UNIT I PRECIPITATION AND ABSTRACTIONS

Hydrologic cycle – Types of precipitation – Forms of precipitation – Measurement of Rainfall – Spatial measurement methods – Temporal measurement methods – Frequency analysis of point rainfall – Intensity, duration, frequency relationship – Probable maximum precipitation.

Hydrology:

The word hydrology is derived from the Greek words, hydro means water and logos means science. Hence hydrology means the science of water which deals with the occurrence, circulation and distribution of water on earth, its physical and chemical properties and its effects on environment. Hydrology is classified as,

- Scientific Hydrology – The study which is concerned with academic aspects.
- Engineering (or) Applied Hydrology - The study concerned with engineering applications

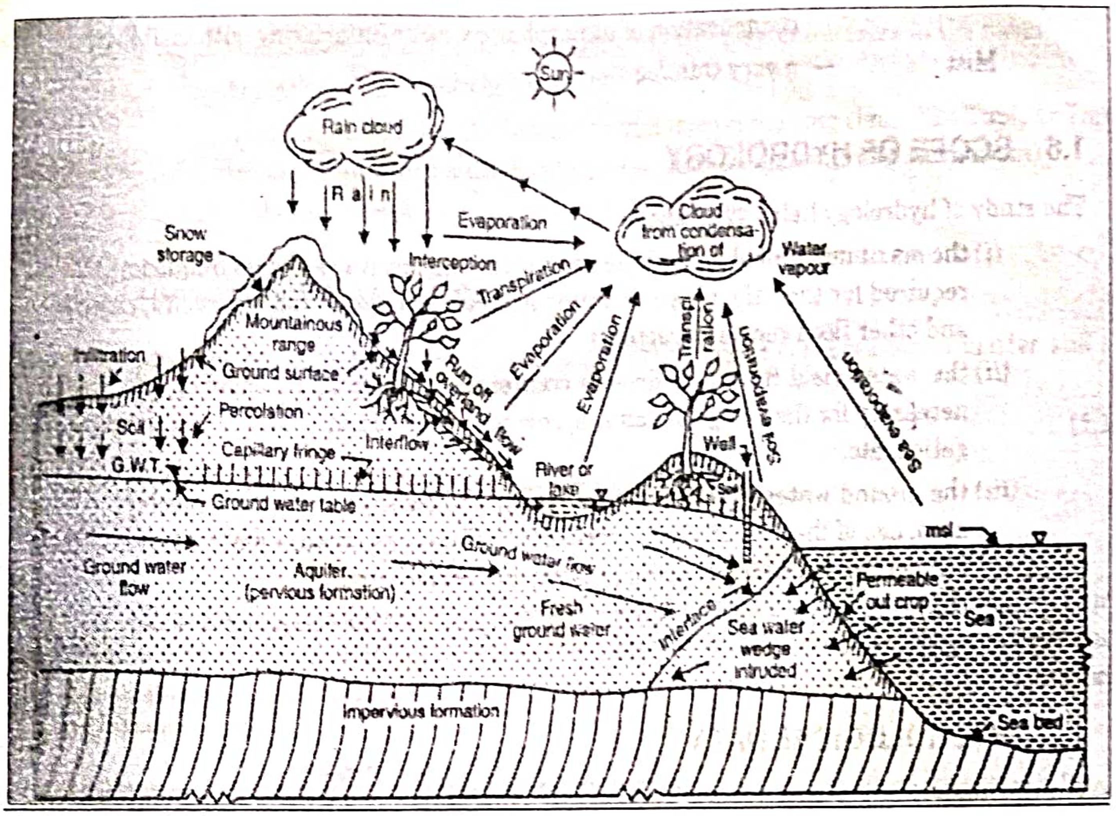
Hydrologic Cycle

Water occurs on the earth in all its three states, i.e., liquid, solid and gaseous state and is circulated through different paths like,

- Evaporation of water from water bodies such as oceans, ponds and lakes.
- Rain and snowfall.
- Runoff and stream flow.
- Groundwater movement.

The cycle which represents the different paths through which the water in nature circulates is called as hydrologic cycle.

Figure shows the schematic representation of the hydrologic cycle.



Hydrologic cycle

A convenient starting point to describe the cycle is oceans. Water in the oceans evaporates due to the heat energy provided by the solar radiation. The water vapour moves upwards and forms clouds. Evaporation of water from land surface, soil and other surface water bodies like ponds, lakes, reservoirs also contribute to the formation of clouds. Much of the clouds condense and fall back to the ocean as rain, while a part of clouds is driven to the land areas by winds. There they condense and precipitate onto the land mass as rain, snow, hail, sleet etc. A part of the precipitation may evaporate back to the atmosphere even while falling. Another part may be intercepted by vegetation, structures and other such surface modifications from which it may be either evaporated back to atmosphere or move down to ground surface.

A portion of the water that reaches the ground enters the earth's surface gets infiltrated through the soil and enhance its moisture content and reaches the groundwater surface. Vegetation sends a portion of the water from the ground surface back to atmosphere through the process of transpiration. The groundwater may come to the surface through springs and other outlets after spending a considerably longer time than the surface flow.

The precipitation reaching the ground surface after travelling a variety of paths above and below the surface of the earth moves down the natural slope over the surface called as runoff. This runoff when reaches a stream, it is called as stream flow. The stream flow travels through the network of rivers to reach the ocean and the hydrologic cycle continues.

Components of hydrologic cycle

The main components of hydrologic cycle can be classified as transportation components (flow components) and storage components as below,

Transportation Components	Storage components
Precipitation	Storage on water surface like oceans, rivers and ponds
Evaporation	Storage on land surface
Transpiration	Storage on soil
Infiltration	Groundwater storage
Runoff	

Nature of hydrologic cycle

- The hydrologic cycle is very vast and complicated cycle in which there are a large number of paths of varying time scales.
- It is a continuous cycle in which there is no beginning or ending or pause.
- The hydrologic cycle is very important in variety of fields like agriculture, forestry, geography, economics, sociology and projects dealing with water like water supply, drainage, irrigation, water power, flood control etc.

Water budget equation

The quantities of water going through various individual paths of the hydrologic cycle in a given system can be described by a principle known as water budget equation or hydrologic equation. For a given area and given time interval, continuity equation for water in its various phases is given as,

$$Mass\ inflow - Mass\ outflow = Change\ in\ mass\ storage$$

While substituting the terms in the hydrologic equation, the expression can be written as,

$$P - R - G - E - T = \Delta S$$

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

P – Precipitation

R – Surface runoff

G – Groundwater flow

E – Evaporation

T – Transpiration

ΔS - Change in storage $= \Delta S_s + \Delta S_{sm} + \Delta S_g$

ΔS_s – Water stored in surface water bodies

ΔS_{sm} – Water stored in soil

ΔS_g – Water stored in groundwater body

The above equation can also be written in terms of rainfall – runoff relationship as,

$$R = P - L$$

Where

P - Precipitation

R – Runoff

L – Loses (water not available to runoff due to infiltration, evaporation, transpiration, groundwater flow etc.)

Precipitation

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

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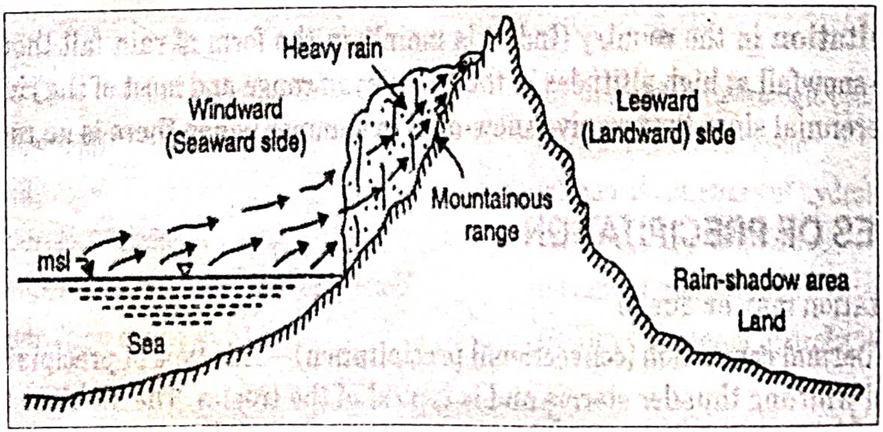
Types of Precipitation (or) Formation of precipitation

1. *Convective precipitation (or) thermal convection*:

In this type of precipitation, moist air mass (a packet of air in which temperature and humidity characteristics are homogeneous at a given elevation) close to the warm earth gets heated and rises upwards because of its lower density. At a particular height, air from cooler surroundings, cools the packet of air resulting in formation of clouds. Depending upon the moisture, thermal and other conditions light showers to thunderstorms can be expected in convective precipitation. Usually the areal extent of such rains is small, being limited to a diameter of about 10 km. This type of precipitation usually occurs in tropical areas.

2. *Orographic precipitation (or) orographic lifting*:

The moist air masses (a packet of air in which temperature and humidity characteristics are homogeneous at a given elevation) may get lifted up to higher altitudes due to the presence of mountain barriers and consequently undergo cooling, condensation and precipitation. Such a precipitation is known as orographic precipitation. Thus in mountain ranges, the windward slopes have heavy precipitation and leeward slopes have light rainfall.



Orographic precipitation

poration - process in which water from liquid state changes to vapour. Molecules are in motion with wide range of velocity. Addition of heat increases velocity - which possess KE and ejected themselves into atmosphere

3. *Cyclonic precipitation*:

A cyclone is a more or less a circular area of low atmospheric pressure in which wind blows spirally inward in counter clockwise direction in the Northern hemisphere and in clockwise direction in Southern hemisphere. The centre of the storm is called as the eye which may extend to about 10 to 50 km in diameter. Outside the eye, very strong winds reaching to as much as 200 kmph exist. The wind speed gradually decreases towards the outer edge. When they move over the seas, they absorb moisture and derive their energy from the latent heat of condensation of moisture and they increase in size as they move on. When they move over the land, because of increase in friction and lack of moisture supply, the cyclone dissipates its energy very fast resulting in heavy precipitation over large areas for several days.

4. *Frontal precipitation*:

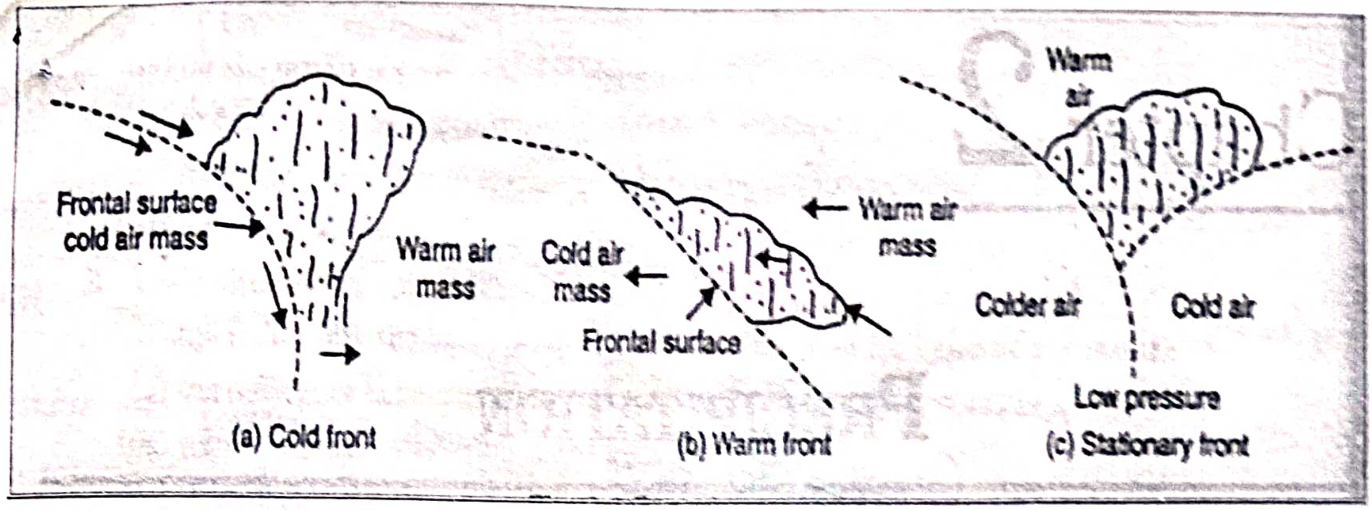
The surface of contact between two distinct air masses is called as a frontal surface or front. Under certain condition when a warm air mass and a cold air mass meet, a frontal surface is created and the warmer air mass is lifted over the cold one above the frontal surface. The warm air above cools with the consequent formation of clouds and precipitation.

The fronts are classified according to their motion as cold front, warm front and stationary front,

Cold front – When the cold air is moving into stationary warm air forcing the warm air up over the frontal surface, then it is called as Cold front.

Warm front – When the warm air is moving over a stationary cold air mass, then it is called as Warm front.

Stationary front – When the two air masses are drawn simultaneously towards a low pressure area, the front developed is called a stationary front.



Frontal precipitation

Forms of Precipitation

1. *Drizzle*

A fine sprinkle of numerous water droplets of size less than 0.5 mm is called drizzle. The intensity of drizzle is usually less than 1 mm/h. The drops are so small that they appear to float in air.

2. *Rain*

It is the most common form of precipitation in India. The term rainfall is used to describe precipitations in the form of water drops of sizes larger than 0.5 mm. The maximum size of raindrop is about 6 mm. Any drop larger in size than this tends to break up into drops of smaller sizes during its fall from the clouds. On the basis of its intensity rainfall may be classified as,

Sl. No.	Type	Intensity (mm/h)
1	Light	< 2.5
2	Moderate	2.5 to 7.5
3	Heavy	>7.5

3. *Glaze*

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

4. Sleet

When rain drops are frozen while falling through a layer of subfreezing air (below 0°C), transparent globular grains of ice called as sleet is formed. They are generally 1 to 4mm in diameter.

5. Dew

Dew forms directly by condensation of the moisture on the ground surface during the night time when the surface has been cooled.

6. Snow

Snow is another important form of precipitation. Snow consists of ice crystals. When these crystals combine together they are called as snowflakes. Snow has an initial density of 0.06 g/cm^3 to 0.15 g/cm^3 and it's assumed to have an initial density of 0.1 g/cm^3. In India, snow occurs only in Himalaya regions.

7. Hail

Hail is a showery precipitation in the form of irregular pellets or lumps of ice of size more than 8 mm. Hail are generally composed of alternating solid and opaque layers. They occur in violent thunderstorms and they produce huge impact.

Measurement of rainfall · (Spatial measurement)

It is the most common form of precipitation in India. Rainfall is expressed (or) measured in terms of depth to which the rainfall water would stand on an area if all rainfall were collected on it. The rainfall is collected and measured using a raingauge. Terms such as pluviometer, ombrometer and hyetometer are also sometimes used to denote a raingauge.

Raingauge

A raingauge essentially consists of a cylindrical vessel assembly kept in open area. The rainfall catch of the raingauge is affected by its exposure condition. To enable the catch of raingauge to accurately represent the rainfall in the area surrounding the raingauge, standard settings are adopted. For siting a raingauge the following considerations are important,

- The ground must be level and in the open and the instrument must present a horizontal catch surface.
- The gauge must be set as near the ground as possible to reduce wind effects but it must be sufficiently high to prevent splashing, flooding etc
- The instrument must be surrounded by an open ~~forced~~ fenced area of at least 5.5 x 5.5 m. No object should be nearer to the instrument than 30 m or twice the height of the obstruction.

Types of raingauge

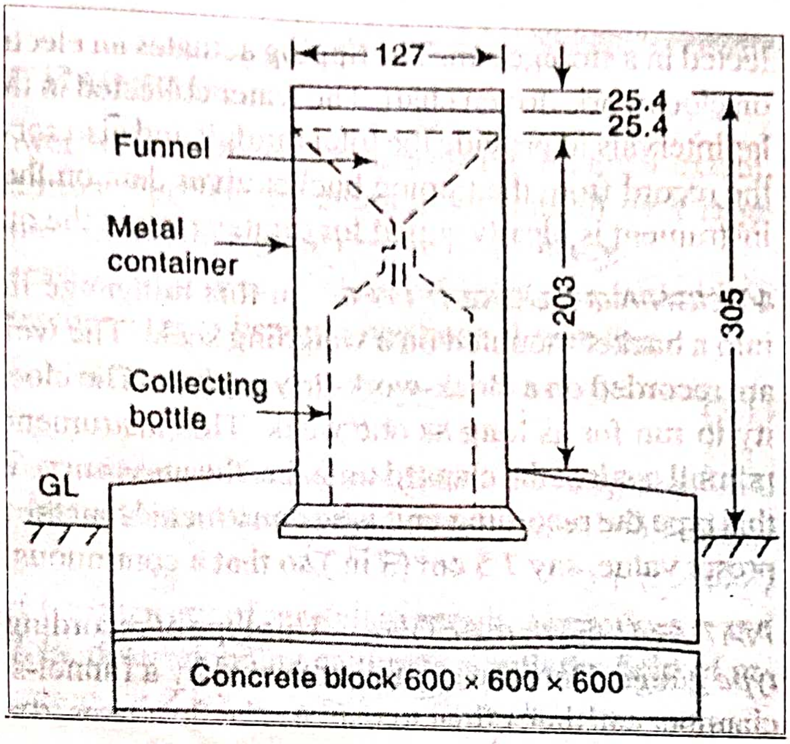
Raingauges can be broadly classified into two categories such as non recording and recording raingauges.

Non recording raingauges

Non recording raingauge gives only the total depth of the rainfall and does not give the intensity and duration of rainfall during different time intervals of the day. The non recording raingauge extensively used in India is Symons Gauge. It essentially consists of a circular collecting bottle of 12.7 cm (5 inch) diameter connected to a funnel. The funnel and the collecting bottle are housed inside a metallic container. The metallic container is fixed vertically to the masonry foundation such that the rim of the collector is set at a height of 30.5 cm above the ground level. The funnel discharges the rainfall catch into the collector bottle. Water contained in the collecting bottle is measured by a suitably graduated measuring glass, with an accuracy upto 0.1 mm.

For uniformity, the rainfall is measured at every day at 8.30 AM (IST) and is ecorded as the rainfall of that day. The collecting bottle normally does not hold more han 10 cm of rain and as such in the case of heavy rainfall the measurements must be one frequently and entered. However, the last reading must be taken at 8.30 AM and the um of the previous readings in the past 24 hours entered as rainfall of that day.

Proper care, maintenance and inspection of raingauges is required, especially during dry weather to keep the instrument free from dust and dirt. The gauge should be protected from being damaged by cattle by erecting a wire fence around it.



Non recording raingauge

This raingauge can also be used to measure snowfall. When snow is expected, the funnel and the collecting bottle are removed and the snow is allowed to collect in the outer metallic container. The snow is then melted and the depth of resulting water is measured. Antifreeze agents are sometimes used to facilitate melting of snow. In areas with high snowfall, special snowgauges with shields (for minimizing wind effects) and storage pipes (to collect snow over longer durations) are used.

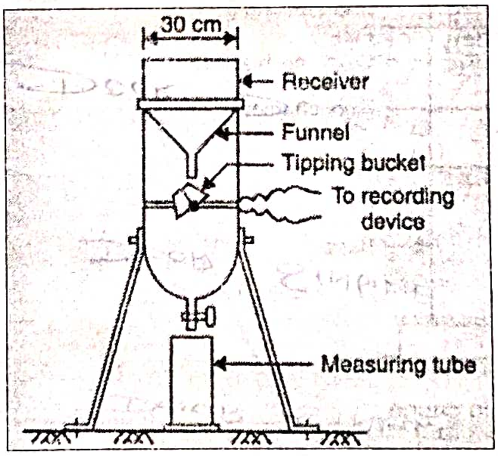
Recording raingauges

This type of raingauges is also called as self-recording, automatic or integrating raingauge. This type of raingauge has an automatic mechanical arrangement consisting of clockwork, a drum with a graph paper fixed around it and a pen. It works on the principle that the clockwork drives the drum with a graph paper on which the pen draws a curve called 'Mass curve'. From this mass curve, the depth of rainfall in a given time, the intensity of rainfall at a particular time and duration of rainfall can be determined.

The raingauge is installed on a concrete or a masonry platform 45 cm square. The gauge is installed so that the rim of the funnel is at a height of 75 cm above the ground surface. Following are some of the commonly used recording raingauges.

1. *Tipping Bucket type*

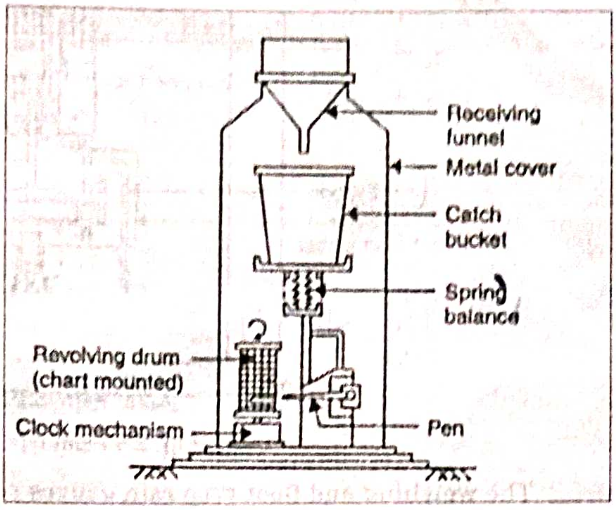
This consists of a cylindrical receiver 30 cm in diameter with a funnel inside. Just below the funnel a pair of tipping buckets is pivoted on a horizontal axis. The rainfall is led from the receiver through the funnel into one of the buckets. When one of the buckets receives a rainfall of 0.25 mm it tips and empties the rainfall into a tank below, while the other bucket takes its position and the process is repeated. The tipping of the bucket actuates an electric circuit and drives the pen to move over the chart on the drum which revolves by a clock mechanism. The water collected in the storage can is measured at regular intervals to provide the total rainfall and also serves as a check. It may be noted that from the number of tips and the time taken, the intensity and duration of rainfall can be calculated.



Tipping bucket type raingauge

2. *Weighing Bucket type*

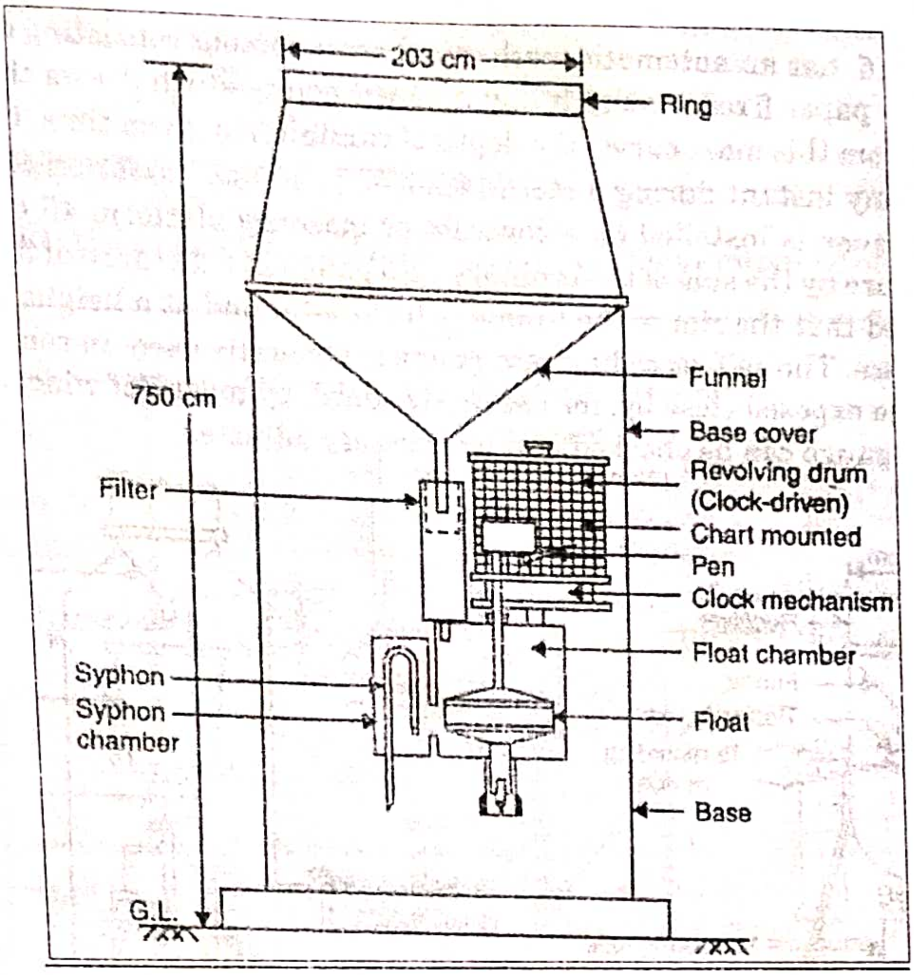
In this raingauge, the rainfall falling through the receiver is led into a catch bucket which rests on a platform provided with spring balance. When a certain weight of the rainfall is collected on the bucket, the spring balance makes the pen to record on a chart wrapped around a clockwork driven drum. The rotation of the drum provides the time taken and the vertical motion of the pen provides the cumulative precipitation from which intensity and duration of rainfall can be found out.



Weighing bucket type raingauge

3. *Natural Syphon type*

This type of recording raingauge is also known as float type gauge. Here the rainfall collected by a funnel shaped collector is led into a float chamber. The float chamber consists of a float with a vertical stem projecting outside, to the top of which a pen is mounted. The rainfall water in the float chamber causes the float to rise. As the float rises, a pen attached to the float, records the elevation of the float on a rotating drum driven by a clockwork. When the float chamber fills up, a syphon arrangement empties the float chamber and the pen is brought to zero again. From the time taken and the vertical motion of the pen, intensity and duration of rainfall can be found out.



Natural syphon type raingauge

~~Mean Precipitation over an area:~~

Spatial analysis of rainfall data

Raingauge represents only rainfall at a point on areal distribution of storm. To convert the point rainfall values at various stations into an average value over the catchment, the following methods are used.

→ Arithmetical mean method

→ Theissen Polygon method

→ Isohyetal method.

1) Arithmetical mean method

When the rainfall measured at various stations in a catchment show little variation, the average precipitation over the catchment area is taken as arithmetic mean of station values. Thus if the $P_1, P_2, \cdots P_m$ are the rainfall values in a given period in 'm' stations of a catchment, then the value of mean precipitation $\bar{P}$ is given as,

$$\bar{P} = \frac{P_1 + P_2 + \cdots + P_m}{M}$$

2) Thiessen Polygon method

In this method, the rainfall recorded at each station is given a weightage factor based on the area close to the station. The procedure of determining

the mean precipitation.. ~~Cons~~ Consider a catchment.
~~1) Consider~~ area as in figure containing three raing
stations (1, 2, 4). There are three stations (3, 5, 6) a
the catchment but in its ~~neighbo~~ neighbourhood.

Following is the procedure,

1) The catchment area is drawn to scale and the posi of the six stations are marked on it.

2) Stations 1 to 6 are joined to form a network of traingles.

3) Perpendicular bisectors of each of the sides of the ~~o~~ triangle are drawn.

4) These bisectors form a polygon around each station called Thiessen polygon

5) The polygonal area around each station the catchment area is measured using planimeter overlay grid.

