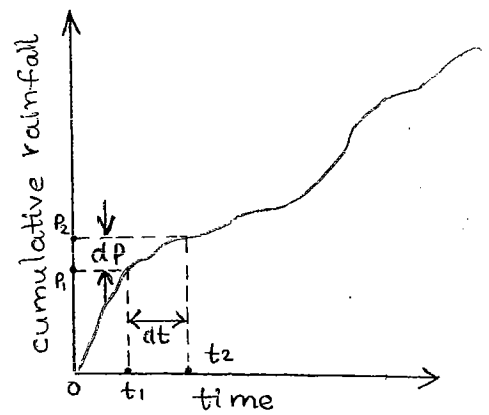
Recording type raingauges record rainfall data in the form of mass curve. Mass curve is a plot b/w accumulated rainfall and time.



* Rainfall Hyetograph:

It is a plot between rainfall intensity and time.

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

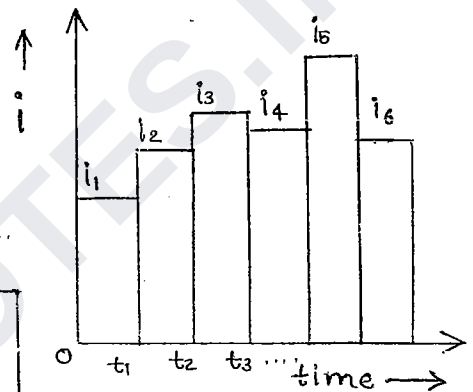


It is a histogram (or) bar diagram, easy to read rainfall information from this.

■ Rainfall Mass Curve

$$i = \frac{dP}{dt}$$

$$\Rightarrow \int dP = \int_0^t i dt = \text{area of hyetograph.}$$



$$\therefore \text{Total rainfall in time 't'} \\ = \text{total area of hyetograph} = \sum_0^t i_i t_i$$

Eg: Total rainfall b/w time intervals t_i & t_{i+n} = area of hyetograph b/w t_i & t_{i+n}

$$= \sum_{t_i}^{t_{i+n}} i_i t_i$$

Total rainfall = total area of hyetograph

$$= (66+75+54) \frac{20}{60} + (48+69+51) \frac{40}{60} + (38+47+25) \frac{60}{60}$$

$$= \underline{\underline{287 \text{ mm}}}$$

07.

time (min)	i	i (20 min duration)
0-10	0.7	$\frac{0.7 \times 10 + 1.1 \times 10}{20} = 0.9$
10-20	1.1	1.65
20-30	2.2	$\frac{2.2 \times 10 + 1.5 \times 10}{20} = 1.85$
30-40	1.5	
40-60	1.2	$\frac{1.2 \times 10 + 1.3 \times 10}{20} = 1.25$
50-60	1.3	
60-70	0.9	$\frac{0.9 \times 10 + 0.4 \times 10}{20} = 0.65$
	0.4	

$\Rightarrow$ Max intensity of rainfall for 20 min duration of storm = 1.85 mm/min

* Depth - Area - Duration curve.

$$P = P_0 e^{-KA^n}$$

where, $P_0 \rightarrow$ depth of rainfall. at storm centre.

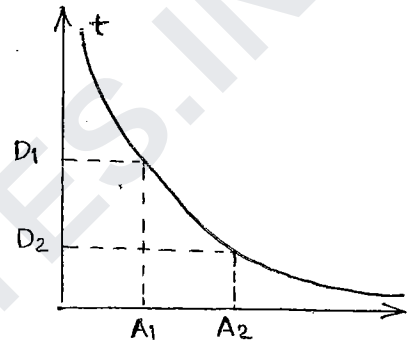
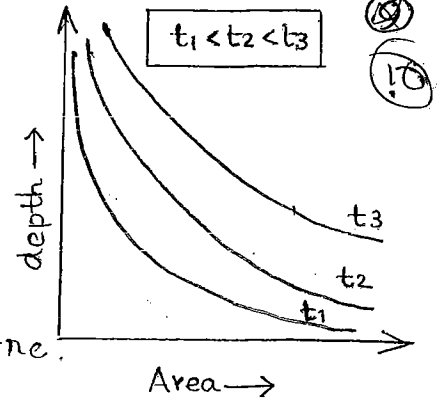
$P \rightarrow$ depth of rainfall.

$A \rightarrow$ areal distribution of storm.

K & n are constants.

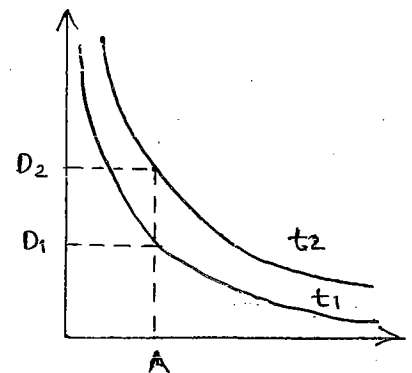
⊙ For a given t hour storm,

if $A_2 > A_1$, then $D_2 < D_1$

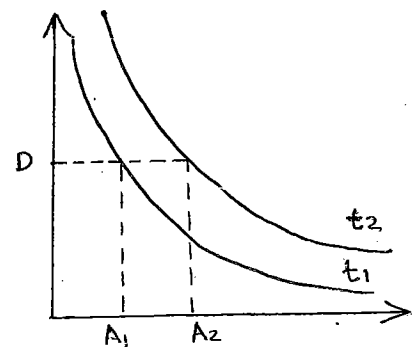


⊙ For a given catchment basin of area A ,

if $t_2 > t_1$, then $D_2 > D_1$



⊙ For given depth ' D ', if $t_2 > t_1$
then $A_2 > A_1$



* Intensity - Duration - Frequency. Curves

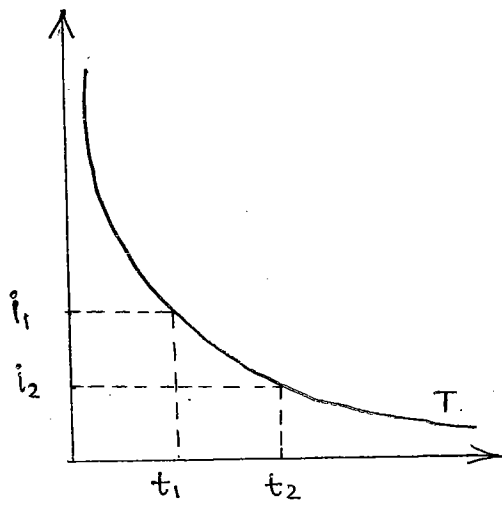
$$i = \frac{KT^x}{(D+a)^n}$$

where $i \rightarrow$ intensity of rainfall.

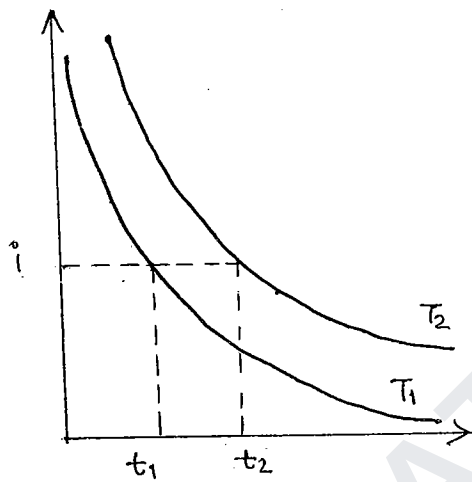
$T \rightarrow$ frequency (year) of rainfall.

$D \rightarrow$ duration of rainfall.

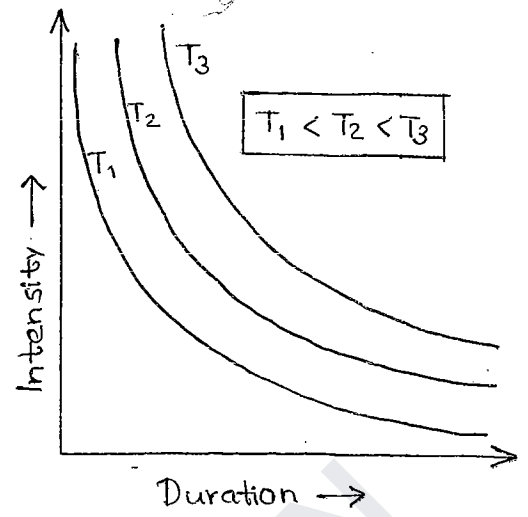
K, x, a, n are constants.



⊙ For given T , if $t_2 > t_1$,
then $i_2 < i_1$

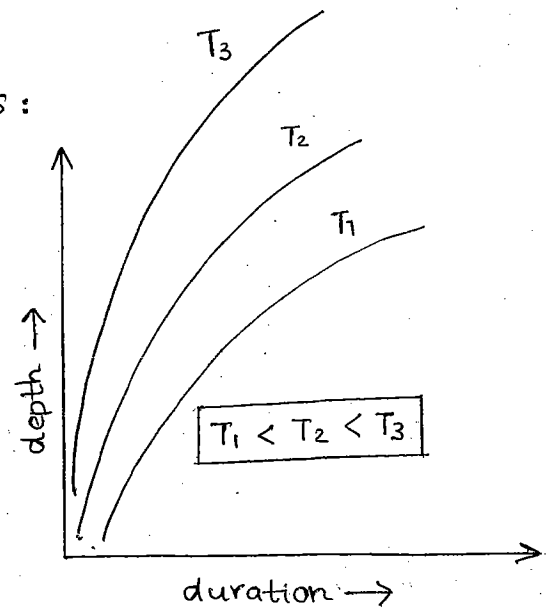


⊙ For given i , if $T_2 > T_1$,
then $t_2 > t_1$



⊙ For given duration ' t ',
if $T_2 > T_1$, then $i_2 > i_1$

* Depth-duration-frequency curves:



02. MEAN PRECIPITATION CALCULATION

Rainfall values recorded at various rain gauge stations in a catchment represent point rainfall data, i.e., point sampling of areal distribution of a storm.

To convert many point rainfall data recorded at various rain gauge stations into single rainfall data representing entire catchment known as 'mean precipitation', the following mathematical methods are used.

→ Arithmetic Mean method

- also known as 'Constant weightage method'.

- applicable for catchments satisfying following conditions:

- (i) catchment should be flat and plain.
- (ii) when rain gauges are uniformly distributed over a catchment.
- (iii) rainfall values recorded at various rain gauge stations show little variation.

- let $P_1, P_2 \dots P_n$ be the rainfall values recorded at rain gauge stations 1, 2, $\dots$ n respectively.

$$\therefore \text{mean precipitation, } \bar{P} = \frac{P_1 + P_2 + P_3 + \dots + P_n}{n}$$

→ Thiessen Polygon Method: (Weighted average method)

- This method is applicable to flat and plain catchments, i.e., catchment with no topographic variations.

- In this method, Thiessen weightages are assigned for each rain gauge station based on area represented by them.

Let $\frac{A_1}{A}, \frac{A_2}{A} \dots \frac{A_n}{A}$ are the Thiessen weightages assigned for rain gauge stations $1, 2, \dots, n$ and $P_1, P_2 \dots P_n$ be the rainfall values recorded at respective rain gauge station.

Then mean precipitation, $\bar{P} = P_1 \times \frac{A_1}{A} + P_2 \times \frac{A_2}{A} + \dots + P_n \times \frac{A_n}{A}$

$$\Rightarrow \bar{P} = \frac{P_1 A_1 + P_2 A_2 + \dots + P_n A_n}{A}$$

-10

$$1. \quad \bar{P} = \frac{75 \times 3 + 125 \times 5 + 150 (4+6)}{500} = \underline{\underline{4.7 \text{ cm}}}$$

$$2. \quad \bar{P} = 10 \times 0.1 + 15 \times 0.2 + 20 \times 0.3 + 25 (1 - (0.1 + 0.2 + 0.3)) \\ = \underline{\underline{20 \text{ cm}}}$$

* Procedure to assign Thiessen weightages:

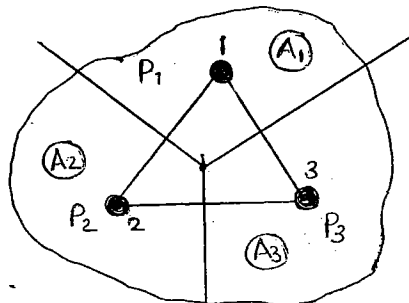
Step 1: Plot catchment to some suitable scale.

Step 2: Identify rain gauge stations within a catchment.

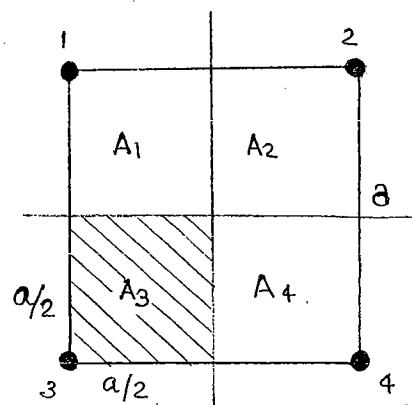
Step 3: Join all adjacent triangle stations by straight lines.

Step 4: Draw perpendicular bisectors. The area enclosed b/w the bisectors and boundary of a catchment; i.e., polygonal area represent a rain gauge station enclosed within that polygon.

Step 5: Measure area of each polygon and total area of polygon using a planimeter and assign Thiessen weightages.

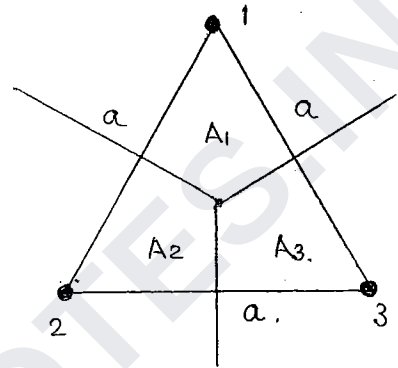


$$A_1 = A_2 = A_3 = A_4 = \frac{a}{2} \times \frac{a}{2}$$



$$A = \frac{\sqrt{3}}{4} a^2$$

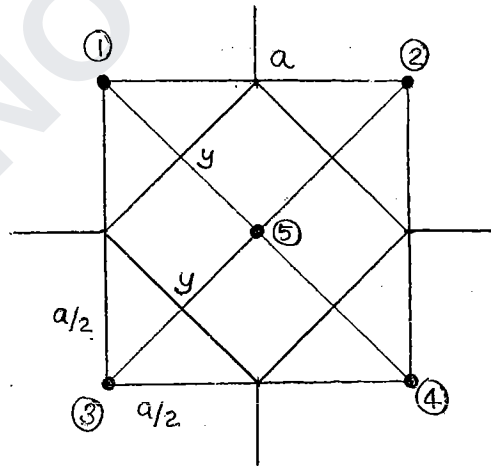
$$A_1 = A_2 = A_3 = \frac{1}{3} \times \frac{\sqrt{3}}{4} a^2$$



$$A_1 = A_2 = A_3 = A_4 = \frac{1}{2} \times \frac{a}{2} \times \frac{a}{2}$$

$$A_5 = y \times y$$

$$y = \sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{a}{2}\right)^2}$$



$$3. \quad A_A = A_B = \frac{20}{2} \times \frac{20}{2} = 100 \text{ km}^2$$

$$A_D = \frac{1}{3} \times \frac{\sqrt{3}}{4} \times 20^2 = 57.735 \text{ km}^2$$

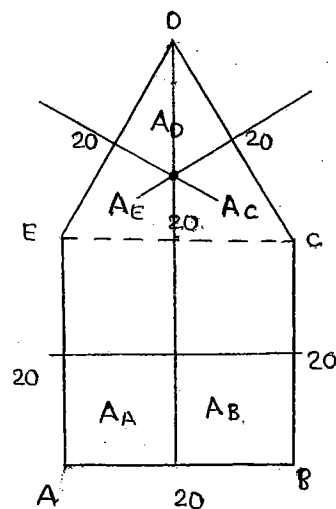
$$A_E = 100 + 57.735 = 157.735 \text{ km}^2$$

$$A_C = 157.735 \text{ km}^2$$

$$\text{Average depth of rainfall} = \frac{\sum P_i A_i}{A}$$

$$= \frac{100 \times 60 + 100 \times 81 + 157.735 \times 73 + 57.735 \times 59 + 157.735 \times 45}{20 \times 20 + \frac{\sqrt{3}}{4} \times 20^2}$$

$$= \underline{\underline{63.01 \text{ mm}}}$$

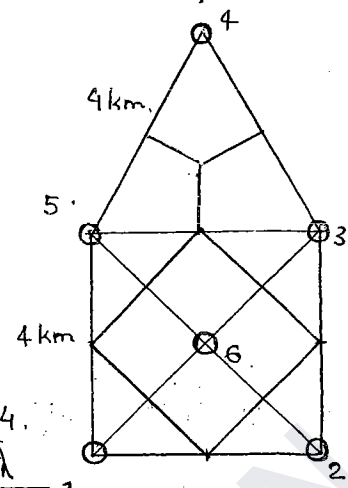


4. $A_1 = A_2 = \frac{1}{2} \times \frac{4}{2} \times \frac{4}{2} = 2 \text{ km}^2$

$A_4 = \frac{1}{3} \times \frac{\sqrt{3}}{4} \times 4^2 = 2.31 \text{ km}^2$

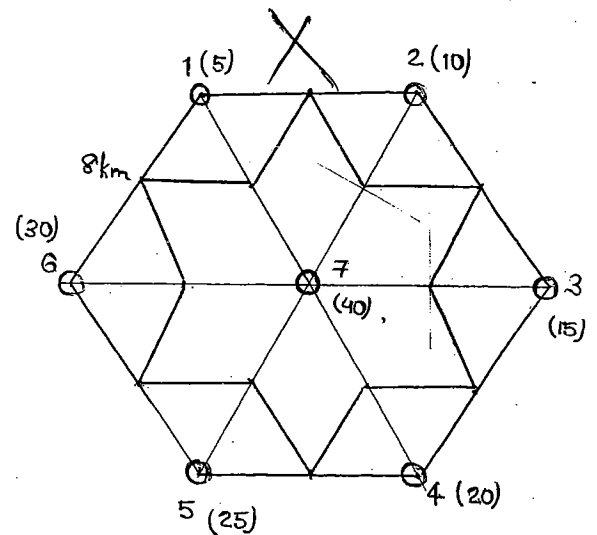
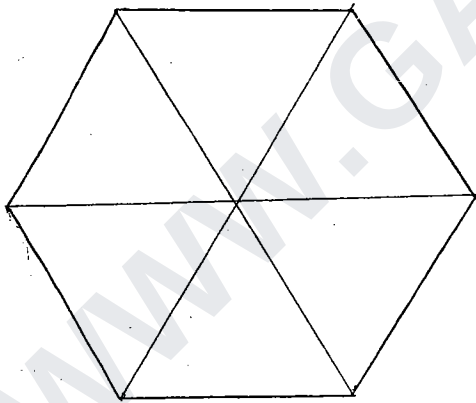
$A_5 = A_3 = 4.31 \text{ km}^2$

$A_6 = 4^2 - 4 \times 2 = 8 \text{ km}^2$



$$\text{Mean precipitation} = \frac{2(8+13) + 4.31(5.4+4.8) + 2.31 \times 3.2 + 8 \times 9.4}{4^2 + \frac{\sqrt{3}}{4} \times 4^2} = \underline{\underline{7.35 \text{ cm}}}$$

Q A catchment is in the form of a regular hexagon of side 8 km. 6 Rain gauges installed, one at each corner and one more at centre recorded 5, 10, 15, 20, 25, 30 & 40 cm at central station. Find mean precipitation by Thiessen polygon method.



- Q. A catchment is in the form of a circle of radius 10 km centre at (0,0). Location of raingauge stations and their respective rainfall values are given below. Find mean precipitation by Thiessen polygon.

Raingauge Stations	1	2	3	4	5
Location (x,y)	(-5,5)	(5,5)	(-5,-5)	(5,-5)	(0,0)
Rainfall (cm)	4	6	3	5	2

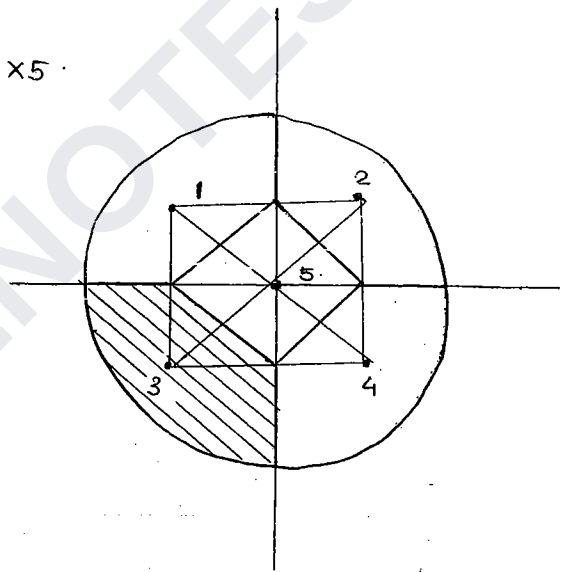
$$A_1 = A_2 = A_3 = A_4 = \frac{\pi}{4} \times 10^2 - \frac{1}{2} \times 5 \times 5$$

$$= 66.04 \text{ km}^2$$

$$A_5 = 10^2 - 4 \times 12.5 = 50 \text{ km}^2$$

$$\bar{P} = \frac{66.04(4+6+3+5) + 50 \times 2}{\pi \times 10^2}$$

$$= \underline{\underline{4.10 \text{ cm}}}$$

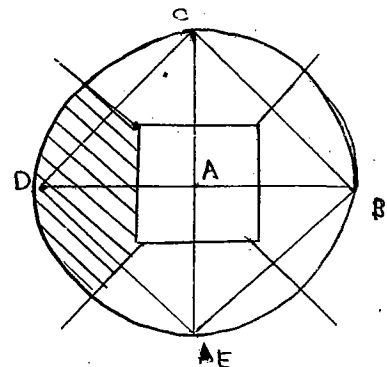


- Q. 5 raingauge stations A, B, C, D, E are located on a circular shaped basin of diameter 20 km as shown in fig. Compute mean areal rainfall over the basin using TP method. If the rainfall at stations A, B, C, D, & E are 100 cm, 90 cm, 110 cm, 120 cm and 80 cm rsptly.

$$A_A = 10 \times 10 = 100 \text{ km}^2$$

$$A_B = A_C = A_D = A_E = \frac{\frac{\pi}{4} \times 20^2 - 10 \times 10}{4}$$

$$= \underline{\underline{53.54 \text{ km}^2}}$$



$$\bar{P} = \frac{53.54(90+110+120+80) + 100 \times 100}{\frac{\pi}{4} \times 20^2} = \underline{\underline{100 \text{ cm}}}$$

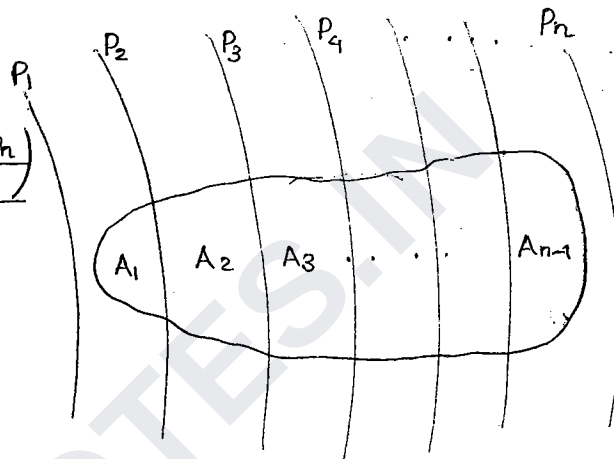
→ Isohyetal Method.

- The best and more accurate method to find mean precipitation.

Isohyet: line joining points of equal rainfall.

Isonif: line joining points of equal snowfall.

$$\bar{P} = \frac{A_1 \left(\frac{P_1 + P_2}{2} \right) + A_2 \left(\frac{P_2 + P_3}{2} \right) + \dots + A_{n-1} \left(\frac{P_{n-1} + P_n}{2} \right)}{A}$$



- At ^{first} extreme ends, if there is no isohyetal line,

$$\text{mean precipitation, } \bar{P} = \frac{A_1 P_2 + A_2 \left(\frac{P_2 + P_3}{2} \right) + \dots + A_{n-1} \left(\frac{P_{n-1} + P_n}{2} \right)}{2}$$

10.

Q.5

$$\bar{P} = \frac{100 \left(\frac{55+45}{2} \right) + 150 \left(\frac{55+65}{2} \right)}{150 + 100} = \underline{\underline{56 \text{ cm}}}$$

6.

$$\bar{P} = \frac{92 \left(\frac{15+12}{2} \right) + 128 \left(\frac{12+9}{2} \right) + 120 \left(\frac{9+6}{2} \right) + 175 \left(\frac{6+3}{2} \right) + 85 \left(\frac{3+1}{2} \right)}{92 + 128 + 120 + 175 + 85} = \underline{\underline{7.4 \text{ cm}}}$$

7.

$$\bar{P} = \frac{30 \times 12 + 140 \times 11 + 80 \times 9 + 180 \times 7 + 20 \times 5}{30 + 140 + 80 + 180 + 20} = \underline{\underline{8.84 \text{ cm}}}$$

03. FREQUENCY ANALYSIS

13
14

- Frequency Analysis is performed for random & rare events.
- Rainfall and floods are the two hydrological events which occur rarely and randomly. The probability of occurrence of these events is worked out by performing frequency analysis. Knowing the frequency, risk associated with that event if used in the design is worked out. Knowing the risk, safety can be evaluated.
- In many hydraulic engineering applications such as those concerned with floods and rains, the probability of occurring max. flood or max. rainfall is the basis. Their probabilities of occurrences are worked out by performing ^{frequency} (probability) analysis using the past data.
- Data used in frequency analysis is usually annual series (time series)

→ Frequency (or) Return Period (or) Recurrence Interval, 'T'

It is defined as time interval between the occurring of an event of certain magnitude which is likely to be equalled or exceeded. The following empirical formulas are used to find frequency (or) return period (T):

1. Weibulls Formula.

$$T = \frac{n+1}{m}$$

n → no. of annual series (time series) of data used in analysis

m → rank assigned for a given data in that series for which T is

2. Hazen's formula

$$T = \frac{n}{m-0.5}$$

3. California formula

$$T = \frac{n}{m}$$

* Procedure to find frequency:

Step 1: Arrange given data in descending order of their magnitude.

Step 2: Assign rank for each data in that order.

Step 3: Using any of the above formula, obtain return period for given data.

2-14

Q1.

14.2	—	1	(i) Hazen Formula
13.0	—	2	
12.0	—	3	
12.0	—	3	(ii) Weibull Formula
7.9	—	5	
6.0	—	6	
6.0	—	6	
4.8	—	8	
3.7	—	9	
2.9	—	10	

$$T = \frac{n}{m-0.5} = \frac{10}{6-0.5} = \frac{20}{11}$$

$$T = \frac{n+1}{m} = \frac{11}{6}$$

11.

