5th Semester B.TECH.

[CIVIL ENGINEERING]

WATER RESOURCES ENGINEERING

The Need…

अजीर्णे भेषजं वारि, जीर्णे वारि बलप्रदम् ।
भोजने चामृतं वारि, भोजनान्ते विषप्रदम् ॥

water is curative in indigestion, water is nourishing after digestion;
water is appetizing during food, and ill-affects immediately after food.

ajIrNe bheShajam vAri, jIrNe vAri balapradam |
bhojane chAmRitam vAri, bhojanAnte viShapradam ||

Water - the least appreciated thing, right before air. We just take it for granted. There was a time, not too long ago, when you could drink water from pretty much any tap in india, or a well, river. There would be water sheds called 'pyaaoo' on road sides, sponsored by local businessman or charitable person, manned by local hands. You would get some of sweetest natural water, along with some jaggery and roasted grams (at least in hot and dry Rajasthan), easing your travel-related travails. Thanks to recent decades of industrial progress, even in india it is difficult to find drinkable water from free natural resources. And the rivers, the life line of any civilization, are terribly polluted as well like the Brahmani, GangA (गङ्गा) and YamunA (यमुना).

WATER WATER WATER …WATER EVERY WHERE…NOT A DROP OF WATER TO DRINK!!!

… BEFORE THIS HAPPENS, LET US GET UP AND GIVE DUE PRESTIGE TO WATER. HENCE IS THE COURSE IMPORTANT FOR THE ENGINEERS, WHO ARE RESPONSIBLE FOR THE WELBEING OF THE SOCIETY.

MODULE 1:

Instructional Objectives

After completion of this Module, the student shall know about

1. Hydrologic cycle and its components
2. Distribution of earth's water resources
3. Distribution of fresh water on earth
4. Rainfall distribution in India
5. Land and water resources of India; water development potential
6. Need for development of water resources
7. Forms and Types of precipitation
8. Methods of Measurement of Precipitation
9. Presentation and interpretation of rainfall data
10. Abstractions from Precipitation

INTRODUCTION

Water on the surface of earth is available in the atmosphere, the oceans, on land and within the soil and fractured rock of the earth's crust. Water molecules from one location to another are driven due to the solar energy transmitted to the surface of the earth from Sun. Moisture circulates from the earth into the atmosphere through evaporation and then back into the earth as precipitation.

Hydrology:

It is the study of physical geographic which deals with the origin, distribution and properties of water present in earth surface.

Hydrological Cycle:-

Precipitation

↑

Condensation

↑

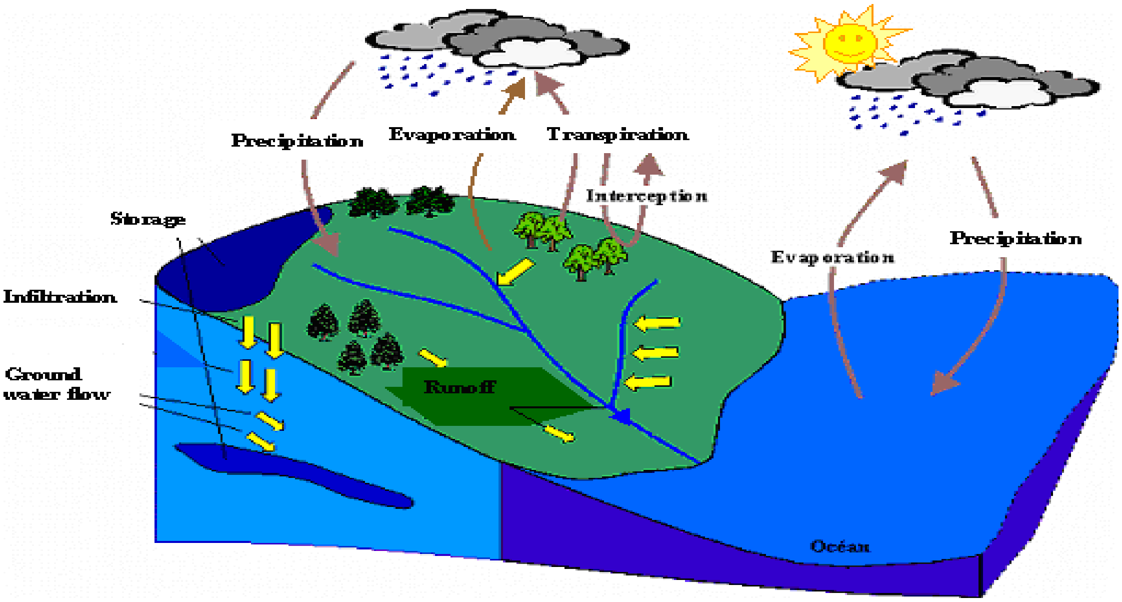
Formation of Clouds

↑

Evaporation

↑

Ocean



Water Budget Equation:-

Mass inflow – Mass outflow = Change in storage

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

Where,

P = Precipitation

T = Transpiration

G = Ground water Resources

R = Runoff

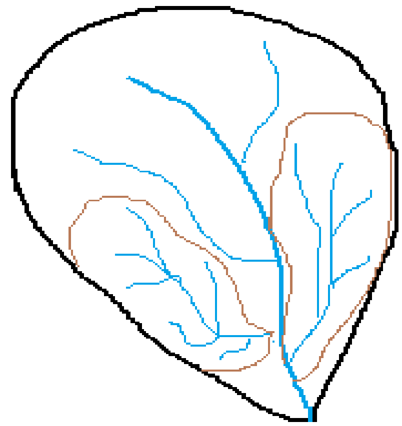
E = Evaporation

ΔS = Chang in Storage

Catchment Area:-

River

Streams



World Water Balance:-

Total quantity of water in the world is estimated to be about 1386 million cubic kilometer (M Km^3). About 96.5% of this water is contained in the oceans as saline water. Some of the water on the land amounting to about 1% of the total water is also saline. Thus, only about 35.0 M Km^3 of fresh water is available. Out of this about 10.6 M Km^3 is both liquid and fresh and the remaining 24.4 M Km^3 is contained in frozen state as ice in the polar regions and on mountain tops and glaciers.

PRECIPITATION

INTRODUCTION:

The term "precipitation" denotes all forms of water that reach the earth from the atmosphere. The usual forms are rainfall, snowfall, hail, frost and dew.

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

FORMS OF PRECIPITATION:

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

1. ***Rain***

It is the principal form of precipitation in India. The term rainfall is used to describe precipitation in the form of water drops of sizes larger than 0.5mm. The maximum size of a raindrop is 6mm. 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 is classified as follows:

Light rain: trace to 2.5 mm/hr
Moderate rain: 2.5mm/hr to 7.5mm/hr
Heavy rain: > 7.5mm/hr

2. ***Snow***

Snow is another important form of precipitation. Snow consists of ice crystals which usually combine to form flakes. When fresh, snow has an initial density varying from 0.06 to 0.15g/cm^3 and it is usual to assume an average density of 0.1 ^{g}/cm^3. In India, snow occurs only in the Himalayan regions.

3. ***Drizzle***

A fine sprinkle of numerous water droplets of size less than 0.5mm and intensity less than 1mm/hr is known as drizzle. In this, the drops are so small that they appear to float in the air.

4. ***Glaze***

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

5. ***Sleet***

It is frozen raindrops of transparent grains which form when rain falls through air at sub freezing temperature. In Britain, sleet denotes precipitation of snow and rain simultaneously.

6. ***Hail***

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

WEATHER SYSTEMS FOR PRECIPITATION:

For the formation of clouds and subsequent precipitation, it is necessary that the moist air masses cool to form condensation. This is normally accomplished by adiabatic cooling of moist air through a process of being lifted to higher altitude. Some of the terms and processes connected with weather systems associated with precipitation are given below.

1. ***Front***

A front is the interface between two distinct air masses. Under certain favorable conditions when a warm air mass and cold air mass meet, the warmer air mass is lifted over the colder one with the formation of front. The ascending warmer air cools adiabatically with the consequent formation of clouds and precipitation.

2. ***cyclone***

A cyclone is a large low pressure region with circular wind motion. Two types of cyclones are recognized: tropical cyclones and extra tropical cyclones.

(a) *Tropical cyclone:*

A tropical cyclone, also called cyclone in India, hurricane in USA and typhoon in south East Asia, is a wind system with an intensely strong depression with MSL pressures sometimes below 915 m bars. The normal areal extend of cyclone is about 100-200 km in diameter. The isobars are closely spaced and the winds are anticlockwise in the northern hemisphere. The center of the storm called the eye, which may extend to about 10-50 km in diameter, will be relatively quiet. However, right outside the eye, very strong winds/reaching to as much as 200 km per hr exist. The wind speed gradually decreases towards the outer edge. The pressure also increases outwards. The rainfall will normally be heavy in the entire area occupied by the cyclone.

(b)Extra tropical cyclone:

These are cyclones formed in locations outside the tropical zone. Associated with a frontal system, they possess a strong counter clockwise wind circulation in the northern hemisphere. The magnitude of precipitation and wind velocities are relatively lower than those of a tropical cyclone. However, the duration of precipitation is usually longer and the areal extend is also larger.

(3)Anticyclones:

These are regions of high pressure, usually of large areal extent. The weather is usually calm act the center. Anticyclones cause clockwise wind circulations in the northern hemisphere. Winds are of moderate speed, and at the outer, cloudy and precipitation conditions exist.

(4) Convective precipitation:

In this type of precipitation, a packet of air which is warmer than the surrounding air due to localized heating rises because of its lesser density. Air from cooler surroundings flows to take up its place, thus setting up a convective cell. The warm air continues to rise, undergoes cooling and results in precipitation. Depending upon the moisture, thermal and other conditions, light showers to thunderstorms can be expected in convective precipitation. Usually, the aerial extent of such rains is small, being limited to a diameter of about 10km.

(5) Orographic precipitation:

The moist air masses 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 of heavy precipitation and the leeward slopes have light rainfall.

ANNUAL RAINFALL:

Considerable areal variation exists for the annual rainfall of the magnitude of 200cm in Assam and north-eastern parts and Western-Ghats, and scanty rainfall in eastern Rajasthan and parts of Gujarat, Maharashtra and Karnataka. The average annual rainfall for the entire country is estimated as 118.3cm.

It is well known that there is considerable variation of annual rainfall in time at a place. The coefficient of variation,

C_v= (100* standard deviation)/ Mean

Of the annual rainfall varies between 15 and 70, from place to place with an average value of about 30. Variability is least in regions of high rainfall and largest in regions of scanty rainfall. Gujarat, Haryana, Punjab and Rajasthan have large variability of rainfall.

Some of the interesting statistics relating to the variability of the seasonal and annual rainfall of India are as follows:

- A few heavy spells of rain contribute nearly 90% of total rainfall.
- While the average annual rainfall of the country is 118 cm, average annual rainfall varies from 10 cm in the western desert to 1100 cm in the north-east region.
- More than 50% rain occurs within 15 days and less than 100 hours in a year.
- More than 805 of seasonal rainfall is produced in 10-20% rain events, each lasting 1-3 days.

MEASUREMENT OF PRECIPITATION

1) Rainfall

Precipitation is expressed in terms of the depth to which rainfall water would stand on an area if all the rain were collected on it. Thus, 1cm of rainfall over a catchment area of $1km^2$ represents a volume of water equal to $10^4 m^3$. In the case of snowfall, an equivalent depth of water is used as the depth of precipitation. The precipitation is collected and measured in a *rain gauge.* Terms such pluviometer ombrometer and hyetometer area also sometimes used to designate a rain gauge.

A rain gauge essentially consists of a cylindrical vessel assembly kept in the open to collect rain. The rainfall catch of the rain gauge is affected by its exposure conditions. To enable the catch of rain gauge to accurately represent the area in the surrounding the rain gauge standard settings are adopted. For setting up a rain gauge 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 fenced area of at least 5.5 m * 5.5 m. No object should be nearer to the instrument than 30 m or twice the height of the obstruction.

Rain gauges can be broadly classified into two categories as

(i) Non recording gauges (ii) Recording gauges.

A. Non-recording Gauges

The non recording gauge extensively used in India is the *Symon's gauge.* It essentially consists of a circular collection area of 12.7 cm (5.0 inch) diameter connected to a funnel. The rim of the collector is set in a horizontal plane at a height of 30.5 cm above the ground level. The funnel discharges the rainfall catch into a receiving vessel. The funnel and receiving vessel are housed in a metallic container. Fig below shows the details of the installation. Water contained in the receiving vessel is measured by a suitably graduated measuring glass, with accuracy up to 0.1mm.

Recently, the Indian Meteorological Department (IMD) has changed over to the use of fiber glass reinforced polyester rain-gauges, which is an improvement over the *Symon's gauge.* These come in different combinations of collector is in two sizes having areas of 200 and 100 cm^2 respectively. Indian standard (IS: 5225-1969) gives details of these new rain-gauges.

For uniformity, the rainfall is measured everyday at 8.30a.m.(*IST)* and is recorded as the rainfall of that day. The receiving bottle normally does not hold more than 10cm of rain and as such, in the case of heavy rainfall, the measurements must be done more frequently and entered. However, the last reading must be taken at 8.30 a.m. and the sum of the previous readings in the past 24 hours entered as the total of that day. Proper care, maintenance and inspection of rain-gauges, especially during dry weather to keep the instrument free from dust and dirt, is very necessary. The details of installation of non-recording rain-gauges and measurement of rain are specified in Indian Standard (IS:4986-1968).

This rain-gauge can also be used to measure snowfall. When snow is expected, the funnel and receiving bottle are removed and the snow is allowed to collect in the outer metal container. The snow is then melted and the depth of resulting water measured. Antifreeze agents are sometimes used to facilitate melting of snow. In areas where considerable snowfall is expected, special snow-gauges with shields (for minimizing the wind effect) and storage pipes (to collect snow over longer durations) are used.

B. **Recording Gauges**

Recording gauges produce a continuous plot of rainfall against time and provide valuable data of intensity and duration of rainfall for hydrological analysis of storms. The following are some of the commonly used recording rain-gauges.

(a)Tipping-Bucket Type

This is a 30.5 cm size rain-gauge adopted for use by the US Weather Bureau. The catch from the funnel falls onto one of a pair of small buckets. These buckets are so balanced that when 0.25 mm of rainfall collects in one bucket, it tips and brings the other one in position. The water from the tipped bucket is collected in a storage can. The tipping actuates an electrically driven pen to trace a record on the clockwork-driven chart. The water collected in the storage can is measured at regular intervals to provide the total rainfall and also serve as a check. It may be noted that the record from the tipping bucket gives data on the intensity of rainfall. Further, the instrument is ideally suited for digitalizing of the output signal.

(b)Weighing-Bucket Type

In this rain-gauge, the catch from the funnel empties into a bucket mounted on a weighing scale. The weight of the bucket and its contents are recorded on a clockwork-driven chart. The clockwork mechanism has the capacity to run for as long as one week. This instrument gives a plot of the accumulated rainfall against the elapsed time, i.e. the mass curve of rainfall. In some instruments of this type, the recording unit is so constructed that the pen reverses its direction at every preset value, say 7.5 cm (3inch)so that a continuous plot of storm is obtained.

(c) Natural-Syphon Type

This type of recording rain-gauge is also known as float-type gauge. Here, the rainfall collected by a funnel-shaped collector is led into a float chamber causing a float to rise. As the float rises, a pen attached to the float through a lever system records the elevation of the float on a rotating drum driven by a clockwork mechanism. A siphon arrangement empties the float chamber when the float has reached a preset maximum level. This type of rain-gauge is adopted as the standard recording-type rain-gauge in India and in details is described in Indian Standard (IS: 5235-1969).

RAINGAUGE NETWORK:

- **NETWORK DENSITY**

Since the catching area of a rain-gauges very small compared to the areal extent of a storm, it is obvious that to get a representative picture of a storm over a catchment, the number of rain-gauges should be as large as possible, i.e. the catchment area per gauge should be small. Economic considerations restrict the number of gauges to be maintained.

- **ADEQUACY OF RAINGAUGE STATIONS**

Optimum number of stations that should exist to have an assigned percentage of error in the estimation of mean rainfall is obtained by:

$$N=(C_v/\varepsilon)^2$$

N= optimal number of stations

ε = allowable degree of error in the estimate of the mean rainfall

C_v= coefficient of variation

If there are m stations in the catchment each recording rainfall values P_1, P_2, P_3, $P_i \ldots P_m$ in a known time, the coefficient of variation C_v is calculated as:

$C_v=(100\times\sigma_{m-1}/\bar{P})$

$\sigma_{m-1}=[\sum(P_i-\bar{P})^2/m-1]^{1/2}$

σ_{m-1}= standard deviation

P_i=precipitation magnitude in the i^{th} station

$\bar{P}=(\sum P_i)/m$=mean precipitation

- **PREPARATION OF DATA**

Before using any rainfall data in application, it's very necessary to check the data for consistency and continuity.

The continuity of record may be broken with missing data due to many reasons such as damage or fault in the rain gauge during a period.

Procedure of missing data estimation:

1. **Statement of the missing data problem:**
   Given the annual precipitation values P_1,P_2,P_3,…P_m at neighboring M stations 1,2,3,..,M resp, it is required to find the missing annual precipitation P at a station X not included in the above M station.

Further, the normal precipitations $N_1, N_2, N_3, \ldots N_i, \ldots$ at each of the above (M+1) stations, including station X, are known.

2. **Procedure:**

    i. If the normal precipitations at various stations are within about 10% of the normal annual precipitation at station X then P_x is calculated as:

    $$P_x=[P_1, P_2, P_3, \ldots P_m]/M$$

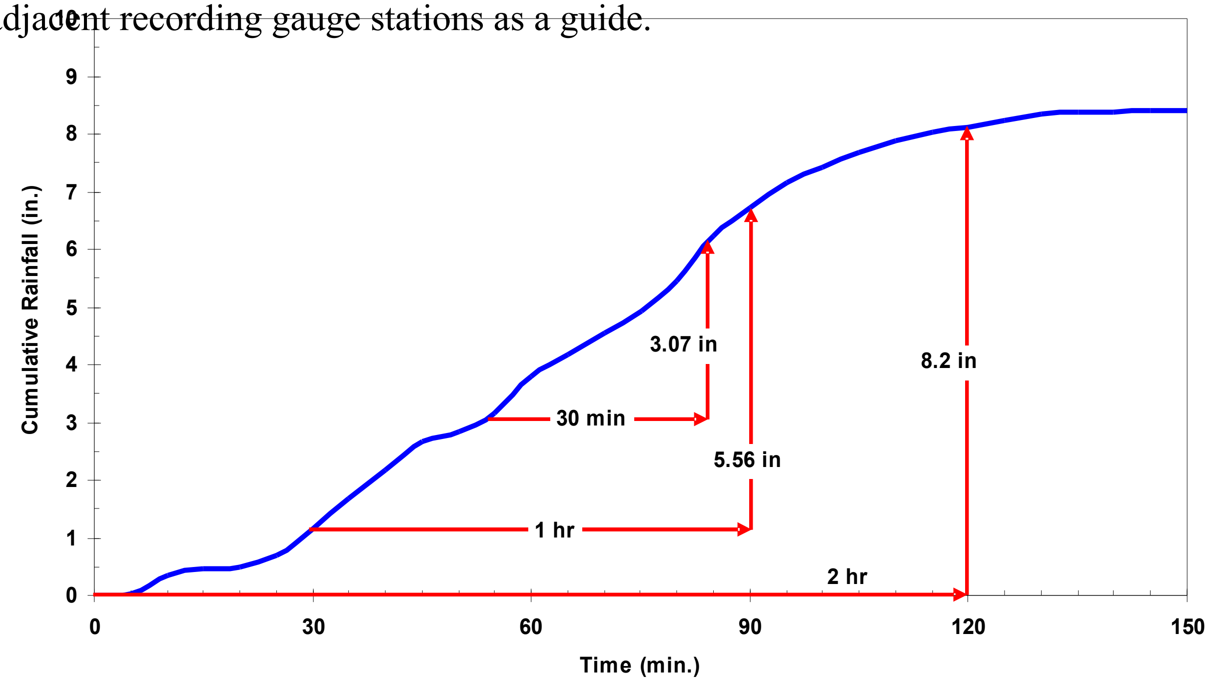
    ii. If the normal precipitation varies considerably then P_x is estimated by weighing the precipitation at various stations by the ratios of normal annual precipitations. This method is known as the "normal ratio method":

    $$P_x=N_x[P_1/N_1, P_2/N_2, P_3/N_3, \ldots P_m/N_m]/M$$

Presentation of Rainfall Data

MASS CURVE OF RAINFALL-

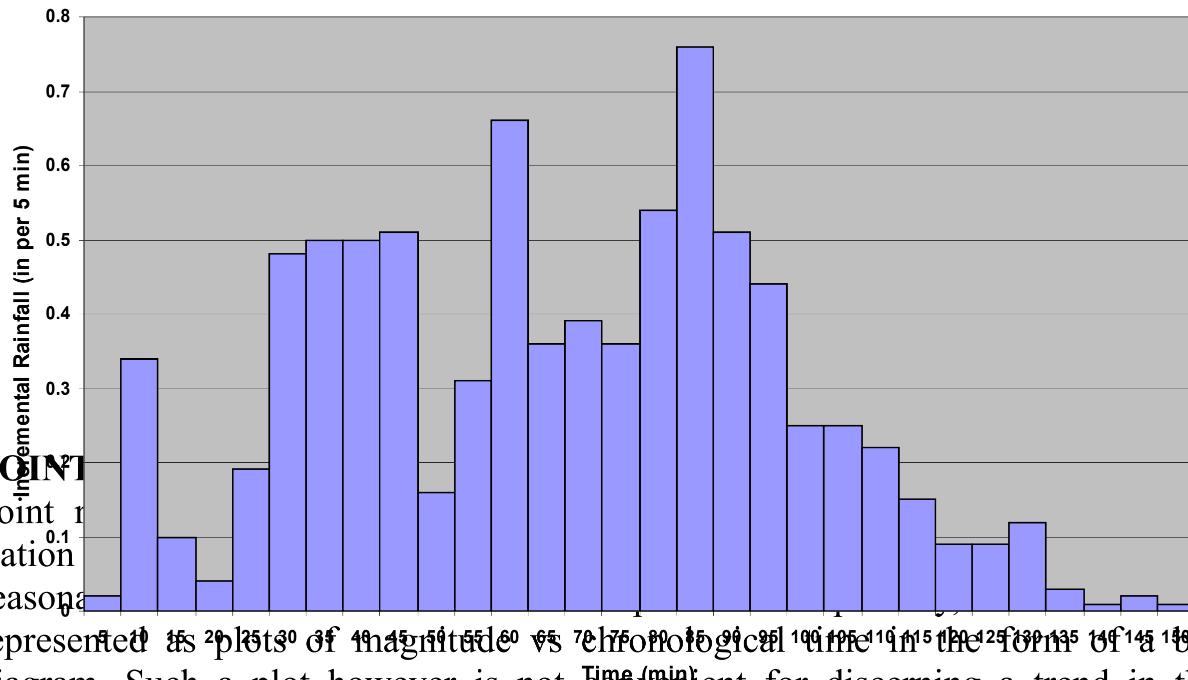
The mass curve of rainfall is a plot of the accumulated precipitation against time, plotted in chronological order. Records of float type and weighing bucket type gauges are of this form. A typical mass curve of rainfall at a station during a storm is shown in the fig2.9. Mass curves of rainfall are very useful in extracting the information on the duration and the magnitude of a storm. Also, intensities at various time intervals in a storm can be obtained by a slope of the curve. For non-recording rain gauges; mass curves are prepared from knowledge of the approximate beginning and end of a storm and by using the mass curves of adjacent recording gauge stations as a guide.