6) If $P_1, P_2 \ldots, P_6$ are the rainfall measured on station …, 6 and $A_1, A_2, \ldots, A_6$ are respective areas of Thi polygon ~~then~~ then,

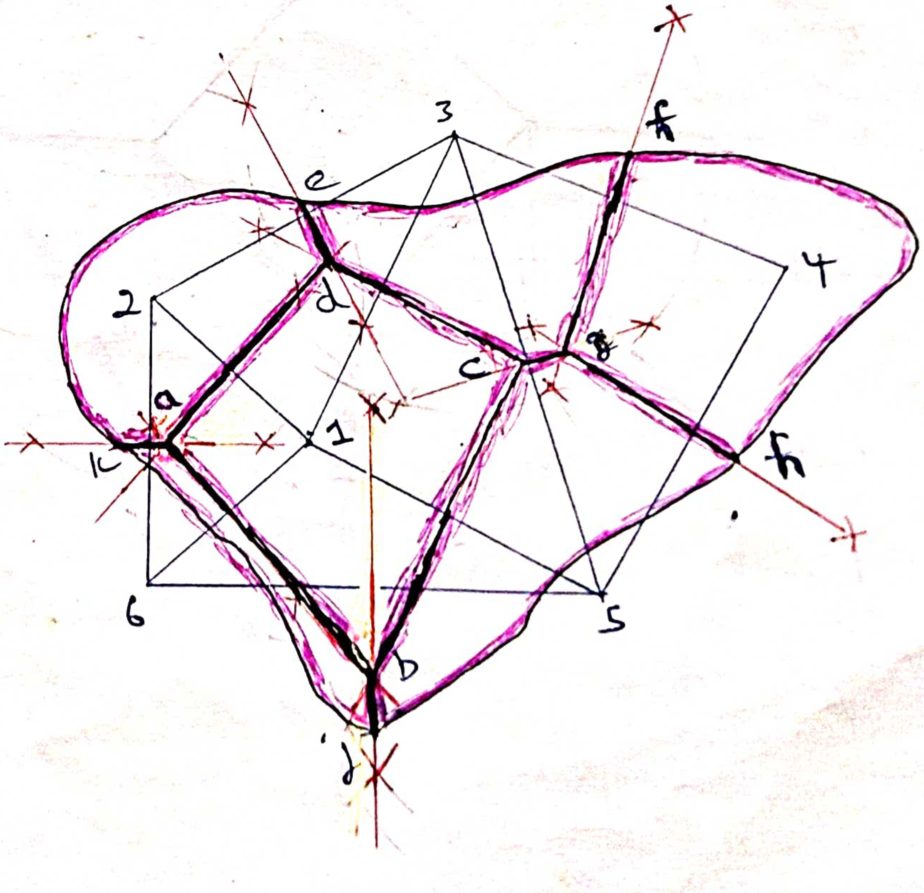
$$\bar{P} = \frac{P_1A_1 + P_2A_2 + \cdots + P_6A_6}{A_1 + A_2 + \cdots + A_6}$$

In general, $\bar{P} = \frac{\sum_{i=1}^{m} P_iA_i}{A} = \sum_{i=1}^{n} \frac{P_iA_i}{A}$

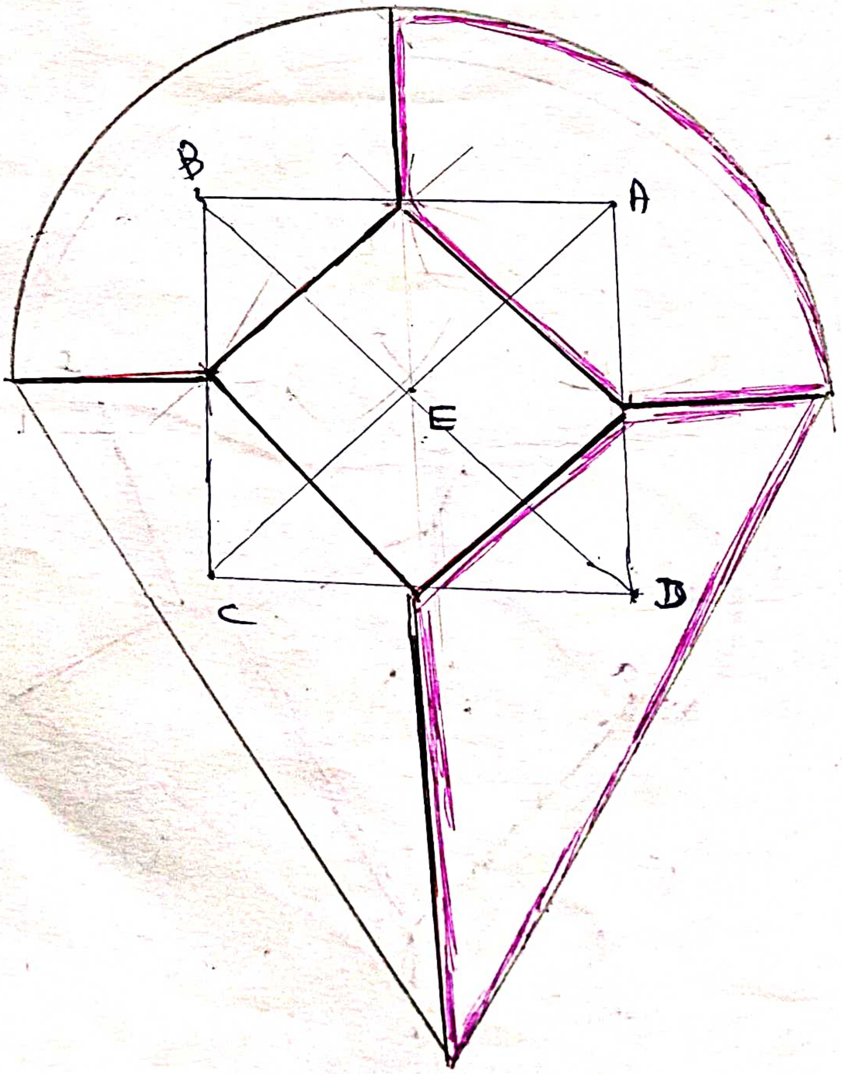
The ratio $\frac{A_i}{A}$ is called weightage factor for each station

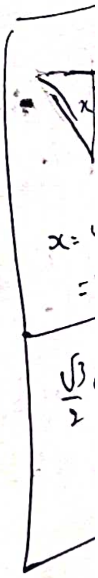
The thiessen ~~polyg~~ polygon method is superior ~~or~~ than arithmetic average method as it gives some weightage to each raingauge station based on its location. Further raingauges outside catchment are also used effectively.

Station	Area
1	abcd
2	kade
3	edcgf
4	fgh
5	hgcbj
6	jbak



Pb) A semicircle of diameter 20km with a equilateral triangle of 20km below its diameter is a close approxiation to a river basin. The position coordinates of 5 raingauge stations A, B, C, D and E located within the basin with respect to a coordinate axes system whose x and origin or coincided with diameter and center of circle are (5,5), (-5,5), (-5,-5), (5,-5) and (0,0) km respectively. If rainfall recorded at these raingauge are 85, 92, 77, 80 and 105 mm respectively. ~~If the rainfall~~ Determine the average rainfall depth using Thiessen polygon method



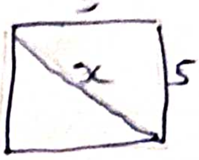


Total area, A = Area of semicircle + Area of equilateral triangle

$= \frac{\pi r^2}{2} + \frac{1}{2} bh$

$= \frac{\pi \times 10^2}{2} + \frac{1}{2} \times 20 \times 17.32 = 157.08 + 173.2$

$= 330.28 \text{ km}^2$



$x = \sqrt{5^2+5^2}$
$= 7.071$

Area of polygon for station E, $A_E = 7.071 \times 7.071$

$= 50 \text{ km}^2$

Area of polygon for station A & B,

$A_A = A_B = \frac{1}{2}(\text{Area of semicircle}) - \frac{1}{4}(\text{Area of square})$

$= \frac{1}{2}(157.08) - \frac{1}{4}(50)$

$= 66.04 \text{ km}^2$

Area of polygon for station C & D,

$A_C = A_D = \frac{1}{2}(\text{Area of equilateral triangle}) - \frac{1}{4}(\text{Area of square})$

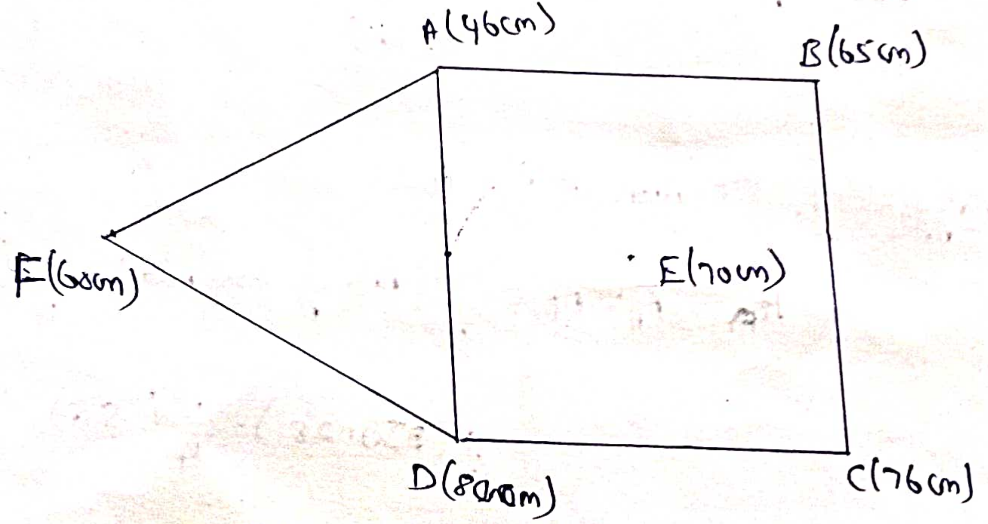
$= \frac{1}{2}(173.2) - \frac{1}{4}(50)$

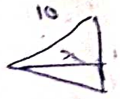
$= 74.1 \text{ km}^2$

Mean precipitation, $\bar{P} = \frac{P_A A_A + P_B A_B + P_C A_C + P_D A_D + P_E A_E}{A_A + A_B + A_C + A_D + A_E} = 86.51 \text{ mm}$

⑲

Pb) The area shown in fig. is composed of a square plus an equilateral triangular plot of side 10 km. The annual precipitation of the ~~raingangle~~ raingauge stations located at four corners and centre of square plot and apex of triangular plot are indicated in fig. Find the mean precipitation over the area by Thiessen polygon method and compare with arithmetic mean.



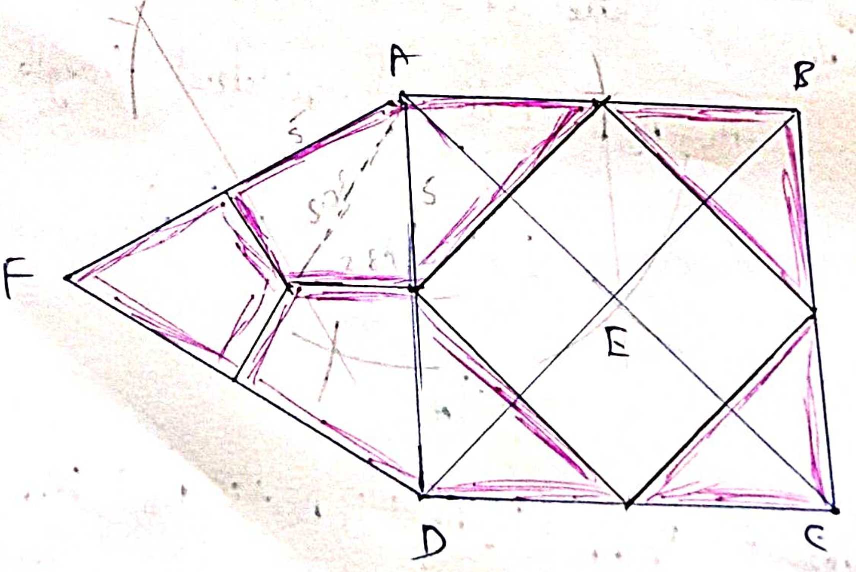


$x = \sqrt{1}$

$= 8$

Solution:

Thiessen polygon method



Equilateral

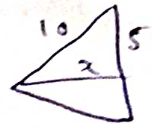
Area $= \frac{\sqrt{3}}{4}$

Height $= \sqrt{}$

Total area = Area of square + Area of equilateral triangle

$$= (10 \times 10) + \frac{1}{2} \times 8.66 \times 10 = 100 + 43.33$$

$$= 143.33 \text{ km}^2.$$



$x = \sqrt{10^2 - 5^2}$

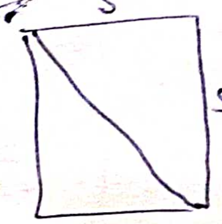
$= 8.66$

$h = \frac{\sqrt{3}a}{2} = \frac{\sqrt{3}(10)}{2}$

$= 8.66$

Area of polygon for, station E $A_E = 7.071 \times 7.071$

$$= 50 \text{ km}^2$$



$x = \sqrt{5^2 + 5^2}$

$= 7.071$

Area of polygon for, station B & C $A_B = A_C = \frac{(10 \times 10) - 50}{4}$

$$= 12.5 \text{ km}^2$$

Area of polygon for station F, $A_F = \frac{1}{3}$(Area of equilateral triangle)

$$= \frac{1}{3}(43.33)$$

$$= 14.44 \text{ km}^2$$

Area of polygon for station A & D, $A_A = A_D$ = Area of trapezoidal portion (A_F) + Area of triangular portion (A_B)

$$= 14.44 + 12.5$$

$$= 26.94 \text{ km}^2$$

Mean precipitation, $\bar{P} = \frac{P_A A_A + P_B A_B + P_C A_C + P_D A_D + P_E A_E}{A_A + A_B + A_C + A_D + A_E}$

$$=\frac{(26.94\times46)+(12.5\times65)+(12.5\times76)+(26.94\times80)+(50\times70)+(14.44\times60)}{\cancel{26.94+}\quad 143.33}$$

$$= 66.44\text{ cm}$$

Arithmatic mean method

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

$$\therefore = \frac{46+65+76+80+70+60}{6}$$

$$= 66.17\text{ cm}$$

Both methods gives approximately same results

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3) Isohyetal Method

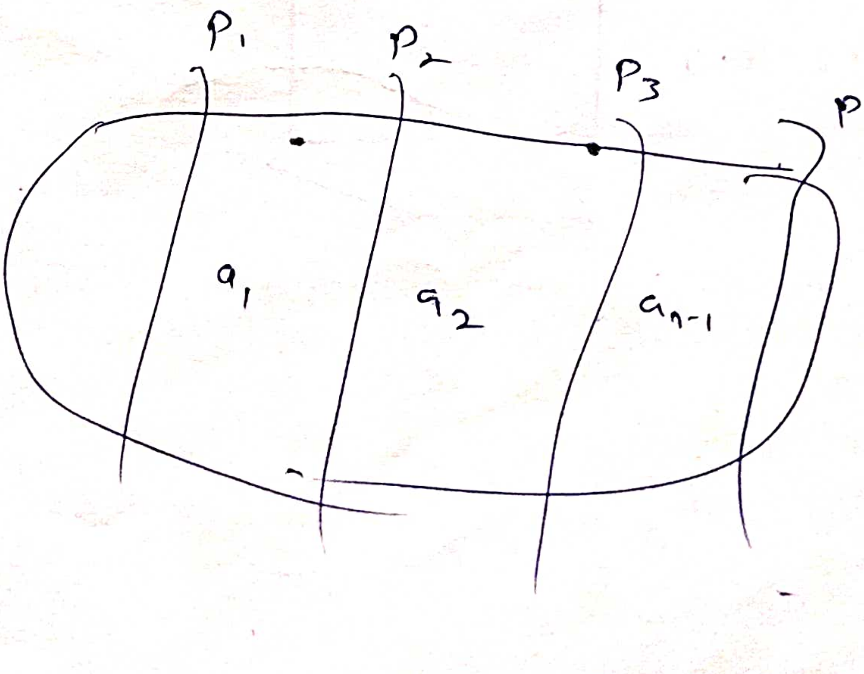
An isohyet is a line joining points equal rainfall magnitude. The following is the procedure for determini mean precipitation by isohyetal method.

1) The catchment area is drawn to scale and the positi of raingauge stations are marked on it.
2) The recorded values of rainfall of the statio are marked on appropriate stations
3) Isohyetes of rainfall values are drawn

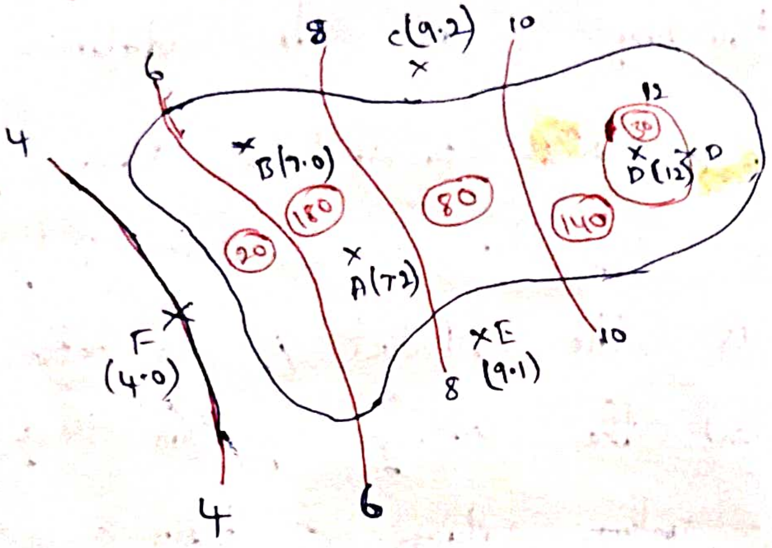
4) The area between two adjacent isohyetes are then determined with a planimeter or overlay grid. If the isohyetes go out of the catchment, the ~~cat~~ catchment boundary is used to determine area.

5) The ~~area between mean precipitation~~ volume of rainfall between any two ~~set~~ successive isohyetes is computed as the product of area between those isohyetes and the average of two isohyetal values. All such ~~values~~ volumes of basin are totalled and divided by basin area to find the average depth of rainfall.

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



Pb: The isohyets ~~&~~ due to a storm in a catchment were drawn as in fig. and the area of catchment bounded by isohyets are tabulated below



Isohyets (cm)	Area (km²)
Station - 12.0	30
12.0 - 10.0	140
10.0 - 8.0	80
8.0 - 6.0	180
6.0 - 4.0	20.

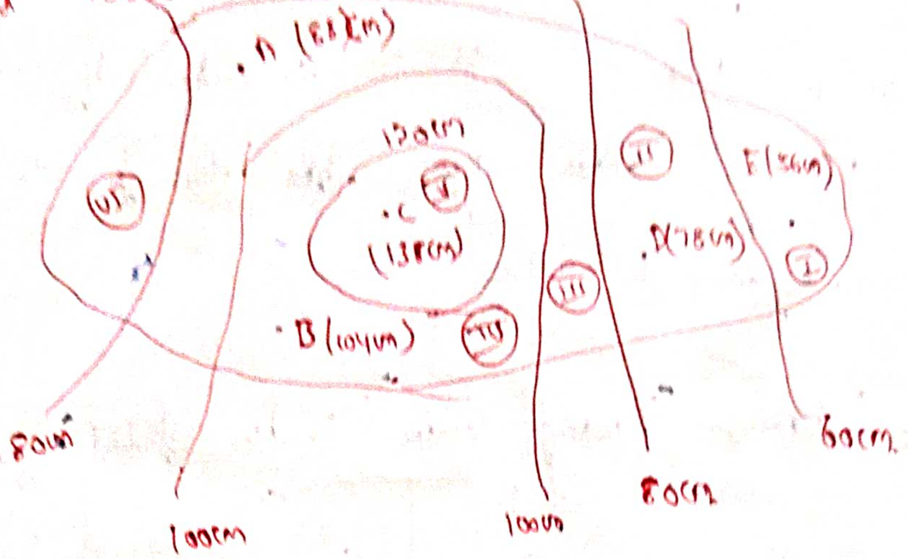
Solution:

For first area 30km², the precipitation value of 12 cm is taken as it is surrounded by a closed isohyet. For all other areas, the mean of two bounding ~~areal~~ isohyets is taken.

Isohyetes ①	Area ②	Average value of P ③	Fraction of total area ④ = ②/450	Weighted P ③×④
12	30	12	0.0667	0.8
12.0-10.0	140	11	0.3111	3.422
10.0-8.0	80	9	0.1778	1.6
8.0-6.0	180	7	0.4	2.8
6.0-4.0	20	5	0.0444	0.222
	450		1.0	8.844

Mean precipitation, $\bar{P} = 8.844$ cm

P1) The isohyetal due to a storm were drawn in fig and area of catchment are tabulated below.



Zone	Area (km²)
I	410
II	900
III	2850
IV	1750
V	720
VI	550

Zones ①	Area ②	Average value of P ③	Fraction of total area ④ = ②/7180	Weighted P ③×④
I	410	60	0·0571	3·4260
II	900	70	0·12535	8·7745
III	2850	90	0·39694	35·7246
IV	1750	110	0·24373	26·8103
V	720	120	0·10028	12·0336
VI	550	80	0·0766	6·128
	7180		1	92·897

Mean precipitation = 92·897 cm

Estimation of evaporation:

The estimation of evaporation from a water surface is frequently required in planning and design of many water resource projects. In providing the reservoirs to meet the needs of water supply, irrigation systems and other needs, its capacity should be found out giving consideration to the evaporation losses. Similarly in the design of a long canal in arid or semi-arid regions, evaporation losses are important. Hence the amount of water evaporated from a water source are estimated using,

- Evaporimeters
- Empirical equations
- Analytical methods

Evaporation - Evaporation is a process in which water from liquid state changes to gaseous state (vapour) and is difessed into atmosphere. The molecules of a water body (or pond) are in constant motion with different velocities. Addition of heat due to solar radiation increases velocity of molecule thereby molecule posses kinetic energy by which they cross water surface and they eject themselves into atmosphere.

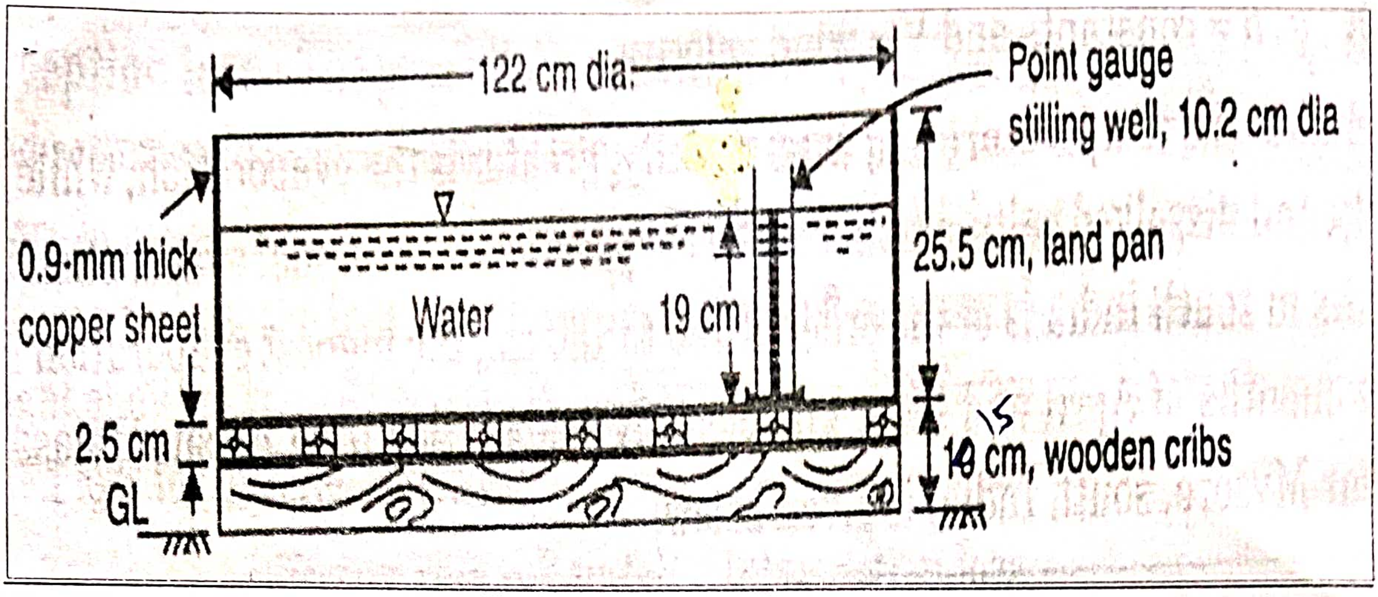
Evaporimeters (or) evaporation pans:

Evaporimeters (or) pans are the most commonly used evaporation measuring devices because they are inexpensive and simple to construct. These are water containing pans which are exposed to atmosphere and the loss of water by evaporation is measured. at regular intervals. Meteorological data such as humidity, wind movement, air and water temperatures and precipitation are also noted along with evaporation measurement. Following are the type of evaporimeters,

1. *Class A land Pan (or) Surface pan*

The most common type of evaporation pan is the surface pan. In most of the countries, the surface pan follows to the standard United States Weather Bureau Class A Land pan shown in fig.

Interception - Part of rainfall that does not reaches the soil but instead intercepted by earth surface like vegetation, buildings etc. This water gets subsequently evaporated.



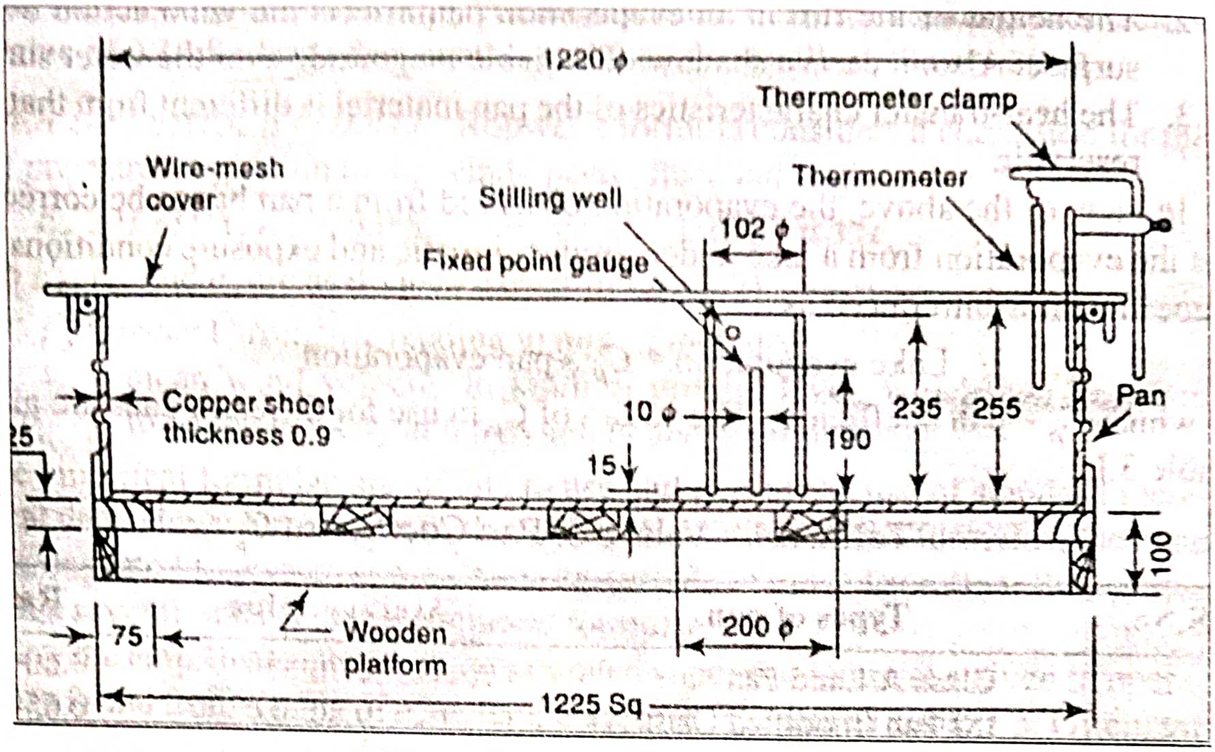
Class A Land pan

The pan is of 122 cm diameter and 25.5 cm deep and is made of unpainted galvanized iron. The pan is placed on a wooden grillage platform 15 cm above the ground level to permit free circulation of air under the pan. A fixed mark is indicated by a point
pipe with small inlets ~~connected~~ ~~with~~ ~~main~~ ~~water~~ ~~body~~. Connected with main water body
gauge in a stilling well which is kept in the pan. This fixed mark indicates the level of water. A calibrated cylindrical measure is used to add or remove water maintaining the water level in the pan to the fixed mark indicated by the point gauge in the stilling well. The depth of water is maintained between 18 cm and 20 cm.

