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NEPAL ENGINEERING COUNCIL
LICENSE EXAM PREPARATION COURSE

FOR

CIVIL ENGINEERS

3. Basic Water Resources Engineering

3.6 Hydrology

Subtopics

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- hydrologic cycle and water balance components;
- flow measurement and rating curves;
- hydrographs analysis and synthetic unit hydrographs;
- rainfall-runoff analysis;
- flood hydrology (flood frequency analysis and design flood);
- groundwater hydrology.

Catchment Area

- The area of land draining into stream or water course at a given location is known as catchment area.
- It is also called **drainage area** or **drainage basin**.
- In USA, it is known as **watershed.**
- It is the area which catches all the rainfall falling on it.

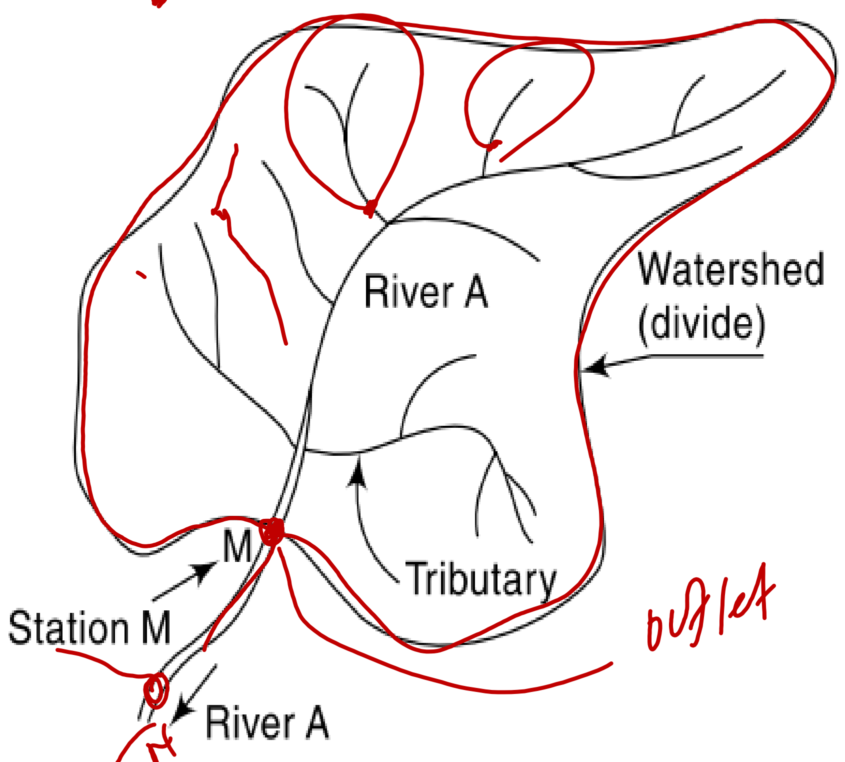
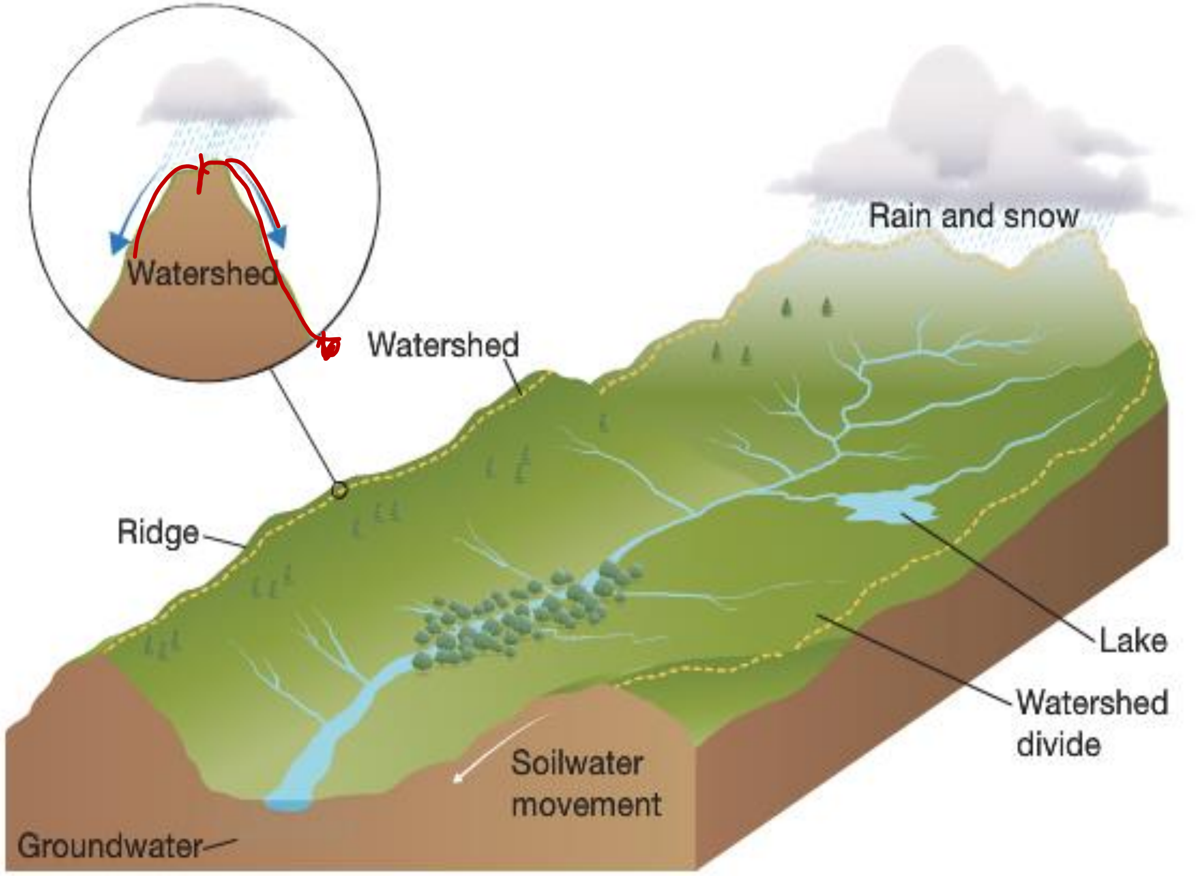
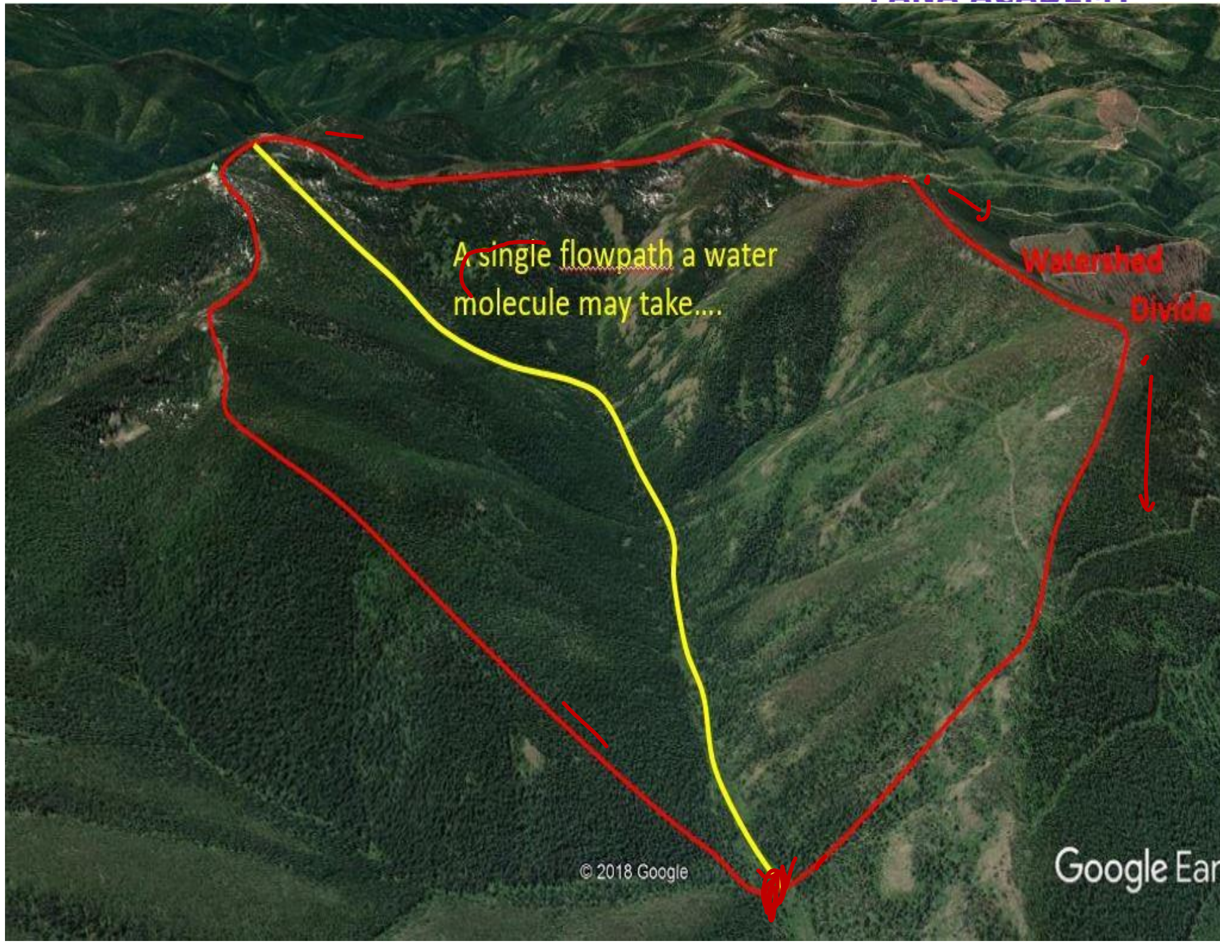


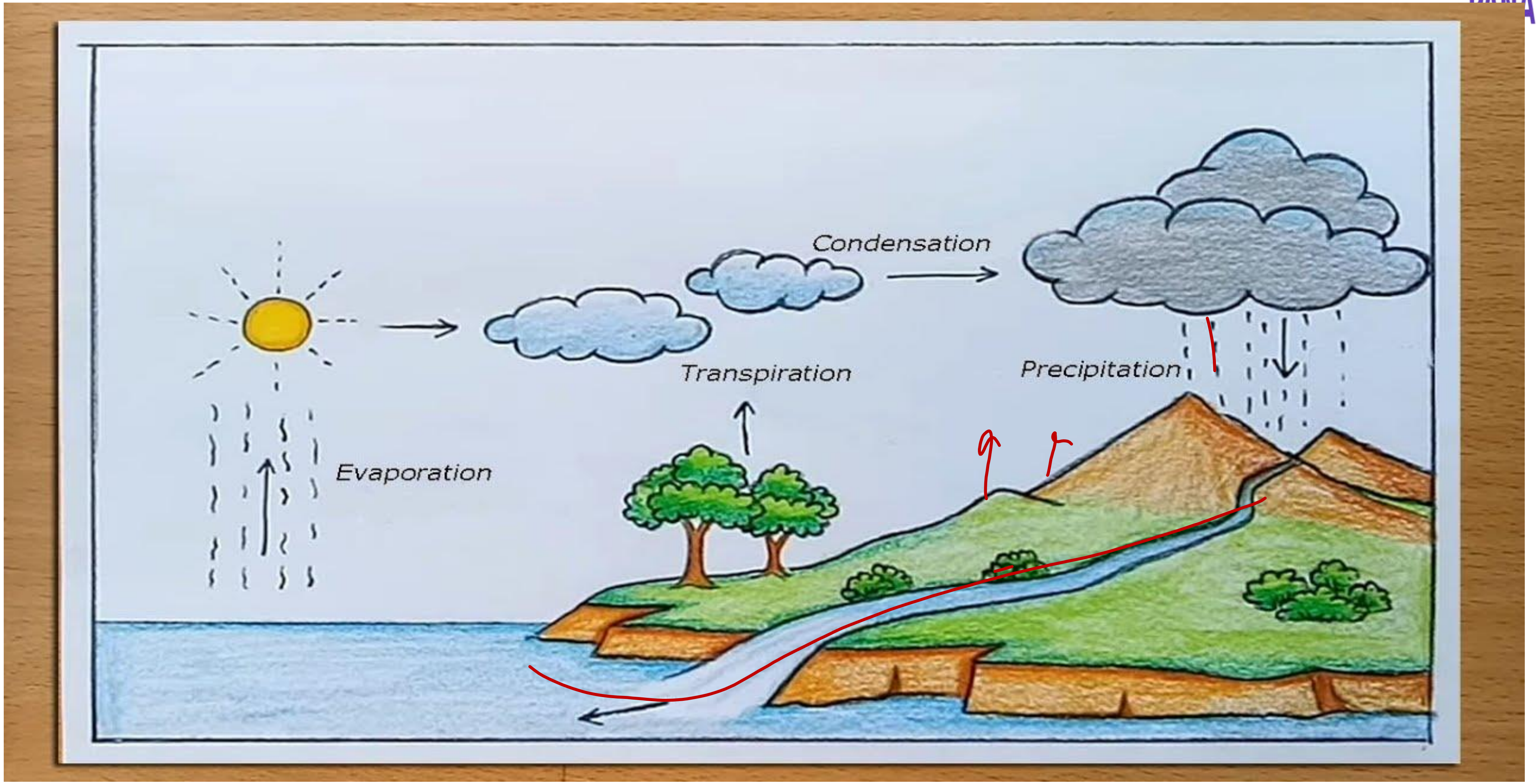
Fig. 1.3 Schematic Sketch of Catchment of River A at Station M

Catchment Area

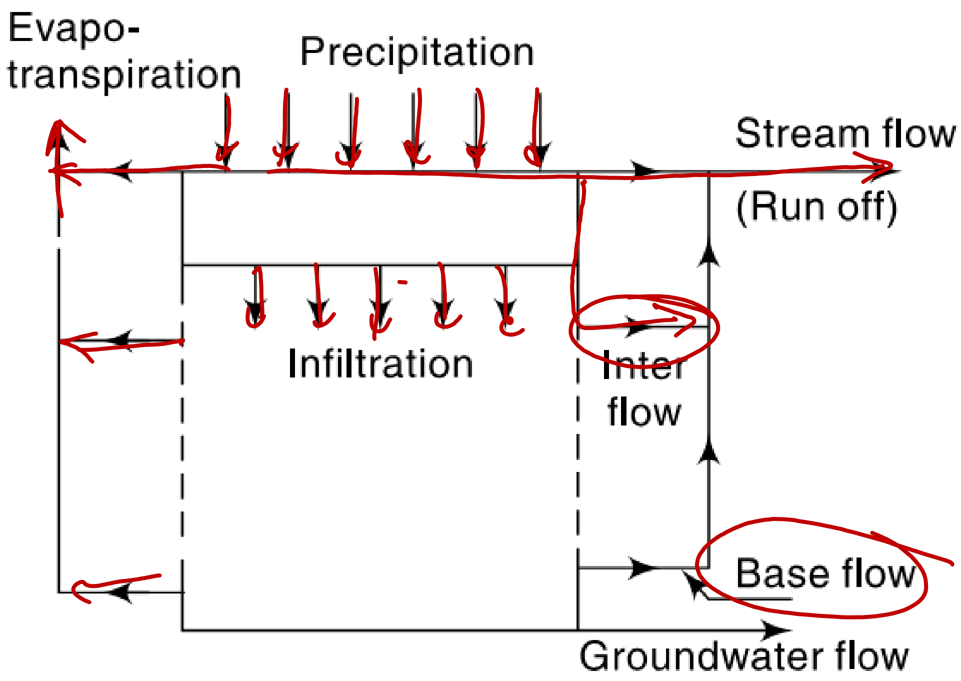


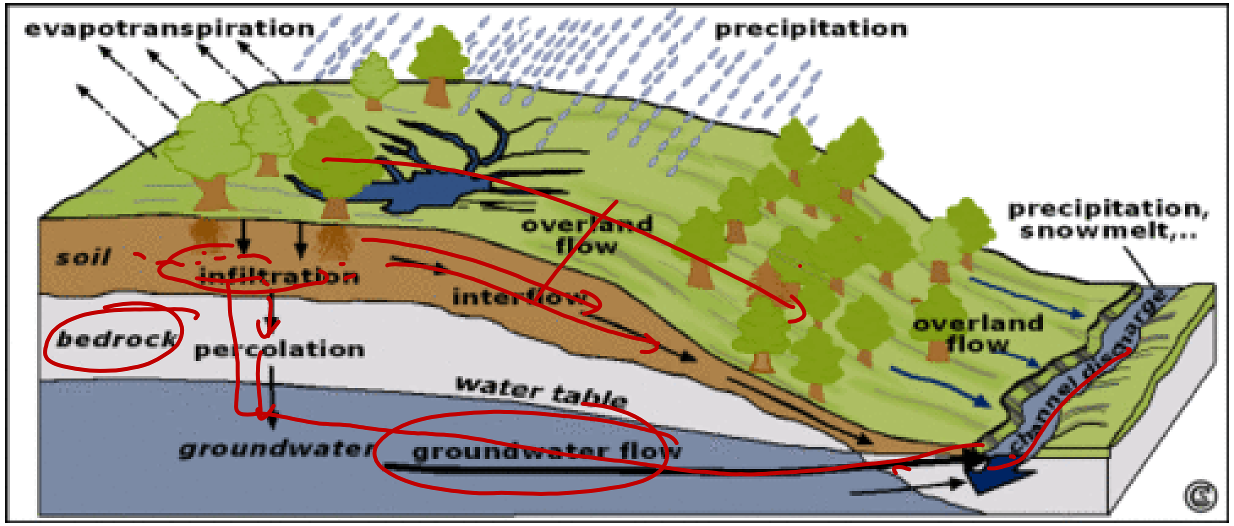


Hydrological cycle



Hydrological cycle





Processes

a) Evaporation: Water is evaporated from the oceans and land surfaces to become part of the atmosphere.
b) Precipitation: Water vapour is transported and lifted in the atmosphere until it condenses and precipitates (falls in the form of solid or liquid) on the land or the oceans.
c) Interception: Part of precipitation is intercepted by vegetation and trees.
d) Infiltration: Part of precipitation infiltrates into the soil.
e) Surface runoff (Overland flow): The fallen precipitation flows over the land surface before reaching the channel
f) Evaporation and Transpiration: Much of the intercepted water and surface runoff returns to the atmosphere through evaporation. Part of the infiltrated water is available to the roots of the trees and returns to the atmosphere through plant leaves by transpiration.

g) Subsurface runoff (Interflow): The infiltrated water flows laterally through the unsaturated soil to the stream channel.

h) Deep percolation: The water from the soil moisture zone percolates deeper to recharge ground water.

i) Ground water flow (Base flow): The flow takes place from the saturated groundwater zone to the streams.

j) Final output: Streamflow

Surface runoff + Interflow + Base flow

- The part of precipitation that reaches the stream through different paths above and below the earth surface is called runoff. Once it enters the channel, the runoff is called streamflow.

k) Finally the precipitated water flows out into the sea which it will eventually evaporate once again and the hydrological cycle continues.

Component of Runoff

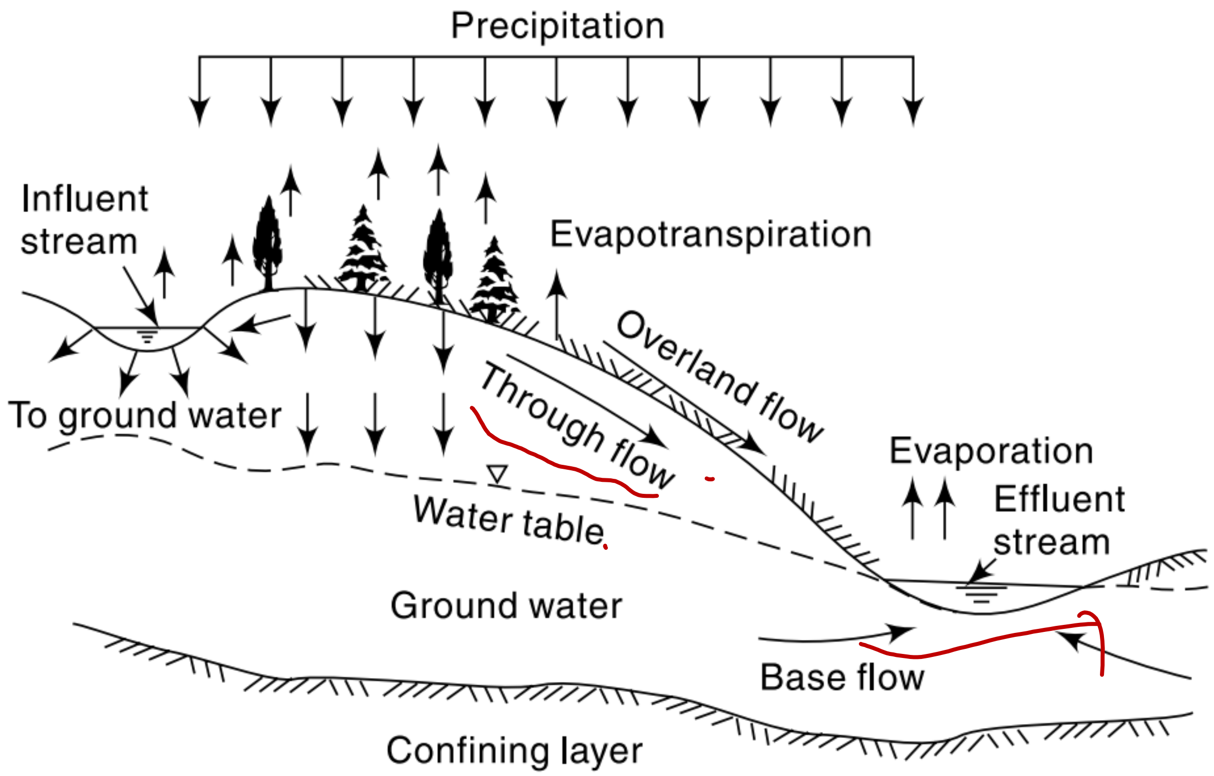


Fig. 5.1 Different routes of runoff

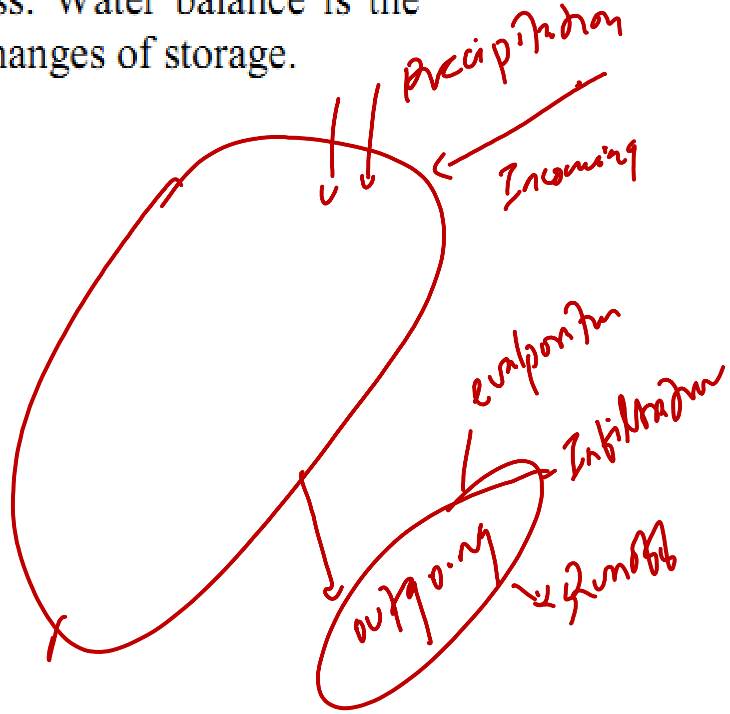
Water budget or water balance equation

The water balance equation is the statement of the law of conservation of mass. Water balance is the balance of input and output of water within a given area taking into account net changes of storage.