Mass Curve of Rainfall

HYETOGRAPH

A hyetograph is a plot of the intensity of rainfall against the time interval. The hyetograph is derived from the mass curve and is usually represented as a bar chart (fig.2.10).It is a very convenient way of representing the characteristics of a storm and is particularly important in the development of design storms to predict extreme floods. The area under a hyetograph represents the total precipitation received in the period .The time interval used depends on the purpose ,in urban-drainage problems small durations are used while in flood-flow computations in larger catchments the intervals are of about 6h.



POINT

Point r... a station ... y, season... re represented as plots of magnitude vs chronological time in the form of a bar diagram. Such a plot however is not convenient for discerning a trend in the rainfall as there will be considerable variations in the rainfall values leading to rapid changes in the plot. The trend is often discerned by the method of moving averages, also known as moving means.

MOVING AVERAGE-

Moving average is a technique for smoothening out the high frequency fluctuations of a time series and to enable the trend, if any, to be noticed. The basic principle is that a window of time range m years is selected. Starting from the first set of m years of data, the average of the data for m years is calculated and placed in the middle year of the range m .The window is next moved sequentially one time unit (year) at a time and the mean of the m terms in the window is determined at each window location .The value of m can be 3 or more years; usually an odd value. Generally the larger size of the range m, the greater is the smoothening .There are many ways of averaging and the method described above is called CENTRAL SIMPLE MOVING AVERAGE.

Mean Precipitation Over An Area:
To convert the point rainfall values at various stations into an average value over a catchment, the following 3 methods are in use:

- Arithmetical-mean method
- Thiessen-mean method
- Isohyetal method

ARITHMETIC-MEAN METHOD:- When the rainfall measured at various stations in a catchment show little variation over catchment area I taken as the arithmetic mean of the station values. Thus, if P_1'P_2......P_i...P_n are the rainfall values in a given period in N stations within catchment then the value of the mean ppt. p over the catchment by the arithmetic mean method is

P==

THIESSEN-MEAN METHOD:
In this method, the rainfall recorded at each station is given a weightage on the basis of an area closest to the station. The procedure of determining the weighing area is as follows: Consider the catchment area as in Fig. below containing six rain gauge stations.

There are three stations outside the catchment but in its neighbor-hood. The catchment area is drawn to scale and the positions of the six stations marked on it. Stations 1 to 6 are joined to for a network of triangles. Perpendicular bisectors for each of the sides of the triangle are drawn. These bisectors form a polygon around each station. The boundary of the catchment, if it cuts the bisectors is taken as the outer limit of the polygon. Thus for station1, the bounding polygon is *abcd.* For station 2, *kade* is taken as the bounding polygon. These bounding polygons are called Thiessen_polygons. The areas of these six Thiessen polygons are determined either with a planimeter or by using an overlay grid. If $P_{1,}P_2$,..,P_6 are the rainfall magnitudes recorded by the stations 1,2,…,6 respectively, and A_1,A_2,…,A_6 Are the respective areas of the Thiessen polygons then the average rainfall over the catchment P is given by

Thus,in general,for M stations,

P==

The ratio A_i/A is called *weightage factor* for each station. The Thiessen-polygon method for calculating the average precipitation over an area is superior to the arithmetic-average method as some weightage is given to the various stations on a rational basis. Further, the rain-gauge stations outside the catchment are also used effectively. Once the weightage factors are determined, the calculation of P is relatively easy for fixed network for stations.

ISOHYETAL METHOD:

An isohyet is a line joining points of equal rainfall magnitude. In the isohyetal method, the catchment area is drawn to scale and the rain-gauge stations are marked. The recorded values for which areal average is to be determined are then marked on the plot at appropriate stations. Neighboring stations outside the catchment are also considered. The isohyets are then drawn by considering point rainfalls as guided and interpolating between them by eye.

The area between two adjacent isohyets are then determined with a planimeter. If the isohyets go out of catchment, the catchment boundary is used as the bounding line. The average value of the rainfall indicated by two isohyets is assumed to be acting over the inter-isohyet area. Thus P1,P2,…..,Pn are the values of isohyets and if a1,a2,….,an-1 are the inter-isohyet areas respectively, then the mean precipitations over the catchment of area A is

P=

It is superior to the two methods.

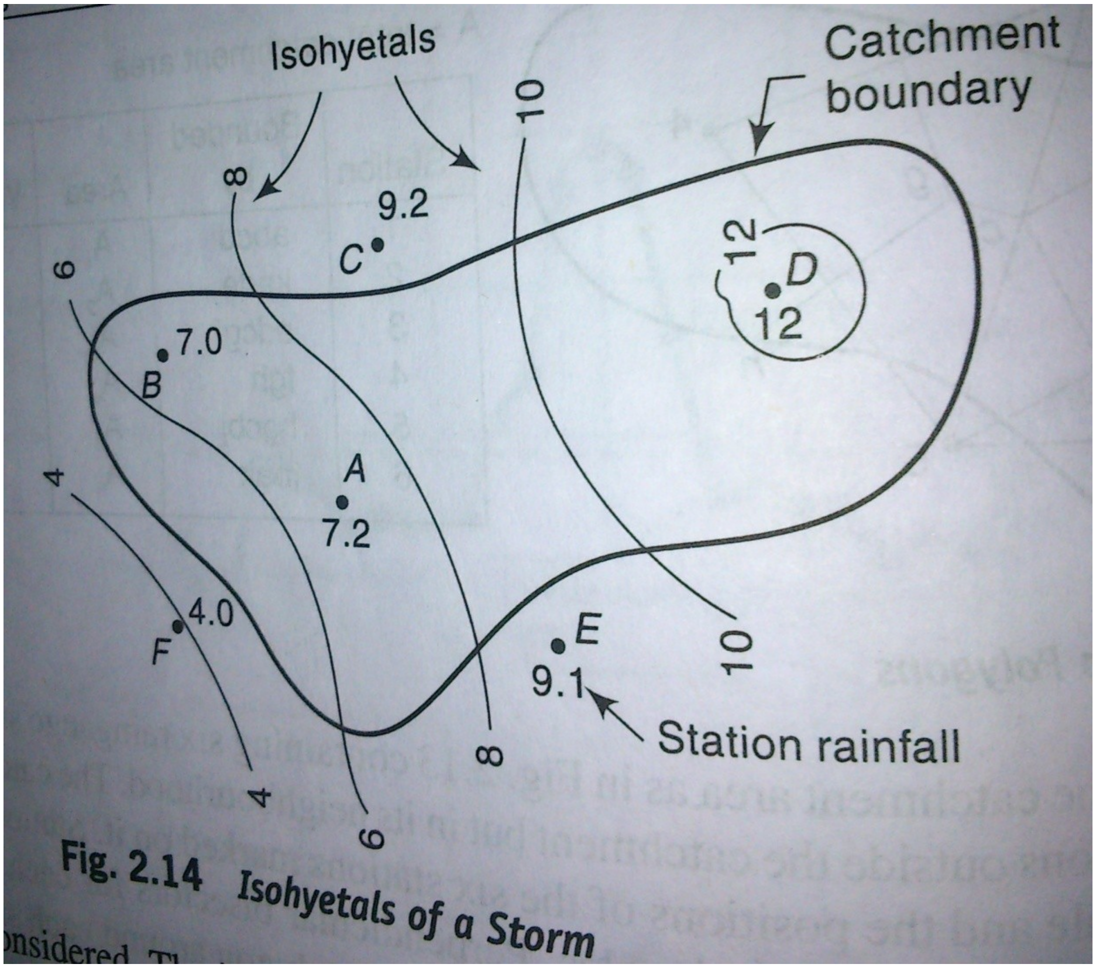


Fig. 2.14 Isohyetals of a Storm

DEPTH-AREA-DURATION (DAD) CURVE:-

DAD analysis is carried out to obtain a curve relating the depth of precipitation D, area of its coverage A and duration of occurrence of the storm D. A DAD curve is a graphical representation of the gradual decrease of depth of precipitation with the progressive increase of the area of storm, away from the storm center, for a given duration taken as the 3rd parameter. This gives a direct relationship between depth, area and duration of ppt. over the region for which the analysis is carried out. The purpose of DAD analysis is to determine the maximum precipitating amounts that have occurred over various sizes of drainage during the passage of storm periods of say 6h, 12h, 24h or other durations. There are two methods available for carrying out DAD analysis-

1. Mass curve method
2. Incremental-isohyetal method

Probable maximum precipitation (PMP):

It is defined as the estimate of the extreme maximum rainfall of a given duration that is physically possible over a basin under critical hydrological and meteorological conditions. This is used to compute flood by using suitable rainfall runoff model.

Two methods of PMP estimation are:

1. Statistical procedure
2. Meteorological approach

The statistical approach of PMP by using Chow's equation

$$PMP = P + k\sigma$$

Where P is the mean of annual maximum values, σ the standard deviation and k is the frequency factor which varies between 5 to 30 according to rainfall duration.

ABSTRACTIONS FROM PRECIPITATION

LOSSES FROM PRECIPITATION

For a surface water resource engineer, precipitation – runoff =losses

Precipitation – surface runoff = total losses

Total losses = Evaporation + Transpiration + Interception + Depression storage + Infiltration

Evaporation and its estimation :-

- Continuous natural process by which a substance changes from liquid to gaseous state.
- In arid regions, 90% loss is due to evaporation.
- So evaporation may otherwise be defined as loss of water to the atmosphere over the period under consideration.
- The main source of evaporation is solar radiation.
- 1 gm of water requires about 597cal of heat at 0^0c or 1gm of ice at $0\ ^0$c requires about 677cal for vaporization. This heat is latent heat of water and supplied by sun.
- Equivalent molar wt. Of air = 28.95,water vapour is = 18
  So water vapor is 62% lighter than air.
- Due to heat radiation, KE of water surface molecules increases . The surface tension and cohesion force can't hold the water molecules .They project into the atmosphere and due to lighter weight than air ,they can rise up to height where they condense .

- The net evaporation takes place during warm periods.
- Therefore the temperature of water surface is maintained at lower level.
- In a hydrologic cycle, evaporation takes place from all stages , even from the falling raindrops .
- Average annual rainfall in India is about 1120mm which is equal to 370 million hector-m of water.

  Total runoff by all the rivers of the country = 170 million hector-m

  Ground water recharge = 37 million hector-m

  So loss due to evaporation and transpiration = 163 million hector-m

Factors responsible for evaporation :-

1. . Meteorological factors :

   A) Vapour pressure

   B) Solar radiation

   C) Air temperature

   D) Wind velocity

   E) Atmospheric pressure

2. Nature of evaporating surface (Heat storage in water bodies)

3 .Quality of water (Presence Soluble salts)

Vapour pressure

- As per Dalton's law of evaporation, 'The rate of evaporation is proportional to the difference between saturated vapour pressure at the water temperature (e_w) and the actual vapour pressure in the air (e_a).

$$E_L=C(e_w-e_a)$$

Where E_L=Rate of evaporation (mm/day)

C=Constant

e_w, e_a (in mm)

- Evaporation continues till $e_w=e_a$ .If $e_w > e_a$, condensation takes place.

Temperature

- Rate of evaporation is directly proportional to increase in water temperature.
- Slight increase due to increase in air temperature also.
- Thus for the same mean monthly temperature ,it is possible to have evaporation to different degrees in a lake in different months.

Wind

- Wind helps in removing evaporated water vapour from the zone of evaporation and creates more scope for further evaporation.
- But it continues up to a certain increase in wind speed i.e critical speed beyond which no effect on evaporation.
- If the water surface is having larger area ,then high speed turbulent winds are required for maximum evaporation.

Atmospheric pressure

- Decrease in barometric pressure at higher altitudes increases evaporation remaining the other factors same.

Quality of water (presence of soluble salts)

- When a solute is dissolved in water, the vapour pressure of the solution becomes less than that of pure water .That causes reduction in evaporation.
- The % reduction in evaporation corresponds to % increase in specific gravity.

e.g. Evaporation from sea water < 2-3% from fresh water.

Nature of evaporating surface: (Heat storage in water body)

- Deep water bodies have more heat storage capacity than shallow.
- Deep lake may store radiation energy received in summer and release it in winter causing less evaporation in summer and more in winter compared to shallow lake in same condition.
- The effect of heat storage is essentially to change the seasonal evaporation rate but the annual evaporated rate is not affected.

Evaporimeters

- Evaporation is estimated by
  - ➢ Measurement using evaporation pans
  - ➢ Empirical equations
  - ➢ Analytical methods
    - ✓ Water balance method
    - ✓ Energy budget method
    - ✓ Mass transfer method

Types of Evaporimeter

- Class A evaporation pan
- ISI standard Pan
- Colorado sunken pan
- US geological survey floating pan.

Class A evaporation pan :

- Pan is normally made up of unpainted galvanized iron sheet.
- Evaporation is measured by measuring the depth of water with a hook gauge in a stilling well.
- Top surface is open to atmosphere.
- Due to absence of top wire mesh, evaporation is 14% extra.

ISI Standard Pan (Modified Class A Pan):-

- Made up of copper sheet, tinned inside and painted white outside.
- Paint gauge is used for water level measurement.
- Calibrated cylindrical measure is used to add or remove water maintaining the water level in the pan.

- Top surface is covered with a hexagonal wire netting of galvanized iron to protect the water in the pan from birds.
- Due to presence of wire mesh, evaporation is 14% less than that of class A pan.

Colorado Sunken pan:-

- Its size is less than the above two pans.
- It is made up of unpainted galvanized iron sheet and buried into the ground within 100m from top.

Advantages:-

Its major advantage is that its radiation and aerodynamic characteristics are similar to those of lake.

Disadvantage:-

- ❖ It is very difficult to detect any leak.
- ❖ Extra care is required to keep the surrounding free from tall grass, dust etc.
- ❖ It is very expensive to install.
- ❖ Atmometer is sometimes used for measuring evaporation
- ❖ It consists of a porous bulb drawing water from a container.
- ❖ Evaporation takes place from the bulb.
- ❖ A coefficient when multiplied to the depth of evaporated water from the porous bulb gives the required evaporation data of the data.

Evaporation recorded by a pan differs from that of a lake or reservoir due to:-

- Depth of exposure of pan above ground.
- Colour of the pan.
- Height of the rim.
- Heat storage and heat transfer capacity with respect to reservoir.
- Pan diameter
- Variation in vapour pressure, wind speed, water temperature.

We have to reduce the evaporation recorded by pan to that of the lake or reservoir by multiplying a pan coefficient between 0.6 to 0.8.

Lake Evaporation=Cp* Pan Evaporation

Where Cp=Pan co-efficient.

Pan types	Avg values of C_p	Range of C_p
● Class A Land Pan	0.70	0.6-0.8

- ISI Standard pan 0.80 0.65-1.10
- Colorado Sunken Pan 0.78 0.75-0.86
- USGS Floating Pan 0.80 0.70-0.82

EMPERICAL EQUATION:

a) General equation:
   $E_L = K f(u) (e_w - e_a)$
   E_L=Lake evaporation (mm /day)
   e_w=saturated vapour pressure of water
   e_a= actual vapour pressure of air
   f(u)=wind speed correction function
   K=coefficient

b) Meyer's formula:
   $E_L = K_M (e_w - e_a)(1 + u_9/16)$
   U_9 = monthly mean wind speed at kmph at 9m above ground
   K_M = 0.36 for large deep lakes
   0.50 For small shallow lakes

c) Rhower's formula
   $E_L = 0.771(1.465 - 0.000732P_a)(0.44 + 0.0733u_0)(e_w - e_a)$
   P_a=mean barometric reading in mm Hg
   U_0=mean wind velocity in kmph at ground level=velocity at 0.6 m height above the ground

- In the lower part of atmosphere, up to a height of about 500m above the ground level , the wind velocity can be assumed to follow the 1/7 power law as

  $$U_h = CH^{1/7}$$

  U_h=wind velocity at height h above ground
  C=constant
  If u_h is given then this equation can be used to determine velocity at any desire level.

  ANALYTICAL METHODS:-

  1) **Water budget method**
     - Simplest of the 5 method and least reliable.
     - Involves hydrological continuity equation for the lake evaporation determination.
     - Considering the daily average values for a lake ,the continuity equation:
       $P + V_{is} + V_{ig} = V_{os} + V_{og} + E_L + S + T_L$
       P=daily precipitation

V_{is}=daily surface inflow into lake
V_{ig}=daily groundwater inflow
V_{os}=daily surface outflow from the lake
V_{og}=daily seepage outflow
E_L=daily lake evaporation
S=increase in lake storage in a day
T_L=daily transpiration loss
All quantities are in unit of volume (m^3) or depth (mm)

2) **Energy budget method**

- Application of the law of conservation of energy
- Energy available for evaporation is determined by considering the incoming energy, outgoing energy and energy stored in the water body.
- Energy balance to the evaporating surface in a period of one day is:

$H_n=H_a+H_e+H_g+H_s+H_i$-----------(1)

Where, $H_n=(H_c-rH_c)-H_b$
$=H_c(1-r)-H_b$

H_n=net heat received by the water surface in which, $H_c(1-r)$ = incoming solar radiation into a surface of reflection coefficient 'r'
H_b=Back radiation (long wave) from water body
H_a=Sensible heat transfer from water body
H_e=Heat energy used up in evaporation
$=\rho LE_L$, ρ=density of water, L=latent heat of evaporation
E_L=evaporation in mm
H_g=Heat flux into the ground
H_s=Head stored in water body
H_i=net heat conducted out of the system by water flow (advected energy)

- All energies are in cal per sq mm per day
- If the time period is small, H_s, H_i can be neglected
- H_a can't be measured directly. It is estimated using Bowen's ratio β

$\beta=H_a/\rho LE_L=6.1\times10^{-4}\times\rho_a\{(T_w-T_a)/(e_w-e_a)\}$---------(2)

where, ρ_a=Atmospheric pressure in mm of Hg
T_w=Temperature of water surface in °C
T_a=Temperature of air

From eq^n(1) and (2), $E_L=(H_n-H_g-H_s-H_i)/\{\rho L(1+\beta)\}$

3) **Mass transfer method**:

- Based on theories of turbulent mass transfer in boundary layer to calculate the mass of water vapour transferred from the surface to the surrounding atmosphere.