1	2	3	4	5	6	7	8	9
130	120	100	80	75	70	60	50	40

(i) Return period 80 m³/s flood = $\frac{n+1}{m} = \frac{10}{4} = 2.5$

(ii) " 75 m³/s flood = $\frac{10}{5} = 2$

(iii) " 50 m³/s flood = $\frac{10}{8} = 1.25$

- Let P be the probability of occurring an event & q be the probability of not occurring an event.

$$\text{Probability of occurrence} = p = \frac{1}{T}$$

$$q = 1 - \frac{1}{T}$$

- Probability of occurring an event r times in n successive years,

$$P(r, n) = {}^n C_r p^r q^{n-r}$$

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

- Probability of not occurring in n successive years $= q^n$

- Probability of occurring an event atleast once in ' n ' successive years $= 1 - q^n$

- Probability of occurring an hydrologic event atleast once in ' n ' successive years $=$ hydrologic risk, ' R ' $= 1 - q^n$

$$\Rightarrow \begin{array}{|l} \text{Hydrologic risk, 'R'} = 1 - q^n \\ \hline \% \text{ safety} = 100 - \% \text{ risk.} \end{array}$$

NOTE:

1. Probability of occurrence if its expressed in fractions, then it is known as 'exceedence probability'. If its expressed in percentage, then its known as 'chance percentage'

02. $T = 20$ years.

$$p = \frac{1}{T} = \frac{1}{20}; \quad q = 1 - \frac{1}{20} = \frac{19}{20}$$

Probability that it may occur in next 12 years
 = occurring atleast once in next 12 years.

$$= 1 - q^n = 1 - \left(\frac{19}{20}\right)^{12} = 45.96 \approx \underline{\underline{46\%}}$$

03. $T = 8$ years.

$$P = \frac{1}{8} \quad q = \frac{7}{8}$$

Probability that flood magnitude will be exceeded once
 in 5 years $= 1 - q^n = 1 - \left(\frac{7}{8}\right)^5 = \underline{\underline{0.487}}$

04. $T = 100$ years, $n = 50$ years

$$P = \frac{1}{100} \quad \& \quad q = \frac{99}{100}$$

Risk associated with hydraulic design $= 1 - q^n$

$$= 1 - \left(\frac{99}{100}\right)^{50} = \underline{\underline{39.5\%}}$$

06. $T = 100$ years, $n = 2$ years

$$P = \frac{1}{100}, \quad q = \frac{99}{100}$$

Risk during 2 year service life of project $= 1 - \left(\frac{99}{100}\right)^2$

$$= \underline{\underline{1.99\%}}$$

05. $0.2 = 1 - \left(1 - \frac{1}{T}\right)^{10}$

$$\left(\frac{T-1}{T}\right)^{10} = 0.8 \quad \Rightarrow \quad T = \underline{\underline{45.32 \text{ years}}}$$

$$\log 1 - \log \frac{1}{T} = -0.022$$

$$\log 1 + \log T = -0.022$$

07. $T = 40$ years.

a) Exceedence probability, $p = \frac{1}{T} = \underline{\underline{2.5\%}}$

b) Probability of occurring atleast once during next 20 years
 $= 1 - q^n = 1 - (0.975)^{20} = 39.73\%$

c) Probability of occurring a flood less than $4000 \text{ m}^3/\text{s}$
 $= \text{probability of not occurring a flood } \geq 4000 \text{ m}^3/\text{s}.$
 $= \underline{\underline{0.975}} \quad (=q).$

level 1

08. $p = \frac{1}{50}; q = \frac{49}{50}$

(i) $P(\text{one time in 10 years}) = {}^{10}C_1 \left(\frac{1}{50}\right)^1 \left(\frac{49}{50}\right)^9$
 $= \underline{\underline{0.167}}$

(ii) $P(2 \text{ time in 10 years}) = {}^{10}C_2 \left(\frac{1}{50}\right)^2 \left(\frac{49}{50}\right)^8 = \underline{\underline{0.0153}}$

(iii) $P(\text{atleast once in 10 years}) = 1 - q^n$
 $= 1 - \left(\frac{49}{50}\right)^{10} = \underline{\underline{0.183}}$

→ Probable Maximum Precipitation, (PMP)

Extreme rainfall which is physically possible to occur.

$$\boxed{PMP = \bar{p} + K\sigma}$$

$\bar{p}$ → mean of rainfall data.

σ → standard deviation of rainfall data

K → frequency factor.

→ Station Year Method.

The method of generating long length of record at an imaginary station by combining the all the records from all of the stations lying in meteorologically and hydrologically homogeneous area (same climatic zone).

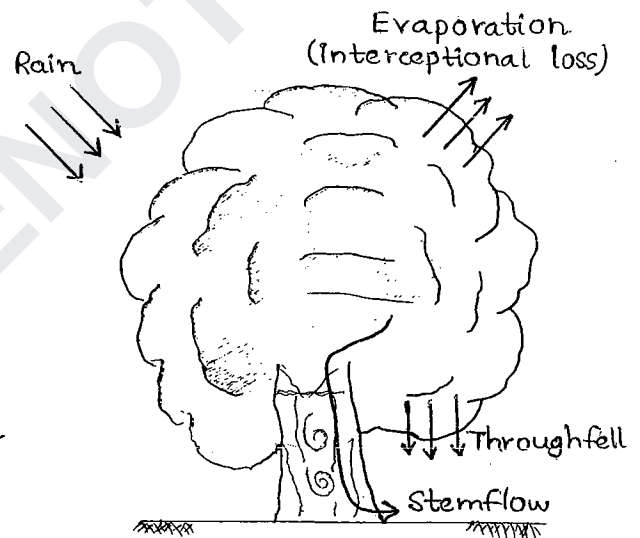
WWW.GATENOTES.IN

ABSTRACTIONS OF PRECIPITATION (Rainfall Losses)

1. Interceptional Loss
2. Evaporation
3. Transpiration
4. Evapotranspiration
5. Infiltration

→ Interceptional Loss

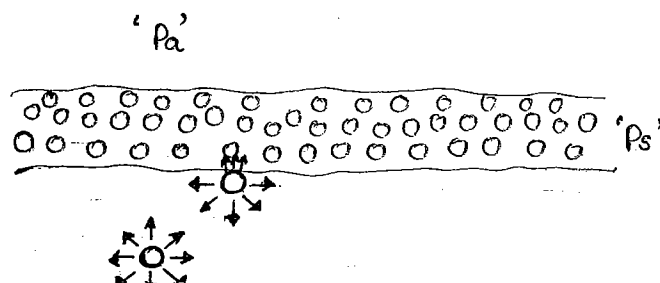
Rain which is intercepted by the tall objects lying above the ground, (ie trees and buildings) evaporate part of the intercepted rain back to space.



Rain without being collected on the ground evaporating back to space from such objects is known as 'Interceptional Loss'

→ Evaporation

Evaporation is the process by which water change its state from liquid to vapour and escape to atmosphere as a vapour.



* Dalton's Law of Evaporation:

$$\text{Rate of evaporation, } E \propto (P_s - P_a)$$

- Evaporation is essentially a cooling process, since average velocity of water molecules in water ^{body} decreases during evaporation (temp. of water body $\propto$ avg. velocity of water molecules)

* Factors affecting Evaporation:

1. Solar Radiation -

$$E \propto R$$

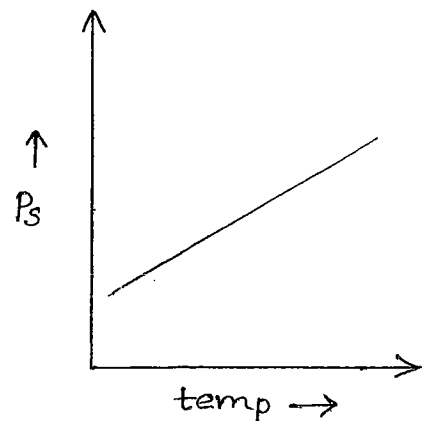
As radiation increases, evaporation also increases.

2. Temperature -

$$P_s \propto \text{temperature}$$

$$E \propto (P_s - P_a)$$

$$\Rightarrow E \propto \text{temperature}$$



As temperature increases, saturation vapour pressure increases and thus rate of evaporation increases.

3. Winds -

$$E \propto V$$

where V is windspeed.

4. Pressure (P_a) -

$$E \propto \frac{1}{P_a}$$

Night time evaporation is due to drop in atmospheric pressure, P_a .

5. Humidity -

$$E \propto \frac{1}{\text{Humidity}}$$

(A)

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6. Surface area of water body -

$$E \propto \text{surface area}$$

7. Depth of water body -

$$E \propto \frac{1}{\text{depth}}$$

Summer evaporation is more for shallow water bodies and less for deep water bodies whereas winter evaporation is less for shallow water bodies and more for deep water bodies.

8. Quality of water. -

$$\text{Evaporation} \propto \text{Quality}$$

More quality means fresh water body

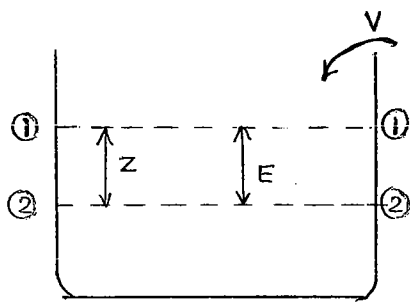
Less quality means saline water body.

In saline water bodies, evaporation is 2-3% less than fresh water bodies.

* Measurement & Estimation of Evaporation:

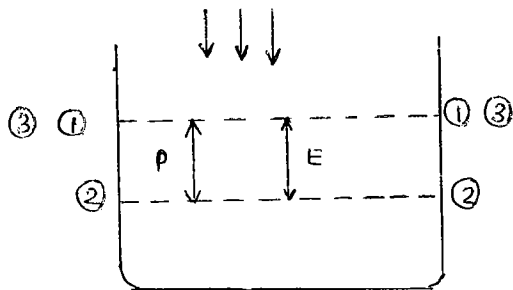
1. Pan Measurement -

Pan is a container of some standard dimensions filled with water to a stipulated level and installed close to the water body. Over a period of time by observing the changes in water level of a container, evaporation loss from the actual water body can be worked out.

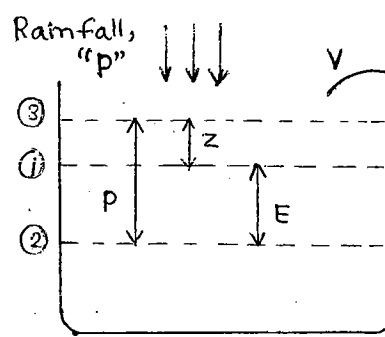


Case 1: no rainfall.
($P=0$).

$$E = Z$$

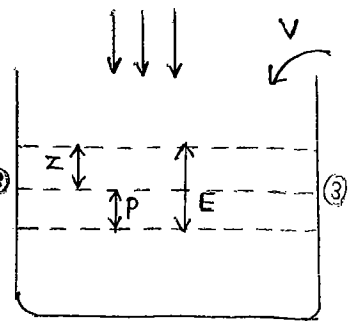


Case 4: $E = P$.
($V=0$, $Z=0$).



Case 2: $P > E$

$$E = P - Z$$



Case 3: $P < E$

$$E = P + Z$$

In general,

$$\text{Pan evaporation, } E = P \pm Z.$$

where $Z \rightarrow$ depth of water added or removed.

$P \rightarrow$ rainfall.

$$Z = \frac{\text{Volume of water added (or) removed.}}{\text{Surface area of pan.}}$$

$Z = +ve$, when water added to pan.

$Z = -ve$, when water removed from pan.

$Z = 0$, no water added or removed.

$P = 0$, if there is no rainfall.

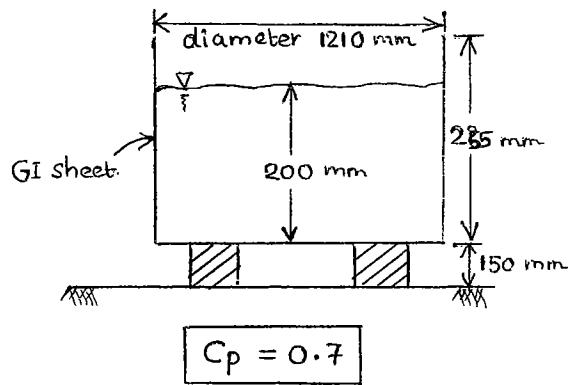
$$\left. \begin{array}{l} \text{Actual evaporation} \\ \text{from water body} \end{array} \right\} = C_p \times \text{pan evaporation.}$$

where $C_p = \text{coefficient of pan} = \frac{\text{actual evaporation}}{\text{pan evaporation}}$

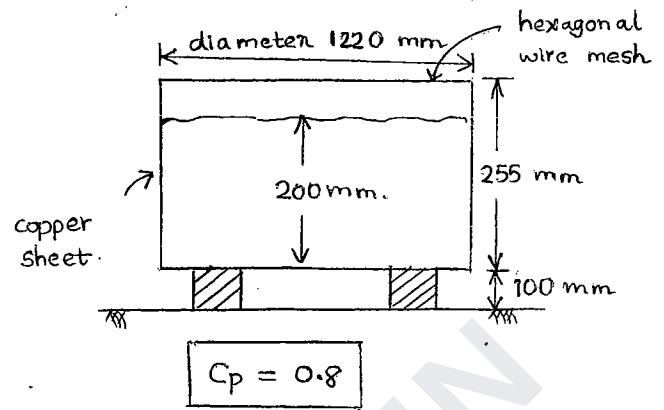
$$\left. \begin{array}{l} \text{Volume of water loss due} \\ \text{to evaporation from water body} \end{array} \right\} = \text{actual evaporation} \times \text{SA of water body.}$$

* Types of Pans.

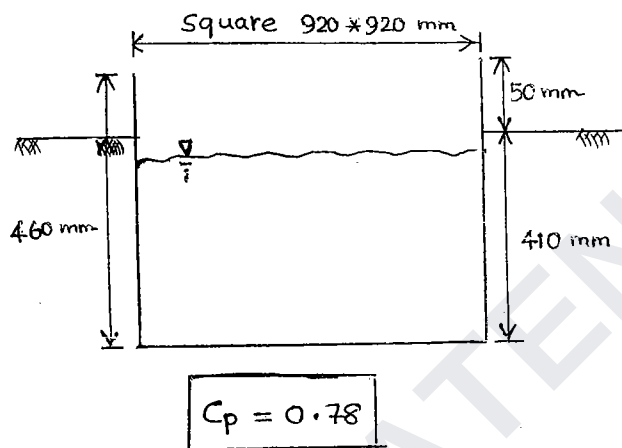
(i) USWB Class A Pan



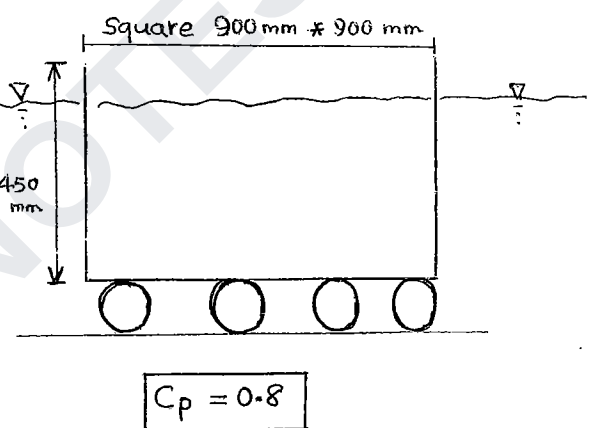
(ii) IS Class A Pan.



(iii) Colorado Sunken Pan.



(iv) USGS Floating Pan.



2-19

Q.1 Volume of water removed = 4.2 L

Diameter of pan = 1.22 m.

Rainfall, $P = 8.75$ mm.

$$\text{Depth of water removed, } z = \frac{4.2 \times 10^{-3}}{\frac{\pi}{4} \times 1.22^2} = 3.59 \text{ mm}$$

$$\text{Pan evaporation, } E = P - z = 8.75 - 3.59 = \underline{\underline{5.16 \text{ mm}}}$$

Q.2. Depth of water added, $z = \frac{8.75 \times 10^{-3}}{\frac{\pi}{4} \times 1.22^2} = \underline{\underline{7.74 \text{ mm}}}$

Rainfall, $P = 4.2$ mm.

$$\text{Pan evaporation, } E = 7.74 + 4.2 = 11.94 \text{ mm}$$

$$\text{Actual evaporation} = \underline{\underline{8.36 \text{ mm}}}$$

03. IS Pan $\Rightarrow C_p = 0.8$

Surface area of reservoir = 100 ha.

Pan evaporation, $E = 4 \text{ cm}$.

Anticipated evaporation loss = ?

Actual evaporation on that day = $C_p \times \text{pan evaporation}$
 $= 0.8 \times 4 = \underline{\underline{3.2 \text{ cm}}}$

$\therefore$ Anticipated evaporation = volume of water evaporated on that day
 $= \text{actual evaporation} \times \text{surface area of reservoir}$
 $= \frac{3.2}{100} \times 100 \times 10^4 \text{ m}^3 = \underline{\underline{3.2 \times 10^4 \text{ m}^3/\text{day}}}$

04.

Day	1	2	3	4	5	6	7
Rainfall.	14	6	12	8	0	5	6
Water added (or) removed.	-5	3	0	0	7	4	3.
Daily Pan evaporation.	9	9	12	8	7	9	9.

Total pan evaporation in that week = 63 mm.

$C_p = 0.75$

Actual evaporation from lake in that week = $C_p \times \text{pan evaporation}$
 $= 0.75 \times 63 = \underline{\underline{47.25 \text{ mm}}}$

Volume of water evaporated from lake = actual evaporation $\times$ S.A.
 $= \frac{47.25}{1000} \times 640 \times 10^4 = \underline{\underline{302400 \text{ m}^3}}$

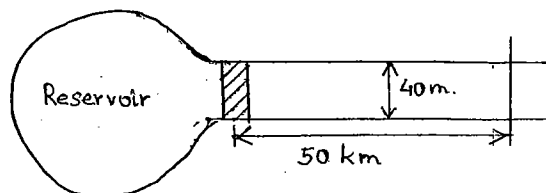
P-61

08. Pan evaporation = 0.5 m

Actual evaporation = $C_p \times 0.5$

$= 0.7 \times 0.5$

$= 0.35 \text{ m/day}$



Evaporation loss to be considered in releasing water

= actual evaporation $\times$ SA of channel.

$$= \frac{0.35 \times 50 \times 10^3 \times 40}{10^4} = \underline{\underline{70 \text{ ha-m}}}$$

2. Empirical Formulae:

(i) Fitzrard Equation

$$\text{Rate of evaporation, 'E'} = (0.4 + 0.124 V) (P_s - P_a) \text{ (mm/day)}$$

where $V \rightarrow$ wind speed (in km/hr).

P_s & $P_a \rightarrow$ saturation & actual vapour pressures (in mm of Hg)

(ii) Meyer's Equation

$$\text{Rate of evaporation} = (1 + 0.06215 V) C (P_s - P_a) \text{ (mm/month)}$$

where $C \rightarrow$ Meyer's constant.

(iii) Rohwer's formula.

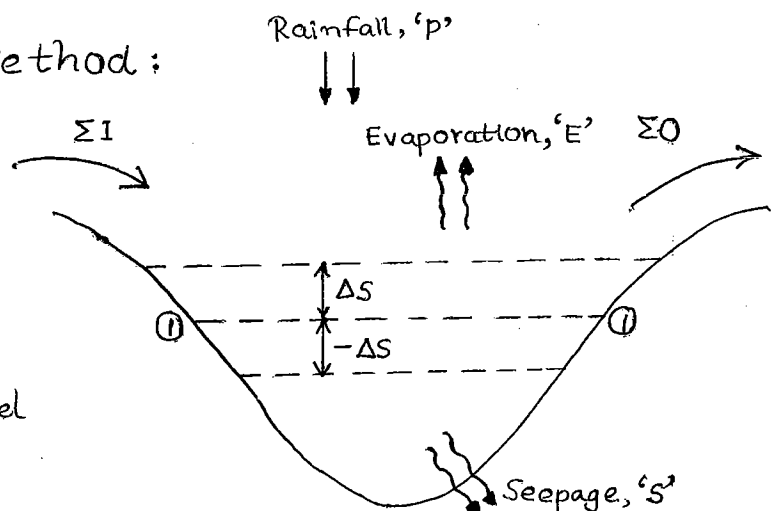
$$\text{Rate of evaporation} = 0.771 (1.465 - 0.000732 P_a) (0.44 + 0.07334 V) (P_s - P_a) \text{ (mm/day)}$$

3. Water Budget Method:

$$\Sigma I - \Sigma O = \pm \Delta S$$

$\Delta S \rightarrow$ '+ve' when water level increases.

$\Delta S \rightarrow$ '-ve' when water level decreases.



Inflows: Rain fall (P), Run off (I).

Outflows: Evaporation (E), Seepage (S), water used (O).

$$\Sigma I - \Sigma O = \pm S$$

$$(I + P) - (O + E + S) = \pm \Delta S.$$

05. $\Delta S = 103.258 - 103.2 = 0.058$

$$\frac{(6 \times 86400 \times 30 + 0.145)}{5000 \times 10^4} - \frac{(6.5 \times 86400 \times 30 + E)}{5000 \times 10^4} = 0.058$$

$$E = 0.06108 \text{ m} = \underline{\underline{61.08 \text{ mm}}}$$

06. $\left(\frac{10 \times 10^4}{(10^3)^2} + 0.03 \right) - \left(\frac{20 \times 10^4}{(10^3)^2} + 0.12 \times 0.7 + S \right) = -0.2$

$$S = 0.046 \text{ m}$$

$$\text{Seepage loss in ha-m} = \frac{0.046 \times 10^6}{10^4} = \underline{\underline{4.6 \text{ ha-m}}}$$

4. Energy Balance Method

$$H_e = R - H_a + H_g$$

$R \rightarrow$ Incoming solar radiation (insolation), watts/m^2

$H_a \rightarrow$ sensible heat loss to atmosphere

$H_g \rightarrow$ ground heat flux.

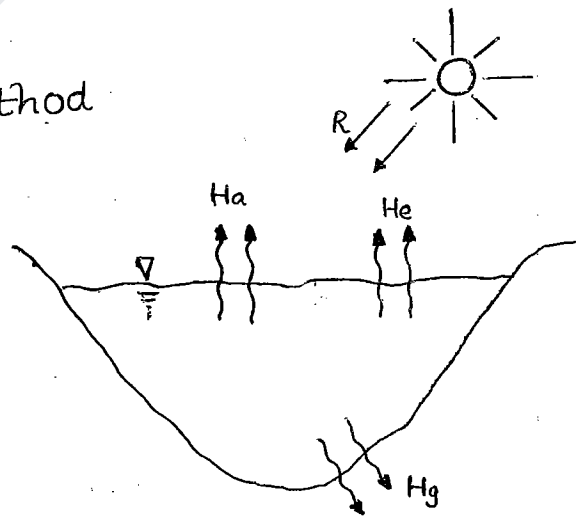
$H_e \rightarrow$ heat energy used in evaporation.

$$H_e = \rho_w L E$$

where $\rho_w \rightarrow$ mass density of water (kg/m^3)

$L \rightarrow$ latent heat of vapourization (J/kg)

$E \rightarrow$ rate of evaporation (m/s)



$$\rho_w L E = R - (H_a + H_g).$$

20
21

$$E = \frac{R - (H_a + H_g)}{\rho_w L}$$

$\therefore H_a$ & H_g being so small, they are neglected.

$$E = \frac{R}{\rho_w L}$$

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07. $R = 200 \text{ watt/m}^2$
 $L = 2441 \text{ kJ/kg} = 2441 \times 10^3 \text{ J/kg.}$
 $\rho_w = 997 \text{ kg/m}^3$

$$E = \frac{200}{2441 \times 10^3 \times 997} = 8.22 \times 10^{-8} \text{ m/s}$$

$$= \underline{\underline{7.1 \text{ mm/day}}}$$

* Methods to Control Evaporation:

(i) Mechanical cover. - used for small water bodies.

(ii) Surface Floats - exposed surface area decreases

(iii) Surface Films - surface active chemical substances

(imp) a) Cetyl Alcohol (Hexa deconol).
 b) Steryl Alcohol. (Octa decanol). } evaporation suppressors
 (or)
 evaporation inhibitors.

(iv) Better Reservoir Planning

(v) Better reservoir operation

(vi) Planting Trees

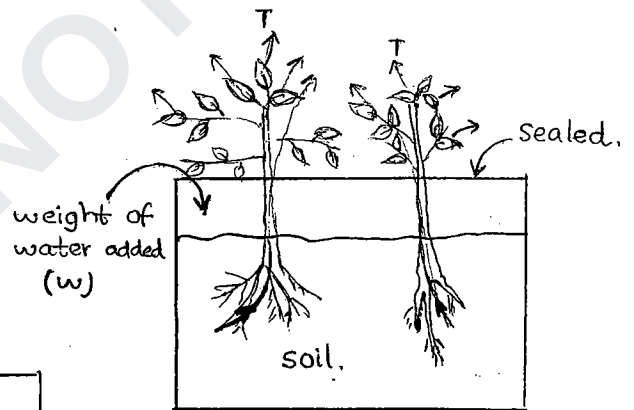
→ Transpiration:

Transpiration is the process by which water leaves the living plant through the stomatal openings of the leaves and diffuse into atmosphere as vapour.

- Transpiration is plant evaporation.
- Transpiration is confined only to daylight hours.
- Plants transpire more than 80 times water than what they consume during photosynthesis.
- Transpiration is measured by a device known as 'Phytometer.'

- * Weight of container along with plant & soil = w_1
- Weight of water added = w
- Final wt. of container = w_2 .

$$\text{Transpiration} = (w_1 + w) - w_2.$$



* Transpiration Ratio, 'Tr'

$$Tr = \frac{\text{Mass of water consumed by plant during its full growth}}{\text{Mass of dry matter produced by plant after wilting}}$$

* Factors affecting Transpiration.

(i) Plant Factors -

- a) Type plant
- b) Stage of plant growth.
- c) type of leaf' structure.

(ii) Soil Factors -

- a) Type of soil
- b) moisture content of soil
- c) Porosity
- d) Permeability

(iii) Weather Factors -

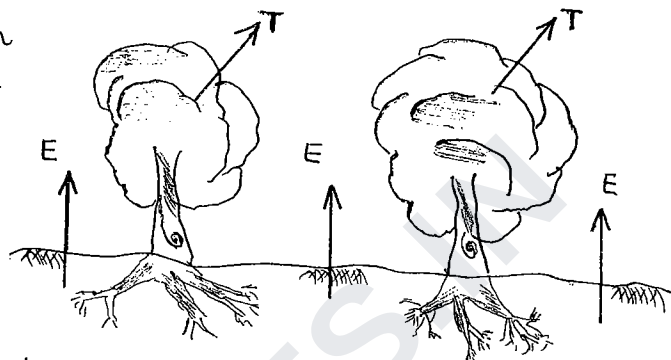
- a) Temperature
- b) Radiation
- c) Winds
- d) Pressure
- e) Humidity

→ Evapotranspiration:

Evapotranspiration is the sum of plant evaporation and land evaporation surrounding the plant.

1. Potential Evapotranspiration (PET)

Evapotranspiration which would occur if soil contain adequate moisture to meet the vegetative needs of the ground covered by full vegetation.



2. Actual Evapo-Transpiration (AET)

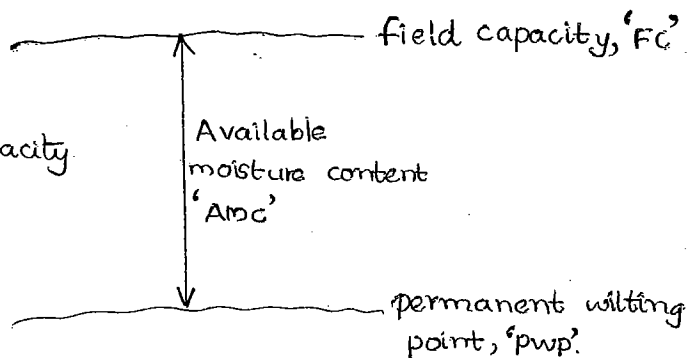
Evapotranspiration at a given time at a given place under specific conditions.