Change in storage = Inflows-Outflows

$$\frac{d}{dt}(Storage) = Inflows - Outflows$$

It is also called continuity equation or conservation equation.



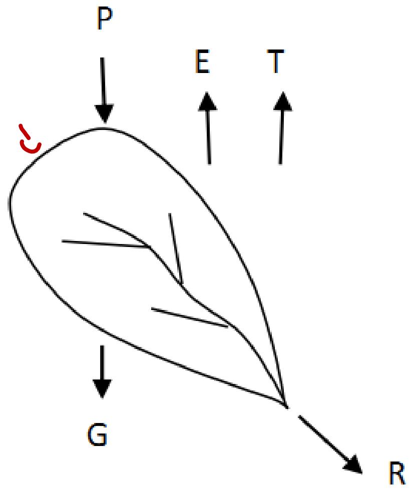


Fig. 1.2: Various components of water balance in a basin

General water budget equation in hydrology for time interval Δt

$$P - (R + G + E + T) = \Delta S$$

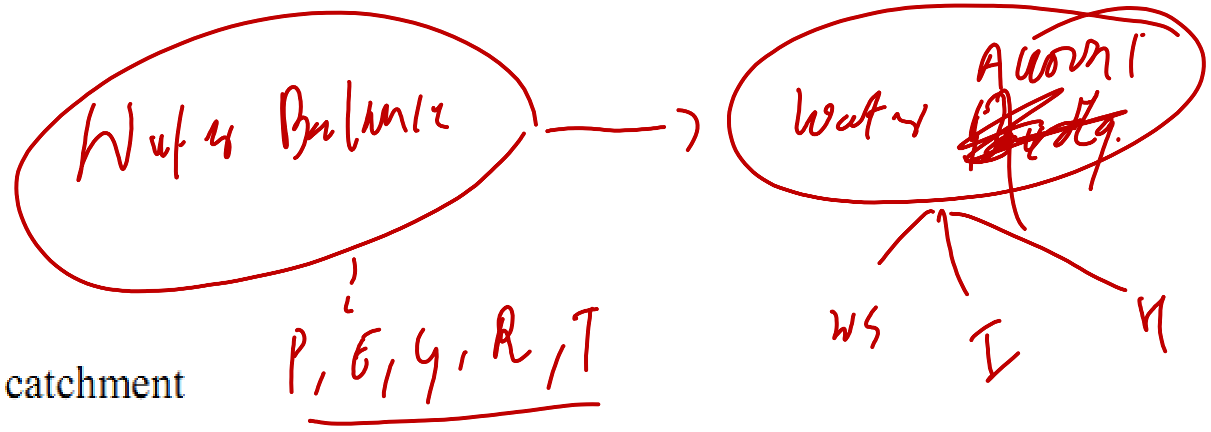
The storage S consists of three components as

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

where S_s = surface water storage

S_{sm} = water in storage as soil moisture and

S_g = water in storage as groundwater.



P= precipitation
R = Surface runoff
G = Net groundwater flow out of the catchment
E = Evaporation
T = Transpiration
ΔS = change in storage (take + for increase in storage, and – for decrease in storage)

All the terms in the equation have the dimensions of either volume or depth.
Conversion of unit given basin area: Volume = Depth x basin area
Conversion to volume given flow rate: Volume = flow rate x time duration

In case of other inflow besides precipitation, the water balance equation is
$(P + I) - (R + G + E + T) = \Delta S$ where I= other inflow

For long term, e.g. annual water balance, change in storage is zero. The general water balance equation is:

Precipitation-Runoff=Evaporation

World Water Q

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Item	Area (M km²)	Volume (M km³)	Percent total water	Percent fresh water
1. Oceans	361.3	1338.0	96.5	—
2. Groundwater				
(a) fresh	134.8	10.530	0.76	30.1
(b) saline	134.8	12.870	0.93	—
3. Soil moisture	82.0	0.0165	0.0012	0.05
4. Polar ice	16.0	24.0235	1.7	68.6
5. Other ice and snow	0.3	0.3406	0.025	1.0
6. Lakes				
(a) fresh	1.2	0.0910	0.007	0.26
(b) saline	0.8	0.0854	0.006	—
7. Marshes	2.7	0.01147	0.0008	0.03
8. Rivers	148.8	0.00212	0.0002	0.006
9. Biological water	510.0	0.00112	0.0001	0.003
10. Atmospheric water	510.0	0.01290	0.001	0.04
Total: (a) All kinds of water	510.0	1386.0	100.0	
(b) Fresh water	148.8	35.0	2.5	100.0

World Water Balance

Item	Ocean	Land
1. Area (M km^2)	361.30	148.8
2. Precipitation (km^3/year)	458,000	119,000
(mm/year)	1270	800
3. Evaporation (km^3/year)	505,000	72,000
(mm/year)	1400	484
4. Runoff to ocean		
(i) Rivers (km^3/year)		44,700
(ii) Groundwater (km^3/year)		2,200
Total Runoff (km^3/year)		47,000
(mm/year)		316

Initial Loss – Interception & Depression Storage

- These are the losses which need to be satisfied before the runoff starts.

Interception

- A part of rainfall that may be caught by vegetation and subsequently evaporated.
- It doesn't include stemflow and throughfall.
- Interception loss is about 10-20% during plant growing season. It may be greater than 25% in case of large no. of small storms.

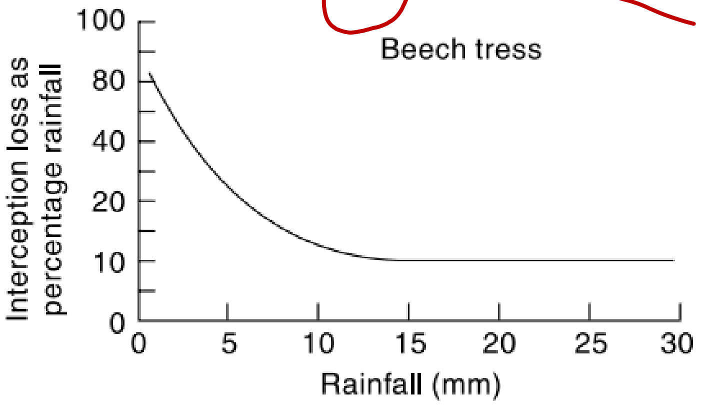

Fig. 3.7 Typical Interception Loss Curve

Initial Loss – Interception & Depression Storage

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Depression Storage

- Part of precipitation used up in filling up the depression before the runoff begins.
- Depends on type of soil, slope of catchment and antecedent precipitation.
- Values of 0.5 cm in sand, 0.4 cm in loam and 0.25 cm in clay.

Precipitation

Precipitation: It represents all the forms of water reaching to earth's surface from the atmosphere.

Forms of precipitation

a) Rain; b) Drizzle; c) Snow; d) Sleet; e) Glaze; f) Hail.

Intensity of rainfall (mm/hr)	Type
0 – 2.5	Light
2.5 – 7.5	Moderate
>7.5	Heavy

a) Rain

- Most dominating mode of precipitation.
- Water droplet of size → 0.5 mm – 6mm

Precipitation

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b) <u>Snow</u>

- Ice crystal having a density 0.1 g/cc.

c) <u>Drizzle</u>

- Water droplets having size < 0.5 mm. Intensity < 1 mm/hr.

d) <u>Glaze</u>

- Water droplets get converted into ice sheets when earth's temperature is nearly zero when it touches surface.

e) <u>Hail</u>

- Lump of ice whose size is > 8 mm.

g) <u>Sleet</u>

- Frozen transparent droplet of water is termed Sleet.

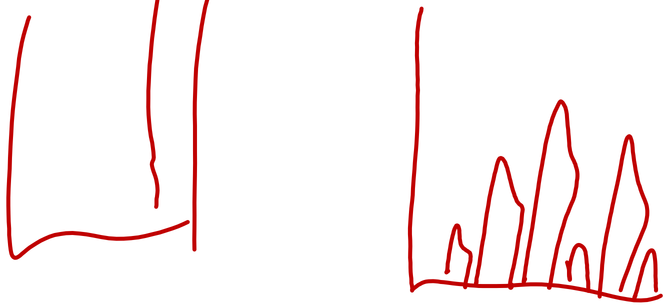
Measurement of precipitation

- Precipitation is measured by using rain-gauge, Radar and satellite.
- Precipitation is measured as depth of water equivalent in cm/mm or inch.

Rain gauge

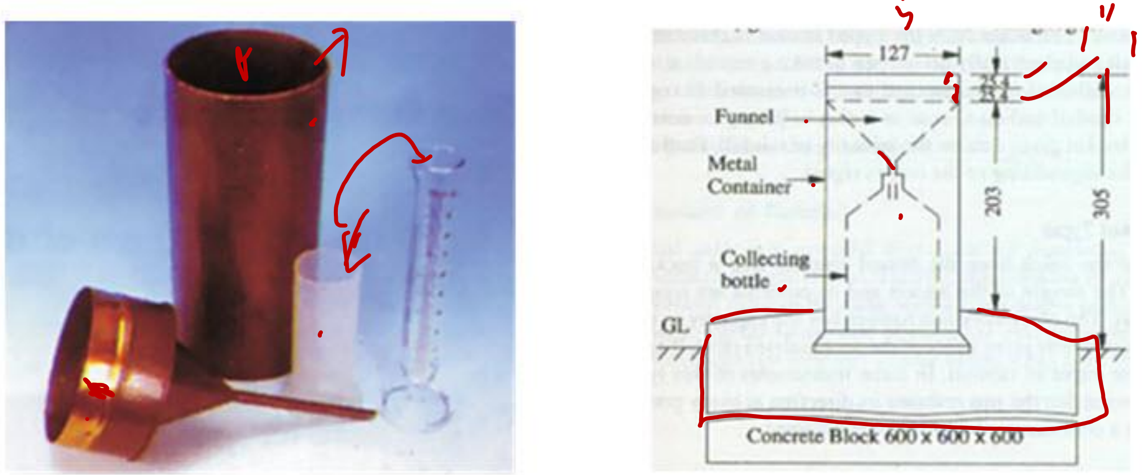
- The instrument used for the measurement of precipitation
- It is also called as Pluviometer, Ombrometer, Hyetometer, and Udometer
- There are two types of rain gauge

1. Non-recording rain-gauge (only measure but does not record the rainfall).
2. Recording rain-gauge (records as well as measure the rainfall)



Suitable Site for Rain gauge station

- The site should be in open place.
- It should be at least 30 m away from the obstruction.
- It should be in level ground.
- The fence of area 5.5m * 5.5m should be erected around the station



(a) (b)

Fig: Symons' gauge

Non recording rain gauge

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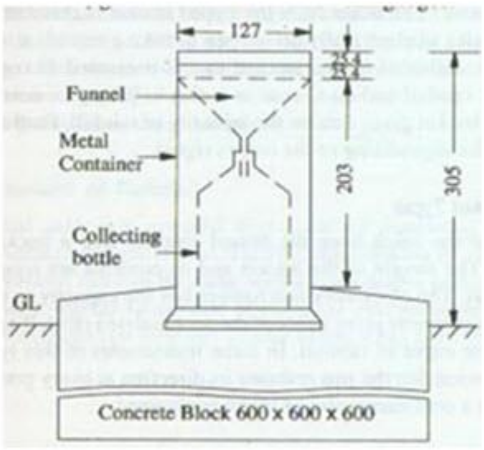
- Non recording rain-gauge is read manually using graduated measuring cylinder or dipstick.
- The measurement of the collected rain water is carried out at regular intervals.
- It does not provide the distribution of precipitation over the time
- It has disadvantage over recording rain-gauge as it does not provide information regarding time, intensity, and duration of rainfall.
- Extensively used non recording rain gauge is Symons' gauge
- Snowfall


(a)



(b)

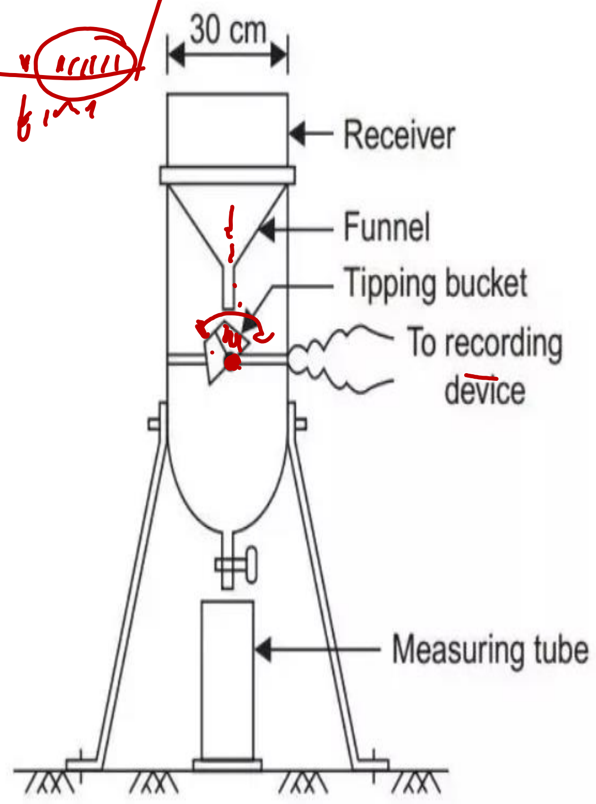
Fig: Symons' gauge

Recording rain gauge

Recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall

1. Tipping bucket

- Rain from the funnel fells onto one of the pair of small buckets
- Each of the two buckets have capacity of 0.25mm
- When 0.25mm of rainfall fall into one bucket, it tips and brings the other one in position.
- The tipping of bucket is traced by electrically or mechanically driven pen to measure intensity of the rainfall.
- The water from small bucket is collected in a storage vessel. Which is measured in a regular intervals to check data and find out total precipitation
- It records intensity of rainfall, but does not produce mass curve.
- Such gauge can be installed in hilly or inaccessible area from where they can supply measurement directly to the control room



Tipping bucket gauge

Recording rain gauge

Disadvantage of Tipping bucket type rainfall recorder:

- For higher intensity, bucket tips rapidly and the record tends to overlap.
- It takes 0.3 s to complete the tip; this makes the intensity of rainfall recorded by the gauge less by some percentage for high intensity.

Recording rain gauge

2. Weighing bucket rain gauge

- Rain failing on the receiving area is collected by the funnel to the storage bucket lies above the weighing platform.
- Weight is calibrated in terms of depth of rainfall.
- The weighing platform contentiously records the amount of rainfall falling into the bucket using a pen on a rotating drum.
- The increasing weight of bucket helps in recording accumulation rainfall over the time period.
- This type of recoding gauge gives more accurate results then tipping bucket rain gauge.
- It will give mass curve.

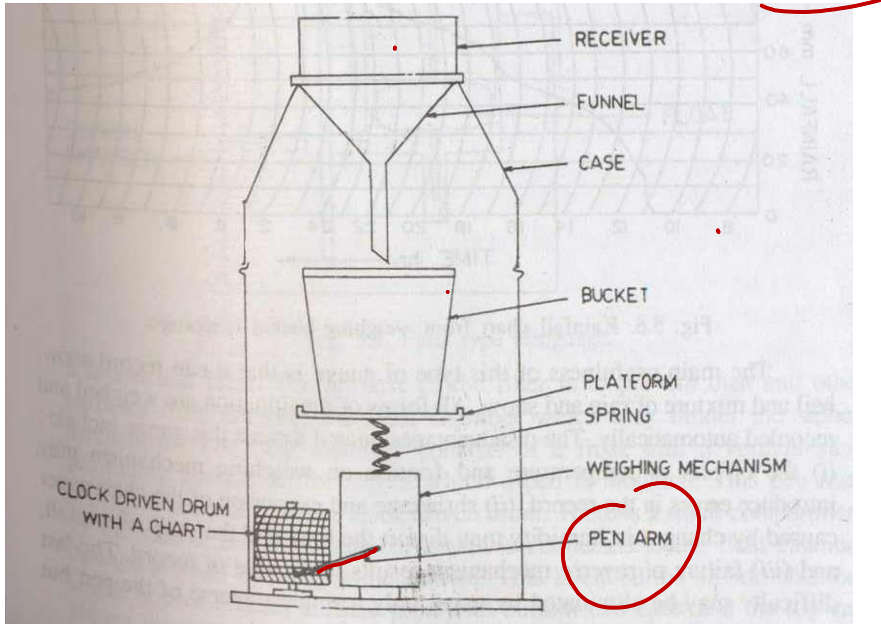


Fig. 5.5. Weighing-bucket raingauge.

Recording rain gauge

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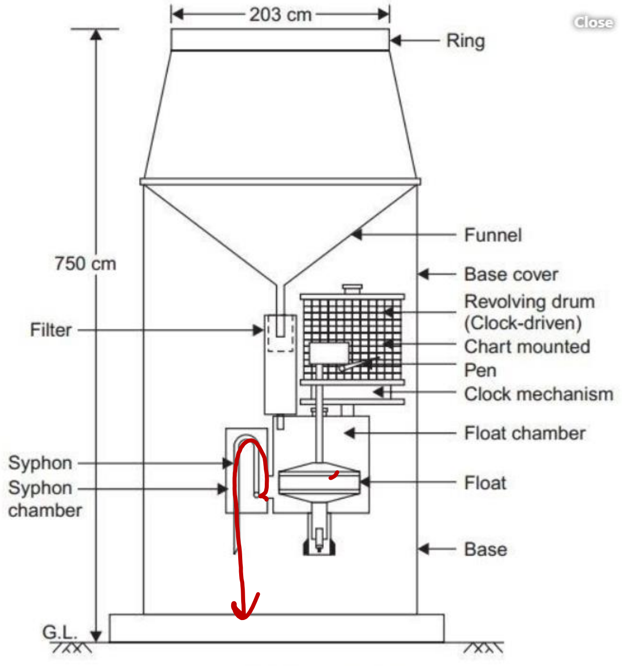
3. Float type rain gauge(siphon type rain gauge)

- Rainwater is collected in a rectangular float chamber via funnel
- A float is provided at the bottom of the chamber and it rises up as the water level rises in the container.
- The movement of float is recorded by a pen moving on a recording drum.
- After water level rises up to a certain level the siphon mechanism is activated to empty the rainwater collected in the float chamber



Float type rain gauge

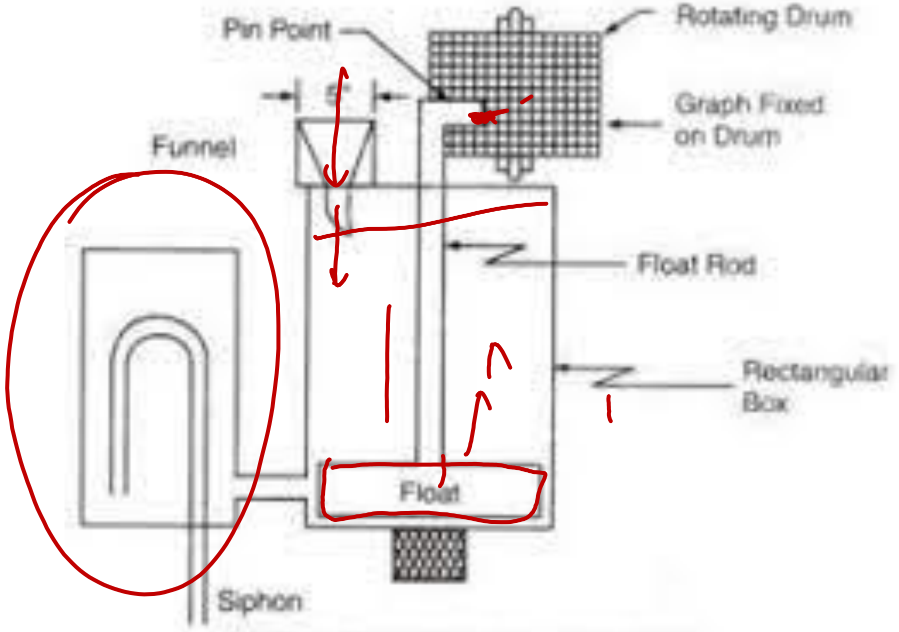
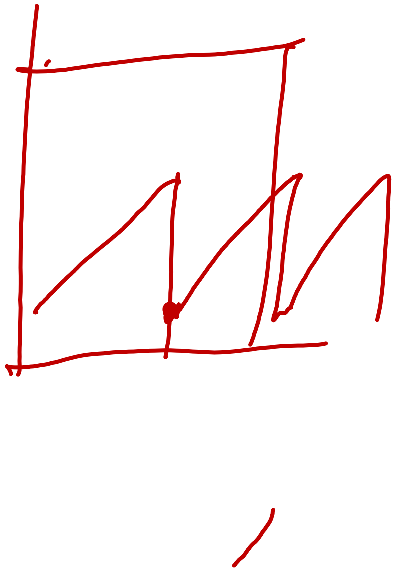


Fig. 2.5. Recording type rain-gauge



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- In flat regions of temperate, Mediterranean and tropical zones

  Ideal—1 station for 600–900 km^2

  Acceptable—1 station for 900–3000 km^2

- In mountainous regions of temperate, Mediterranean and topical zones

  Ideal—1 station for 100–250 km^2

  Acceptable—1 station for 250–1000 km^2

- In arid and polar zones: 1 station for 1500–10,000 km^2 depending on the feasibility.

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

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

Average Annual and Normal Rainfall

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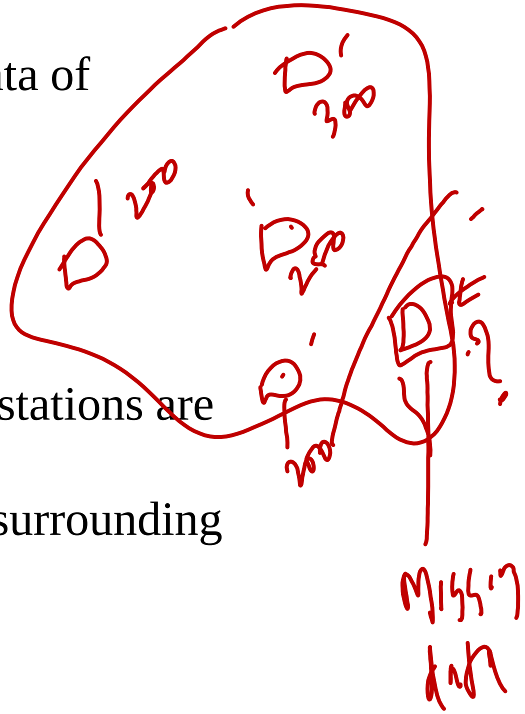
- The amount of rainfall collected by rain gauge in the last 24 hours is called **daily rainfall**.
- The amount collected in 1 year is called **annual rainfall**.
- The average value of annual rainfall for the last 30 year (or any other suitable time interval) is called **average annual rainfall**.
- The **normal rainfall** is the average value of rainfall at a particular date, month, or year over a specified 30-year period.

  e.g., normal rainfall of May month, normal annual rainfall, normal rainfall for 18 May etc.