Eq^n proposed by Thornthwait and Holtzman(1939),

$E=\{0.000119(e_1-e_2)(u_2-u_1)\}/[P\times\{\log_e(h_2/h_1)\}^2]$
Where, u_1,u_2=wind velocity in m/s at heights h_1 and h_2 meter respectively
e_1,e_2=vapour pressure of air in Pa (1Pa=1N/m^2)
P=Mean atmospheric pressure in Pa between lower height $h_1$and upper height h_2

- Height $h_1$is taken close to water surface.

Module 2 (Runoff, Stream Flow, Flood Design)

RUNOFF

RUNOFF

It means the draining/flowing off of precipitation from catchment area through a surface channel.

Otherwise it represents the output from the catchment in a basin unit of time.

BASIN:

- Area bounded by the highest contour called ridge line from where precipitated water is collected by surface and subsurface flows & drained out through the natural river.
- The ridge line divides one basin from the other basin/catchment/watershed/drainage basin.
- Watershed discharge 'Q' can be related to the area 'A' as
  $Q=x.A^y$
  Where x, y = parameters (Depending on this values Q = peak flow min. or mean flow.

STREAM:-

It is a natural flow channel in which water from a basin is collected and drained out to the water body.

OVERLOAD FLOW & SURFACE RUNOFF-

- After meeting all the losses, the excess rain water flows over the land surface in the form of a sheet of water to join the nearest stream and is called over land flow.
- The surface runoff is considered as overland flow so long as it does not join the nearest stream.
  L_{of} =
  L_{of} = Length of overland flow
  D_s = Stream density

SURFACE RUNOFF

The flow where it travels all the time over the surface is overland flow and through the channels as open channel flow and reaches the catchment outlet is called surface runoff.

SUBSURFACE RUNOFF

- Otherwise known as interflow/ subsurface flow/ through flow/Storm seepage/ quick return flow.
- The part of precipitation which infiltrates into the ground and moves laterally/ horizontally in the soil and returns to the surface at some location away from the point of entry into the soil is called as interflow.
- Depending upon the time delay between the infiltration and outflow,

Prompt (with least time log)

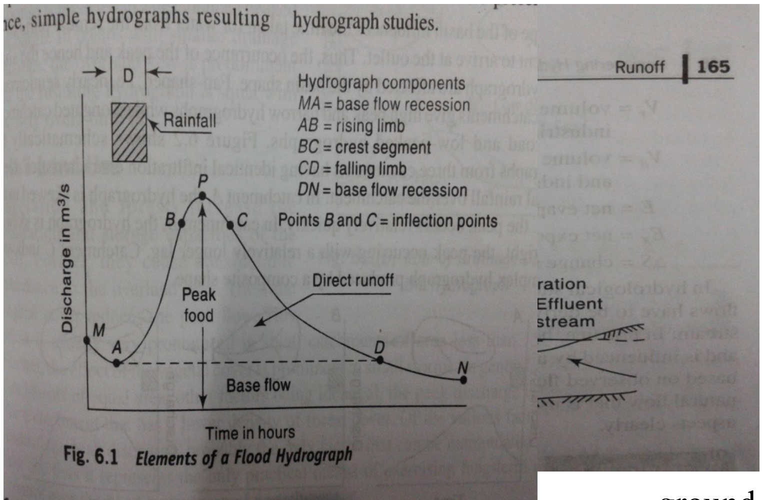


Fig. 6.1 Elements of a Flood Hydrograph

Interflow

Delayed

GROUND WATER FLOW

- Another route for the infiltrated water is to undergo deep resolution and reach the ground water storage in the soil.
- The part of runoff is called ground water runoff/ flow.

STREAM FLOW

- The total runoff consisting of surface flow, subsurface flow, ground water or base flow & the precipitation falling directly in the stream is the stream flow/ total runoff of a basin.

Effluent stream (When the ground water table is higher than the water level of stream, then the stream receives water from ground water reservoir)

Stream

Influent stream (When the position of ground water table is lower then the water level of stream, s.t. water from the stream contributes to the ground water storage. e.g. In early part of rainy season all rivers of India.

Based on the time delay between the precipitation and the runoff,

Direct runoff

Runoff

Base flow

DIRECT RUNOFF

Direct/storm runoff is that part of stream flow occurring promptly as precipitation starts & contributes for an acceptable period after the storm ceases.
Contribution from subsurface flow is considered constant during the period.

BASE FLOW

It is that part of stream flow available mainly from ground water reservoir and delayed sub-surface flow appearing during dry period.

Direct runoff and base flow are distinguished by mainly on time of arrival of flow to the catchment.

RAINFALL EXCESS:

The part/percentage of precipitation which is equal to the vol. of direct runoff from a basin is called rainfall excess.
Effective rainfall = Direct runoff volume + subsurface runoff = Rainfall excess + Subsurface runoff

⇨ Effective rainfall > Rainfall excess

CHANNEL STORAGE

⇨ At any instant, the water content of a stream within its defined c/s^n is known as channel storage.

HYDROLOGIC YEAR

⇨ The period of one year starting with the time when the ground and surface water storage of a basin is usually the minimum & called as hydrologic year/ water year.
⇨ In India it is taken as just before the onset of monsoon to the same period of next year ***(1st June to 31st May)***

FACTORS AFFECTING RUNOFF:

(i) Climatic factors
(ii) Basin characteristics
(iii) Basin geology
(iv) Basin infiltration characteristics

(i) CLIMATIC FACTORS :

a.i.1.a.i. Intensity (rainfall intensity & runoff)
a.i.1.a.ii. Duration (Duration Runoff volume)
a.i.1.a.iii. Aerial distribution (Area of catchment

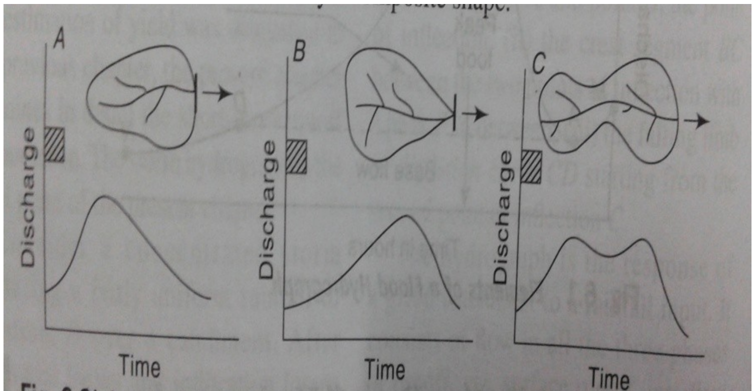


Fig. 6.2(a) *Effect of Catchment Shape on the Hydrograph*

contributing)

a.i.1.a.iv. Direction of storm movement (If U/s to d/s then more)

a.i.1.a.v. Forms of precipitation (Liquid form > more runoff)

a.i.1.a.vi. Evapotranspiration (Evapotranspiration rate α 1/ runoff vol.)

(ii) BASIN CHARACTERISTICS :

(a.i.1.i) Size (peak flow per unit area α 1/Area period of surface runoff α area)

(a.i.1.ii) Shape

(a.i.1.iii) Slope

(a.i.1.iv) Drainage density

(a.i.1.v) Topography

(a.i.1.vi) Geology

SHAPE

- An elongated catchment has lower peak and longer runoff than that of a fan shaped.
- In a carrot shaped catchment early peak then other.
- Sometimes multiple peaks depending upon the catchment shape.

SLOPE

- A catchment having extensive flat area gives rise to low peak and less runoff with respect to steep slope catchment.

- Rate of infiltration from a flat catchment is more which affects the velocity of overland flow. Therefore the time of arrival of peak flood at the outlet is late and so is the total time period of runoff for such that shaped catchment.
- For a high intensity and long duration of storm, the effect of basin slope is pronounced.

DRAINAGE DENSITY (D_d)

- Ratio of total length of all streams of the catchment divided by its area.
- It indicates the drainage efficiency of the basin.
- The higher the value, quicker is the runoff and lower is the infiltration & other losses.

$$D_d = L_s/A$$

STREAM DENSITY (D_S)

- Defined as the No. of streams "N_s" of given order per Sq. Km computed by dividing the total No. of streams of the same order of the basin with the catchment area.

  $D_s = N_s/A$

  $L_o = 1/2D_s$

  (D_s = Stream density)

  (L_o : Length of overland flow)

TOPOGRAPHY

Shape factor (B_s)

- Ratio of Sq. of watershed length 'L' to the watershed over A

  $B_s = L^2/A \geq 1$

  For a sq watershed $B_s = 1$

CHANNEL SLOPE

It affects the velocity and flow carrying capacity at given location at the basin outlet.
Incorporated in mannings, chezys eqn.

Slope(S) = =

FORM FACTORS (F_S)

- Horton expressed it as the ratio of watershed area A to the square of its length L^2.
- Also defined as the ratio of the width of the basin W_b to its aerial length L_b measured between the stream outlet to the most remote point on the basin.
  - $F_f = A/L^2 = W_b/L_b < 1$

  $F_f = 1/B_s$

BASIN GEOLOGY

- Responsible for the rate of infiltration during a storm of good aquifer material forms the basin then surface runoff will be less due to high infiltration rate.
- But for an impervious basin runoff will be highly peaked.
- Presence of cracks, fissures results in the diversion of storm water to a new location may be to an adjoining basin as watershed leakage.

BASIN INFILTRATION CHARACTERISTICS

Main features are : (i) Nature of the surface of catchment
(ii) Surface storage characteristics.

- Vegetation forces a good quantity of storm water to infiltrate & responsible for the reduction of surface runoff.

- Cultivation activities also decrease the runoff.
- Small depressions to large lakes reduce the amount of runoff from a basin because they hold water during storm.

RUNOFF COMPUTATION

Total runoff from a project catchment over the period of 1 year is called the annual yield.
It represents the total runoff volume from the catchment.
Various methods used for the runoff analysis are

a) Extension of flow data
b) Rainfall- runoff correlation
c) Empirical relations
d) Runoff simulation models
e)

EXTENSION OF FLOW DATA (minimum 12 years of runoff data required)

1) Thomas - Fiering Model
2) Harmonic analysis Model
3) Correlation with the Adjoining station
4) Regression Techniques
5) Longbeins Method
6) Flow duration curve method

THOMAS-FIERING MODEL

- The model has been applied successfully to generate sequentially the monthly, 10-daily or weekly volumes of discharges from a serially dependent series.

- This is an extension of Markov Model which assumes a monthly or 10-daily variable is dependent only on the just recent one or two variables involving non-stationary both in mean & std. dev^n.
- Eg : Flow vol. of July are dependent on the vol. of June to some extent, the mean and std. dev^n of all June months are diff. to that of July.

$Q_{j+1} = Qav_{j+1} + b_{j,j+1}\ (q_j - q_{avj}) + Z_j S_{j+1}$

Which Q_{j+1}, Q_j = Discharge volumes during (j+1) th & jth month
Qav_{j+1}, Qav_j = Mean monthly discharge volumes for (j+1)th and jth months
S_{j+1}, S_j = Std devn for (j+1) &jth months
r_j, r_{j+1} + Correlation coefficient between the months j and (j+1)
Z_j = Random independent variable with zero mean and unit variance
$b_{j,j+1} = r_{j,j+1}\ (S_{j+1}/S_j)$
If j for June then (j+1) for July

REGRESSION TECHNIQUES

Most common method is to fit a linear regression line between R & P and to accept the result if the correlation coefficient is unity
The eqn. of the straight line regression between runoff R & rainfall P is
$R = aP + b$
Where a = & b =

In which N = No. of observation sets R &P
Coefficient of correlation, r

R =

The value of R lies between 0 & 1 as R can have only +ve correlation with P.
$0.6 < r < 1$ => good correlation
$R \geq 0$

For large catchments, sometimes exponential correlation is advantageous.
$R = \beta P^m$ where m, β = constants

It can be reduced to linear form
$\ln R = m \ln P + \ln \beta$

here m, β can be determined by the formula discussed earlier.

Flow duration curve method

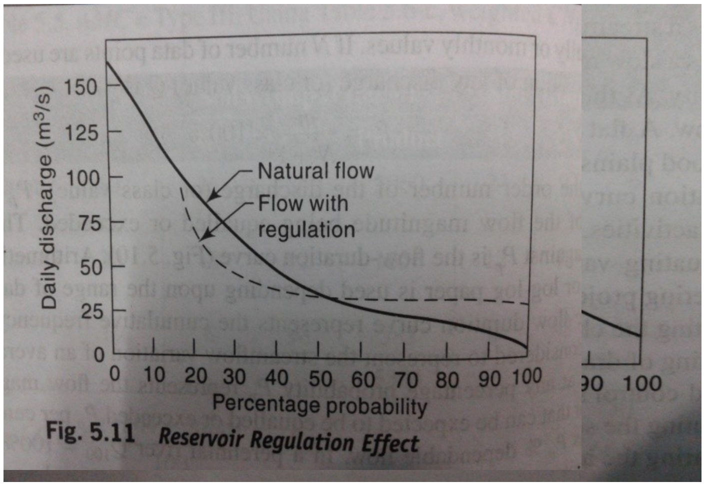


Fig. 5.11 *Reservoir Regulation Effect*

FLOW DURATION CURVE

It is well known that the stream flow varies over a water year. One of the popular methods of studying this stream flow variability is through flow duration curves. A flow duration curve of a stream is a plot of discharge against the percent of time the flow was equaled or exceeded. The curve is also known as discharge-frequency curve.

The stream flow data is arranged in a descending order of discharges, using class intervals if the number of individual values is very large. The data used can be daily weekly, ten daily or monthly values. If N number of data points are used in this listing the plotting position of any discharge (or class value) Q is

$P_p = m/N+1 \times 100\%$

Where m is the order number of the discharge (or class value) Pp = percentage probability of the flow magnitude being equaled or exceeded. The plot of the discharge Q against P_p is the flow duration curve (Fig 5.10). Arithmetic scale paper or semi-log or log-log paper is used depending upon the range of data and use of the plot. The flow duration curve represents the cumulative frequency distribution and can be considered to represent the stream flow variation of an average year. The ordinate Q_p at any percentage probability Pp represents the flow magnitude in an average year that can be expected to be equaled or exceeded Pp percent of time and is termed as P_p & dependable flow. In a perennial river Q_{100} = 100% dependable flow is a finite value. On the other hand, in an intermittent or ephemeral river the stream flow is zero for a finite part of the year and as such Q_{100} is equal to zero.

The following characteristics of the flow duration curve are of interest.

- The slope of a flow duration curve depends upon the interval of data selected. For example, a daily stream flow data gives steeper curve than a curve based on monthly data for the same stream. This is due to the smoothening of small peaks in the monthly data.
- The presence of a reservoir in a stream considerably modifies the virgin-flow duration curve depending on the nature of flow regulation. Figure 5.9 shows the typical reservoir regulation effect.
- The virgin-flow duration curve when plotted on a log probability paper plots as a straight line at least over the central region. Form this property, various coefficients expressing the variability of the flow in a stream can be developed for the description and comparison.
- The chronological sequence of occurrence of the flow is masked in the flow duration curve. A discharge of say 1000 m^3/s in a stream will have the same percentage Pp whether it has occurred in January or June. This aspect a serious

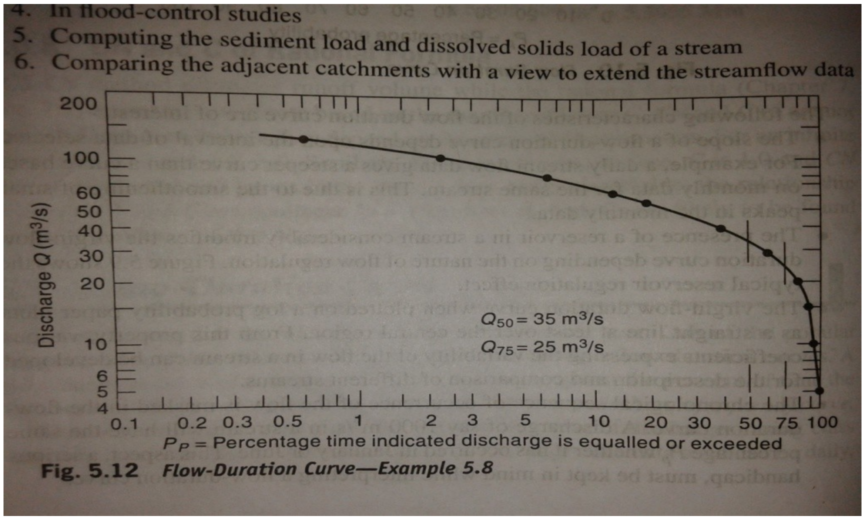


Fig. 5.12 *Flow-Duration Curve—Example 5.8*

handicap, must be kept in mind while interpreting a flow duration curve.

- The flow duration curve plotted on a log-log paper (fig 5.12) is useful in comparing the flow characteristic of different streams. A steps slope of the curve indicates a stream with a highly variable discharge. On the other hand, a flat slope indicates a slow response of the catchment to the rainfall and also indicates small variability. At the lower end of the curve, a flat portion indicates considerable base flow. A flat curve on the upper portion is typical of river basins having large flood plains and also or rivers having large snowfall during a wet season.

Flow – duration curves and considerable use in water resources planning and development activities.

Some of the important uses are

1) In evaluating various dependable flows in the planning of water resources engineering projects.
2) Evaluating the characteristics of the hydropower potential of a river
3) Designing of drainage systems
4) In flood-control studies
5) Computing the sediment load and dissolved solids load of stream
6) Comparing the adjacent catchments with a view to extend the stream flow data.

STREAMFLOW MEASUREMENT

- ❖ Stream-flow represent runoff phase of a hydrologic cycle. So this is the basic data required.
- ❖ Precipitation, Evaporation, Evapotranspiration, all is difficult to measure exactly and accurately.
- ❖ Interestingly only stream-flow part of hydrologic cycle can be measured with accuracy.
- ❖ Stream can be defined as flow channel into which the surface runoff from a specified basin drains.
- ❖ Stream-flow measurement has the same unit as discharge (m^3/s)

- Discharge from a stream plays an important role in hydrometry (science & Practice of water measurement).
- Stream-flow can be measured :

Direct method
- Area velocity method
- Dilution technique
- Electro magnetic method
- Ultrasonic method
- By hydraulic Structure

Indirect method
- Slope area method

Direct method
- It is difficult to measure directly the discharge
- So this is a 2 step method

Step-1

Plot a relation between stage and discharge

Step-2

Measure the stage and relate it to discharge

Stage measurement is easy, economic & continuous Stage measurement

(i) Manual Gauge

Staff gauge

Weir gauge

Wei

(ii) Automatic guage

Float gauge

Bubble gauge

- Velocity measurement through current meter

(a) Vertical axis (b) Horizontal axis

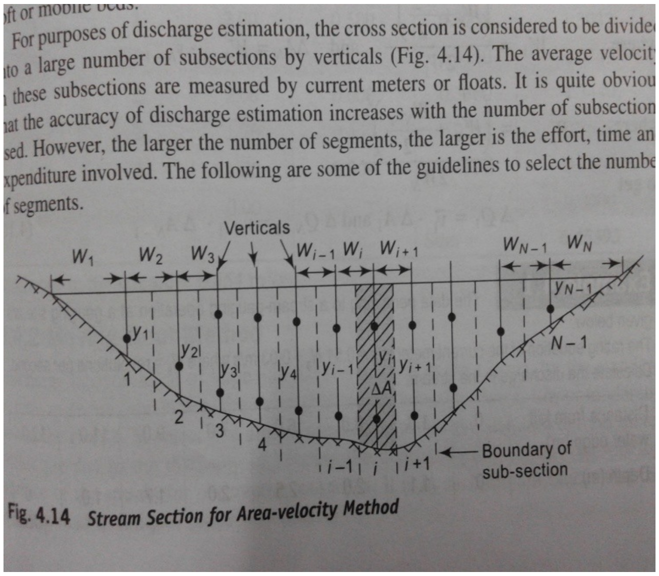
- This velocity is used in area-velocity method. So this method is otherwise known as standard current meter method

(1.) **AREA VELOCITY METHOD**

- ❖ This method consists of measuring the area of Cross section of the river at a selected section called gauging site & measuring the velocity of flow through the Cross sectional area.
- ❖ The site must be selected so that the stage-discharge curve is reasonably const over a long period of about a few year.
  - ✓ The Cross section of the stream should be well defined which does not charge in various seasons.
  - ✓ Should be easily accessible in all seasons.
  - ✓ Site should be in a straight stable reach.
  - ✓ Site should be free from backwater effects in the channel.
- ❖ At the selected site the section line is marked off by permanent survey markings and the Cross section is determined.
- ❖ Depth at various locations is measured by sounding rods or sounding weights.
- ❖ For accurate depth measurement, electro acoustic instrument called echo-depth recorder is used.
- ❖ In this a high frequency sound wave is sent down by a transducer kept immersed at the water surface and the echo reflected by the bed is also picked up by the same transducer. By comparing the time interval between the transmission of the signal and the receipt of its echo, the distance of the bed is obtained & recorded in the instrument. Advantageous in high-velocity streams, deep streams & streams with soft or mobile beds.
- ❖ For discharge estimation, the Cross section is divided into a large No. of sub-sections by verticals.
- ❖ The velocity in these sub-sections is measured by current meters.
- ❖ Accuracy & discharge estimation increases with the No. of subsections used. But the effort, time & expenditure will also be involved.
- ❖ Guidelines for selecting sub-sections are
  - ✓ Segment width should not be greater than $1/15^{th}$ to $1/20^{th}$ of the width of the river.
  - ✓ Segment discharge < 10% of total discharge
  - ✓ Difference in velocity in adjacent segments not greater than 20%.
- ❖ Area –velocity method using current meter is called as standard current meter method

CALCULATION OF DISCHARGE

- ❖ In this cross section (N-1) verticals are drawn
- ❖ The velocity averaged over the vertical at each section is known.
- ❖ Considering the total area to be divided into (N-1) segments, the total discharge is calculated by the method of mid-sections:


ft or mobile beds.