The advantage of this pan is that it is easy to install and take observation, more stability, free from dirt and economic.

2. *ISI Standard pan*

This pan is also known as modified Class A pan. This pan is of 122 cm in diameter and a depth of 25.5 cm. The pan is made of copper sheet of 0.9 mm thickness tinned inside and painted white outside. The pan is placed over a square wooden grillage platform of 122.5 cm width and height 10 cm to permit free circulation of air under the pan. A fixed mark is indicated by a point gauge in a stilling well which is kept in the pan. This fixed mark indicates the level of water. A calibrated cylindrical measure is used to add or remove water maintaining the water level in the pan to the fixed mark indicated by the point gauge in the stilling well. A thermometer clamped at the top is used to read the air and water temperature. An anemometer is mounted at the level of instrument to note down the wind information.

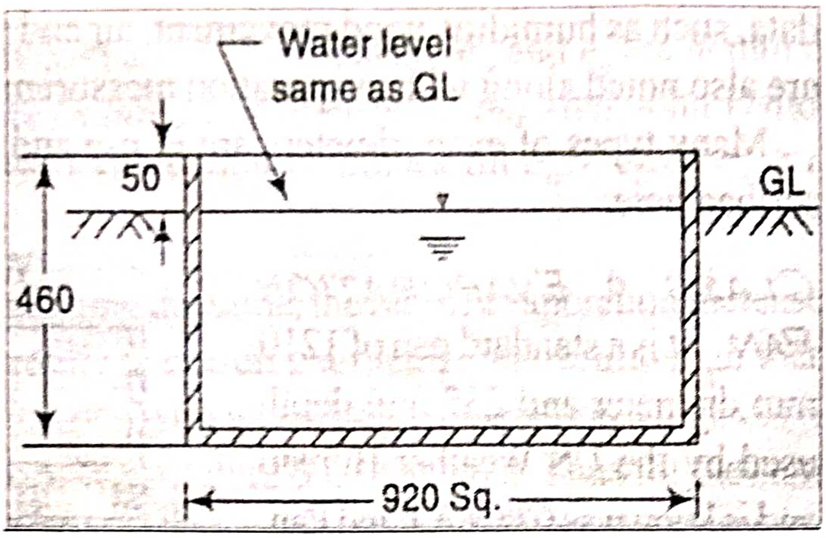


ISI Standard pan

The top of the pan is covered with a hexagonal wire mesh of galvanized iron to protect the water in the pan from birds. Further the presence of the wire mesh makes the temperature uniform during day and night. The evaporation from this pan is found to be less by about 14% compared to that of unscreened pan.

3. *Colorado sunken pan*

This pan is 92 cm square and 46 cm deep. The pan is made up of unpainted galvanized iron sheet and buried into the ground such that the top of its rim is 5 cm above the ground surface.



Colorado sunken pan

The chief advantage of this pan is that direct solar radiation on side walls and heat exchange through side wall are negligible and a condition similar to those of lake can be obtained. However it has disadvantages like it is difficult to install the pan, difficult to detect leaks, extra care is needed to keep the surrounding area free from tall grasses, dust etc.

4. *US Geological Survey floating pan*

In order to simulate the same characteristics of evaporation from a large water body of water US Geological Survey floating pan is used. This pan is square in plan with a side of 90 cm and 45 cm deep. It is supported by drum floats in the middle of raft of size 4.25 x 487 m and is kept floating in a lake. The water level in the pan is maintained at the same level as the water surface in the lake while the rim of the pan is 7.5 cm above the water level.

The use of this pan is not common due to its difficulty in installation, maintenance together with the difficulty involved in performing measurements. Splashing of water into the pan due to wave action takes place which can be reduced by providing diagonal baffles.

Pan coefficient:

Evaporimeters are not exact models of large lake or reservoir and have the following drawbacks.

- They differ in the heat storing capacity and heat transfer from the sides and bottom. Usage of sunken pan and the floating pan reduces this deficiency.
- The height of the rim in the evaporation pan affects the wind action over the surface. Also it creates a shadow of variable magnitude over the water surface which affects the radiation incident on the water surface.
- The heat transfer characteristic of the pan material is different from that of reservoir.

Due to the above drawbacks, the evaporation observed from a pan has to be corrected to get the evaporation from a lake under similar climatic and exposure conditions.

Lake evaporation = C_p x Pan evaporation

Where C_p = Pan Coefficient

The values of C_p for different pans is given below.

Sl. No.	Type of Pan	Average value	Range
1	Class A land Pan	0.70	0.60 – 0.80
2	ISI Standard pan	0.80	0.65 – 1.10
3	Colorado sunken pan	0.78	0.75 – 0.86
4	US Geological Survey floating pan	0.80	0.70 -0.82

Empirical equations:

A large number of empirical equations are available to estimate lake evaporation using commonly available meteorological data. Most of the formulae are based on the Dalton equation, $E_L = k(e_w - e_a)$ and can be expressed in general form,

$$E_L = Kf(u)(e_w - e_a)$$

Reservoir Evaporation and methods of reduction

Out of the methods used for estimation of evaporation, analytical methods provide better results but parameters" are difficult to access. or expensive to obtain. Emprical equations gives only approximate values. Hence pan measurements is considered to give better results and they are accepted for practical applications.

The water volume lost from the reservoir in a month is calculated as

$$V_E = A E_{pm} C_p$$

where V_E → Volume of water lost in evaporation in a month (m^3)

A → Average reservoir area during the month (m^2)

E_{pm} → Pan evaporation loss in a month (m)

$= E_L (mm/day) \times$ No. of days in a month $\times 10^{-3}$

C_p → Relevant pan coefficient.

Evaporation suppression

Evaporation from a water surface is a continuous process. The quantity of water lost in evaporation in a year is quite considerable as surface area of many natural and man made lakes are very large. As the construction of reservoir involves economy, there is an importance in conservation of water by reducing the evaporation. Various methods available for reduction of evaporation losses ~~can~~ ~~be~~ are

(i) Reduction of surface area

Volume of water lost by evaporation is ~~directly~~ directly proportional to the surface area of water body. Hence it is essential to construct deep reservoirs in place of wide reservoirs

(ii) Mechanical Covers:

Permanent roofs, temporary roofs and floating roofs such as rafts and light weight floating particles can be adopted. But these roofs are limited to very small water bodies like ponds etc

(iii) Chemical films:

This method consists of applying a thin chemical film on the water surface to reduce evaporation. Currently this is only the ~~easy~~ feasible method available for reduction of evaporation of water from ~~moderate~~ reservoirs of moderate size.

Certain chemicals like cetyl ~~alcohol~~ alcohol (hexadecanol) and stearyl alcohol (octadecanol) are used. Out of the two chemicals, cetyl alcohol is the most suitable chemical used as evaporation inhibitor. It is a white, waxy, crystalline solid and is available as lumps, flakes and powder. It can be ~~obta~~ applied on water surface in the form of powder, emulsion or solution. Roughly 3.5 N/ hectare/day of cetyl alcohol is needed for effective action. ~~The~~

The thin chemical film formed has the following features

-> The film is strong and flexible and does not break due to wave action

-> If punctured due to impact of raindrops, or by birds, insects etc the film closes back

-> The film is pervious to oxygen and carbon di oxide and hence water quality is not affected by its presence.

-> It is odourless and non toxic.

(iv) By growing tall trees like Causerina on reservoir to act as wind break

(v) By allowing flow of water, temp is reduced hence less evaporation

EVAPOTRANSPIRATION

Transpiration

Transpiration is the process by which water leave the body of a living plant and reaches the atmospher as water vapour. The water is taken up by the plant root system and escapes through the leaves.

Problems (pan evaporation)

1) The following are the monthly pan evaporation data at a certain place in the certain year. The water spread area in lake ~~is~~ nearby in the beginning of January in that year was 2.80 km². And at the end of December it was measured as 2.55 km². Calculate the loss of water due to evaporation in that year. Assume pan coefficient of 0.7

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Evaporation (mm)	167	143	178	250	286	214	164	167	167	214	167	167

Solution

Month ①	Avg water spread area (km²) ②	Evaporation (mm) ③	Montly lake evaporation ④ = ~~Col3~~ (Col 3 × Pan coeff) (mm)	Monthly evaporation loss (Col 2 × Col 4) km²·mm
Jan	~~16~~ ~~2.80~~ 2.8	167	116.9	327.32
Feb	~~2.78~~ 2.77	143	100.1	277.27
Mar	~~2.76~~ 2.75	178	124.6	342.65
Apr	~~2.74~~ 2.73	250	175	477.75
May	~~2.72~~ 2.71	286	200.2	542.54
Jun	~~2.7~~ 2.69	214	149.8	402.96
Jul	2.66	167	116.9	310.95
Aug	2.64	167	116.9	308.62
Sep	2.62	167	116.9	306.28
Oct	2.6	214	149.8	389.48
Nov	2.57	167	116.9	300.43
Dec	2.55	167	116.9	298.09

Unit II -

Annual evaporation loss $= \Sigma$ Monthly evaporation loss.

$= 4284.34\ km^2.mm.$

$= 4284.34 \times 10^6 \times 10^{-3}$

$= 4284.34 \times 10^3 m^3 = 4.29 Mm^3$

Net of Actual

Theory (Infiltration)

Infiltration

Infiltration is the ~~process~~ flow of water into the ground through void in the soil ~~surface~~. The infiltrated water first fulfills the deficiency in the soil profile and the excess water moves downwards to reach the ground water table.

Infiltration rate & Infiltration ~~capact~~ capacity

Infiltration rate is the velocity or speed at which the water flows through the soil. It is designated as 'f' and expressed in units of cm/hr

Infiltration capacity is the maximum rate at which a given soil at a given time can absorb water. It is designated as 'fp' and expressed in cm/hr.

Infiltration rate and infiltration capacity are related as,

$$f = f_p \text{ when } i \geq f_p$$

$$f = i \text{ when } i < f_p$$

where $i \rightarrow$ intensity of rainfall

~~During high intensity rainfall, rainfall fulfils the soil storage capacity and the a stage caries such that the infiltration rate becomes equal to the infiltration capacity and hence the balance water contributes to runoff. ground water flow.~~

~~During low intensity rainfall, rainfall gets stored in soil and the infiltration rate depends on rainfall and never becomes equal to infiltration capacity. Hence there is no contribution to ground water flow.~~

Cumulative infiltration

Cumulative infiltration is defined as the accumulation of infiltration volume over a time period from the start of infiltration process. It is designated as 'F_p' and have units of 'cm'.

Mathematical relation between infiltration ~~rate~~ ~~capacity (f)~~ capacity (f_p) and Cumulative infiltration (F_c) (or) Horton's equation :

Horton's equation is given as,

$$f_p = f_c + (f_o - f_c)e^{-k_h t} \quad — ①$$

where $f_p \rightarrow$ Infiltration capacity at time 't'

$f_o \rightarrow$ Infiltration capacity at time, [t=0] (Initial infiltration

P6) The infiltration capacity of (41) soil in a small watershed was found to be a 6cm/hr before a rainfall event. It was found to be 1·2cm/hr at the end of 8hrs of storm. The total infiltration during the 8 hours period of storm was 15 cm. Estimate the value of decay coefficient k_h in Horton's infiltration capacity equation

Given

f_0 = Infiltration capacity at time $(t=0)$ = 6cm/hr

f_c = " " " " $(t=8)$ = 1·2cm/hr

Total infiltration (Cumulative), F_p = 15cm

t = 8hrs

Solution

Horton's equation is $f_p = f_c + (f_0 - f_c) e^{-k_h t}$

Cumulative infiltration capacity is given by $F_p = \int_0^t f_p(t)\,dt$

$$\therefore F_p = \int_0^t f_c + (f_0 - f_c) e^{-k_h t}\,dt$$

$$15 = \int_0^8 1{\cdot}2 + (6 - 1{\cdot}2) e^{-k_h t}\,dt$$

$$15 = \int_0^8 1.2\,dt + \int_0^8 4.8\,e^{-k_h t}\,dt$$

$$= \left[1.2t\right]_0^8 \cancel{+ 4.8\int_0^8 e^{-k_h t}\,dt}$$

$$= \left[1.2t\right]_0^8 + 4.8\left[\frac{e^{-k_h t}}{-k_h}\right]_0^8$$

$$= \left[1.2t\right]_0^8 - \frac{4.8}{k_h}\left[\frac{1}{e^{k_h t}}\right]_0^8$$

$$= (1.2\times 8) - \frac{4.8}{k_h}\left[\frac{1}{e^{8k_h}} - \frac{1}{e^0}\right]$$

$$= (1.2\times 8) - \cancel{\frac{4.8}{k_h e^{8k_h}}}^{\to 0} + \frac{4.8}{k_h}$$

$$15 = (1.2\times 8) + \frac{4.8}{k_h}$$

$$\Rightarrow 5.4 = \frac{4.8}{k_h}$$

$$\Rightarrow \boxed{k_h = 0.888\ h^{-1}}$$

✓Pb) The Horton's infiltration equation for a basin is given as $f = 6+16e^{-2t}$ ~~where~~ where f is in mm/h and t is in hours. Determine values of f_0, f_c and k. If storm occurs on this basin with a intensity of more than 22 mm/hr determine the depth of infiltration for the first 45min and average infiltration rates (4.7) for first 75minutes

Solution

Horton's equation is $f_p = f_c + (f_o - f_c)\, e^{-k_h t}$

Given equation is $f = 6 + 16\, e^{-2t}$

On comparing. $f_c = 6\,mm/h$, $f_o = 16+6 = 22\,mm/h$, $k_h = -2\,h^{-1}$

Case i - Depth of infiltration for first 45 min.

$$F = \int_0^t f_p(t)\,dt$$

$$= \int_0^{0.75} (6+16)\, e^{-2t}\, dt.$$

$$= [6t]_0^{0.75} + 16\left[\frac{e^{-2t}}{-2}\right]_0^{0.75}$$

$$= [6t]_0^{0.75} + 8\left[e^{-2t}\right]_0^{0.75}$$

$$= 6 \times 0.75 - 8\left[e^{-2\times 0.75} - e^0\right]$$

$$= 4.5 - 8[\cancel{0.092}\ 0.223 - 1]$$

$$= 10.716\ mm$$

Case (ii) - Infiltration rate for first 75 minutes (d4) (17p)

Solution $F = \int_0^t f_p(t)\,dt$

$= \int_0^{1\cdot25} 6 + 16e^{-2t}\,dt$

$\boxed{Runoff = P - I - E_a}$

$= \left[6t\right]_0^{1\cdot25} - 8\left[e^{-2t}\right]_0^{1\cdot25}$

$= \left(6\times1\cdot25\right) - 8\left[e^{-2\times1\cdot25} - e^{0}\right]$

$= 7\cdot5 - 8\left[0\cdot082 - 1\right]$

$= 14\cdot844$ mm

Infiltration rate $= \frac{F}{t} = \frac{14\cdot844}{1\cdot25} = 11\cdot875$ mm/h

---

Infiltration indices

The infiltration capacity curves which are developed from various infiltration measuring devices can be used to estimate runoff (or) rainfall excess (or) effective rainfall when superimposed with rainfall hyetograph.

The following figure shows the relationship between raifall, runoff and infiltration after superimposing infiltration curve and rainfall hyetograph.

ϕ index :

The ϕ index is the average rainfall value above which the rainfall volume equals to runoff volume. The ϕ index is derived from the rainfall hyetograph with the knowledge of resulting runoff volume. The amount of rainfall in excess of ϕ index is called rainfall excess (or) effective rainfall (~~or runoff~~. Following is the procedure for calculating ϕ index ~~and~~ from rainfall hyetograph and resulting runoff.

- Consider a rainfall hyetograph of duration D (N pulses of time interval) such that $N \cdot \Delta t = D$
- Let I_i be the intensity of rainfall in i^{th} pulse ($I_1, I_2 \dots$)

~~and Rd be the total direct runoff then total runoff.~~

and then total rainfall is given as,

$$\text{Total rainfall}, P = \sum_{1}^{N} I_i \cdot \Delta t$$

- Let R_d be the total direct runoff and ϕ be ϕ index.
- The relation between P, Rd and ϕ is given as,

$$\boxed{P - \phi t_e = R_d} \Rightarrow \boxed{\sum_{1}^{N} I_i \Delta t - \phi t_e = R_d}$$

$t_e \to$ Duration of rainfall excess

(i) Assume that out of N pulse, M number of pulses have rainfall excess (runoff). Select M number of pulses in decreasing order of intensity (I_i)

(ii) Find the value of ϕ using the formula $P - \phi t_e = R_d$

(iii) Using the value of ϕ find out the number of pulses having rainfall intensity greater than ϕ. Let it be M_c

(iv) If $M = M_c$, then the value of ϕ is correct. If not with a new value of M repeat the above steps until $M = M_c$.

~~Pb) A storm with 10cm of precipitation~~

Pb) A 6h storm produced rainfall intensities of 7, 18, 25, 12, 10 and 3 mm/h in successive one hour intervals over a basin of 800 sqkm. The resulting runoff is observed to be 2640 hectare-metres. Determine ϕ index of the basin.

Given data:

* Duration (D) = 6h

* Number of pulse (N) = 6

Time interval (Δt) = 1h

Rainfall intensity (I_i) = 7, 18, 25, 12, 10 and 3 mm/h

Runoff = 2640 hectares - metres (volume)

Area = 800 sqkm.

Solution

$$\text{Runoff depth} = \frac{\text{Runoff volume}}{\text{Basin area}}$$

$$= \frac{2640 \times 10^4}{800 \times 10^6}$$

$$= 0.033\text{m}$$

$$= 33\text{mm}$$

Relation is $\sum_{1}^{N} I_i \Delta t - \phi t_e = R_d$

Trial 1 - Let $M = 6$, $t_e = 6$ hrs

$$\left[(7\times1) + (18\times1) + (25\times1) + (12\times1) + (10\times1) + (3\times1)\right] - (\phi \times 6) = 33$$

$$\phi = 7\text{mm/hr}$$

Number of pulses having rainfall intensity greater than 7mm/h,

$M_e = 4$

$M \neq M_c$

Trial 2 - Let $M = 5$, $t_e = 5$ hrs

$$\left[(7\times1)+(18\times1)+(25\times1)+(12\times1)+(10\times1)\right]-(\phi\times5) = 33$$

$\phi = 7.8$ mm/hr

Number of pulses having rainfall intensity greater than 7.8 mm/hr, $M_c = 4$

$M \neq M_c$

Trial 3 - Let $M = 4$, $t_e = 4$ hrs

$$\left[(18\times1)+(25\times1)+(12\times1)+(10\times1)\right]-(\phi\times4) = 33$$

$\phi = 8$ mm/hr

Number of pulse having rainfall intensity greater than 8 mm/hr, $M_c = 4$

$\boxed{M = M_c}$

Result :

ϕ index = 8 mm/hr, $t_e = 4$ hrs

P1) A storm with 10cm of precipitation produced a direct runoff of 5.8 cm. The duration of the rainfall was 16 hours and its distribution is given below. Estimate the ϕ index.

Time from start	0	2	4	6	8	10	12	14	16
Cumulative rainfall (cm)	0	0.4	1.3	2.8	5.1	6.9	8.5	9.5	10.0

Solution

Ignore

Time from start hr	0	2	4	6	8	10	12	14	16
Cumulative rainfall (cm)	0	0.4	1.3	2.8	5.1	6.9	8.5	9.5	10.0
Incremental (cm) rainfall	-	0.4	0.9	1.5	2.3	1.8	1.6	1.0	0.5
Intenisty (cm/hr)	-	0.2	0.45	0.75	1.15	0.9	0.8	0.5	0.25

Duration (D) = 16h

Number of pulse(N) = 8

Time interval (Δt) = 2

Runoff = 5.8cm

Relation is $\sum_{1}^{N} I_i \Delta t - \phi t_e = R_d$

Solution

Trial 1: let $M = 8$, $t_e = 16$ hrs

$$\Big[(0.20\times2)+(0.45\times2)+(0.75\times2)+(1.15\times2)+(0.90\times2)+(0.80\times2)+(0.5\times2)+(0.25\times2)\Big]-(\phi\times16) = 5.8$$

~~$\phi = 0.80$~~

$\phi = 0.263$ cm/hr

Number of pulses having rainfall intensity greater than 0.263 cm/hr, $M_c = 6$

$M \neq M_c$

Trial 2: let $M = 7$, $t_e =$ ~~12hrs~~ $7\times2 = 14$ hrs

$$\Big[(0.45\times2)+(0.75\times2)+(1.15\times2)+(0.90\times2)+(0.80\times2)+(0.5\times2)+(0.25\times2)\Big]-(\phi\times14) = 5.8$$

$\phi = 0.271$ cm/h

Number of pulses having rainfall intensity greater than 0.275 cm/hr, $M_c = 6$

$M \neq M_c$

Trial 3. Let $M = 6$, $t_e = 6\times2 = 12$ hrs

$$\Big[(0.45\times2)+(0.75\times2)+(1.15\times2)+(0.9\times2)+(0.8\times2)+(0.5\times2)\Big]-(\phi\times12) = 5.8$$

~~$M = M_c$~~

$\phi = 0.275$ cm/hr

$M_c = 6 \Rightarrow M = M_c$

Result

ϕ index $= 0.275$ cm/hr.

Pb) A 500 sq km watershed received a 8h storm which produced hourly intensities of 6, 9, 20, 16, 4, $\overset{14}{\wedge}$ 12 and 2 mm/h. If the initial abstractions are estimated to be 15mm and ϕ index is 5mm/hr what would be the runoff volume produced by the storm.

Solution (with abstractions)

The rainfall occuring in first two hours is 15mm/hr which is same as initial abstractions 15mm. So neglecting the first two hour rainfall and considering 6h period,

$$\sum_{i=1}^{N} I_i \Delta t - \phi t_e = Rd$$

$$\left[\cancel{(20\times1)+(16\times1)+(4\times1)}^{\,0}+\cancel{(14\times1)+(\overset{12}{12}\times1)}\right]-\left(\overset{5\times6}{\cancel{5\times5}}\right)=Rd$$

$$+(2\times1)^{\,0}$$

$$\therefore \left[(20\times1)+(16\times1)+(14\times1)+(12\times1)\right]-(5\times4)=42=Rd$$

$\therefore$ Runoff depth = 42mm

Runoff volume = Runoff depth × Basin area = $42\times10^{-3}\times500\times10^{6}$

$= 21\times10^{6}\,m^3$

Without abstractions

$$\left[(6\times1)+(9\times1)+(20\times1)+(16\times1)+(14\times1)+(12\times1)\right]-(5\times6)=47\text{ mm}=Rd$$

Runoff volume = Runoff depth × Basin area

$= 47\times10^{-3}\times500\times10^{6}$

$= 23.5\times10^{6}\ m^3$

Error in runoff volume if initial abstractions are neglected $= \dfrac{23.5-21}{21}\times100 = 11.9 \simeq 12\%$

W index

W index is the refined version of ϕ index. The initial losses like interception, storage, evaporation are separated from the total abstractions. W index is the average infiltration rate given as

$$W = \frac{P - R - I_a}{t_e}$$

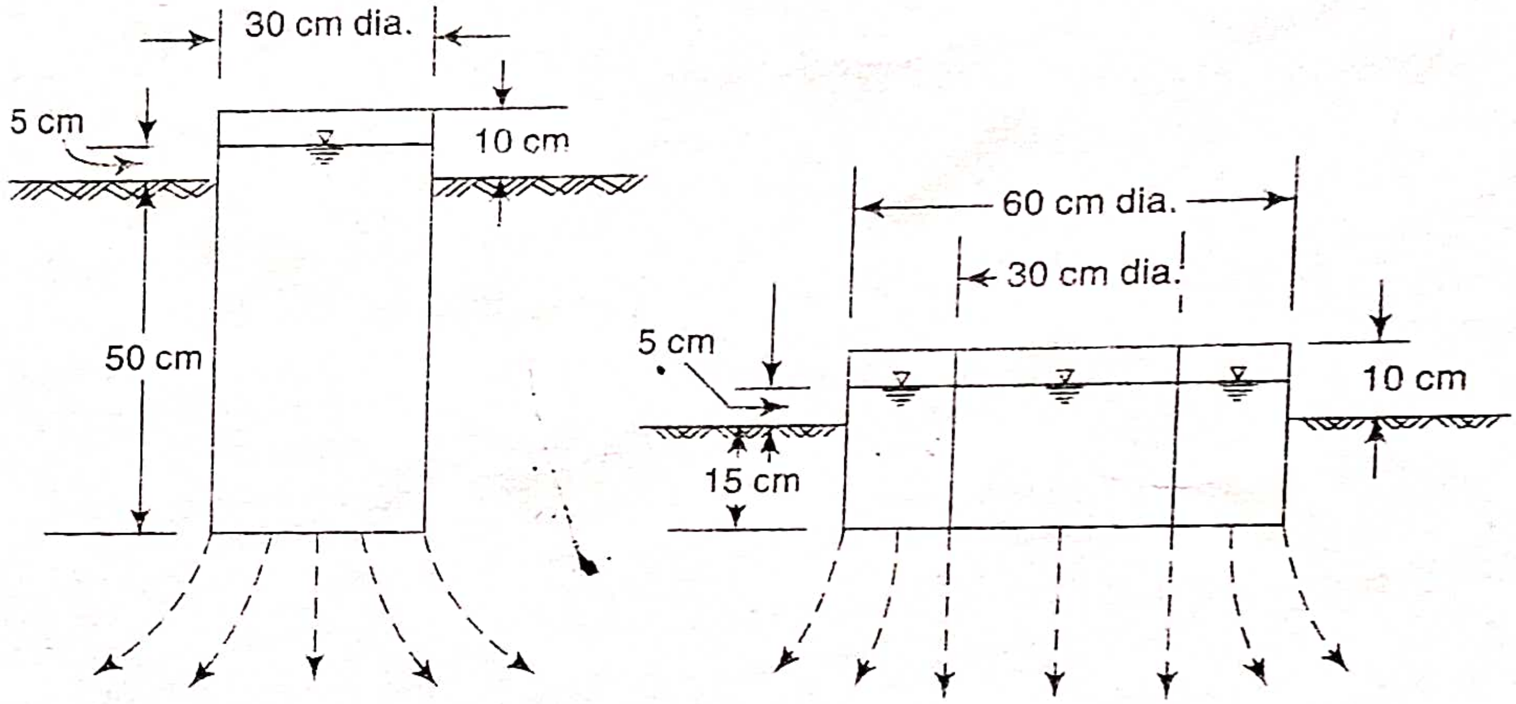
where $P \rightarrow$ Total precipitation (cm)

$R \rightarrow$ Runoff (cm)

$I_a \rightarrow$ Initial losses (interception, storage, evaporation)

$t_e \rightarrow$ Duration of rainfall excess

Since I_a values are difficult to obtain, the accurate estimation of W index is difficult.