The average annual rainfall in Nepal is **1500 mm.**

Estimation of missing rainfall data

- Precipitation plays significant role in water resources engineering especially for solving problems such as floods, droughts, landslides etc.
- The consistency and continuity of rainfall data are very important in statistical analysis
- Due to several reasons such as absence of the observer, instrument failure etc.
- In such conditions, the missing data is usually estimated from the available data of neighboring station.



A. Arithmetic Average Method

- This method is only applied when the annual precipitation at the surrounding stations are within 10% of the annual precipitation of the missing station.
- The missing rainfall data is estimated as the simple arithmetic average of the surrounding rainfall stations

$$P_x = \frac{1}{m}(P_1 + P_2 + \cdots + P_m)$$

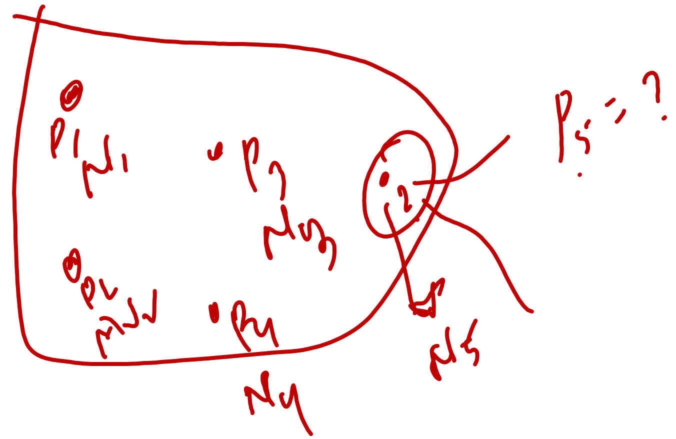
B. Normal Ratio Method

- If the annual normal rainfall at the surrounding gauges differ from the normal of the station by more than 10% then, normal ratio method is used.
- The rainfall values at surrounding station are weighed by the ratio of the normal annual rainfall.

$$P_x = \frac{1}{m}\left(N_x \frac{P_1}{N_1} + N_x \frac{P_2}{N_2} + \cdots + N_x \frac{P_m}{N_m}\right)$$

$$P_x = \frac{N_x}{m}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \cdots + \frac{P_m}{N_m}\right)$$

Where P_x =rainfall of missing station
N_x =normal annual rainfall at station X
N_1, N_2 ....=normal annual rainfall at surrounding stations
m= number of surrounding stations
P_1, P_2 ....= precipitation at the surrounding stations



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The normal annual rainfall at stations A, B, C and D in a basin are 80.97, 67.59, 76.28 and 92.01 cm respectively. In this year 2020, the station D was inoperative and the stations A, B, and C recorded annual precipitations of 91.11, 72.23 and 79.89 cm respectively. Estimate the rainfall at station D in that year.

Ans: 99.49 cm

$$P_x = \frac{N_x}{m}\left(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \cdots + \frac{P_m}{N_m}\right)$$

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

Estimation of mean rainfall over an area

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- The mean monthly or mean yearly value of rainfall from the rain gauge station represents the point value of rainfall.
- These data must be converted into areal rainfall data to obtain average rainfall over the catchment.
- As the rainfall over a large area is not uniform, the average depth of rainfall over the area is determined by one of the following three methods.

Estimation of mean rainfall over an area

1. Arithmetic average method

In this method mean average rainfall is obtain simply by averaging amount of rainfall at the individual rain-gauge stations in the area

$$P_{av} = \frac{\sum P_i}{n}$$

Where Pav=average depth of rainfall over the area
∑Pi=sum of rainfall amount of each rainfall stations
n= number of rainfall stations

- This method is fast and simple and yields good results in flat country where rain gauge stations are uniformly distributed.
- **Rain gauges outside the catchment are not considered unlike in case of Thiessen polygon and Isohyetal method.**

2. Thiessen Polygon Method

- In this method, Perpendicular bisectors are constructed to the lines joining each measuring station with those immediately surrounding it.
- These bisectors form a series of polygons called Thiessen polygon, each polygon containing one station.
- The value of precipitation measured at a station is assigned to the whole area covered by the enclosing polygon.
- If P1,P2,P3............. Are the rainfalls at the individual stations, and A1, A2, A3......... are the areas of the polygons surrounding these stations, the average depth of rainfall for the entire basin is given by.

$$P_{av} = \frac{\sum_{i=1}^{n} P_i A_i}{\sum_{i=1}^{n} A_i}$$

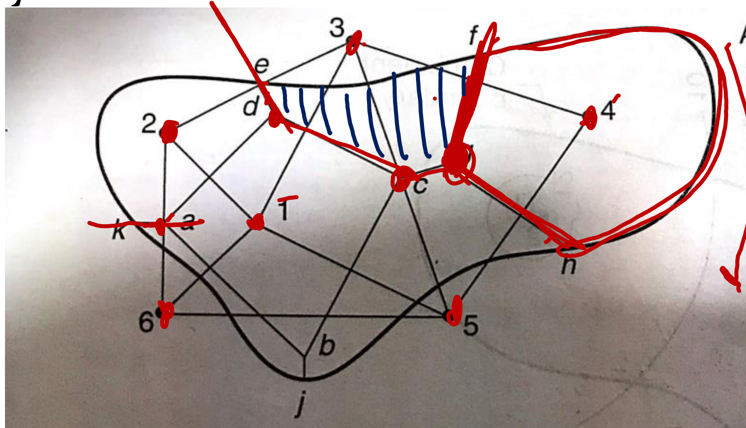

Fig. 2.13 *Thiessen Polygons*

A = total catchment area

Station	Bounded by	Area	Weightage
1	abcd	A_1	A_1/A
2	kade	A_2	A_2/A
3	edcgf	A_3	A_3/A
4	fgh	A_4	A_4/A
5	hgcbj	A_5	A_5/A
6	jbak	A_6	A_6/A

2. Thiessen Polygon Method

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- Suitable for plain areas as it does not consider elevation difference.
- Whole area is divided into number of smaller areas where we assume uniform rainfall distribution.
- It is more accurate than arithmetic method but less accurate than isohyetal method.

Question

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- Calculate the average rainfall depth using i) arithmetic mean method, and ii) Thiessen polygon method if stations 4, 6 and 8 are outside the catchment. [Ans: 15.6 mm, 12.933 mm]

Station	Rainfall (mm)	Area (km^2)
1	10	7
2	20	4
3	15	10
4	12	12
5	8	5
6	14	8
7	25	4
8	18	10

3. Isohyetal method

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- The isohyetal method is used to estimate the mean precipitation across an area by drawing lines of equal precipitation (**Isohyets**).
- The method uses topographic and other data to yield reliable estimates.
- Isohyets are contours of equal precipitation analogous to contour lines on a topographic map.
- In the isohyetal method, precipitation values are plotted at their respective stations on a suitable base map, and isohyets are drawn to create an isohyetal map.
- Isohyetal lines are based on interpolation between rain gauge stations. While constructing isohyets, it is assumed that rainfall between two stations varies **linearly.**

$$P = \frac{\sum_{i=1}^{n} P_i^* A_i}{A_T}$$

Where,
Pi*=average of two successive isohyets
Ai=Area between two successive isohyets
At=Total area of watershed

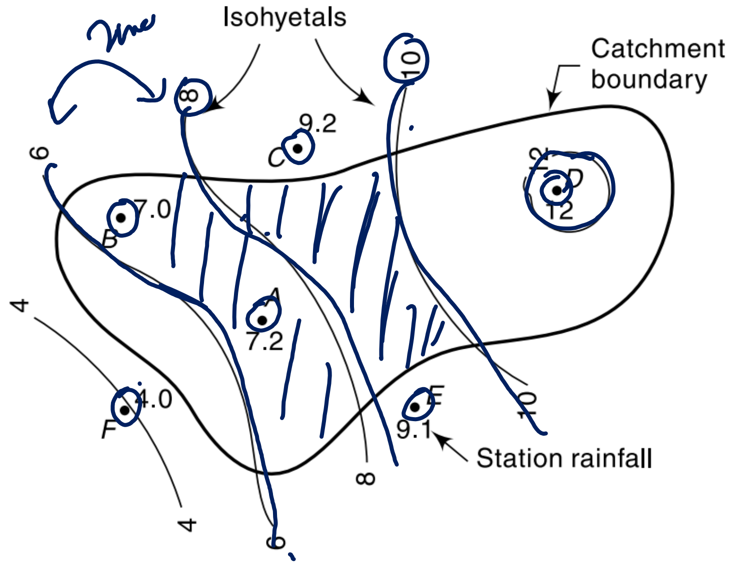


Fig. 2.14 Isohyetals of a Storm

$$P = \frac{\sum_{i=1}^{n} P_i^{*} A_i}{A_T}$$

Where,
Pi*=average of two successive isohyets
Ai=Area between two successive isohyets
At=Total area of watershed

Limitations:

- Requires dense gauge network.
- Isohyets need to be drawn for each storm.

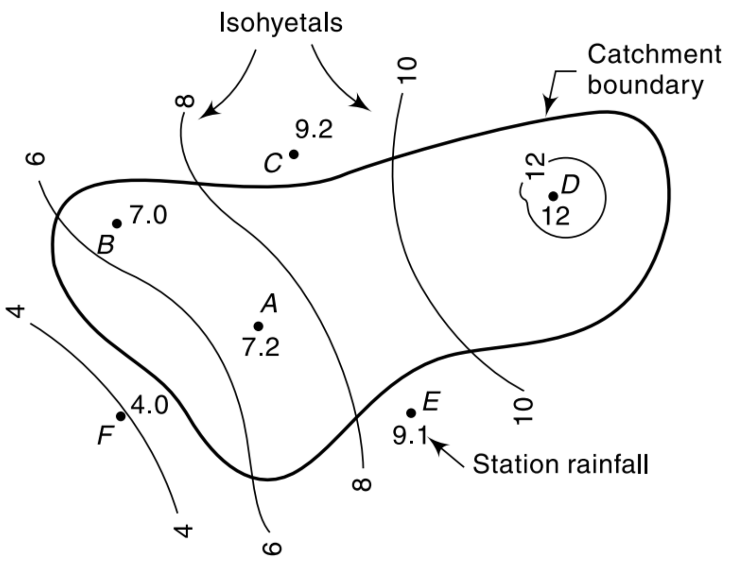
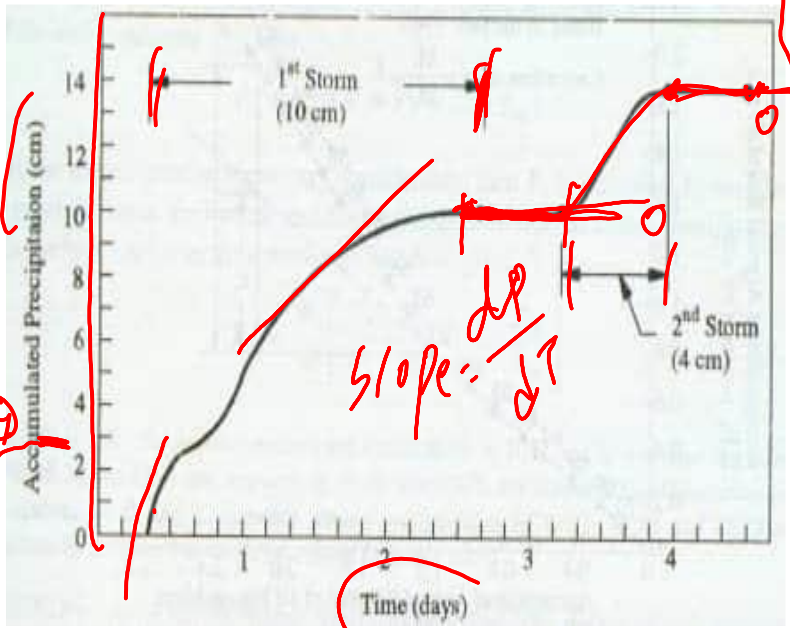


Fig. 2.14 Isohyetals of a Storm

Presentation of rainfall data

a. Mass curve

- The mass curve of rainfall is a plot of the accumulated precipitation against time, plotted in chronological order.
- Records of float type and weighing-bucket type gauges are of this form.
- Mass curves of rainfall are very useful in extracting the information on the duration and magnitude of a storm.
- Intensities at various time intervals in a storm can be obtained by the slope of the curve.

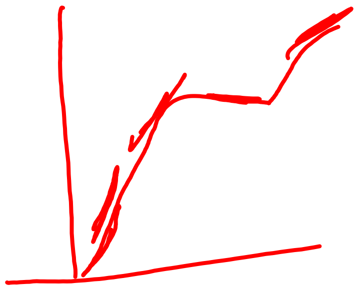


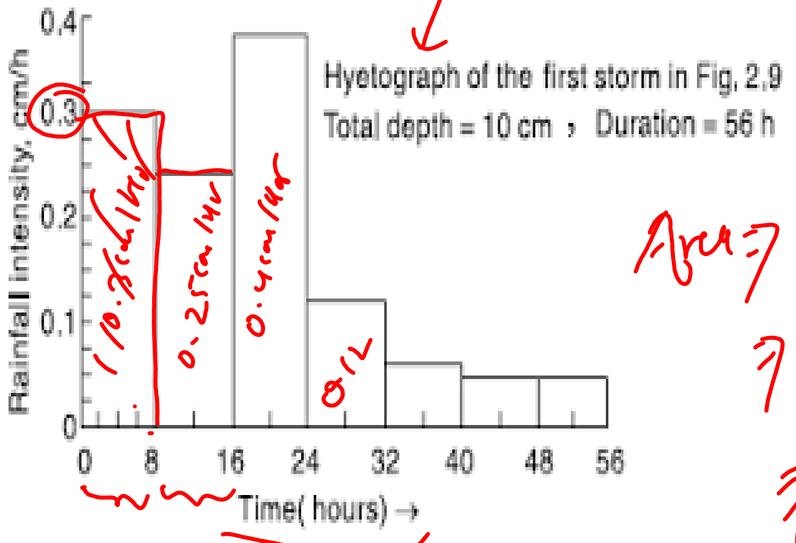
Hyetograph

- A hyetograph is a graphical representation of the distribution of rainfall intensity over time.
- The hyetograph is usually represented as a bar chart
- It is a very convenient way to represent characteristics of a storm and is particularly important in the development of a design storms to predict extreme floods.
- The area under a hyetograph

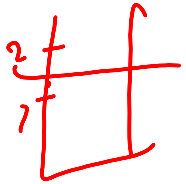
  represents the total precipitation

  received in that period.





Double mass Analysis

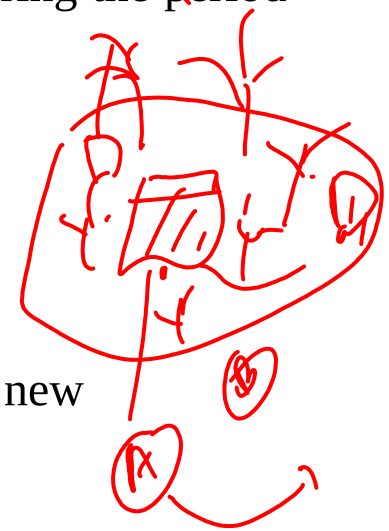


Definition:

- The plot of accumulated annual rainfall of a particular station versus the accumulated annual values of mean rainfall of surrounding stations is called double mass curve .
- Double mass analysis is used for checking consistency of the rain fall record of a particular rain gauge station.
- If the condition at a particular rain gauge station change significantly during the period of record, the rainfall data of that station is inconsistent.

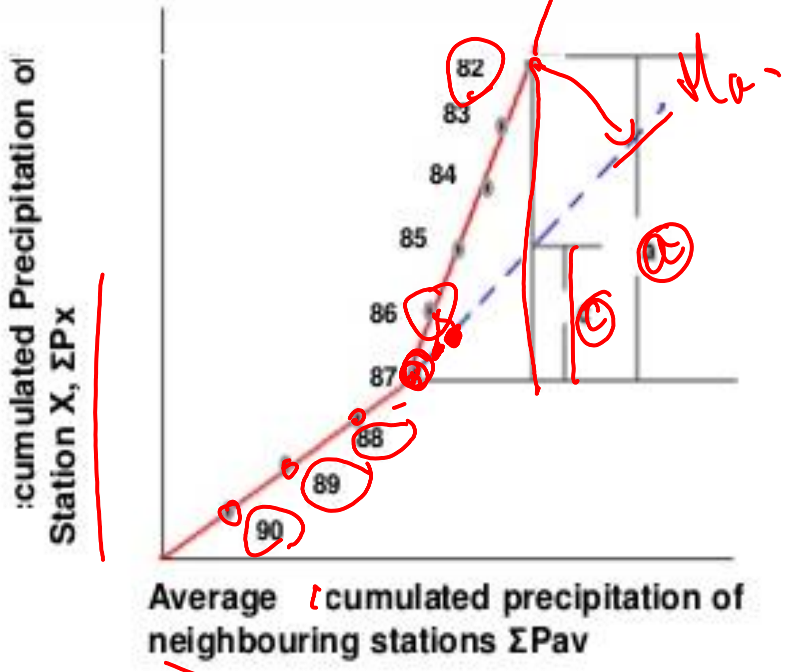
Causes of inconsistency of records:

1. Shifting of the rain gauge station from one place to other.
2. Replacement of the old instrument with a new one.
3. Change of the observer or change in the method of observation.
4. Changes in the ecosystem near the station, such as forest fire, land slide, new construction, etc.



Test for consistency of record

- Break in the year : 1987
- Correction Ratio : Mc/Ma = c/a
- Pcx = Px*Mc/Ma



P_{cx} – corrected precipitation at any time period t_1 at station X

P_x – Original recorded precipitation at time period t_1 at station X

M_c – corrected slope of the double mass curve

M_a – original slope of the mass curve

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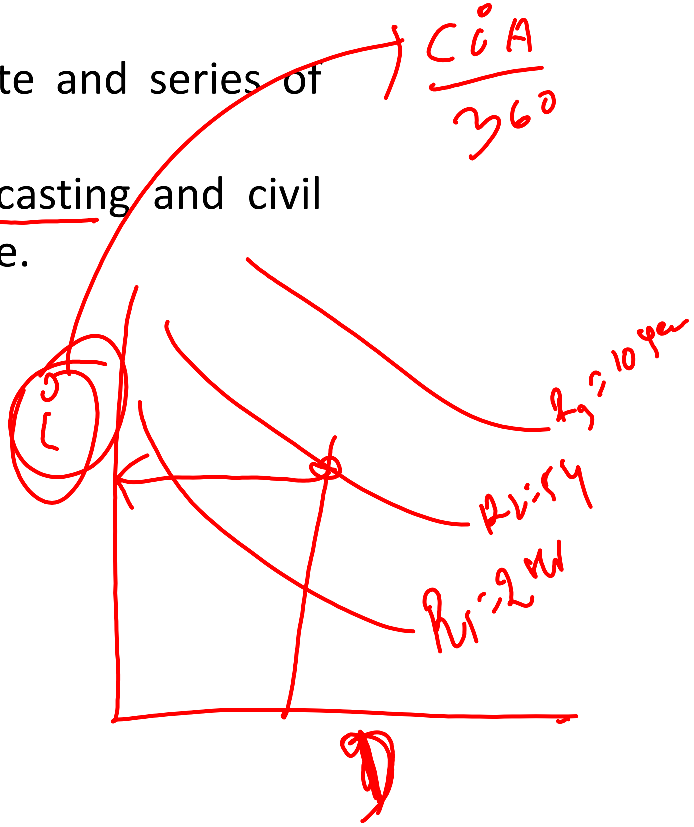
Intensity-Duration-Frequency Curve

- An **intensity-duration-frequency curve** (**IDF curve**) is a mathematical function or graph that relates the rainfall intensity with its duration and frequency of occurrence.
- In IDF curve, Duration plotted as abscissa, intensity as ordinate and series of curves one for each return period
- These curves are commonly used in hydrology for flood forecasting and civil engineering for urban drainage design, design of hydraulic structure.

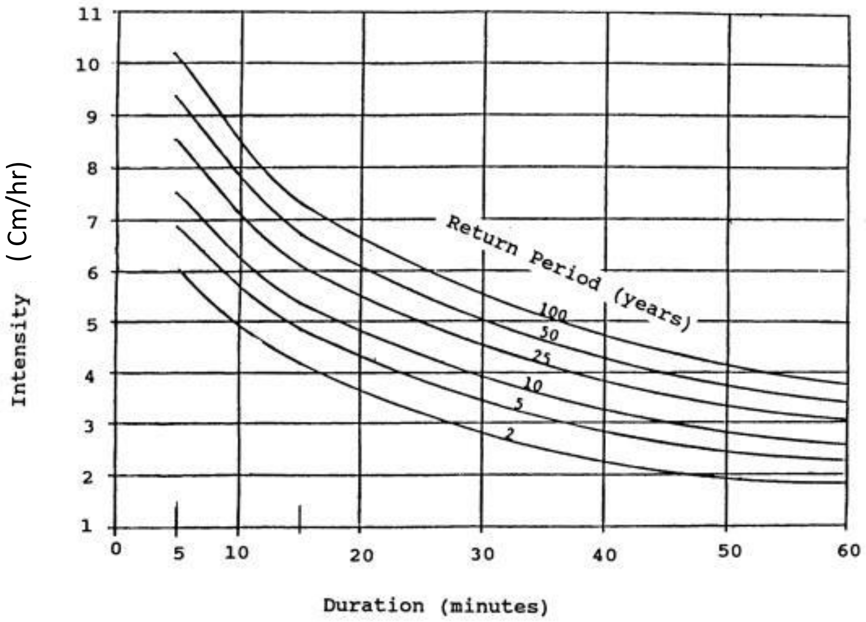


Intensity-Duration-Frequency Curve

IDF curves can be expressed as equation in the exponential form given by:

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

Where, i=intensity
T=return period or frequency
D=Duration
K,x,a,n=constants



Depth-Area-Duration (DAD) curve

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- Rainfall rarely occurs uniformly over a large area
- Variations in intensity and total depth of rainfall from the centers to peripheries of storm causes average depth of rainfall decreases from the maximum as the area considered increases.
- If we plot depth of precipitation and area of its coverage for different duration of storm the curve thus obtained is called DAD curve.
- It is useful to analyze areal distribution of rainfall

Depth-Area-Duration(DAD) curve

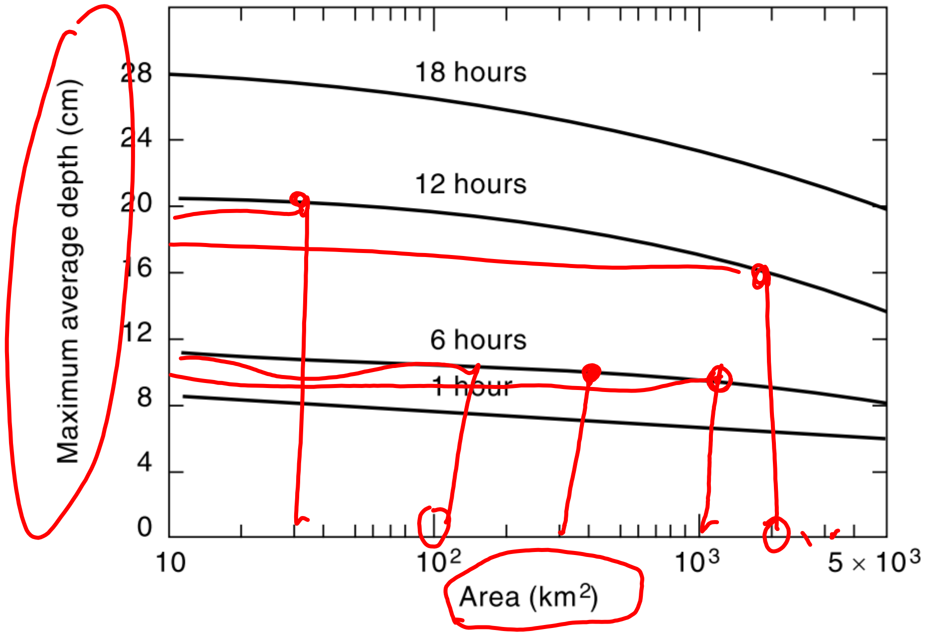

Fig. 2.16 Typical DAD Curves

- Duration Fixed
  - Volume = area * depth
- Area Fixed
  - Intensity constant
  - As duration increases, depth also increases.