For purposes of discharge estimation, the cross section is considered to be divide
to a large number of subsections by verticals (Fig. 4.14). The average velocit
these subsections are measured by current meters or floats. It is quite obviou
at the accuracy of discharge estimation increases with the number of subsection
sed. However, the larger the number of segments, the larger is the effort, time an
xpenditure involved. The following are some of the guidelines to select the numbe
f segments.

Fig. 4.14 Stream Section for Area-velocity Method

Where ΔQ_i = Dischage in the i^{th} segment

=Area x velocity

=(width x Depth) x velocity

= (Depth at the i^{th} segment) x (½ width to left + ½ to right) x (Avg. velocity at the i^{th} vertical)

x Velocity

For i= 2 to (N-2)

For the 1[st] & last sections, the segments are taken to have triangular areas and

Area = $\Delta A_1 = W_1.Y$, & $\Delta A_{N-1} = W_{N-1} . Y_{N-1}$

Where $W_1 = (W_1 +)$

$W_{N-1} = (W_{N-1} +)$

⇨ $\Delta A_{1} =$

$\Delta A_{N-1} =$

$\Delta Q_1 = V_1 \Delta A_1$ & $\Delta Q_{N-1} = V_{N-1} \; \Delta A_{N-1}$

INDIRECT METHODS

- It includes the methods which make use of the relationship between the flow discharge and depths at specified locations.
- The field measurement is restricted to the measurements of these depths only.
  (1) Flow measuring structure (2) Slope Area method

(1) Flow measuring structure.

- Structures are notches, weirs, flumes and sluice gates for flow measurement in lab.
- Basic principles governing the use of these structure is
  - ✓ These structure produce a unique control section in the flow.
  - ✓ At these structure discharge Q is a function of water surface elevation measured at a specified u/s location

  i.e $Q = F(H)$ (1) where H = Water surface elevation measured from a specified datum.

For weirs, $Q = KH^n$ --------------------- (2)

Where H = head over the weir, K_n = system constant

- ➢ Eqn (1) is applicable till the water level is below a certain limiting water level known as modular limit.
- ➢ Flows which are independent of the d/s water level are known as free flows.
- ➢ If the tail water conditions do affect the flow, that flow is known as drowned or submerged flow.

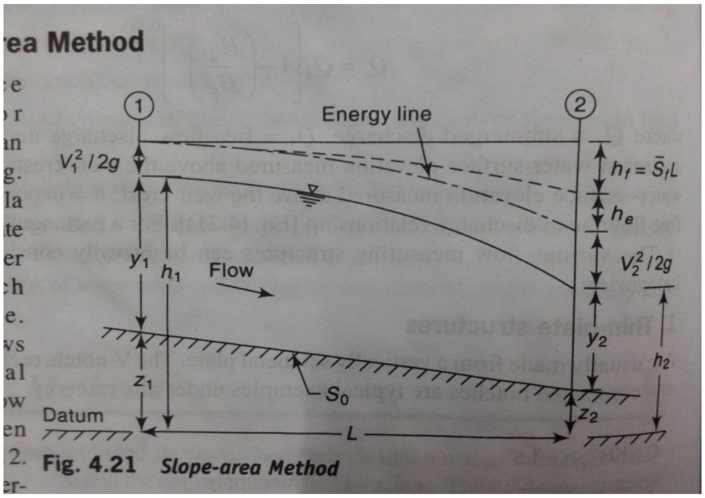


Fig. 4.21 Slope-area Method

- Discharges under drowned condition are obtained by applying a reduction factor to the free flow discharges.
- The submerged flow over a weir is estimated by Villemonte Formula,
  $Q_s = Q_1[1-^{n}]^{0.385}$ ---------- (3)
  Where Q_s = submerged discharge, Q_1 = free flow discharge under head H1.
  H_1 = u/s water surface elevation measured above the weir crest
  H_2 = d/s water surface elevation measured above the weir crest.
  n = exponent of head in the free flow head discharge relation
- For a rectangular weir n = 1.5
  $Q = KH_1^n$, n = 1.5
  $K = C_d L \sqrt{2g}$
  $Q = C_d L H^{3/2} \sqrt{2g}$

- Various flow measuring structure can be broadly classified under 3 categories

(1)Thin plate structure
- Usually made from a vertically set metal plate
- Eg:- V-notch, rectangular full width and contracted notches

(2) Long base weirs :-
- Otherwise known as broad- created weirs
- Made up of concrete or masonry
- Used for large discharge values

(3) Flumes :-
- Made of concrete, masonry or metal sheets depending upon their use and location.
- Primarily depend upon the width constriction to produce a control section.

(2) SLOPE AREA METHOD

- The resistance eqn for uniform flow in an open channel, (Manning's eqn) can be used to relate the depths at either ends of a reach to the discharge.
- In figure longitudinal section of the flow in a river between section (1) & (2).

- ❖ To estimate the discharge, water surface elevation should be known.
- ❖ Applying the energy equation to sec (1) & (2)

$Z_1 + Y_1 + \;= Z_2 + Y_2 + \;+ h_L$

Where $h_{L =}$ head loss in the reach

$h_L = h_f + h_e$ where h_f – frictional loss

$Z + Y = h$ h_e = eddy loss

h = water surface elevation above date

⇨ $h_1 + \;= h_2 + \;+ h_e + h_f$

⇨ $h_f = (h_1 - h_2) +(-h_e$ -------------------- (4)

If L = Length of the reach,

By manning's formula for uniform flow,

$= S_f$ =Energy slope = --- (5)

Where K = Conveyance of the channel = $AR^{2/3}$

⇨ In non-uniform flow, an average conveyance is used to estimate the avg. energy slope.

$= S_f =$

Where $K = \sqrt{K_1 K_2}$; $K_1 = A_1R_1^{2/3}$, $K_2 = A_2R_2^{2/3}$

Eddy loss $h_e = K_e|$ --------------- (6) Eq. (4), (5) (6) along with continuing eqn. $Q = A_1V_1 = A_2V_2$ enable the discharge Q to be estimated for known values of h, channel c/s properties and n.

(1) Assure $V_1 = V_2 \Rightarrow V_1^2/2g = V_2^2/2g$ so equation (4) $h_f = h_1 - h_2 = F$ = Fall in water surface between sec (1) and (2)
(2) Using equation (5) calculate discharge Q.
(3) Compute $V_1 = Q_1/A_1, V_2 = Q_2/A_2$ calculate velocity heads & eddy loss(he).
(4) Now calculate a refined value of h_f & go to step-2

⇨ Repeat the calculation till 2 successive calculations give values of discharge (or h_f) differing by a negligible margin.

⇨ This method of estimating the discharge is known as the slope area method.

It requires

⇨ Selection of a reach in which c/s properties including bed elevations ae known at its ends.

⇨ The value of manning's n

⇨ Water surface elevations at the 2^{nd} sections

<u>APPROXIMATE AREA-SLOPE METHOD</u>

- ❖ During very high floods, a site may become inaccessible or the gauge –discharge setup may be fully inundated under such situations this method is adopted.
- ❖ The previous peak flood stages at two locations can be collected from the flood marks in the river course which gives the water surface slope of the peak flood.

- By knowing the distance between the 2 points along the river, slope S_f can be computed.
- $Q = (1/n). AR^{2/3} S_f^{1/2}$ where S_f = Slope of the energy line between 2 points
- The area of c/s may vary between the 2 sections and also the slope of the energy line S_f for various flood heights.
- 'n' value for natural channel may very 0.02-0.10

<u>STAGE-DISCHARGE RELATIONSHIP</u>

- Measurement of discharge by direct method involves a 2 step procedure.
- Development of stage – discharge relationship (G-Q)
- Then after measuring stage (G), discharge Q can be calculated from the (G-Q) relationship
- Thus the aim of current – meter and other direct discharge measurements is to prepare a (G-Q) relationship for the channel gauging station.
- This curve is otherwise known as Rating Curve.
- The measured value of discharges when plotted against the corresponding sages gives relationship that represents the integrated effect of a wide range of channel and flow parameters.
- The combined effect of these parameters is termed as control.
- If the (G-Q) relation is const for a gauging station & does not change with time, the control is permanent.
- If it changes with time it is called shifting control.

<u>PERMANENT CONTROL</u>

- Majority of streams and rivers especially non alluvial rivers exhibit permanent control.
- For this the relationship between stage and discharge is a single valued relation which is expressed as

$$Q = C_r (G-a)^{\beta} \quad \text{------} \quad (7)$$

Q = Stream discharge
G = Gauge Height
a = Constant which represents stage @ zero discharge
C_r, β: Rating curve constant

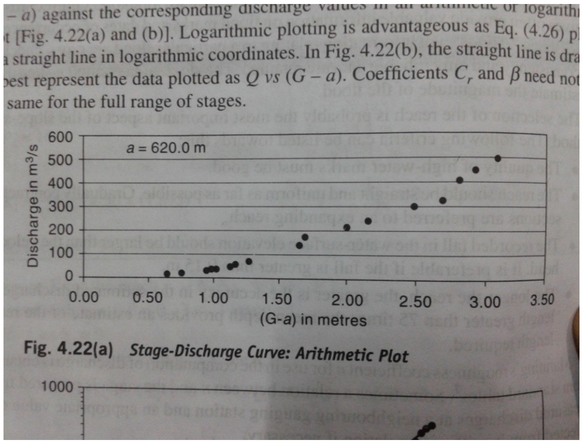


Fig. 4.22(a) Stage-Discharge Curve: Arithmetic Plot

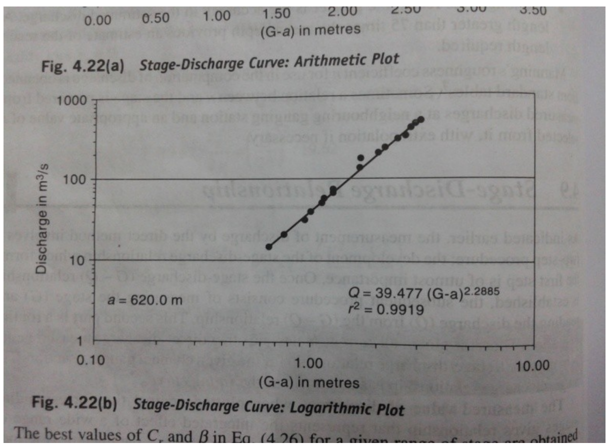


Fig. 4.22(b) Stage-Discharge Curve: Logarithmic Plot

- ❖ This relationship can be expressed graphically by plotting the observed relative stage (G-a) against the corresponding discharge values in an arithmetic or logarithmic plot.
- ❖ The best values of Cr and β in equation for a given range of stage are obtained by the least square-error method. By taking logarithms

$$\text{Log } Q = \beta \text{ Log } (G-a) + \text{Log } C_r \qquad (8)$$

$$\text{Or, } Y = \beta X + b \qquad (9)$$

In which the dependent variable = Y = log Q

Independent variable = X = log (G-a)

$b = \log C_r$

For the best fit straight line of N observations of X & Y, by regressing

X = Log (G-a) on Y = log Q

=

b =

r =

- ❖ ‘r’ reflects the extent of linear relationship between 2 data sets.

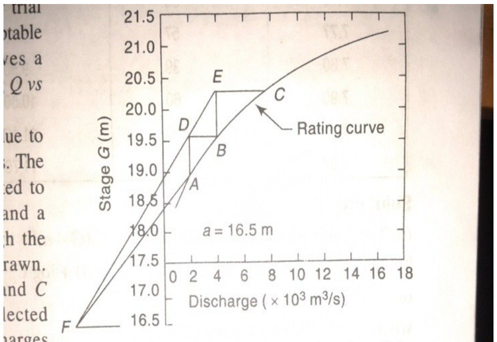


Fig. 4.23 *Running's Method for Estimation of the Constant a*

- ❖ For a perfect co-relation r =1. r = 0.6-1 is good
- ❖ Here Q α (G-a) => 'r' is +ve => +vely co-related
- ❖ Equation 7 is called rating equation of the stream and can be used for estimating the discharge of the stream for a given gauge reading G within range of data used in its derivation.

STAGE FOR ZERO DISCHARGE

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

- ❖ In this equation Constant 'a' = Stage (gauge ht.) for zero discharge in the stream
- ❖ This is a hypothetical parameter & can't be measured in field.
- ❖ The alternative methods for determining 'a' are

1. Plot Q vs G on an arithmetic graph paper and draw a best fit curve. By extrapolating the curve through eye judgment find 'a' as the value of G corresponding to Q = 0
   Using the value of 'a' plot logQ vs log(G-a) and verify whether the data plots as a straight line. If not, select another value in the neighbourhood of previously assumed value and by trial and error find an acceptable value of 'a' which gives a straight line plot of logQ vs log(G-a)
2. Q vs G data are plotted in arithmetic scale.
   - ❖ A smooth curve is drawn
   - ❖ Three points A, B & C are selected such that their discharges are in GP $Q_A/Q_B = Q_B/Q_C$
   - ❖ At A,B, vertical lines are drawn and at B,C horizontal lines are drawn
   - ❖ Their intersections are D,E points respectively.
   - ❖ Two straight lines ED and BA are extended so that they will intersect at F.
   - ❖ The ordinate at F, is the required value of 'a' the gauge height corresponding to zero discharge.
   - ❖ This method assumes the lower part of Rating curve to be a parabola.

3. Plot Q vs G to an arithmetic scale and draw a smooth good-fitting curve by eye- judgment.
   - ➢ Select three discharges Q1, Q2 and Q3 s.t.

   $Q_1/Q_2 = Q_2/Q_3$
   - ➢ Note from the curve, corresponding values of gauge readings G1, G2, and G3.

   From equation (7)

   =

   a = --------- (8)

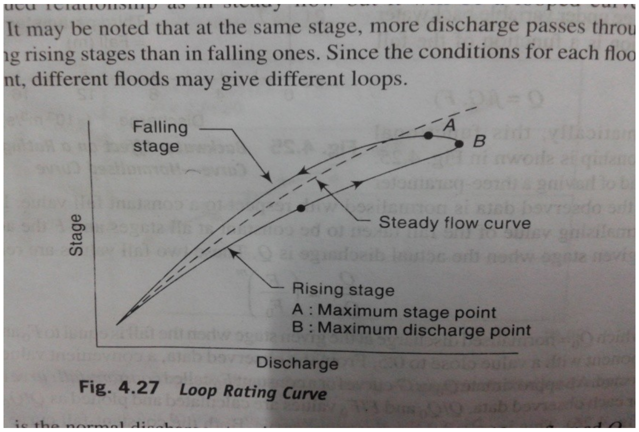


Fig. 4.27 Loop Rating Curve

4. A No. of optimization procedures are available to estimate the best value of ‘a’. A trial & error search for ‘a’ which gives the best value of the co-relation co-efficient is one of them.

<u>EFFECT OF CHANGING STAGE ON STAGE DISCHARGE CURVE</u>

- ❖ The discharge measured for a particular given stage is different for a changing stage than for a constant stage.
- ❖ The stage of a river may be constant, may be rising or may be falling
- ❖ During the rising stage of a river, the measured discharge is more that for a const stage. (reverse in case for falling stage)
- ❖ While plotting a stage-discharge curve, the values of discharges must be taken for a constant stage. But practically these discharges are measured either at rising or at falling stage.
- ❖ During a rising stage, the measured discharge > true discharge for a given gauge height.
- ❖ So in order to make this observed point fall on the true discharge curve, either the discharge should be reduced or the gauge height should be increased.
- ❖ Hence a –ve correction should be applied to the discharge value or a +ve correction to the gauge reading for a rising river stage.

(Reverse case for falling stage)

- ❖ The results of discharge measurements for a rising stage fall to the right side and that for a falling stage to the left side of the true discharge curve.
- ❖ The amount of deviation from the true discharge curve does not depend upon the total rise or fall but depends upon the rate of change of stage.
- ❖ Graph can be plotted between the rate of change of stage and the % correction applied to the observed discharge values in order to obtain true discharge.
- ❖ This curve is different for rising & falling stages generally the relation is found to be a st. line or a very flat curve as shown above.
- ❖ These corrections (+ve for falling stage & -ve for rising) can be applied to the observed discharge values.

<u>EFFECT OF SHIFTING CONTROL ON DISCHARGE VALUES</u>

- A control does not always behave as a permanent control while fixing a velocity area station.

Due to this shift, the observed discharge values are not true values

- For a fixed control either the discharge should fall right side or left side of true value as rising or falling stage.
- But if on plotting, if it is found that the points are not falling on true or rising or falling i.e. if for a rising stage, the observed points fall to the left side or for falling to the right side or for a const. stage, the observed points don't fall on the true discharge curve then there may be possibility of change in control.
- If the control is changing, then we have to find out the speed of changing.
- If the control is changing very slowly or only at the time of floods, then the best method to deal with the problem is to draw a new rating curve. This new curve is then applied for a period till sufficient deviation due to change in control is again detected.
- Almost once a year, the rating curve has to be changed.
- But on many other rivers, the control changes quite rapidly and constantly. In this case daily discharge records are obtained and corrected.

DESIGN FLOOD

A flood used for the design of a structure on consideration of its safety, economy, life expectancy & probable damage consideration is called design flood.

The flood selected for design of such structure should probably be the highest one.

	Frequency based flood (FBF)
Design flood	Probable maximum flood (PMF)
	Standard project flood (SPF)

FBF (Frequency based flood)

A design flood estimated using flood-frequency analysis for an accepted return period is called FBF.

PMF (Probable max. flood)

It is the extreme flood, which is physically possible in a region due to the most severe combination of critical meterological and hydrological factors that are reasonably possible over the region under consideration.

It is used to design of all important structures with virtually no-risk criteria.

SPF (Standard Project flood)

A flood computed from the standard project storm (SPS) that have occurred over the project area under consideration or on the adjoining areas with similar hydrometerological and basin characteristics without its maximization as in PMF is called SPF

It usually varies between 40% to 60% of the PMF

Computation of design flood — Rational approach (<50 km^2) small size catchment
Empirical equation
UH –Technique (<50000 km^2) moderate size)
Flood freq. studies

The use of particular method depends upon (i) desired object (ii) available date (iii) Importance of the project.

RATIONAL METHOD

- It is used for calculating peak discharge for small catchments (<50 km^2)
- The formula is called rational because of the units of the quantities considered being numerically consistent.
- Original formula was in FPS unit. (Rainfall-inch, Area-Acre)
- The runoff gradually increases form zero to peak when rainfall duration reaches the time of concentration 't_c' and thereafter it becomes const. for the remaining period of rainfall excess ($t-t_c$) i.e. from time t_c onwards. After the cessation of rain, the runoff recedes gradually to become zero at time t_c from the end of the peak. In rational formula a certain % of rainfall is considered as runoff.
- In FPS unit, Q_p = CIA ---- (1) where Q_p = peak discharge
- In SI units $Q_p = 0.278$ CIA — C= Runoff Coefficient = runoff/Rainfall
  I = Rainfall intensity in mm/h
  A = Area of catchment in km^2
- C varies 0.05-0.95, it represents the cumulative effect of the watershed losses.