(a) Simple (tube-type) infiltrometer (b) Double-ring infiltrometer

Fig. 3.12 Flooding Type Infiltrometers

A major objection to the simple infiltrometer as above is that the infiltered water reads at the outlet from the tube (as shown by dotted lines in Fig. 3.12(a)) and as ch the tube area is not representative of the area in which infiltration is taking place.

OUBLE-RING INFILTROMETER This most commonly used infiltrometer is de-gned to overcome the basic objection of the tube infiltrometer, viz. the tube area is t representative of the infiltrating area. In this, two sets of concentrating rings with ameters of 30 cm and 60 cm and of a minimum length of 25 cm, as shown in g. 3.12(b), are used. The two rings are inserted into the ground and water is applied o both the rings to maintain a constant depth of about 5.0 cm. The outer ring pro-des water jacket to the infiltering water from the inner ring and hence prevents the eading out of the infiltering water of the inner ring. The water depths in the inner d outer rings are kept the same during the observation period. The measurement of the water volume is done on the inner ring only. The experiment is carried out till a constant infiltration rate is obtained. A perforated disc to prevent formation of turbidity and settling of fines on the soil surface is provided on the surface of the soil in the inner ring as well as in the annular space.

As the flooding-type infiltrometer measures the infiltration characteristics at a spot only, a large number of pre-planned experiments are necessary to obtain representative infiltration characteristics for an entire watershed. Some of the chief disadvantages of flooding-type infiltrometers are:

1. the raindrop impact effect is not simulated;
2. the driving of the tube or rings disturbs the soil structure; and
3. the results of the infiltrometers depend to some extent on their size with the larger meters giving less rates than the smaller ones; this is due to the border effect.

Unit II - Runoff ①

Watershed, catchment and basin - Catchment characteristics - Factors affecting runoff - Runoff estimation using empirical - Strange's table and SCS method - Stage discharge relationships - flow measurements - Hydrograph - Unit hydrograph - IUH

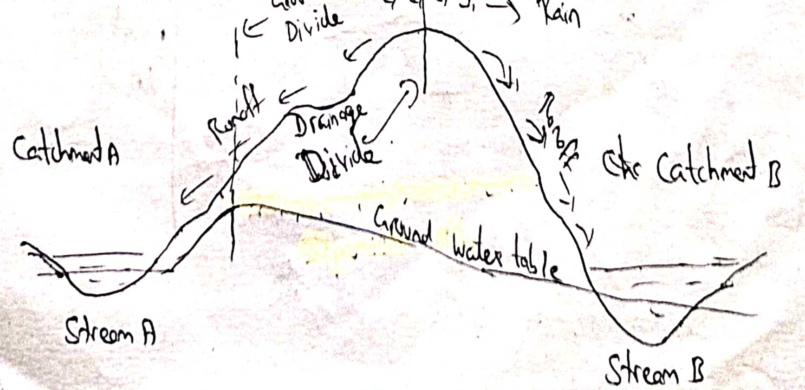
Watershed catchment and basin:

Catchment area refers to all the area of land from which the runoff resulting from rainfall is collected and drained into stream, lake or river.

The catchment area of large rivers is called as river basin while that of small river, lake is called as watershed.

Catchment characteristics

The boundary line which divides the surface runoff between two adjacent river basins is called as drainage divide or divide or water divide. The divide follows the ridge line around the basin crossing the stream or rivers only at outlet point. Hence the basin area can be easily identified using ridge points. The single point or location at which all surface runoff from a river basin passes to river is called as concentration point or measuring point. The time required for the rain falling at most distant point in a basin area to reach the concentration point is called as concentration time. The concentration time is an important variable as only rainfall of duration greater than the concentration time will be able to produce runoff



The line of ground water table from which water slopes downward away on both sides is called ground water divide.

Large

The characteristics of catchment may be physically described by
→ the number of streams
→ length of streams
→ stream density
→ drainage density

* The stream density of a drainage basin is expressed as the number of streams per square kilometre

stream density, $D_s = \frac{N_s}{A}$

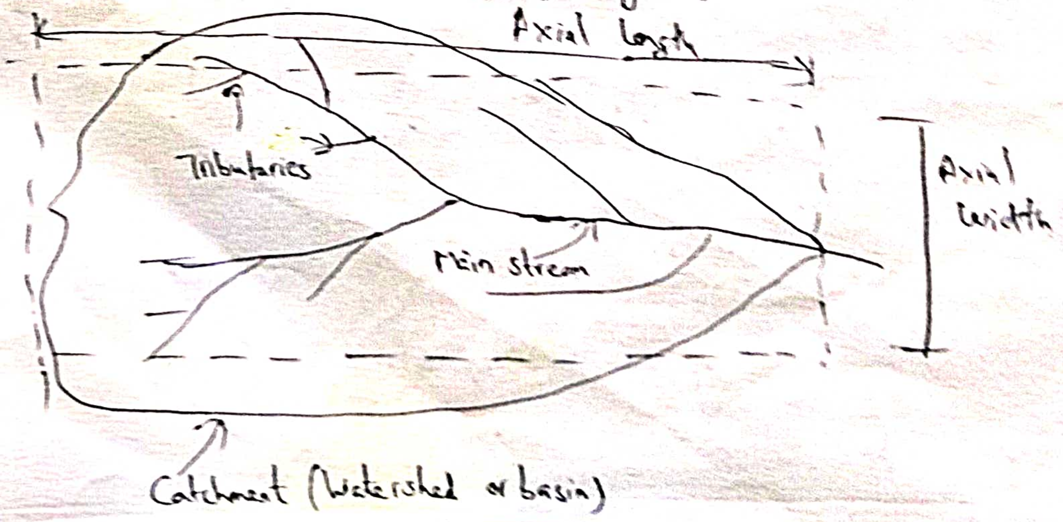
where N_s → Number of streams
A → Area of basin

* Drainage density is expressed as the total length of all stream channels per unit area of the basin

Drainage density, $D_d = \frac{L_s}{A}$

where L_s → Total length of all stream channels
A → Area of basin

Drainage density serves as an index for area channel development of the basin. A high value indicates well developed network runoff and low value indicates moderate runoff and high permeability of ground.



Horton has suggested a method of determining the slope of large drainage areas (ie) the area is subdivided into a number of square grids of equal size. The number of contours crossed by each subdividing line is counted and the length of grid lines are measured. Then the slope of basin is given by,

$$S = \frac{1.5\,(CI)\,N_c}{\Sigma L}$$

Where S -> Slope of basin
CI -> Contour Interval
N_c -> Number of contours crossed by subdividing lines.
ΣL -> Length of subdividing lines (grid)

The slope of a drainage basin is expressed by
(i) Form factor
(ii) Compactness coefficient

-> Form Factor, $F_f = \frac{W_b}{L_b}$

As $A = W_b \cdot L_b \Rightarrow W_b = A/L_b$

$$\therefore F_f = \frac{A}{L_b^2}$$

where W_b -> Axial width of basin
L_b -> Axial length of basin

-> Compactness Coefficient, $C_c = \frac{P_b}{2\sqrt{\pi A}}$

Where P_b -> Perimeter of basin
$2\sqrt{\pi A}$ -> Circumference of circular area equal to basin area

$(A = \pi R^2 \Rightarrow R = \sqrt{A/\pi}$, Circumference $= 2\pi R = 2\pi\sqrt{\frac{A}{\pi}} = 2\sqrt{\pi A})$

A fan shaped catchment produces greater flood intensity, since all the tributaries are nearly of same length and hence time of concentration is nearly same and less, whereas in fern shaped (leaf) catchment, the time of concentration is more and discharge is distributed.

Runoff:

The precipitation reaching the ground surface after ~~reaching~~ the ~~ground~~ surface ~~after~~ meeting needs of infiltration, evaporation, interception storage, moves down the natural slope reaches streams called as runoff.

Components of runoff

According to the source from which the flow is derived, the total runoff is classified as,

→ Surface runoff
→ Sub surface runoff
→ Ground water runoff

Consider a catchment area receiving precipitation. Before reaching the ground a small portion of precipitation evaporates back to atmosphere while small portion is intercepted and which evaporates back. The remaining precipitation after infiltration and storage, called as runoff moves over the land surface to reach small stream channel called as overland flow. Flow from several stream channel joins bigger channel and inturn combines to for longer stream an so on till it reaches catchment outlet. The flow where runoff travels over the surface as overland flow to reach channel and through the channel to reach the outlet is called surface runoff.

Water which infiltrates the soil surface moves laterally (sideways) through upper soil crust and returns to the surface and moves laterally the stream channels is called as interflow, through flow, storm seepage, subsurface runoff, subsurface storm flow. Generally subsurface flow moves slowly and than surface flow and hence take longer period to reach stream channel.

The infiltrated water which percolates becomes ground water. When the ground water table rises and ~~it~~ intersects the stream channels it discharges the ground water to stream channels. This part of runoff is called ground water runoff. The movement of ground ~~wa~~ water is very slow and takes several week or days to reach the stream

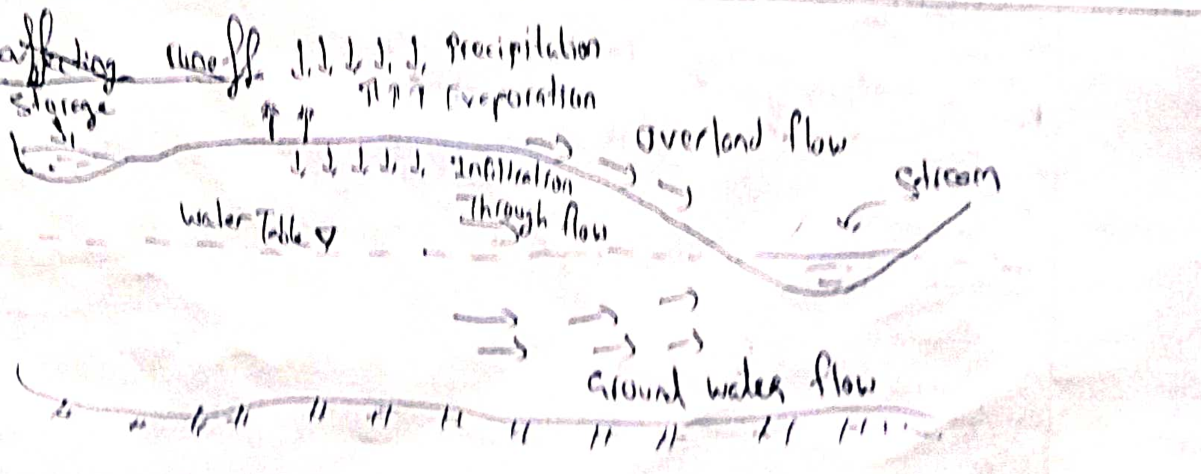
For practical purpose of analysis, total runoff is classified as

- Direct Runoff
- Base Flow

Direct runoff is the part of runoff which enters the stream immediately after the rainfall. It includes surface runoff and interflow than enters the stream rapidly. This represents the major runoff contribution during rainfall and it is reason for major floods.

Base flow is the delayed flow that reaches the stream especially ground water flow and delayed interflow.

Factors affecting runoff



Factors affecting runoff

The various factors which affect the ruoff from drainage basin depend on following characteristics,

(i) **Storm characteristics**

→ Type of precipitation
→ Intensity of rainfall
→ Duration of rainfall
→ Areal extent of rainfall (areal distribution)
→ Direction of storm movement
→ Antecedent precipitation

(ii) **Meteorological Characteristics**

→ Temperature
→ Humidity
→ Wind velocity
→ Pressure variation

(iii) **Basin Characteristics**

→ Land Use / Vegetation
→ Type of soil / Geology
→ Size of basin
→ Slope of basin
→ Shape of basin
→ Elevation / Altitude
→ Orientation
→ Type of drainage network
→ Topography

(iv) **Storage Characteristics**

→ Depressions
→ Ponds / Lakes
→ Streams
→ Channel
→ Check dams
→ Reservoir
→ Ground water storage

~~Though it is difficult to~~

Though it is easy to identify the various factors that affect runoff, it is difficult to quantify some of them and more difficult to express their maximum, minimum runoff values. Some of the factors are discussed below,

Type of precipitation

If the precipitation falls in the form of rainfall, its effect of runoff is immediate as its intensity is large. If the precipitation is entirely in the form of snow, it may not contribute to runoff at that time. But due to melting of snow in warm periods may contribute heavily to runoff sometimes causing floods.

Intensity of rainfall

For rainfall intensities exceeding the infiltration capacity, the runoff increases. But due to storage effect of basin, the increase in runoff rate is not the same as increase in rainfall intensity.

~~Duration of rainfall~~

Low intensity rainfall over long duration contribute to ground water storage and produce less runoff. A high intensity rainfall over smaller area increases the runoff since loss like infiltration and evaporation are less.

Duration of rainfall

If rainfall is of sufficiently prolonged duration, infiltration capacity is greatly reduced resulting in high runoff rates. The infiltration may even raise the water table to ground leading to zero infiltration, Hence ~~rainf~~ rains of long duration may produce high runoff though the intensity is mild.

⑧

Areal distribution of rainfall

Uniform distribution of rainfall over a basin is ra observed in nature. Some portion of basin will receive rainfall which is much less than the average rainfall over the basin while remaining portion will receive rainfall which is ~~much less~~ more than the average rainfall over the basin.

Direction of storm Movement

If a storm striking a long and narrow basin is moving in upstream direction, the runoff contributed by lower tributaries would have been already drained out, by the time the runoff from the middle and upper tributaries reaches the basin outlet and hence less peak discharge.

When the storm moves downstream the runoff from individual tributaries are more likely to arrive the basin ~~outlet~~ outlet at same time, hence runoff when storm moves downstream will be many times more than that of storm moving upstream.

Antecedent precipitation

The soil moisture conditions of basin existing at time of occurence of storm would greatly influence runoff.

In summer, even when rainfall is heavy, as ~~the~~ soil runoff is low as most of the water enters the soil moisture. In winter and rainy season, since the rainfall occured in earlier periods would have raised the soil moisture to high ~~rainfall~~ level and hence high runoff.

Meteorological Characteristics

Apart from rainfall, other meteorological characteristics, like temperature, humidity, wind velocity, atmospheric pressure. Greater humidity decreases evaporation and hence the precipitation falling on basin is high and hence high runoff. The pressure distribution helps in movement of storms. Loss of rainfall due to temperature, wind affects runoff. More the losses, lesser will be the available runoff.

Land Use

Land use affects runoff by interception due to buildings, evapotranspiration due to plants and soil moisture movement. In urban areas, there is less scope for infiltration and transpiration and hence all the rainfall becomes runoff causing high ~~rainfall~~ runoff discharge. Rainfall falling on thick forest area may not produce runoff because in forest thick layer of grass and dry leaves exist which absorbs lot of rainfall. In non forest area, interception and transpiration losses are less and hence high runoff.

Type of soil / Geology

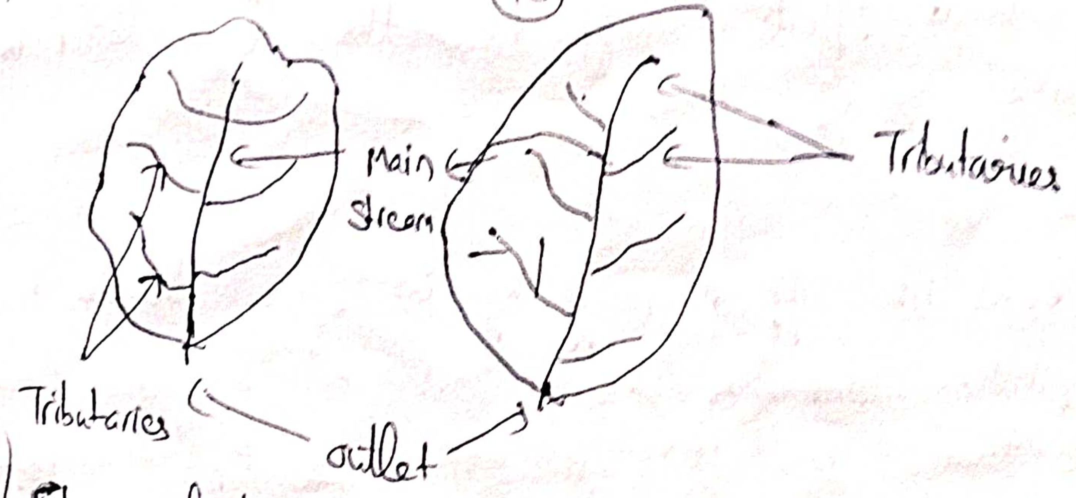
Geological characteristics include surface and sub surface soil type, rocks, their permeability. The soil type determines the infiltration capacity and hence affects runoff. open textured Sandy soil (Sand) have high infiltration rate and hence produce less runoff. Fine grained and closely packed soil (clay) have less infiltration rate and hence produce high runoff

Size of basin

~~More~~ Large basin gives more constant minimum flow than smaller ones.

Shape of catchment

Fan shaped catchments give greater runoff because tributaries are nearly of same size and hence time of concentration of runoff at outlet is same resulting in large and rapid runoff. Moreover runoff discharge from fern shaped catchment is less due to different length of tributaries



<u>Slope of basin</u>

If the slope of the basin is more, runoff will be more

<u>Elevation / Altitude</u>

Catchment located at higher altitude receive more rainfall and hence high runoff.

<u>Orientation</u>

The orientation of the basin decides the amount of solar radiation received from the sun. The solar radiation may affect runoff through its influence on evaporation, transpiration.

<u>Drainage network</u>

The characteristics of runoff is greatly influenced by the efficiency of drainage system. If the basin is well drained with large number of tributaries shortening the length of overland flow, the surface runoff concentrates quickly

<u>Topography of basin</u>

The runoff depends on surface condition, slope and land features. Runoff will be more from a smooth surface than from rugged surface. Also if the surface slope is steep, water will flow quickly and evaporation loss will be less. If the catchment is mountainous, the rainfall intensity will be high and hence runoff will be more.

Storage characteristics of basin

Storage in channel (natural) and depressions will reduce flood magnitude. Storage in reservoir, lake (artificial), tank also reduce flood magnitude. These structure also gives rise to greater evaporation

Runoff estimation

The runoff from rainfall may be estimated by the following methods,

- → Emprical formulae
- → Curves
- → Tables
- → Infiltration method
- → Rational method
- → Overland flow hydrograph
- → Unit hydrograph method
- → Coaxial graphical correlation

(I) Emprical formulae method

1) Inglis and DeSouza formula

→ For Ghats region of Western India

$$R = 0.85P - 30.5$$

→ For Deccan Plateau (Plains)

~~$R = P(P - 17.8)$~~ $R = \frac{1}{254} P(P - 17.8)$

where R → Annual runoff

P → Annual precipitation

2) Lacey's formula

$$R = \frac{P}{1+}$$

2) Lacey's formula

$$R = \frac{P}{1 + \frac{304.8}{P}\left(\frac{F}{S}\right)}$$

Where F → Monsoon duration factor varying between 0.5 and 1.5

S → Catchment factor depending upon the slope and varies from 0.25 for flat areas to 3.45 for hilly areas.

3) Khosla's formula

$$R_m = P_m - L_m$$

Where $L_m = 0.48 T_m$ for $T_m > 4.5°C$

R_m = Monthly runoff in cm
P_m = Monthly rainfall in cm
L_m = Monthly losses in cm
T_m = Mean monthly temperature of the catchment in °C

Khosla's formula is applicable with $L_m = 0.48 T_m \ngtr P_m$

Pb) For a catchment in UP, India, the mean monthly temperatures are given. Estimate the annual runoff and annual runoff coefficient by Khosla's method.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temp(°C)	12	16	21	27	31	34	31	29	28	29	19	14
Rainfall P_m (cm)	4	4	2	0	2	12	32	29	16	2	1	2

Solution

$R_m = P_m - L_m$ where $L_m = 0.48 T_m \ngtr P_m$

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Temp(°C) T_m	12	16	21	27	31	34	31	29	28	29	19	14
Rainfall(cm) P_m	4	4	2	0	2	12	32	29	16	2	1	2
Monthly loss (cm) L_m $0.48T_m \ngtr P_m$	$0.48 \times 12 = 5.76 \ngtr 4 = 4$	$0.48 \times 16 = 7.68 \ngtr 4 = 4$	$0.48 \times 21 = 10.08 \ngtr 2 = 2$	$0.48 \times 27 = 12.96 \ngtr 0 = 0$	$0.48 \times 31 = 14.88 \ngtr 2 = 2$	$0.48 \times 34 = 16.32 \ngtr 12 = 12$	$0.48 \times 31 = 14.88 \ngtr 32 = 14.88$	$0.48 \times 29 = 13.92 \ngtr 29 = 13.92$	$0.48 \times 28 = 13.44 \ngtr 16 = 13.44$	$0.48 \times 29 = 13.92 \ngtr 2$ 2	$0.48 \times 19 = 9.12 \ngtr 1$ 1	$0.48 \times 14 = 6.72 \ngtr 2$ 2
$R_m = P_m - L_m$	0	0	0	0	0	0	17.12	15.08	2.56	0	0	0

Total annual runoff = 34.76 cm , Total annual rainfall = 106 cm

$$\text{Total Annual runoff coefficient} = \frac{\text{Annual runoff}}{\text{Annual rainfall}} = \frac{34.76}{106} = 0.323$$

(II) Tables

i) Strange's table

Total monsoon rainfall (mm)			Runoff coefficient in percentage (percentage of runoff to rainfall)					
			Good Catchment		Average Catchment		Bad Catchment	
76.2	76.2	76.2	0.4	4.3	0.3	3.2	0.2	2.1
		101.6	0.7		0.5	11.3	0.3	7.5
101.6	101.6	228.6	3.5	15.0	2.6		1.7	13.1
228.6	228.6	254.0	4.3	26.3	3.2	19.7	2.1	
254.0	[illegible]	381	9.4	37.5	7.0	28.0	4.7	18.7
		406.4	10.5		7.8		5.2	23.8
381	125	431.8	11.6	47.6	8.7	35.7	5.8	
406.4		609.6	19.5	58.9	14.6	44.1	9.7	29.4
431.8	150	784.7	27.4		20.5		13.7	

P3) Monthly rainfall values of the 50% dependable year at a site selected for construction of an irrigation tank is given below. Estimate the monthly and annual runoff volume of this catchment of area 1500 ha. Assume the catchment classification as good catchment.

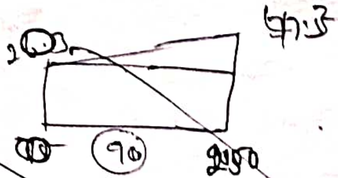
Month	June	July	Aug	Sept	Oct
Monthly rainfall (mm)	90	160	145	22	240

Solution

Month	June	July	August	September	Octo
Monthly Rainfall (mm)	90	160	145	22	240
Cumulative monthly rainfall (mm)	90	90+160 = 250	250+145 = 395	395+22 = 417	417+240 = 657
Percentage of runoff to rainfall (%)	0.56	4.17	10.01	10.96	21.64
Cumulative runoff (mm)	0.50	10.43	39.54	45.7	142.18
Monthly runoff (mm)	0.50	10.43 − 0.5 = 9.93	39.54 − 10.43 = 29.11	45.7 − 39.54 = 6.16	142.18 − 45.7 = 96.48

~~Percentage of runoff to rainfall~~

~~Rainfall %~~
~~0 → [illegible]~~
~~250 → [illegible]~~



~~0 + $\left(\frac{4.3-0}{250-0}\right) \times 90$~~

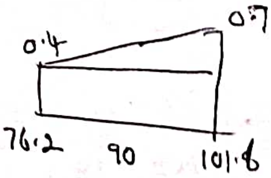
~~percentage = 26 + $\left(\frac{37.5-26.3}{250-0}\right)$ × (90 − 75) = 26 + $\frac{11.2}{25}$ × 15 = 32.72~~

~~Runoff~~

Percentage of runoff to rainfall

1) Rainfall %

76.2 0.4
101.6 0.7

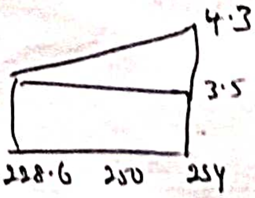


$$\% = 0.4 + \left(\frac{0.7-0.4}{101.6-76.2}\right)(90-76.2) = 0.56$$

2) Rainfall %

228.6 3.5
254 4.3

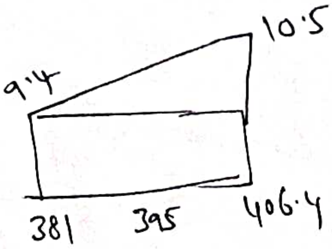
$$\% = 3.5 + \left(\frac{4.3-3.5}{254-228.6}\right)(250-228.6)$$



$= 4.17$

3)

Rainfall	%
381	9.4
406.4	10.5

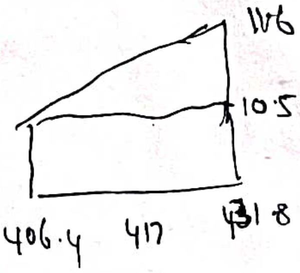


$$\% = 9.4 + \left(\frac{10.5 - 9.4}{406.4 - 381}\right)(395 - 381) = 10.01$$

4)

Rainfall	%
406.4	10.5
431.8	11.6

$$\% = 10.5 + \frac{(11.6 - 10.5)}{(431.8 - 406.4)}(417 - 406.4)$$



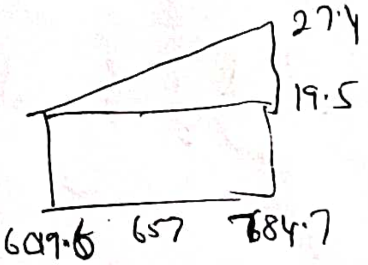
$$= 10.96$$

5)

Rainfall	%
609.6	19.5
784.7	27.4

$$\% = 19.5 + \left(\frac{27.4 - 19.5}{784.7 - 609.6}\right)(657 - 609.6)$$

$$= 21.64$$



Cumulative runoff

1) Percentage of runoff to rainfall = 0.56%

$$\frac{\text{Runoff}}{\text{Rainfall}} = 0.56\%$$

$$\text{Runoff} = \frac{0.56 \times 90}{100} = 0.50$$

2) $$\frac{\text{Runoff}}{\text{Rainfall}} = 4.17\%$$

$$\text{Runoff} = \frac{4.17 \times 250}{100} = 10.43$$

3) $\frac{\text{Runoff}}{\text{Rainfall}} = 10.01\%$

$\text{Runoff} = \frac{10.01 \times 395}{100} = 39.54$

4) $\frac{\text{Runoff}}{\text{Rainfall}} = 10.96\%$

$\text{Runoff} = \frac{10.96 \times 417}{100} = 45.7$

5) $\frac{\text{Runoff}}{\text{Rainfall}} = 21.64\%$

$\text{Runoff} = \frac{21.64 \times 657}{100} = 142.18$

$\text{Total monthly runoff} = 0.50 + 9.93 + 29.11 + 6.16 + 96.48$

$= 142.18 \text{ mm}$

$\text{Total runoff volume} = \underbrace{142.18 \times 10^{-3}}_{m} \times 1500 \times 10^{4}$

$= 2.133 \times 10^{5} \times 10^{-3} \times 10^{4} = 2.13 \times 10^{6} \text{ m}^3$

$= 2.13 \text{ Mm}^3$

III) Curves

1) SCS – CN method

→ Developed by Soil Conservation Services (SCS) of USA in 1969.