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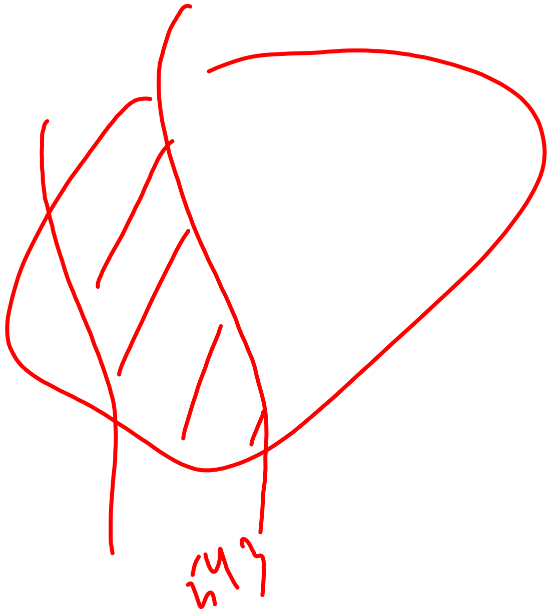
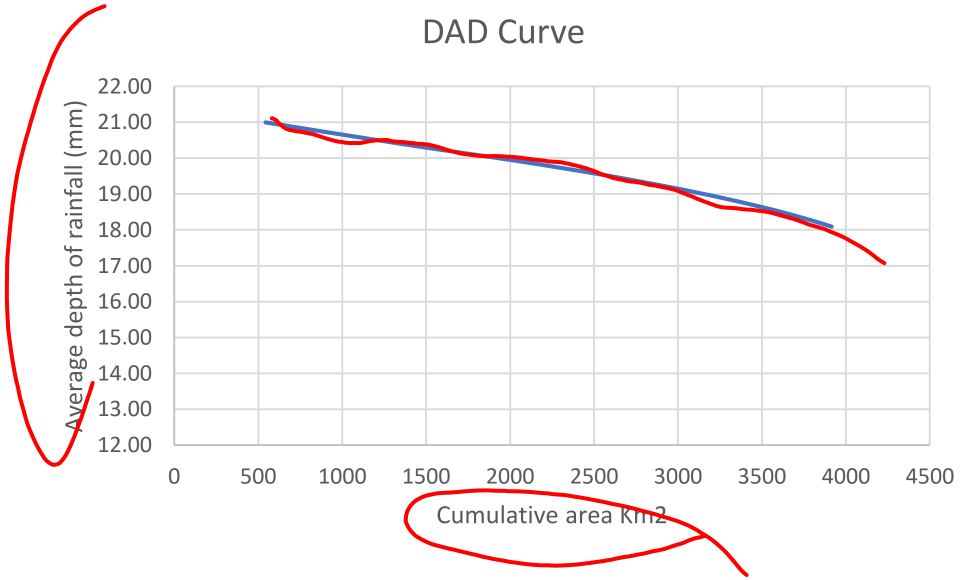
Draw the depth area duration curve due to storm lasting for 12 hours, assuming the storm centre to be located at the centre of area. The isohytes for that storm and the are enclosed between different isohytes are as follows.

Isohytes (mm)	Area (km2)
20-22	543
19-21	1345
18-20	2030
17-19	2545
16-18	2955
15-17	3280
14-16	3535
13-15	3710
12 -14	3880
11 -13	3915



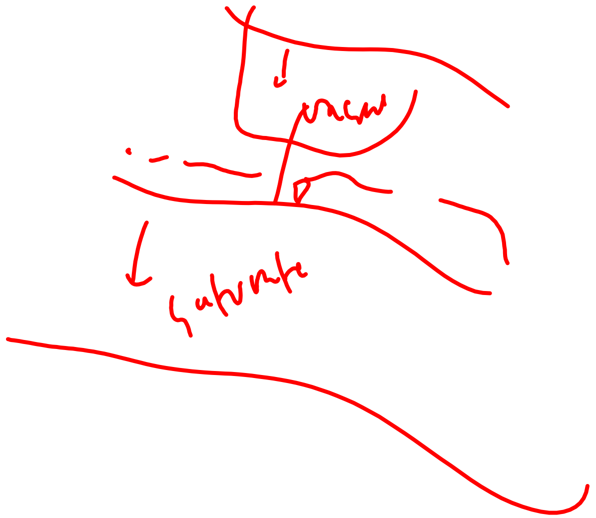
Isohytes	Average rainfall	cumulative area	Net area between isohytes	Volume	Cumulative Volume	Avg. depth
20-22	21	543	543	11403	11403	21.00
19-21	20	1345	802	16040	27443	20.40
18-20	19	2030	685	13015	40458	19.93
17-19	18	2545	515	9270	49728	19.54
16-18	17	2955	410	6970	56698	19.19
15-17	16	3280	325	5200	61898	18.87
14-16	15	3535	255	3825	65723	18.59
13-15	14	3710	175	2450	68173	18.38
12 -14	13	3880	170	2210	70383	18.14
11 -13	12	3915	35	420	70803	18.09



PANA ACADEMY

Infiltration

- Infiltration is the process by which water enters the soil from the ground surface. Infiltration first replenishes the soil moisture deficiency. The excess water then moves downwards by the force of gravity. This downward movement under gravity is called percolation. Percolation is thus the movement of water within the soil.



Infiltration rate (f) is the rate at which water enters the soil at the surface. Cumulative infiltration (F) is the accumulated depth of water infiltrated during a given time period.

$$F(t) = \int_{o}^{t} f(t)dt$$

$$f(t) = \frac{dF(t)}{dt}$$

Infiltration capacity (fc) is the maximum rate at which a given soil can absorb water under a given set of conditions at a given time.

The actual rate of infiltration (f) can be expressed as

f = fc for i ≥ fc

f = i for i < fc

i = intensity of rainfall

Infiltration capacity of a soil is high at the beginning of a storm and has an exponential decay as the time elapses.

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If ‘F’ is the infiltration volume which gets infiltrated during T hour then,
Average infiltration rate(f) = F/T

3.4.2 Horton equation for infiltration

According to Horton, Infiltration begins at some rate f_0 and exponentially decreases until it reaches a constant value f_c

$$f(t) = f_c + (f_0 - f_c)e^{-kt}$$

f(t): infiltration capacity at any time t from the start of the rainfall
f_0: initial infiltration capacity at t = 0
f_c : infiltration rate at the final steady stage when the soil profile becomes fully saturated
k : decay constant depending upon soil characteristics and vegetation cover, known as Horton coefficient
Three parameter to fix: f_0, f_c, k, practical difficulty in determination

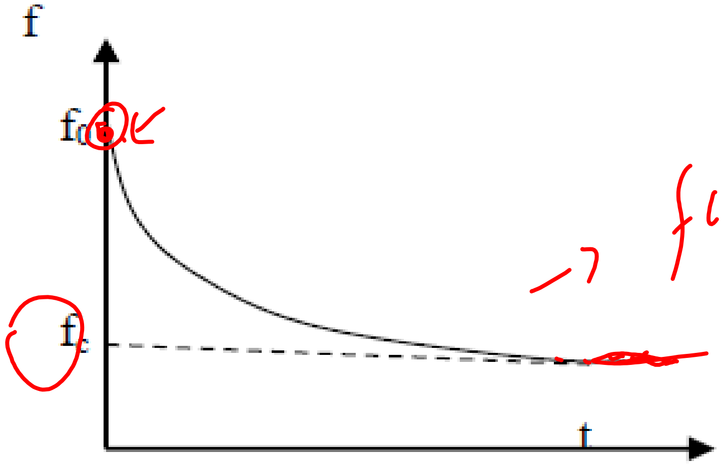


Fig. 3.6 : Infiltration curve

$f(t) = f_c + (f_0 - f_c)e^{-kt}$

$F(t) = f_c t + \frac{f_0 - f_c}{k}(1 - e^{-kt})$

$f(t)_{average} = f_c + \frac{f_0 - f_c}{kt}(1 - e^{-kt})$

Cumulative infiltration or total infiltration using Horton's equation for time t from start

$$F(t) = \int_0^t f(t)dt$$

$$= \int_0^t [f_c + (f_0 - f_c)e^{-kt}]dt$$

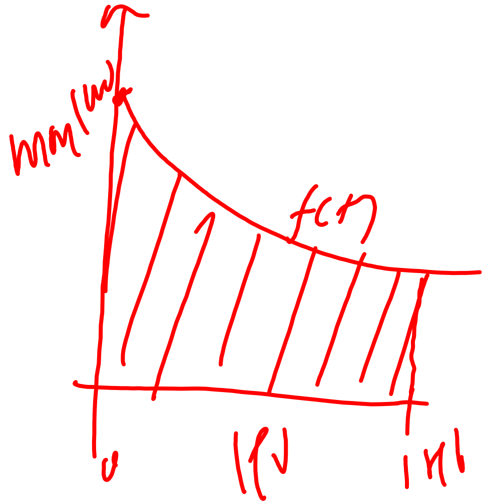
$$= f_c t + (f_0 - f_c)\left|\frac{e^{-kt}}{-k}\right|_0^t$$

$$F(t) = f_c t + \frac{f_0 - f_c}{k}(1 - e^{-kt})$$

Average infiltration in time t = $F(t)/t = f_c + \frac{f_0 - f_c}{kt}(1 - e^{-kt})$

The area under curve of $f(t) = f_c + (f_0 - f_c)e^{-kt}$ gives

(a) Total infiltration
(b) Average "
(c) instantaneous "
(d) Can give all of above



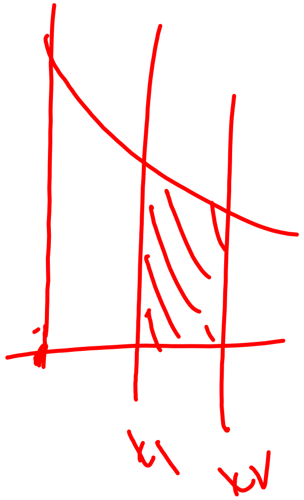
Total → mm
Avg → mm/hr
instantaneous → mm/hr

Cumulative infiltration or total infiltration depth in between time t1 and t2

$$F(t) = \int_{t1}^{t2} f(t)dt$$

$$= \int_{t1}^{t2} [f_c + (f_0 - f_c)e^{-kt}]dt$$

$$= f_c(t2 - t1) + \frac{f_0 - f_c}{(-k)}(e^{-kt2} - e^{-kt1})$$



To determine k with known values of F(t), f_c, f_o and t

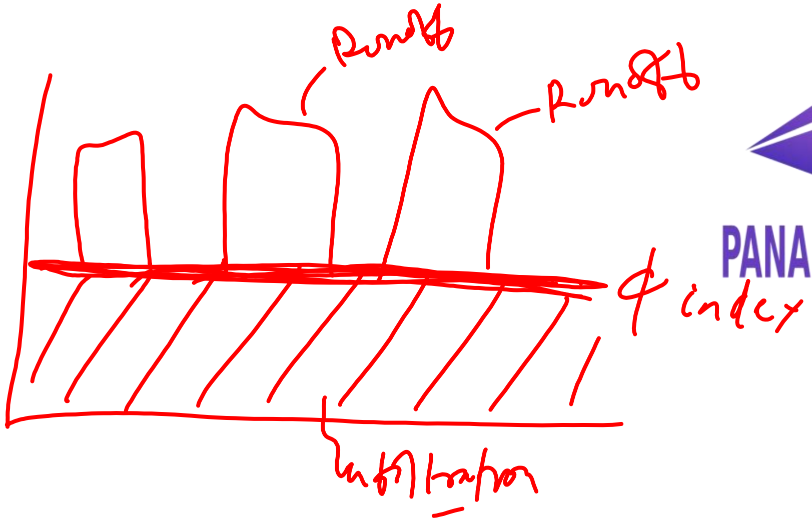
For large t, the value of e^{-kt} becomes negligible. Hence above equation reduces to

$$F(t) = f_c t + \frac{f_0 - f_c}{k}$$

$$k = \frac{f_0 - f_c}{F(t) - f_c t}$$

If rainfall intensity (i) is less than f, all rainfall is infiltrated. Runoff occurs only after i>f.

Infiltration indices



Two common infiltration indices

a. φ index

The average rate of rainfall above which the rainfall volume equals to runoff volume is called φ index. It is based on the assumption that for a specified storm with given initial conditions, the rate of basin recharge remains constant throughout the storm period. i.e. φ remains constant.

For $i < \varphi$, $f = i$

For $i > \varphi$, runoff = $i - f$

i = rainfall intensity

f = infiltration rate

φ : total abstractions

The amount of rainfall in excess of the index is known as effective rainfall or rainfall excess.

- Here, initial loss is also considered as an infiltration.

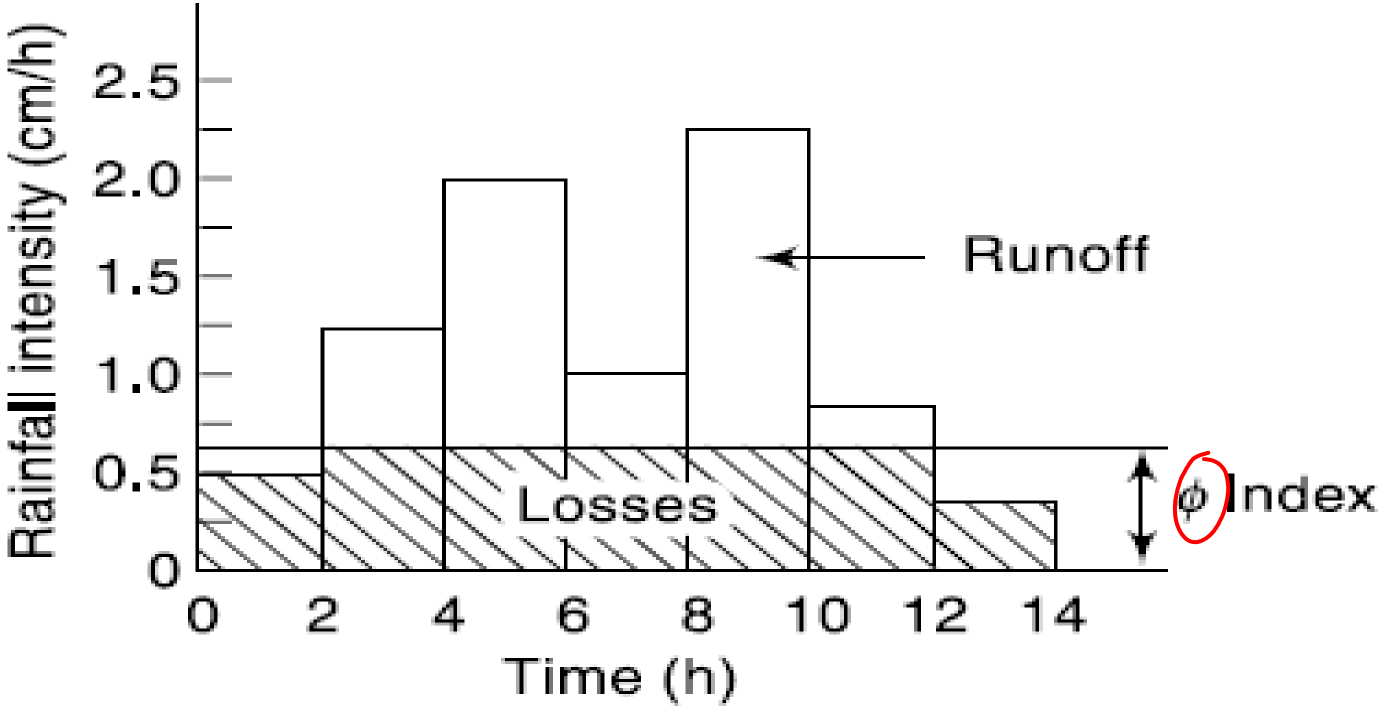


Fig. 3.16 *φ*-Index

Note: Also give the concept of relation between infiltration capacity, infiltration rate and rainfall intensity

B. W-index

The W- index is refined version of ϕ index. It can be defined as the average rate of infiltration during the period when the rainfall intensity exceeds the infiltration rate. This index is considered as an improvement over ϕ index in the sense that initial losses (interception and surface storage) are considered.

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

ϕ index − loss = W index

Where,

P = Total storm Precipitation

R = Total storm runoff

I_a = Initial losses (Depression and interception loss)

t_s = Time during which rainfall intensity exceeds infiltration rate

Streamflow Measurement

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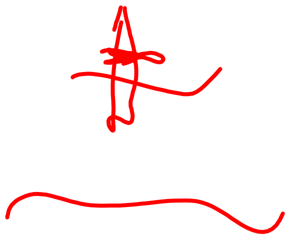
1. Direct Determination
   - ✓ Area-velocity method
   - ✓ Dilution techniques
   - ✓ Electromagnetic method
   - ✓ Ultrasonic method
2. Indirect Determination
   - ✓ Hydraulic structures such as weirs, flumes and gated structures.
   - ✓ Slope-area method

Streamflow Measurement



- Direct measurement of discharge is a very time-consuming and costly procedure.
- Hence, a two step procedure is followed.
- First the discharge in a given stream is linked to the elevation of the water surface (stage) through a series of careful measurements.
- In the next step, the stage of the stream is observed routinely in a relatively inexpensive manner and the discharge is estimated by using previously determined stage-discharge relationship.
- The observation of the stage is easy, inexpensive and if desired continuous readings can also be obtained.

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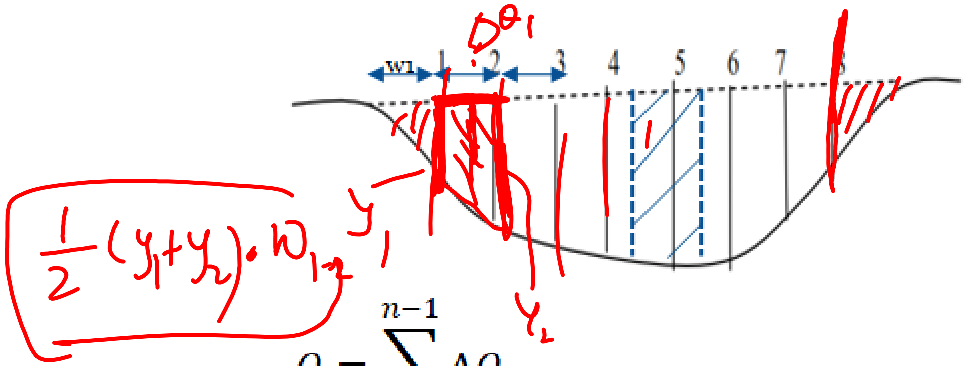
Stream Gauging:

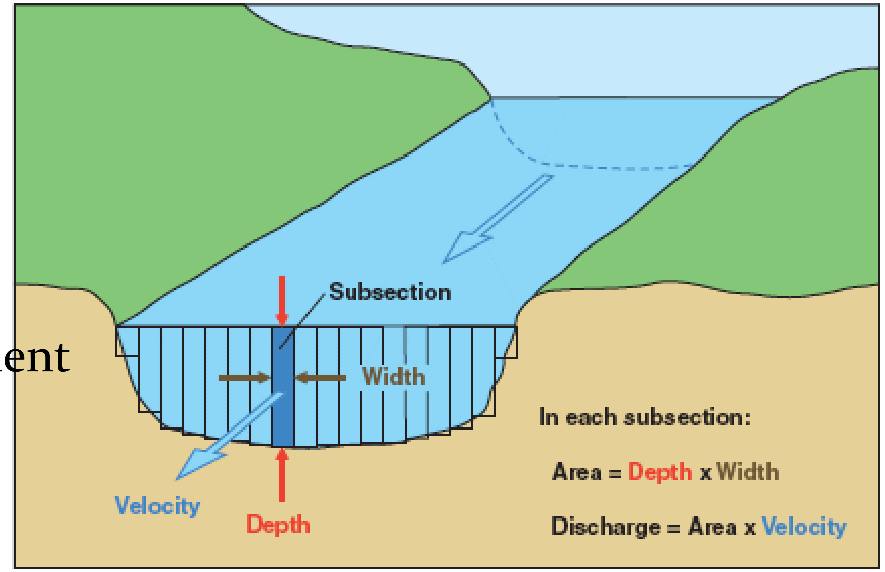
- It is a technique used to measure the discharge, or the volume of water moving through a channel per unit time, of a stream.
- The height of water in the stream channel, known as a stage or gage height, can be used to determine the discharge in a stream.
- Runoff from a catchment can be determined by measuring the discharge of the stream draining it.

Velocity area method

This involves the measurement of velocity at the gauging site and the corresponding discharge to obtain river discharge.

a. Mid section method of discharge measurement





Current-meter discharge measurements are made by determining the discharge in each subsection of a channel cross section and summing the subsection discharges to obtain a total discharge.