FACTORS AFFECTING VALUE OF C:

- Initial losses
- Depression storage
- Nature of the soil
- Surface slope
- Degree of saturation
- Rainfall intensity
- Geology of the catchment
- Geo-hydrological characteristics of basin

  $C_w = \sum (C_i A_i)/A$, Value can be used in equation (2)

  General form correlating intensity duration-return period is

  $I = K.T^a/(t_c+b)^n$

  I = intensity of rainfall (cm/h)

T = Return period (yrs)
T_c = time of concentration (hr)
K,a,b,n = const

TIME OF CONCENTRATION (T_C)

No. of empirical equation available for the estimation of t_c

1) US practice
   For small basins, $t_c = t_p = C_{tl}\,((LL_{ca})/\sqrt{s})^n$
   Where C_{tl}, n = Basin Const
   S = Basin slope
   $(LL_{ca})/\sqrt{s}$ = Catchment parameter
   L = Basin length measured along the water course from the basin divide to the gauging stn.
   L_{ca} = dist along the main water course from the gauging station to a point app to the watershed controlled (Km)
2) KIRPICH Equation
   The formula relates the t_c of the length of travel and slope of the catchment as
   $t_c = 0.01947 L^{0.77} S^{-0.385}$ L = max length of travel of water
   S = slope of catchment $\Delta H/L$
   This equation can easily be written as $t_c = 0.01947\, K_1^{\;0.77}$
   Where $K1 = \sqrt{(L^3/\Delta H)}$

RAINFALL INTENSITY (I OR $I_{TC,P}$)

The rainfall intensity corresponding to a duration t_c and the desired probability of exceedence P, (Return period T=1/P)

$i_{tc,p} = kT^x/(t+a)^n$
k,x,a,n = Area specific co-efficient

RUNOFF CO-EFFICIENT (C)

'C' Represents the integrated effect of the catchment losses and depends upon the nature of the surface, surface slope and rainfall intensity.
Equation (2) assumes a homogenous catchment surface. If it is non homogenoous, then it can be divided into subareas each having diff. runoff coefficients & then each coefficient is calculated separately & then merged.
If the non-homogenous sub areas can't be separated, then equivalent C_e is used

C_i = R.C. for subarea i having area A_i

EMPERIAL FORMULAE

Flood Peak area relationship

The simplest relationship is those which relate the flood peak to the drainage area. The max flood discharge Q_p from a catchment area A is given by $Q_p = f(A)$

Dickens formula

Where $Q_p = C_d A^{3/4}$
Q_p= Max flood discharge (m^3/s)
C_d = Dickens const (6-30)
A = Catchment area (km^2)
Dickens formula is used in the central and northern parts of the country.

Ryves formula

$Q_p = C_R A^{2/3}$
where Cr = Ryves coefficient
used in Tamilnadu and parts of Karnataka & Andhra Pradesh
CR = 6.8 for areas within 80 Km from the east loc.
8.5 for areas which are 80-160 Km
= 10.2 for limited areas near hills

INGLIS FORMULA

Based on flood data of catchments in Western Ghats in Maharashtra
$Q_p = 124A/ (\sqrt{(A+10.4)})$

OTHER FORMULAE

Some other formulae are these which relate the Q_p with A along with flood frequency
Fuller's formula ($Q_{TP} = C_f A^{0.8} (1+0.8\log T)$)
Where Q_{TP} = Max 24 h flood with a frequency of Tyr in m^2/s
C_f = Const with values between 0.18-1.88

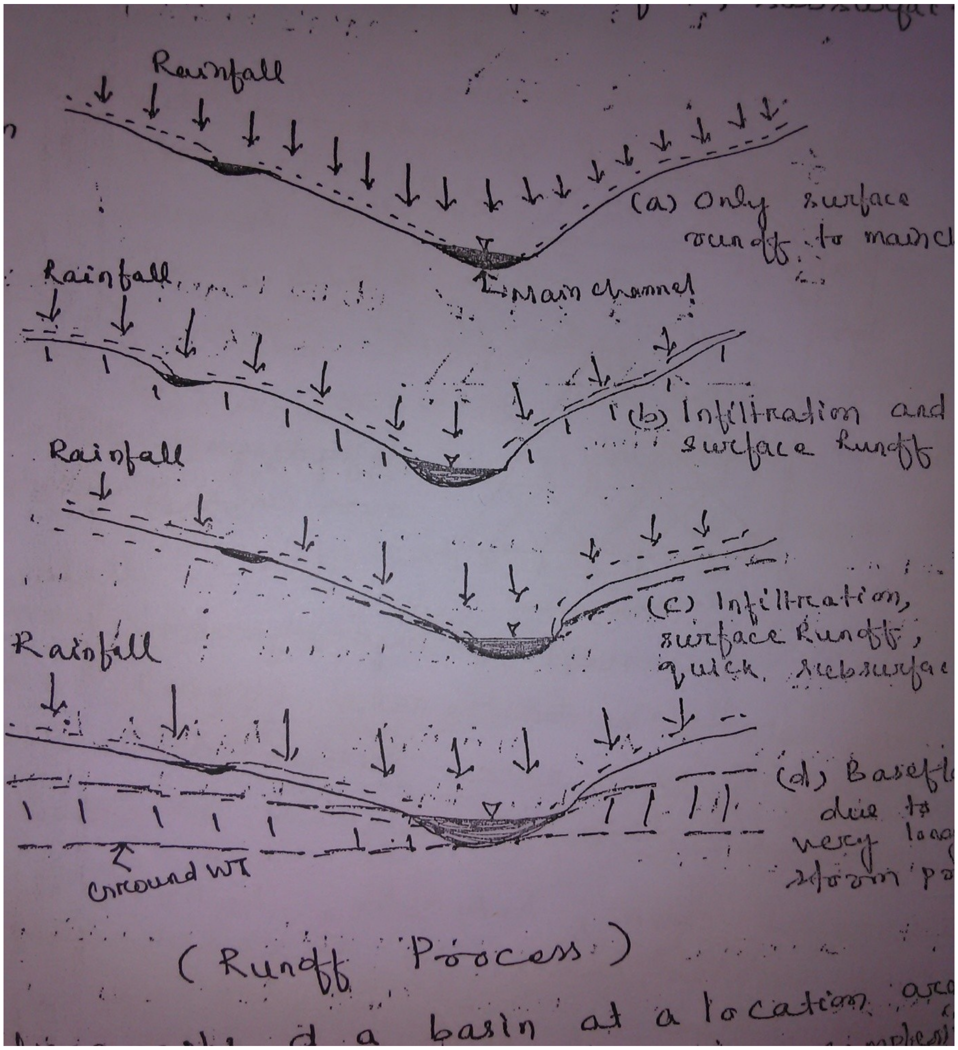
ENVELOPE CURVES

$Q_{mp} = 3025A/(278+A)^{0.78}$
Q_{mp} = max flood discharge (m^3/s)
A = Catchment Area (km^2)

HYDROGRAPH

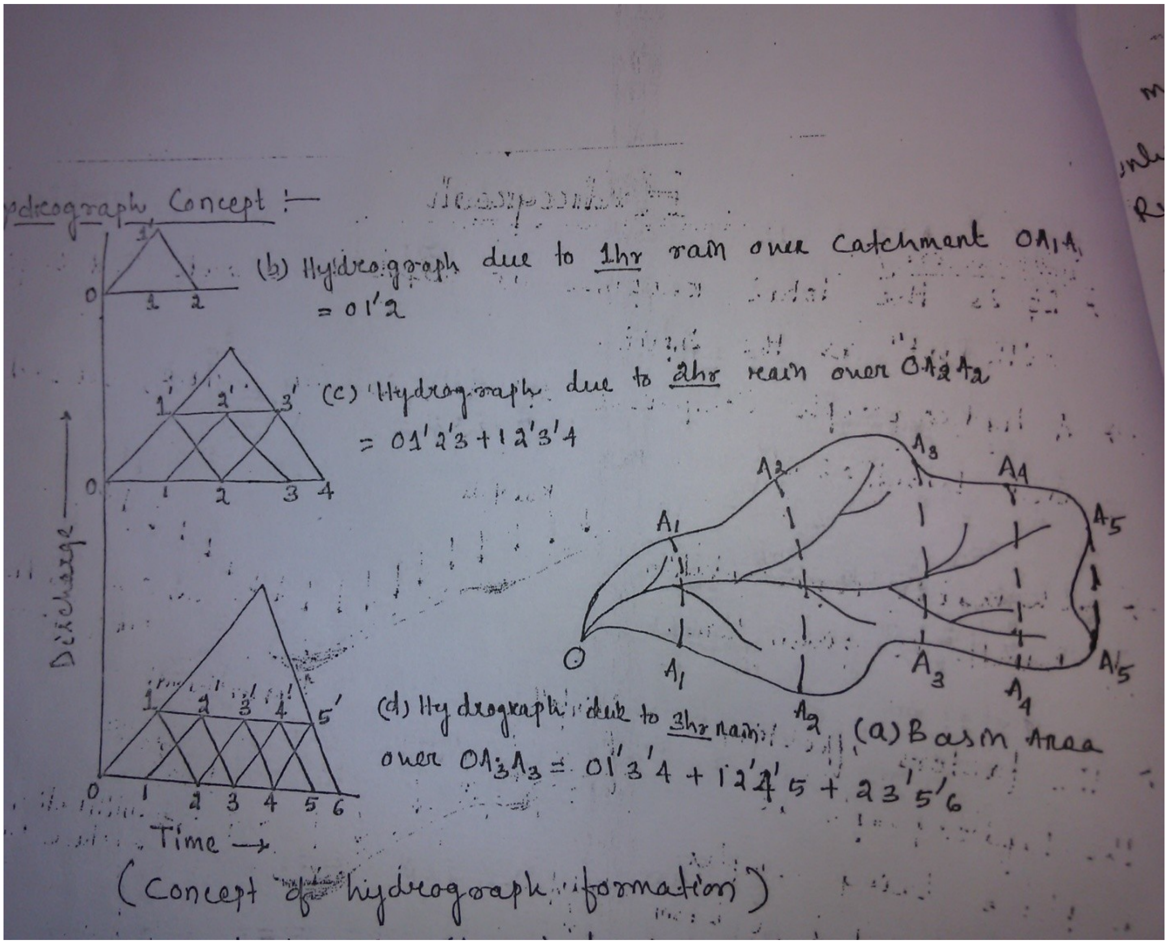
INTRODUCTION

- It is the total response or output of a watershed being with precipitation as input.
- A hydrograph comprises three phases namely surface, subsurface, and base flow .
- Schematic representation of runoff is given below:



- The factors affecting the hydrograph at a place being complex and interrelated a basin may not produce two exact flood hydrographs with two similar precipitations as input, nor can two basin of the same drainage area produce the same flood hydrographs with similar precipitation.
- When large number of hydrographs of a basin at a location is analyzed, their irregular shapes representing completely of the storm and the catchment character can be noticed.
- To being with a hydrograph resulting from a single storm is taken and its components are studied.

HYROGRAPH CONCEPT:



- Let us assume a basin area having uniform basin character with the entire area subjected to uniform rainfall and the condition of the catchment producing runoff are also uniform.

- The areas OA1A1,A1A1A2A2, A2A2A3A3,……….. are so divided that water takes one hour to reach from one boundary to the next below.
- First examine the hydrograph resulting from the first hour of the storm.
- Rainfall over the area OA1A1 is occurring for first hour. The runoff from line A1A1 takes one hour to reach at O . The hydrograph from the catchment area OA1A1 is shown as triangle 01’2. At the end of first hour when the runoff from the point O is still continuing at the catchment outlet, contribution from the boundary line A1A1 has started arriving. At this time all the area lying in boundary OA1A1 is contributing at O due to one hour rainfall. So the peak runoff resulting from the area OA1A1due to one hour rainfall occurs at the end of the one hour storm from the line A1A1takes one more hour to reach the at outlet O, that is at the end of second hour , when the last drop of the water from the boundary line A1A1 reaches at O ,the runoff hydrograph becomes zero .

- It may be noted that the whole area contributed for one hour only at the outlet due to one hour rainfall.
- Runoff from the boundary area A1A1contributed at O from the end first hour to end of second hour and runoff from Oat O is available for one beginning and ending with storm period from zero to one hour
- Next imagine that rainfall for one hour occur only in the area A1A1A2A2 which has started contributing to the outlet O after end of one hour and continued till the end of third hour .The resulting hydrograph is a triangle 12'3 as shown in the fig. with peak of flow at the second hour . Similarly if a second hour rainfall is imagined to have occurred in the area OA2A2 then the resulting hydrograph at O is the large triangle in fig(c).
- Similarly a three hour rainfall concentration over the area OA3A3 will produce a hydrograph of shape shown in fig (d) .
- Thus the hydrograph produced by one hour rainfall in the area are triangle at lags shown in figure. The combined effect will be when the total area is subjected to an uniform rainfall.
- The resulting hydrograph is the observed discharge from the catchment at outlet O . Any rainfall exceeding this time with the same intensity will produce a larger time base hydrograph. However the peak of the hydrograph will be of same magnitude and of longer time equal to the total rainfall period minus the time of travel of the drop of the water from extreme boundary point to the basin outlet.

FACTORS AFFECTING FLOOD HYDROGRAPH

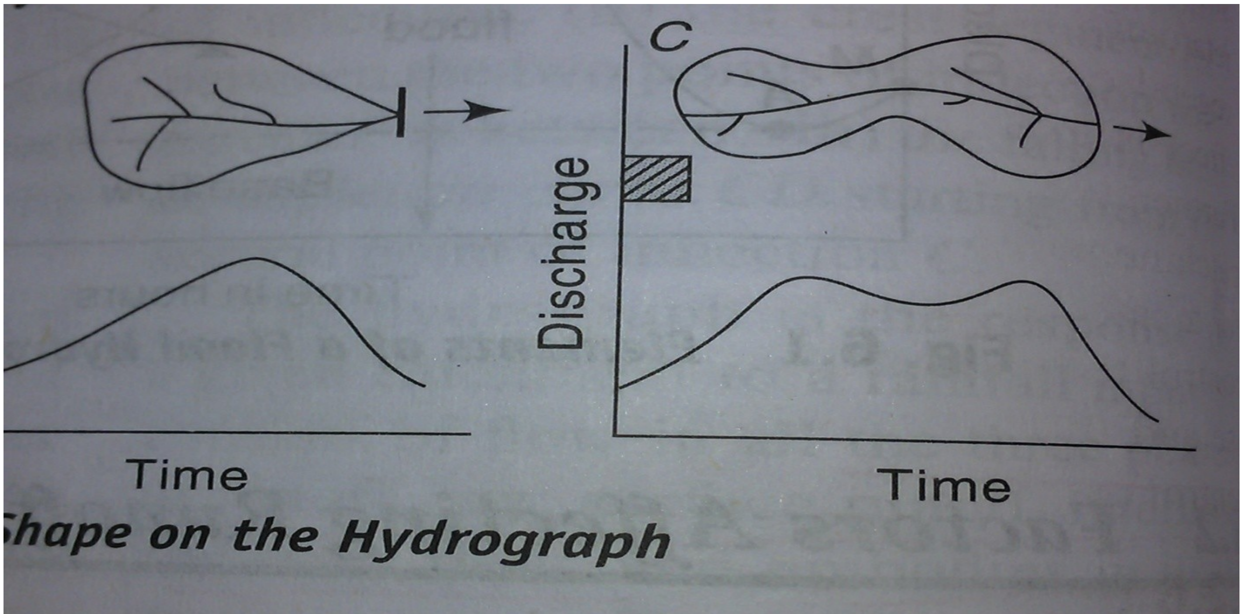
Two types of factors

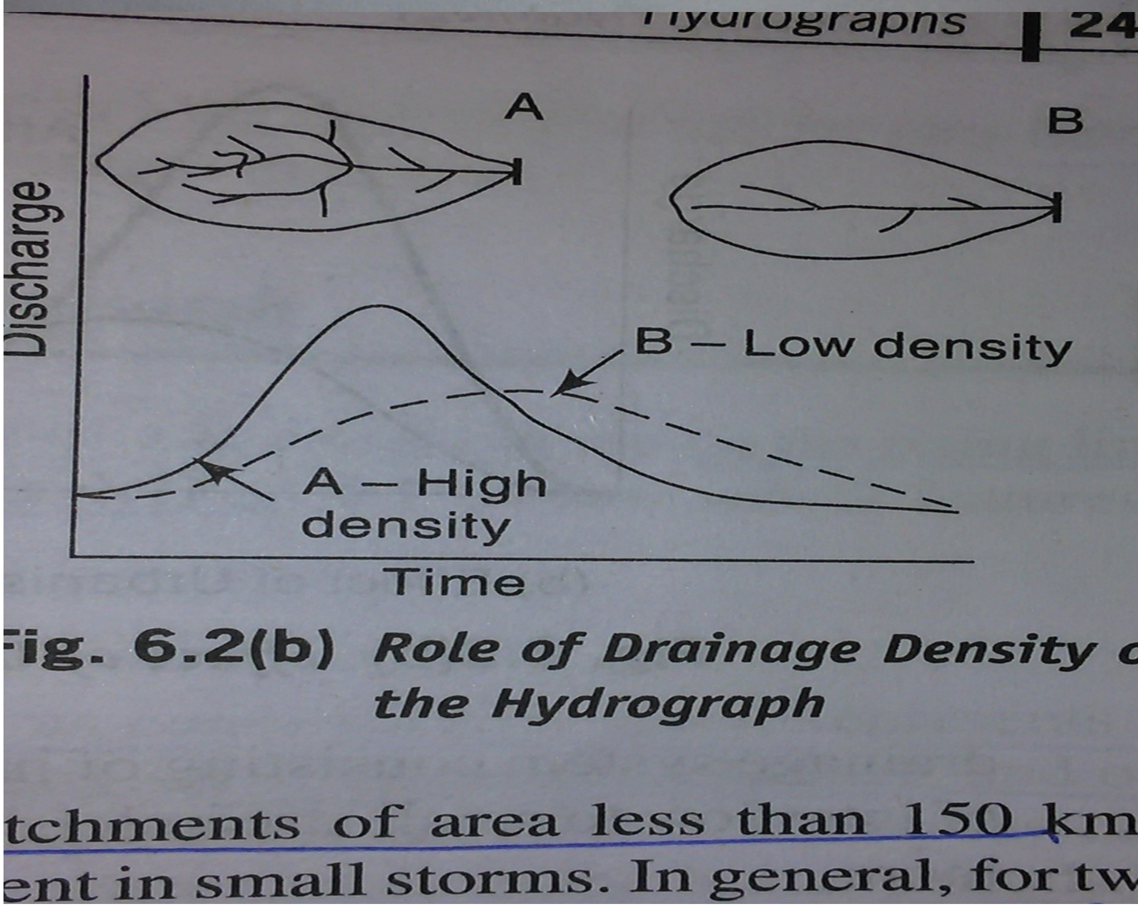
1. Physiographic
2. Climatic

- Climatic factors control the risking limb and recession limb is independent of storm character, only determined by catchment character.

1. Shape of the basin

- Shape of the basin influences the time taken for water from the remote part of the catchment to arrive at the outlet. So the occurrence of the peak and hence the shape of the hydrograph are affected.
- For semi circular shaped basin – high peak and narrow hydrograph.
- Elongated catchment – Broad and low peaked hydrograph.





2. Size of the basin

- In small catchment overland flow phase dominates channel flow. Hence land use and intensity of rainfall have important role on the peak flood.

- In large basin, these effects are suppressed as channel flow is dominant. Peak discharge is directly proportional to the A^n ,where A=area of the basin , n=exponent <1 (0.5 taken)
- Time base for large basin is greater than that of the smaller basin.
- Duration of the surface runoff from the time of occurrence of the peak is directly proportional to the A^m ,where m=0.2

3. Slope

- The slope of the main stream controls the velocity of the velocity of the flow in the channel.
- Recession limb represents the depletion of storage, hence slope has pronounced effect on it.
- Large stream slope – Quicker depletion – Steeper recession limb – Smaller time base

4. Drainage density

- Drainage density = (total channel length) / (total drainage area)
- Large drainage density – Quick disposal of runoff – Pronounced peak
- Small drainage density – Squat hydrograph with slowly rising limb

5. Land use

- Vegetation – increase infiltration – retards overland flow – reduces peak flow
- The effect is more pronounced in small catchment (<150Km^2) and small storms.
- This is the only factor which can be manipulated.

6. CLIMATIC FACTOR

- Three types 1.Intensity , 2.Duration , 3.Direction
- For a given duration, peak and volume of the surface runoff is directly proportional to the intensity.
- For small catchments shape of the hydrograph can also be affected by intensity.
- For a given intensity, duration of the storm is directly proportional to the volume of the run-off , effect of duration is reflected in the rising limb and peak. If rainfall of given intensity "i" lasts sufficiently long enough; "Q" is directly proportional to the "iA" will be reached.
- If the storm direction is u/s to d/s =Quicker concentration at outlet basin = Peaked hydrograph results

- If the storm direction is d/s to u/s = lower peak and larger time base
- Long and narrow catchment = hydrographs are most sensitive to storm movement direction.