→ Simple, predictable method of estimation

→ Depends on only one parameter called Curve Number (CN)

$\text{Curve Number, } CN = \frac{25400}{S + 254}$

where S → Potential maximum retention depending upon soil, vegetation, land use of catchment (in mm)

⇒ Antecedent Moisture Condition (AMC) refers to the moisture content present in the soil at the beginning of rainfall runoff event

→ Based on Amc Condition, daily runoff is given from by

$$Q = \frac{(P - 0.1S)^2}{P + 0.9S} \text{ for } P > 0.1S$$

Valid for Black soils under Amc of Type II and III

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S} \text{ for } P > 0.3S$$

Valid for Black soils under Amc of Type I and for all other soils having Amc of types I, II, III

→ AMC I – Soils are dry but not to wilting point. Satisfactory cultivation has taken place

AMC II – Average Conditions

AMC III – Sufficient rainfall has occurred within immediate past 5 days. Saturated soil conditions prevail

Pb) A small watershed is 250 ha in size has group C soil. The land cover can be classified as 30% open forest and 70% poor quality pasture. Assuming Amc at average condition and the soil to be black soil, estimate the direct runoff volume due to a rainfall of 75mm in one day. CN for open forest is 60 and pasture is 86

Solution:

Amc at average condition ⇒ Amc II

Land Use	%	CN	Product
Open forest	30	60	1800
Pasture	70	86	6020
TOTAL	100		7820

Average CN = 7820/100 = 78.2

$$CN = \frac{25400}{S + 254}$$

$$78.2 = 25400 / S + 254$$

$S = 70.81$

For Black soil,

$$Q = \frac{(P - 0.1S)^2}{P + 0.9S}$$

$$= \frac{[75 - (0.1 \times 70.81)]^2}{75 + (0.9 \times 70.81)}$$

$$= 33.25 mm$$

Total runoff Volume $= 250 \times 10^4 \times 33.25 \times 10^{-3}$

$= 8.313 \times 10^4 m^3$

Stage Discharge relationship

The river stage has been defined as the height of the water surface in the ~~[illegible]~~ river at a given section above any arbitrary datum. It is expressed in metres. In many cases, datum is taken as the mean sea level. The stage can be easily measured by installing a vertical staff guage (graduated scale)

Continuous measurement of stream discharge is very difficult, very time consuming and costly procedure. Hence a two step procedure is followed. First the discharge in a given stream is related to elevation of water surface (stage). Stage discharge relationship is established.

In second step the stage of stream is observed routinely in a inexpensive manner and ~~disthage~~ discharge is estimated by using previously determined stage discharge relationship

Definition

After a sufficient number of discharge measurements have been made along with simultaneous stage observations, at a guaging station, the results are plotted on ordinary graph. Discharge is taken at abscissa and stage ~~ad~~ as ordinate. Such a plot between discharge and stage is called as stage discharge relationship. Once the relationship is established, it is required to record only the stages continuously which can be converted to discharge.

The combined effect of the parameters stage and discharge is called as control. If the relationship between the parameters is ~~conte~~ constant and ~~dees~~ does not change with time, the control is said to be permanent. If it changes with time, it is called shifting control.

Flow Measurements

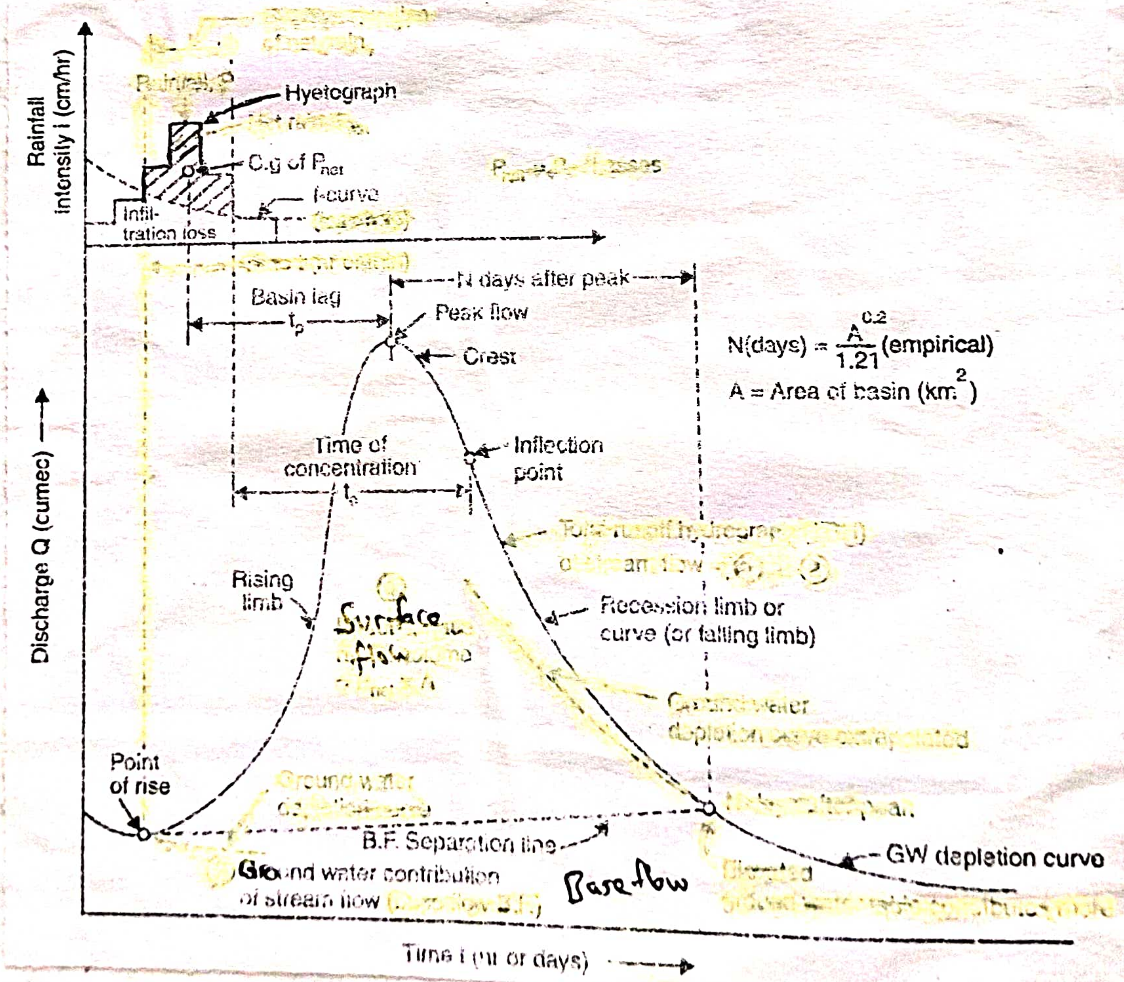
Stream flow measurements can be classified into two categories namely,

1) Direct determination
- → Area velocity methods
- → Dilution techniques
- → Electromagnetic method
- → Ultrasonic method.

2) Indirect determination
- → Hydraulic structures
- → Slope area method

Hydrograph:

A hydrograph is a graph showing discharge (ie) streamflow at concentration point (runoff) versus time. At the begining there is only base flow (ie) ground water contribution to the stream gradually depleting in exponential form.



After the storm commences, the rainfall contribu the stream after fulfilling the needs of interception and infiltration. This is called as <u>surface flow</u>. The hydrograph gradually rises and reaches its peak value at a time t_p (called as lag time or basin time) measured from centre of hyetograph. Thereafter it declines and there is a change of slope at inflection point (ie) there has been inflow of rain upto this point and after this there is gradual withdrawal from catchment storage. By this time ground water table has been built up by infiltrating and percolating water and now the ground water contributes more into stream flow. After this Ground water table declines and hydrograph goes on depleting in exponential form called as ground water depletion curve or the recession curve. If a second storm occurs now, again the hydrograph starts rising till it reaches the new peak and then falls again. Thus in practice, hydrograph may have multiple peaks. For flood analysis a single peaked hydrograph is preferred

Components of Hydrograph

The essential components of hydrograph are the rising limb, crest segment and recession limb

(i) Rising limb

* The rising limb of hydrograph is also known as Concentration curve
* During initial period, the rise of hydrograph is slow due to high ~~infl~~ infiltration and initial losses.
* As the storm continues, more water reaches the outlet. Also the infiltration losses is less. This results in rapid rise of the rising limb.

(ii) Crest Segment

* Crest segment is the most important part of hydrograph as it contains the peak. ~~portion~~
* Peak occurs when maximum amount of water reaches the basin outlet.
* Multiple peaked complex hydrographs occur in two or more storms occur successively.

(iii) **Recession limb**

- Recession limb ~~starts~~ extends from point of inflection at which catchment storage contributes to runoff
- ~~due~~ By this time rainfall also stops and hence catchment storage contributes more to runoff
- The shape of recession limb is independent of rainfall as it entirely depends on basin storage.

Factors affecting hydrograph:

The factors that affect the shape of the hydrograph can be broadly grouped into climatic factors and physiographic features. Generally climatic factors control the rising limb. Following are the factors,

Physiographic factors	Climatic factors
Basin characteristics - (i) shape (ii) size (iii) slope (iv) nature of valley (v) elevation (vi) drainage density Infiltration Characteristics - (i) land use and land cover (ii) soil type and geological conditions (iii) lakes and other storage Channel characteristics (i) cross section (ii) roughness (iii) storage capacity	Storm characteristics (i) precipitation (ii) intensity (iii) duration (iv) magnitude (v) movement of storm Initial loss Evapotranspiration

Shape of basin

The shape of the basin influences the time taken for water from remote parts of the catchment to arrive at the outlet. Fan shaped (ie) nearly semicircular shaped catchments give high peak and narrow hydrographs while elongated catchments give low peak and elongated hydrograph

Size of basin

Small basins behave different from the large ones In small catchments, the overland flow is predominant than channel flow. On large catchments channel flow (storage flow) is predominant. Further the time base is larger for large basins. Hence elongated hydrographs are obtained for large catchments.

Peak discharge = A^n ($n < 1$ generally 0.5)

Time base = A^m ($n < 1$, generally 0.2)

Slope

The slope of the land controls the velocity of flow. As the recession limb of hydrograph represents withdrawal from catchment storage, slope has an important effect on hydrograph. Large slopes gives rise to quick withdrawal of water from storage and hence results in steeper recession limbs.

Drainage density:

Drainage density is defined as the ratio of the total channel length to the total drainage area. A large drainage density results in quick disposal of run off. Hence the rising limbs are steep and high peak is obtained.

Land use

Vegetation and forests increase the infiltration and storage capacity of soil. Further they retard overland flow. Hence vegetation reduces peak flow and the hydrograph becomes elongated.

Climatic factors

Among climatic factors itensity, duration and directions of storm movement are the three important factors.

Intensity - For a given ~~dura~~ duration, peak and volume of surface runoff (hydrograph) is proportional to the intensity

Duration - For a given intensity, volume of runoff is directly proportional to duration. This results in high rising limb and peak.

Storm movement - If storm moves from upstream of catchment to the downstream end, the runoff will be high. This results in a peaked hydrograph. If the storm movement is from downstream to upstream, the resulting hydrograph will have a lower peak and long time base.

Unit hydrograph:

Unit hydrograph is defined as the hydrograph of direct runoff resulting from one unit depth (1cm) of rainfall excess (or) runoff occuring uniformly over a basin at a uniform rate for a specified duration 'D' hours.

Assumptions:

The following are the basic assumption of unit hydrograph.

(a) The rainfall excess (or) runoff is uniformly distributed within the specified duration. (intensity)

(b) The rainfall excess (or) runoff is uniformly distributed throughout the catchment.

(c) The base periods (duration) of direct runoff hydrograph resulting from rainfall excess (or) runoff is constant [though the intensities are different

(d) The ordinates of direct runoff hydrographs of a common base period (duration) are directly proportional to total volume of direct runoff represented by respective hydrographs.

runoff

(e) For a given catchment, the runoff hydrograph reflects the unchanging characteristics of basin

Assumption (a)&(b) are incorporated in the definition itself. Assumption (d) is known as the principle of linearity or principle of superposition. Assumptions (c) and (e) implies that the shape of runoff hydrograph remains same irrespective of time as long as the duration is same. This is known as principle of time invariance.

Procedure for deriving unit hydrograph

1) Select the runoff hydrograph for which unit hydrograph is to be derived

2) Separate the base flow from total runoff hydrograph to obtain the direct runoff hydrograph. This is done by simply ~~data~~ deducting the ordinates of base flow from ordinates of ~~the~~ total runoff hydrograph.

3) Divide each of direct runoff ~~ordinated~~ ordinates by

runoff depth. Run off depth is obtained by dividing runoff volume by catchment area. The resulting hydrograph is called as unit hydrograph.

Use of Unit hydrograph :

Unit hydrographs are used in many Hydrological problems such as

- → development of flood hydrographs for extreme rainfall for the use in design of hydraulic structures
- → extension of flood flow records based on rainfall records
- → development of flood forecasting and warning systems.
- → in watershed simulation models.

Limitations of Unit hydrograph

→ Unit hydrographs assumes that the runoff is uniformly distributed within the specified duration (intensity). Also the runoff is assumed to be uniformly distributed over the catchment. In practice these two conditions are never satisfied. Non uniform intensity and non uniform area distribution are common. Lower limit and upper limit of areas are taken as 2 km² & 5000 km² respectively. Basins with area larger than this can be studied by dividing them into a number of smaller basins and developing hydrographs.

→ Precipitation must be from rainfall only. Snow-melt runoff cannot be represented by unit hydrograph

→ The catchment should not have large storages ~~the~~

Variations of unit hydrograph of ± 20% in base period and ± 10% in peak discharge is normally considered as acceptable.

H/W

Instantaneous Unit Hydrograph

When a 'D' h unit hydrograph is available other than unit hydrographs whose duration is an integral multiple of 2D, 3D etc can be easily derived by the application of principle of Superposition. On other hand, if the unit hydrograph required is of duration less than 'D', it becomes necessary to derive S curve hydrograph and then derive unit hydrograph of required duration. Hence it is preferable to have unit hydrograph with very short duration, theoretically zero. Accordingly the unit hydrograph of zero duration is called as Instantaneous Unit Hydrograph (IUH)

Derive the unit hydrograph for a drainage basin of area 104 km^2 from the observed total runoff hydrograph given below.

Date	Time (hr)	Runoff (m^3/s)	Date	Time (hr)	Runoff (m^3/s)
June 10	2	16	June 11	2	76.4
	4	15		4	65
	6	14.2		6	55.2
	8	158.5		8	46.7
	10	260		10	39.6
	12	286.0		12	34
	14	221.0		14	28.3
	16	186.5		16	22.7
	18	157.0		18	21.5
	20	133		20	20.6
	22	113		22	19.9
	24	93.4		24	19.2

The ordinates of the rainfall mass curve which produced the above runoff are as given below.

Date	Time (hr)	Cumulative Rainfall (cm)
June 10	2	0
	4	1.5
	6	3.0
	8	10.5
	10	19.0
	12	20.0
	14	20.0

Solution

Date ①	Time(h) ②	Ordinate of TRH (m³/s) ③	Base flow (m³/s) ④	Ordinates of DRH (m³/s) ⑤ = ③ - ④	Ordinates of UH (m³/s) ⑤ ÷ 11.5
	6	14.2	14.2	0	0
	8	158.5	14.7	143.8	12.5
	10	266	15.2	244.8	21.87
	12	286	15.7	270.3	
June 10	14	221	16.2	204.8	
	16	186.5	16.7	169.8	
	18	157	17.2	139.8	
	20	133	17.7	115.3	
	22	113	18.2	94.8	
	24	93.4	18.7	74.7	
	㉖ 2	76.4	19.2	57.2	
	㉘ 4	65	19.7	45.3	
	㉚ 6	55.2	20.2	35.0	
	㉜ 8	46.7	20.7	26	
	㉞ 10	39.60	21.2	18.4	
June 11	㊱ 12	34.0	21.7	12.3	
	㊳ 14	28.3	22.2	6.1	
	㊵ 16	22.7	22.7	0	
	㊷ 18				
	㊹ 20				
	㊻ 22				
	㊽ 24				

(iii) Base flow separation

~~B~~ (i) By physical observation

Starting, $t = 6h$

End, $t = 24h$

(ii) From formula, $N = 0.83A^{0.2}$

$= 0.83 \times 104^{0.2}$

$= 2.1$ days

$= 50.4h$

$\therefore$ End $= 12 + 50.4 = 62.4h$ which is too long.

Hence the start and end are fixed as 6th hour of June 10 and 16th hr of June 11.

Runoff

Runoff volume = Discharge × Time

= (Sum of ordinates of DRH) × Time.

$= 1658.4 \times 2 \times 60 \times 60$

$= 1.194 \times 10^7 \, m^3$

Runoff depth $= \dfrac{\text{Runoff volume}}{\text{Catchment area}} = \dfrac{1.194 \times 10^7}{104 \times 10^6} = 0.115m$

$= 11.5cm$

begining hydrograph (m³/s)

Time from begining(h) ①	Ordinate of total runoff hydrograph (m³/s) ②	Base flow (m³/s) ③	Ordinate of direct runoff hydrograph ④ = ② ③ (m³/s)	Ordinate of 6h unit hydrograph ⑤ = ④/3cm
-6	10	10	0	–
0	10	10	0	0
6	30	10.167	19.833	6.61
12	87.5	10.333	77.167	25.72
18	117.5	10.5	108	33.367
24	102.5	10.667	91.833	30.611
30	85	10.833	74.167	24.722
36	71	11	60	20
42	59	11.167	47.833	15.944
48	47.5	11.333	36.167	12.05
54	39	11.5	27.5	9.167
60	31.5	11.667	19.833	6.611
66	26	11.833	14.167	4.722
72	21.5	12	9.5	3.167
78	17.5	12.167	5.333	1.777
84	15	12.33	2.67	0.89
90	12.5	12.5	0	0
96	12	12	0	–
102	12	12	0	–
108				

$$\text{Runoff depth} = \frac{\text{Runoff volume}}{\text{Catchment area}}$$

$$\text{Runoff volume} = 6\times60\times60\Big[\left(\frac{0+19.833}{2}\right)+\left(\frac{19.833+77.167}{2}\right)+\left(\frac{77.167+101}{2}\right)$$

$$+\left(\frac{101+91.833}{2}\right)+\left(\frac{91.833+74.167}{2}\right)+\left(\frac{74.167+60}{2}\right)$$

$$+\Big[\left(\frac{60+47.833}{2}\right)+\left(\frac{47.833+36.167}{2}\right)+\left(\frac{36.167+27.5}{2}\right)$$

$$+\left(\frac{27.5+19.833}{2}\right)+\left(\frac{19.833+14.167}{2}\right)+\left(\frac{14.167+9.5}{2}\right)$$

$$+\left(\frac{9.5+5.333}{2}\right)+\frac{5.333+2.67}{2}\Big]$$

$$= 6\times60\times60\,[9.917+84.5+89.084+96.417+83+$$

$$67.084+53.917+42+31.834+$$

$$23.667+17+11.834+7.417+4.002]$$

$$= 6\times60\times60\times621.673$$

$$= 13.428\times10^{6}\ \text{m}^3$$

$$\text{Runoff depth} = \frac{13.428\times10^{6}}{423\times10^{6}} = 0.03174\ \text{m} = 3\ \text{cm}.$$

Unit III - Flood and Drought

Natural Disasters - Flood Estimation - Frequency analysis - Flodd control - Definitions of drought - Meteorological, hydrological and agricultural droughts - IMD method - NDVI analysis - Drought Prone Area Programme (DPAP)

Natural Disasters:

Natural event such as flood, earthquake or hurricane drought, volcanoes, tsunami that causes great damage or loss of life is called as natural disaster.

Classification of flood

1) Probable maximum flood (PMF) or Maximum Probable Flood (MPF)

MPF is the extreme flood that is physically possible in a region that would result from severe combination of meteorological data and hydrological condition. This is used in situations where the failure of structure would result in loss of life and catastrophical damage (that cannot be recovered) This is used in design of spillways.

2) Standard Project Flood (SPF)

SPF is the flood that would result from most severe combination of meteorological data and hydrological condition This is used where the failure of structure would cause less severe damage. The values of SPF is generally 40 to 60% of PMF.

3) Design Flood

Design flood is the flood adopted for the design of hydraulic structures like spillways, flood banks or embankments, bridges, culverts, drainage and diversion works. It may be maximum probable flood or standard project flood depending

on recurrence interval ② of flood, degree of protection requ..
cost incurred for protection works.

Flood Estimation methods

Following are the estimation of flood peak,

- → Rational method
- → Emprical method
- → Unit hydrograph method.
- → Flood frequency studies

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1) **Rational method**

Assumed that maximum flood is produced by a certain rainfall intensity for a very long duration equal to or greater than concentration time (Concentration time is nothing but time required for surface runoff from remote part of catchment to reach the basin outlet. Runoff peak is given by,

$$Q_p = 2.778\, CAI$$

Where Q_p → Peak Discharge (m^3/s)
C → Runoff Coefficient ~~f~~ (Runoff / Rainfall)
A → Area of catchment (km^2)
I → Intensity of rainfall (cm/hr)

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2) **Emprical method**

Emprical formula used for estimation of peak floods. Correlates peak value and catchment properties. This method gives approximate values because catchment area is used as a parameter while flood frequency is neglected.

Dicken's formula

$$Q_p = C_D A^{3/4}$$

Where Q_p → Peak Discharge (m^3/s)
A → Area of catchment (km^2)

C_D → Dickens Constant (6 → North Indian plains,
11-14 → North Indian hilly
14-28 → Central India
22-28 → Andhra, Orissa)

Ryve's formula

$$Q_p = C_R\,n^{2/3}$$

where Q_p → Peak Discharge (m^3/s)

C_R → Ryve's coefficient = 6.8 for areas within 80 km from east coast

= 8.5 for areas which are 80-160 km from east coast

= 10.2 for limited areas near hills

A → Area of catchment (km^2)

Inglis formula

$$Q_p = \frac{124A}{\sqrt{A+10.4}}$$

where Q_p → Peak Discharge

A → Area of catchment (km^2)

Used in Maharashtra

Based on records (World experience)

$$Q_{mp} = \frac{3025A}{(278+A)^{0.78}}$$

where Q_{mp} → Maximum flood discharge (m^3/s)

A → Catchment Area (km^2)

Pb) Estimate the maximum flood flow for the following catchments by using an appropriate emprical formula:

1) A_1 = 40.5 km^2 for Western Ghat area, Maharashtra
2) A_2 = 40.5 km^2 in Gangetic plain
3) A_3 = 40.5 km^2 in the Cauvery delta, Tamil nadu
4) What is the peak discharge for A = 40.5 km^2 by maximum world flood experience?

④

Solution

Western ghat region, Maharashtra

By Inglis formula, $Q_p = \frac{124A}{\sqrt{A+10.4}}$

$$= \frac{124 \times 40.5}{\sqrt{40.5+10.4}}$$

$$= \underline{704 m^3/s}$$

Gangetic plain

By Dicken's formula, $Q_p = C_D A^{3/4}$

where $C_D = 6$ for plains

$$Q_p = 6 \times 40.5^{3/4}$$

$$= \underline{96.3 m^3/s}$$

Cauvery Delta

By Ryve's formula, $Q_p = C_R A^{2/3}$

where $C_R = 6.8$ for areas within 80km from east coast

$$Q_p = 6.8 \times 40.5^{2/3}$$

$$= \underline{80.2 m^3/s}$$

World experience

$$Q_{mp} = \frac{3025 A}{(278+A)^{0.78}}$$

$$= \frac{3025 \times 40.5}{(278+40.5)^{0.78}}$$

$$= 1367 m^3/s$$

3) Unit hydrograph method

An unit hydrograph can be used to generate design flood hydrograph. From the design flood hydrograph, peak discharge can be estimated.

4) Flood frequency studies

Another method used to prediction of flood flows, and also applicable to other hydrological processes such as rainfall etc is statistical method of flood frequency studies.

Following are the steps involved,

-> Selection of data
-> Arrangement of data
-> Probability plotting
-> General equation of frequency
-> Frequency distribution function

(i) Selection of data

For frequency studies, the flood data may consist of annual value series. Annual series is defined as the data series of annual maximum flood from a given catchment for large number of successive years.

(ii) Arrangement of data

The flood data are arranged in decreasing order of magnitude.

(iii) Probability plotting

Probability is given by plotting position formula,

$$P = \frac{m}{N+1}$$

where P -> Probability
m -> Order number of event
N -> Total number of event

Recurrence interval also called as return period or frequency is given as,

$$T = \frac{1}{P}$$

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

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

(iv) <u>General equation of frequency analysis</u>

$$x_T = \bar{x} + k\sigma$$

where x_T → Values of x at time 'T'

$\bar{x}$ → Mean

σ → Standard deviation $= \sqrt{\frac{\Sigma(x-\bar{x})^2}{N-1}}$

k → Frequency factor (depends on frequency distribution function)

(v) <u>frequency distribution function</u>

Some of the commonly used frequency distribution functions are,

- → Gumbel's extreme value distribution
- → Log Pearson Type III distribution
- → Log normal distribution.

<u>Gumbel's method</u>

The extreme value distribution is introduced by Gumbel (1941) and it is commonly known as Gumbel's distribution. It is the most widely method for prediction of flood peaks, maximum rainfall, maximum wind speed etc.

Gumbel defined the flood as the largest of the 365 daily flows and the annual series of flood flows constitute a series of largest values ⑦ of flows. According to his theory, the probability of occurrence of an event equal to or larger than a value 'x_0' is,

$$P(x \geq x_0) = 1 - e^{-e^{-y}} \quad \text{—①}$$

where $y \to$ Dimensionless variate given by

$$y = \alpha(x - a) \quad \text{———} ②$$

where $a = \bar{x} - 0.45005\,\sigma_x$

$$\alpha = \frac{1.2825}{\sigma_x}$$

$$② \Rightarrow y = \frac{1.2825}{\sigma_x}\left[x - (\bar{x} - 0.45005\,\sigma_x)\right]$$

$$= \frac{1.2825x}{\sigma_x} - \frac{1.2825\bar{x}}{\sigma_x} + 0.5771$$

$$y = \frac{1.2825(x - \bar{x})}{\sigma_x} + 0.5771$$

$$① \Rightarrow P = 1 - e^{-e^{-y}}$$

$$e^{-e^{-y}} = 1 - P$$

Taking natural logarithm on both sides,

$$-e^{-y} = \ln(1-P)$$

$$e^{-y} = -\ln(1-P)$$

Taking natural logarithm on both sides,

$$-y = -\ln(1-P)$$

$$y = -\left[-\ln(1-P)\right]$$

$$y = \ln\ln(1-P)$$

Substituting $T = 1/P$,

$$y = \ln\ln\left(1 - \frac{1}{T}\right)$$

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

$$y = -\ln\ln\left(\frac{T}{T-1}\right)$$

General equation is given as,

$$x_T = \bar{x} + k\sigma$$

where $k = \dfrac{y_T - \bar{y}_n}{S_n}$

$\bar{y}_n \rightarrow$ Reduced mean (for $n=\infty$, $\bar{y}_n = 0.577$)

$S_n \rightarrow$ Reduced standard deviation (for $n=\infty$, $S_n = 1.2825$)

$\bar{x} \rightarrow$ Mean

$\sigma \rightarrow$ Standard deviation $= \sqrt{\dfrac{\Sigma(x-\bar{x})^2}{N-1}}$

Pb) Annual maximum flood in a river for the period 1951 to 1977 is given below. Estimate the flood discharge with reccurence interval of 100 years and 150 years.