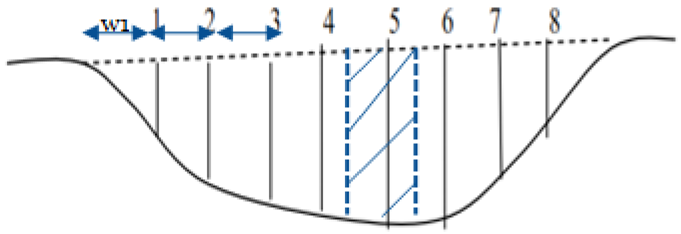
$$Q = \sum_{i=1}^{n-1} \Delta Q_i$$

Where ΔQ_i=Discharge of each segment

$\Delta Q_i = A_i * v_i$

$A_i = y_i * (W_i + W_{(i+1)})/2$ for other than first and last segment (assuming rectangular section)

Velocity area method



$$Q = \sum_{i=1}^{n-1} \Delta Q_i$$

Where ΔQ_i=Discharge of each segment

$\Delta Q_i = A_i * v_i$

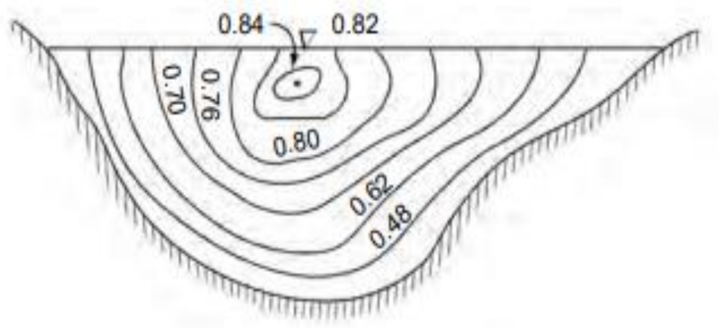
$A_i = y_i * (W_i + W_{(i+1)})/2$ for other than first and last segment (assuming rectangular section)

For first segment and last segment

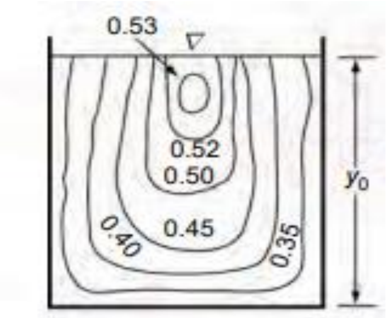
$$A_1 = \frac{\left(W_1 + \frac{W_2}{2}\right)^2}{2W_1} y1 \qquad A_{n-1} = \frac{\left(W_n + \frac{W_{n-1}}{2}\right)^2}{2W_n} y_{n-1}$$

Velocity Distribution in open channel flow

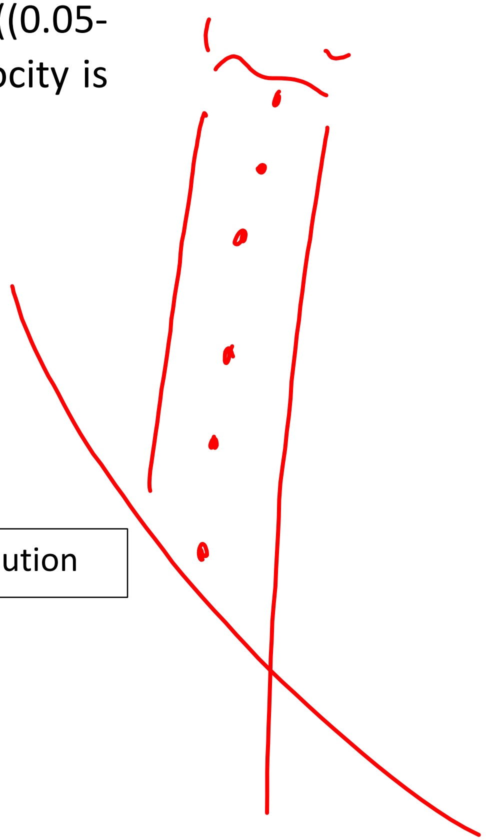
- The velocity of flow at any channel section is not uniformly distributed due to the presence of a free surface and the frictional resistance along the channel boundary. The velocity is zero at the solid boundary and gradually increases with the increase in distance from the boundary. The maximum velocity occurs at some distance ((0.05-0.25) *times depth of flow) below the free surface. At the free surface, the velocity is less than the maximum value due to the air resistance.



Natural channel velocity distribution



Rectangular channel velocity distribution



- In a macro-analysis, one is concerned only with the major component, viz., the longitudinal component, Vx. The other two components being small are ignored and Vx is designated as v i.e. 1D analysis.

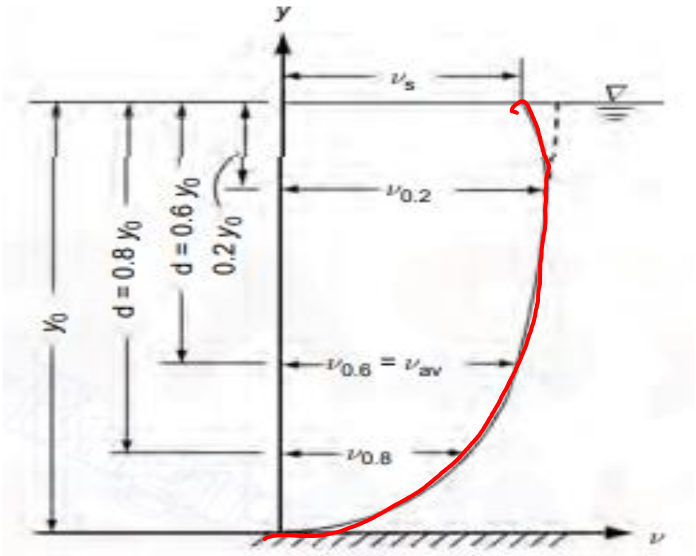


Fig: velocity profile

- Field observations in rivers and canals have shown that the average velocity at any cross section is computed as:

1.For shallow depth up to 3m

$\bar{v}$= velocity at 0.6m from free surface($v_{0.6}$).

depth

2. For deep stream

$\bar{v} = v_{0.6}$

- $\bar{v}=\frac{v_{0.2}+v_{0.8}}{2}$ Two Point method
- $\bar{v}=\frac{v_{0.15}+v_{0.5}+v_{0.85}}{3}$ Three Point method
- $\bar{v}=0.1*(v_s + 2v_{0.2} + 2v_{0.4} + 2v_{0.6} + 2v_{0.8}+v_b)$ Six Point method
- v_s – velocity measured near water surface.
- v_b -- velocity measured channel bed.
- $v_{0.2}$ - velocity at a depth of $0.2*y_0$ from the free surface, and $v_{0.8}$ = velocity at a depth of $0.8*y_0$ from the free surface.

Guidelines for selecting no. of segments

- The segment width should not be greater than 1/15 to 1/20 of the width of the river.
- The discharge in each segment should be less than 10% of the total discharge.
- The difference of velocities in adjacent segments should not be more than 20%.

Slope area method

-This is the application of open channel hydraulics to estimate the discharge flowing through a channel section.

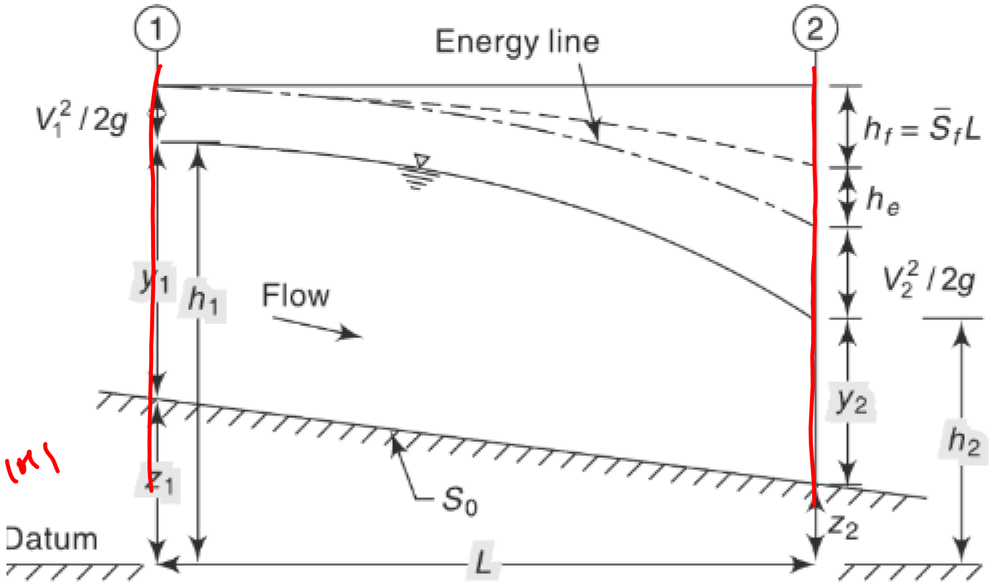
Applying energy equation
Through A and B

$$Z_1 + y_1 + \frac{V_1^2}{2g} = Z_2 + y_2 + \frac{V_2^2}{2g} + h_L$$

Where, h_L=head loss in the section=h_f+h_e
h_f= frictional loss
h_e=eddy loss

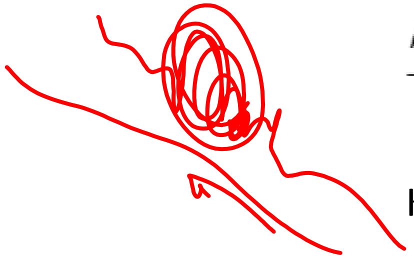
or,
$$h_1 + \frac{V_1^2}{2g} = h_2 + \frac{V_2^2}{2g} + h_e + h_f$$

or,
$$h_f = (h_1 - h_2) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right) - h_e$$



Where, h_1 and h_2 are water surface elevation above datum

If L is the length between two sections.



$$\frac{h_f}{L} = S_f = \text{energy slope} = \frac{Q^2}{K^2}$$

K=conveyance of the channel

$$= \frac{1}{n} A R^{2/3}$$

For non uniform flow the conveyance of the channel is calculated as

$$K = \sqrt{K_1 K_2} \; ; K_1 = \frac{1}{n_1} A_1 R_1^{2/3} \text{ and } K_2 = \frac{1}{n_2} A_2 R_2^{2/3}$$

Eddy loss: $$h_e = K_e \left| \frac{V_1^2}{2g} - \frac{V_2^2}{2g} \right|$$

Ke=eddy loss coefficient

$$Q = C_r(G - a)^{\beta}$$

The best values of Cr andβ for given range of stage are obtained by least square error method.

Taking logarithmic

logQ= βlog(G-a)+logC_r

y= βx+b Where y=logQ

x=log(G-a)

b=logCr

From regression analysis

$$\beta = \frac{N\sum xy - \sum x \sum y}{N\sum x^2 - (\sum x)^2}$$

$$b = \frac{\sum y - \beta \sum x}{N}$$

Correlation coefficient:

$$r = \frac{N\sum xy - \sum x \sum y}{\sqrt{(N\sum x^2 - (\sum x)^2)(N\sum y^2 - (\sum y)^2)}}$$

r must lies between 0.6 to 1 for good correlation

The stage-discharge data of a river are given below. Establish the stage-discharge relationship to predict the discharge for a given stage. Assume the value of stage for zero discharge as 35.00 m. (2) What is the correlation coefficient of the relationship established above? (3) Estimate the discharge corresponding to stage values of 42.50 m and 48.50 m respectively.

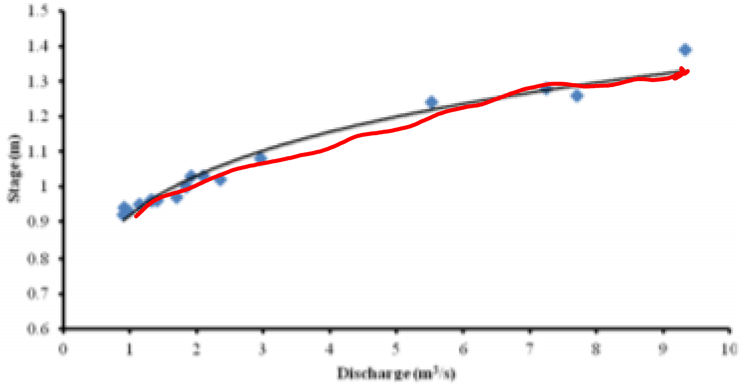
Stage (m)	Discharge (m^3/s)	Stage (m)	Discharge (m^3/s)
35.91	89	39.07	469
36.90	230	41.00	798
37.92	360	43.53	2800
44.40	3800	48.02	5900
45.40	4560	49.05	6800
46.43	5305	49.55	6900
		49.68	6950

Finding Stage corresponding to zero discharge

a. Method-1

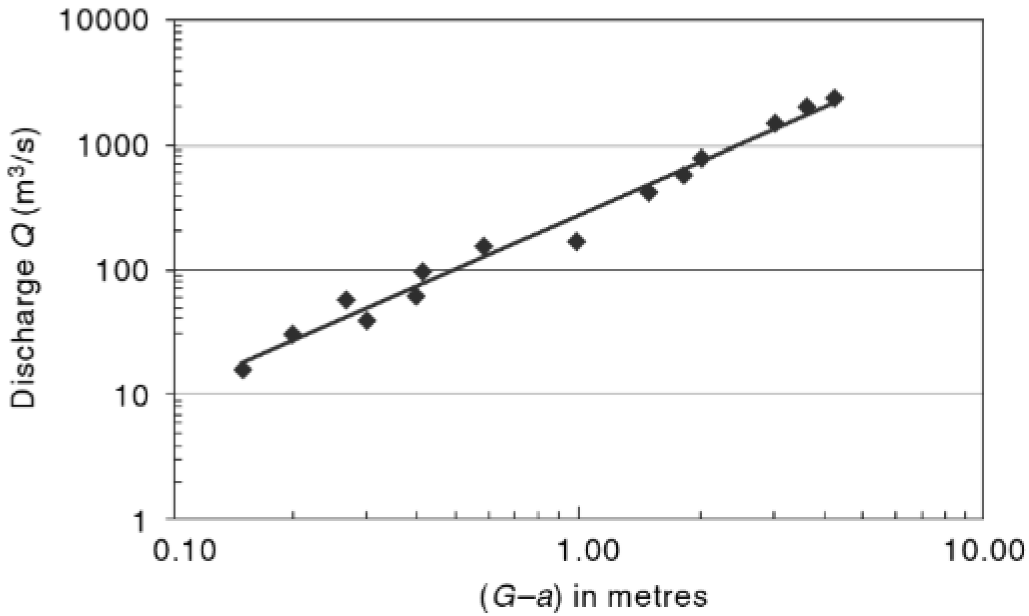
Step i)

- In this method, plot of stage vs discharge is best fitted to obtain a stage discharge curve.
- The curve is than extrapolated backward by judgment. It intersects Y-axis at a point(a) corresponding to zero discharge.



ii)

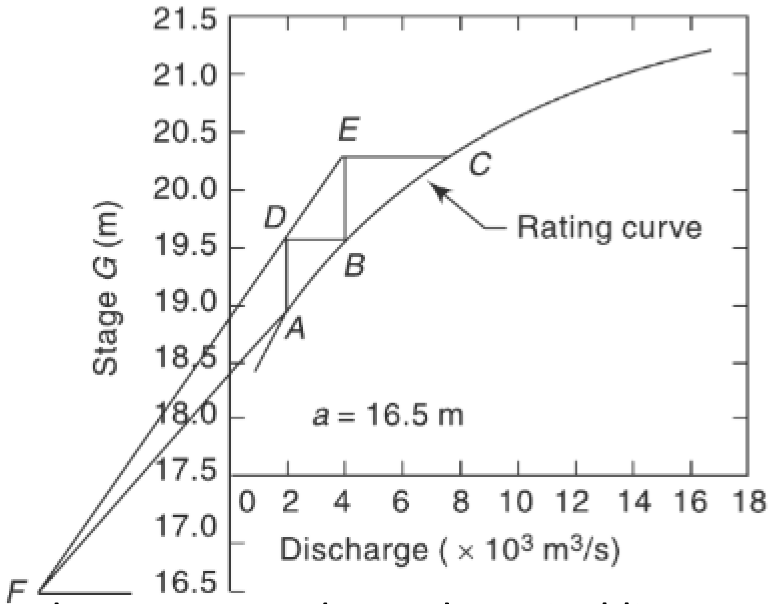
- For ‘a ‘obtain from step 1, plot a graph of logQ vs log(G-a)
- If the graph is straight line the value of a is acceptable
- If graph is not straight line repeat above process.



Method:2 Graphical method

➢In graphical method, Discharge vs stage data are plotted to an arithmetic scale.
➢A smooth curve is fitted by plotting given data.
➢Three points A,B,C on the curve are selected such that their discharge are in geometric progression

$$\frac{Q_A}{Q_B} = \frac{Q_B}{Q_C}$$



Point D and E are the intersection of horizontal line drawn at C and B and Vertical line drawn at B and A respectively

Two straight lines joining point A and B, D and E are intersected at point F, whose ordinate is the required value of **a**.

Method 3:

- Plot Q vs G to an arithmetic scale and draw a smooth good fitting curve.
- Select three discharges Q1,Q2,Q3 such that Q1/Q2=Q2/Q3 and note from the curvethe corresponding values of gauge reading G1,G2 and G3

$$(G_1 - a)/(G_2 - a) = (G_2 - a)/(G_3 - a)$$

$$a = \frac{G_1 G_3 - G_2^2}{(G + G_3) - 2G_2}$$

Permanent and Shifting Control

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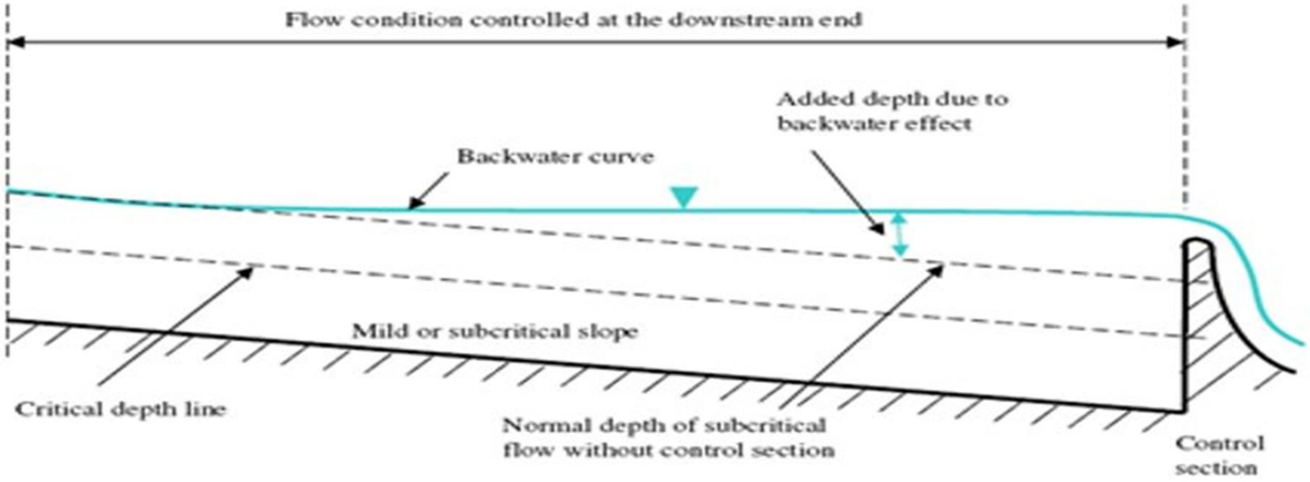
- If the stage-discharge relationship for a gauging section is constant and does not change with time, the control is said to be **Permanent Control**.
- Permanent control is usually in non-alluvial river.
- If the relationship changes with the time then it is called **Shifting Control**.

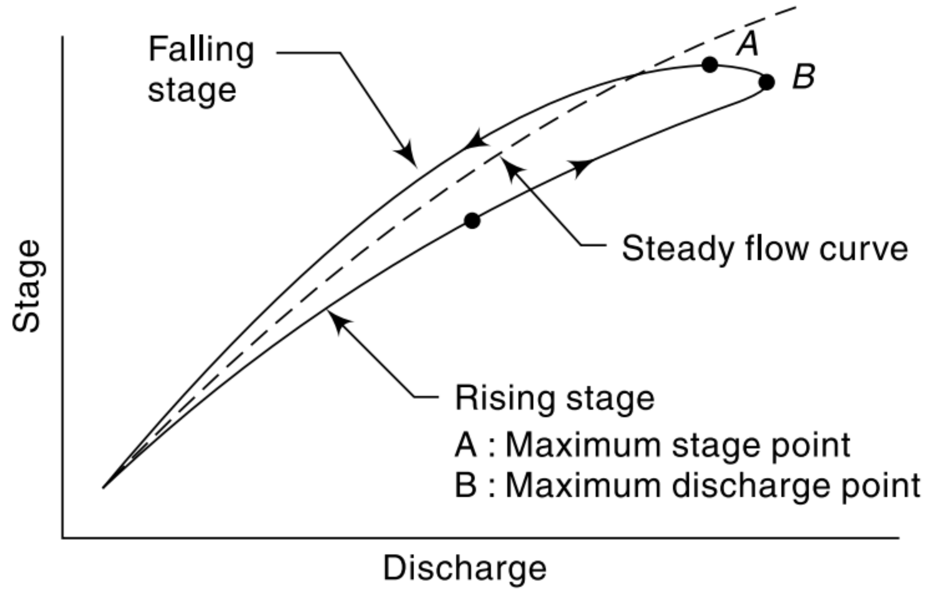
Causes of shifting control

- Vegetative growth
- Erosion and silting
- Backwater effect
- Unsteady flow effect.



Backwater Effect

Unsteady Flow Effect



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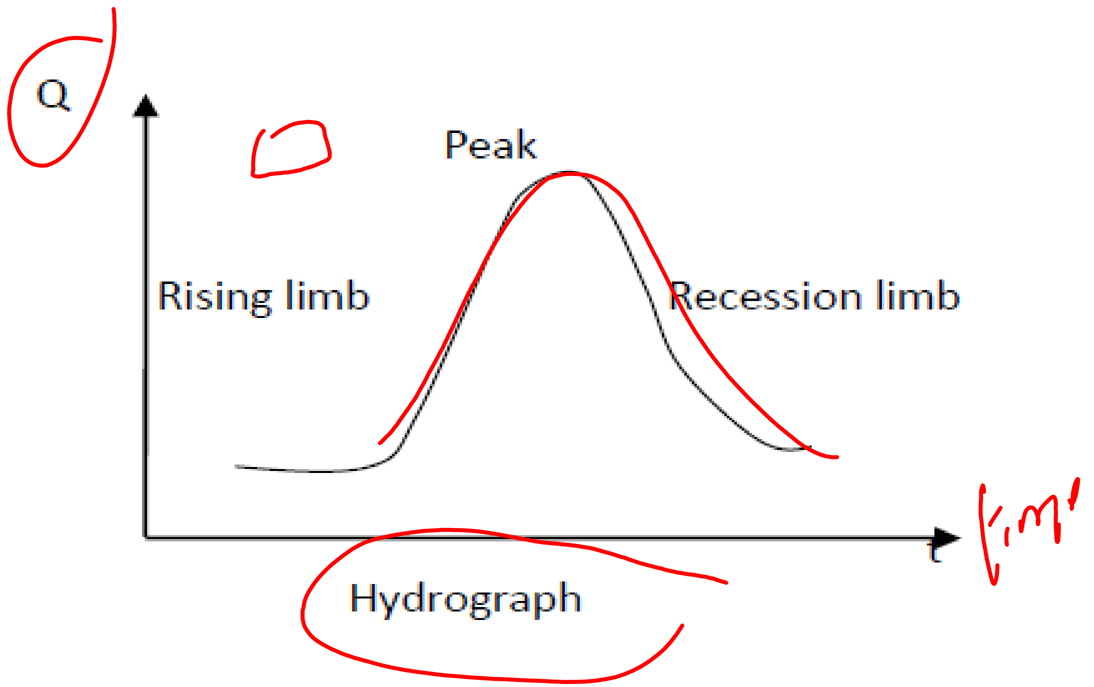
Hydrograph

- Hydrograph is a graphical plot of discharge (Q) of a river at a given location over time.
- It is the output or total response of a basin.