COMPONENTS OF HYDROGRAPH

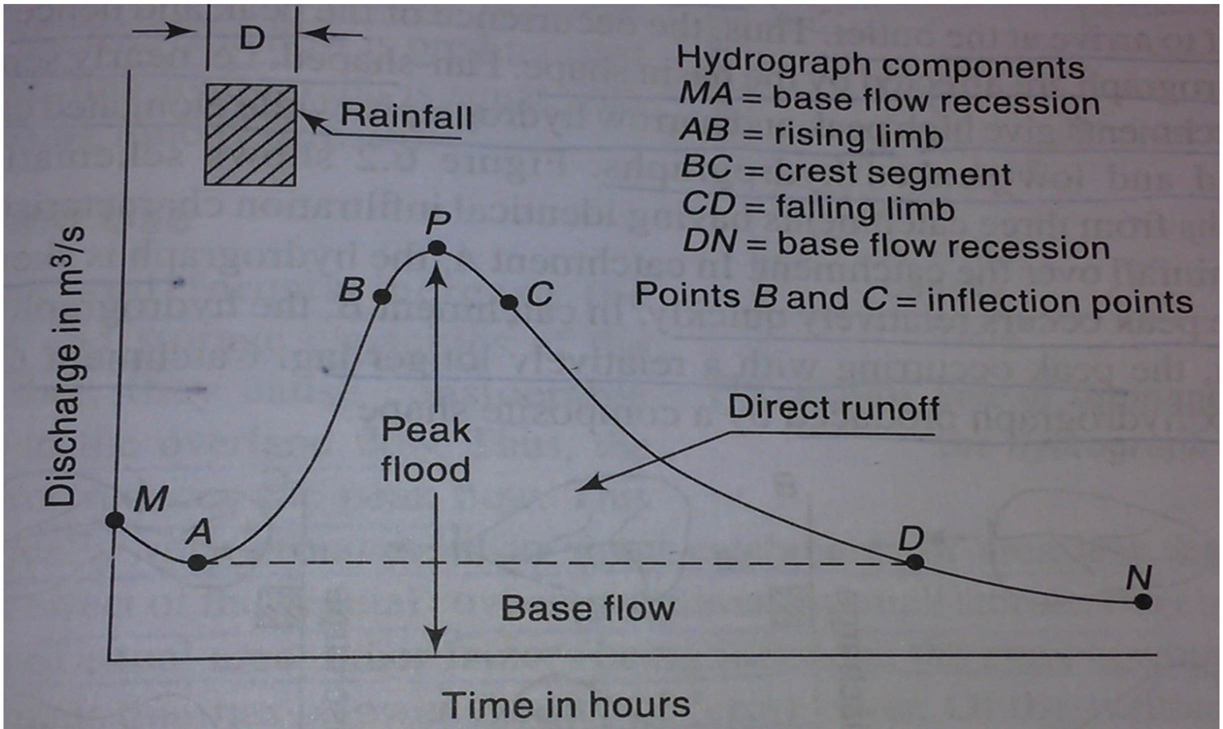


Fig. 6.1 Elements of a Flood Hydrograph

- Component of a hydrograph are
  1. Rising limb
  2. Creast segment
  3. Recession limb

Rising limb (A to B)

- Also known as concentration curve and represents the increase in discharge due to gradual increase in channels and over the catchment.
- It mainly influenced by storm and basin character.
- Generally it is concave, rising slowly in the early stage of the flood , but more rapidly to the end of the portion and this is due to high and variable initial losses at early stage.

- The rising limb is attributed due to contribution of more and more area at the gauging site over time, and also due to decrease in losses over time.
- It gradually reaches the peak when maximum area contributes their runoff at given outlet.

Creast segment (B to C)

- Most important portion as it contains peak flow.
- This is the portion between two inflection points of rising and falling limb.
- Peak occurs when various part of basin contribute simultaneously to the outlet at maximum rate.
- Generally peak flow occurs after cessation of rainfall.
- Multiple peaked complex hydrographs in a basin occur when two or more storm occurs in succession.

Recession limb (C to D)

- This limb is the convex curve representing the withdrawal of water from the storage build up in the basin up in the basin with max at "C".
- Since the depletion of the storage takes place after the recession of rainfall , the shape of the hydrograph is independent of the storm character and depends entirely on the basin character.
- Point "D" represents where the contribution to the channel is purely from ground water.
- When he storm concentrates more near to the outlet , then the length of this curve is shorter where as if rainfall concentrates at the far end of the catchment the recession limb is channel storage.
- The curve is mathematically represents as :

$$Qt = Qo\ (Kr \wedge t)$$

{Where, Qt =discharge at time t

Qo = discharge at time t=0

Kr =recession constant <1 }

Otherwise ,

$$Qt = Qo\ (e \wedge -at) \quad \text{where } a = -\ln Kr$$

- This equation is good for the lower portion of the curve where the contribution is mainly from ground water.
- In the upper part of the curve, contribution from surface storage, subsurface storage and ground water.

$$K_r = K_{rs} \cdot K_{ri} \cdot K_{rb}$$

K_{rs} =recession constant for surface storage

K_{ri} =recession constant for interflow

K_{rb} =recession constant for base flow

When time in days,

K_{rs} =0.05 to 0.2

K_{ri} =0.5 to 0.85

K_{rb} =0.85 to 0.99

When interflow is not significant, K_{ri} =1

If at 2time instances t1 &t2

(Q1/Q2) = Kr ^ (t1 – t2)

(Q1/Q2) = e ^ -a(t1-t2)

- Time to peak (t_p)

- It is the time lapse between the starting points of the rising limb (A) to the peak of the hydrograph (P).
- It is represented in days for large basins for and hours for small basins.
- Factor affecting "tp" are rainfall distribution over the basin , storm duration , travel time of water and other catchment character

- Time lag (t_l)

- It is the interval between center of mass of rainfall hyetograph to the centre of mass of runoff hydrograph, measured from the same axis.
- Otherwise it can be taken as time lapse between the centre of mass of the effective rainfall hyetograph and peak of hydrograph.

- Time of concentration (t_c)

- It is the time taken by the raindrop at farthest point of the catchment to reach at outlet.
- It can estimated by Kirpich formula

  (tc)=0.000323*L^0.77*S^-0.385

  (tc) =time of concentration (hr)

  L =max length of travel of water (m)

  S =sloe of channel =H/L

  H =elevation diff bet^ remote point in the channel and outlet point
- Basically time to peak +storm duration =tc =tp+tr
- (tc) =1.42*tl

- Time base of hydrograph (T_b)

- It is considered as the time bet^ the starting of the runoff hydrograph (A) to the end of direct runoff (D) due to storm.
- Tb = tc +tr

❖ Direct runoff

- It is the part of precipitation which appears quickly as flow in the river.
- DR = surface runoff +sub surface runoff

❖ Base flow

- The part of runoff represented by a hydrograph which receives water from the ground water storage is called as base flow.
- Natural springs and river banks contribute to base flow in non rainy periods.
- Total Runoff = Direct runoff + base flow
- When a storm hydrograph is available , after separation the base flow , the residual left is DRH.

Base flow separation

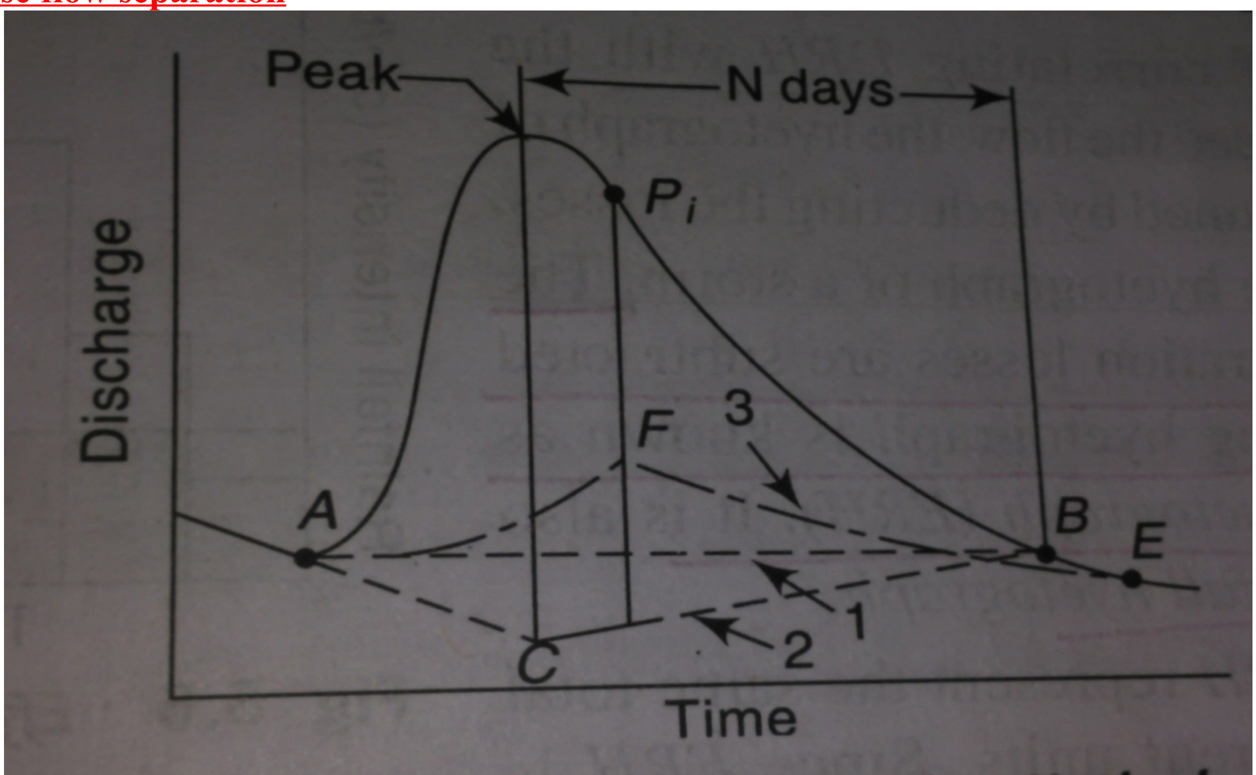


Fig 6.5 *Base Flow Seperation Methods*

- The relationship bet^ the surface flow hydrograph and the effect rainfall is to be established.
- The surface flow hydrograph is established by deducting the base flow from the storm hydrograph.

Method:1 (Straight Line Method)

- It is the simplest method of base flow separation which is obtained by joining the beginning point of DRH (A) to the end of DRH (D) through a straight line.
- Point "A" is easily identified by noticing the sharp charge in the runoff rate at that point.
- Point "D" is located empirically as "N" days from peak.
- N=0.83*A^0.2 ; where A=Drainage area N=time in days

Method:2

- Here base flow curve existing prior to the commencement of surface runoff (A'A)is extended till it intersects the ordinate drawn from peak at Pi.
- Join Pi to D by a straight line.
- This method is most widely used.

Method:3

- In this method , the base flow recession curve after the depletion of the flood water (ED) is extended back word till it intersects the ordinate at the point of the inflection.
- Point A and F are joined by an arbitrary smooth curve.
- This method is realistic when ground water contribution is significant and the stream quickly.
- The surface runoff hydrograph after the separation of base flow is known as runoff hydrograph (DRH).

Unit hydrograph:

- An unit hydrograph or unit graph is the hydrograph of direct runoff resulting from unit depth of 1cm rainfall excess generated uniformly over the basin for a specified duration (D hrs) at a uniformly rate.
- The "unit depth of rainfall excess" mean excess rainfall over and above all losses in the basin under consideration.
- The "duration" is the period of the rainfall excess which is assumed to be uniformly distributed over the basin.
- The specified duration is important as the shape and the peak of hydrograph of a basin depends on it. e.g.- 3hr rainfall excess means 3h-UH

- An UH of D hr means, it is the duration of rainfall excess giving rise to the UH,but not duration of occurrence of UH.

Assumptions and conditions in UH:

1. Time Invariance:
   - This is the first basic assumption which says that direct runoff response to a given effective rainfall in a catchment is time invariant.
   - The DRH for a given ER in a catchment is always
   - Same irrespective of the time when it occurs.

2.Linear Response :
   - The direct runoff response to the rainfall excess is assumed to be linear.
   - Most important assumption of UH theory.
   - It means if an input X1(t)causes output Y1(t) and X2(t) – Y2(t) , then X1(t) +X2(t) gives Y1(t)+Y2(t) Consequently if X2(t) = r*X1(t) ; Y2(t)=r*Y1(t)
   - Thus, if a rainfall excess in a duration D is r times the unit depth , the resulting DRH will have ordinates bearing ratio "r" to those of the corresponding D-hr . The base will same but the area of DRH will be increased r times that of UH.

Application of UH:

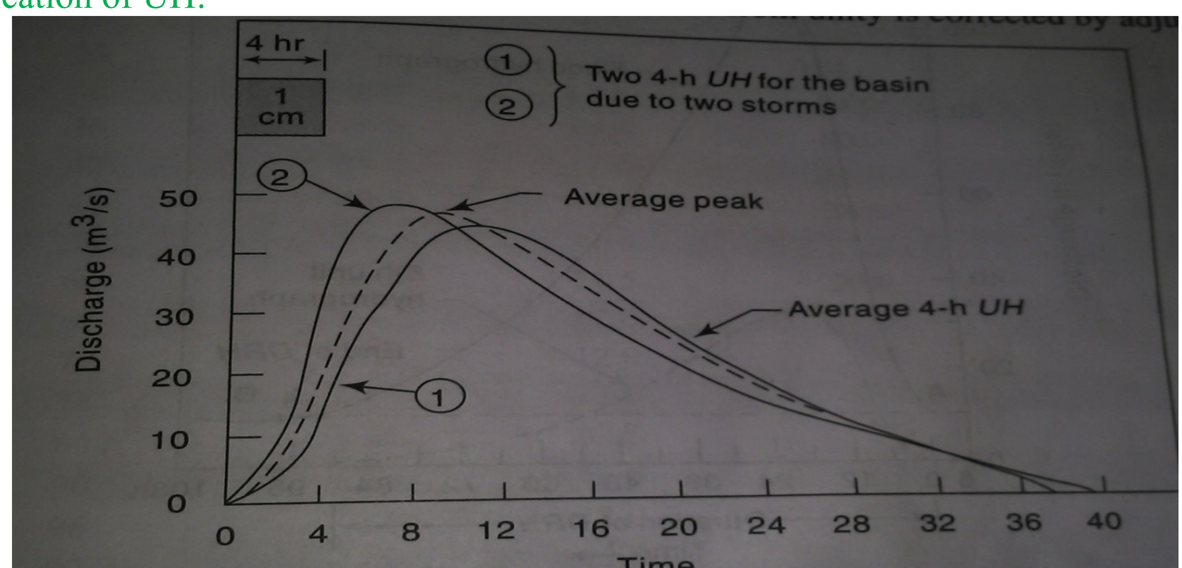


Fig. 6.12 *Derivation of an Average Unit Hydrograph*

- The number of isolated storm hydrographs caused by short spells rainfall excess, each of approx same duration (0.9 to 1.1 Dh) are selected.
- For each storm hydrographs, the base flow is separated.
- The area under each DRH is evaluated and the volume of the direct runoff obtained is divided by catchment area to obtained the depth of ER.
- The ordinate of various DRH are divided by the respective ER value to obtain the ordinate of the UH.
- Flood hydrograph used in the analysis should have the following features:
    - Storm should be isolated i.e occurring individually
    - Rainfall should be fairly uniform during the duration and should cover the entire catchment area.
    - The duration of rainfall should be 1/5 to ½ of the basin lag.
    - The rainfall excess of the selected storm should be high. (Range :1to 4 cm preferred)
- A number of UH of a given duration are derived by above method and plotted on a common pair of axes.
- Mean of such curves as the UH is adopted.
- While deriving the mean curve, the average of peak flows and time to peaks are first calculated.
- Then a mean curve of best fit is drawn through the average peak on an average base length.
- The volume of DRH is calculated and any departure from unity is corrected by adjusting the value of the peak.
- The average ERH is drawn of unit depth to indicate the type and duration of rainfall causing the UH.

UH from a complex storm :

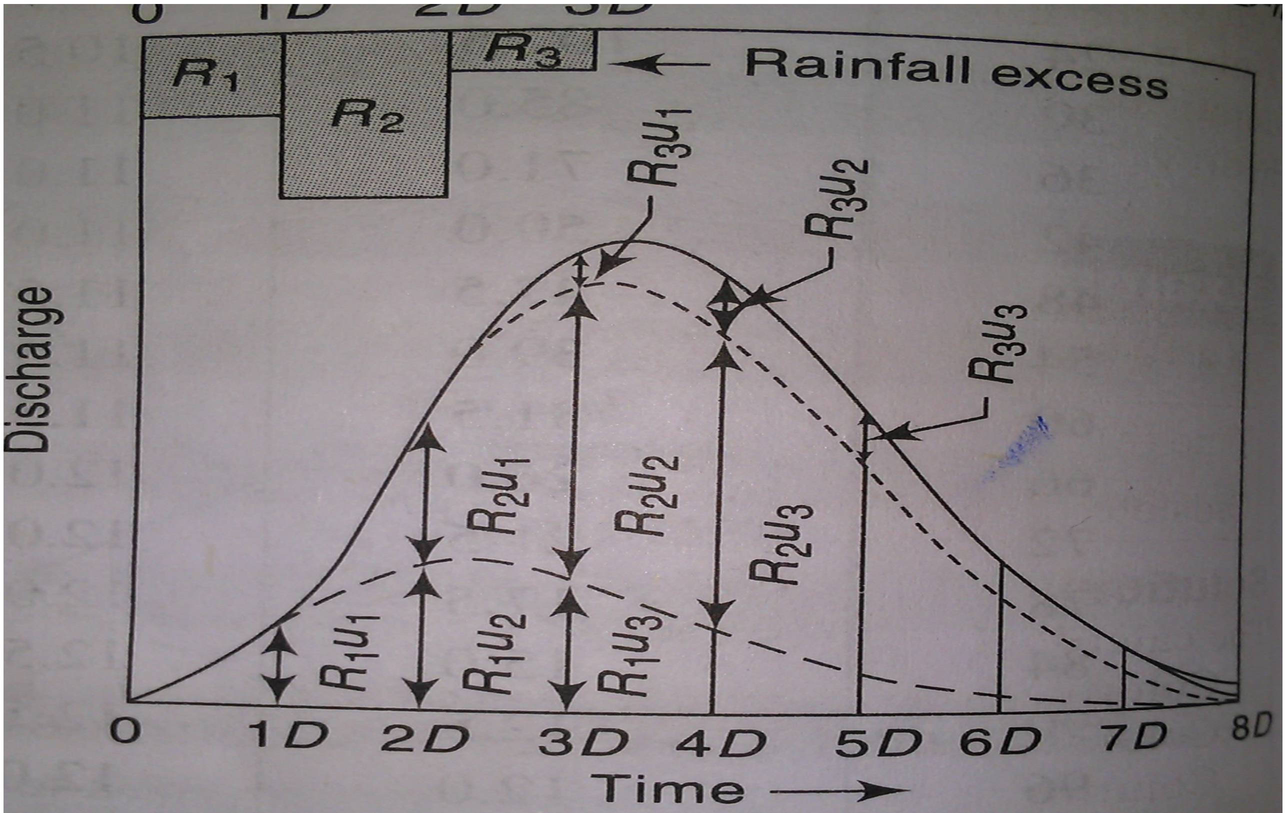


Fig. 6.14 *Unit Hydrograph from a Complex Storm*

- When simple isolated storms are not available, data from complex storms of long duration are used for UH.
- 1st to decompose a measured composite flood hydrograph into its components DRH and base flow.
- A common UH of appropriate duration is assumed to exist.
- Let a rainfall excess of 3 duration of D-h and ER of R1 , R2 , and R3 interval 1D ,2D ,3D ……… from the short of ERH.
- Let the ordinates of UH be U1,U2 ,U3 ……. And ordinates of composite DRH be Q1, Q2, Q3………

  Then

  Q1=R1u1

  Q2=R1u2+R2u1

  Q3=R1u3+R2u2+R3u1

  Q4=R1u4+R2u3+R3u2

  ………………………………

From the above equations u1, u2, u3 can be determined. In this method, error propagate and huge calculation.

Distribution Graph:

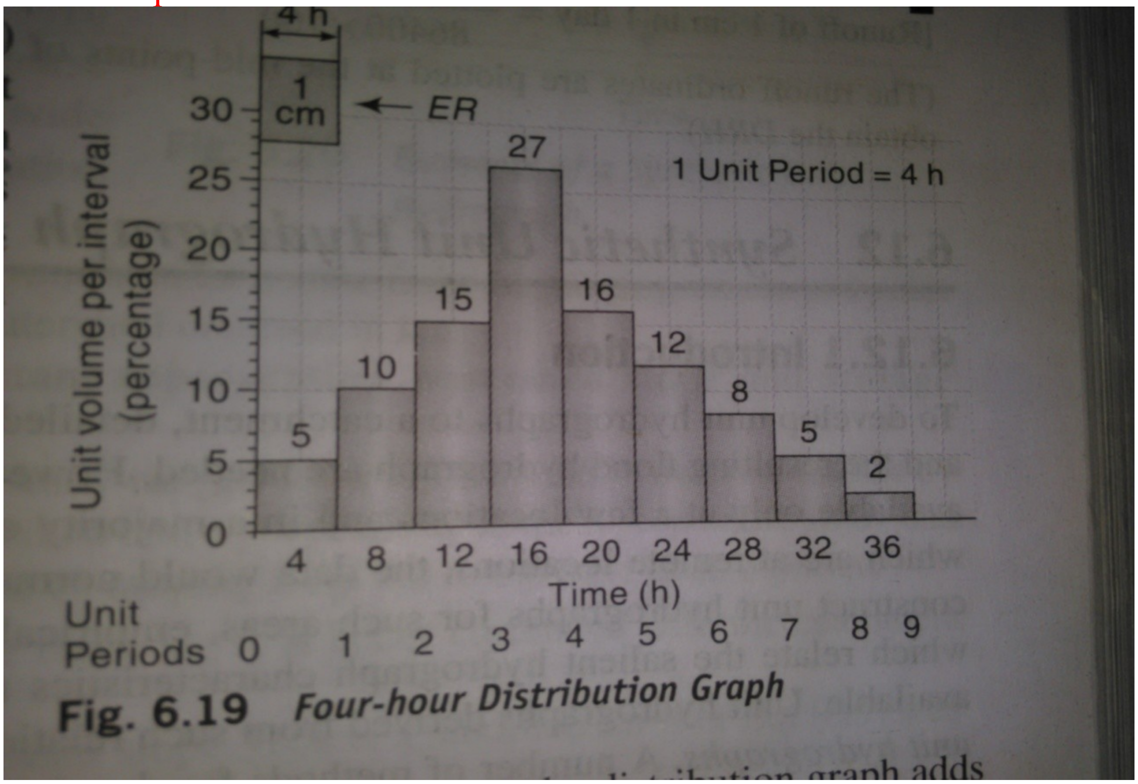


Fig. 6.19 Four-hour Distribution Graph

- Introduced by Bernard (1935)
- Shows variation if the UH.
- It is a D hr with ordinates showing the % of the surface runoff occurring in successive periods of equal time intervals of D hr.
- The duration ER is taken as unit interval and distribution graph ordinates are indicated at successive such intervals.
- In fig. interval =4 hr

  Total area under the distribution graph =100%
- The use of distribution graph is to generate a DRH for a known ERH is exactly the same as that of UH.
- These are used to compare the runoff character of different catchment.

Instantaneous Unit Hydrograph (IUH):

- UH are named as per their duration of rainfall excess.
- With decrease in duration, peak will shifted towards left axis.
- In a limiting case , when the duration of rainfall excess becomes infinitesimally small e.g 1cm of ER is spread over the catchment uniformly and instantaneously , the resulting DRH is know is known as 1UH.(D-0)
- The notation of 1UH is U(0,t) where as for UH is U(D,t).

- Since it is impossible for a basin to get 1 cm ER in 0 time so 1UH concept is purely theoretical and defined as a fictitious UH representing the surface hydrograph from a basin resulting from instantaneous rainfall excess volume of 1cm over the basin.
- The advantages of 1UH is the eliminated of a major parameter “the duration of effective rainfall” from the UH.
- The ordinate of DRH at time t , derived from an 1UH is

  Qt= ∫ U(t-T) I(T) dT

  U(t-T) = IUH ordinate at time T

  I(T) = rainfall excess function of duration to at the time T

  dT = extreme small element of ERH

  t’ =t when t<to

  t’ =to when t>to
- This Eq^ is called convolution integral or Duhamel integral in which the IUH , U(t-T)is called Kernel function
- Convolution of IUH and I(T) is shown in fig. where the shape of the IUH resembles a single peaked hydrograph.
- Here an instantaneous rainfall function I(t) of duration to get DRH from a catchment whose discharge at any time t is given by the integral.
- If UH is represented by U(D,t) where D is the unit duration or simply the duration of ER and t represents the time , then the ordinate of UH is represented as U or U(D,t)
- For an IUH , D=0 the ordinate of IUH at time t is U(0,t) or simply U(t)
- Properties of IUH are :
  - U(t)>0 ,when t>0
  - U(t)=0 ,when t<0
  - U(t)---0 when t---∞
  - ∫U(t) dt =unit depth of catchment
  - ∫U(t) t dt = the time lag of IUH (tl)
  - tp of IUH <time of the centroid of the curve

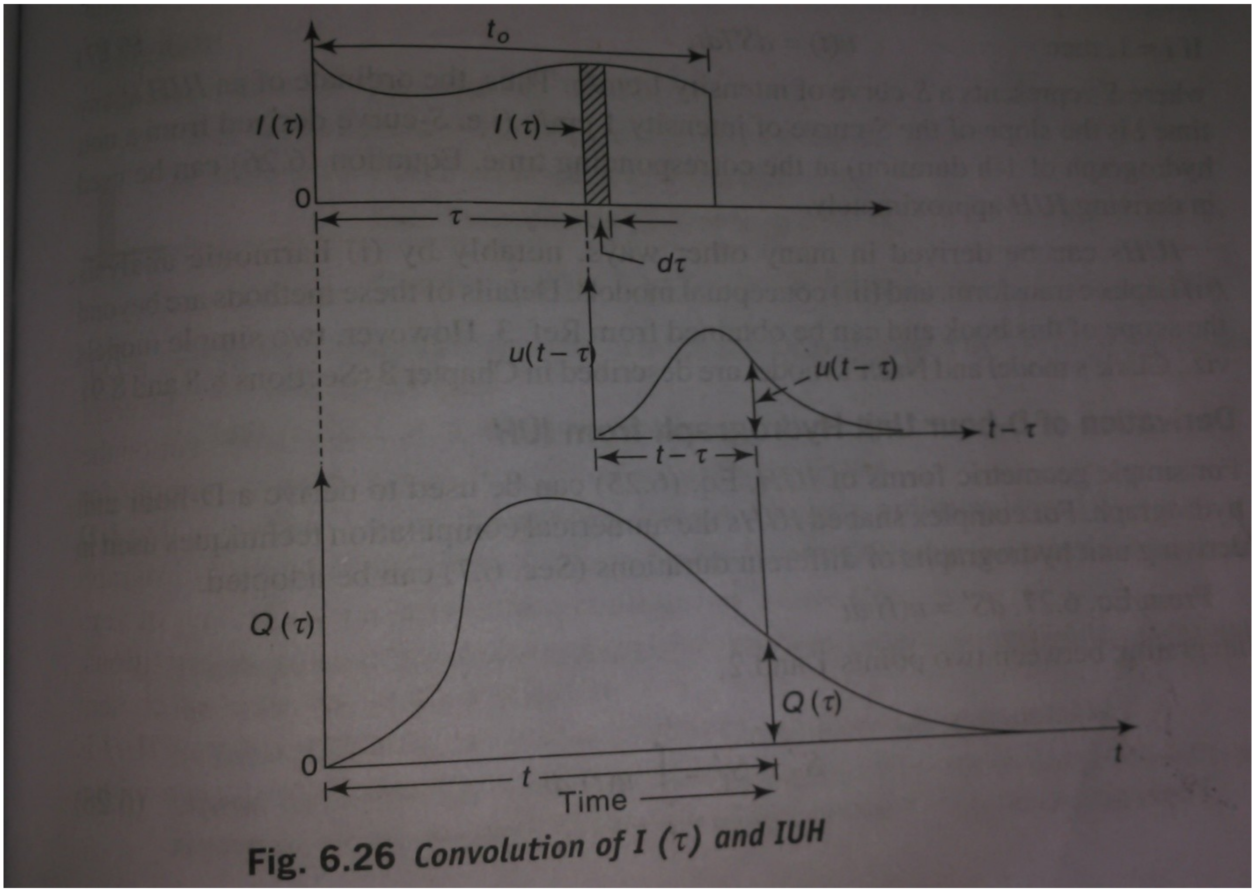


Fig. 6.26 *Convolution of I (τ) and IUH*

Derivation of IUH :

- IUH can be derived by :
  1. From S-Hydrograph
  2. From conceptual models
  3. By fitting harmonic series to DRH and ERH
  4. Theorytically from Laplace transform function

From S – hydrograph:

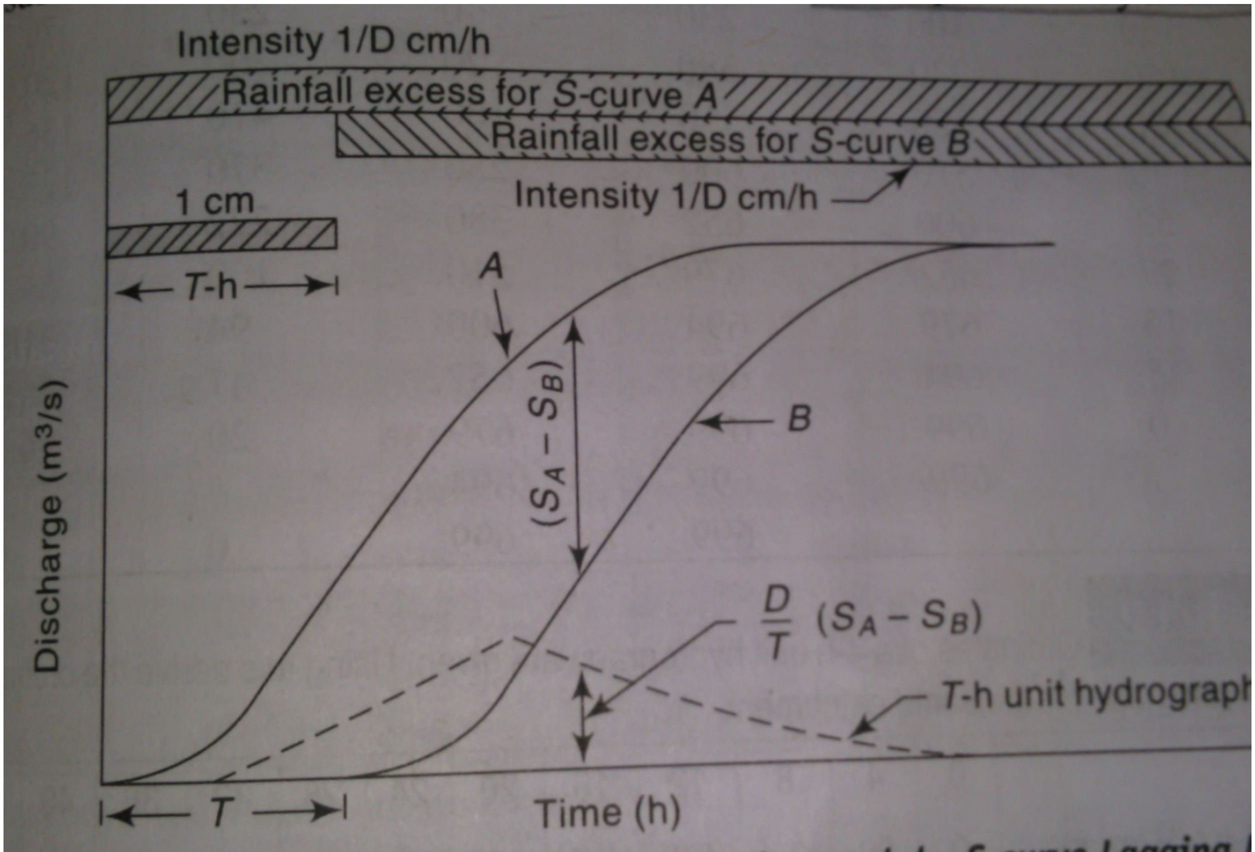


Fig. 6.18 *Derivation of a T-h Unit Hydrograph by S-curve Lagging*

- When 2S hydrographs are separated by dt hr , then dt hr ordinate = (S1-S2)/(dt/D) =(S1-S2)/(i*dt) ,i=1/D cm/hr
- In a limiting case where case where dt—0, then the time of ER is infinitesimally small and the result will be IUH.
- So the IUH ordinate at any instant "t" is given as:
- U(t)= ΔS/(i*Δt) =ΔS/Δt =ds/dt
- This means that when a S-hydrograph derived from an UH of 1 hr ER i.e 1cm/hr , then the slope of the S-hydrograph gives IUH ordinate at any time t from the origin of the S-hydrograph.

Derivation of UH from IUH :

- IUH is derived from any conceptual model then it can be used for UH derivation in the following steps:
- Prepare a table in which col (1) contains and col (2) contains IUH ordinates
- In col(3) enter the IUH ordinates of step(2) by lagging D hr , the required duration of UH.
- Col(4)= col(2) + col(3)
- Col(5)=col(4)/2 (this col shows UH of D hr duration)

- It is to be noted that the D hr UH obtained by the above process should not be >3hr
- If larger duration is required, then the process of S-hydrograph or method of superposition may be adopted.
- The ordinate of UH at any instant (t) is (S1-S2)/(i*dt)
- If the intensity of rainfall for the UH from which S-hydrograph is derived is i=1cm/hr i.e S hydrograph his derived from a 1hr UH ,then U(t)=Δs/Δt ,is approx the slope of S-hydrograph is derived .Ina limiting case where dt—0,then ER time will be small.
- As ΔS becomes very small, the slope of S-curve at any instant "t" is the ordinate of IUH.

U(t)=ds/dt as dt—0

ds=U(t) dt

=∫ds=∫U(t) dt

=S2-S1=∫U(t) dt

=1/2 [u(t2)+u(t1)](t2-t1)

As bet^ 1&2 we can always take

U(t)=1/2[U(t2)+U(t1)]

(S2-S1)/(t2-t1)=1/2 [U(t2)+U(t1)]

- Thus by taking average of IUH ordinate at dt =(t2-t1) gives a dt hr UH. Dt<1hr because bet^ t2 and t1, the profile of hydrograph is curvilinear and for large diff of time it may error in its average value.

FLOOD ROUTING

- Flood routing is the technique of determining the flood hydrograph at a section of a river by utilizing the data of flood flow at one or more upstream sections.
- Useful for flood fore-casting, flood protection, reservoir design, spillway design etc.
- Flood routing is of two types :-

  1. Reservoir routing

2. Channel routing

RESERVOIR ROUTING

- Here the effect of a flood wave entering a reservoir is studied.
- Knowing the volume-elevation relation of reservoir, outflow-elevation relation and spillways, the effect of a flood wave entering the reservoir is studied to predict the variations of reservoir elevation and outflow discharge with time.
- This is essential
  1. For design capacity of spillways and other outlet structures.
  2. In the location and sizing of the capacity of reservoir to meet specific requirements

CHANNEL ROUTING

- Here the change in the shape of a hydrograph as it travels down a channel is studied.
- By considering an input hydrograph at upstream end, it helps to predict flood hydrographs at various reach.
- Provides information on the flood peak attenuation and the duration of high water levels obtained by channel routing which help in flood forecasting.

ROUTING METHODS

- It is of two types:-
  1. Hydraulic routing
  2. Hydrologic routing
- Hydrologic routing methods employ only the equation of continuity whereas the hydraulic routing methods employ the continuity as well as equation of motion of unsteady flow.
- Basic differential equation used in hydraulic routing is known as st. venant equation.

BASIC EQUATIONS

- Flood hydrograph through a reservoir is an unsteady flow phenomenon.
- Equation of continuity used in all hydrologic routing as the one degree equation which states that the difference between the inflow and outflow rate is equal to change of storage i.e

Where I = inflow rate
Q = outflow rate
S = storage

If Δt = small time interval

$I\,\Delta t - Q\,\Delta t = \Delta S$

I = average inflow in time Δt
Q = average outflow in time Δt
ΔS = change in storage

By taking $I = (I_1 + I_2) / 2$, $Q= (Q_1 + Q_2)/2$, $\Delta S= S_2 - S_1$

⇨ $() \Delta t - () \Delta t = S_2 - S_1$

- In the differential form the equation continuity for unsteady flow in a reach with no latenal flow is given by

Where T= top width of the section
Y= depth of flow

- The equation of motion for a flood wave is derived from the application of the momentum equation as

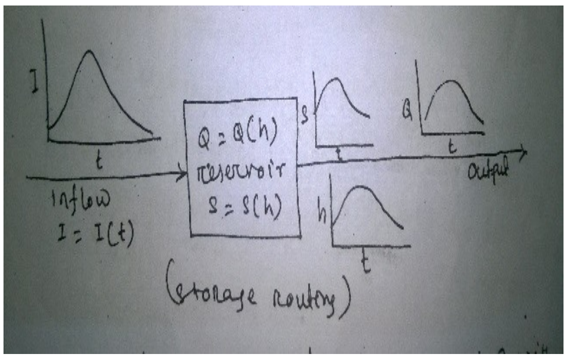
Where V= velocity of flow at any section
So = Channel bed slope
Sf = Slope of the energy line

Eqn 4 is the continuity equation and Eqn 5 is eqn of motion and both are known as st. venant equation.

HYDROLOGIC STORAGE/RESERVOIR ROUTING

- Let the inflow to the reservoir = I(t)

Outflow is a function of reservoir elevation only. Q=Q (h)
Storage in the reservoir is a function of the reservoir elevation. S = S (h).
Due to the passage of the food wave through reservoir, the water level in the reservoir changes with time, h = h (t).And hence the storage and discharge change with time.



- It is required to find the variation of S, h and Q with time i.e find s =s(t), Q= Q(t) and h = h(t) given I = I (t).

- If an uncontrolled spillway is provided in a reservoir, typically

)
Where L = effective length of spillway crest
Cd = Coefficient of discharge

- For reservoir routing, the following data should be known.
  1. Storage volume vs elevation for the reservoir.
  2. Water surface elevation vs outflow and hence storage vs outflow discharge.
  3. Inflow hydrograph, I = I(t)
  4. Initial values of S, I and Q at time t=0.

As the horizontal water surface is assumed in the reservoir, the storage routing is also known as level pool routing.

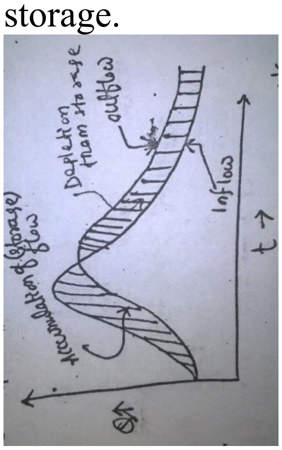
MODIFIED PUL'S METHOD

) Δt – =

- At the starting of flood routing, the initial storage and outflow discharges are known.
  In the above equation all the terms in the lhs equation are known as beginning of a time step Δt.
- Hence the value of the function at the end of time step is calculated by the above equation.
- The relation S= S(h) and A= A(h) are known, will enable one to determine the reservoir elevation and hence the discharge at the end of the time step. The process is repeated to cover the full inflow hydrograph.

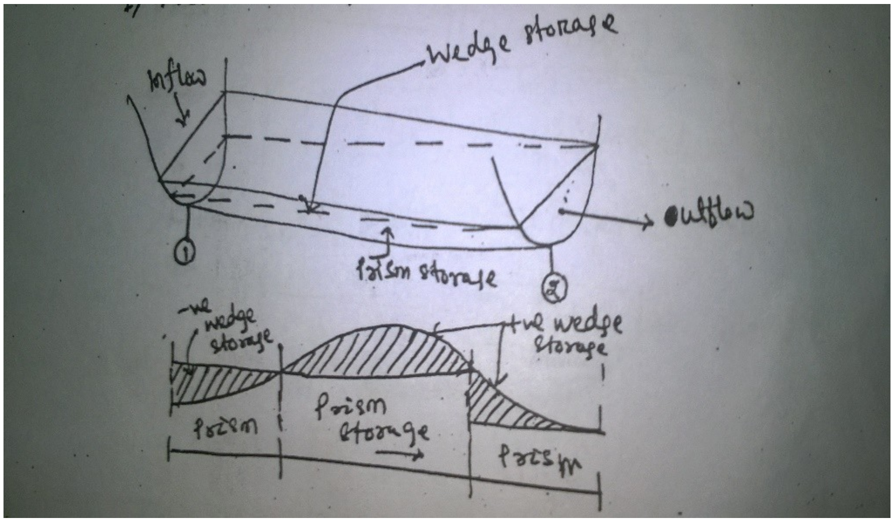
ATTENUATION

- Because of the storage effect, the peak of the outflow hydrograph will be smaller than that of the inflow hydrograph. The reduction in peak value is called attenuation.
- The peak of outflow occurs after the peak of the inflow, the time difference between the two peaks is known as lags.
- In the rising part, the inflow curve is higher than outflow. So the in between area represents accumulation of flow or storage.
- In the falling part, reverse case and the area represents depletion from storage.



HYDROLOGIC CHANNEL ROUTING

- In reservoir routing, storage is a unique function of outflow discharge i.e S = f(Q).
  But in channel routing the storage is a function of both inflow and outflow discharges.

- Considering a channel reach having a flood flow, the total volume in storage can be considered under two categories
  1. Prism storage
  2. Wedge storage
  3. 

PRISM STORAGE

- It is the volume that exist in the uniform flow occurred at the downstream depth i.e the volume formed by an imaginary plane parallel to the channel bottom drawn at the outflow section water surface.

WEDGE STORAGE

- It is the wedge like volume formed between the actual water surface profile and the top surface of the prism storage.at the fixed depth at a downstream reach, the prism storage is constant while the wedge storage changes from a positive value at an advancing flood to a negative value during a receding flood.
- The prism storage is similar to a reservoir and can be expressed as a function of the outflow discharge Sp = f(Q).
- The wedge storage can be accounted for, by expressing it as Sw = f(I).
  The total storage in the channel reach can then be expressed as

$$S = K\,[\,xI^{M} + (I - x)Q^{M}\,]$$

Where K & x = coefficients, m = constant exponent
m = 0.6 for rectangular channel
= 1.0 for natural channel

MUSKINGUM EQUATION

- Using m= 1.0, in above equation, it reduces to a linear relationship for S in terms of I and Q as

$$S = K [xI + (I - x)Q]$$

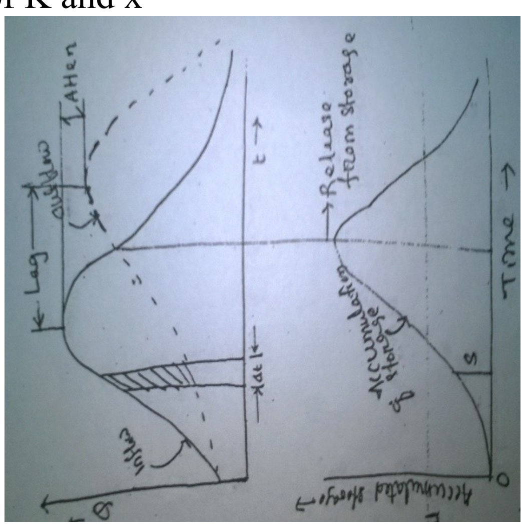
And this relationship is known is known as muskingum's equation,

Here x= weighting factor = 0 – 0.5

When x= 0 => S=KQ
Where S = linear storage/linear reservoir.

When x= 0.5, both I and Q are important for S calculation.
K = storage time constant (dimension same with time)
= time of travel of a flood wave through the channel required.

- Estimation of K and x



1. In the figure, the outflow peak doesn't occur at the point of intersection of the inflow and outflow hydrographs.
2. Using the continuity equation

$) \Delta t - () \Delta t = S_2 - S_1$

The increment in storage at any time t and time element Δt can be calculated. Summation of various incremental storage values enables one to find the channel storage S vs T.

3. In an inflow and outflow hydrograph set is available for a given reach, values of S at various time intervals can be determined by the above technique.
4. By choosing a trial value of x, values of S at any time t are plotted against corresponding [xI + (I – x)Q] values.
5. If the values of x is chosen correctly a straight line relationship given by above equation will result. If incorrect x, then a looping curve.
6. By trial and error the x values is so selected that straight line should be plotted.
7. The increased slope of this straight line will give the value of k.
8. For natural channels x ranges from 0 to 0.3.

For a given reach, the values of x and K are assumed to be constant.

MUSKINGUM'S METHOD OF ROUTING

For a given channel reach by selecting a routing interval Δt and using the muskingum eqn

The change in storage is

$$S_2 - S_1 = K [x(I_1 - I_2) + (I - x)(Q_2 - Q_1)]$$

Where 1,2 refer conditions before and after time interval Δt the continuity equation for the reach is

$$) \Delta t - () \Delta t = S_2 - S_1$$

From above two equation, Q2 is evaluated as

$$Q_2 = C_0 I_2 + C_1 I_1 + C_2 I_1$$

Where

C1 +C2+ C3 = 1.

Above equation can be written as in general form for the nth time step as

$$Q_n = C_0 I_n + C_1 I_{n-1} + C_2 I_{n-}$$

The above equation is known as Muskingum routing equation and provides a simple linear equation for channel routing.

For best results, Δt should be so selected as

$$K > \Delta t > 2kx, C_0 = \text{positive}$$

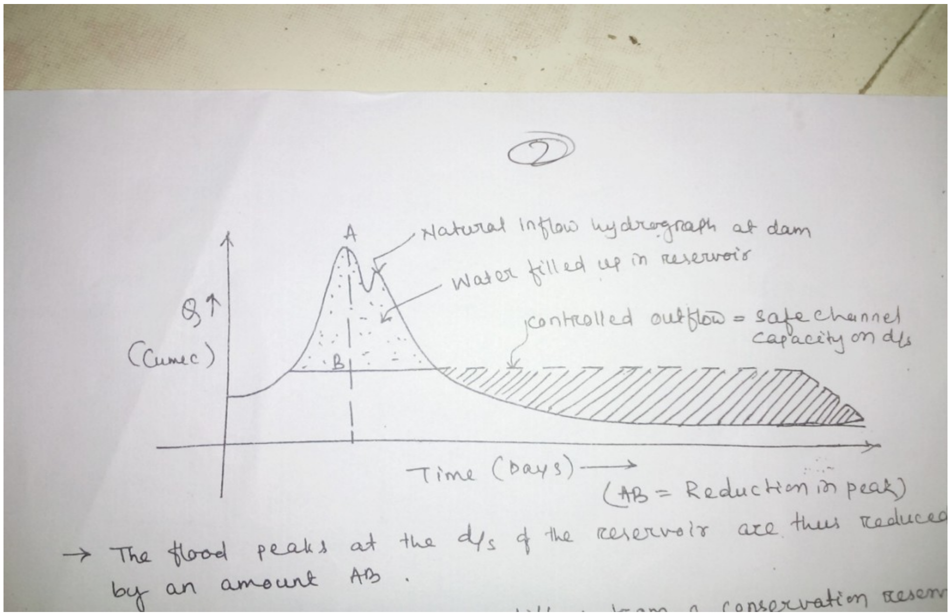
RESERVOIR MANAGEMENT

->when a barrier s constructed across some river in the form of a dam , water gets stored on the upper stream side of the barrier, forming a pool of water ,generally called a dam reservoir or an impounding reservoir or a river reservoir or a storage reservoir .

- Depending upon the purpose of by a given reservoir they may be classified as:
    1. Storage or conservation reservoirs
    2. Flood control reservoirs
    3. Multipurpose reservoir
    4. Distribution reservoir

- Storage or conservation reservoirs:-
    - ✓ It can be retain excess supplies during periods of peak flow and can release them gradually during low flows and when the need arises
- Flood control reservoir
    - ✓ Otherwise known as flood mitigation reservoir.

- ✓ It stores a portion of the flood flows in such a way as to minimize the flood peaks at the area to be protected downstream
- ✓ The inflows in access is stored in the reservoir, which is then gradually released so as to cover the storage capacity for next flood

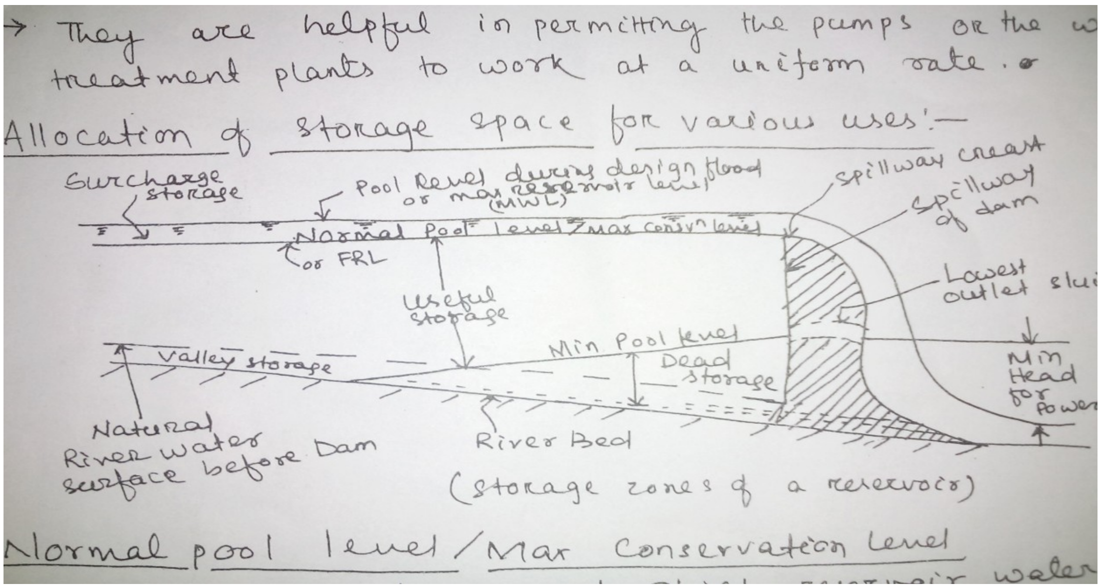


- ✓ The flood peaks at the downstream of the reservoir are thus reduced by an amount AB
- ✓ A flood control reservoir differs from a conservation reservoir only in its need for a large sluice way capacity to permit rapid draw down before or after flood
- ✓ FLOOD CONTROL RESERVOIRS:
  1. Storage reservoir/detention basin
  2. Retarding basin
  - ✓ A reservoir having gates and valves installation at its spillway and at its sluice outlet is storage reservoir while a reservoir with uncontrolled and ungated outlets is retarding basin

- MULTIPURPOSE RESERVOIR
  - ✓ A reservoir planned for and constructed to solve more than one problem together is called multipurpose reservoir
  - ✓ A reservoir is designed to protect downstream areas from flood and also to conserve water for water supply,irrigation ,industrial needs , hydroelectric purposes etc shall be called a multipurpose reservoir

    Eg:bhakra nangal dam ,nagarjun sagar yojna

- DISTRIBUTION RESERVOIR
  - ✓ It is a small storage reservoir constructed within a city water supply system
  - ✓ Such a reservoir can supply at higher rates than inflow in critical demand periods
  - ✓ They are helpful in permitting the pumps or the water treatment plant to work at a uniform rate
- ALLOCATION OF STORAGE SPACE FOR VARIOUS USES:-



- NORMAL POOL LEVEL/MAXIMUM CONSERVATION LEVEL
  - ✓ It is the maximum elevation to which reservoir water surfaces will raise during normal operating conditions.
  - ✓ It is equivalent to the elevation of the spillway crest or the top of the spillway gates
- ✓ MINIMUM POOL LEVEL
  - ✓ The lowest water surface elevation, which has to be maintained under normal operated conditions in a reservoir
  - ✓ This level may be fixed by the elevation of the lowest outlet in the dam or may be guided by the minimum head required for the efficient functioning of turbines

- ✓ USEFUL AND DEAD STORAGE
  - ✓ The volume of water stored in a reservoir between the minimum and normal pool level is called the useful storage

- ✓ Water stored in the reservoir below the minimum pool level is known as dead storage in a multipurpose reservoir useful storage is composed of conservation storage and flood mitigation storage

✓ MAXIMUM POOL LEEL OR FULL RESERVOIR LEVEL:-
- ✓ During high floods ,water is discharge over the spillway but will cause the water level to rise in the reservoir above the normal pool level
- ✓ The maximum level to which the water rises during the worst design flood is known as the maximum pool level

✓ SURCHARGE STORAGE
- ✓ THE volume of water stored between the normal pool level and the maximum pool level is called surcharge storage
- ✓ It is an uncontrolled and temporary because it exist till the flood is in progress and cant be retained for later use .

✓ BANK STORAGE

- ✓ When the reservoir is filled up , certain amount of water seeps into the permeable reservoir banks .this water comes out as soon as the reservoir gets depleted .This volume of water is known as bank storage .
- ✓ The bank storage increases the reservoir capacity above indicated by the elevation capacity curve of the reservoir

✓

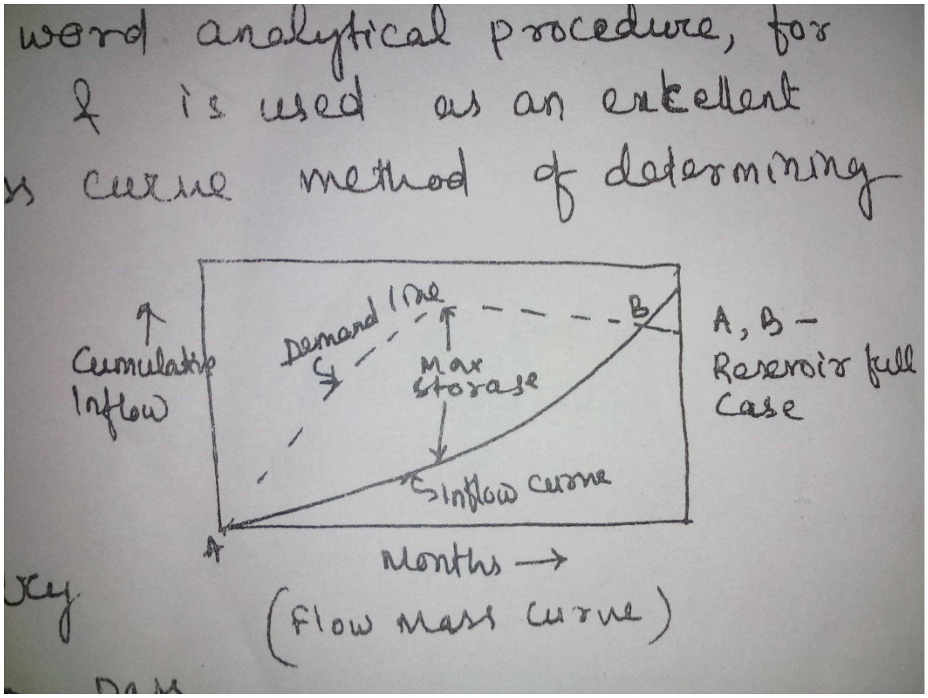
✓ VALLEY STORAGE
- ✓ Before the construction of dam certain variable amount of water is stored in the stream channel called valley storage.
- ✓ After the reservoir is formed the storage increases and the actual net increase in the storage is equal to the storage capacity of the reservoir is called natural valley storage
- ✓ EFFECTIVE STORAGE=USEFUL STORAGE +SURCHARGE STORAGE –VALLEY STORAGE

✓ FIXATION OF RESERVOIR CAPACITY
- ✓ Storage Capacity of a reservoir is the maximum difference between the cumulative supply and demand during the period of the driest year of the available records.
- ✓ Two popular methods for calculation of reservoir capacity are:
  - (a) Flow Mass Curve/ Ripple Mass Curve
  - (b) Sequent Peak Algorithm

✓ SEQUENT PEAK ALGORITHM

- ✓ It is a simple and straightforward analytical procedure, for computing reservoir capacity & is used as an excellent alternative to the flow mass curve method of determining reservoir capacity.

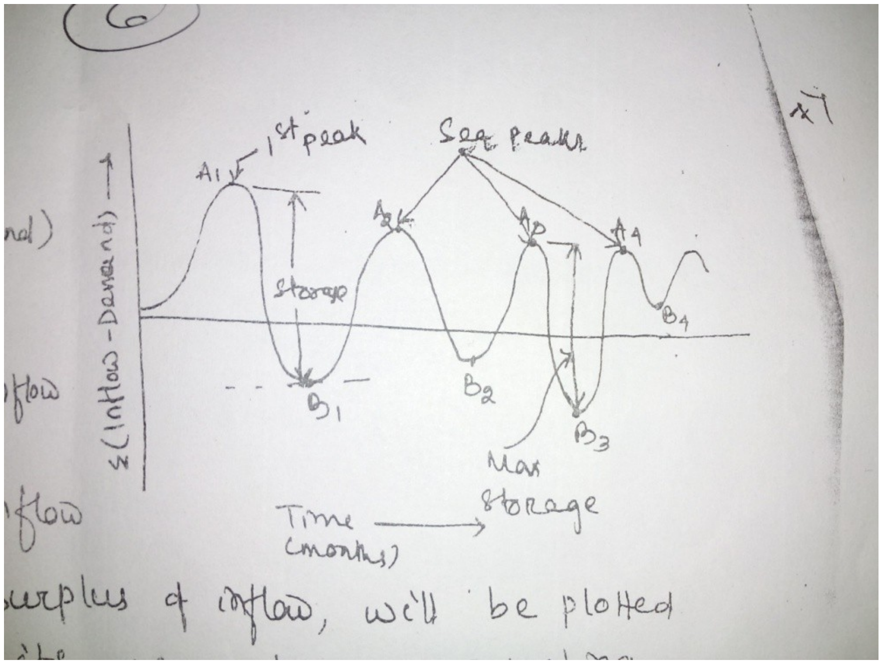
DEMERITS OF MASS CURVE



- ✓ In the mass curve analysis, the reservoir is assumed to be full at the beginning of the dry period and storage required to pass the dry period is estimated.
- ✓ If the mass curve contains only one ridge point and there are no well defined subsequent trough points, it may become necessary to repeat the given data for one more cycle.
- ✓ Also the demand line is usually not a straight line (but assumed as straight) because, it is generally non uniform due to seasonal variation in demand.

The sequent peak algorithm technique helps us to device simple mathematical solution to the problem of computing reservoir capacity.

SEQUENT PEAK ALGORITHM



- ✓ It is a plot between time in X- axis and sum of (inflow- demand) in Y-axis. ∑(Inflow- Demand)=∑Net Inflow
- ✓ The positive values of net inflow representing cumulative surplus of inflow, will be plotted above X-axis while its negative values representing cumulative deficit of inflow, will be plotted below X-axis.
- ✓ The first ridge point A1 is the first peak in the figure shown above while subsequent ridges A2, A3, A4 etc are called sequent peak.
- ✓ Similarly B1 is the first trough but B2, B3 etc are sequent troughs.
- ✓ The difference between first peak= Normal storage in reservoir under normal inflows. But the maximum difference between any sequent peak and following trough = Maximum Storage.
- ✓ The Normal and Maximum storage through sequent peak algorithm is calculated as:
  1. Convert the monthly inflows into the volume units for the period of available data.
  2. Estimate the monthly volume of all the outflows from the reservoir. This should include losses from evaporation, seepage and others.
  3. Compute the cumulative inflow and cumulative outflows.

4. Compute (∑Inflows-∑Outflows).
5. Plot a graph by taking time (months) in X-axis and (∑Inflow-∑Outflow) on Y-axis.
6. The data will plot peaks and troughs. The 2^{nd} and subsequent peaks are called sequent peaks.
7. The max difference between any sequent peak and the just following through is the max storage required for the reservoir .
   The difference between 1^{st} pick and following through =Normal storage

- RESERVOIR SEDIMENTATION:
  - ✓ The sediment particles try to settle down to the river bottom due to the gravitational force , but may be kept in suspension due to the upstream current in the turbulent flow which may overcome the gravity force .Due to these reasons, the river carries fine sedimentation in suspension load and larger solids along the river bed as bed load.
- SEDIMENT YEILD :
  - ✓ It is the total flow of sediment from a watershed measured at a location in a riverat a specified time.
- EROSION:
  - ✓ It is the process of detachment and transportation of sediment by erosive agent.
- SEDIMENT DELIVERY RATIO:
  - ✓ Ratio of sediment delivered at a gauging site in a river to a total erosion from the entire area upstream it.
- BED LOAD:
  - ✓ The coarse sediment material moving close to the river bed by rolling or sliding is called bed load.
  - ✓ E.g. material moving within 10-15 cm from bed.
- SUSPENDED LOAD :
  - ✓ Relatively finer particle which mix and move with river water in suspension and are found throughout the channel water in the downstream is called suspended load.
- WASH LOAD:
  - ✓ Fine , very fine ,and electrochemically charged soil particle carried by river water are called wash load and don't ordinarily settle down at the bottom of the container even after keeping it undisturbed for hours.
- RESERVOIR SEDIMENTATION CONTROL :
  - ✓ The deposition of sediment in reservoir is known as reservoir setting or reservoir sedimentation.

- ✓ The total volume of silt deposited during the design period of dam is estimated and approx that much volume is left unused to allow the silting and is known as dead storage.
- ✓ TOTAL CAPACITY OF RESERVOIR –DEAD STORAGE =LIVE STORAGE/EFFECTIVE STORAGE
- ✓ The dead storage generally varies between 15-20% of the total capacity.

- TRAP EFFICINCY:
  - ✓ It is defined as the % of the sedimentation deposited in the reservoir even in spite of taking precautions and measures to control its deposition.
  - ✓ ή =Total sediment deposited in the reservoir /total sediment flowing in the river
- CAPACITY INFLOW RATIO:
  - ✓ It is the ratio of reservoir capacity to the total inflow of water in it ή=f(capacity/inflow)
  - ✓ In order to increase the time of the reservoir it is necessary to control the deposition of sediment.
  - ✓ Methods are
    Pre constructing measures
    Post constructing measures

- PRE CONSTUCTING MEASURES:
  - ✓ These are the methods which are adopted before and during the execution of the project
  1. Selection of dam site
  2. Construction of dam in stages
  3. Construction of check dam
  4. Vegetation screens
  5. Construction of under sluice in the dam

- POST CONSTRUCTION MEASURES:
  - ✓ These measures are to be taken during the operation of project.
    1. Removal of post flood water
    2. Mechanical stirring of the project
    3. Erosion control and soil conservation.

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