Year	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963
Max Flood (m^3/s)	2947	3521	2399	4124	3496	2947	5060	4903	3757	4798	4290	4652	5050

Year	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Max Flood (m^3/s)	6900	4366	3380	7826	3320	6599	3700	4175	2988	2709	3873	4593	6761	1971

Solution

The flood discharge values are arranged in descending order and the plotting position formula,

$$T_p = \frac{N+1}{m}$$

where $N \rightarrow$ Total number of event $= 27$

$$\therefore T_p = \frac{27+1}{m} = \frac{28}{m}$$

Order Number (m)	Flood Discharge x (m^3/s)	Return period $T_p = 28/m$ (yrs)	$(x-\bar{x})^2$
1	7826	28/1 = 28	1.27×10^7
2	6900	28/2 = 14	6.954×10^6
3	6761	28/3 = 9.333	6.24×10^6
4	6599	7	5.457×10^6
5	5060	5.6	6.353×10^5
6	5050	4667	6.194×10^5
7	4903	4	4.097×10^5
8	4798	3.5	2.863×10^5
9	4652	3.11	1.514×10^5
10	4593	2.8	1.089×10^5
11	4366	2.55	1.062×10^4
12	4290	2.33	7.812×10^2
13	4175	2.154	7.737×10^3
14	4124	2	1.931×10^4
15	3873	1.867	1.521×10^5
16	3750	1.75	2.56×10^5
17	3700	1.647	3.169×10^5
18	3521	1.556	5.505×10^5
19	3496	1.474	5.882×10^5
20	3380	1.4	7.796×10^5
21	3320	1.333	8.892×10^5
22	2988	1.273	1.626×10^6
23	2947	1.217	1.732×10^6
24	2947	1.167	1.732×10^6
25	2704	1.12	2.43×10^6
26	2399	1.078	3.474×10^6
27	1971	1.037	5.253×10^6
	115100		5.348×10^7

$$\text{Mean}, \bar{x} = \frac{\Sigma x}{M} = \frac{115100}{27} = 4262.96 \, m^3/s$$

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

$$= \sqrt{\frac{5.348 \times 10^7}{27-1}}$$

$$\sigma = 1434.14 \, m^3/s$$

$$k = \frac{y_T - \bar{y}_n}{S_n}$$

where $S_n = 1.2825$, $\bar{y}_n = 0.577$

$$y = -\ln\ln\left(\frac{T}{T-1}\right)$$

(i) Folood discharge with recurrence interval of 100years

$$y_T = -\ln\ln\left(\frac{100}{100-1}\right)$$

$$= 4.6$$

$$k = \frac{4.6 - 0.577}{1.2825}$$

$$= 3.137$$

$$x_T = \bar{x} + k\sigma$$

$$= 4262.96 + (3.137 \times 1434.14)$$

$$\boxed{x_{100} = 8761.86 \text{ m}^3/\text{s}}$$

(ii) Flood discharge with recurrence interval of 150years

$$y_T = -\ln\ln \frac{150}{150-1}$$

$$= 5$$

$$k = \frac{5 - 0.577}{1.2825}$$

$$= 3.449$$

$$x_T = 4262.96 + (3.449 \times 1434.14)$$

$$\boxed{x_{150} = 9209.309 \text{ m}^3/\text{s}}$$

Pb) Flood frequency computation for a river by using Gumbel method yielded the following result.

Return period (T) yrs	Peak flood (x) m^3/s
50	40,809
100	46,300

Estimate the flood magnitude with the return period of 500 years.

Solution

General equation is $x_T = \bar{x} + k\sigma$

$$x_{50} = \bar{x} + k_{50}\sigma$$

$$40809 = \bar{x} + k_{50}\sigma \quad -①$$

$$x_{100} = \bar{x} + k_{100}\sigma$$

$$46300 = \bar{x} + k_{100}\sigma \quad -②$$

$$② - ① \Rightarrow 46300 - 40809 = (\bar{x} + k_{100}\sigma) - (\bar{x} + k_{50}\sigma)$$

$$5491 = (k_{100} - k_{50})\sigma \quad -③$$

When T = 50 years, $k = \frac{y_T - \bar{y}_n}{S_n}$

$$y_T = -\ln\ln\left[\frac{T}{T-1}\right]$$

$$y_{50} = -\ln\ln\left(\frac{50}{50-1}\right)$$

$$y_{50} = 3.902$$

$$\boxed{k_{50} = \frac{3.902 - \bar{y}_n}{S_n}}$$

When $T = 100$ years, $K = \dfrac{y_T - \bar{y}_n}{S_n}$

$$y_{100} = -\ln\ln\left(\frac{T}{T-1}\right)$$

$$= -\ln\ln\left(\frac{100}{100-1}\right)$$

$$y_{100} = 4.6$$

$$\boxed{K_{100} = \frac{4.6 - \bar{y}_n}{S_n}}$$

Substituting K_{50} and K_{100} in ③

$$\Rightarrow 5491 = \left[\left(\frac{4.6-\bar{y}_n}{S_n}\right) - \left(\frac{3.902-\bar{y}_n}{S_n}\right)\right]\sigma$$

$$5491 = 0.698\frac{\sigma}{S_n}$$

$$\boxed{\frac{\sigma}{S_n} = 7866.76}$$

Flood magnitude with return period, T = 500 yrs

When $T = 500$ years, $y_{500} = -\ln\ln\left(\dfrac{T}{T-1}\right)$

$$= -\ln\ln\left(\frac{500}{500-1}\right)$$

$$= 6.214$$

$$\boxed{K_{500} = \frac{6.214 - \bar{y}_n}{S_n}}$$

When $T = 100$ years, $K_{100} = \dfrac{4.6 - \bar{y}_n}{S_n}$

Substituting, $x_{500} - x_{100} = \left[\left(\dfrac{6.214-\bar{y}_n}{S_n}\right) - \left(\dfrac{4.6-\bar{y}_n}{S_n}\right)\right]\sigma$

$$x_{500} - 46{,}300 = 1\cdot614 \frac{\sigma}{S_n}$$

$$= 1\cdot614 \times 7866\cdot76$$

$$= 12696\cdot951$$

$$x_{500} = 12696\cdot951 + 46300$$

$$= 58996\cdot957 \ m^3/s$$

Flood magnitude with return period of 500 years $= 58996\cdot957 \ m^3/s$

Pb) The mean annual flood of a river is 600 m³/s and standard deviation of the annual flood time series is 150 m³/s. What is the probability of a flood of magnitude 1000 m³/s occuring in the river within next 5years. Use Gumbel's method and assume the sample size to be very large.

Given

Mean $\bar{x} = 600 \ m^3/s$

Standard deviation, $\sigma = 150 \ m^3/s$

Flood discharge, $x_T = 1000 \ m^3/s$

Duration, $n = 5$yrs

Solution

General equation is $x_T = \bar{x} + K\sigma$ — ①

$$K = \frac{y_T - \bar{y}_n}{S_n} \quad \text{—②}$$

$$y = -\ln\ln\left(\frac{T}{T-1}\right) \quad \text{—③}$$

① ⇒ $1000 = 600 + (K \times 150)$

$$K = 2\cdot667$$

② ⇒ $$2\cdot667 = \frac{y_T - 0\cdot577}{1\cdot2825}$$

$$3.42 = y_T - 0.577$$

$$y_T = 3.997$$

$$3.997 = -\ln\ln\left(\frac{T}{T-1}\right) \Rightarrow -3.997 = \ln\ln\left(\frac{T}{T-1}\right)$$

Taking e power on both sides,

$$e^{-3.997} = \ln\left(\frac{T}{T-1}\right)$$

$$0.018 = \ln\left(\frac{T}{T-1}\right)$$

Taking e power on both sides,

$$e^{0.018} = \frac{T}{T-1}$$

$$1.018 = \frac{T}{T-1}$$

$$1.018(T-1) = T$$

$$1.018T - 1.018 = T$$

$$1.018T - T = 1.018$$

$$0.018T = 1.018$$

$$\boxed{T = 56.556 \text{ years}}$$

Probability

Probability of exceedance of the event atleast once in 5 years,

$$P_x = 1-(1-P)^n$$

where $P = \frac{1}{T} = \frac{1}{56.556} = 0.018$

$$P_x = 1-(1-0.018)^5$$

$$P_x = 0.087 \quad \left(1/0.087 = 11.4\%\right)$$

Log Pearson Type III Distribution

This distribution is extensively used in USA. In this the variate is first transformed into logarithmic form (base 10) and the transformed data is then analysed. If x is the variate of a random hydrological series, then the series of z variates where

$$z = \log x$$

is first obtained. For this z series, for any recurrence interval 'T',

$$z_T = \bar{z} + K_z \sigma_z$$

where $K_z \rightarrow$ Frequency factor

$T \rightarrow$ Recurrence Interval

$\bar{z} \rightarrow$ Mean $= \Sigma z / N$

$\sigma_z \rightarrow$ Standard Deviation $= \sqrt{\frac{\Sigma(z-\bar{z})^2}{N-1}}$

$N \rightarrow$ sample size (or) number of years of record.

After finding z_T, the corresponding value of x_T is obtained by

$$x_T = \text{antilog}(z_T)$$

Sometimes skew coefficient (C_s) is used in accordance to size of of sample.

Log normal distribution

When the skew is zero ($C_s = 0$) the log Pearson Type III distribution, reduces to log normal distribution. The log normal distribution plots as a straight line on logarithmic probability paper.

Drought

Drought is a period of prolonged shortage of water supply, either atmospheric moisture or surface water or ground water.

Drought

Drought is a prolonged dry period in the natural climate cycle that occurs anywhere in the world. This is due to deficiency of precipitation, resulting in water shortage.

Indicators of drought

- Precipitation
- Temperature
- Stream flow
- Ground water and reservoir level
- Soil moisture
- Snow pack.

Impact of drought

Drought can have the following impacts

- Health
- Economy
- Agriculture
- Energy
- Environment.

Types of drought

Many classifications are available in nature. The following classification into three categories proposed by the National Commission on Agriculture (1976) is widely adopted in the country.

- Meteorological drought
- Hydrological drought

→ Agricultural drought

(i) Meteorological drought

Meteorological drought is based on the degree of dryness in comparison to some normal or average amount of rainfall and the duration of the dry period. Definitions of a meteorological drought must be considered as region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region. Usually meteorological drought is the drought in which there is more than 25% decrease in precipitation from normal over an area (rainfall less than 75% of normal value)

The Indian Meteorological Department (IMD) has adopted the following criteria for sub classification of meteorological droughts,

→ Drought is classified as moderate if seasonal deficiency is between 26% and 50% of normal value.

→ Drought is said to be severe if seasonal deficiency is more than 50% of normal value.

Further a year is considered to be a drought year in case the area affected by moderate or severe drought is either individually or collectively is more than 20% of the total area of the country.

Following is the drought zones,

→ If the drought occurs in an area with a probability of 0.2 to 0.4, the area is classified as drought prone area.

→ If the drought occurs in an area with probability greater than 0.4, the area is called as chronically drought prone area.

Prediction of occurrence of such drought in a region is done based on forecast of monsoon season and its distribution. Such forecast is not accurate.

(ii) Hydrological drought

Hydrological drought is based on the impact of shortfall of rainfall on surface water supply like stream flow, reservoir and lake levels and sub surface water supply like ground water, soil moisture. Although all droughts originate due to precipitation, it is essential to identify how its deficiency affects hydrological drought because at beginning of drought it takes time for the deficiencies to show up in soil moisture, ground water and reservoir levels. As a result, these impacts do not occur like impacts of meteorological and agricultural drought. For example deficiency in precipitation may result in rapid depletion of soil moisture that immediately affects agriculture while the impact of deficiency on reservoir level may not affect hydroelectric power production for months.

(iii) Agricultural Drought

Agricultural drought refers to the impacts on agriculture by ~~due to precipitation shortages~~ such that available water supplies are not able to meet crop water demands. It usually occurs when soil water availability ~~to~~ in specific area has dropped to a level ~~that is~~ such that it affects crop yield. The various causes of agricultural drought are low precipitation, soil water deficiency, reduced ground water, reduced reservoir levels, timely availability of water, decreased access to water supply.

Unit IV

Flood Control methods / measures :

A flood is an unusual high stage of a river overflowing its banks and creating damages to surrounding ~~life~~ living beings and property. This is due to severe rainfall of meteorological and hydrological combinations. To avoid the damages due to flood, the flood needs to be controlled.

The term flood control is used to denote all the measures adopted to reduce damages to life and property by flood. Following are the control measures,

→ Structural measures - Storage reservoirs
Detention reservoirs
Levees
Flood ways
Channel improvement
Watershed ~~mang~~ management.

→ Non structural measures - Flood plain zoning
Flood forecast / warning
Evacuation and relocation.

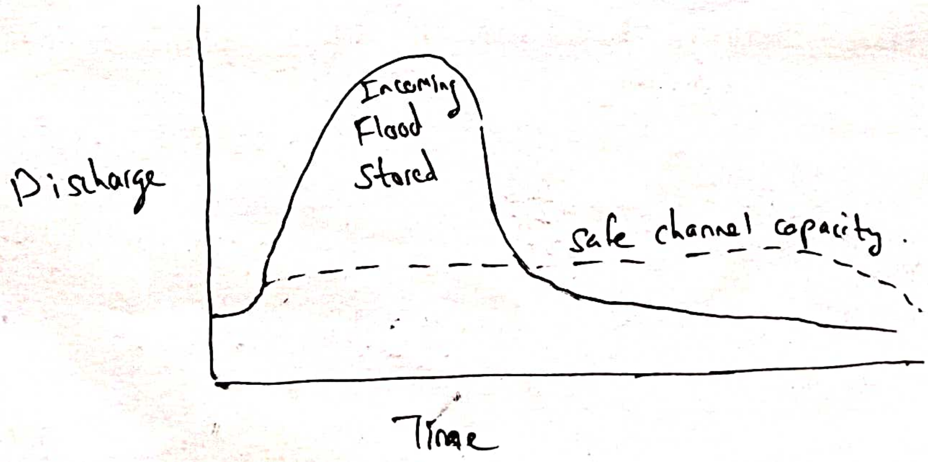
Structural measures

(i) Storage reservoirs

Storage reservoirs is one of the most

reliable and effective methods of flood control. In this method, a part of the storage in reservoir is kept free to absorb the incoming flood. By absorbing the incoming flood, flood peaks can be reduced and damages can be avoided.

To keep the reservoir free for ~~storage~~ storing incoming flood, the stored water should be released in a control way over extended time so that the downstream channels do not get flooded. The capacity that can be discharged safely depends on the capacity of channel called as "Safe downstream channel capacity" All inflow into the reservoir in excess of safe channel capacity is stored until the inflow drops below the safe chanel capacity and then the stored water is released and reservoir is kept ready for next flood

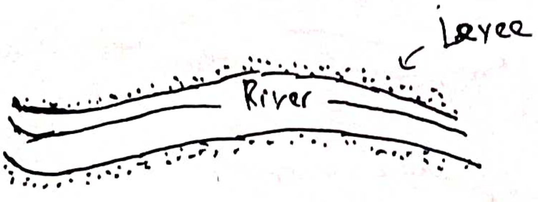


(ii) Detention reservoirs :

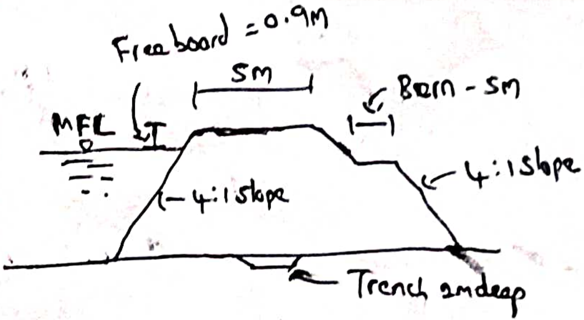
A detention reservoirs consists of an obstruction to a river with an uncontrolled outlet. This results in restriction of flow rate.

(iii) Levees :

Levees also know as dikes or flood embankments are earthen banks that are constructed on the sides of reservoir along its length. In general levees are confined to a limited cross sectional width and hence height is kept maximum. Usually the height of levees will be higher than design flood level with sufficient free board.



Plan



Cross section

Levees are the most common methods of flood protection works. They are the cheapest method. The protection offered by a levee against flood damage is high but it requires considerable care and maintenance. In case of failure, the damage caused will be enormous. If the bed level of the levees rise, the top of levees have to be raised at frequent intervals. to prevent failure of levees.

(iv) ~~F~~loodways

Floodways~~ways~~ are channels into which a part of flood will be diverted during high flood. A flood way can be a natural channel or man made channel. Floodways are economical when compared to other structural flood control measures.

(v) Channel improvement

Channel safely discharges the flood water stored in reservoir. Hence the channels should be maintained completely. Following are the works under this category.

→ Widening or deepening of the channel to increase the cross sectional area

→ Reduction in channel roughness by clearing vegetation from the channel.

→ Avoiding meandering path (zig zag path) of channel.

vi) Watershed management

Watershed management ~~involves~~ means treating the land and dalaying runoff before it enters river. Watershed management can be done by developing soil cover and vegetation in land and developing Nalabunds, Check dams and contour bunding. These treatments cause increase in infiltration ~~rate~~ rate, greater evapotranspiration, reduction in soil erosion thereby reducing flood.

Non structural measures

(i) Flood plain zoning

Flood plain zoning ~~idenf~~ identifies the flood prone areas and modification of ~~land~~ land use to restrict the damage due to floods. The location and areas to be affected by floods ~~are~~ of different return periods are identified and development plans are prepared. Following table indicates the zones with their corresponding return period and land use.

Zone	Return period	Land Use
1	100 yrs	Residential Buildings, offices, factories
2	25 yrs	Parks
3	Frequent	No construction

(ii) Flood forecast / warning :

Floods should be forecast in advance ~~and~~ so that warning can be given to the people who are likely to be affected by flood. This ~~also~~ helps the authoilties to ~~take~~ take proper precautions. This is a very important ~~and~~ and inexpensive non structural flood measure. The flood forecasting technique can be broadly classified into three categories

Short range forecast –

* The stages (~~study~~) of river at successive stations on a river are studied and compared with parameters like rainfall, precipitation index and travel time of flood.
* This method can give a advance warning of 12 to 40hrs

Medium range forecast

* The rainfall runoff relationships, storm duration is studied
* This method can give warning of 2 to 5 days.

Long range forecasts

* Using radars and meteorological satellite data weather conditions, rain potential are studied and flood is predicted

(iii) Evacuation and relocation

Evacuation of human beings along with ~~lfuin~~ live stocks and valuables in flood affected areas and relocation of them to a safer location is one among the non structural flood control measures. Permanent shifting of human beings ~~may~~ is termed as structural measure.

IMD Method

Indian Meteorological Department (IMD) monitors the incidence (Occurrence), spread, intensification (seriousness) and cessation (decrease and stopping) of drought on a weekly time scale over the Country based on Aridity Anomaly Index

Aridity Anamoly Index is used to describe the water deficiency experienced by plants. Aridity Anamoly Index are simply aridi ~~aridity~~ aridity index is given by

$$AI = \frac{PE-AE}{AE} \times 100$$

where PE - Potential evapotranspiration which denotes the water need of plants

AE- Actual evapotranspiration denotes the water deficiency

PE is computed by Penman's equation. AE is obtained from water balance procedure which takes into account the water holding capacity of soil at that place.

According to this procedure, rainfall is first utilized by the plants for evapotranspiration purpose. When the evapotranspiration needs of plants are met (PE) ~~the~~ the excess amount of rainfall penetrates and recharge the soil. The soil moisture recharge continues till the soil reaches its field capacity. The excess water after the evapotranspiration needs are met and soil is recharged completely is called surplus water which goes down as surface runoff.

When the rainfall is less than the evapotranspiration demands, the plant extracts moisture from soil till the soil becomes dry. During the periods of less rainfall, soil loss of moisture is given as,

$$S = f_c \times \exp\left(\frac{APME}{f_c}\right)$$

S → Moisture remaining in soil
APWL → Accumulated Potential Water Loss
fc → Field Capacity

Based on Aridity Anomaly Index, weekly Drought Outlook, weekly Aridity Anomaly Reports and maps for the whole country during monsoon season are prepared and ~~sed~~ send to agricultural authorities of ~~se~~ State and Central government, research institutes for their use in agricultural planning purposes. These maps/reports helps to assess and monitor agricultural drought in country.

Normal values of this index are worked out for stations representing different climatic zones of the country using weekly total rainfall and antecedent soil moisture conditions. The difference between actual aridity index and normal aridity index is obtained. Negative or zero value of the difference indicates less drought conditions / arid conditions, positive value of difference indicates more drought condition. The positive values are classified into three different classes as below,

Difference of Aridity Index	~~Agric~~ Agricultural Drought Intensity
1-25	Mild
26-50	Moderate
>50	Severe

Further Aridity Anomaly maps can be prepared using the above information which helps in irrigation scheduling the amount and time at which water is needed by plants.

NDVI Analysis

Normalized Difference Vegetation Index (NDVI) is a simple graphical indicator that can be used to analyze remote sensing ~~measurefe~~ measurements, often from a space platform, assessing whether the place observed contains live green vegetation.

NDVI is calculated in accordance with the formula,

~~$NDVI = \frac{NIR + RED}{NIR - RED}$~~

$$NDVI = \frac{NIR - RED}{NIR + RED}$$

where NIR → Reflection in the near infrared spectrum

RED → Reflection in the red range of spectrum

According to this formula, the density of vegetation at a certain point of the image is equal to the difference in the intensities of reflected light in red and infrared range divided by the sum of these intensities.

This index defines values from −1.0 to 1.0 basically representing greens where,

negative values – formed from clouds, water and snow

values close to zero – formed from rocks, soil

0.1 or less – empty areas

0.2 to 0.3 – Shrubs and grass

0.6 to 0.8 – Forests

NDVI is a measure of state of plant health based on how plant reflects light (or absorbs light). Chlorophyll, a health indicator of plants strongly absorbs ~~gree~~ red light and reflects green light ~~visible light~~ and cellular structure of leaves strongly reflect near

Infra red light. When the plant becomes dehydrated, subjected to disease, the plant absorbs more near infrared light instead of reflecting it. This means ~~the~~ that a healthy plant, one with lot of chlorophyll and cellulose structure absorbs RED ~~and~~ and reflects NIR, while unhealthy plant do exact opposite.

NDVI analysis can be used to ~~asses~~ assess ~~agricul~~ agricultural production, monitor drought, forecasting fire zones and desert, vegetation monitoring.

Drought Prone Area Programme (DPAP)

Drought Prone Area Programme (DPAP) is the "earliest area development programme" launched by the ~~Gov~~ Central Government in 1973-1974 to address special problems faced by areas which are constantly affected by severe drought conditions.

The programme is implemented in the form of rural works project which will

- → mitigate adverse effect of drought on crops and productivity of land, water and livestock by developing natural resource
- → Create additional employment in these areas

~~Strategies~~

Strategies followed

- → Development of and scientific management of resources
- → Land improvement
- → Soil Conservation
- → Desiltation of tanks, canals
- → Afforestation and pasture development
- → Restructuring of cropping pattern

→ Scientific agronomic practices
→ Live stock development
→ Focus on small and marginal farmers
→ Development of infrastructure like dams for water storage
→ Watershed management

Unit IV Floods and Flood Routing

Classification (or) classes of flood

1) Probable maximum flood (PMF) or Maximum Probable Flood (MPF)

MPF is the extreme flood that is physically possible in a region that would result from rare combination of meteorological data and hydrological condition. This is used in situations where the failure of structure would result in loss of life and catastrophic (harmful) damage. This is used in design of spillways.

(can) be recovered

2) Standard Project Flood (SPF)

SPF is the flood that would result from most severe combination of meteorological data and hydrological condition. This is used where the failure of structure would cause less severe damages. The value of SPF is generally 40 to 60% of PMF.

3) Design Flood

Design flood is the flood adopted for the design of hydraulic structures like spillways, flood banks or embankments, bridges, culverts, drainage and diversion works. It may be of maximum probable flood or standard project flood depending on the recurrence interval of flood, degree of protection required, cost incurred for protection works.

4) Design storm or probable maximum precipitation

Gumbel's method of determination of flood magnitude (or) How will you determine magnitude of flood of specific return period.

Gumbel method is one of the most widely method of determination of flood magnitude. This method was introduced by Gumbel in 1941. Gumbel defined flood as the largest of 365 daily flows and the annual series constitute a series of largest value of flows. According to his theory, the probability of occurrence of an event equal to or greater than a value 'x_0' is given by

$$P(X \geq x_0) = 1 - e^{-e^{-y}} \quad \text{—} ①$$

where $y \rightarrow$ dimensionless or reduced variate given by

$$y = \alpha(x - a) \quad \text{—} ②$$

where $a = \bar{x} - 0.45005\,\sigma_x$

$\alpha = 1.2825 / \sigma_x$

$$② \Rightarrow y = \frac{1.2825}{\sigma_x}\left[x - [\bar{x} - 0.45005\,\sigma_x]\right]$$

3) Find reduced variate y_T for the given return period 'T'

4) Find ~~facto~~ frequency factor k ~~while~~ $\left(k = \frac{y_T - \bar{y}_n}{S_n}\right)$ while the values $y_T, \bar{y}_n$ and S_n are known

5) Determine x_T which is the flood magnitude of specific return period 'T'

Probability (~~Type I~~)

1) A flood of a certain magnitude has a return period of 40 years Determine the probability exceedance and probability of the flood of magnitude equal to or greater than the given magnitude occuring at least once in 10 successive years, two times in 10 successive years and once in 10 successive years.

Exceedance probability

Exceedance probability, $P = \frac{1}{T} = \frac{1}{40} = 0.025$, $q = 1 - P = 0.975$

Probability of ~~magnitude~~ flood occuring at least once in 10 yrs

$$P = 1 - (1-P)^n \qquad (1 - q^n)$$

$$= 1 - (1 - 0.025)^{10}$$

$$= 0.224$$

Probability of flood occuring two times in 10 successive years.

$$P_{r,n} = {}^{n}C_r \, p^r \, q^{n-r}$$

$P_{2,10} = 10C_2\, p^2 q^{10-2}$

$= 10C_2\, p^2 q^8$

$= 10C_2 \times 0.025^2 \times 0.975^8$

$= 0.023$

Probability of flood occuring one time in successive 10 years

$P_{1,10} = 10C_1\, p^1 q^{10-1}$

$= 10C_1\, p^1 q^9$

$= 10C_1 \times 0.025^1 \times 0.975^9$

$= 0.199$

UNIT IV – RESERVOIRS

Reservoirs

When a barrier is constructed across river in the form of a dam, water gets stored on the upstream side of the dam and released on the downstream side. The dam along with upstream side and downstream side is called as reservoir.

Reservoirs are used to store or conserve water, to control floods and to distribute the water. Depending on above mentioned use, reservoirs are classified as

→ Single Purpose Reservoirs – Storage or Conservation reservoirs
Flood Control reservoirs
Distribution reservoirs

→ Multipurpose reservoirs

I) Single purpose reservoirs

As the name implies single purpose reservoirs are used for single purpose like storage or ~~Conse~~ Conservation, flood control or distribution.

1) Storage or conservation reservoir

Water is required for irrigation, domestic and ~~indus~~ industrial water supply, hydroelectric power generation. This water thus required cannot be directly obtained from a river because it may fail during periods of low supply ~~flows~~. Hence it is required to store the excess water during period of large supplies and release it gradually whenever it is needed. ~~To store the water~~ The reservoir thus constructed to store water is called 'Storage or Conservation reservoirs'.