Hydrograph

Hydrograph: It is a continuous plot of instantaneous discharge (runoff) v/s time.

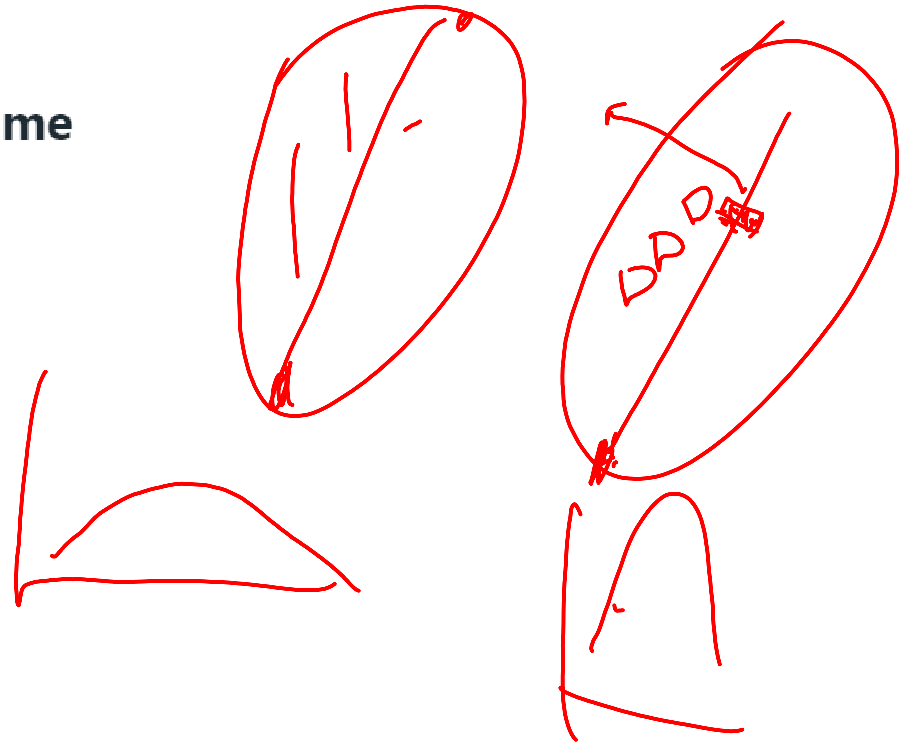
It results from a combination of physiographic and meteorological conditions in a watershed and represents the integrated effects of climate, hydrologic losses, surface runoff, interflow, and groundwater flow.

Factors that influence the hydrograph shape and volume

i. Meteorological factors

ii. Physiographic or watershed factors and

iii. Human factors



Hydrograph

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Hydrograph: It is a continuous plot of instantaneous discharge (runoff) v/s time.

It results from a combination of physiographic and meteorological conditions in a watershed and represents the integrated effects of climate, hydrologic losses, surface runoff, interflow, and groundwater flow.

Factors that influence the hydrograph shape and volume

i. Meteorological factors

ii. Physiographic or watershed factors and

iii. Human factors

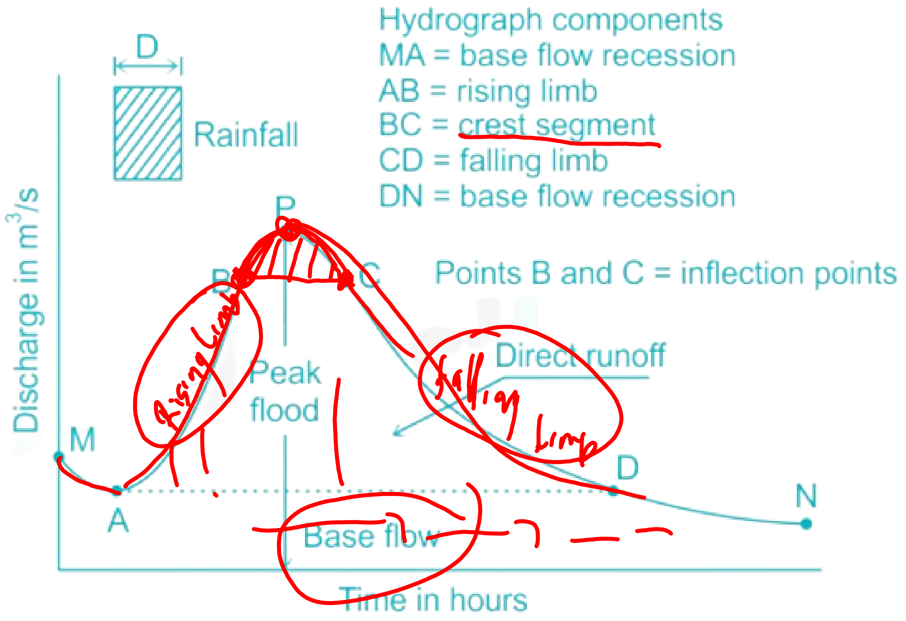
Hydrograph

Flood hydrograph has three characteristic regions:

(i) Rising limb AB: Curve Joining point A, the starting point of the rising curve and point B, the point of inflection. It is concave in shape and the shape depends both upon the rainfall and the catchment parameters.

(ii) Crest segment BC: Between the two points of inflection B and C with a peak P. For large catchments it generally occurs sometimes after the rainfall has ended.

(iii) Falling limb/ Recession Limb: Curve CD starting from the second point of inflection C and the shape depends only on catchment parameters (Basin characteristics only) as the rainfall has ceased by then.



Elements of a Flood Hydrograph

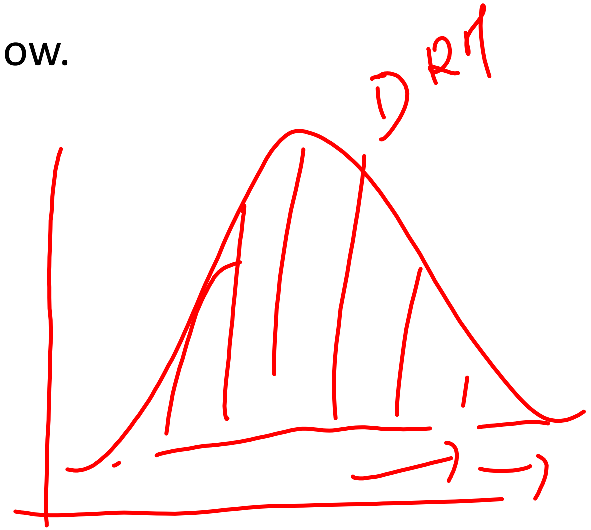
Direct runoff and base flow

- **Direct runoff**

It is the part of precipitation which appears quickly as flow in the river. (direct runoff = surface +subsurface). Surface runoff, prompt interflow and channel precipitation all contributes to direct runoff

- **Base flow**

The part of runoff which receives water from the groundwater storage is called base flow.



Effective rainfall /Excess rainfall

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- It is that part of rainfall which becomes direct runoff at the outlet of the catchment.
- It is obtained by deducting the abstractions such as infiltration, initial losses etc. from total rainfall.

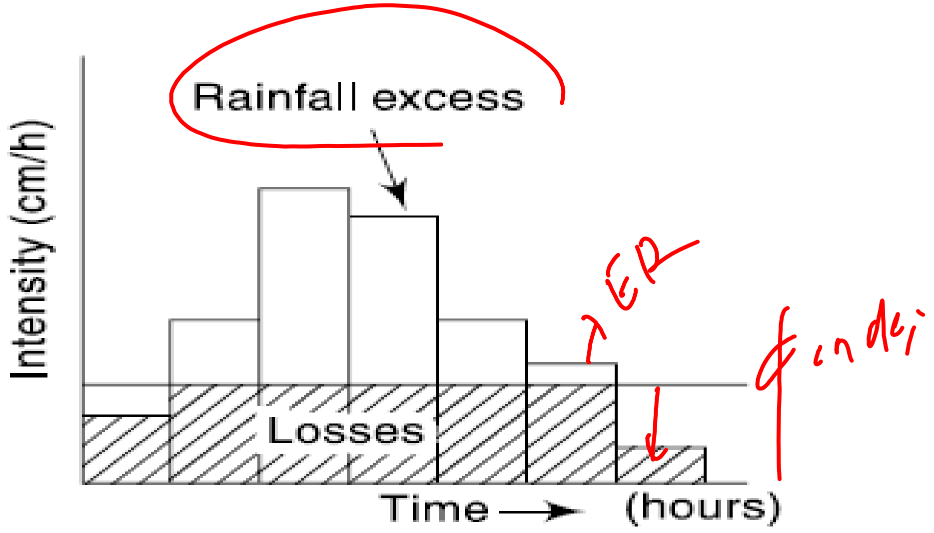
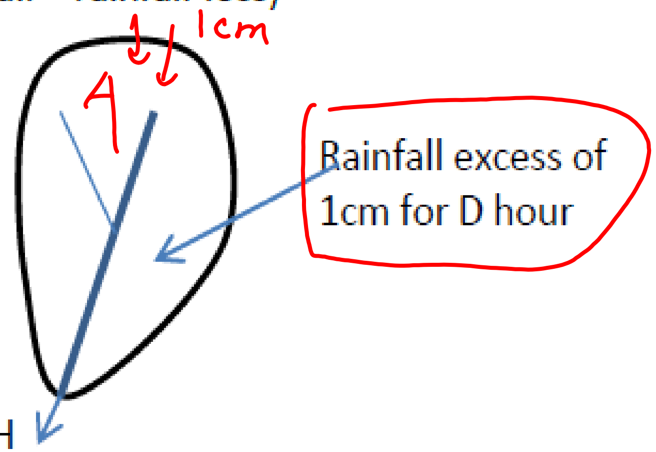


Fig. 6.6 Effective Rainfall Hyetograph (ERH)

Unit Hydrograph

A unit hydrograph (UH) of a basin is defined as a direct runoff hydrograph (DRH) resulting from one unit depth of rainfall excess generated uniformly over the basin at a constant rate for an effective duration (D). The term unit refers to a unit depth of rainfall excess which is 1cm in SI unit and 1 inch in FPS unit. (Rainfall excess/effective rainfall = rainfall-loss)

Volume = A × 1cm
= A×1cm



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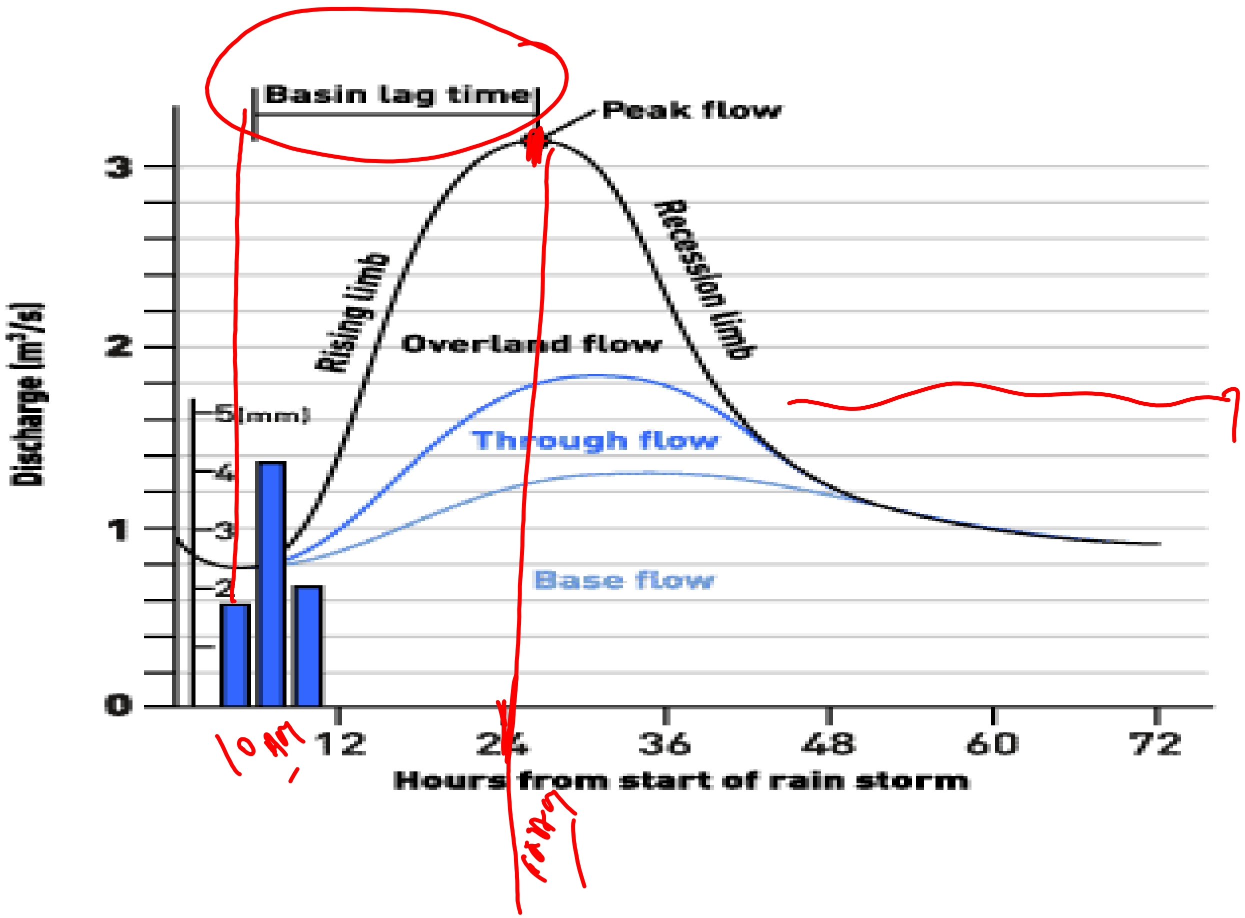
Features

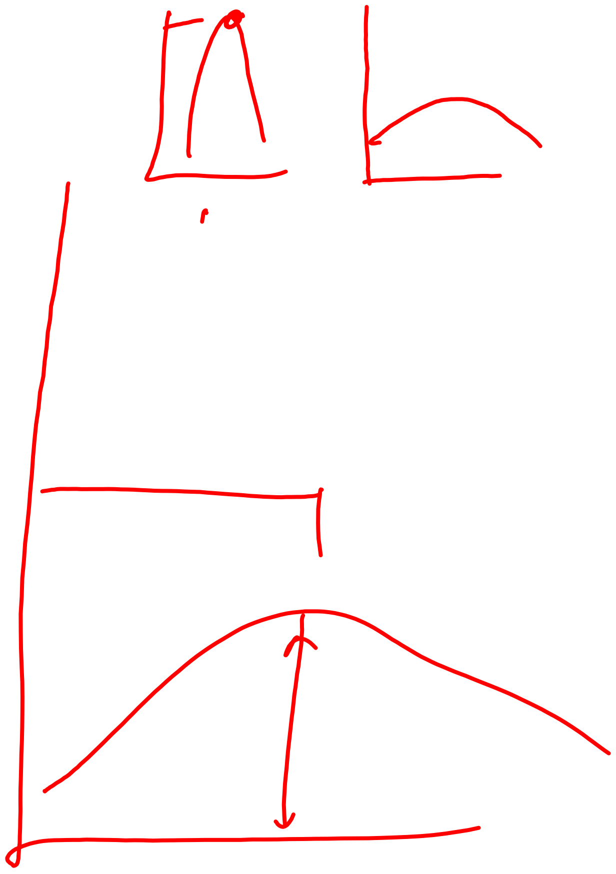
- Rainfall excess (r_e) = 1cm, runoff depth (r_d) = 1cm

Continuity: Total depth of rainfall excess = total depth of direct runoff

- Runoff volume (V_d) = Basin area(A) x r_d = Ax1cm
- Rainfall intensity: 1/D in cm/h
- Lumped response: catchment as a single unit
- Initial loss absorbed by basin, no effect of antecedent storm condition

The best unit period of a unit hydrograph is calculated by dividing the basin lag by **four**. This is because the peak of the unit hydrograph occurs at one-fourth of the basin lag duration. Therefore, the best unit period is equal to basin lag divided by four.





Assumption in UH

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- Constant intensity of excess rainfall within the effective
- Uniform distribution of excess rainfall over the basin
- Constant base time of the DRH for excess rainfall of given duration
- Linear model: principle of superposition and proportionality holds
- Principle of time invariance holds

  -Given excess rainfall will always produce the same DRH whatever may be the season of the year (unchanging basin characteristics)

Principles applied in UH

I. Linearity principles

Linear relationship means output varies linearly with input. This principle is expressed by convolution theorem.

There are two principles of linearity.

a. Principle of proportionality: If a solution y is multiplied by a constant c, the resulting function cy is also a solution.

r_e = excess rainfall, UH = Unit hydrograph (solution)

Output (DRH) = r_e*UH

b. Principle of superposition: If two solutions y1 and y2 of the equation are added, the resulting function y1+y2 is also a solution of the equation.

r_{e1}, r_{e1} = excess rainfall at t hr interval, UH = Unit hydrograph (solution)

Output (DRH) = (r_{e1}*UH)+ (r_{e2}*UH lagged by t hr)

II. Principle of time invariance:

Given excess rainfall will always produce the same DRH whatever may be the season of the year (unchanging basin characteristics)

Question1

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- The peak of a flood hydrograph due to a storm is 470 m^3/s. The mean depth of a rainfall is 8 cm. Assuming an infiltration loss of 0.25 cm/hr and a constant baseflow of 15 m^3/s, estimate the peak discharge of a 6 hr unit hydrograph for this catchment. [Ans: 70 m^3/s]

ER 6.5 cm → 455 m^3/s

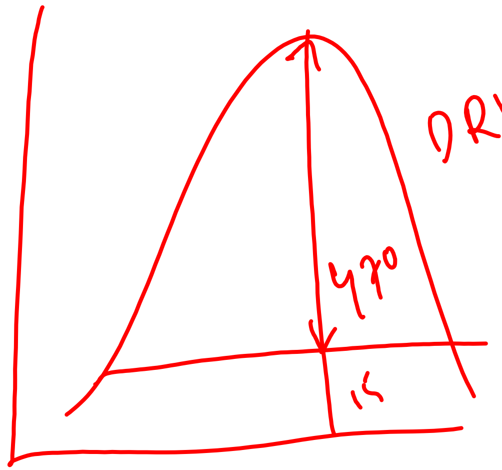
UH → 1 cm → $\frac{455}{6.5}$ m^3/s = 70

8 cm

0.25 × 6 cm

Loss →

ER = 8 − 1.5 = 6.5 cm



DRH = 470 − 15 = 455

Question1

Duration of rainfall excess = 6 h

Mean depth of rainfall = 8 cm

Infiltration loss @ 0.25 cm/h for 6h = 0.25 x 6 = 1.5 cm

Rainfall excess = Mean depth of rainfall - Infiltration loss = 8 - 1.5 = 6.5 cm

Peak of flood hydrograph

= 470 m^3/s

Base flow

= 15 m^3/s

Peak flow DRH

= 470 – 15 = 455 m^3/s

Peak of 6 h unit hydrograph

$= \frac{455}{6.5} = 70\ m^3/s$

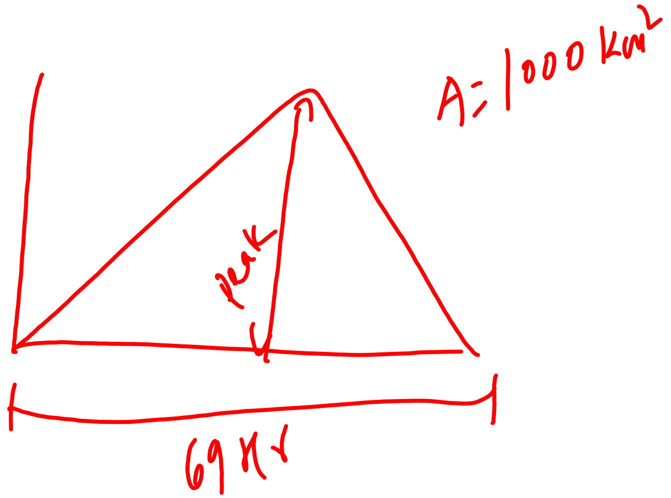
Question2

- A 6hr-unit hydrograph for a catchment of area 1000 km^2 is approximated as a triangle with base of 69 hr, calculate the peak discharge of this UH. [Ans: 80.5 m^3/s]

Area of UH = area of catchment x 1 cm

$$\frac{1}{2} \times 69 \times 3600 \times Q_p = 1000 \times (10^3)^2 \times (10^{-2}) \ m^3$$

$$Q_p = \_\_\_\_$$



Question3

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A triangular direct runoff hydrograph due to 6 hour storm in a catchment has a time base of 100 hour, and peak of flow of 40 m^3/s. The catchment is 180 km^2. Determine the peak flow value of 6 hour unit hydrograph of this catchment? (in m^3/s units)

[Ans: 10 m^3/s]

Area of UH = area of catchment x 1 cm

Question4

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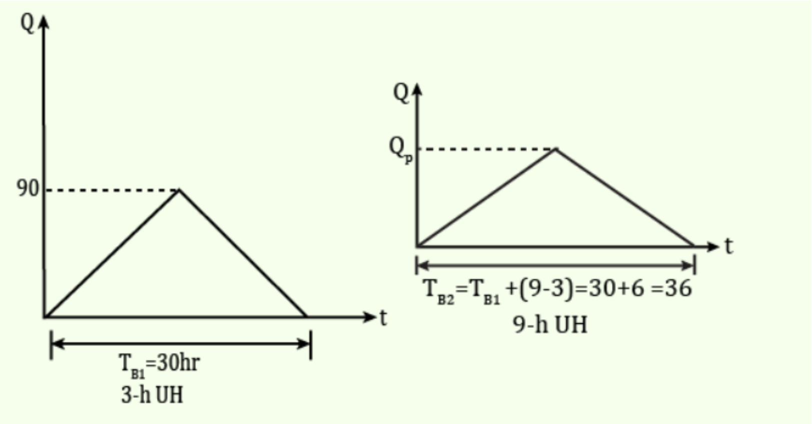
A 3 hour triangular unit hydrograph (UH) has a time base of 30 hours with peak discharge of $90 m^3/s$. For the same catchment 9 hour unit hydrograph was derived using 3 hour UH. The peak of 9 hour UH will

[Ans: $75\ m^3/s$]