* Relation b/w PET & AET :

① If moisture content = field capacity

Then, $AET = PET$

$$\frac{AET}{PET} = 1$$



② If moisture content < field capacity, then $AET < PET$

$$\frac{AET}{PET} < 1$$

③ If moisture content = permanent wilting capacity, then $AET = 0$

$$\frac{AET}{PET} = 0$$

NOTE:

④ Above relation is true for all soils except clayey soils. For clayey soils, moisture content is greater than 50% FC, then

$MC \geq 0.5 F_c \Rightarrow \frac{AET}{PET} = 1$. (due to low coefficient of permeability)

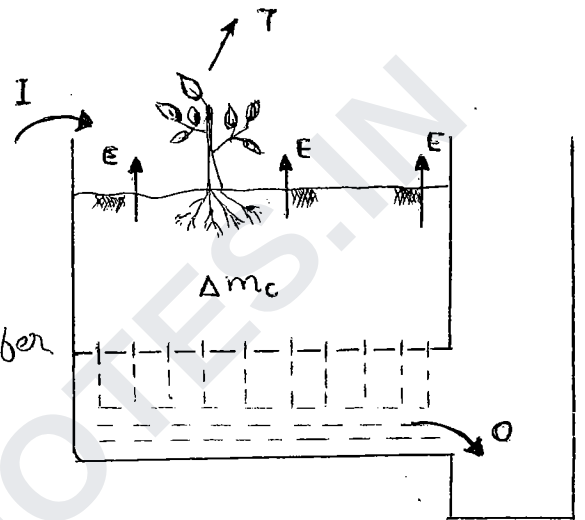
If $MC < 0.5 F_c$, soil behaves normally.

5th Friday
November

* Measurement & Estimation of Evapotranspiration

1. Lysimeter

$$ET = I - O - \Delta mc$$



2. Penman's Equation.

- Energy balance & mass transfer

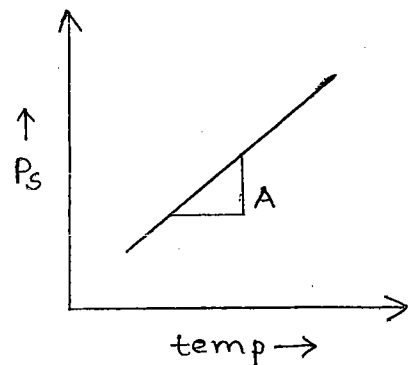
$$PET = \frac{\Delta H_n + E \gamma}{A + \gamma}$$

where $A \rightarrow$ slope of P_s -temp curve

$H_n \rightarrow$ net radiation.

$E \rightarrow$ constant which account wind speed 'V' & $P_s - P_a$.

$\gamma \rightarrow$ Psychrometric constants.



3. Blanney - Criddle Formula.

$$PET = \frac{K P T_m}{100}$$

; $P \rightarrow$ % daylight hours in a month.

PET in 'inch per month'

where $K \rightarrow$ crop factor (or) consumptive use factor.

$T_m \rightarrow$ mean monthly temperature, in '°F'

$$K = \frac{\text{consumptive use, } C_u}{\text{evapotranspiration}}$$

$$^{\circ}F = 1.8^{\circ}C + 32$$

NOTE

• $C_u \approx PET \rightarrow$ when water used by the plants is neglected.

$$C_u = PET = \frac{KPT_m}{100}$$

22
23

① $C_u > PET \rightarrow$ when water used by plants is considered.

In general, $C_u \geq PET$

P-19.

08

$$P = 7.2 \text{ hours}$$

$$T_m = 18^\circ\text{C} = 1.8 \times 18 + 32 = 64.4^\circ\text{F}$$

$$K = 0.7.$$

$$C_u = \frac{KPT_m}{100} = \frac{0.7 \times 7.2 \times 64.4}{100} = 3.246 \text{ inch/month}$$

$$= \frac{3.246 \times 25.4}{30} = \underline{\underline{2.748}} \text{ mm/day}$$

09. Pan evaporation in January = 9.5 cm.

$$K = 0.52$$

$$K = \frac{C_u}{\text{Pan evaporation}}$$

$$C_u = 0.52 \times 9.5 = 4.94 \text{ cm/month.}$$

$$= \frac{4.94 \times 10}{31} = \underline{\underline{1.6}} \text{ mm/day}$$

10.

Month	Mean monthly temp, (°C)	Mean monthly temp (°F)	% day time hours	K	PET
April	25	80.6	8.6	0.6	4.16
May	27	80.6	9.29	0.65	4.976
June	28	82.4	9.18	0.7	5.41
July	29	84.2	9.39	0.75	5.93
August	29	84.2	9.04	0.75	5.71

PET for the season = 65.4 cm

* Isoplith - line joining points of equal evapotranspiration.

$$* \text{Aridity Index (AI)} = \frac{\text{PET} - \text{AET}}{\text{PET}} \times 100$$

$$\text{AI} \propto \frac{1}{\text{AET}} \quad \& \quad \text{AET} \propto \text{moisture content. (mc)}$$

$\text{mc} \propto \text{Rainfall.}$

$$\Rightarrow \text{AI} \propto \frac{1}{\text{rainfall.}}$$

With areas of less rainfalls AET will be less and aridity index will be maximum. (arid or drought prone areas).

$\text{AI} > 50\% \quad \rightarrow \text{Severe drought.}$

$25\% < \text{AI} < 50\% \quad \rightarrow \text{moderate drought}$

$\text{AI} < 25\% \quad \rightarrow \text{mild drought.}$

$\rightarrow$ Infiltration

Infiltration is the method (or) process by which water get into surface strata of Earth to meet soil moisture deficiencies.

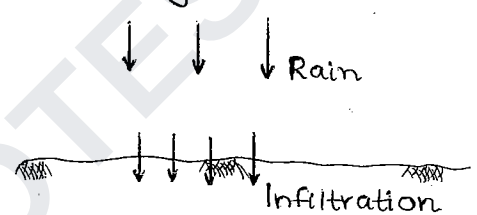
05. INFILTRATION

Infiltration is the method by which water get into surface strata of the Earth to meet soil moisture deficiency.

- After meeting the soil moisture deficiency if any excess water remain in the ground, flow vertically deep into the ground and join ground water table.
- Deep vertical movement of water in the ground is known as 'Precipitation'. 'Percolation'

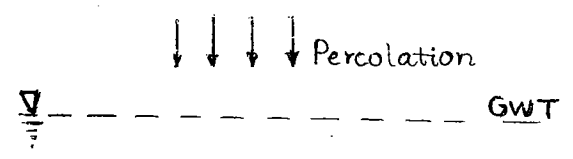
* Infiltration Capacity: (f_c)

It is the maximum rate at which soil is capable of absorbing water.



* Infiltration Rate: (f_a)

It is the actual rate of infiltration at a given time at a given place under specific conditions.



* Relation among f_a, f_c, i :

$$f_a = f_c \quad \text{when } i \geq f_c$$

$$f_a = i \quad \text{when } i < f_c$$

-23.

1. When $i < f_c$, $f_a < f_c$ or $f_a = i$

2. $f_c = 0.2 \text{ cm/hr.}$

$i = 0.5 \text{ cm/hr.}$

$$i > f_c \Rightarrow f_a = f_c = \underline{\underline{0.2 \text{ cm/hr}}}$$

→ Factors affecting Infiltration:

1. Porosity of Soil, (n)

$$f \propto n$$

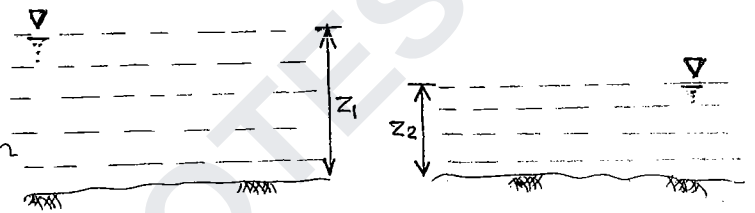
2. Moisture content of Soil, (mc)

$$f \propto \frac{1}{mc}$$

3. Depth of Surface retention, (z)

$$f \propto z$$

more depth $\Rightarrow$ more infiltration



4. Vegetation

$$f \propto \text{vegetative cover}$$

5. Compaction (due to men, animal, rain etc).

$$f \propto \frac{1}{\text{compaction}}$$

6. Washing of fines

$$f \propto \frac{1}{\text{washing of fines}}$$

7. Entrapment of air.

$$f \propto \frac{1}{\text{entrapment of air}}$$

8. Temperature

As temperature increases, viscosity decreases and resistance to flow decreases and infiltration increases.

$$f \propto \text{temperature.}$$

→ Measurement & Estimation of Infiltration :

1. Infiltrometer

- For field measurement of infiltration.

(i) Single Ring Infiltrometer

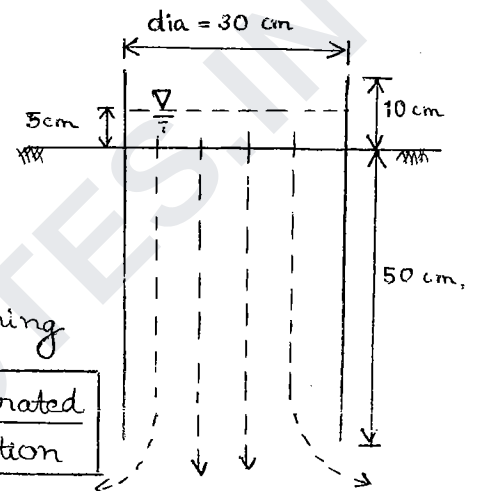
- Depth of water infiltrated
(infiltration)

$$= \frac{\text{vol. of water infiltrated}}{\text{c/s area of infiltrometer.}}$$

Volume of water infiltrated

$$= \text{volume of water added to ring}$$

$$\text{Infiltration rate} = \frac{\text{depth of water infiltrated}}{\text{duration of infiltration}}$$



- Test is conducted till constant infiltration rate is achieved.

- Single ring infiltrometer always overestimate because of lateral movement of water. To overcome this problem, double ring infiltrometers are used

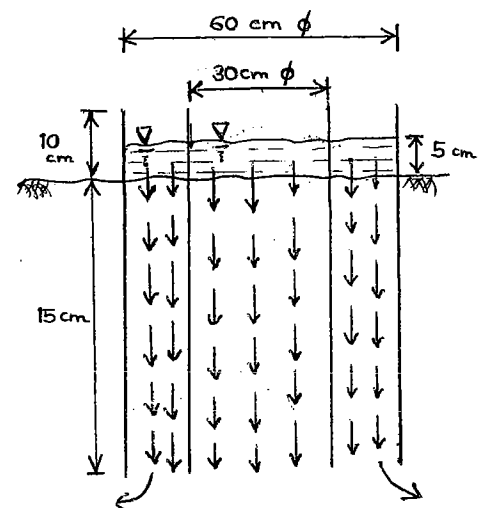
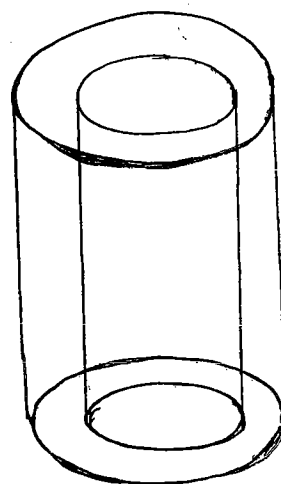
(ii) Double Ring Infiltrometer

Infiltration

$$= \frac{\text{vol. of water added to internal ring}}{\text{c/s area of internal ring}}$$

Infiltration rate

$$= \frac{\text{infiltration}}{\text{duration of infiltration}}$$



2. Rainfall Simulator

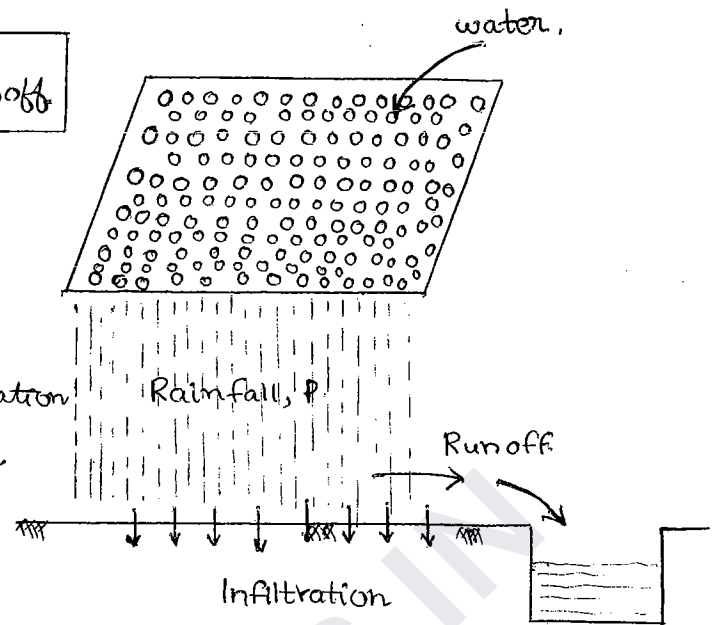
- laboratory measurement

- test plot of size 2m x 4m

$$\text{Infiltration} = \text{Rainfall} - \text{Runoff}$$

$$③ f_{(\text{infiltrometer})} > f_{(\text{rainfall simulator})}$$

As depth of retention increases in infiltrnometer, rate of infiltration is more in infiltrnometer compared to rainfall simulation.



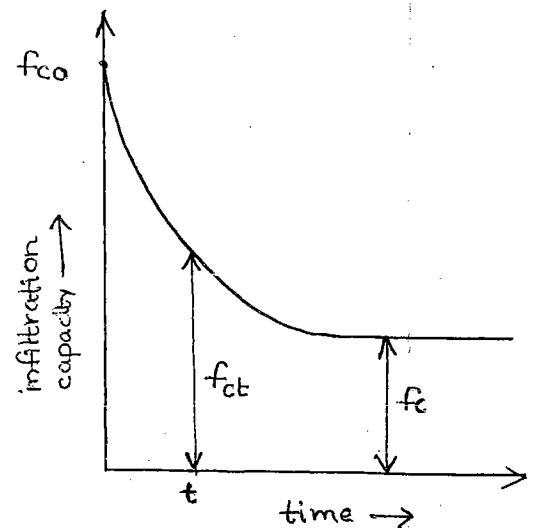
3. Horton's Infiltration Capacity Curve.

- Horton has conducted infiltration studies in his laboratory by simulating $i > f_c$ on different soils and concluded the following:

- (i) Infiltration capacity is more at the beginning of the storm and it exponentially decreases as storm duration increases
- (ii) It attain steady state at some point of time and remain in that state indefinitely.

(iii)

- The above diagram is obtained by plotting the observations of the test known as 'Horton's Infiltration Capacity Curve'.



$$f_{ct} = f_c + (f_{co} - f_c) e^{-kt}$$

Above equation represents the curve, where.

$f_{co} \rightarrow$ infiltration capacity at time $t=0$

$f_c \rightarrow$ steady state infiltration capacity.

$f_{ct} \rightarrow$ infiltration capacity at any time 't'

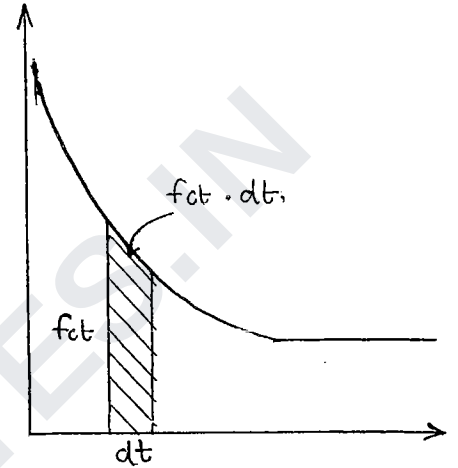
$k \rightarrow$ infiltration rate constant'

- using the Horton Infiltration Curve, total infiltration in given time 't' as well as infiltration b/w any two periods can be worked out along with actual rate of infiltration.

① Infiltration in time 'dt'

= Area under Horton's Infiltration Capacity Curve in time, 'dt'

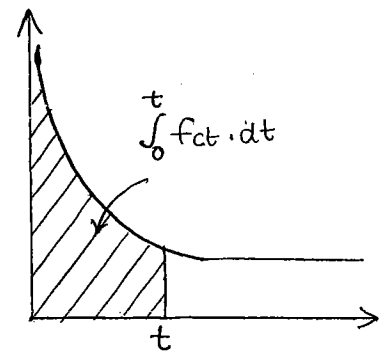
$$= f_{ct} \cdot dt$$



⇒ Total infiltration in time t

= Area under Horton's IC Curve upto time t.

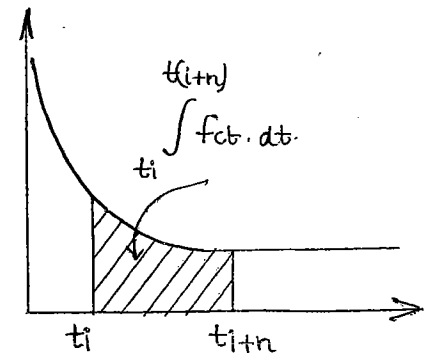
$$= \int_0^t f_{ct} \cdot dt$$



② Infiltration b/w time intervals

$$t_i \text{ \& \; } t_{i+n} = \int_{t_i}^{t_{i+n}} f_{ct} \cdot dt$$

= Area under Horton's IC Curve b/w time intervals t_i & t_{i+n} .



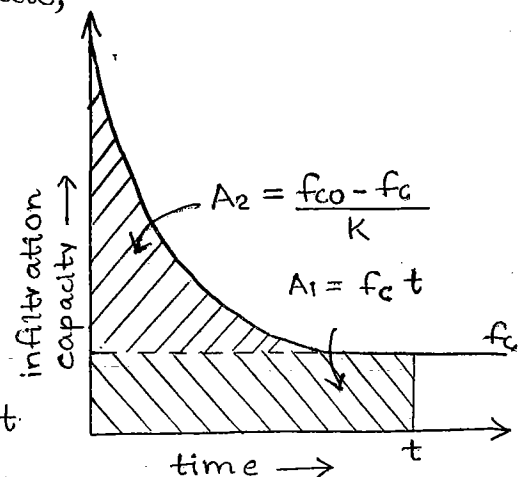
③ When Soil has attained steady state,

At any time, 't', $f_{ct} = f_c$

Total infiltration = area under IC Curve

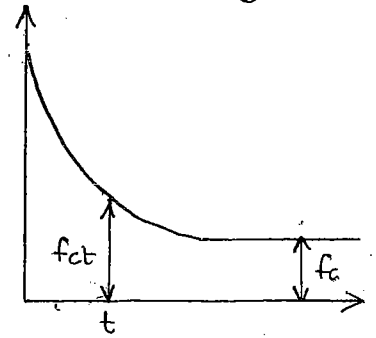
$$= A_1 + A_2$$

$$\left. \begin{array}{l} \text{Total infiltration} \\ \text{in time 't'} \end{array} \right\} = f_c t + \frac{f_{co} - f_c}{K} = \int_0^t f_{ct} dt$$



⊙ At any time t , $f_{ct} > f_c$, soil yet to attain steady state

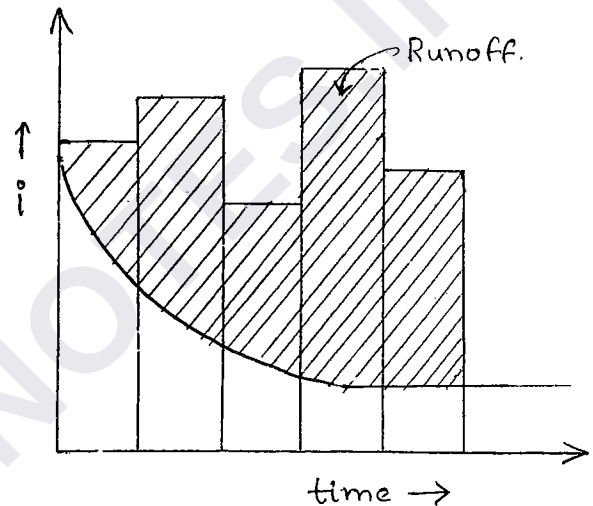
$$\text{Infiltration} = \int_0^t f_{ct} \cdot dt$$



- By superimposing, Horton's IC curve over Rainfall Hyetograph, along with infiltration, runoff can also be estimated.

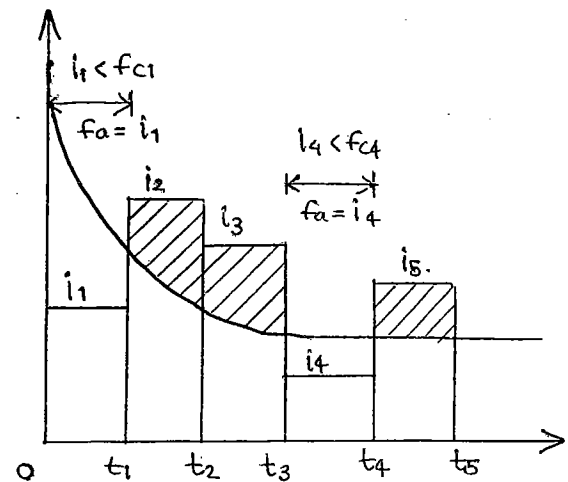
Run off = Area of Hyetograph.
above Horton IC Curve

$$\text{Runoff} = \sum_0^t i_i t_i - \int_0^t f_{ct} dt$$



$$\begin{aligned} \text{Total rainfall} = & i_1(t_1 - 0) + \\ & i_2(t_2 - t_1) + i_3(t_3 - t_2) \\ & + i_4(t_4 - t_3) + i_5(t_5 - t_4) \end{aligned}$$

$$\begin{aligned} \text{Total infiltration} = & i_1(t_1 - 0) + \\ & \int_{t_1}^{t_2} f_{ct} dt + i_4(t_4 - t_3) + \\ & \int_{t_4}^{t_5} f_{ct} dt \end{aligned}$$



2.23

03. $f_c = 1.34$, $f_0 = 7.62$, $k = 4.182$, $t = 2$ hours

$$\text{Infiltration at the end of 2 hours} = f_c t + \frac{f_0 - f_c}{k} \times$$

$$= 1.34 \times 2 + \frac{7.62 - 1.34}{4.182}$$

$$= \underline{\underline{4.182 \text{ cm}}}$$

04. $f_c = 0.5 \text{ cm/hour}$, $t = 8 \text{ hours}$.

$f_0 = 2 \text{ cm/hour}$; $K = 4 \text{ (hour)}^{-1}$

$$\text{Total infiltration during 8 hours} = f_c t + \frac{f_0 - f_c}{K}$$

$$= 0.5 \times 8 + \frac{2 - 0.5}{4}$$

$$= \underline{4.375 \text{ cm}}$$

05. Rainfall in 24 hours = 10 cm.

Pan evaporation in 24 hours = 0.6 cm.

Actual evaporation in 24 hours = $0.6 \times 0.7 = 0.42 \text{ cm}$.

Steady state has attained @ 15th hour:

$$f_{c0} = 1 \text{ cm/hr}, f_c = 0.3 \text{ cm/hr}$$

$$K = 5 \text{ (hr)}^{-1}$$

$$\text{Total infiltration in 24 hours} = 0.3 \times 24 + \frac{1 - 0.3}{5}$$

$$= 7.34 \text{ cm.}$$

$$\text{Run off} = \text{Rainfall} - (\text{infiltration} + \text{evaporation})$$

$$= 10 - (7.34 + 0.42) = 2.24 \text{ cm.}$$

$$\begin{aligned} \text{Volume of run off} &= 2.24 \times 10^{-2} \times 18 \times 10^6 \\ &= \underline{40320 \text{ m}^3} \end{aligned}$$

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th Dec,
SATURDAY

$$f_{ct} = 6 + 16 e^{-2t} \quad (f_{ct} = f_c + (f_{c0} - f_c) e^{-Kt})$$

$$f_c = 6 \text{ mm/hr}$$

$$f_{c0} - f_c = 16$$

$$\therefore f_{c0} = 16 + 6 = 22 \text{ mm/hr}$$

$$K = 2 \text{ hr}^{-1}$$

$$\text{Total infiltration in first 45 min} = \int_0^{0.75} (6 + 16e^{-2t}) dt.$$

$$= 10.715 \text{ mm}$$

Total Infiltration at 75 min (1.25 hours)

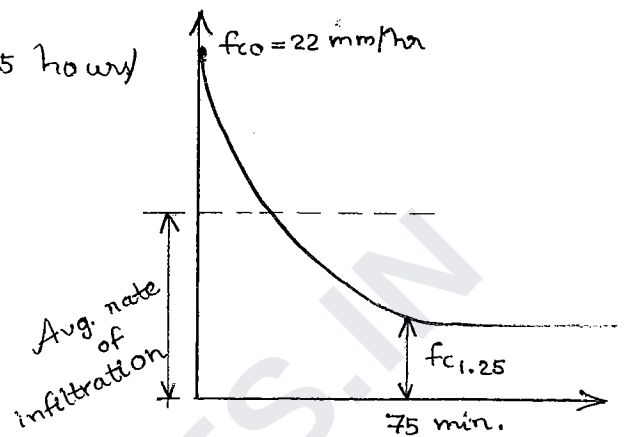
$$= 6 + 16e^{-2 \times 1.25}$$

$$= 7.31 \text{ mm/hr.}$$

Total infiltration in 1.25 hours.

$$= \int_0^{1.25} f_{ct} dt = \int_0^{1.25} (6 + 16e^{-2t}) dt$$

$$= 14.84 \text{ mm.}$$

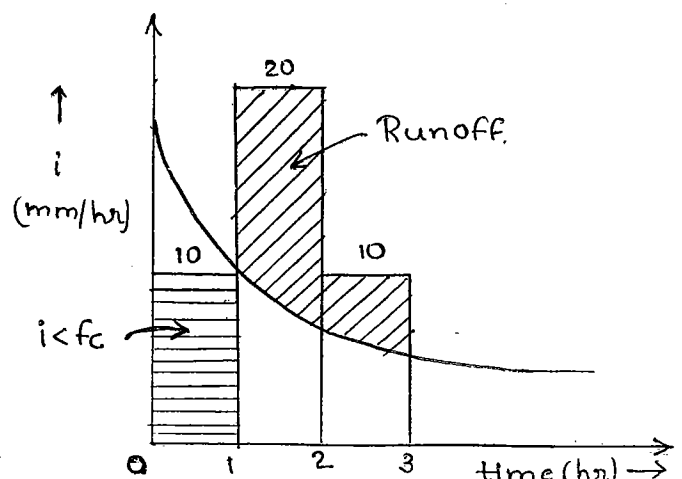


$\therefore$ Average infiltration rate for first 75 min = $\frac{\text{total infiltration}}{\text{time}}$

$$= \frac{14.844}{1.25} = 11.875 \text{ mm/hr}$$

07.	Time	i (mm/hr)	$f_{ct} = 6.8 + 8.7e^{-t}$ (mm/hr)	
	0	10	15.5	Horton's approach failed $i < f_c \Rightarrow f_a = i$
	1	20	10	
	2	10	7.97	Horton's approach is true. $i > f_c \Rightarrow f_a = f_{ci}$
	3	10	7.23	

Run off = Effective rain
 = Rainfall excess
 = Excess rainfall.
 = Net rain.



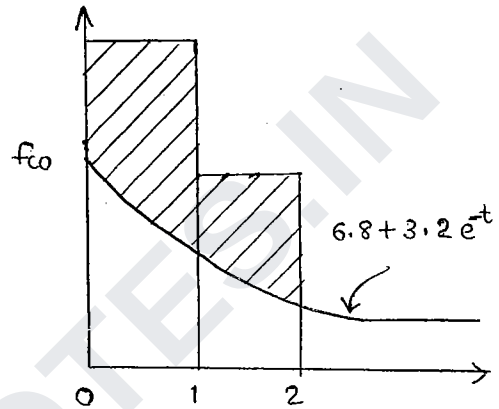
$$\text{Runoff} = \left. \begin{array}{l} \text{area of hyetograph} \\ \text{above IC curve} \end{array} \right\} = \sum_{i=1}^3 i_i \Delta t_i - \int_1^3 f_{ct} dt.$$

$$= 20 \times 1 + 10 \times 1 - \int_1^3 (6.8 + 8.7 e^{-t}) dt.$$

$$= 30 - 16.367 = \underline{\underline{13.633 \text{ mm}}}$$

(OR)

$$\begin{aligned} f_{ct} &= 6.8 + (10 - 6.8) e^{-t} \\ &= \underline{\underline{6.8 + 3.2 e^{-t}}} \end{aligned}$$



$$\text{Runoff} = \text{rainfall} - \text{infiltration}.$$

$$= 20 \times 1 + 10 \times 1 - \int_0^2 (6.8 + 3.2 e^{-t}) dt.$$

$$= \underline{\underline{13.63}}$$

Q. Rainfall over a basin. In 3 consecutive hours are 4 cm, 5 cm, 3 cm asptly. Estimate the surface runoff from basin assuming negligible surface retention and evaporation losses. Infiltration loss can be estimated using Horton's equation $f = 1.2 + 4.2 e^{-2.5t}$, where f is infiltration in cm/hr, t is time in hour from start of rainfall.

Time t	Rainfall intensity i (cm/hr).	$f_{ct} = 1.2 + 4.2 e^{-2.5t}$
-------------	------------------------------------	--------------------------------

0	}	_____	4
1		_____	
2	}	_____	5
3		_____	3

$$f_{c0} = 5.4$$

$$f_{c1} = 1.54$$

$$f_{c2} = 1.23$$

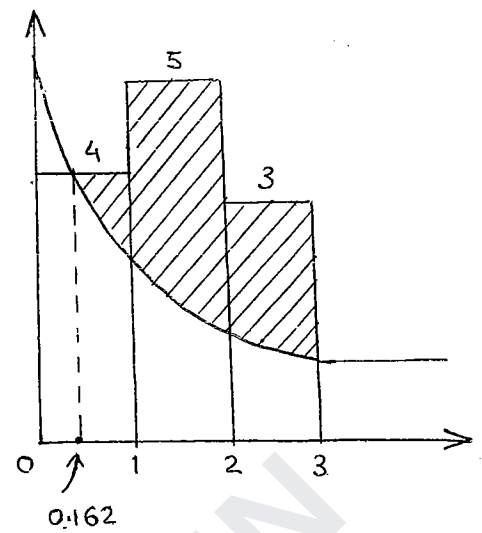
$$f_{c3} = 1.20$$

$$f_{ct} = 4 = 1.2 + 4.2 e^{-2.5t}$$

$$e^{-2.5t} = \frac{4 - 1.2}{4.2}$$

$$t = \frac{0.415}{2.5} = 0.162 \text{ hr.}$$

Runoff = area of hyetograph above IC Curve.



$$= \sum_{t=0.162}^3 i_t \Delta t - \int_{0.162}^3 f_{ct} \cdot dt$$

$$= (4 \times 0.838 + 5 \times 1 + 3 \times 1) - \int_{0.162}^3 (1.2 + 4.2 e^{-2.5t}) dt$$

$$= \underline{\underline{6.8627 \text{ cm}}}$$

08. $f_{co} = 10 \text{ mm/hr}$, $f_c = 1.2 \text{ mm/hr}$, $t = 10 \text{ hr}$.

$$\text{Total infiltration} = f_c t + \frac{f_{co} - f_c}{K}$$

$$33 = 1.2 \times 10 + \frac{10 - 1.2}{K}$$

$$\Rightarrow \underline{\underline{K = 0.42 \text{ hr}^{-1}}}$$

* Limitations of Horton's Approach:

1. True only for $i \geq f_c$
2. Applicable only for catchments with homogenous soil conditions.

→ Infiltration Indices:

(28)

(29)

Infiltration indices represents infiltration at an average rate.

- There are two infiltration indices:

1. ϕ index

ϕ index is the average rate of infiltration during the period of a storm at which there is runoff.

$$\phi \text{ index} = \frac{\text{infiltration during period of effective storm}}{\text{duration of effective storm.}}$$

Let P_e be the magnitude of effective storm.

t_e be the duration of effective storm.

R be the runoff.

$$\phi \text{ index} = \frac{P_e - R}{t_e}$$

2. ω index.

ω index is the average rate of infiltration during the entire period of a storm.

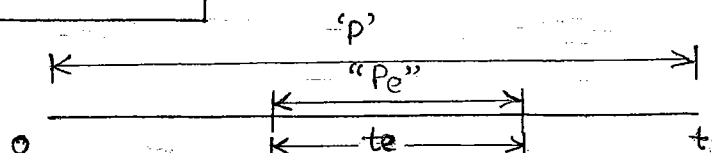
Let P be the total rainfall

t be the duration of total storm.

R be the runoff

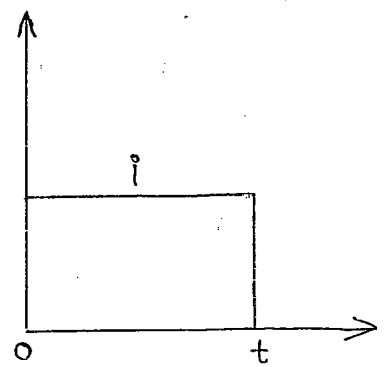
$$\omega \text{ index} = \frac{\text{total infiltration during storm}}{\text{duration of storm}}$$

$$\omega \text{ index} = \frac{P - R - \text{losses}}{t}$$



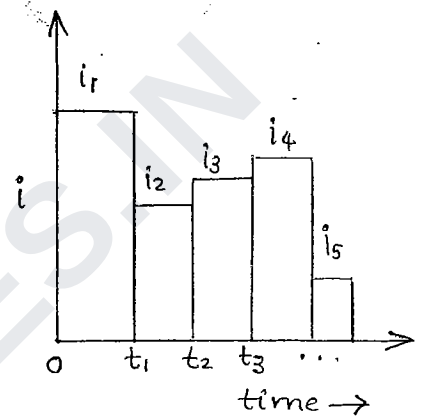
• For uniform rains, $P = P_e$
 $t = t_e$

$\Rightarrow \phi \text{ index} = \omega \text{ index.}$
 (neglecting losses).



• For non-uniform rains, $P > P_e$
 $t > t_e$

$\Rightarrow \phi \text{ index} > \omega \text{ index.}$



- When ϕ index line is superimposed over rainfall hyetograph, then, ϕ index is also defined as 'average rainfall intensity'; anything above which is runoff.

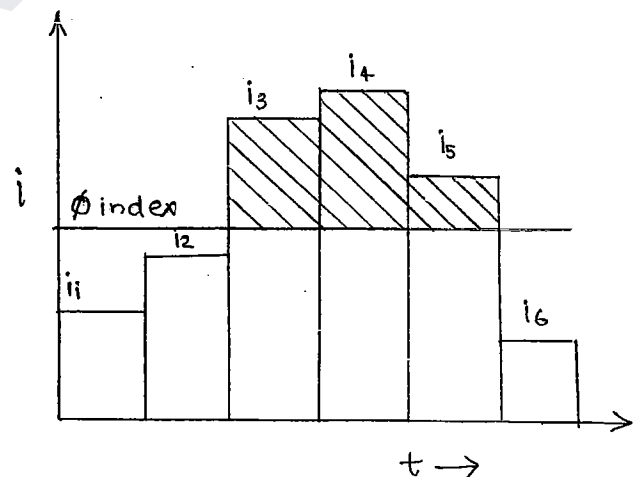
For the given example,

$$P = i_1 t_1 + i_2 t_2 + i_3 t_3 + i_4 t_4 + i_5 t_5 + i_6 t_6$$

$$P_e = i_3 t_3 + i_4 t_4 + i_5 t_5$$

$$t = t_1 + t_2 + t_3 + t_4 + t_5 + t_6$$

$$t_e = t_3 + t_4 + t_5$$



- Hyetograph lying above ϕ index is known as Effective Rainfall Hyetograph, 'ERH'

Runoff = Area of effective rainfall hyetograph.

$$\boxed{\text{Run off} = \sum (i_i - \phi) t_i} \quad ; \quad i_i > \phi \text{ index.}$$

9. ϕ index = 0.5 cm/hr Rainfall @ uniform storm, $P = P_e = 2$ cm. (26)
 $P = 2$ cm, $t = 6$ hour. (30)

$$\phi = \frac{P_e - R}{t}$$

$$0.5 = \frac{2 - R}{6} ; R = -1 \Rightarrow R = 0$$

whenever run off value is -ve, then equate it to zero.

10. Uniform intensity - uniform storm.

$$P = P_e \quad \& \quad t = t_e = 4 \text{ hour.}$$

$$P = P_e = i \times t = 2.8 \times 4 = 11.2 \text{ cm.}$$

$$\text{Volume of runoff} = 25.2 \times 10^6 \text{ m}^3.$$

$$\text{Catchment area} = 280 \text{ km}^2 = 280 \times 10^6 \text{ m}^2.$$

$$\begin{aligned} \text{Depth of runoff} &= \frac{\text{volume of runoff}}{\text{catchment area}} = \frac{25.2 \times 10^6}{282 \times 10^6} \\ &= 0.09 \text{ m} = \underline{\underline{9 \text{ cm}}} \end{aligned}$$

Average infiltration rate of ϕ index = ω index

$$\begin{aligned} &= \frac{P_e - R}{t_e} = \frac{11.2 - 9}{4} \\ &= \underline{\underline{5.5 \text{ mm/hour}}} \end{aligned}$$

11. 4 hour storm.

4 cm = rainfall.

$$\phi \text{ index} = \frac{P - R}{t_e} = \frac{4 - 2}{4} = 0.5 \text{ cm/hour.}$$

$$0.5 \text{ cm/hr} = \frac{10 - R}{8} \Rightarrow R = \underline{\underline{6.0 \text{ cm}}}$$

12. Storm 1

$$t_e = 5 \text{ hour.}$$

$$i = 2 \text{ cm/hour}$$

$$R = 4 \text{ cm}$$

Storm 2

$$t_e = 8 \text{ hour.}$$

$$R = 8.4 \text{ cm}$$

$$\phi \text{ index} = \frac{P-R}{t_e} = \frac{5 \times 2 - 4}{5} = \underline{\underline{1.2 \text{ cm/hr}}}$$

13.

Storm II:

$$\phi \text{ index} = \frac{P-R}{t_e}$$

$$P = 1.2 \times 8 + 8.4 = 18 \text{ cm}$$

$$i = \frac{18}{8} = 2.25 \text{ cm/hour}$$

14.

$$P = 7 \times 1 + 18 \times 1 + 25 \times 1 + 17 \times 1 + 11 \times 1 + 3 \times 1$$

$$= 81 \text{ mm.}$$

$$R = 39 \text{ mm.}$$

$$\phi \text{ index} = \frac{P-R}{t} = \frac{81-39}{6} = \underline{\underline{7 \text{ mm/hr}}}$$

15.

$$P = 1.6 \times 0.5 + 3.6 \times 0.5 + 5 \times 0.5 + 2.8 \times 0.5 + 2.2 \times 0.5 + 1 \times 0.5$$

$$= 8.1 \text{ cm.}$$

$$\phi \text{ index} = \frac{P-R}{t} = \frac{8.1-3.6}{3} = \underline{\underline{1.5 \text{ cm/hr}}}$$

14.

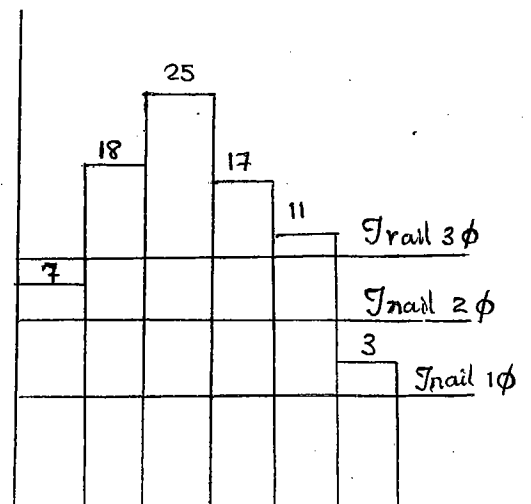
Trail 1: Assuming $\phi \text{ index} < 3 \text{ mm/hr.}$

$$\text{Run off} = \sum (i - \phi) t_i \rightarrow i_1 > \phi$$

$$39 = (7 - \phi) + (18 - \phi) + (25 - \phi) + (17 - \phi) +$$

$$(11 - \phi) + (3 - \phi)$$

$$\phi = \frac{81-39}{6} = 7 \text{ mm/hr (assumption failed)}$$



Trail 2: Assuming $3 < \phi < 7$ mm/hr

29
31

$$\text{Run off} = \sum (i_i - \phi) t_i \rightarrow i_i > \phi$$

$$39 = (7 - \phi) + (18 - \phi) + (25 - \phi) + (17 - \phi) + (11 - \phi)$$

$$\phi = \frac{79 - 39}{5} = 7.8 \text{ mm/hr} \Rightarrow \text{assumption failed.}$$

Trail 3: Assuming $7 < \phi \text{ index} < 11$ mm/hr.

$$\text{Run off} = \sum (i_i - \phi) t_i \rightarrow i_i > \phi \text{ index.}$$

$$39 = (18 - \phi) + (25 - \phi) + (17 - \phi) + (11 - \phi)$$

$$\phi = \underline{8 \text{ mm/hr}}$$

(OR)

$$P = \sum P_i t_i = 7 \times 1 + 18 \times 1 + 25 \times 1 + 11 \times 1 + 3 \times 1 \\ = 81 \text{ mm.}$$

$$t = 6 \text{ hour.}$$

$$W \text{ index} = \frac{P - R - \text{losses}}{t} = \frac{81 - 39}{6} = \underline{7 \text{ mm/hr}}$$

To find P_e & t_e , neglect $i_i \leq W \text{ index}$:

$$\therefore P_e = 18 \times 1 + 25 \times 1 + 17 \times 1 + 11 \times 1 = 71 \text{ mm}$$

$$t_e = 4 \text{ hours}$$

$$\phi \text{ index} = \frac{71 - 39}{4} = \underline{8 \text{ mm/hr}}$$

$$P = \sum P_i t_i = 1.6 \times 0.5 + 3.6 \times 0.5 + 5 \times 0.5 + 2.8 \times 0.5 + 2.2 \times 0.5 + 1 \times 0.5 \\ = 8.1 \text{ cm/hr.}$$

$$t = 3 \text{ hour.}$$

$$W \text{ index} = \frac{8.1 - 3.6}{3} = 1.5 \text{ cm/hour.}$$

$\phi \text{ index}$: to find P_e & t_e neglect $i \leq W \text{ index}$

$$P_e = 1.6 \times 0.5 + 3.6 \times 0.5 + 5 \times 0.5 + 2.8 \times 0.5 + 2.2 \times 0.5$$

$$= 7.6 \text{ cm/hour}$$

$$t_e = 3 - 0.5 = 2.5 \text{ hour.}$$

$$\phi \text{ index} = \frac{7.6 - 3.6}{2.5} = \underline{\underline{1.6 \text{ cm/hr}}}$$

16. $P = 1.6 + 5.4 + 4.1 = 11.1$

$$w \text{ index} = \frac{P - R - L}{t} = \frac{11.1 - 4.7 - 0.6}{24} = \underline{\underline{0.242 \text{ cm/hr}}}$$

$$i_1 = \frac{1.6}{8} = \underline{\underline{0.2 \text{ cm/hr}}} \quad i_2 = \frac{5.4}{8} = \underline{\underline{0.675 \text{ cm/hr}}}$$

$$i_3 = \frac{4.1}{8} = 0.5125 \text{ cm/hr}$$

Neglect i_1 because $i_1 < w \text{ index}$.

$$P = 0.675 \times 8 + 0.5125 \times 8 = 9.5 \text{ cm}$$

$$t = 16 \text{ hours.}$$

$$\phi \text{ index} = \frac{P - R}{t} = \frac{9.5 - 4.7}{16} = \underline{\underline{0.3 \text{ cm/hr}}}$$

17. $w \text{ index} = \frac{P - R}{t} = \frac{(0.5 + 2.8 + 1.6) - 3.2}{2 + 2 + 2} = \underline{\underline{0.283 \text{ cm/hr}}}$

$$i_1 = \frac{0.5}{2} = 0.25 \text{ cm/hr}$$

$$i_2 = \frac{2.8}{2} = 1.4 \text{ cm/hr}$$

$$i_3 = \frac{1.6}{2} = 0.8 \text{ cm/hr.}$$

$$P = 1.4 \times 2 + 0.8 \times 2 = 4.4.$$

$$t_e = 2 + 2 = 4$$

$$\phi \text{ index} = \frac{P - R}{t} = \frac{4.4 - 3.2}{4} = \underline{\underline{0.3 \text{ cm/hr}}}$$

18. $\phi \text{ index} = 10 \text{ mm/hour.}$

Time	Rainfall (mm)	i (mm/hr) = P/t
0-1	9	9
1-2	28	28
2-3	12	12
3-4	7	7

$$\phi \text{ index} = \frac{P - R}{t}$$

$$10 = \frac{28 + 12 - R}{2}$$

$$\Rightarrow R = \underline{\underline{20 \text{ mm}}}$$

19 Total $P = 3 + 8 + 12 + 6 + 2 = \underline{\underline{31 \text{ cm}}}$

$$w \text{ index} = \frac{P - R}{t} = \frac{31 - 15}{24 \times 5} = 0.1333 \text{ cm/hr.}$$

$$i_1 = \frac{3}{24} = 0.125 \text{ cm/hr.} \quad i_4 = \frac{6}{24} = 0.25 \text{ cm/hr.}$$

$$i_2 = \frac{8}{24} = 0.33 \text{ cm/hr.} \quad i_5 = \frac{2}{24} = 0.0833 \text{ cm/hr.}$$

$$i_3 = \frac{12}{24} = 0.5 \text{ cm/hr}$$

Neglecting $i_1 \leq w \text{ index}$,

$$P = 8 + 12 + 6 = 26 \text{ cm}$$

$$\phi \text{ index} = \frac{P - R}{t} = \frac{26 - 15}{24 \times 5} = 0.153 \text{ cm/hr} \\ = \underline{\underline{1.53 \text{ mm/hr.}}}$$

WWW.GATENOTES.IN

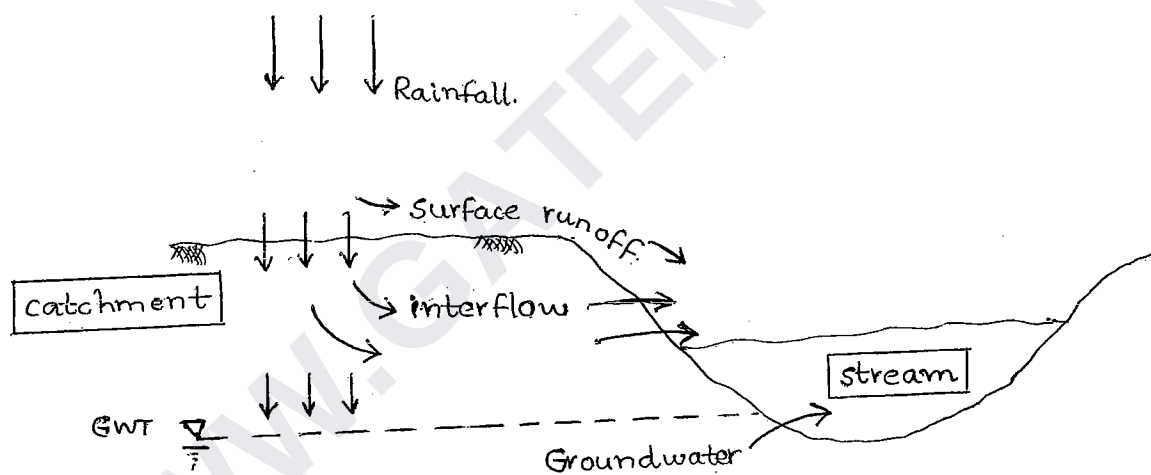
06. RUNOFF

Run off is that portion of a rain which ultimately joins streams and rivers.

- It is an output produced by the catchment for a given input rainfall.

→ Components of Runoff

1. Surface Runoff (Overland Flow)
2. Subsurface Runoff (Interflow)
3. Groundwater



* Based on time delay in joining the runoff into stream:

(i) Direct Runoff.

Runoff without much delay in joining the stream.

(ii) Base flow

Runoff which take its own time; i.e. late joining runoff.

- Direct Runoff includes:

- a) Surface Runoff
- b) Prompt Interflow.
- c) Channel Precipitation.

- Base Flow includes:

- a. Delayed interflow.
- b) Groundwater flow.

→ Classification of Streams:

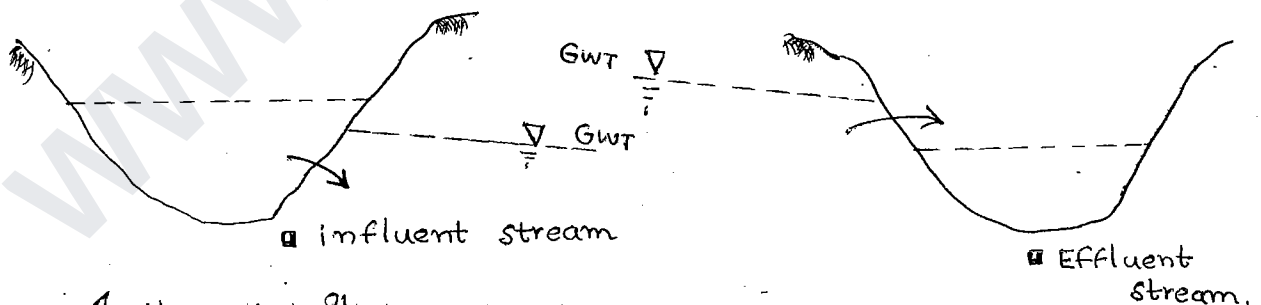
- Based on availability of flow in stream:-

- (i) Perennial Streams
- (ii) Non perennial Streams.
- (iii) Ephemeral Streams (shortlived (or) temporary streams)

- Based on contribution of ground to stream (or) stream to ground.

(i) Effluent Stream.

When ground contribute flow to stream.

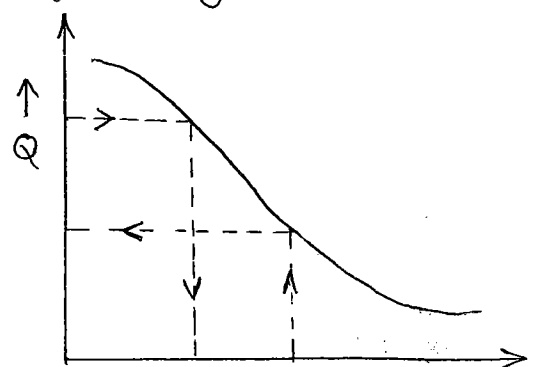


(ii) Influent Stream.

When stream contribute flow to groundwater.

* Flow Duration Curve.

x axis: % times flow equals
(or) exceeds.



→ Methods to Estimate Run off

33
34

1. Rainfall & Runoff relation (regression analysis)
2. Empirical Procedures.

Eg :- Binny's Percentages - used for catchments in Vidarbha & MP.

Barlow's Tables - for catchments in UP.

Strange Tables - for catchments in Karnataka & Maharashtra.

3. Watershed Simulation

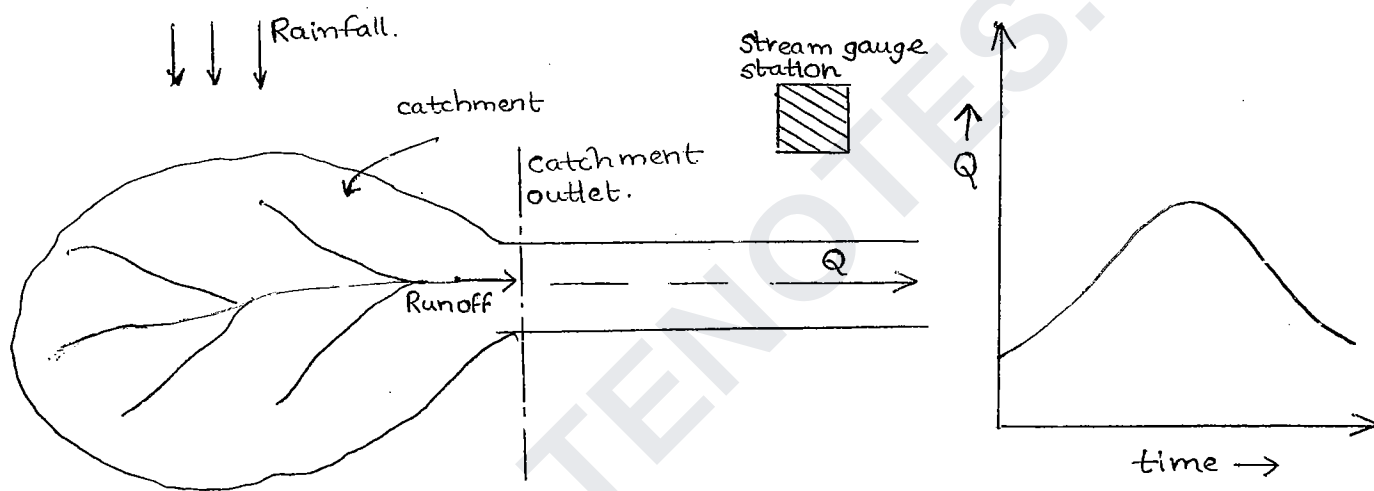
$$R = P - E - T - ET - I$$

4. Horton's Infiltration Capacity Curves
5. Infiltration Indices.
6. Hydrographs.

07. HYDROGRAPHS

Hydrograph is a plot between discharge versus time.

- Hydrograph shows time distribution of runoff.
- Hydrograph is the measure of response of catchment for a given storm.



1. Storm Hydrograph (or) Flood Hydrograph. (or)

Total Runoff Hydrograph (SHG (or) FHG (or) TRH)

A storm of certain duration if it occurs over a catchment after meeting the catchment losses, the rainfall excess (runoff) delivered into stream, then it results into stream flow variation. If stream flow variation is measured at a point in a stream, the resulting plot is known as 'Storm Hydrograph' (or) 'Flood Hydrograph' (or) 'Total Runoff Hydrograph'.

OA $\rightarrow$ approach segment

AB $\rightarrow$ rising limb.

BD $\rightarrow$ crest segment.

DE $\rightarrow$ recession limb (or)
falling limb.

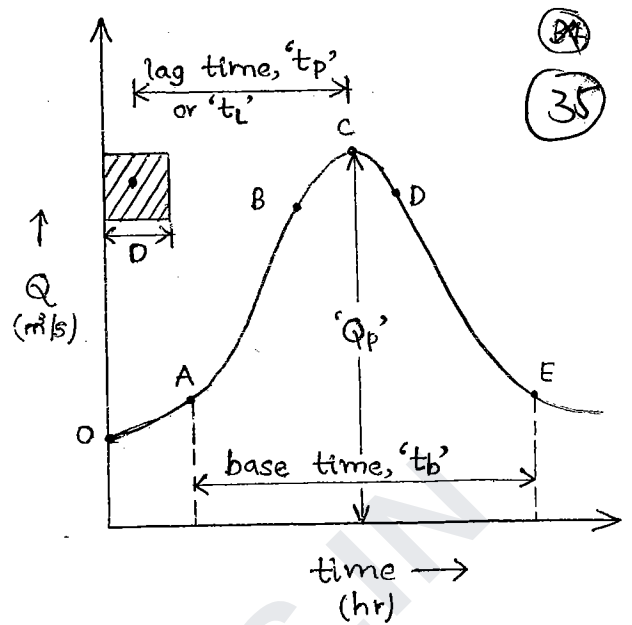
A : Point of rise.

B & D : Inflection point.

C : Peak point.

D : End of overland flow.

E : End of direct runoff.



* factors affecting hydrograph:

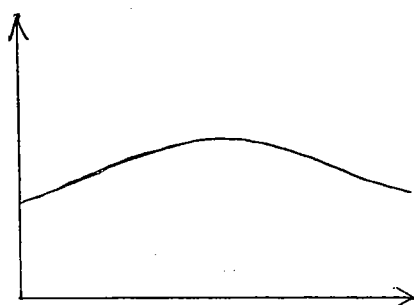
(i) Catchment factors -

- Size of Catchment
- Shape of Catchment
- Slope of catchment.
- Drainage density.

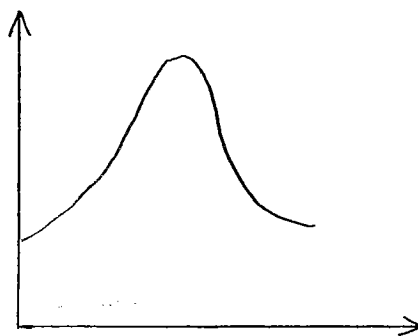
(ii) Storm factors -

- Duration of storm
- Intensity of storm
- Direction of storm.

- For small catchment, overland flow $>$ channel flow.
- land use pattern influences shape of hydrograph.

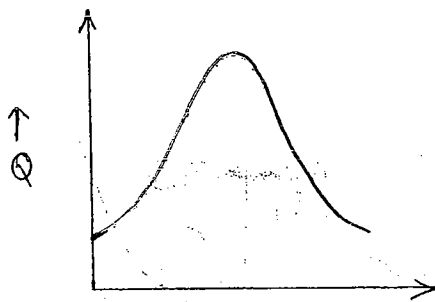


■ catchment with vegetation

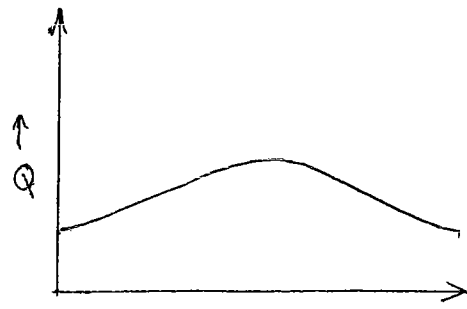


■ catchment without vegetation.

- For large catchments, channel flow > overland flow.



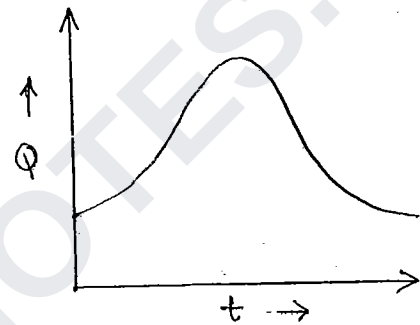
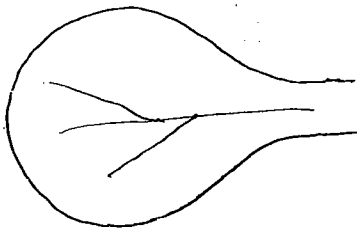
■ steep channel



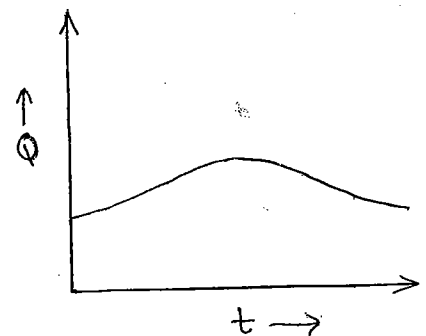
■ flat channel.

- Based on shape, catchments are classified as:

a) Fan shaped catchment

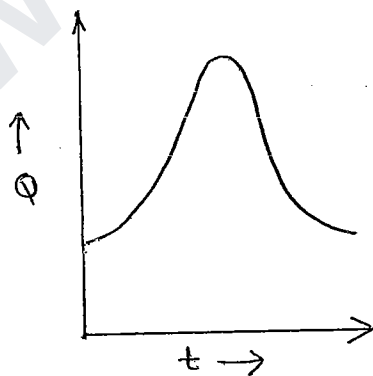


b) Fern shaped catchment

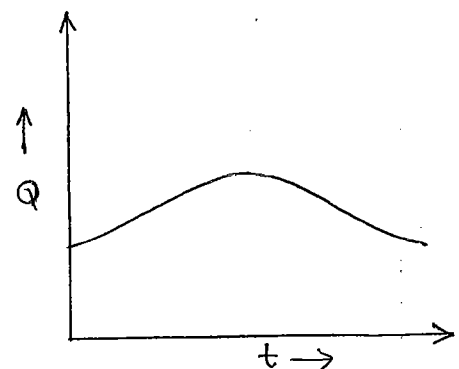


- Slope of catchment classifies catchments into:

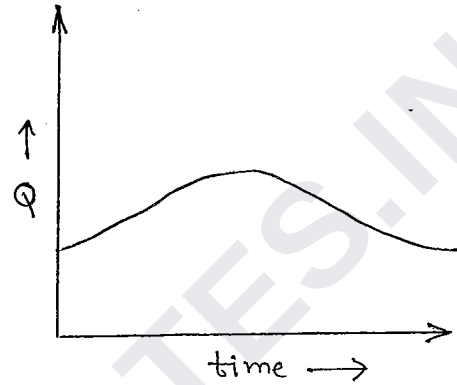
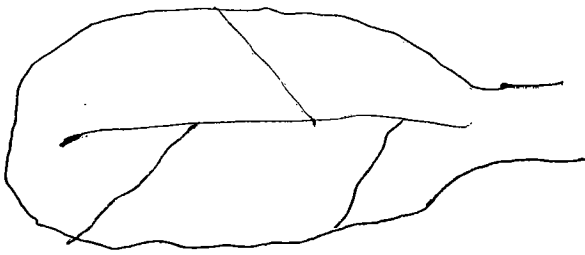
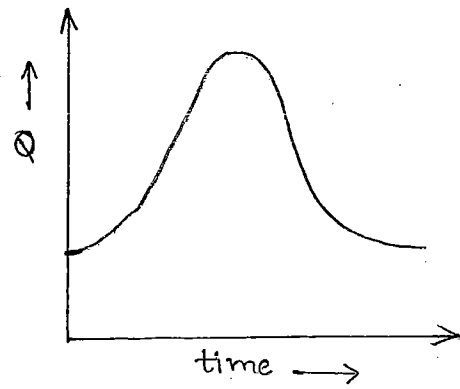
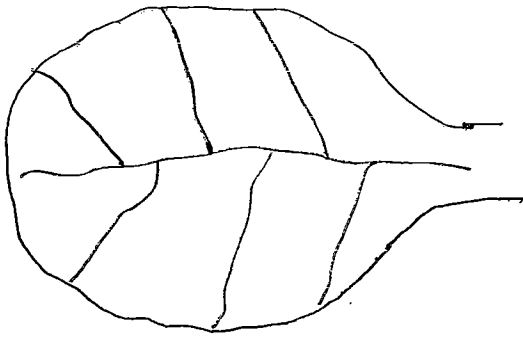
a) Steep Catchment



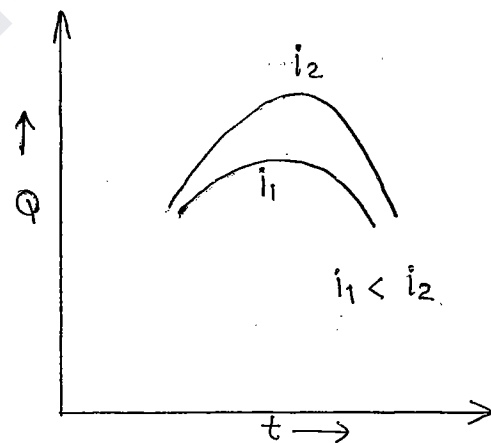
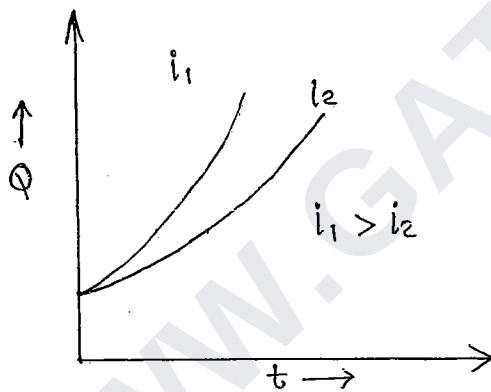
b) Flat catchment.



- Drainage density = $\frac{\text{total length of channels}}{\text{catchment area}}$



- Intensity of rain influences rising limb and crest segment.



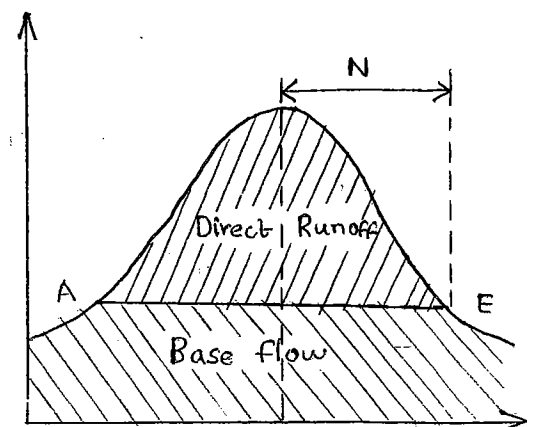
⊙ Rising limb & crest segments are influenced by storm factors and catchment factors but recession limb is influenced by catchment factors only.

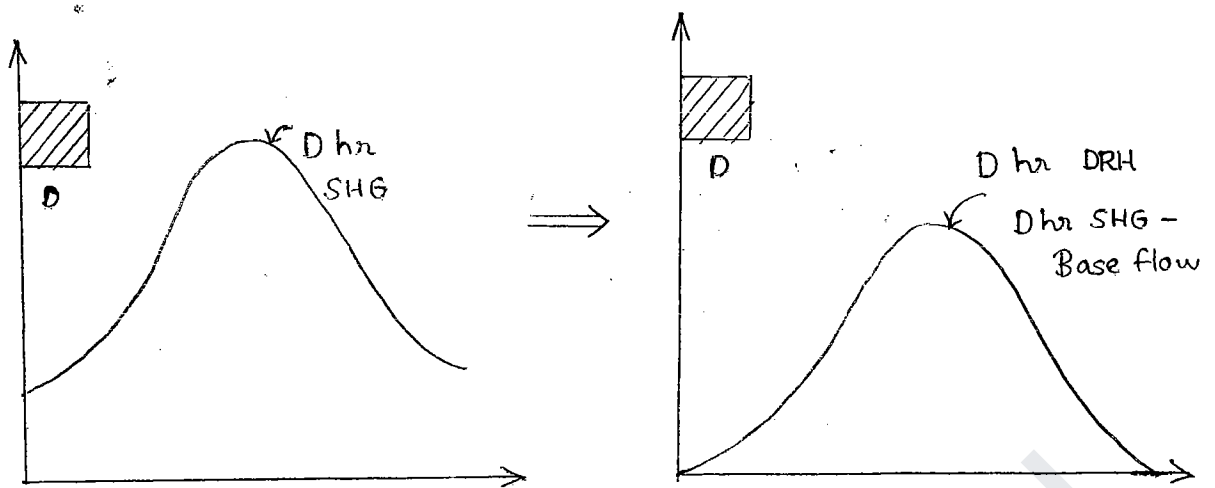
* Base flow Separation:

$$N = 0.83 (A)^{0.2}$$

where,

A → catchment area (in km²)

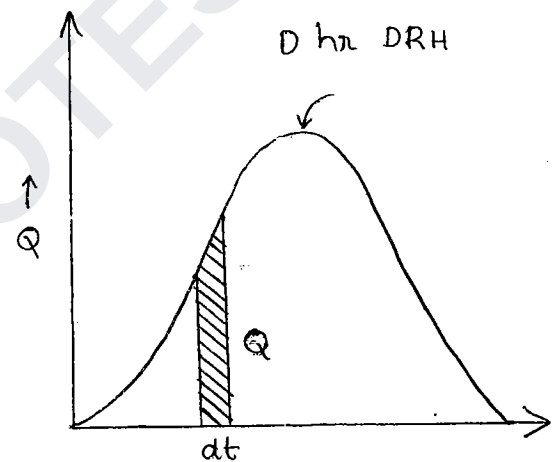




→ Runoff estimation using Direct Runoff Hydrograph (DRH)

D hr DRH obtained from the D hr SHG is used in finding the runoff resulting from a catchment of area 'A' km².

(A storm of D hr duration if it occur over a catchment area A km² yield D hr SHG. After subtracting base flow from D hr SHG, then D hr DRH is obtained)



- Volume of runoff drained into stream by the catchment in time interval 'dt' = $Q \cdot dt$

= area under D hr DRH in time period 'dt'

- Total volume of runoff = area under D hr DRH

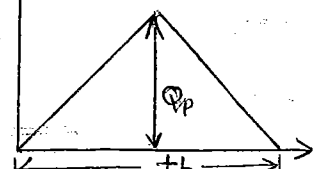
$$\text{Depth of runoff} = \frac{\text{Volume of Runoff}}{\text{Catchment area.}}$$

NOTE :

1. If D hr DRH is in the form of a triangle,

Volume of Runoff = area of DRH.

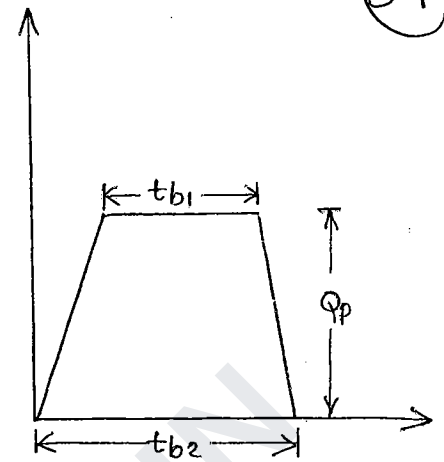
$$= \frac{1}{2} \times Q_p \times t_b$$



2. If Dhr DRH is in trapezoidal form,

Volume of Runoff = area of Dhr DRH.

$$= \left[\frac{tb_1 + tb_2}{2} \right] \times Q_p$$



3. If Dhr DRH is non linear,

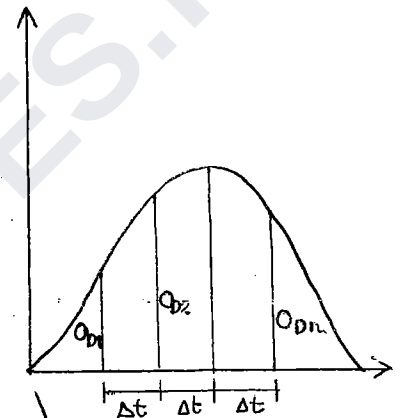
Area of non linearly shaped hydrograph can be worked out by finite integration method using Trapezoidal Rule.

Volume of Runoff = area of Dhr DRH

$$= \Delta t \left(\frac{\text{1st ord} + \text{last ord}}{2} + \sum \text{remaining ordinates} \right)$$

$$= \Delta t \left(\frac{0+0}{2} + \sum \text{Remaining ordinates} \right)$$

$$= \Delta t (O_{D1} + O_{D2} + O_{D3} + \dots + O_{Dn})$$



-34.

1. Catchment area = 1440 km².

$$\text{Volume of run off} = \frac{1}{2} \times 200 \times 3600 \times 80$$

$$\text{Depth of runoff} = \frac{0.5 \times 200 \times 3600 \times 80}{1440 \times 1000^2} = 0.02 \text{ m} = \underline{\underline{2 \text{ cm}}}$$

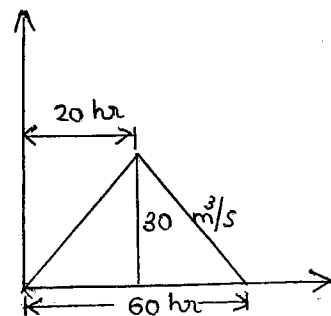
2

Catchment area = 300 km².

$$\text{Volume of runoff} = \frac{1}{2} \times 30 \times 60 \times 60 \times 60 \text{ m}^3$$

$$\text{Depth of runoff} = \frac{\frac{1}{2} \times 30 \times 3600 \times 60}{300 \times 1000^2}$$

$$= 0.0108 \text{ m} = \underline{\underline{10.8 \text{ mm}}}$$

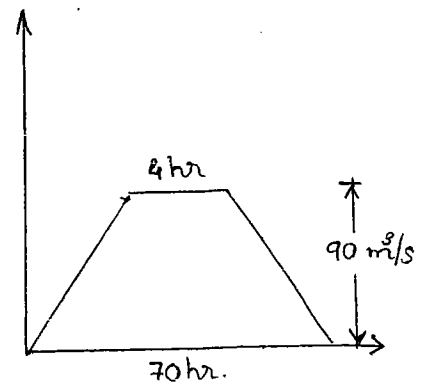


3. Volume of runoff = area of DRH.

$$= \left(\frac{4+70}{2} \right) \times 90 \times 3600$$

Effective rainfall = runoff

$$= 2 \text{ cm.}$$



Catchment area = $\frac{37 \times 90 \times 3600}{0.02 \times 10^6} = 599.4 \text{ km}^2$

4. Area of DRH = $A_1 + A_2 + A_3 + A_4 + A_5$.

$$A_1 = \frac{1}{2} \times 10 \times 10 \times 3600$$

$$A_2 = \left(\frac{10+70}{2} \right) \times 10 \times 3600$$

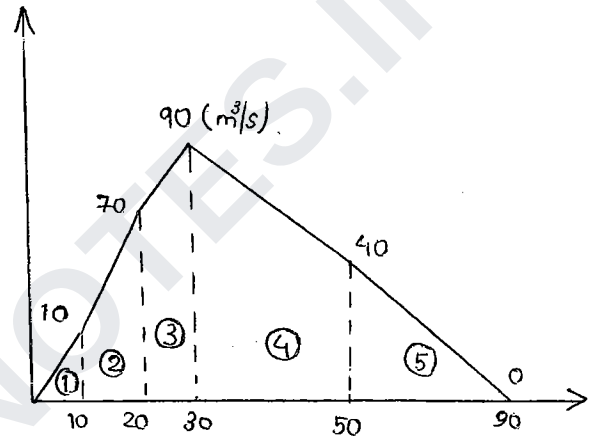
$$A_3 = \left(\frac{70+90}{2} \right) \times 10 \times 3600$$

$$A_4 = \left(\frac{90+40}{2} \right) \times 20 \times 3600$$

$$A_5 = \frac{1}{2} \times 40 \times 40 \times 3600$$

Volume of runoff = area of DRH = $12.06 \times 10^6 \text{ m}^3$.

Rainfall excess = $\frac{12.06 \times 10^6}{300 \times 10^6} = 0.0402 \text{ m} = \underline{\underline{4.02 \text{ cm}}}$



5. $Q_p = 10 \text{ m}^3/\text{s}$; $t_b = 20 \text{ hr}$, area of catchment = 10 km^2 .

Volume of runoff = $\frac{1}{2} \times Q_p \times t_b$.

$$= \frac{1}{2} \times 10 \times 3600 \times 20$$

Rainfall excess = $\frac{\frac{1}{2} \times 10 \times 3600 \times 20}{10 \times 10^6} = 0.036 \text{ m} = \underline{\underline{3.6 \text{ cm}}}$

6. time (hr).	0	6	12	18	24	30	36
4 hr FHG ordinates (m^3/s)	6	18	30	24	12	8	6
Base flow (m^3/s).	6	6	6	6	6	6	6
4 hr DRH ordinates = 4 hr FHG - base flow.	0	12	24	18	6	2	0

Volume of runoff = area of 4 hr DRH.

$$= 6 \times 60 \times 60 (12 + 24 + 18 + 6 + 2)$$

$$= 1.3392 \times 10^6 \text{ m}^3$$

$$\text{Rainfall excess} = \frac{1.3392 \times 10^6 \times 10^2}{50 \times 10^6} = \underline{\underline{2.67 \text{ cm}}}$$

2. Unit Hydrograph (UH)

Unit Hydrograph is a direct runoff hydrograph produced by a uniform storm of certain duration resulting into a runoff depth of unity (1 cm) uniformly over the entire catchment.

- Concept was proposed by 'Sherman' based on following two assumptions:

(i) Time invariance.

(ii) Linear Response.

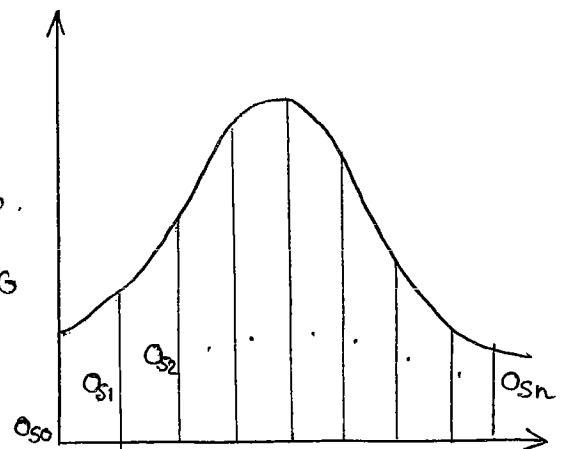
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→ Construction of D hr UHG from the given D hr SHG:

Let $O_{s0}, O_{s1}, \dots, O_{sn}$ be the ordinates of D hr SHG @ respective time interval. and 'B' be the base flow.

1) Construct D hr DRH from D hr SHG

D hr DRH ordinates = D hr SHG ordinates - base flow.



⇒ Ordinates of D hr DRH are:

$$O_{D0} = O_{s0} - B, \quad O_{D1} = O_{s1} - B, \quad \dots, \quad O_{Dn} = O_{sn} - B$$

2) Find volume of runoff resulting from storm.

Volume of runoff = area of DRH.

$$= \Delta t \left(\frac{O_0 + O_n}{2} + \sum \text{remain ordinates} \right).$$

3) Find depth of runoff, 'R' produced by the storm.

$$R = \frac{\text{Volume of Runoff}}{\text{Catchment area}}.$$

4) Construct Dhr UHG by dividing the ordinates of Dhr DRH by 'R'.

$$\text{Dhr UHG Ordinates} = \frac{\text{Dhr DRH ordinates}}{R}$$

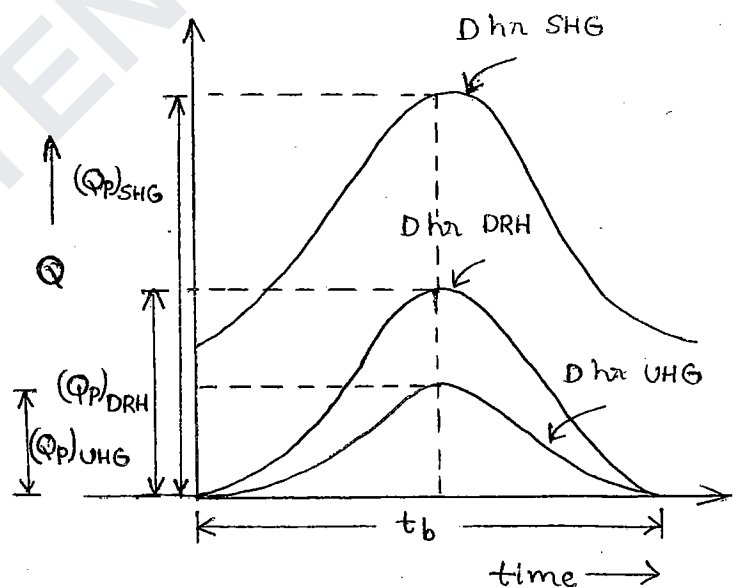
⇒ Ordinates of Dhr UHG:

$$O_{u0} = \frac{O_{d0}}{R}$$

$$O_{u1} = \frac{O_{d1}}{R}$$

⋮

$$O_{un} = \frac{O_{dn}}{R}$$



7 Volume of runoff = area of UHG

$$= 0.5 \times 300 \times 48 \times 3600$$

$$\text{Catchment area} = \frac{0.5 \times 300 \times 48 \times 3600}{10^{-2} \times 10^6} = \underline{\underline{2592 \text{ km}^2}}$$

08. $t_b = 20 \text{ hr.}$, Area of watershed = $500 \times 10^4 \text{ m}^2$.

$$\frac{1}{2} \times 20 \times Q_p = 500 \times 10^4 \times 10^{-2} \Rightarrow Q_p = \underline{\underline{5000 \text{ m}^3/\text{hr}}}$$

9. $Q_p = 100 \text{ m}^3/\text{s}$, $t_b = 72 \text{ h}$

$$\text{Area of catchment} = \frac{\frac{1}{2} \times 100 \times 3600 \times 72}{10^{-2} \times 10^6} = \underline{\underline{1296 \text{ km}^2}}$$

(39)

10. For 2 hr UHG, $t_b = 40 \text{ hr}$, $Q_p = 10 \text{ m}^3/\text{s}$

$$\text{Area of catchment} = \frac{0.5 \times 40 \times 10 \times 3600}{10^{-2} \times 10^6} = 72 \text{ km}^2$$

For 6 hr UHG, $t_b = 44 \text{ hr}$, Area = $72 \times 10^6 \text{ m}^2$.

$$\frac{1}{2} \times Q_p \times 44 = 72 \times 10^6 \times 10^{-2}$$

$$\Rightarrow \underline{\underline{Q_p = 9.09 \text{ m}^3/\text{s}}}$$

11. For 1st catchment area,

$$A = 235 \text{ km}^2$$

$$Q_p = 30 \text{ m}^3/\text{s}$$

$$\frac{1}{2} \times t_b \times 30 \times 3600 = 235 \times 10^6 \times 10^{-2}$$

$$\underline{\underline{t_b = 43.52 \text{ hour}}}$$

For 2nd catchment area,

$$Q_p = 90 \text{ m}^3/\text{s}$$

$$t_b = 43.52 \text{ hour.}$$

$$\text{Area of catchment} = \frac{\frac{1}{2} \times 90 \times 3600 \times 43.52}{10^{-2} \times 10^6} = \underline{\underline{705 \text{ km}^2}}$$

12.