2) Flood Control reservoirs

~~Flood control reservoirs are those which are used to store a portion of water during flood and release it gradually and safely when the flood reduces. Generally~~

2) Flood Control Reservoirs

Flood control reservoirs store a portion of flood in such a way that flood peak gets minimised and downstream areas get protected. To accomplish this, the entire inflow entering the reservoir is discharged till the outflow reaches the safe capacity of downstream channel. The inflow in excess of safe capacity of downstream channel is stored in the reservoir which is then gradually released in order to keep the flood reservoir free for storing excess water for next flood. Flood control reservoirs are of two types namely a retarding reservoir and detention basins

9, 23, 26, 30, 41, 46

(a) Retarding reservoir

A retarding ~~da~~ reservoir is ~~[illegible]~~ usually provided with uncontrolled spillway and and ~~ungated~~ ~~c~~ ungated outlets (canal). As there is uncontrolled outlets, ~~the~~ the reservoir operation takes place automatically. The maximum discharging capacity of the dam should be kept equal to the maximum safe carrying capacity of downstream channel. As the floods occur the reservoir gets ~~f~~ filled and discharges through uncontrolled spillway and uncontrolled outlets. As the reservoir elevation increases ~~outflow~~ ~~increases~~ inflow increases and the outflow also increases and reaches its maximum discharging capacity. After this the inflow water automatically gets withdraw from the reservoir until the stored water is completely discharged and this process continues.

Advantages.

→ Cost of expensive gate installation and ~~operation~~ is saved

→ There are no gates and hence possibility of human error and reservoir operation is eliminated.

Disadvantages

→ Ideal location of reservoir is essential at the reservoir operation is automated. and Can be used for small rivers only.

→ If there or two or more canals, off taking from reservoir, there will be a coincidence of water level in both ~~Cana~~ Canals.

(b) Detention basins

A detention ~~reser~~ basin is provided with gated spillways and gated outlets. The reservoir temporarily stores the water when inflow exceeds outflow and then the stored water is ~~comple~~ released in a controlled way so that the downstream ~~canal~~ channels do not get flooded.

Advantages

- The gate installation provides more flexibility of operation and thus gives better control and use of reservoir
- Can be used on large ~~reservoirs~~ rivers
- Water level in offtaking canals can be controlled.

Disadvantages

- There is a risk of human error while operating the gates
- High initial and maintenance cost.

3) Distribution reservoirs

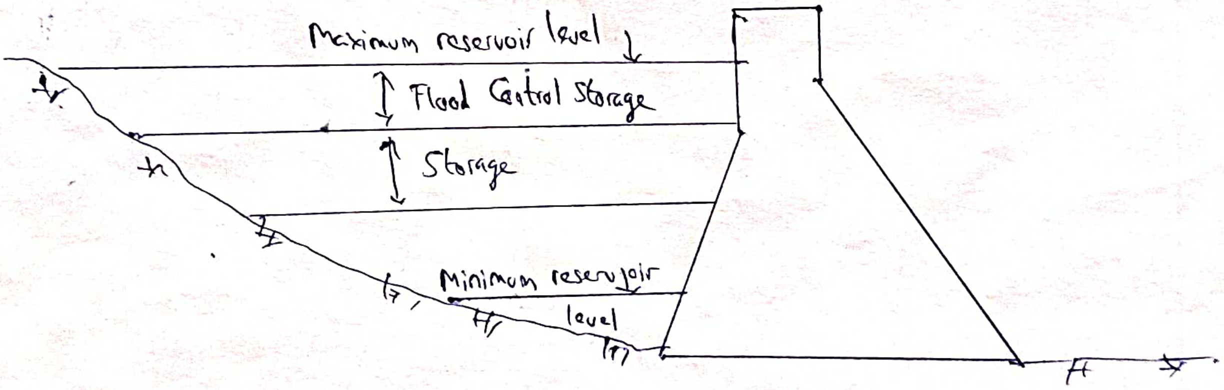
A distribution reservoir is a small storage reservoir constructed and used for water supply in a city. Such a reservoir can be filled by pumping water at a certain rate and can be usually used for water supply during periods of water demand. This permits pumping plants and water treatment works to perform at a constant rate

13, 37, 42, 57,

II) Multi purpose reservoir

A multipurpose reservoir is ~~one~~ one which serves more than one purpose. Such Multipurpose reservoir can be used for purposes like irrigation water supply, domestic and industrial water supply, navigation, flood control, hydroelectric power generation etc. It is therefore necessary to store water individually for each purpose and separate space should be allocated for each purpose.

For example if a reservoir is to be constructed for a dual purpose of storage and flood control necessary space for individual storage can be identified using water levels. Following figure indicates the dual use of multipurpose reservoir.



Fixation of Storage Capacity

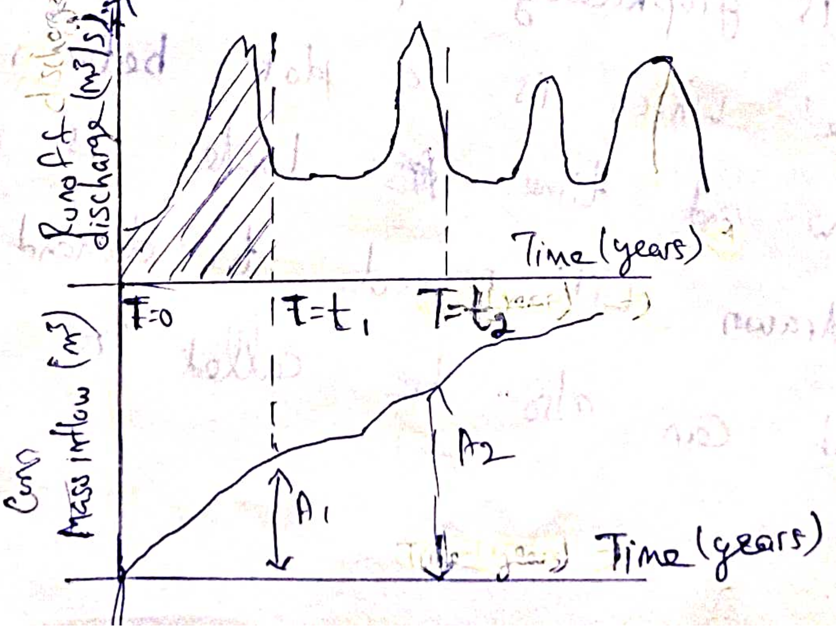
The inflow to the reservoir and outflow from the reservoir are the two factors which govern the storage capacity of reservoir. Storage capacity of the reservoir is given by below equation,

Storage capacity of reservoir = Inflow to the reservoir − Outflow from the reservoir

Inflow to the reservoir

The inflow to the reservoir is represented anually and called as annual inflow or Catchment yield. It is graphically represented by 'Mass Inflow Curve' which is plot between cumulative inflow to the reservoir with time.

Following figure shows a flood hydrograph for several years (say 25 to 30 yrs). A hydrograph is a plot of runoff discharge vs ~~time~~ time

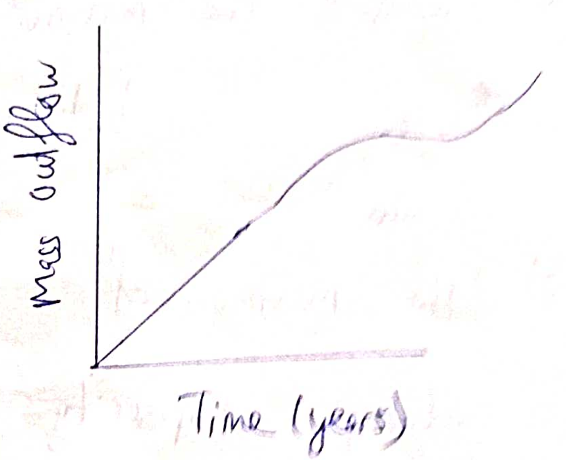


From the graph, quantity of water (A1) from time T=0 and T=t1 can be found out by the area under ~~of~~ hydrograph between time T=0 and time T=t (hatched portion). Similarly the quantity of water (A2) from time T=0 and T=t2 is found out. This processes is repeated for all time intervals and quantity of water A1, A2, A3, ... is found out.

Finally a graph between the quantity of water and time is plotted (Mass inflow vs Time) called as 'Mass Inflow Curve'

Outflow from reservoir

The outflow from the reservoir is also called as reservoir yield. Reservoir yield is the amount of water that can be withdrawn from a reservoir in a specified interval of time. It is graphically represented by 'mass Outflow Curve' which is a plot between cumulative outflow and time. ~~AS~~ Water is going to be withdrawn with respect to demand. Hence the graph can also be called as 'Demand Curve'



If a constant rate of withdraw is done, the ~~Mass curve of~~ demand curve will be a straight line. Demand curves are generally straight but in practice they may be curved.

Determination of reservoir Storage Capacity from Mass Inflow curve and Demand Curve

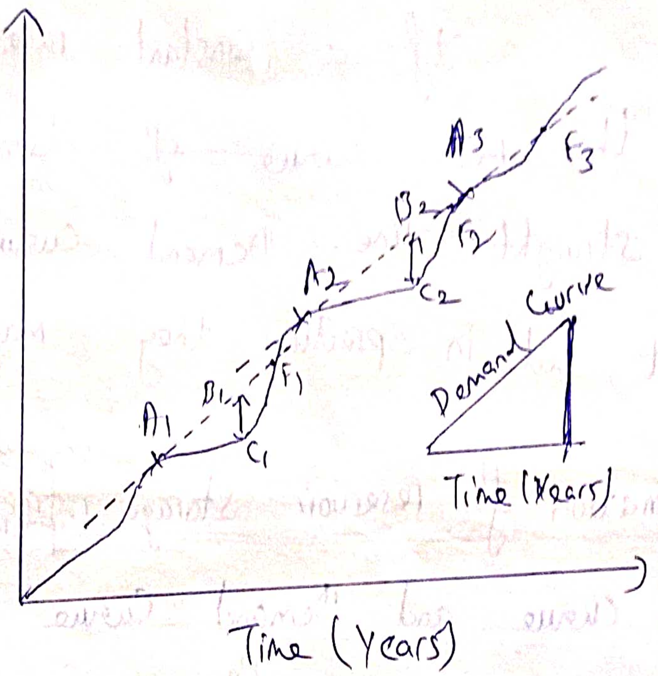
1) Prepare the mass inflow curve from the flood hydrograph and draw it to some scale. Also prepare the Demand Curve to the same scale.

2) From the points A_1, A_2, A_3 .... draw tangents parallel to the demand ~~curve~~ curve (draw with slope as that of demand curve)

3) The tangents intersects the Mass Inflow curve say at points F_1, F_2, F_3, ...

4) Measure the maximum vertical intercepts B_1C_1, B_2C_2, B_3C_3, ... between the tangent and mass inflow curve

5) The maximum of B_1C_1, B_2C_2, ... gives the storage capacity of reservoir



Strategies of Reservoir Operation (or) Planning of Reservoir Operation

The operation of a reservoir is a planned process of using available water resources optimally to derive maximum benefit by making use of reservoir capacity. Therefore it is essential to make sufficient planning before construction of reservoir to ensure that there is no wastage of water. Planning must be based on consideration of the following

-) Performance of past flow characteristics of the river

runoff dir vs time.

-) Control of ~~flow by~~ low hydrographs to achieve maximum reservoir efficieny

-) Effects of sudden release of flood waters from the reservoir to the river and agricultural lands on downstream side.

~~Most~~ Principles and Methods of Reservoir Operation

1) Single Purpose Conservation Reservoirs

(a) Annual Utilization method

This method is based on ~~having~~ storage of water in reservoir during season and use of stored water in reservoir during a year. The reservoirs are designed such that they gets completely filled up during monsoon and completely depleted during dry periods. No storage should be stored to carry over it to the next year. Filling period is from June to September and depletion period is from October to May.

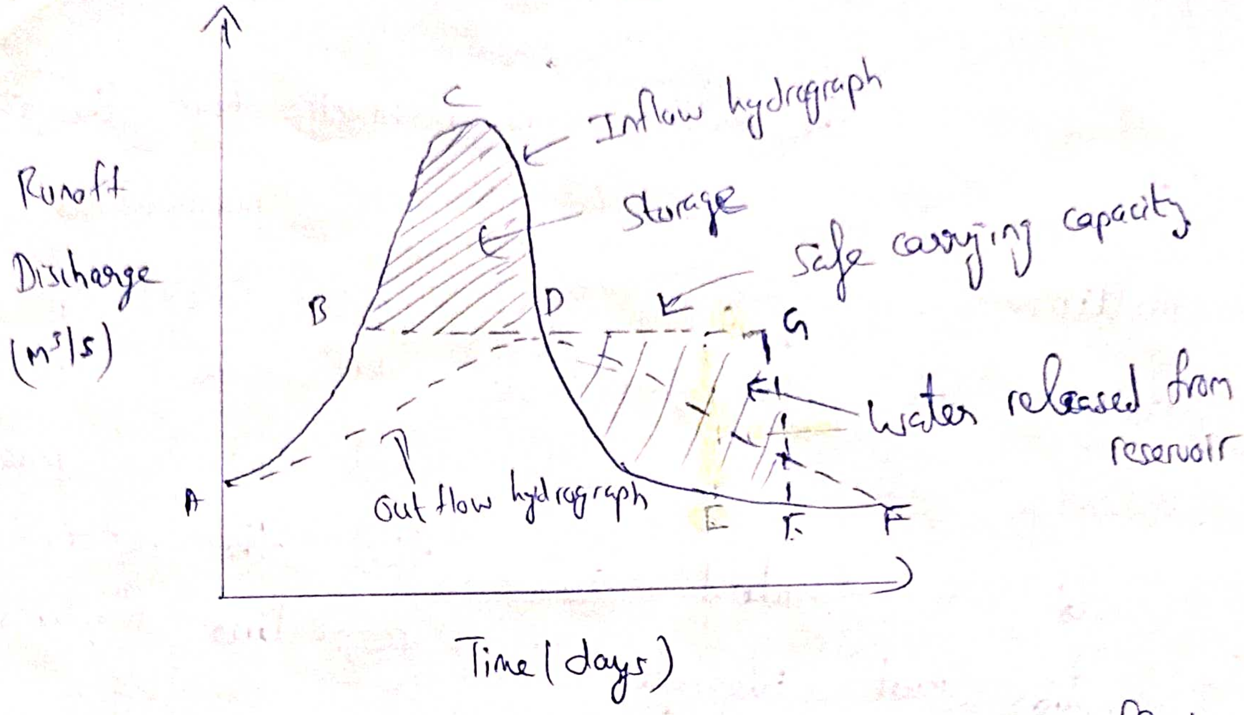
(b) Insurance method:

This method is based on carry over storage which is necessary to take care water requirements during drought periods. Water requirements ~~for~~ during dry periods are calculated and water is released according to requirement. The balance water is stored and released during drought. as carry over storage

2) Single purpose flood control reservoir — Retarding. Detention

Flood control reservoirs are operated on the principle of temporarily storing flood waters and releasing them in a controlled manner such that the outflow discharge does not exceed safe carrying capacity of canal.

The principle of operation of flood control reservoir can be explained using below figure,



ABCDEF ~~rapts~~ represents the ~~inflow or~~ flood hydrograph of the flood discharge that enters the reservoir By regulating (opening) the sluice gates the flow is allowed to pass directly through the downstream channel. Once the outflow exceeds safe carrying capacity (BG) water gets stored indicated by BCD. After the water in downstream gets depleted the ~~storg~~ water stored BCD is released ~~gradually~~ ~~such~~ ~~that~~ indicated by DGE. Once the flood storage volume of the reservoir gets empty the ~~hyd~~ peak of hydrograph gets reduced from C to D and outflow hydrograph is indicated by ADF. This process gets repeated for next incoming flood.

3) Multi purpose Reservoir

The multi purpose reservoir have the ~~characte~~ characteristics of serving two or more purposes. Mainly multipurpose reservoir serves the purpose of storage and flood control which have specific volumes for storage and flood control. Spaces should be allocated such that the reservoir operation must integrate the respective functions of storage and flood control.

Practically the integration of different functions is not easy to achieve. For example during monsoon season high floods occur and there will be a need of high flood control storage. Hence a compromise should be made such that a part of storage can be used for flood control ~~also~~.

Design Flood

Design flood is the flood adopted for for the design of hydraulic structures like spillways, embankments, culverts, drainage and diversion head works etc.

Levees and Flood walls

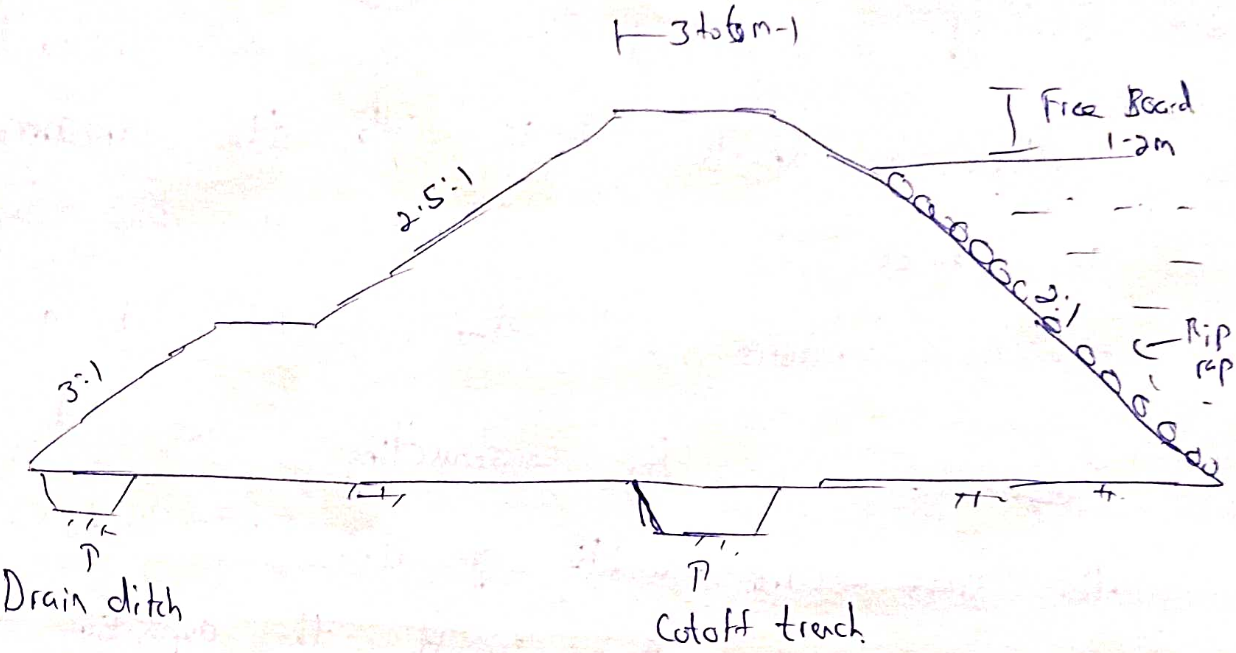
Levees and Flood walls are constructed in order to confine the flow of river so that overflow of ~~ff~~ river is prevented. If the confinement is done by constructing earthen embankments, ~~it is calle~~ the structure is called as Levees. If the confinement is done by constructing masonry structures, the structure is called as Flood walls.

~~Levees~~ By constructing levees and flood walls the ~~cross section~~ width of river is limited resulting in high velocity. As a result the deposition of suspended particles ~~become~~ becomes less.

Levees

Levees are the most common method adopted since it is the cheapest method of protection. Levees are ~~usu~~ usually built with material excavated from borrow pits nearby.

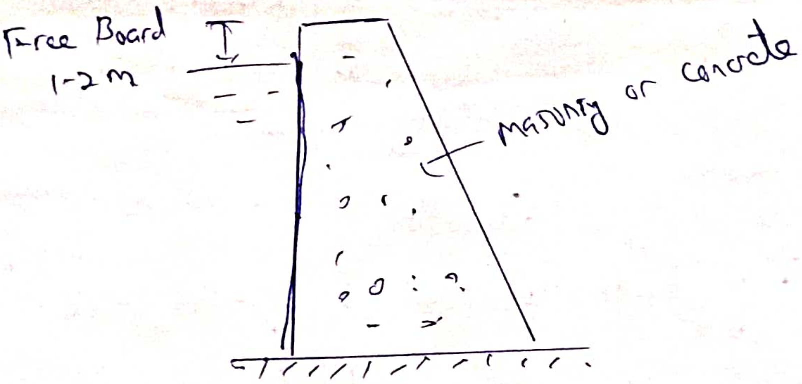
The section of levee adopted must ensure proper strength and stability. The top ~~wit~~ width of levees should be sufficient to permit movement of vechicles and maintenance equipment. The top width should not be less than 3m. Bank slopes are usually flat generally between 2:1 to 3:1



Some measures against erosion ~~do~~ of banks by river should be provided. To avoid erosion apron, rip rap is provided As ~~the~~ the embankments are made with soil there is a possibility of seepage and hence drain ditches should be provided in order to drain the seepage water. Cut off trenches should be provided to cut off pore water pressure.

Flood walls

Because of flat slopes of levees, the base width of levees ~~incre~~ increases. This may result in land acquisition ~~prop~~ problems and hence construction of levees becomes uneconomical. In such a case, flood walls are used. Flood walls are constructed with masonry or concrete with solid foundations. It should be capable of withstanding ~~by~~ water pressure, uplift pressure etc.



Elevation - Area - Capacity - storage estimation

The main function of a reservoir is to store water and hence the most important physical characteristic of a reservoir is its storage capacity. The capacity is determined from the contour maps of the area. A topographic survey of the dam site is carried out and contour maps are established. The area enclosed within each contour can be measured with planimeter. The general practice adopted for capacity computation is to actually survey the site contours only at a vertical distances of 5m. The areas of intervening contours at small intervals (say 0.5m) are then interpolated by taking square root of the surveyed contours and to assure that the square root of the interpolated values, vary in exact proportion to their vertical distance apart. The areas computed is used to determine the incremental volumes (ΔS) stored between two successive contours, by using simple average method (i.e.) by multiplying the average of the two areas at the two elevations by the elevation difference (Δh). The summation of these incremental volumes below any elevation is the storage volume. Instead of using the simple average formula,

$$\Delta S = \frac{a_1+a_2}{2}(\Delta h)$$

Sometimes the below formula can also be used.

$$\Delta S = \frac{\Delta h}{3}\left(a_1+a_2+\sqrt{a_1a_2}\right)$$

Prismoidal formula can also be used when three consecutive sections are taken,

$$\Delta S = \frac{\Delta h}{6}[4a_1 + a_2$$

$$\Delta S = \frac{\Delta h}{6}\left[A_1 + 4A_2 + A_3\right]$$

where $A_1, A_2, A_3 \rightarrow$ Areas of succeeding contours

$\Delta h \rightarrow$ Vertical distance between two alternate contours.

The areas at different elevations and storage at different elevations can be mathematically worked out and plotted on a graph paper to obtain Area Elevation Curve and Storage Elevation Curve.

Another method for computing capacity is by the use of integration techniques. When the area elevation curve is integrated it yields capacity elevation curve. Hence area elevation curve is plotted on a simple graph paper and a smooth curve is obtained. The equation of this curve is obtained by statistical methods which can be integrated to obtain capacity ~~elevation~~ curve (storage).

Unit V - Ground water & Management

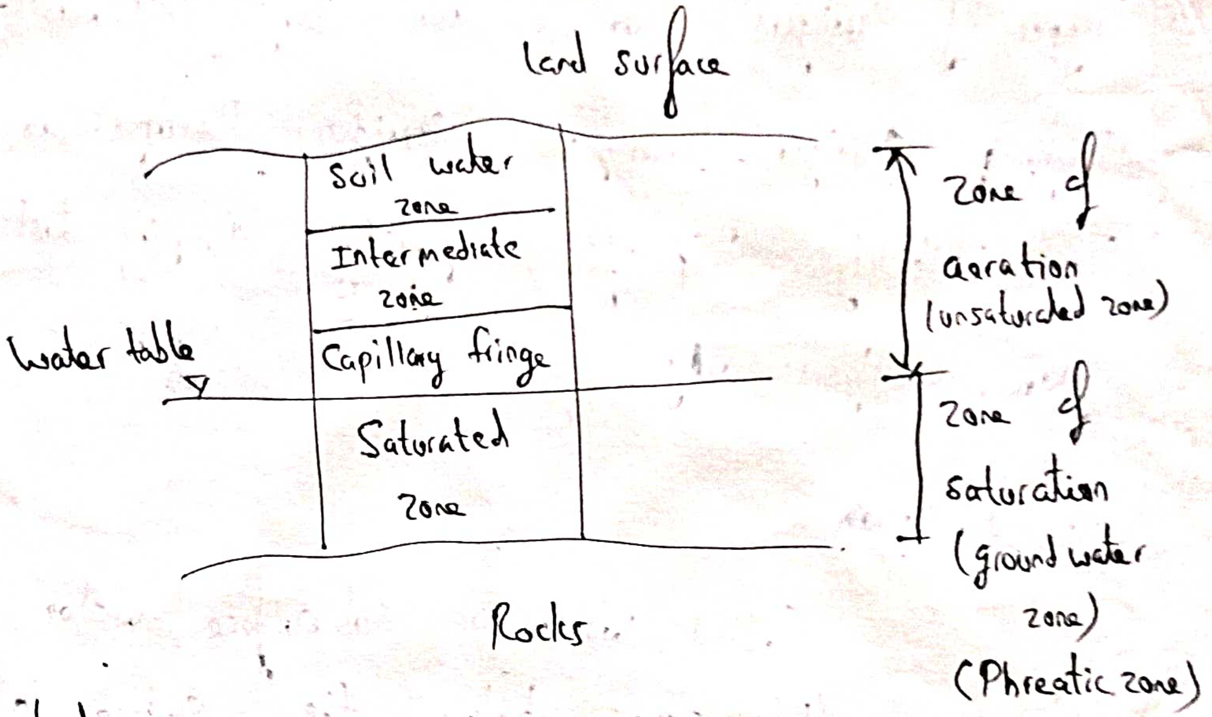
Types of aquifers - Darcy's law - Dupit assumptions - Confined aquifer - Unconfined aquifer - Recuperation test - Transmissibility - Specific capacity - Pumping test - Steady flow analysis only.

Ground water

Ground water or sub surface water refers to the water that occurs below the surface of earth. The main source of ground water is infiltration. The infiltrated water after meeting the soil moisture deficiency percolates and becomes ground water. The ground water is free from pollution and very useful for domestic use. Ground water can be made available at a small capital cost and least possible time. Ground water has been considered as the most reliable source for irrigation during deficiency.

Zones of ground water

The formation below the earth surface is divided Classified into two zones by an irregular surface called water table. Following are the zones



Saturated zone

The zone below the water table is called saturated zone and the soil pores are completely filled with water. The water table forms the upper limit of saturated zone and all the points on water table have atmospheric pressure. This zone may extend to considerable depth, but as the depth increases the weight of overburden tends to close the pores and relatively little water is found at depths greater than 3km.

Zone of aeration

The zone between the ground surface and

the water table is called unsaturated zone or zone of aeration. In this zone, the soil pores are partially saturated with water and contains air. Hence this zone is called as zone of aeration. The zone of aeration has three sub zones namely

Soil water zone - This zone lies close to the ground surface ~~water in this zone~~ near the root of the plants and trees. The water in this zone is lost to the atmosphere by evapotranspiration.

Capillary fringe - Water in this zone is held to the soil particles by capillary action. Hence water from this zone cannot move into wells.

Intermediate zone - The zone between soil water zone and capillary fringe is called intermediate zone.