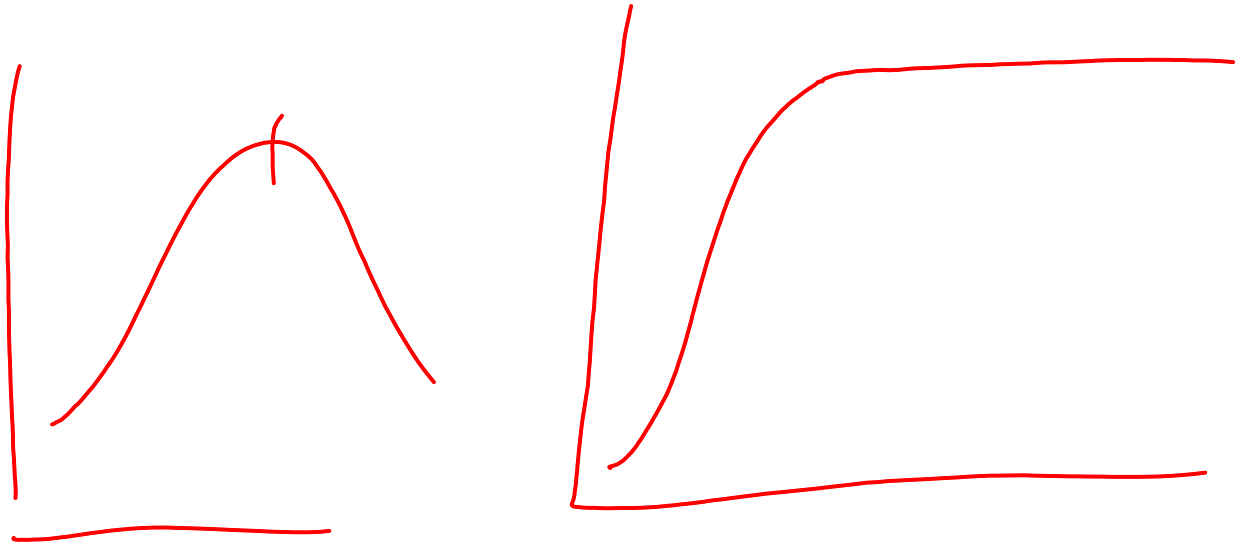
∴ Area of UH_1 = Area of UH_2

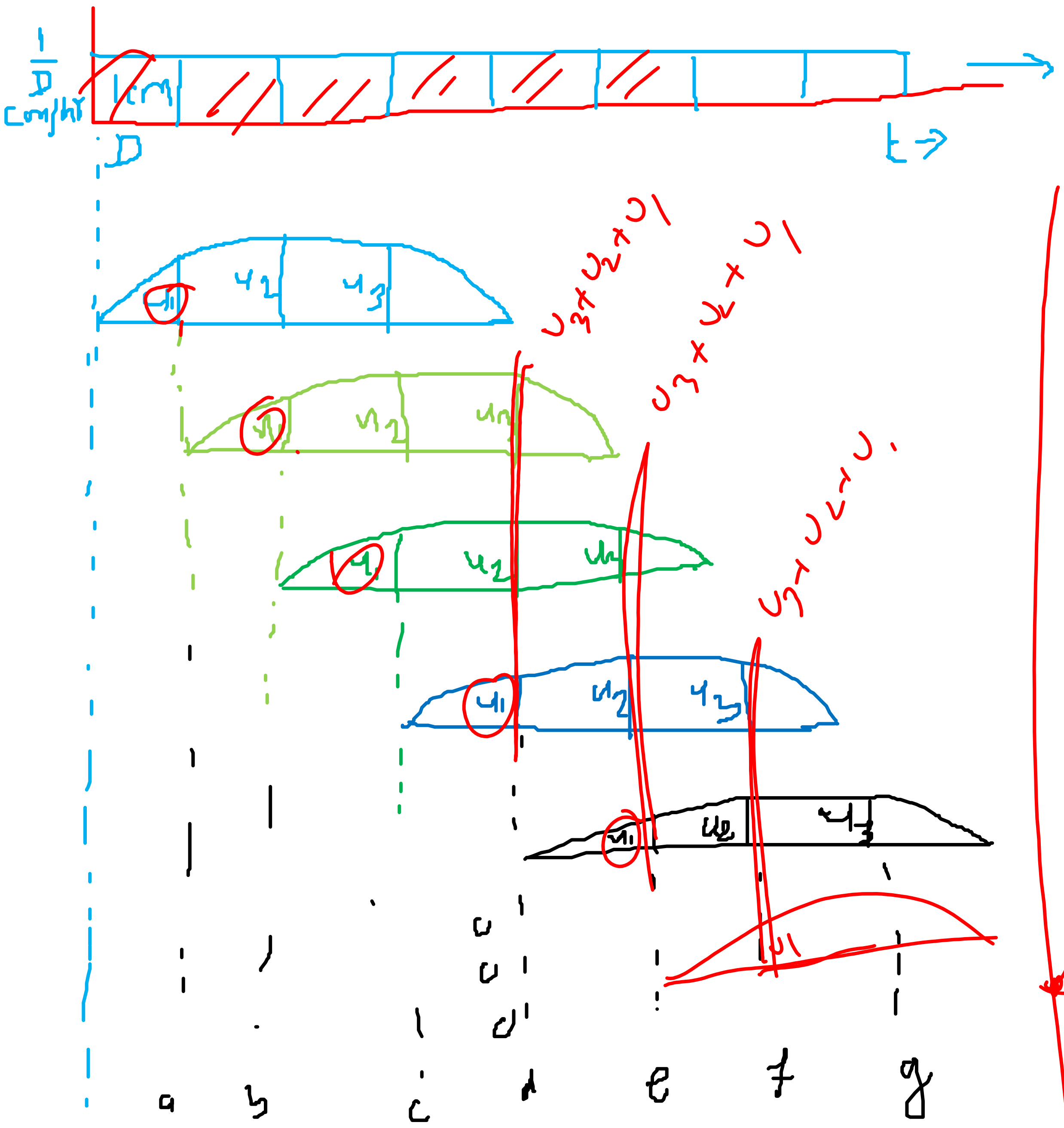
$$\frac{1}{2} \times 30 \times 90 = \frac{1}{2} \times 36 \times Q_P$$

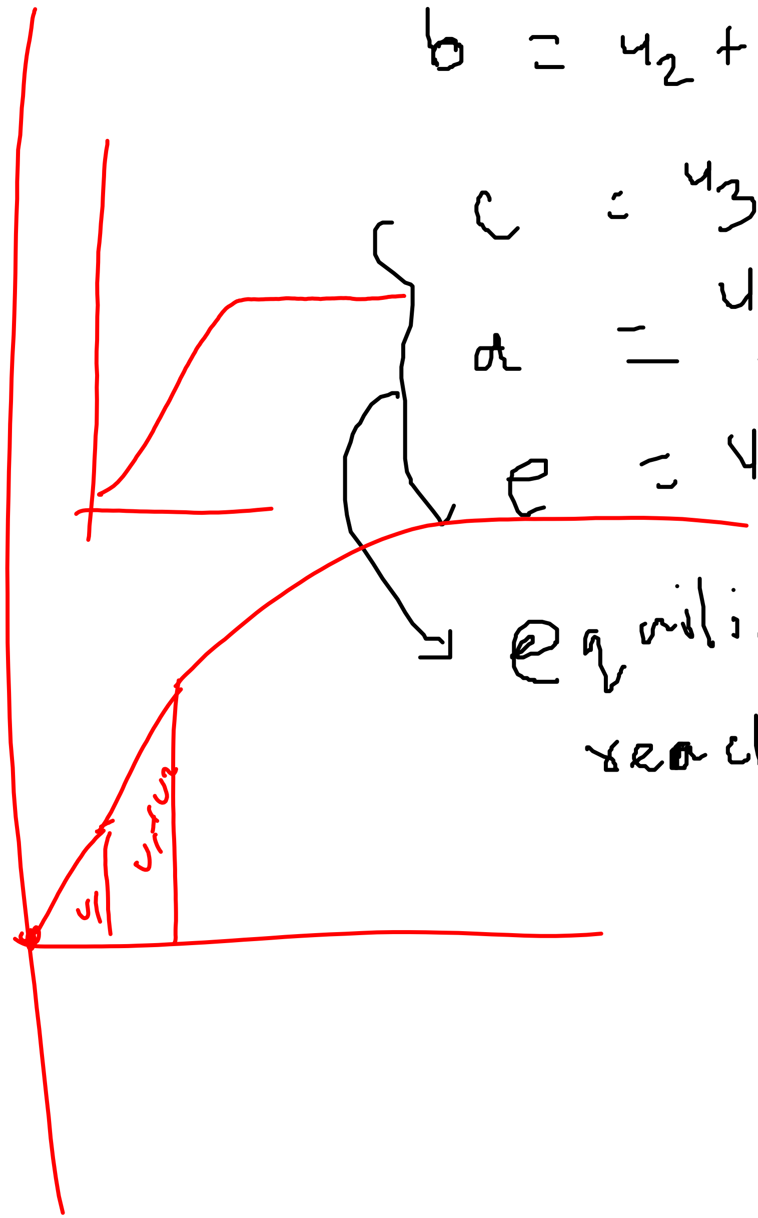
$$Q_P = 75\ m^3/s$$

S Hydrograph

- It is a hydrograph produced by a continuous effective rainfall at a constant rate for an infinite duration.







$a = u_1$

$b = u_2 + u_1$

$c = u_3 + u_2 + u_1$

$d = u_3 + u_2 + u_1$

$e = u_3 + u_2 + u_0$

equilibrium Q is reached.

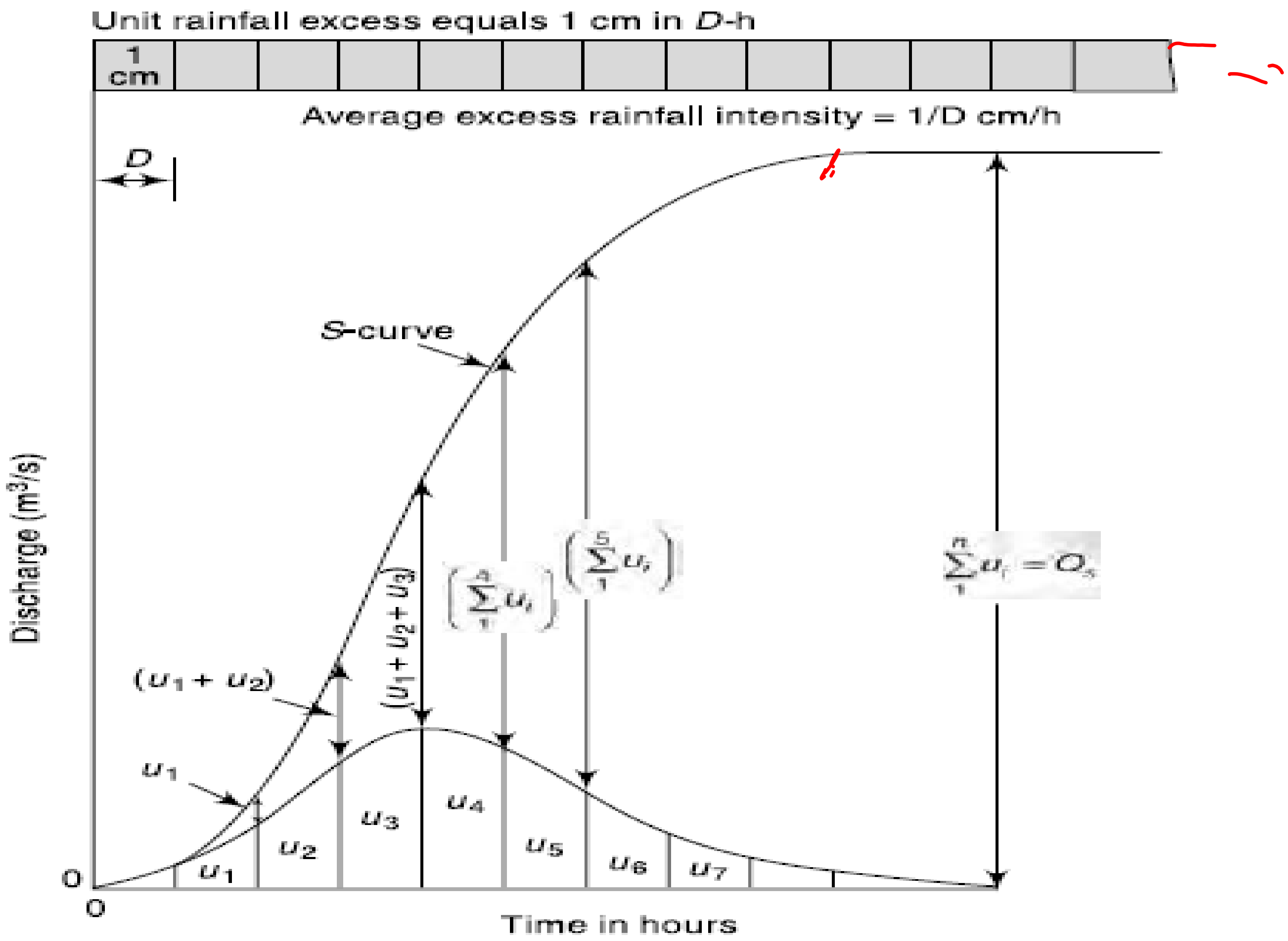


Fig. 6.16 *S*-curve

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the equilibrium discharge,

$$Q_s = \left(\frac{A}{D} \times 10^4\right) \text{ m}^3/\text{h},$$

where A = area of the catchment in km^2 and D = duration in hours of ER of the unit hydrograph used in deriving the S-curve. Alternatively

$$Q_s = 2.778 \frac{A}{D} \text{ m}^3/\text{s} \quad (6.7)$$

where A is the km^2 and D is in h. The quantity Q_s represents the maximum rate at which an ER intensity of $1/D$ cm/h can drain out of a catchment of area A. In actual

Question5

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- A 6hr-unit hydrograph for a catchment is approximated as a triangle with base of 64 hr and a peak ordinate of 30 m^3/s. Calculate the equilibrium discharge of an S-curve obtained by using this 6hr-UH. [Ans: 160 m^3/s]

Uses of UH

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- To develop flood hydrograph for extreme rainfall event for use in design of hydraulic structures.
- Extension of flood flow records based on rainfall records.
- Development of flood forecasting and warning system based on rainfall.

Limitations of UH

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- Assumptions of uniform rainfall distribution and constant rainfall intensity are never practically possible. This impose upper limit (5000 km^2) on catchment area for UH use. So, in case of large basins, they are divided into sub-basins to obtain DRH for each smaller sub-basins. Then, these DRH are routed to obtain hydrograph at the basin outlet.
- For catchment area less than 200 ha, UH is not applicable.
- Precipitation must be from rainfall only (No snowfall).
- No large storage within the catchment in the form of large lakes, dams etc.

Instantaneous UH (IUH)

- As the duration D approaches to 0 i.e., D $\rightarrow$ 0 for 1 cm rainfall excess, the resulting hydrograph is called IUH

Synthetic UH

- An empirically derived UH is called synthetic UH.
- Snyder's method is commonly used synthetic UH.
- The parameters used for deriving UH is taken from the meteorologically similar catchment whose UH is known already.
- Formula used: (Discuss)

Return Period

- The return period of 100 years simply means that its probability of occurring in any year is only 1/100 = 0.01 = 1%.
- It does not mean that if a flood with such a return period occurs this year then, the next will occur in about 100 year time period. Instead, it means that in a given year, there is 1% chance that it will happen regardless of when the last similar event was.
- Simply, it is 10 times less likely to occur than a flood with a return period of 10 years whose probability of occurrence in any year is 10%.

Flood Frequency studies

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The values of the annual maximum flood from a given catchment area for large number of successive years constitute a hydrologic data series called the *annual series*. The data are then arranged in decreasing order of magnitude and the probability P of each event being equalled to or exceeded (plotting position) is calculated by the plotting-position formula

$$P = \frac{m}{N+1} \tag{7.11}$$

where m = order number of the event and N = total number of events in the data. The recurrence interval, T (also called the *return period* or *frequency*) is calculated as

$$T = 1/P \tag{7.12}$$

The relationship between T and the probability of occurrence of various events is the same as described in Sec. 2.11. Thus, for example, the probability of occurrence of the event r times in n successive years is given by

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

where $\quad q = 1 - P$

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Formulae

a. Probability of an event (P) with return period T is given by (Probability of occurrence in any year)

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

b. Probability of not occurrence of event = 1- P = $1 - \frac{1}{T}$

c. Probability of not occurrence in n years (P_n) = $(1 - P)^n$ = $\left(1 - \frac{1}{T}\right)^n$ → Reliability

d. Probability of occurrence of event at least once in n year = $1 - P_n$ = $1 - \left(1 - \frac{1}{T}\right)^n$ — Risk

Reliability is the probability of not occurring of flood in n years

Risk is occurance of flood atleast one time.

RT 100 years

DP = 25 years.

Risk: $1 - \left(1 - \frac{1}{T}\right)^n$

$= 1 - \left(1 - \frac{1}{100}\right)^{25}$

The probability of occurrence of an event ($x \geq x_T$) at least once over a period of n successive years is called the risk, $\overline{R}$. Thus the risk is given by

$\overline{R}$ = 1 – (probability of non-occurrence of the event $x \geq x_T$ in n years)

$$\overline{R} = 1 - (1 - P)^n$$

$$= 1 - \left(1 - \frac{1}{T}\right)^n \quad (7.29)$$

where P = probability $P(x \geq x_T) = \frac{1}{T}$

T = return period

The reliability R_e, is defined as

$$R_e = 1 - \overline{R} = \left(1 - \frac{1}{T}\right)^n \quad (7.30)$$

EXAMPLE 7.11 *A bridge has an expected life of 25 years and is designed for a flood magnitude of return period 100 years. (a) What is the risk of this hydrologic design? (b) If a 10% risk is acceptable, what return period will have to be adopted?*

↓ Risk RP ↑

↑ Reliability RP ↑

SOLUTION:

(a) The risk $\bar{R} = 1 - \left(1 - \frac{1}{T}\right)^n$

Here $n = 25$ years and $T = 100$ years

$$\bar{R} = 1 - \left(1 - \frac{1}{100}\right)^{25} = 0.222$$

Hence the inbuilt risk in this design is 22.2%

(b) If $\bar{R} = 10\% = 0.10$ $\qquad 0.10 = 1 - \left(1 - \frac{1}{T}\right)^{25}$

$$\left(1 - \frac{1}{T}\right)^{25} = 0.90 \quad \text{and} \quad T = 238 \text{ years} = \text{say } 240 \text{ years.}$$

Hence to get 10% acceptable risk, the bridge will have to be designed for a flood of return period $T = 240$ years.

Estimating Flood Peak – Various Methods

1. **For Ungauged Basin**
   A. Rational Method (for area<50 km^2)
   B. Empirical Methods
      – Dicken's Method (1865)
      – R. D. Richard's Method
      – Fuller's Method
      – Horton's Method
      – WECS/ DHM Method (or HYDEST Method)
2. **For Gauged Basin**
   A. Statistical Methods (or Flood Frequency Analysis)
      – Gumbel's Extreme Value Type I Method;
      – Log Pearson Type Methods – Type II, Type III
      – Log – Normal Distribution Based Method
   B. Unit Hydrograph Method (for area<5000 km^2)

Selection of Suitable Methods depends on:

1. **Desired Objectives.**
2. **Availability of data.**
3. **Importance of the objectives.**

Methods used in estimating design flood

1. Increasing the observed maximum flood by a certain percentage.
2. For Ungauged Basin
   - Rational method
   - Empirical method
3. For Gauged Basin
   - Unit hydrograph technique
   - Flood frequency analysis

Rational Method

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- Rational means logically justified.
- This method is used for computing peak discharge in small basin.

$$Q_p = CiA$$

Where Q_p = peak discharge

C = runoff coefficient

A = basin area in

i = mean intensity of rainfall for a duration equal to time of concentration (t_c) and an exceedence probability P

C: runoff coefficient. It is ratio of runoff to rainfall, represents total cumulative effect of watershed loss. It depends on initial losses, depression storage, nature of soil, surface slope, degree of saturation, rainfall intensity, geology of the basin, geohydrological characteristics of the basin.

C varies from 0 to 1.

With SI unit (Computing Q in m^3/s, given i in mm/hr and A in km^2)

Q_p =Ci A = $Cx\frac{i}{1000x3600}xAx10^6 = \frac{CiA}{3.6}$ =0.278 Ci A

If A is in hectors (ha), i is in mm/hr, then Q in m^3/s is

Q_p =CI A = $Cx\frac{i}{1000x3600}xAx10^4 = \frac{CiA}{360}$

i - mm/hr

A - ha

$\frac{CiA}{360}$ m^3/s

Assumptions

- Rainfall intensity is constant throughout the storm duration.
- Time of rainfall> Time of concentration

To get Q_p, we need t_c, i and C.

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C is the runoff coefficient

Table7. 1: Runoff coefficients for rational formula

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

For non-homogeneous basin, divide into sub-basins, get C for each sub-basin and compute weighted average C. ($C = \frac{\sum C_i A_i}{A}$)

$$C = \frac{\sum C_1 A_1 + C_2 A_2 + C_3 A_3 + \cdots.}{A_1 + A_2 + A_3 + \cdots.}$$

C =

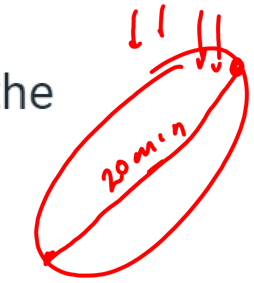
In the absence of data on rainfall intensity, *i* shall be estimated by

$$i = \frac{KT^a}{(t_c + b)^n}$$

T = return period = 1/P, where P = probability of exceedence
t_c = time of concentration
K, a, b, n: constants

Time of Concentration is the time required by the entire drainage area to contribute to the runoff is called the time of concentration or time required by the most extreme point in the drainage to reach the point of interest.

In Other Words, it is the maximum time taken by the rainwater to reach the outlet of the basin.



- Time of concentration = overland flow time + channel flow time
- Overland flow is also called sheet flow. It is the phase of runoff when water flows as a sheet on plain land.
- Channel flow time is the time during which runoff flows in open channel up to the gauging site.
- Time of concentration depends upon the slope, the catchment characteristics and the flow path.
- For a hydrograph analysis, time of concentration is defined as the time duration from the end of excess rainfall to the point of inflection.

Kirpich equation is an **empirical equation** used to determine the **time of concentration** in runoff hydrograph and it is given as:

$$t = 0.0194L^{0.77}S^{-0.385}$$

Where,

t = time of concentration in minutes

L = the maximum length of water travel in m.

S = the slope of the catchment and it is given as

$$S = \frac{\Delta H}{L}$$

ΔH is the difference in elevation between most remote points on the catchment outlet.

Analytically, these relationships are commonly expressed in a condensed form by general form

$$i = \frac{KT^x}{(D+a)^n} \tag{2.15}$$

where i = maximum intensity (cm/h), T = return period (years), D = duration (hours) K, x, a and n are coefficients for the area represented by the station.

British ministry of health formula

$$i = \frac{760}{t_c + 10} \quad \text{for duration of } 5 \text{ to } 20 \text{ minutes}$$

$$i = \frac{1020}{t_c + 10} \quad \text{for duration of } 20 \text{ to } 100 \text{ minutes}$$

$$t_c \text{ is in minutes}, i \text{ is in mm/hr}$$

Applications of rational method: for design of storm sewers, channels, and other drainage structures

Limitations of rational method

- Applicable to small basins (up to 50 km2)
- Duration of rainfall intensity>t_c
- Gives only peak, does not give complete hydrograph
- C assumed to be same for all storms
- Rainfall intensity must be constant over the entire basin during t_c.

$t_c = 20 min$

$D = 10 min$

$D = 20 min$

1.1.2 Empirical Methods

All regional formulae are based on statistical correlation of the observed peak and important catchment properties.

Q_P =f (A) where Q_p = peak discharge and A = area

Empirical formulae shall be used only when a more accurate method for flood prediction cannot be applied because of lack of data. For flood prediction in ungauged basins of Nepal, the empirical formulae discussed in the following sections may be used with great caution and proper justification.

Modified Dicken's Method

Using Dicken's method, the T year flood discharge Q_T, in m^3/sec, shall be determined as

$$Q_T = C_T A^{0.75}$$

where A is the total basin area in sq. km and C_T is the modified Dicken's constant proposed by the Irrigation Research Institute, Roorkee, India, based on frequency studies on Himalayan rivers. This constant shall be computed as

$$C_T = 2.342 \log(0.6T) \log\left(\frac{1185}{p}\right) + 4$$

$$p = 100 \frac{a+6}{A+a}$$

where a is perpetual snow area in sq. km. and T is the return period in years.

Fuller's Method

Although developed for basins in the United States of America, Fuller's formula may be used to estimate flood discharges in the ungauged basins of Nepal for comparison purposes. Using this method, the maximum instantaneous flood discharge Q_{max} in m^3/s shall be estimated as

$$Q_{\max} = Q_T\left[1 + 2\left(\frac{A}{2.59}\right)^{-0.3}\right]$$

where Q_T is the maximum 24 hour flood with frequency once in T years in m^3/s and A is the basin area in sq. km. Q_T shall be given by

$$Q_T = Q_{av}\left(1 + 0.8\log T\right)$$

in which Q_{av} is the yearly average 24 hour flood over a number of years, in m^3/s, given by

$$Q_{av} = C_f A^{0.8}$$

where C_f is Fuller's coefficient varying between 0.18 to 1.88. For Nepal, C_f may be taken as the average of these values, i.e. equal to 1.03.

Horton’s Formula

Horton’s formula may be used to compute the flood *qtr*, in m^3/s/sq. km, equaled or exceeded in a *T* year return period using the relation

$$q_{tr} = 71.2 \frac{T^{0.25}}{A^{0.5}}$$

where A is the drainage area in sq. km.

WECS Formula

In Nepalese context, Water and Energy Commission Secretariat (WECS) developed empirical relationships for analyzing flood of different frequencies.

The formula for 2 year return period is

$Q_2 = 1.8767(A_{3000} + 1)^{0.8783}$

The formula for 100 year return period is

$Q_{100} = 14.63(A_{3000} + 1)^{0.7342}$

where A_{3000} = Basin area (Km^2) below 3000m elevation

For other return period,

$$Q_T = exp(lnQ_2 + S\sigma)$$

where Q_T = Flood of T year return period (m^3/s), S = standard normal variate, σ = parameter

$$\sigma = \ln(Q_{100}/Q_2)/2.326$$

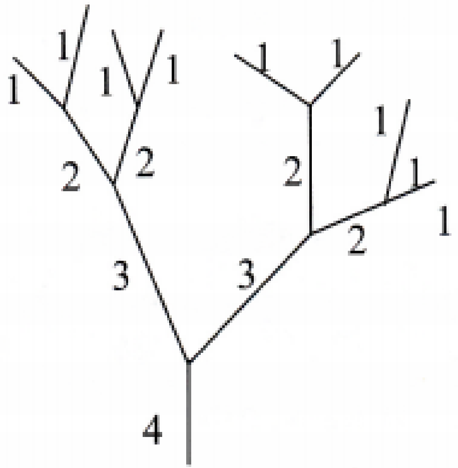
Value of T and S

T (years)	S
2	0
5	0.842
10	1.282
25	1.645
50	2.054
100	2.326
500	2.878
1000	3.09
10000	3.719

i. **Order of stream**

Measures of amount of branching within a basin

a. 1st order - non branching tributary
b. 2nd order - receives flow from 1st order stream.
c. 3rd order - receives flow from 2nd order



ii. **Drainage density (D.D.):-**

D.D. is expressed as length of the stream per unit area

D.D = L/A

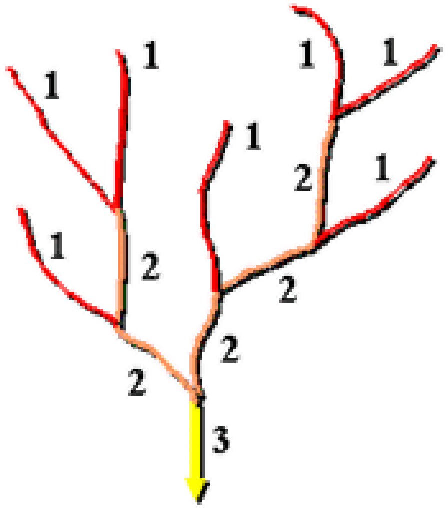
High DD - Fast hydrology response

Low DD - Low hydrology response

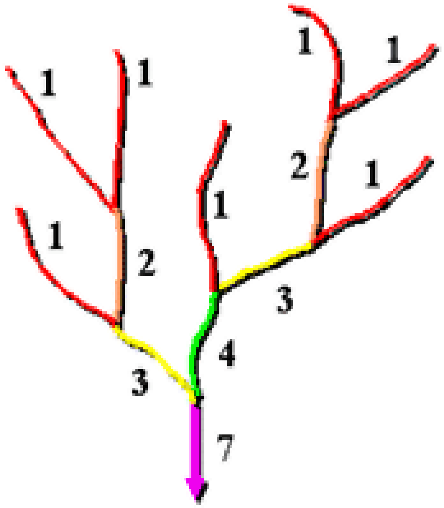
Usually velocity is 10 times higher in channel than in overland flow resulting in high peak corresponding to high DD.

v_p = 0.0417 m/s

v_c = 0.3 m/s



Strahler stream ordering method



Shreve stream ordering method

v. Shape of the basin

Shape of the basin governs the rate at which water enters the stream. The shape of basin is expressed by form factor.

$$\text{Form factor} = \frac{\text{Average width of the basin (B)}}{\text{Axial length of the basin (L)}}$$

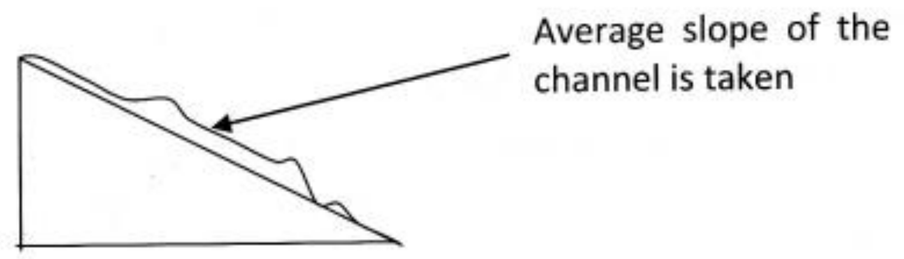
Average width of the basin = A/L

Form factor = A/L^2

If catchment area is long and narrow, L increases leading to decrease of form factor, time base increases, peak discharge decreases

If catchment area is short and broad, L decreases leading to increase of form factor, time base decreases, peak discharge increases

vi. **Slope of the Channel**



If catchment area has steep slope, time base decreases, peak discharge increases

If catchment area has steep slope, time base increases, peak discharge discharge

2.8. Form factor (Rf)

Form factor is a ratio of watershed area to the square of the length of the watershed. Flood hydrograph always affects the basin form [4]. There are some different value ranges of form factor. The range values for form factor are <0.78 (elongated) and >0.78 (circular) [1,6]. There are also other range values for Rf classification, i.e., elongated (0 or low value) and circular (1) [4]. An elongated watershed means it has low peak flows for longer duration while a circular watershed means it has high peak flows for a shorter duration.

2.9. The length of overland flow (Lg or AOLF)

Length of overland flow is a length of water over the ground before it gets concentrated into certain stream channels. Lg = 1/(Dd X 2), where Dd (drainage density) is in km/km^2. Length of overland flow is mentioned with other term, i.e., average over land flow (AOLF) [4]. Dd as an input in calculating Lg must be in km/km^2. There are three classes of Lg i.e., low value (< 0.2), moderate value (0.2 – 0.3), and high value (>0.3) [2]. Low value of Lg indicates high relief [6], short flow paths, more runoff, and less infiltration [2] which leads to more vulnerable to the flash flooding [1]. Meanwhile, a high value of Lg means gentle slopes and long flow paths [1], more infiltration, and reduced runoff [2].

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Types of stream

- Perenniai: This type of stream always carries flow.
- Intermittent: limited contribution from groundwater
- Ephemeral: no base flow

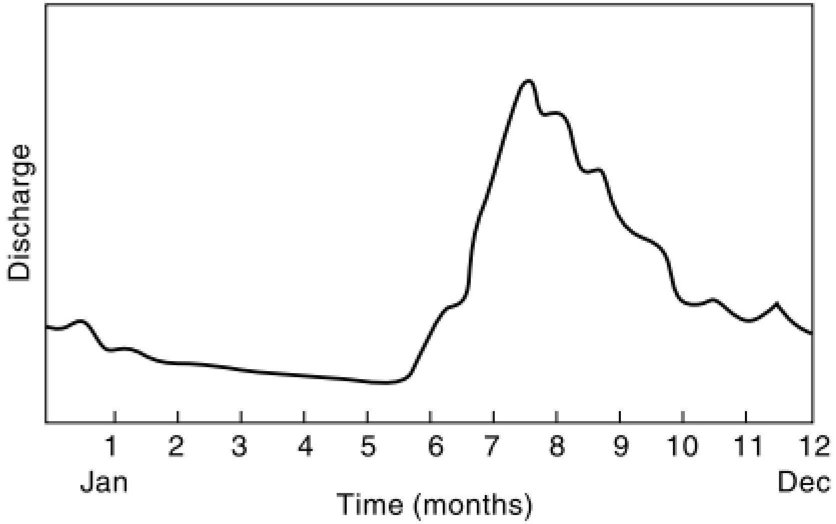

Fig. 5.2 Perennial stream

A perennial stream is one which always carries some flow (Fig. 5.2). There is considerable amount of groundwater flow throughout the year. Even during the dry seasons the water table will be above the bed of the stream.

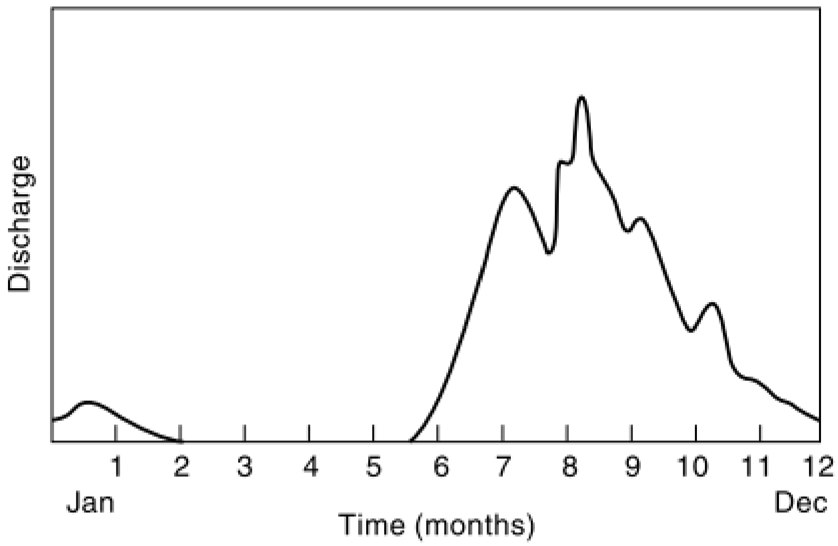

Fig. 5.3 Intermittent stream

An intermittent stream has limited contribution from the groundwater. During the wet season the water table is above the stream bed and there is a contribution of the base flow to the stream flow. However, during dry seasons the water table drops to a level lower than that of the stream bed and the stream dries up. Excepting for an occasional storm which can produce a short-duration flow, the stream remains dry for the most part of the dry months (Fig. 5.3).

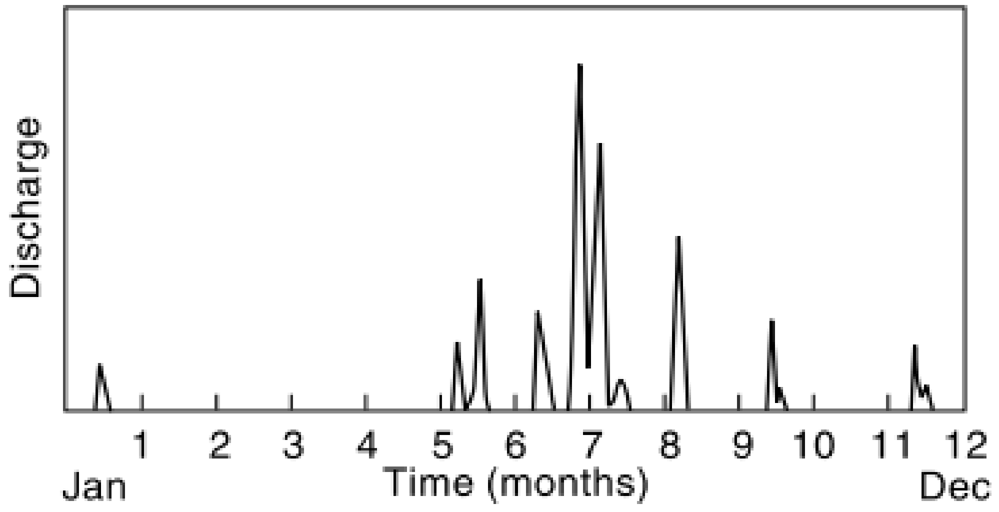

Fig. 5.4 Ephemeral stream

An ephemeral stream is one which does not have any base-flow contribution. The annual hydrograph of such a river shows series of short-duration spikes marking flash flows in response to storms (Fig. 5.4). The stream becomes dry soon after the end of the storm flow.

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Effluent and influent stream

If water table is higher than the water level of the stream, it contributes to the runoff and the stream is called an effluent stream. On the other hand, when water table is lower, water flows from the stream to the ground water reservoir, and the stream is called influent stream.

Groundwater Hydrology

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- About 30% of freshwater is available in the form of groundwater.

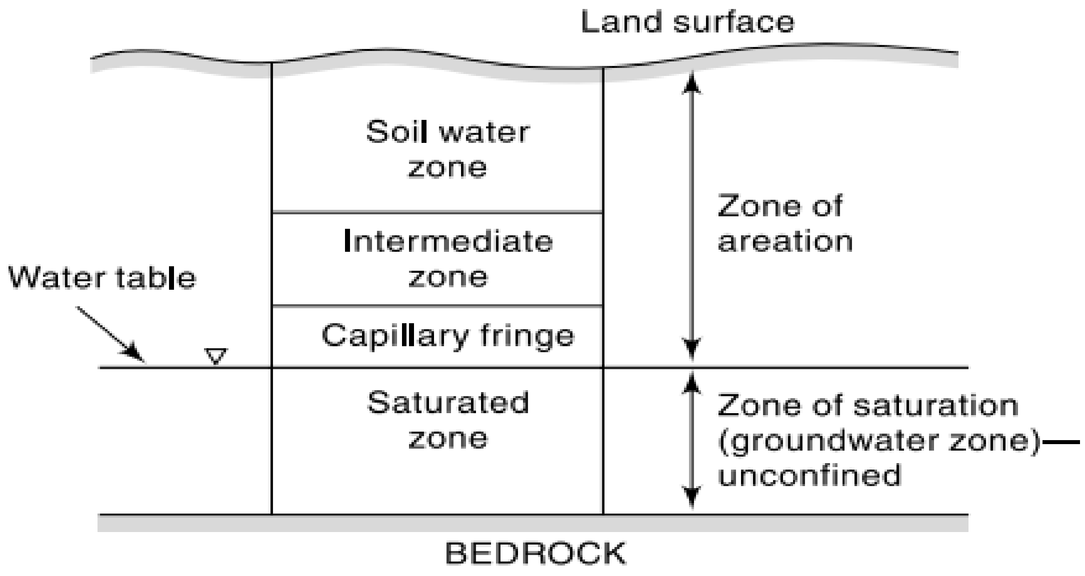

Fig. 9.1 Classification of Subsurface Water

Groundwater Hydrology

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- Saturated Zone
  - All the pores are filled with water.
  - Degree of saturation (S) = 1
  - The water table forms its upper limit and marks a free surface, i.e. a surface having atmospheric pressure
- Zone of aeration
  - The soil pores are partially saturated with water.
  - The space between the land surface and the water table marks the extent of this zone.
  - It has three sub-zones

Groundwater Hydrology

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- Soil water zone
  - Major root band of the vegetation.
  - Here water is lost to the atmosphere by evapotranspiration
- Capillary Fringe
  - Water is held by capillary action
  - Extends from water table to the limit of capillary rise.
- Intermediate zone
  - Lies between capillary fringe and soil water zone.

Notes: The soil moisture in zone of aeration is important for irrigation engineer. Here, in hydrology, we will be concerned about saturated zone

Aquifer Property

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- Porosity (n)
  - Water holding capacity of the soil.
  - Amount of pore space per unit volume of aquifer.
  - n = volume of void * 100 / Total volume of porous medium.
  - Porosity of fine grained (clay and silt) soil is greater than the porosity of coarse grained soil (sand and gravel).
- Coefficient of Permeability or hydraulic conductivity (K)
  - It is the ease with which water is allowed to flow through the soil medium.
  - K of coarse grained soil is greater than the fine grained soil.

  Notes:

  For groundwater extraction, we need a medium which is both porous as well as permeable (e.g., fine sand and coarse silt).

  For e.g., clay is highly porous but impermeable. Gravel is highly permeable but less porous.

Groundwater Hydrology

- Specific Yield (S_y) and Specific retention (S_r)
  - Not all the water held in the pores is available for extraction by pumping or draining by gravity.
  - Some of the water is held by molecular attraction and surface tension.
  - The actual volume of water that can be extracted by the force of gravity from a unit volum of aquifer is called specific yield.
  - The fraction of water held back in the aquifer is known as specific retention (S_r).

$$n = S_y + S_r$$

Groundwater Hydrology

- Specific Yield (S_y) and Specific retention (S_r)

$$n = S_y + S_r$$

Table 9.1 Porosity and Specific Yield of Selected Formations

Formation	Porosity, %	Specific yield, %
Clay	45–55	1–10
Sand	35–40	10–30
Gravel	30–40	15–30
Sand stone	10–20	5–15
Shale	1–10	0.5–5
Lime stone	1–10	0.5–5

Different types of geological formation

- **Aquifer**
  - This geological formation is highly porous and highly permeable, hence they give sufficient yields.
  - For e.g., fine sand and coarse silt.
- **Aquiclude**
  - This geological formation is highly porous (more porosity than aquifer) but they are impermeable, hence no sufficient yield.
  - For e.g., clay

Different types of geological formation

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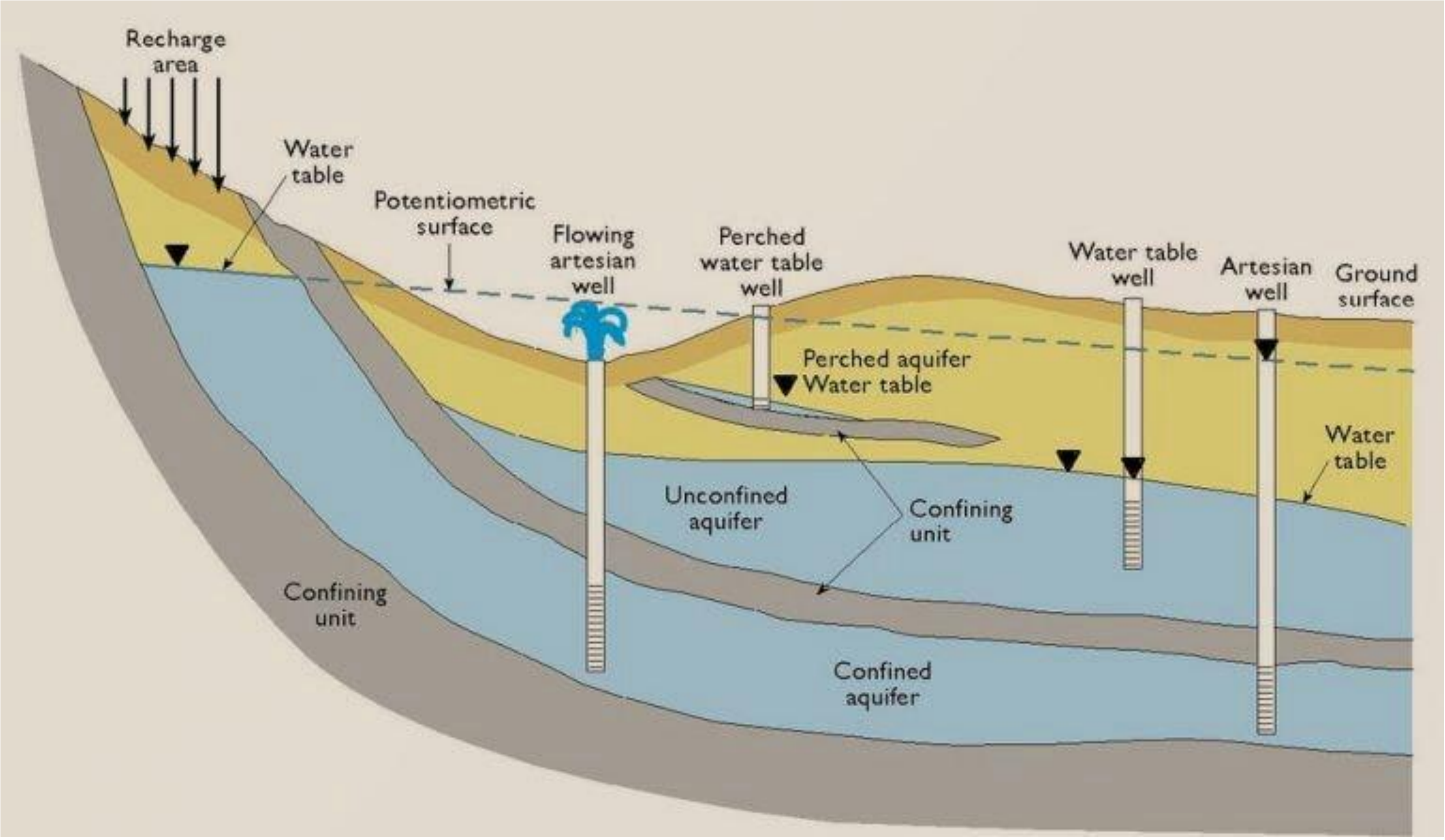
- **Aquitard**
  - Those geological formations which are porous (less than aquiclude) and less permeable (greater than aquiclude).
  - For e.g., Sandy clay
- **Aquifuge**
  - Those geological formation which are neither permeable nor porous.
  - For e.g., rock

Types of Aquifer

- Unconfined/ Non-artesian/ Water table aquifer
- Confined Aquifer
- Perched Aquifer



Types of Aquifer

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- Confined aquifer
  - It is a type of an aquifer in which aquicludes lie above and below it.
  - The groundwater moves under the pressure.
  - The water pressure depends on the difference in height between it and the recharge area.
  - A region supplying water to the confined aquifer is called recharge area.
- Unconfined aquifer
  - It is also called water table aquifer.
  - The upper surface of water table is under atmospheric pressure.
  - When tapped through a test well, the free water will rise to a level in the well equivalent to the water table of the area.

Types of Aquifer

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- Perched aquifer
  - It is the term used for isolated water table in the aquifer held by a small extension of impervious rocks within a large pervious tract.
  - In such case, the main water table is located much below.
  - Supplies from such isolated aquifer with perched water table are often unreliable.