Time (hr)	0	12	24	36	48	60	72	84	96
Ordinates of SHG (m^3/s)	10	87.5	102.5	71	47.5	31	21	15	12
Base flow (m^3/s)	10	10	10	11	11.5	11.5	12	12	12
Ordinates of DRH	0	77.5	92.5	60	36	19.5	9	3	0
Ordinates of UHG	0	25.51	30.44	19.7	11.85	6.42	2.96	0.99	0

$= O_{DR} / 3.034$

$$\text{Runoff} = \frac{12 \times 3600 (77.5 + 92.5 + 60 + 36 + 19.5 + 9 + 3 + 0)}{423 \times 10^6}$$

$$= 3.04 \text{ cm} = 0.0304 \text{ m}$$

$$(i) \text{ Peak ordinate of 6 hr unit hydrograph} = \frac{92.5}{3.04} = \underline{\underline{30.5 \text{ m}^3/\text{s}}}$$

$$(ii) \text{ Duration of storm} = 6 \text{ hour}$$

$$\text{Uniform storm} \Rightarrow t = t_e = 6 \text{ hr}$$

$$i = 1.5 \text{ cm/hr}$$

$$\phi \text{ index} = 0.4 \text{ cm/hr}$$

$$P = P_e * = i \times t = 1.5 \times 6 = \underline{\underline{9 \text{ cm/hr}}}$$

$$\phi \text{ index} = \frac{P_e - R}{t_e} \Rightarrow 0.4 = \frac{9 - R}{6}$$

$$\therefore R = 6.6$$

$$\text{Peak ordinate 6 hr UHG} = 30.5 \text{ m}^3/\text{s}$$

$$\begin{aligned} \text{Peak ordinate of 6 hr DRH} &= \text{Peak ordinate of 6 hr UHG} \times R \\ (R = 6.6 \text{ cm}) &= 30.5 \times 6.6 = \underline{\underline{201.3 \text{ m}^3/\text{s}}} \end{aligned}$$

13.

Time (hr)	0	1	2	3	4	5	6
UHG ordinates	0	5	15	12	10	6	0

$$P = P_e = 4.2 \text{ cm}; t_e = 2 \text{ hour}, \phi \text{ index} = 0.8 \text{ cm/hr}$$

$$\phi \text{ index} = \frac{4.2 - R}{t_e}$$

$$0.8 = \frac{4.2 - R}{2} \Rightarrow R = \underline{\underline{2.6 \text{ cm}}}$$

$$\text{Peak discharge of 2 hr UHG} = 15 \text{ m}^3/\text{s}$$

$$\text{Peak discharge of 2 hr DRH } (R = 2.6 \text{ cm}) = 15 \times 2.6 = \underline{\underline{39 \text{ m}^3/\text{s}}}$$

$$\text{Max flood discharge} = \text{Peak 2 hr DRH} + \text{base flow} = 39 + 7 = \underline{\underline{46 \text{ m}^3/\text{s}}}$$

14. 6 hr UHG ordinates 0 15 36 30 17.5 8.5 30.

33
40

Peak 6 hr UHG ordinate = 36 m³/s

$$0.06 = \frac{P-4}{6}$$

Peak 6 hr SHG ordinate = 150 m³/s

Peak 6 hr DRH ordinate = 150 - Base flow
= 150 - 6 = 144 m³/s

$$\text{Run off, } R = \frac{\text{Peak 6 hr DRH}}{\text{Peak 6 hr UHG}} = \frac{144}{36} = \underline{4 \text{ cm}}$$

$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.6 = \frac{P-4}{6}$$

⇒ Depth of storm rainfall, P = 7.6 cm

Stream flow at 15th hour = (OSHG)₅ = (OUHG)₅ * runoff + baseflow.

$$= 8.5 \times 4 + 6 = \underline{40 \text{ m}^3/\text{s}}$$

15. 3 hour duration storm:

P = 2.7 cm, ϕ index = 0.3 cm/hr.

$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.3 = \frac{2.7-R}{3}$$

$$R = \underline{1.8 \text{ cm}}$$

Peak of 3 hr unit HG = $\frac{\text{Peak FHG} - \text{baseflow}}{\text{Run off}}$

$$= \frac{210-20}{1.8} = \underline{105.55 \text{ m}^3/\text{s}}$$

16. Peak flood HG = $470 \text{ m}^3/\text{s}$

Base flow = $15 \text{ m}^3/\text{s}$.

$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.25 = \frac{8-R}{6} \Rightarrow R = \underline{\underline{6.5 \text{ cm}}}$$

$$\text{Peak UHG ordinate} = \frac{470-15}{6.5} = \underline{\underline{70 \text{ m}^3/\text{s}}}$$

17. For 4 hr UHG,

$$t_b = 80 \text{ hours, Area of catchment} = 720 \text{ km}^2$$

$$\frac{1}{2} \times Q_p \times t_b = \text{Area of catchment} \times 10^{-2}$$

$$\frac{1}{2} \times Q_p \times 3600 \times 80 = 720 \times 10^6 \times 10^{-2}$$

$$\underline{\underline{Q_p = 50 \text{ m}^3/\text{s}}}$$

$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.1 = \frac{4-R}{4} \Rightarrow R = 3.6 \text{ cm.}$$

$$\therefore \text{Peak flood discharge} = \text{Peak UHG discharge} \times \text{runoff} + \text{baseflow.}$$

$$= 50 \times 3.6 + 30 = \underline{\underline{210 \text{ m}^3/\text{s}}}$$

19. For 1 hr UHG,

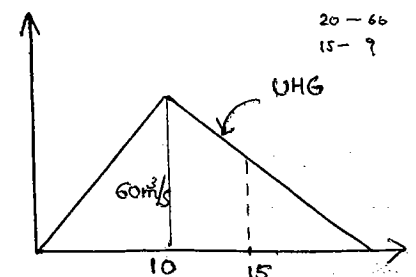
$$Q_p = 60 \text{ m}^3/\text{s}, t_b = 30 \text{ hours.}$$

$$\text{Area of catchment} = \frac{1}{2} \frac{60 \times 3600 \times 30}{10^2 \times 10^6} = \underline{\underline{324 \text{ km}^2}}$$

20. 15th hour UHG ordinate:

$$\frac{30-10}{30-15} = \frac{60}{x}$$

$$x = 45 \text{ m}^3/\text{s}$$



$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.4 = \frac{5.4-R}{1} \Rightarrow \underline{R=5 \text{ cm}}$$

41

Ordinate of FHG at 15th hour = Ordinate of UHG at 15th hour * runoff + baseflow.

$$= 45 \times 5 + 15 = \underline{240 \text{ m}^3/\text{s}}$$

21.

Area of watershed = 50 km² ; ϕ -index = 0.5 cm/hr

Baseflow = 10 m³/s ; t_b = 15 hours, Depth of rainfall = 5.5 cm

$$\frac{1}{2} \times Q_p \times t_b = \text{Area of catchment} \times 10^{-2}$$

$$\frac{1}{2} \times Q_p \times 3600 \times 15 = 50 \times 10^6 \times 10^{-2}$$

$$Q_p = \underline{18.52 \text{ m}^3/\text{s}}$$

22.

$$\phi \text{ index} = \frac{P-R}{t}$$

$$0.5 = \frac{5.5-R}{1} \Rightarrow R = 5 \text{ cm.}$$

Peak ordinate of FHG = $Q_p \times \text{run off} + \text{baseflow.}$

$$= 18.52 \times 5 + 10 = \underline{102.6 \text{ m}^3/\text{s}}$$

23.

Area = 252 km² ; t_b = 35 h.

$$\frac{1}{2} Q_p t_b = \text{area} \times 10^{-2}$$

$$\frac{1}{2} \times Q_p \times 3600 \times 35 = 252 \times 10^6 \times 10^{-2}$$

$$\Rightarrow Q_p = 40 \text{ m}^3/\text{s.}$$

Effective rainfall = run off = 5 cm.

Peak discharge of PRH (run off = 5 cm) = $40 \times 5 = \underline{200 \text{ cumecs.}}$

th dec,
MONDAY → Hydrograph Analysis of Complex T-hr Storms:

To find complex T hr storm information from the given D hr UHG of a simple storm, the following methods are used:-

- For uniform storms;

(i) Method of Superposition.

(ii) S-Curve method (Summation Curve method)

- For non-uniform storms;

(i) Convolution.

(ii) Deconvolution

* Method of Superposition

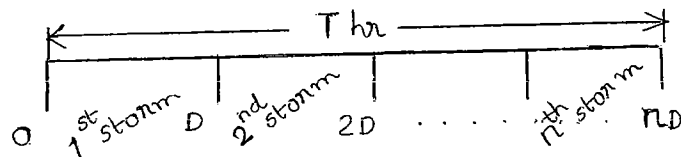
This method is applicable for uniform storms if it satisfies the following conditions:-

- $T > D$ (to find T hr UHG from D hr UHG)

- $T = nD$ (where $n = 2, 3, 4 \dots$)

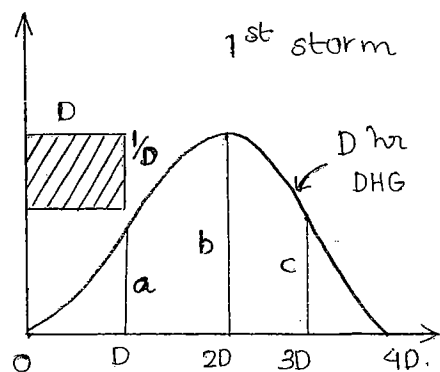
Procedure:-

Step 1: Split the T hr storm into n number of D hr storms.

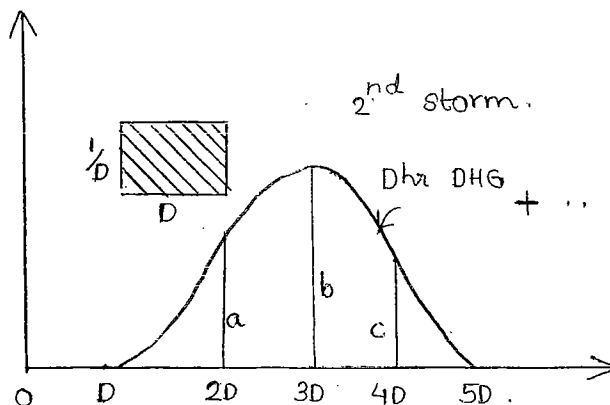


assuming that each D hr storm occur in succession (one after the other)

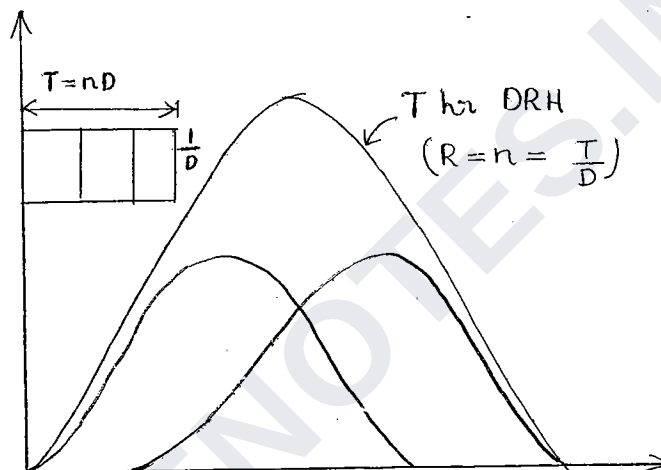
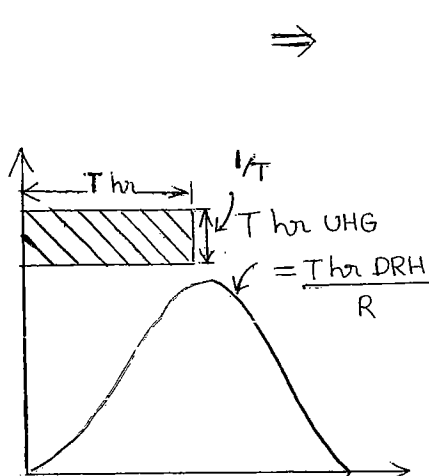
Step 2: Superimpose D hr unit hydrographs one above the other each with a time delay of D hr duration.



+



+ ... + nth storm



Step 3: The combined resulting hydrograph represents T hr. Direct runoff hydrograph resulting into a runoff depth of n cm, where $R = n = \frac{T}{D}$

Step 4: Find the T hr unit hydrographs by dividing the T hr DRH ordinates by R .

time	1 st storm D hr DRH ordin.	2 nd storm (D hr lagged). D hr DRH ond.	3 rd storm (2D hr lagged). D hr DRH ond.	T hr DRH ond. (= 1 st + 2 nd + 3 rd)	T hr UHG ond. = $\frac{\text{T hr DRH ond.}}{R}$
0	0	—	—	0	
D	a	0	—	a	
2D	b	a	0	a+b	
3D	c	b	a	a+b+c	
4D	0	c	b	b+c	
5D	—	0	c	c	
6D	—	—	0	0	

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24.

Time	1 st storm 2hr UHG and (m ³ /s)	2 nd storm. 2hr delayed 2hr UHG and (m ³ /s)	4 hr DRH and. (1 st + 2 nd)	4hr UHG and = 4hr DRH R $R' = n = 2 \text{ cm.}$
0	0	—	0	0
1	20	—	20	10
2	60	0	60	30
3	80	20	100	50
4	50	60	110	55
5	20	80	100	50
6	0	50	50	25
7	—	20	20	10
8	—	0	0	0

Uniform Storm: 2hr UHG $\rightarrow$ 4hr UHG

$$D = 2 \text{ hr} \quad \& \quad T = 4 \text{ hr.}$$

$$n = \frac{T}{D} = \frac{4}{2} = \underline{\underline{2 \text{ cm}}}$$

$T > D$
 $T = nD$ } conditions satisfied.

Max discharge of 4 hr UHG = Peak ordinate of 4 hr UHG
= 55 m³/s

27

1 hr UHG ($D = 1 \text{ hr}$)

$$D = 1, T = 3$$

$$n = 3$$

1 hr UHG $\rightarrow$ 3 hr UHG (uniform storm)

Time	1 st storm. 1hr UHG	2 nd storm. 1hr delayed	3 rd storm. 2hr delayed	3hr DRH. ordinates ($R=n=3 \text{ cm}$)	Diagram: 3 hr UHG 0 1st storm 1 2nd storm 2 3rd storm 3
0	0	—	—	0	
1	2	0	—	2	
2	6	2	0	8	
3	4	6	2	12	
4	2	4	6	12	
5	1	2	4	7	
6	0	1	2	3	
7	—	0	1	1	
8	—	—	0	0	

$$\text{Catchment area} = \frac{1 \times 60 \times 60 (2+6+4+2+1)}{1/100 \times 1000^2}$$

$$= \underline{\underline{5.4 \text{ km}^2}}$$

$$3^{\text{rd}} \text{ hour ordinate of 3 hour UHG} = \frac{12}{3} = \underline{\underline{4 \text{ m/s}}}$$

Time	1 st storm 2hr UHG.	2 nd storm (2hr delayed).	4hr DRH (R=2 cm).	4hr UHG. (4hr DRH/2).
0	0	—	0	0
2	12	0	12	6
4	54	12	66	33
6	126	54	180	90
8	112	126	238	119
10	94	112	206	103
12	64	94	158	79
14	36	64	100	50
16	14	36	50	25
18	0	14	14	07
20	—	0	0	0

$$\text{Peak ordinate of 4hr UHG} = \underline{\underline{119 \text{ m}^3/\text{s}}}$$

25. Uniform storm:

$$P = P_e = 16 \text{ cm.}$$

$$t = t_e = 12 \text{ hour}$$

$$\phi \text{ index} = 0.5 \text{ cm/hr.}$$

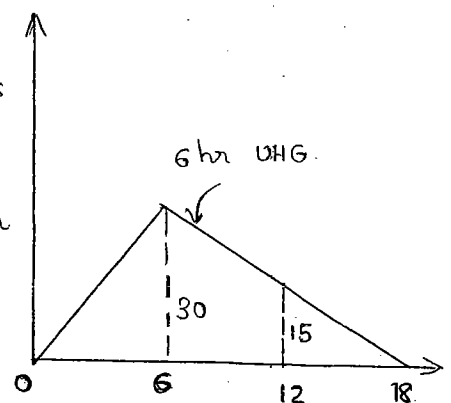
$$\left. \begin{array}{l} D = 6 \text{ hour} \\ T = 12 \text{ hour} \\ n = \frac{T}{D} = 2 \end{array} \right\} \begin{array}{l} \text{conditions} \\ \text{satisfied} \\ \text{for} \\ \text{superposition} \end{array}$$

$$\phi \text{ index} = \frac{P_e - R}{t_e}$$

$$0.5 = \frac{16 - R}{12}$$

$$\therefore R = 10 \text{ cm.}$$

$$12 \text{ hr DRH ordinates} = 12 \text{ hr UHG} \times 10.$$



Time	1 st storm 6hr UHG	2 nd storm 6hr delayed	12hr DRH ($R=n=2\text{ cm}$)	12 hr. UHG $=\left(\frac{12\text{ hr DRH}}{2}\right)$	12 hr DRH ($R=10\text{ cm}$)
0	0	—	0	0	0
6	30	0	30	15	150
12	15	30	45	22.5	225
18	0	15	15	7.5	75
24	—	0	0	0	0

Peak discharge of resulting DRH = Peak ordinate of 12 hr DRH.
= 225 m^3/s .

26. Area of catchment = $\frac{0.5 \times 30 \times 3600 \times 18}{10^{-2} \times 10^4} = \underline{\underline{9720 \text{ ha}}}$
= $\frac{0.5 \times 22.5 \times 3600 \times 24}{10^{-2} \times 10^4} = \underline{\underline{9720 \text{ ha}}}$

* Summation Curve Method (S-Curve method)

This method is applied for uniform storms.

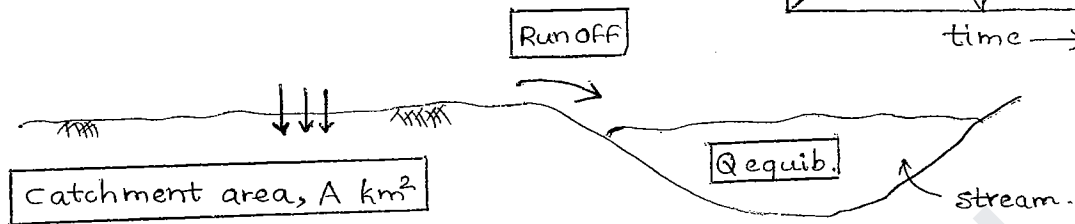
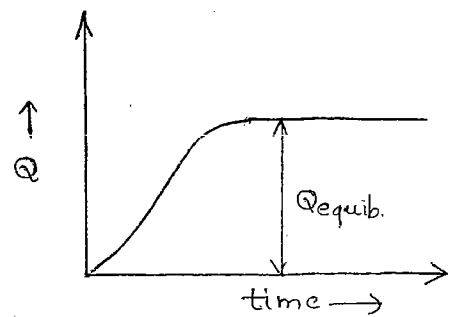
There is no precondition to apply this method. i.e., this method is applicable for conditions $T < D$ or $T > D$ and $T = nD$ or $T \neq nD$.

A storm of effective rainfall intensity $\frac{1}{D}$ cm/hr if it occur over a catchment of area $A \text{ km}^2$ for a per infinite duration, after meeting the initial losses catchment drain constant amount of runoff into stream. Then stream attain equilibrium discharge (const. discharge). For such storm if stream flow variation is measured at a point on a stream, the hydrograph resulting is known as S-curve hydrograph or simply S-curve.

Duration of storm: $t = \infty$

Rainfall

Effective Rainfall Intensity = $\frac{1}{D}$



in every D hour

- Volume of runoff delivered by catchment into stream
 $= \text{catchment area} \times \text{depth of runoff.}$
 $= A \times 1.$
- Discharge delivered into stream $= \frac{A \times 1}{D}$

$$Q_{\text{equil}} = \frac{A \times 1}{D} \left(\frac{\text{km}^2 \cdot \text{cm}}{\text{hr}} \right)$$

$$= A \times (1000)^2 \times \frac{1}{100} \times \frac{1}{D \times 60 \times 60}$$

$$\Rightarrow \boxed{Q_{\text{equil}} \left(\frac{\text{m}^3}{\text{s}} \right) = \frac{2.778 A}{D}}$$

where $A \rightarrow$ area of catchment (in km^2).

$D \rightarrow$ duration of UHG (in hour)

29. $A = 270 \text{ km}^2, D = 3 \text{ hr}$

$$Q_{\text{equil}} = \frac{2.778 \times 270}{3} = \underline{\underline{250 \text{ m}^3/\text{s}}}$$

30. Area of catchment, $A = \frac{0.5 \times 30 \times 3600 \times 64}{10^{-2} \times 10^6} = 345.6 \text{ km}^2.$

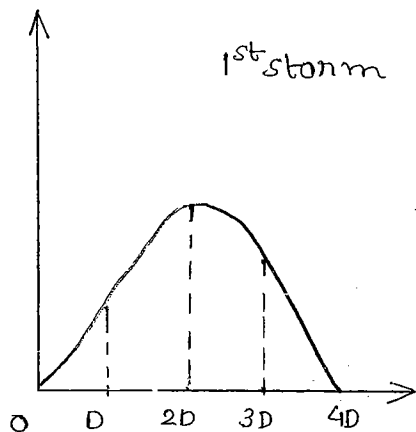
$$Q_{\text{equil}} = \frac{2.778 \times 345.6}{6} = \underline{\underline{160 \text{ m}^3/\text{s}}}$$

- Procedure for construction of S curve:

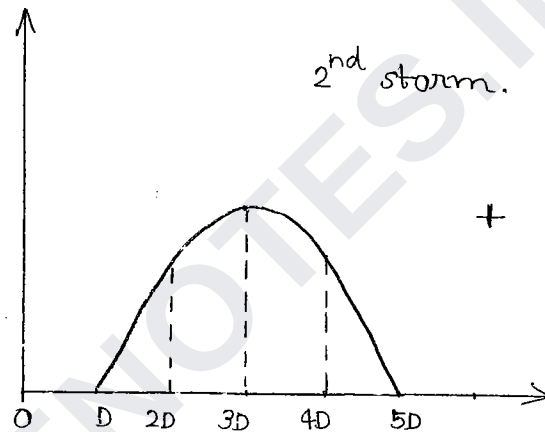
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Step 1: Split infinite duration storm into infinite no: of D hr. storms assuming that they occur in succession each, with a time delay of D hours.

Step 2: Superimpose D hr UHG one above the other till eqbm. discharge is obtained and find the ordinates of S curve.



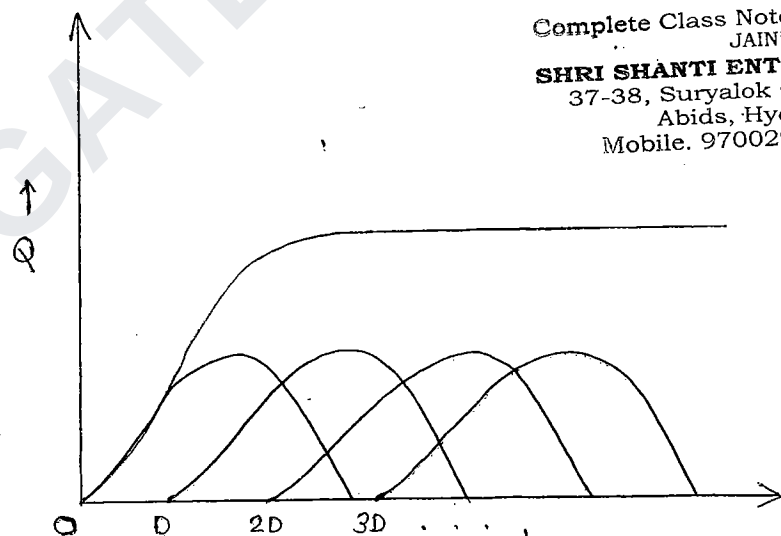
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□ S curve

time	1 st storm D hr UHG	Delayed D hr UHG Ord.				S curve ordinate
		1D	2D	3D	4D.	
0	0	—	—	—	—	0
D	a	a	—	—	—	a
2D	b	a	0	—	—	a+b
3D	c	b	a	0	—	a+b+c
4D	0	c	b	a	0	a+b+c
5D	—	0	c	b	a	a+b+c
6D	—	—	0	c	b	

time	Dhr UHG (m ³ /s).	S-curve additions (m ³ /s).	S-curve ordinates (m ³ /s).
0	0		0
D	a	0	a.
2D	b	a	a+b.
3D	c	a+b	a+b+c.
4D	0	a+b+c	a+b+c

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32.

time	4 hr UHG ordinates (m ³ /s).	S curve additions	S curve ordinates
0	0		0
2	6		6
4	33	0	33
6	90	6	96
8	119	33	152
10	103	96	199
12	79	152	231
14	50	199	249
16	25	231	256
18	7	249	256
20	0	256	256
	0	256	256

$$\text{Area} = \frac{2 \times 60 \times 60 (6 + 33 + 90 + 119 + 103 + 79 + 50 + 25 + 7)}{1/100 \times (1000)^2} = \underline{\underline{368.64 \text{ km}^2}}$$

$$Q_{\text{equi}} = \frac{2.778 A}{D} = \frac{2.778 \times 368.64}{4} = \underline{\underline{256 \text{ m}^3/\text{s}}}$$

- Q. Construct S curve from 3 hr UHG having ordinates at one hour time intervals starting $t=0$ are

45

time	3 hr UHG ordinates.	S curve addition	S curve ordinates.
0	0		0
1	$\frac{2}{3}$	$\rightarrow$	$\frac{2}{3}$
2	$\frac{8}{3}$		$\frac{8}{3}$
3	4	0	4
4	4	$\frac{2}{3} \rightarrow$	$\frac{14}{3}$
5	$\frac{7}{3}$	$\frac{8}{3}$	5
6	1	4	5
7	$\frac{1}{3}$	$\frac{14}{3} \rightarrow$	5
8	0	5	5

— Construction of T hr UHG using S curve :-

Step 1: Construct S curve from the given D-hr UHG.

Let it be ' S_A '

Step 2: Construct one more S curve with time delay of T hours. Let it be ' S_B '.

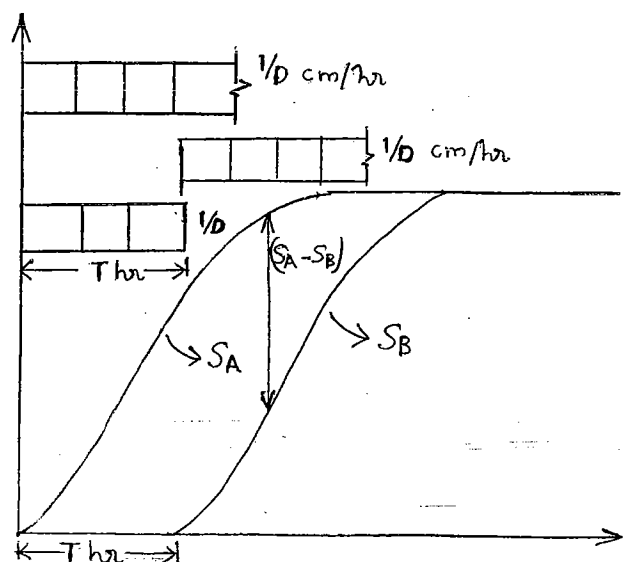
Step 3: Find difference in ordinates of two S curve, ie, $S_A - S_B$.

$$T \text{ hr DRH ord} = S_A - S_B.$$

$$(R = \frac{T}{D} \text{ cm})$$

$$T \text{ hr UHG ord} = \frac{S_A - S_B}{R}$$

$$= \frac{S_A - S_B}{T/D} = \frac{(S_A - S_B)D}{T}$$



7th Dec,

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time	1hr UHG	S-curve ordinates. (S _A)	S-curve delayed by 3hr (S _B)	3hr DRH (S _A -S _B)	3hr UHG $\{(S_A - S_B) \frac{1}{3}\}$
0	0	0	—	0	0
1	5	5	—	5	5/3
2	8	13	—	13	13/3
3	5	18	0	18	18/3
4	3	21	5	16	16/3
5	1	22	13	9	3
6	0	22	18	4	4/3
7	0	22	21	1	1/3
8	0	22	22	0	0

Watershed area = $\frac{1}{2} \times 60 \times 60 \times (8 + 5 + 5 + 3 + 1) = 7.92 \text{ km}^2$
 $10^{-2} \times 10^6$

34.

Catchment area = $\frac{1 \times 3600 \times (3 + 8 + 6 + 3 + 2)}{10^{-2} \times 10^4} = 7.92 \text{ km}^2$

35.

time	2hr UHG	S-curve additions	S-curve ordinates (S _A)	S-curve delayed by 3 hours	3 Hr DRH (S _A -S _B)	3hr UHG $\frac{(S_A - S_B) \frac{2}{3}}$
0	0		0	—	0	0
1	3		3	—	3	2
2	8		8	—	8	5.33
3	6	0	9	0	9	6
4	3	3	11	3	8	5.33
5	2	8	11	8	3	2
6	0	9	11	9	2	1.33
7	0	11	11	11	0	0

ϕ -index = $\frac{P - R}{t}$; Baseflow = $5 \text{ m}^3/\text{s}$

$0.2 = \frac{6.6 - R}{3} \Rightarrow R = 6 \text{ cm.}$

Peak flow due to storm = 3 hr UHG peak ordinate * runoff + baseflow.

= $6 \times 6 + 5$

= $41 \text{ m}^3/\text{s}$

36. S curve ordinates due to rainfall of intensity 1 cm/hr is :

$$Q = 1 - (1+t) e^{-t}$$

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time	S-curve ordinates (S _A)	S-curve delayed by 2 hr (S _B)	2hr DRH (S _A -S _B)	2hr UHG (S _A -S _B) × $\frac{1}{2}$
0	0	—	0	0
1	0.264	—	0.264	0.132
2	0.594	0	0.594	0.297
3	0.8008	0.264	0.537	0.2685
4	0.908	0.594	0.314	0.157
5	0.959	0.8008	0.1582	0.079
6	0.983	0.908	0.075	0.037
7	0.993	0.959	0.034	0.017
8	0.997	0.983	0.014	0.007

From given S-curve ordinates,

$$Q_{\text{equib}} = 0.999 \sim 1 \text{ m}^3/\text{s}$$

$$ERI = \frac{1}{D} \text{ cm/hr} = 1 \text{ cm/hr}$$

$$\Rightarrow D = 1 \text{ cm/hr}$$

$$Q_{\text{equib}} = 2.778 \frac{A}{D}$$

$$\therefore \text{Area of catchment} = \frac{1 \times 1}{2.778} = \underline{\underline{0.36 \text{ km}^2}}$$

37. Ordinate of 2 hr UHG at 3rd hour = 0.2685 m³/s $\approx$ 0.27 m³/s

(OR)

At time $t = \infty$, $Q = Q_{\text{equi}}$.

$$Q = Q_{\text{equi}} = 1 - (1+t) e^{-t}$$

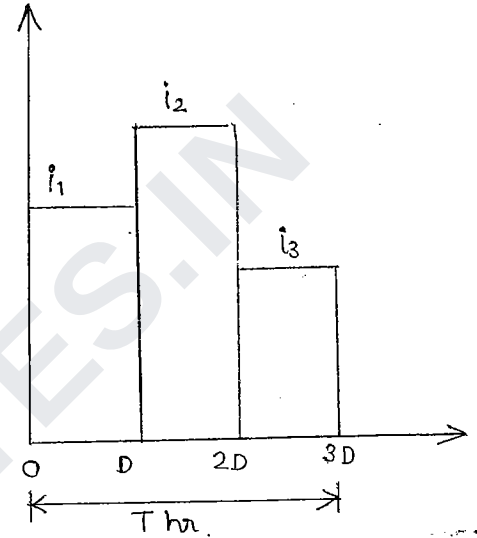
$$= 1 - (1+\infty) e^{-\infty} = \underline{\underline{1 \text{ m}^3/\text{s}}}$$

* Convolution

This method is used to find T hr complex storm information using D hr UHG (D -hr storm) for non-uniform storm. This method is used if it satisfies the following:

(i) $T > D$

(ii) $T = nD$; $n = 2, 3, 4, \dots$



Procedure :-

(i) Split the T hr storm into n number of D hr storms.

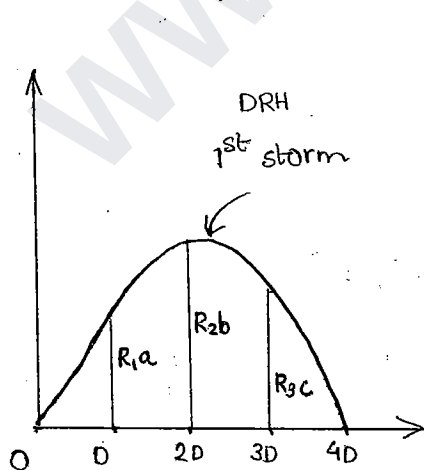
(ii) Find runoff resulting from each of the T hr storm by using ϕ index.

(iii) Find DRH for each D hr storm separately.

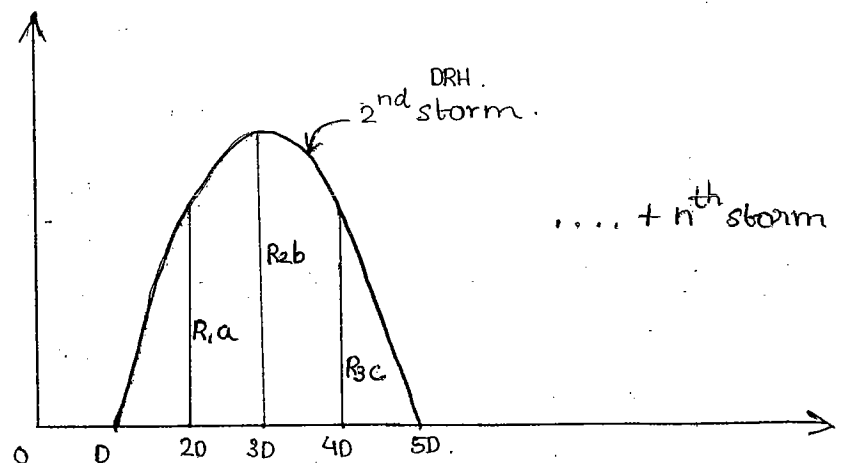
(DRH ordinates = UHG ordinates $\times R$)

(iv) Superimpose D hr DRH one above the other, each with a time delay of D hours.

0	1 st storm	D	2 nd storm	2D	3 rd storm	3D
	$P_1 = P_{e1}$		$P_2 = P_{e2}$		$P_3 = P_{e3}$	
	$t_1 = t_{e1}$		$t_2 = t_{e2}$		$t_3 = t_{e3}$	
	R_1 (using ϕ index)		R_2		R_3	

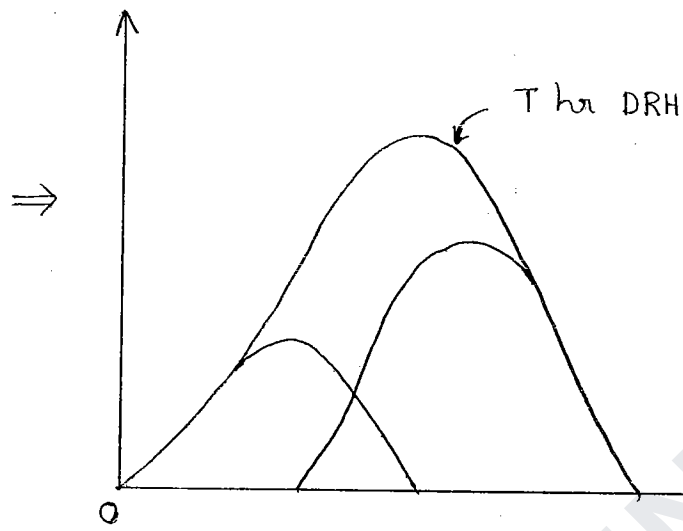


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(v) The combined resulting direct runoff hydrographs for multiple storms represent T hr DRH.

(vi) Find T hr SHG by adding baseflow to T hr DRH.



time	Dhr UHG ond.	1 st storm Dhr DRH and = Dhr UHG * R ₁	2 nd storm Dhr delayed Dhr DRH and = Dhr UHG * R ₂	T hr DRH ond. = 1 st + 2 nd	Baseflow	T hr SHG = T hr DRH + baseflow.
0	0	0	—	0		
D	a	R ₁ a	0	R ₁ a.		
2D	b	R ₁ b	R ₂ a	R ₁ b + R ₂ a.		
3D	c	R ₁ c	R ₂ b	R ₂ b + R ₁ c		
4D	0	0	R ₂ c	R ₂ c		
5D	—	—	0	0		

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$$P_{e1} = 3.8 \text{ cm}$$

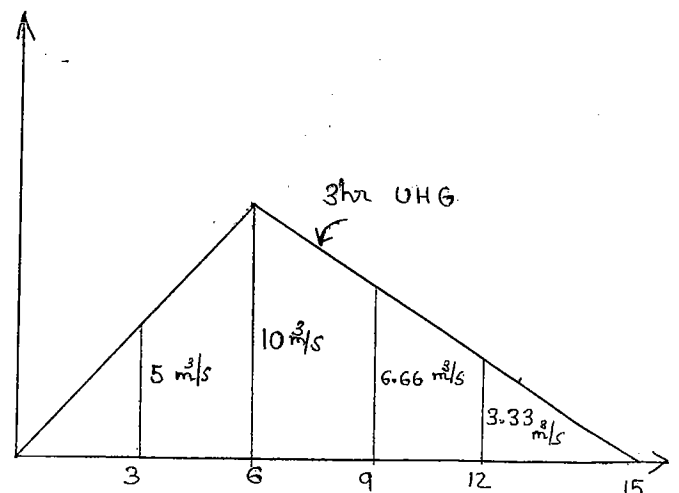
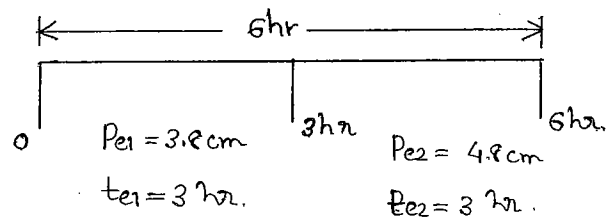
$$\phi = \frac{3.8 - R_1}{3}$$

$$\Rightarrow R_1 = 2 \text{ cm}$$

$$P_{e2} = 4.8 \text{ cm}$$

$$\phi = \frac{4.8 - R_2}{3}$$

$$\Rightarrow R_2 = 3 \text{ cm}$$



time	3hr UHG	1 st storm. (3hr UHG × 2)	2 nd storm 3 hr delayed. (3hr UHG × 3)	6hr DRH
0	0	0	—	0
3	5	10	0	10
6	10	20	15	35
9	6.66	13.33	30	43.33
12	3.33	6.667	20	26.667
15	0	0	10	10
18	0	0	0	0

∴ Peak discharge of 6hr DRH = 43.33 m³/s

39.

Time	6h UHG	1 st storm. (6h UHG × 1.5)	2 nd storm. 6hr delayed. (6h UHG × 3.5)	12 hr DRH	12hr SHG (12 hr DRH + 10)
0	0	0	—	0	10
6	20	30	0	30	40
12	60	90	70	160	170
18	150	225	210	435	445
24	120	180	525	705	715

$$\phi = \frac{3 - R_1}{6}$$

$$\Rightarrow R_1 = 3 - 6 \times 0.25$$

$$= 1.5 \text{ cm}$$

$$\phi = \frac{5 - R_2}{6}$$

$$\Rightarrow R_2 = 5 - 6 \times 0.25$$

$$= 3.5 \text{ cm}$$

Given baseflow = 10 m³/s

12 hr SHG = 12 hr DRH + baseflow.

Resulting discharge at 24th hour = 715 m³/s

40. $t_b = \frac{72}{24}$ hours, $Q_p = 100 \text{ m}^3/\text{s}$

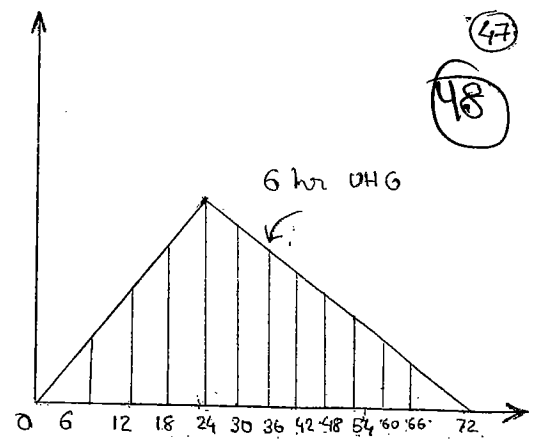
$$\text{Area of catchment} = \frac{\frac{1}{2} \times 72 \times 100 \times 3600}{10^{-2} \times 10^6} = \underline{\underline{1296 \text{ km}^2}}$$

$$R_1 = 2 \text{ cm} \quad \& \quad R_2 = 4 \text{ cm}.$$

$$\text{Base flow} = 25 \text{ m}^3/\text{s}$$

Ordinates of 6 hr UHG from $t=0$ to $t=72$ with 6 hr interval are:

0, 25, 50, 75, 100, 87.5, 75, 62.5, 50, 37.5, 25, 12.5, 0.



Time	6 hr UHG	1 st storm. (6 hr UHG $\times$ 2)	2 nd storm. (6 hr UHG $\times$ 4)	12 hr DRH	12 hr SHG $\frac{42}{6} \rightarrow 100$
0	0	0	—	0	25
6	25	50	0	50	75
12	50	100	100	200	225
18	75	150	200	350	375
24	100	200	300	500	525
30	87.5	175	400	575	(600)
36	75	150	350	500	525
42	62.5	125	300	425	450
48	50	100	250	350	375
54	37.5	75	200	275	300
60	25	50	150	200	225
66	12.5	25	100	125	150
72	0	0	50	50	75

* Deconvolution

This method is used to find D hr unit hydrograph from the given T-hr DRH of a non-uniform storm.

Procedure:-

- Assume D hr UHG ordinates as 0, a, b, ... 0.
- Apply method convolution in terms of assumed ordinates and obtain T hr DRH ordinates

(ii) Equate 12 hr DRH ordinates in terms of assumed ordinates to real 12 hr DRH ordinates (given in problem).

(iv) Solve for a, b, c, ... and obtain 12 hr UHG ordinates.

12 hr complex storm DRH ordinates are given, and we are asked to find 4 hr UHG. (non uniform storm)

∴ deconvolution technique is used.

$$R_1 = 2 \times 4 = 8 \text{ cm} \quad \left\{ \text{Run off} = \text{Effective rainfall intensity} \times \text{time} \right\}$$

$$R_2 = 0.75 \times 4 = 3 \text{ cm.}$$

$$R_3 = 4 \times 4 = 16 \text{ cm.}$$

time	4 hr UHG ord (assumed)	1 st storm. 4 hr DRH ord (4 hr UHG × 8)	2 nd storm 4 hr delayed. (4 hr UHG × 3)	3 rd storm. 8 hr delayed. (4 hr UHG × 16)	12 hr DRH	12 hr DRH (given)
0	0	0	—	—	0	0
4	a	8a	0	—	8a	160
8	b	8b	3a	0	8b + 3a	300
12	c	8c	3b	16a	8c + 3b + 16a	570
16	d	8d	3c	16b	8d + 3c + 16b	636
20	e	8e	3d	16c	8e + 3d + 16c	404
24	f	8f	3e	16d	8f + 3e + 16d	234
28	0	0	3f	16e	3f + 16e	105
32	—	—	0	16f	16f	48
36	—	—	—	0	0	0

Solving,

$$a = 20, b = 300, c = 20, d = 12, e = 6, f = 3, \text{ etc.}$$

$$8a = 160 \Rightarrow a = 20$$

$$8b + 3a = 300 \Rightarrow b = \frac{300 - 3 \times 20}{8} = 30$$

∴ 4 hr UHG ordinates are (in m³/s):

0, 20, 300, 20, 12, 6, 3, 0.

10th dec,
WEDNESDAY

→ Instantaneous Unit Hydrograph (IUH):

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- Also known as 'Clark's IUH'.

- IUH is a UHG produced by a storm of δ shortest possible duration. i.e. zero duration. (like UHG, S-curve etc, this is also another hypothetical concept)

Let ' Δt ' be the shortest possible duration rain. To find Δt hr UHG from the given DRH UHG (1 hr UHG)

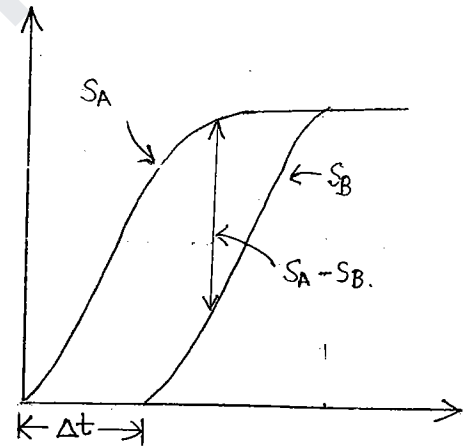
$$\left\{ T = \Delta t, D = 1 \text{ hr}, \Delta t < D \text{ \& } \Delta t \neq nD \right\}$$

⇒ S-curve method used.

$$\Delta t \text{ hr DRH ordinates} = S_A - S_B$$

$$(R = \frac{\Delta t}{D} \text{ cm})$$

$$\begin{aligned} \Delta t \text{ hr UHG ordinates} &= \frac{S_A - S_B}{\Delta t / D} \\ &= \frac{(S_A - S_B) D}{\Delta t} \end{aligned}$$



$$\therefore \Delta t \text{ hr UHG ordinates} = \frac{\Delta S}{\Delta t} D ;$$

$$\Delta S = S_A - S_B$$

$$D = 1 \text{ hr}$$

$$= \frac{\Delta S}{\Delta t} (1)$$

$$\lim_{\Delta t \rightarrow 0} \frac{\Delta S}{\Delta t} = \text{IUH} = \frac{ds}{dt}$$

∴ IUH ordinate = $\frac{ds}{dt}$ = Slope of S curve constructed by a storm of effective rainfall intensity 1 cm/hr.

→ Synthetic Unit Hydrograph (SUH):

— Also known as 'Snyder's SUH'.

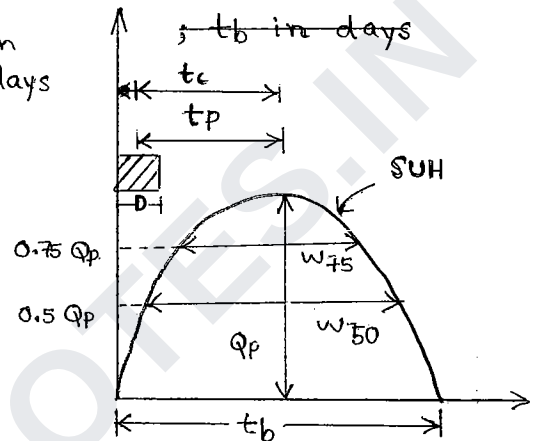
1. Basin lag (or), $t_p' = C_t (L * L_c)^{0.3}$; L & L_c in km.
Lag time (hr)

2. Peak Discharge, $Q_p' = 2.78 C_p \frac{A}{t_p}$; A in km^2 , t_p in hr

3. Base time, $t_b' = 3 + \frac{t_p}{8}$; t_b in days
(or) time base

4. $W_{50} = 5.87 \left(\frac{Q_p}{A} \right)^{-1.08}$; $Q_p \rightarrow m^3/s$
 $A \rightarrow m^2$

5. $W_{75} = \frac{W_{50}}{1.75}$ & $D = \frac{t_p}{5.5}$



Time of concentration,

$$t_c = \frac{D}{2} + t_p$$

42.

$$A = 400 \text{ km}^2$$

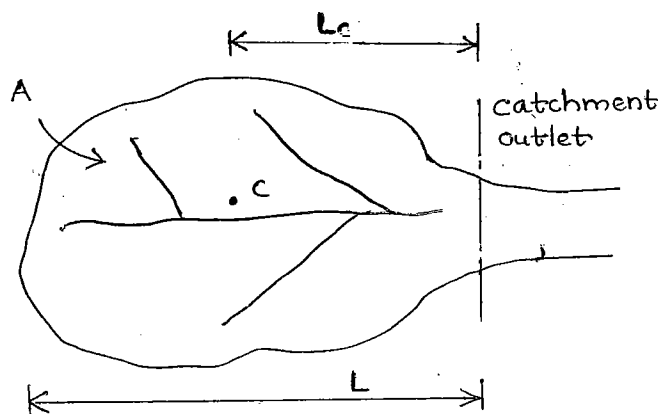
$$L = 45 \text{ km}, L_c = 25 \text{ km}$$

$$C_t = 1.257, C_p = 0.576$$

$$\begin{aligned} \text{Basin lag or lag time, } t_p &= C_t (L L_c)^{0.3} \\ &= 1.257 (45 * 25)^{0.3} \\ &= \underline{10.34 \text{ hrs}} \end{aligned}$$

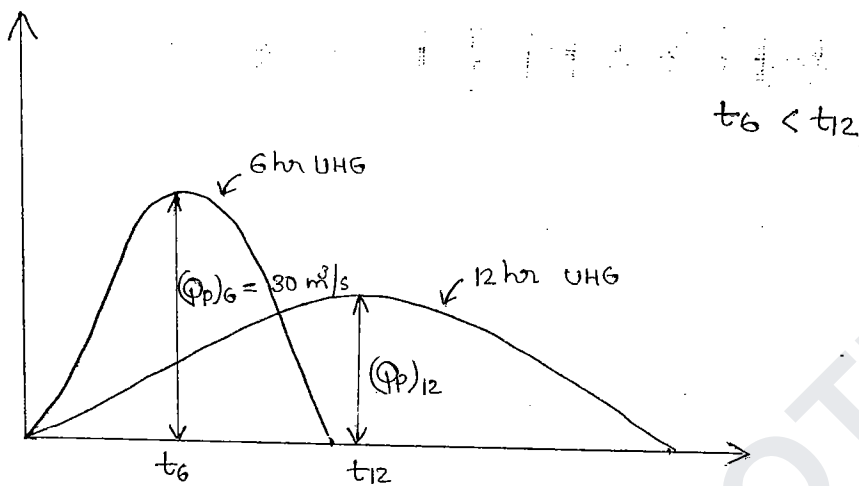
$$\begin{aligned} \text{Peak discharge, } Q_p &= 2.78 C_p \frac{A}{t_p} \\ &= 2.78 * 0.576 * \frac{400}{10.34} = 61.92 \text{ m}^3/\text{s} \end{aligned}$$

$$\text{Base time, } t_b = 3 + \frac{t_p}{8} = 3 + \frac{10.34}{8} = 4.29 \text{ days} = \underline{103.02 \text{ hours}}$$



For ungauged catchments, to derive UHG, Snyder has proposed set of empirical equations. The hydrograph derived from empirical equations is known as 'Synthetic UHG'.

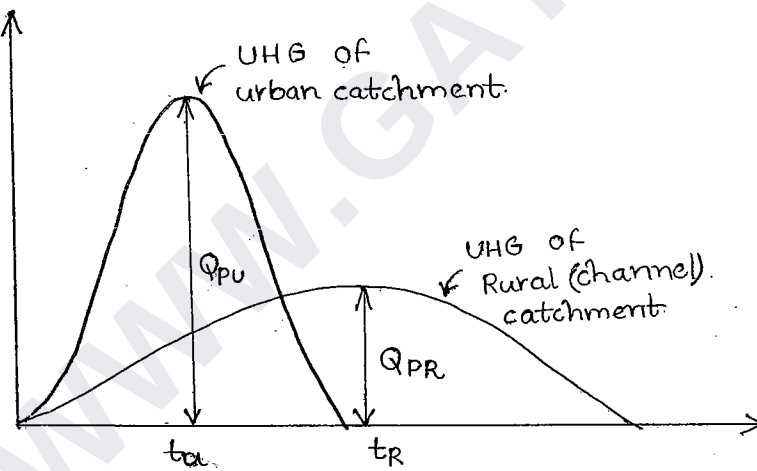
43.



44.

Line joining points of equal time of concentration are known as Isochrones (Iso - same, Chrono - time)

47.



→ Limitations of UHG

- Only direct runoff contributed by storms included. in UHG. Direct runoff contributed by melting of ice (or) snow not included in UHG assessment.
- UHGs are valid only catchments whose area $< 5000 \text{ km}^2$
- UHGs are valid only for catchment without storage facility.
- valid only for uniform storm.

08. MAXIMUM FLOOD ESTIMATION

Flood is a usual stage (depth of flow) in a river, water accumulate to such a level that it overtop the banks and inundate (submerge) large area and cause loss of life and economic loss.

- Floods occur due to :

- (i) Heavy rainfall in a catchment
- (ii) Sudden melting
- (iii) Obstruction to the flow.

- Floods are estimated and data is used :

- (i) in the design of hydraulic structures
- (ii) in the design of 'levee' (flood protection wall)
- (iii) flood management

→ Methods to estimate flood Discharge:

1. Using past flood marks.

Wetted area, wetted perimeter, hydraulic mean radius ' R ' are calculated and $Q = A \cdot V$.

2. Using empirical formula.

(i) Dicken's formula (North Indian Catchment)

$$Q = C_D A^{3/4}$$

(ii) Ryve's formula (South Indian Catchment)

$$Q = C_R A^{2/3}$$

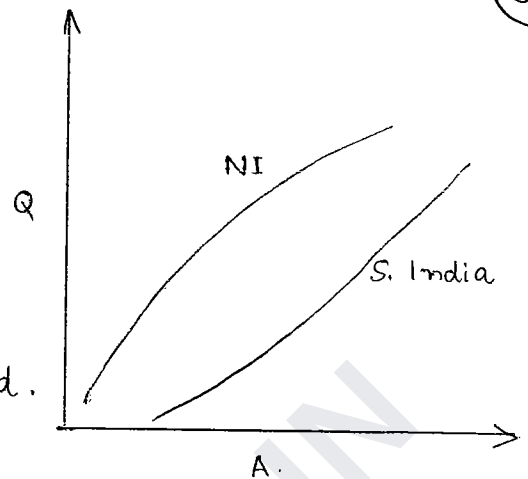
(iii) Inglis Formula

$$Q = \frac{124 A}{\sqrt{A + 10.4}}$$

3. Flood envelope curves

Q vs A plots are made for different parts of India by Central Water Commission (CWC).

Knowing the area of catchment (A), max. flood discharge can be calculated. (Q).



4. Unit Hydrograph method.

UHG $\rightarrow$ DRH $\rightarrow$ FHG.

For short term flood forecasting, this method is used.

5. Flood Frequency Analysis.

Probable max. flood, PMF = X_T

$$X_T = \bar{X} + K\sigma$$

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This method is used for long range (term) flood forecasting.

$\bar{X}$ $\rightarrow$ mean of flood data.

σ $\rightarrow$ standard deviation of flood data.

k $\rightarrow$ frequency factor.

$$k = \frac{y_t - y'}{s'}$$

y' & s' depends on sample size 'N', they are obtained from Gumbell's tables

$$K = \frac{y_t - 0.577}{1.2825} \quad (\text{when sample size, } N = \infty)$$

$$y_t = -\ln(-\ln(1-p)) ; \text{ where } p = \frac{1}{T}$$

6. Rational Formula.

- It is an empirical formula but universal.
- best suitable for urban catchments whose catchment area < 5000 ha (50 km^2).

$$\text{Max. flood discharge, } Q_{\max} = \frac{A I R}{360}$$

where $A \rightarrow$ area of catchment (ha)

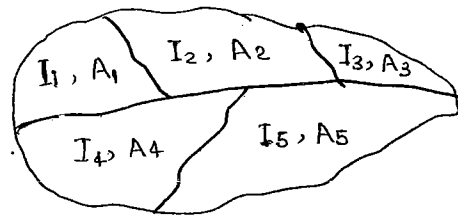
$I \rightarrow$ impermeability factor (or) runoff factor $\left(= \frac{\text{Runoff}}{\text{Rainfall}} \right)$

$R \rightarrow$ rainfall intensity (mm/hr) $\left\{ = \frac{\text{depth of rainfall}}{\text{duration of rainfall}} \right\}$

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

When duration of rainfall, ' t ', is not given, it is taken as time of concentration, ' t_c '

$$I = \frac{\sum A_i I_i}{A}$$



NOTE :

⊙ Rational formula is applicable only for such storms whose duration is $\geq t_c$. i.e. minimum time storm has to occur to produce max discharge is time of concentration, t_c .

$$Q \propto A, \quad Q \propto R, \quad Q \propto \frac{1}{t}$$
$$R \propto \frac{1}{t}$$

-42

01 Run off coefficient, $I = 0.4$.

$$P = 45 \text{ mm/hr}$$

Area of catchment, $A = 90$ ha.

$$Q_{\max} = \frac{A I R}{360} = \frac{90 \times 0.4 \times 45}{360} = \underline{\underline{4.5 \text{ m}^3/\text{s}}}$$

$$Q_{\max} = \frac{AIR}{360} = \frac{60 \times 0.4 \times 30}{360} = \underline{\underline{2 \text{ m}^3/\text{s}}}$$

Q2

$$Q3. A_1 = 30\% A, A_2 = 70\% A.$$

$$I_1 = 0.4 \quad I_2 = 0.6.$$

$$I = \frac{\sum A_i I_i}{A} = 0.4 \times 0.3 + 0.6 \times 0.7 = \underline{\underline{0.54}}$$

$$Q4. A = 1.5 \text{ km}^2 = 150 \text{ ha} \quad \{1 \text{ km}^2 = 100 \text{ ha}\}$$

$$I = 0.42, t_c = 28 \text{ min.}$$

$$P = 48 \text{ mm.}$$

$$R = \frac{48 \text{ mm}}{28/60} = 102.86 \quad (\text{duration of rainfall } t \text{ not given } \Rightarrow t = t_c)$$

$$Q_{\max} = \frac{150 \times 0.42 \times 102.86}{360} = \underline{\underline{18 \text{ m}^3/\text{s}}}$$

$$Q5. \text{Equivalent runoff coefficient} = \frac{10 \times 0.7 + 20 \times 0.1 + 50 \times 0.3 + 20 \times 0.8}{10 + 20 + 50 + 20} = \underline{\underline{0.4}}$$

$$Q6. I = 0.3, A = 0.85 \text{ km}^2 = 85 \text{ ha.} \quad \left\{ \begin{array}{l} \text{Entire catchment starts} \\ \text{contributing when } t \geq t_c \end{array} \right\}$$

$$t_c = 30 \text{ min.}, P = 50 \text{ mm}$$

$$R = \frac{50}{30/60} = 100 \text{ mm/hr.}$$

$$Q_{\max} = \frac{85 \times 0.3 \times 100}{360} = \underline{\underline{7.0833 \text{ m}^3/\text{s}}}$$

$$Q8. Q_{\max} = \frac{150 \times 0.4 \times 100/10}{360} = 1.667 \text{ m}^3/\text{s}$$

$$= \underline{\underline{100 \text{ m}^3/\text{min}}}$$

09. FLOOD ROUTING

Flood Routing is the method of generating flood hydrograph on d/s side by using the flood data available on the upstream side.

- Flood routing is carried out by two methods:

- (i) Hydraulic Flood Routing
- (ii) Hydrologic Flood Routing

* Hydraulic Flood Routing:

- This method is very complex but accurate.
- It requires high speed digital computer with advanced programming language.
- This method uses
 - (i) Continuity Equation.
 - (ii) St. Venant's equation of motion of unsteady gradually varied flow.

* Hydrologic Flood Routing:

- This method is simple but approximate.
- This method uses only continuity equation.

$$I - Q = \frac{dS}{dt}$$

- Hydrologic flood routing is applied:-

- (i) for channels with reservoir b/w u/s & d/s, known as

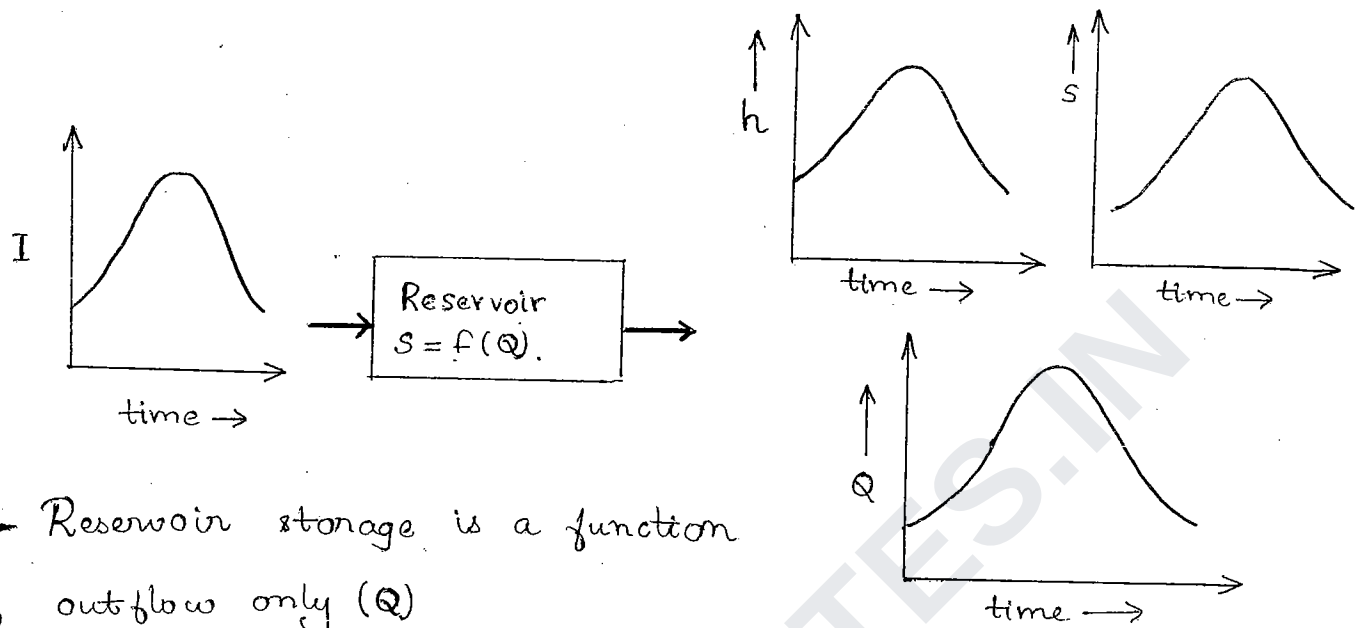
'Hydrologic Reservoir Routing'

- (ii) for channels without reservoir b/w u/s & d/s, known as

'Hydrologic Channel Routing'

→ Hydrologic Reservoir Routing

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- Reservoir storage is a function of outflow only (Q)

$h \rightarrow$ depth of flow.

$S \rightarrow$ storage.

$$I - Q = \frac{dS}{dt}$$

$$\frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} = \frac{\Delta S}{\Delta t}$$

$$\frac{I_1 + I_2}{2} - \frac{Q_1 + Q_2}{2} = \frac{S_2 - S_1}{\Delta t}$$

- To find out flow from the above equation:-

(i) Modified Puls Method.

(ii) Goodrich method

anyone is used.

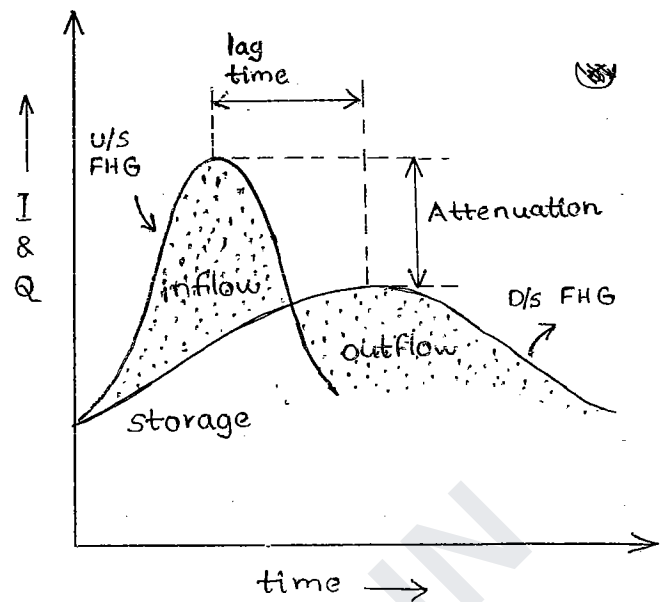
* Modified Puls Equation

$$\left(\frac{I_1 + I_2}{2} \right) \Delta t + \left(S_1 - \frac{Q_1}{2} \Delta t \right) = \overbrace{S_2 + \frac{Q_2}{2} \Delta t}^{\text{unknowns}}$$

* Goodrich method.

$$(I_1 + I_2) + \left(\frac{2S_1}{\Delta t} - Q_1 \right) = \frac{2S_2}{\Delta t} + Q_2$$

Overlapped area b/w inflow curve and outflow curve represents storage.



→ Hydrologic Channel Routing

The effect of floodwave while passing from u/s to d/s is evaluated assuming that there is no lateral addition of flow by:
by * Muskingum Method

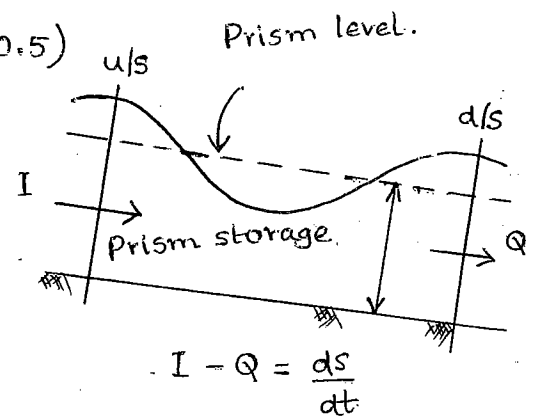
$$\text{Storage, } S = k(xI + (1-x)Q)$$

where $k \rightarrow$ storage time constant.

$x \rightarrow$ weightage factor (0 to 0.5)

$I \rightarrow$ inflow (u/s)

$Q \rightarrow$ outflow (d/s)



- Solution to Muskingum equation for outflow, Q

$$Q_n = C_0 I_n + C_1 I_{n-1} + C_2 Q_{n-1}$$

where C_0, C_1 & C_2 are Muskingum constants.

time	u/s FHG (I)	d/s FHG (Q)
t_{n-1}	I_{n-1}	Q_{n-1}
t_n	I_n	Q_n
t_{n+1}	I_{n+1}	Q_{n+1}

$$C_0 + C_1 + C_2 = 1$$

$$C_0 = \frac{-Kx + 0.5 \Delta t}{K - Kx + 0.5 \Delta t} ; C_1 = \frac{Kx + 0.5 \Delta t}{K - Kx + 0.5 \Delta t}$$

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time	$I (m^3/s)$	$Q (m^3/s)$	
3 rd	18	15	$C_0 = 0.042$
4 th	42	$Q_4 = ?$	$C_1 = 0.538$
			$C_2 = 1 - (0.042 + 0.538) = 0.42$

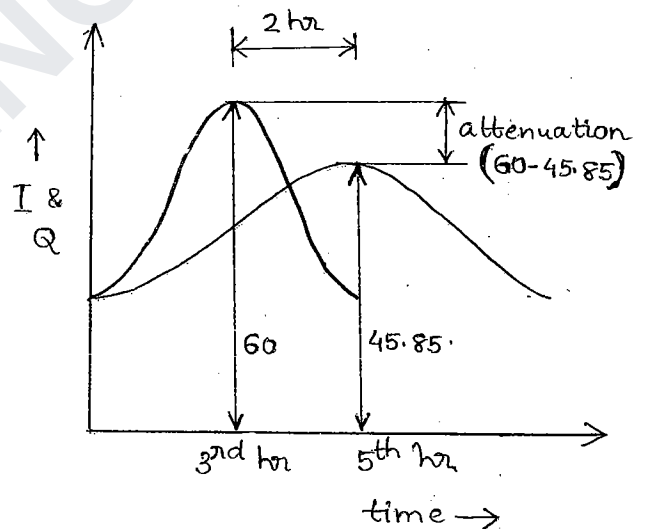
$$Q_4 = 0.042 \times 42 + 0.538 \times 18 + 0.42 \times 15 = \underline{\underline{17.748 \text{ m}^3/\text{s}}}$$

5. $C_0 = 0.048$

4. $C_1 = 0.429$

$C_2 = 0.523$

time	u/s FHG (I) (m^3/s)	d/s FHG (Q) (m^3/s)
0	10	10
1	20	10.48
2	40	15.98
3	60	28.39
4	50	42.98
5	40	<u>(45.85)</u>
6	30	42.37



$$Q_1 = 0.048 \times 20 + 0.429 \times 10 + 0.523 \times 10 = 10.48 \text{ m}^3/\text{s}$$

$$Q_2 = 0.048 \times 40 + 0.429 \times 20 + 0.523 \times 10.48 = 15.98 \text{ m}^3/\text{s}$$

$$Q_3 = 0.048 \times 60 + 0.429 \times 40 + 0.523 \times 15.98 = 28.39 \text{ m}^3/\text{s}$$

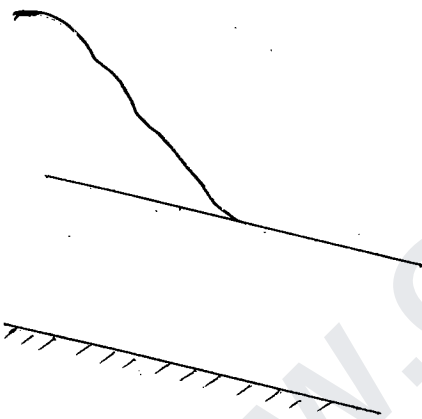
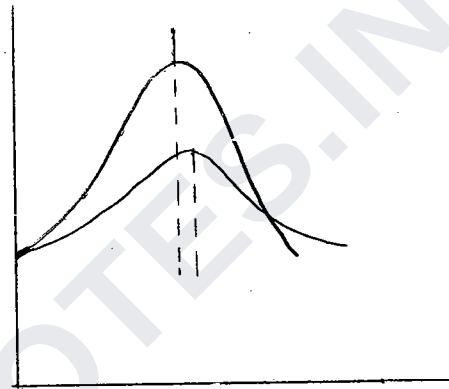
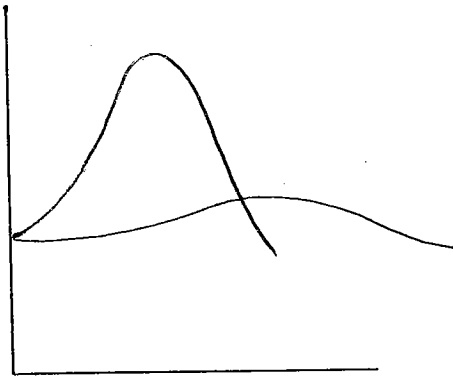
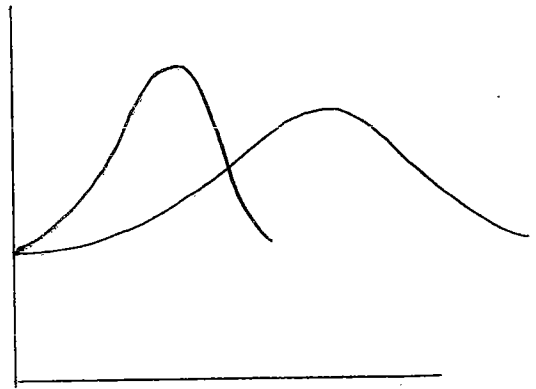
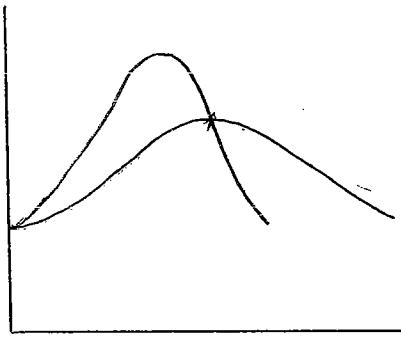
$$Q_4 = 0.048 \times 50 + 0.429 \times 60 + 0.523 \times 28.39 = 42.98 \text{ m}^3/\text{s}$$

$$Q_5 = 0.048 \times 40 + 0.429 \times 50 + 0.523 \times 42.98 = 45.85 \text{ m}^3/\text{s}$$

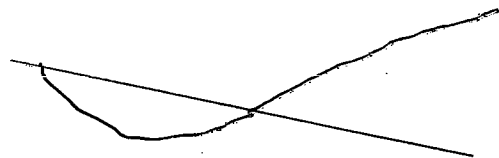
$$Q_6 = 0.048 \times 30 + 0.429 \times 40 + 0.523 \times 45.85 = 42.37 \text{ m}^3/\text{s}$$

Peak flood discharge on d/s = 45.85 m³/s

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Rising Phase
(Advancing stage)



Receding stage
(falling phase of flood).

10. WELL HYDRAULICS

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- Thirty percent of world's fresh water is available in the form of groundwater, compelled to use in the absence of surface water source.

- Before extraction and usage of groundwater it is necessary to know the groundwater potential.

- Water present in soil mantle is known as Groundwater.
Based on the availability of water in the ground, ground is classified into:

- (i) Zone of aeration.
- (ii) Zone of saturation.

- Saturation formations of Earth further classified into:-

(i) Aquifer:- formations which are porous and permeable. They only yield reliable amounts of water.
Eg: Sandy soils.

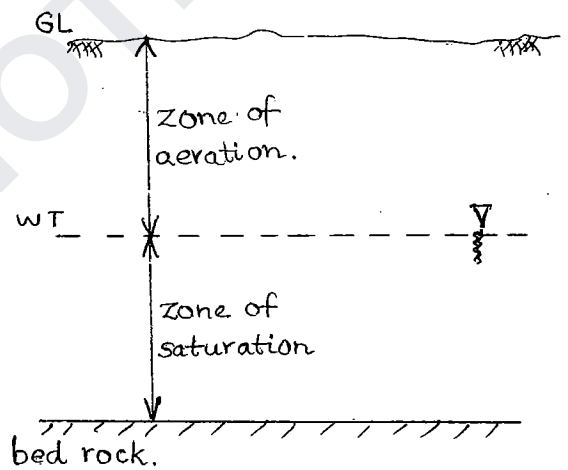
(ii) Aquitard - formations which are porous & semi permeable.
Eg: Sandy, clayey soils.

(iii) Aquiclude - porous and impermeable formations.
Eg: Clayey soils.

(iv) Aquifuge - formations which are neither porous nor permeable.
Eg: Granite, rock etc.

- Aquifers are further classified into:

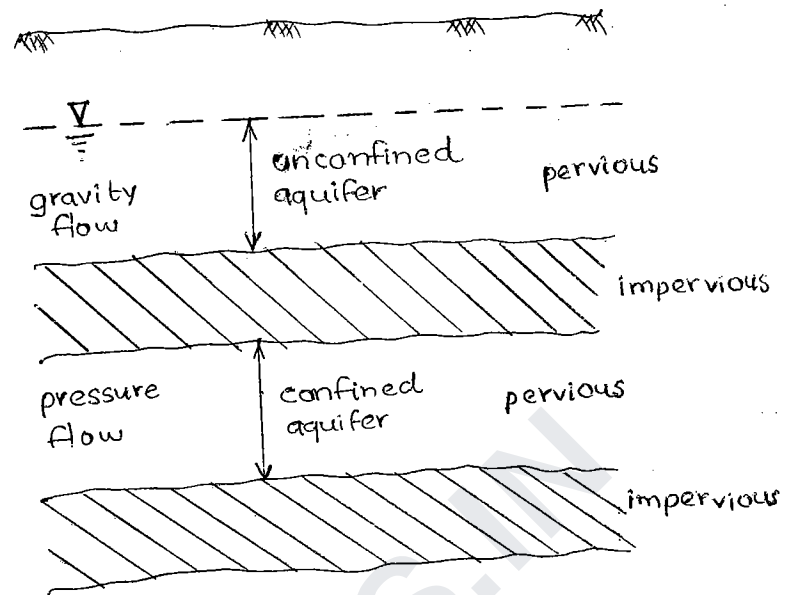
1. Unconfined Aquifer
2. Confined Aquifer.



Unconfined aquifer is also called as 'Water Table Aquifer'.

Confined aquifer is also called as 'Artesian Aquifer'.

Flow in unconfined aquifer is under gravity whereas that in confined aquifer is under pressure.



→ Aquifer Properties:

1. Porosity, 'n'
2. Specific Yield, 'Sy'
3. Specific retention, 'Sr'

* Porosity (n):

Storage capacity of soil depends on porosity.

$$n = \frac{V_v}{V}$$

$n > 20\%$ → adequate water

$5 < n < 20\%$ → moderate amounts of water

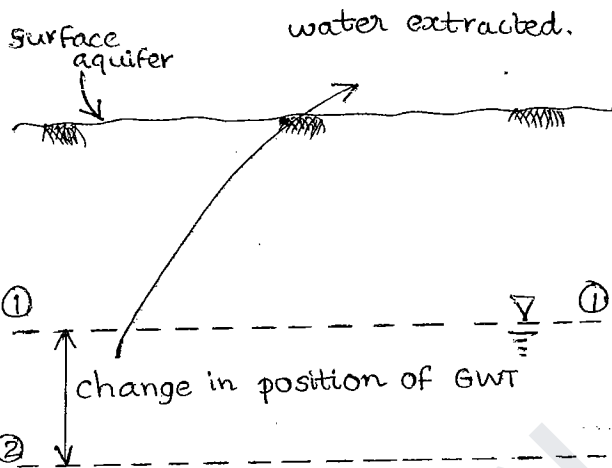
$n < 5\%$ → very less amount of water.

* Specific Yield (Sy):

Volume of water extracted by force of gravity from unit volume of aquifer is known as Specific Yield.

$$S_y = \frac{\text{volume of water extracted}}{\text{volume of aquifer}}$$

ΔGWT = thickness of aquifer from which water extracted.



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Volume of aquifer
= Surface area of aquifer
 $\times \Delta GWT$

Change in groundwater storage = volume of water extracted = $S_y \times$ volume of aquifer

* Specific Retention (S_r):

Fraction of water retained by the soil against force of gravity is known as Specific Retention.

- Relation among Porosity, Specific Yield & Specific Retention

$$n = S_y + S_r$$

-54.

01. $n = 0.4, S_r = 0.15$

$$\Rightarrow S_y = 0.4 - 0.15 = 0.25$$

$$\begin{aligned} \text{Volume of aquifer} &= 150 \times 10^4 \times (23-20) \times 25 \\ &= 112.5 \times 10^4 \text{ m}^3 = 112.5 \text{ ha.m} \end{aligned}$$

Change in ground water storage of aquifer = $S_y \times$ volume of aquifer

$$= 0.25 \times 150 \times 3 = 112.5 \text{ ha.m}$$

02. Volume of water extracted = $3 \times 10^6 \text{ m}^3$

Volume of aquifer = $(102-99) \times 5 \times 10^6$

$$\text{Specific yield} = \frac{\text{volume of water extracted}}{\text{volume of aquifer}}$$

$$= \frac{3 \times 10^6}{3 \times 10^6 \times 5} = \frac{1}{5} = \underline{\underline{0.2}}$$

03. $n = 0.3$, $S_y = 0.2$, $\Delta GWT = 0.25 \text{ m}$, $A = 100 \text{ km}^2$

$$\begin{aligned} \text{Volume of water lost} &= \text{volume of water extracted} \\ &= S_y \times \text{volume of aquifer} \\ &= 0.2 \times 100 \times 10^6 \times 0.25 \\ &= 5 \times 10^6 \text{ m}^3 = \underline{\underline{5 \text{ million m}^3}} \end{aligned}$$

- Groundwater flow is governed by 'Darcy's Law'.

$$v = ki$$

where $v \rightarrow$ apparent velocity of flow.

$i \rightarrow$ slope of HGL = slope of water table.

$$Q = kiA$$

where $A \rightarrow$ area perpendicular to flow direction.

$k \rightarrow$ permeability of soil (horizontal hydraulic conductivity of soils)

• Infiltration is the vertical hydraulic conductivity of soils.

$$\text{Actual flow velocity} = v_a = \frac{v}{n}$$

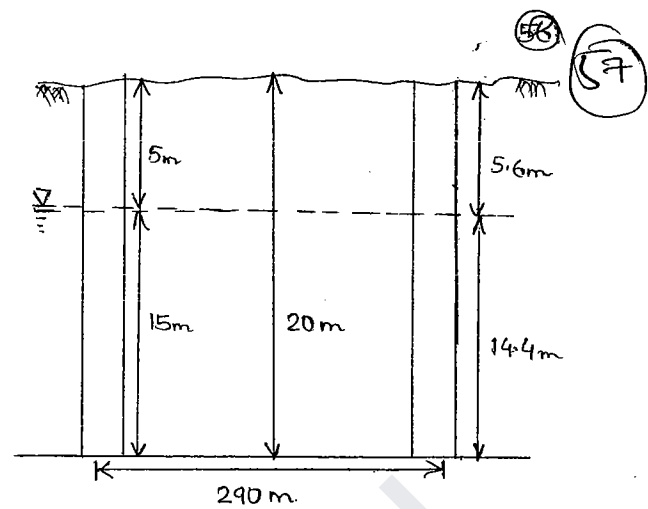
04. $K = 4 \times 10^{-3} \text{ cm/s} = \frac{4 \times 10^{-3} \times 10^{-2}}{1/86400} = \underline{\underline{3.456 \text{ m/day}}}$

$$i = \frac{5.6 - 5}{290} = 2.069 \times 10^{-3}$$

$$A = \left(\frac{15 + 14.4}{2} \times 1 \right)$$

$$Q = 3.456 \times 2.069 \times 10^{-3} \times \left(\frac{15 + 14.4}{2} \right)$$

$$= 0.105 \text{ m}^3/\text{day/m}$$



05. $i = \frac{50 - 25}{1500} =$

$$k = 30 \text{ m/day.}$$

$$v = ki = \frac{25}{1500} \times 30 = 0.5 \text{ m/day.}$$

$$v_a = \frac{v}{n} = \frac{0.5}{0.25} = 2 \text{ m/day.}$$

$$\text{Time of travel} = \frac{v_a \text{ Distance b/w wells}}{v_a}$$

$$= \frac{1500 \text{ m}}{2 \text{ m/day}} = 750 \text{ days}$$

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09. $i = \frac{45 - 39.5}{2000} = \frac{5.5}{2000}$

$$\text{Thickness} = 25 \text{ m.}$$

$$\text{Width} = 2000 \text{ m.}$$

$$k = 30 \text{ m/day.}$$

$$(1). \text{Total daily flow through aquifer} = 30 \times \frac{5.5}{2000} \times (25 \times 2000)$$

$$= 4125 \text{ m}^3/\text{day}$$

(ii) $i = \frac{45 - 39.5}{2000} = \frac{45 - h}{300}$

$$\Rightarrow h = 44.175 \text{ m}$$

$$\begin{aligned} 45 & \rightarrow 5.5 \\ 39.5 & \rightarrow ? \end{aligned}$$