~~Types of a~~

Formations of earth (or) occurence & transmission of ground water

Ground water occurs at ~~various~~ various locations below the earth's surface depending

~~on the formations of earth below the ground surface~~. Although the pores below the water table are completely filled with water, they cannot move easily or transmitted. The transmission depends upon the formations of earth below the water table. On this basis, the formations are classified as,

- → Aquifer
- → Aquitard
- → Aquiclude
- → Aquifuge

→ **Aquifer**

The saturated formation that not only stores water but ~~yields it in sufficient quantity is~~ (yielding) ~~called aquifer~~ also capable of transmitting water in sufficient quantities is called as aquifer. The amount of water stored in aquifer depends upon the porosity of the formations while the amount of water that it can transmit or yield depends upon permeability. The formations that serve as good aquifers are unconsolidated gravels and sands, sand stones, limestones, granites and marbles with fissures, basalts, slates etc.

(i) Unconfined aquifer

Unconfined aquifer also called as water table aquifer is the aquifer in which water table serves as the upper surface while the bottom surface is of less permeable or impermeable layer. Unconfined aquifer is also known as free aquifer, phreatic aquifer etc. The well drilled into this aquifer is called as water table well and it indicates ~~of this aquifer takes place through infiltration of water from ground surface.~~ a static (unchanging) water level corresponding to water table at that location. Recharge of this aquifer takes place through infiltration of water from ground surface.

(ii) Confined aquifer :

Confined aquifer also called as artesian aquifer which is confined between two impermeable layers. It is also called as pressure aquifer as the water is confined ~~between two~~ under pressure. The well drilled into this aquifer is called as artesian well and the level in this well rises due to the pressure to ~~its initial~~ a ~~level~~ a imaginary level called piezometric level or piezometric surface. Piezometric surface is generally assumed to be the level of water surface at recharging area. At some locations the piezometric level may attain a level higher than the ground level and hence well flows freely without any pumping and such a well is called "Flowing artesian well". The well in which the piezometric level is below the ground level is called as "non flowing artesian well". Recharge of this aquifers takes place only in area where it is exposed to ground surface.

Perched water table

Sometimes a small ground water body is separated from the main ground water body by a impermeable strata of small area (in the zone of aeration) above the main ground water body. The water level in them is called 'perched water table'. Usually the perched water table ~~is of~~ yields small quantity of water

→ Aquiclude

It is a formation which is porous but impermeable. ~~Hence~~ Hence there is no water movement or yield even though they contain large amounts of water

Ex.. Clay

→ Aquifuge

It is a formation which is neither porous nor ~~permeable~~ permeable. There are no pores to transmit water. Ex Granite rock.

→ Aquitard

It is a formation which is partly permeable. It does not yield water sufficient for pumping but can transmit water to adjacent aquifer at slow rate. Ex. Sandy clay.

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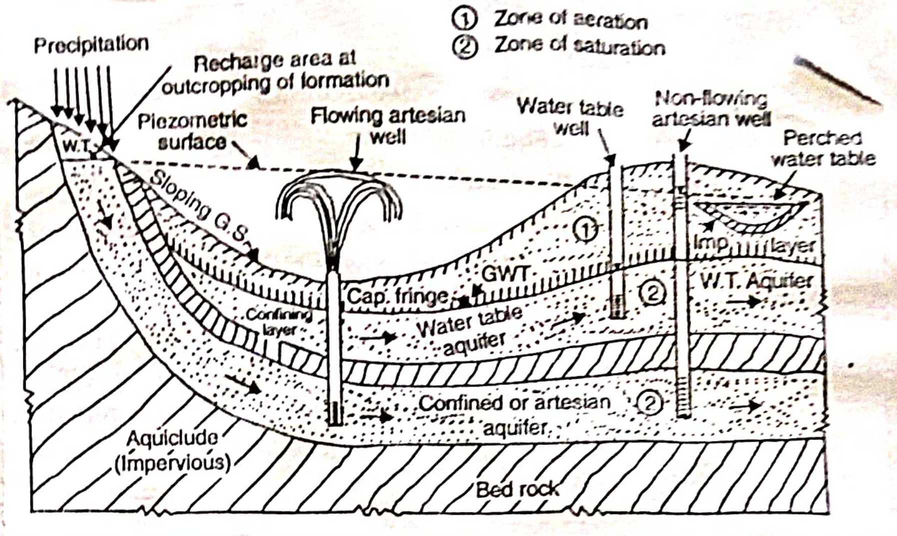


Darcy's law:

Darcy's law states that the rate of flow per unit area of the aquifer is propotional to the gradient of the potential head measured in the direction of flow (hydraulic gradient). Since flow per unit area (Q/A) denotes the velocity of flow, Darcy's law may be written as,

$$V = ki$$

where V → Apparent velocity.

k → Coefficient of permeability or hydraulic conductivity

~~i=~~ i → hydraulic gradient = ~~$-\frac{h}{l}$~~ $-\frac{dh}{dL}$ ~~(-ve sign indicates that the piezo~~

h → Piezometric head

l → Distance measured in flow direction

-ve sign of hydraulic gradient indicates that the piezometric head drops in the direction of flow.

Discharge, $Q = V \cdot A$

$= k\,i\,A$

Darcy's law is valid for laminar flows only. For a flow to be laminar the value of Reynold's number is taken a less than or equal to unity.

$$R_e = \frac{\rho V d_a}{\mu} \leq 1$$

Where ρ → Mass density of water

μ → Dynamic viscosity of water

d_a → ~~Grain~~ Particle size of aquifer soil (Usually $d_a = d_{10}$, where d_{10} represents a size such that 10% of aquifer material is smaller)

V → Apparent Velocity.

It may be noted that the apparent velocity (V) used in Darcy's law is not the actual velocity of flow through the pores. Due to irregular pore geometry the actual velocity of flow varies from point to point and the bulk pore velocity (Va) represents the actual speed of travel of water in porous media expressed as,

$$V_a = \frac{V}{\eta}$$

Where $\eta \rightarrow$ Porosity.

Coefficient of permeability.

Coefficient of permeability also called as hydraulic conductivity is dependant on the combined effects of properties of medium and properties of fluid. Coefficient of permeability can be expressed as

$$k = C d_m^2 \frac{\gamma}{\mu} \quad -①$$

where $d_m \rightarrow$ mean particle size of porous medium

C → ~~Spe~~ Shape factor which depends on porosity, packing, grain size etc.

$\gamma = \rho g$ = unit wt. of fluid

ρ → density of fluid.

g → acceleration due to gravity.

① can be written as $k = k_0 \frac{\gamma}{\mu}$

where $k_0 = Cd_m^2$ (k_0 is called as specific or intrinsic permeability which is a function of medium only. k_0 has dimensions of L^2. It is expressed in cm^2 or m^2 or darcy's

where 1 darcy $= 9.87 \times 10^{-13}\ m^2$.

Transmissibility

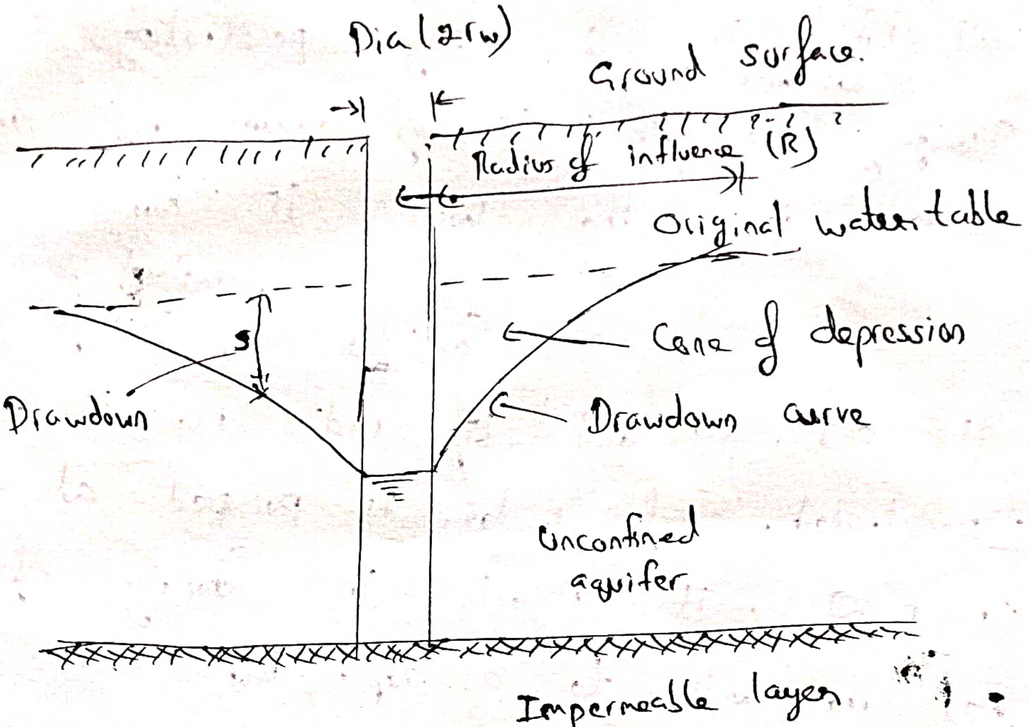
~~Consider~~ ~~an~~ The transmissibility or transmissivity of an aquifer is defined as the product of ~~co~~ coefficient of permeability (k) and the thickness of aquifer (H).

$$T = kH$$

Transmissibility has the dimension of L^2/T. Its unit is m^2/s or litres per day/metre width (lpd/m). Values of T lies between 1×10^6 lpd/m to 1×10^4 lpd/m. A well with value of $T = 1 \times 10^5$ lpd/m is considered satisfactory for irrigation purposes.

Wells

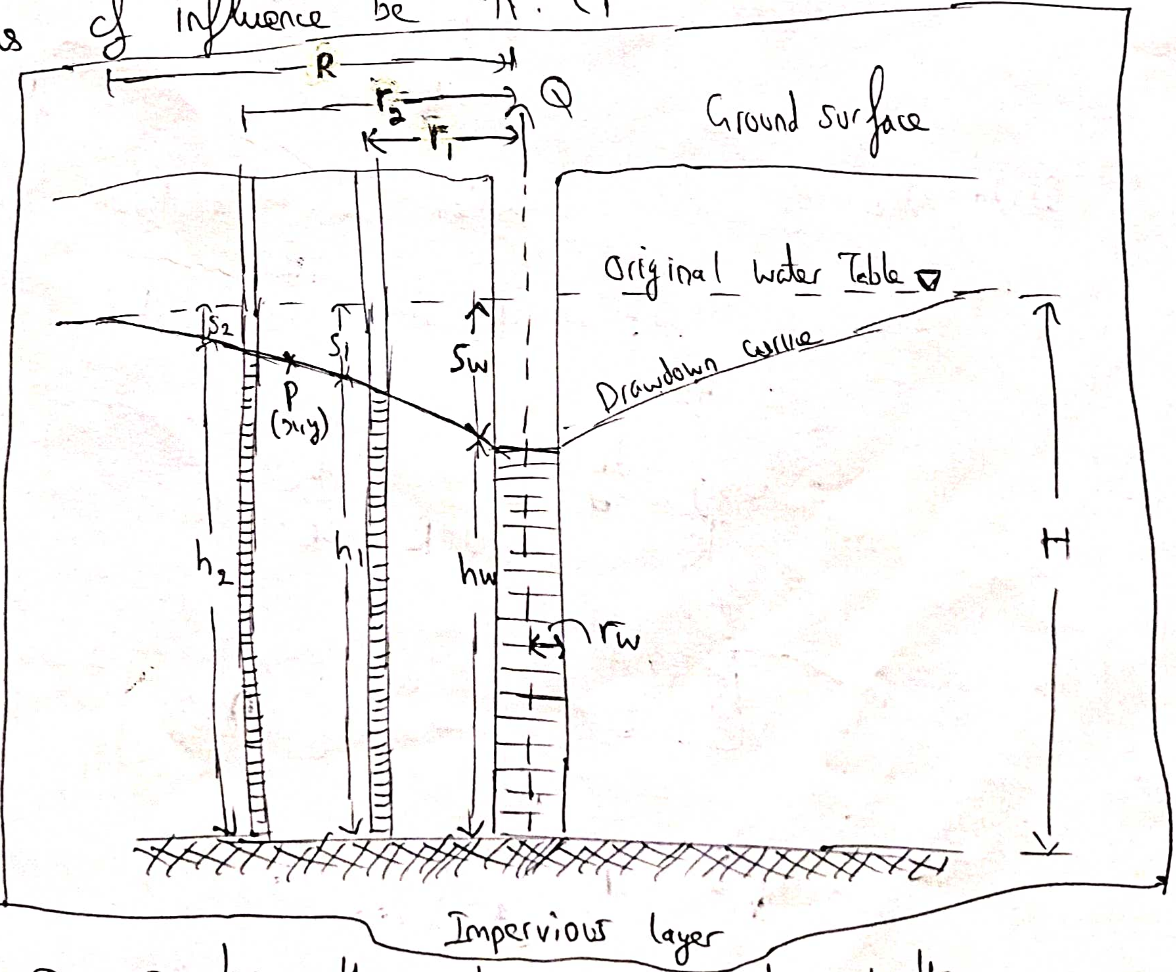
Wells form the important mode of ground water extraction from aquifer. Consider an aquifer that the water in unconfined aquifer is being pumped at constant rate through a well drilled in aquifer.



Prior to the pumping, the water level in the well indicates the static level (level as that of level of water table). During pumping, lowering of water table takes place. Recharge into the well takes place as radial flow. Hence the water table assumes a conical shape called as cone of depression. The drop in water table elevation (height) at any point from its previous static level is called drawdown. The areal extent of the cone of depression is called as radius of influence 'R'

Steady radial flow into well (or) well hydraulics (unconfined aquifer)

Consider a unconfined aquifer of thickness 'H' and a well of radius 'r_w' is completely penetrated through the entire thickness. Initially the level of water in the well is equal to the level of water table (ie) aquifer thickness 'H'. If water is pumped out at a constant rate 'Q', it results in lowering of water level at the well to a depth 'h_w' and the corresponding drawdown is 'S_w'. Let the radius of influence be 'R'. (pt at which drawdown is zero)



Let ① & ② be the two observation wells.

From Darcy's law, $Q = kiA$

~~where $i = \frac{h}{L} = -\frac{dh}{dr}$~~

~~$A = 2\pi r \times h$~~

At point $P(x,y)$, $i = \frac{dy}{dx}$

$$A = (2\pi x)y$$

$$\therefore Q = k\frac{dy}{dx}\,2\pi xy$$

~~$\frac{Q}{k}\,2\pi x\,dx = y\,dy$~~

$$y\,dy = \frac{Q\,dx}{2\pi k x}$$

Integration of above equation with the known boundary conditions at two observation wells 1 and 2,

$$\int_{h_1}^{h_2} y\,dy = \frac{Q}{2\pi k}\int_{r_1}^{r_2}\frac{dx}{x}$$

$$\left[\frac{y^2}{2}\right]_{h_1}^{h_2} = \frac{Q}{2\pi k}\left[\ln x\right]_{r_1}^{r_2}$$

$$h_2^2 - h_1^2 = \frac{Q}{\pi k}(\ln r_2 - \ln r_1)$$

~~$Q = \pi k (h$~~

$$\boxed{Q = \frac{\pi k \left(h_2^2 - h_1^2\right)}{\ln\left(\frac{r_2}{r_1}\right)}} \quad - ①$$

Where $h_1, h_2 \to$ water levels in two observation wells 1 and 2 respectively

$r_1, r_2 \to$ radial distance of observation wells 1 and 2 respectively

When the face of the well ($x = r_w, y = h_w$) and the point of zero drawdown ($x = R, y = H$) are taken as boundary.

(ie) $x \to r_w$ to R & $y \to h_w$ to H;

$$\boxed{Q = \frac{\pi k \left(H^2 - h_w^2\right)}{\ln \frac{R}{r_w}}} \quad - ②$$

Equations ① & ② are used to estimate the discharge or yield from a unconfined aquifer.

Pb) A 30 cm dia well completely penetrates a unconfined aquifer of saturated depth 40m. After a long period of pumping at a steady ~~state~~ rate of 1500 lpm, the drawdown in two observation wells 25m &

75m from the pumping well were found to be 3.5 and 2.0m respectively. Determine the transmissivity of the aquifer. What is the drawdown at the pumping well.

Given

~~$r_w = 30/2 = 15cm$~~ Radius of well, $r_w = 30/2 = 15cm$

Depth of aquifer, $H = 40m$

Discharge, $Q = 1500\ lpm = \frac{1500 \times 10^{-3}}{60} = 0.025\ m^3/s$

Drawdown of observation wells, $S_1 = 3.5m$, $S_2 = 2.0m$

Radial distance of " " , $r_1 = 25m$, $r_2 = 75m$

$h_1 = H - S_1 = 40 - 3.5 = 36.5m$

$h_2 = H - S_2 = 40 - 2 = 38\ m.$

Solution

(i) Transmissivity

Transmissivity, $T = kH$

$$Q = \frac{\pi k (h_2^2 - h_1^2)}{\ln(r_2/r_1)} \Rightarrow 0.025 = \frac{\pi k (38^2 - 36.5^2)}{\ln(75/25)}$$

$\Rightarrow k = 7.823 \times 10^{-5}\ m/s$

$T = KH$

$= 7.823 \times 10^{-5} \times 40$

$= 3.129 \times 10^{-3}\ m^2/s$

(ii) Drawdown at pumping well

At pumping well, $r_w = 0.15\ m$

Drawdown, $S_w = H - h_w$

Discharge $Q = \dfrac{\pi k (H_1^2 - h_w^2)}{\ln \dfrac{r_1}{r_w}}$

$0.025 = \dfrac{\pi \times 7.823 \times 10^{-5} \times (36.5^2 - h_w^2)}{\ln (25/0.15)}$

$h_w = 28.49\ m$

$\therefore S_w = 40 - 28.49 = 11.51\ m$

Pb) An unconfined aquifer has a thickness of 30m. A fully penetrating 20 cm dia well in this aquifer is pumped at a rate of 35 lit/s. The drawdown measured in two observation wells located at a distances of 10m and 100m from the well are 7.5m and 0.5m respectively. Determine the hydraulic conductivity of the aquifer. At what distance from the well the drawdown is insignificant.

Given:

Radius of well, $r_w = 20/2 = 10$ cm.

Thickness of aquifer, $H = 30$ m

Discharge = 35 lits/s = 35×10^{-3} m³/s

Drawdown of observation wells, $s_1 = 7.5$ m

$s_2 = 0.5$ m

Radial distance of " , $r_1 = 10$ m

$r_2 = 100$ m

$h_1 = H - s_1 = 22.5$ m

$h_2 = H - s_2 = 29.5$ m

Solution

(i) Hydraulic conductivity

$$Q = \frac{\pi k \left(h_2^2 - h_1^2\right)}{\ln(r_2/r_1)}$$

$$35\times10^{-3} = \frac{\pi \times k\left(29.5^2 - 22.5^2\right)}{\ln(100/10)}$$

$k = 7.047\times10^{-5}$ m/s.

(ii) Distance at which drawdown is insignificant

Drawdown is insignificant ($s=0$) at radius of influence, R

$$Q = \frac{\pi k\left(H^2 - h_2^2\right)}{\ln\left(\frac{R}{r_2}\right)}$$

$$\cancel{35\times10^{-3} = \frac{\pi k\left(30^2 - 22.5^2\right)}{\ln(R}}$$

$$35\times10^{-3} = \frac{\pi\times7.047\times10^{-5}\left(30^2 - 29.5^2\right)}{\ln\left(\frac{R}{100}\right)}$$

$$\ln\left(\frac{R}{100}\right) = \cancel{249.062}\ 0.1882$$

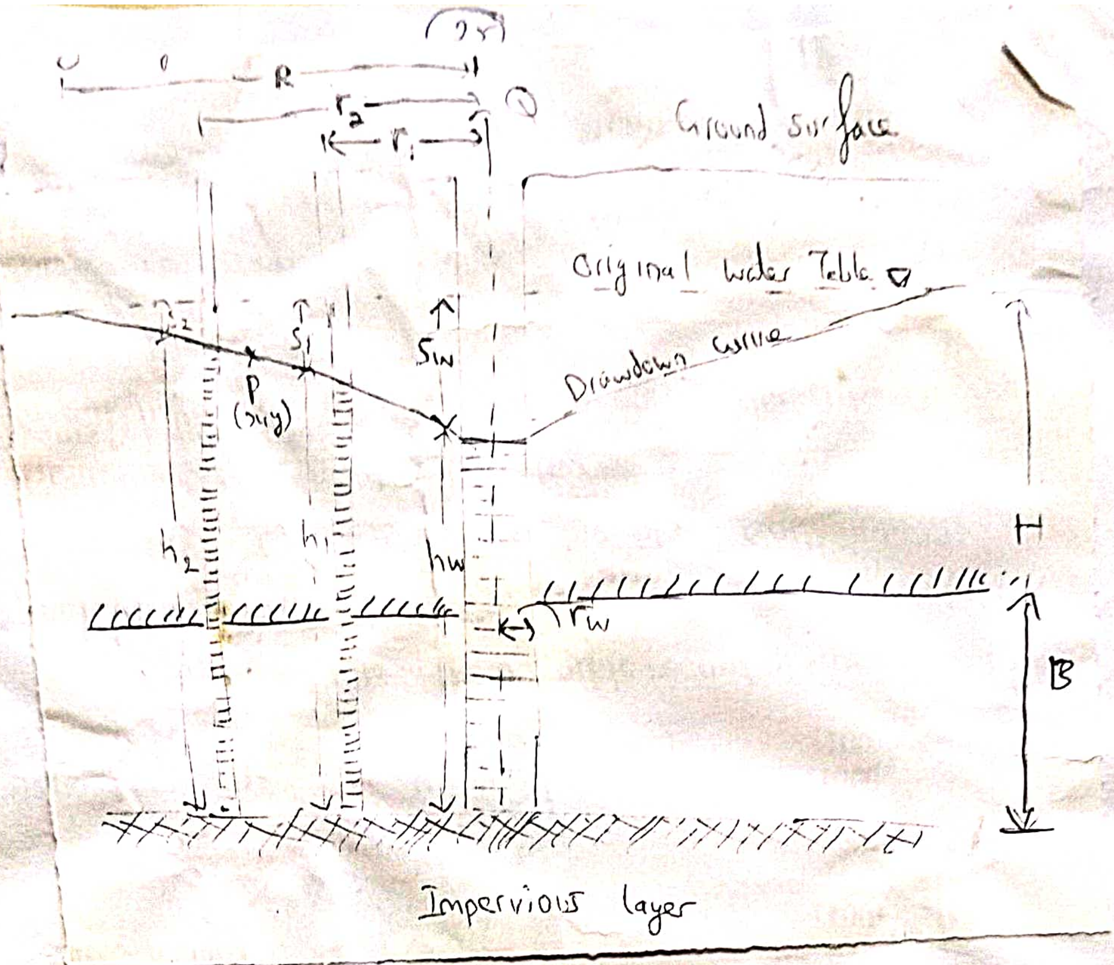
$$\frac{R}{100} = e^{0.1882}$$

$$= 1.207$$

$$\Rightarrow \boxed{R = 120.7\,m}$$

Steady state radial flow into well (confined aquifer)

Consider a confined aquifer of thickness 'B'. (Repeat the same theory in unconfined aquifer)



From Darcy's law, $Q = kiA$

At point $P(x,y)$, $i = \frac{dy}{dx}$

$$A = (2\pi x)B$$

$$\therefore Q = k\frac{dy}{dx}2\pi x B$$

$$dy = \frac{Q\,dx}{k\cdot 2\pi x B}$$

Integrating, $$\int_{h_1}^{h_2} dy = \frac{Q}{k2\pi B}\int_{r_1}^{r_2}\frac{dx}{x}$$

$$[y] = \frac{Q}{k\cdot 2\pi B}[\ln x]_{r_1}^{r_2}$$

$$h_2 - h_1 = \frac{Q}{2\pi B}\left[\ln r_2 - \ln r_1\right]$$

$$h_2 - h_1 = \frac{Q}{2\pi B}\left[\ln \frac{r_2}{r_1}\right]$$

$$\boxed{Q = \frac{2\pi kB\,(h_2 - h_1)}{\ln\left(\frac{r_2}{r_1}\right)}}$$

(Repeat theory)

$$\boxed{Q = \frac{2\pi kB\,(H - h_w)}{\ln \frac{R}{r_w}}}$$

$$\boxed{Q = \frac{2\pi kBS_w}{\ln(R/r_w)}}$$

Pb) A 30 cm dia well completely penetrates a confined aquifer of permeability 45 m/day. The length of strainer is 20m. Under steady state of pumping the drawdown at the well was found to be 3.0m and the radius of influence was 300m. Calculate the discharge

Given

Radius of well, $r_w = 0.3/2 = 0.15\,m$, Draw down, $S_w = 3m$

Permeability, $k = 45\ m/day = \frac{45}{24 \times 60 \times 60}$

$= 5.208 \times 10^{-4}\ m/s$

Length of strainer, $B = 20m$

Radius of influence, $R = 300m.$

Solution

Discharge, $Q = \frac{2\pi k B S_w}{\ln(R/r_w)}$

$= \frac{2\pi \times 5.208 \times 10^{-4} \times 20 \times 3}{\ln(300/0.15)}$

$= 0.0258\ m^3/s$

Pb) In an artesian aquifer of 8m thick, a 10cm diameter well is pumped at a constant rate of 100 lit/min. The steady state drawdown observed in two wells located at 10m and 50m distances from the centre of well are 3m and 0.05m respectively. Compute the transmissivity and hydraulic conductivity of the aquifer.

(25)

Given :

Thickness of artesian aquifer, $B = 8\,m$

Radius of well, $r_w = 0.1/2 = 0.05\,m$

Drawdown at observation wells 1 & 2, $S_1 = 3\,m$

$S_2 = 0.05\,m$

Radial distance, $r_1 = 10\,m$

$r_2 = 50\,m$

$h_1 = H - S_1 = H - 3$; $h_2 = H - S_2 = H - 0.05$

Discharge, $Q = 100\,lit/min = \frac{100 \times 10^{-3}}{60} = 1.667 \times 10^{-3}\,m^3/s$

Solution

$$Q = \frac{2\pi k B (h_2 - h_1)}{\ln\left(\frac{r_2}{r_1}\right)}$$

$$= \frac{2\pi \times k \times 8 \left(\cancel{H} - 0.05 - \cancel{H} + 3\right)}{\ln\left(\frac{50}{10}\right)}$$

$$1.667 \times 10^{-3} = k \times 92.134$$

$$k = 1.809 \times 10^{-5}\,m/s$$

Transmissivity, $T = kB = 1.809 \times 10^{-5} \times 8 = 1.447 \times 10^{-4}\,m^2/s$

Assumptions in steady state flow

Following are the assumptions used in the steady flow into well from a unconfined or confined aquifer.

- The curvature of the surface is very small so that the flow is assumed to be horizontal at all sections.
- The velocity of flow is proportional to the tangent of the hydraulic gradient instead of its sine.

The above two assumptions are called Dupit assumptions. In addition, ~~there~~ ~~are~~ to Dupit's assumptions, following assumptions are also made in steady flow analysis.

- Aquifer is ~~fo~~ homogeneous, isotrophic and of infinite ~~arent~~ extent.
- The well fully penetrates the aquifer and receives water from entire thickness of aquifer.
- Pumping is continued at a constant rate, so that steady flow conditions is reached.
- Darcy's law is valid (ie) flow is laminar.

Specific Capacity

Specific capacity of a well is defined as the discharge per unit drawdown at the well. Specific capacity indicates the performance of a well (The flow towards a open well is different. In case of tube well or radial well flow takes place all around the well and there is no flow from bottom of well. In open well, the flow is from bottom of well)

$$\text{Specific capacity},\ S_c = \frac{Q}{S_w}$$

Open wells (or) Yield of a open well: