CE 15015

WATER RESOURCES ENGINEERING

LECTURE NOTES

MODULE-II

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COURSE CONTENTS

Module – II

Run off: Computation, factors affecting runoff, Design flood: Rational formula, Empirical formulae, Stream -flow: Discharge measuring structures, approximate average slope method, area-velocity method, stage-discharge relationship.

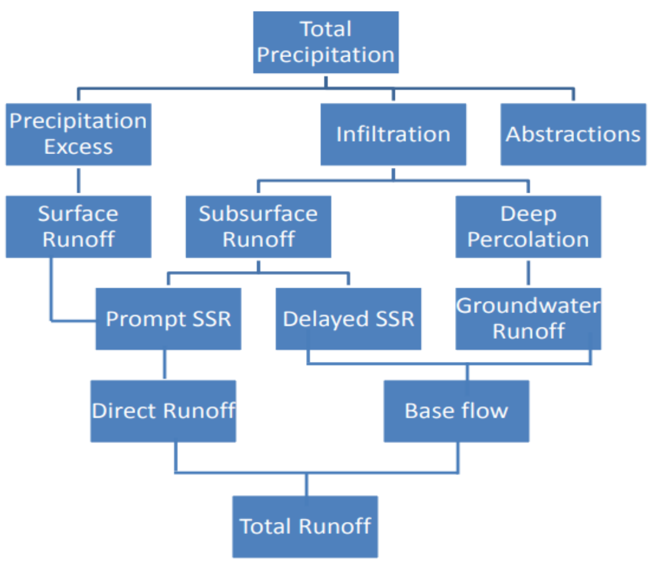
Hydrograph; Concept, its components, Unit hydrograph: use and its limitations, derivation of UH from simple and complex storms, S-hydrograph, derivation of UH from S-hydrograph. Synthetic unit hydrograph: Snyder's approach, introduction to instantaneous unit hydrograph (IUH).

Lecture Note 1

Runoff

1.1 Introduction

Runoff can be defined as the portion of the precipitation that makes it's way towards rivers or oceans etc, as surface or subsurface flow. Portion which is not absorbed by the deep strata. Runoff occurs only when the rate of precipitation exceeds the rate at which water may infiltrate into the soil.



1.2 Types of Runoff

• Surface runoff – Portion of rainfall (after all losses such as interception, infiltration, depression storage etc. are met) that enters streams immediately after occurring rainfall – After laps of few time, overland flow joins streams – Sometime termed prompt runoff (as very quickly enters streams)

• Subsurface runoff – Amount of rainfall first enter into soil and then flows laterally towards stream without joining water table – Also take little time to reach stream

• Base flow

– Delayed flow

– Water that meets the groundwater table and join the stream or ocean

– Very slow movement and take months or years to reach streams

Factors affecting runoff

• Climatic factors

– Type of precipitation

• Rain and snow fall

– Rainfall intensity

• High intensity rainfall causes more rainfall

– Duration of rainfall

• When duration increases, infiltration capacity decreases resulting more runoff

– Rainfall distribution

• Distribution of rainfall in a catchment may vary and runoff also vary

• More rainfalls closer to the outlet, peak flow occurs quickly

• Direction of prevailing wind

– If the wind direction is towards the flow direction, peak flow will occur quickly

• Other climatic factors

– Temperature, wind velocity, relative humidity, annual rainfall etc. affect initial loss of precipitation and thereby affecting runoff

• Physiographic factors

– Physiographic characteristics of watershed and channel both

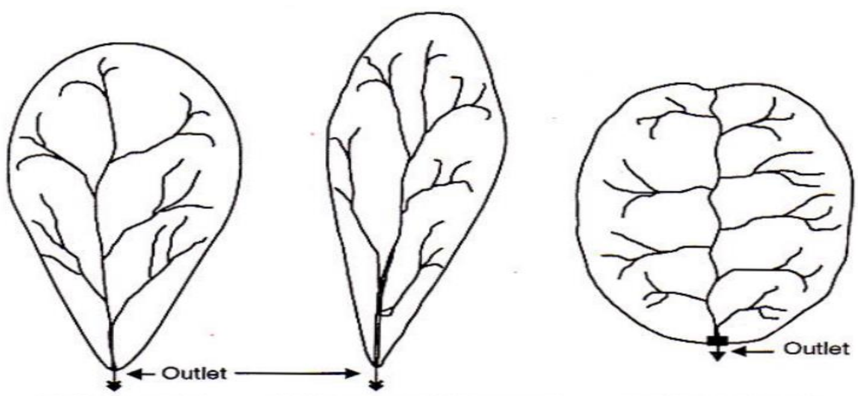
– Size of watershed

• Larger the watershed, longer time needed to deliver runoff to the outlet

• Small watersheds dominated by overland flow and larger watersheds by runoff

– Shape of watershed

• Fan shaped, fan shaped (elongated) and broad shaped



(a) Fan shaped (b) Fan shaped (Elongated) (c) Broad shaped

• Fan shaped – runoff from the nearest tributaries drained out before the floods of farthest tributaries. Peak runoff is less

• Broad shaped – all tributaries contribute runoff almost at the same time so that peak flow is more

– Orientation of watershed

• Windward side of mountains get more rainfall than leeward side

– Landuse

• Forest – thick layer of organic matter and undercover

– huge amounts absorbed to soil

– less runoff and high resistance to flow

• barren lands

– high runoff

– Soil moisture

• Runoff generated depend on soil moisture

– more moisture means less infiltration and more runoff

• Dry soil

– more water absorbed to soil and less runoff

– Soil type

• Light soil (sandy)

– large pores and more infiltration

• Heavy textured soils

– less infiltration and more runoff

– Topographic characteristics

• Higher the slope, faster the runoff

• Channel characters such as length, shape, slope, roughness, storage, density of channel influence runoff

- Drainage density

$$Drainage\ Density = \frac{Total\ Channel\ Length}{Total\ area\ of\ watershed}$$

• More the drainage density, runoff yield is more

1.1 Runoff Computation

• Computation of runoff depend on several factors

• Several methods available

– Rational method

– Cook's method

– Curve number method

– Hydrograph method

– Many more

1.1.1 Rational Method

• Computes peak rate of runoff

• Peak runoff should be known to design hydraulic structures that must carry it.

$$Q_{Peak} = \frac{CIA}{360}$$

Q_{Peak} = Peak runoff rate (m3 /s)

C = runoff coefficient

I = rainfall intensity (mm/h) for the duration equal to the time of concentration

A = Area of watershed (ha)

1.1.1 .1 Runoff coefficient

– Ratio of peak runoff rate to the rainfall intensity

– No units, 0 to 1

– Depend on landuse and soil type

– When watershed has many land uses and soil types, weighted average runoff coefficient is calculated

$$C_w = \frac{C_1 a_1 + C_2 a_2 + C_3 a_3}{a_1 + a_2 + a_3}$$

$$C_w = \frac{\sum_{i=1}^{n} C_i a_i}{A}$$

Runoff coefficient for Rational Method

S.No.	Land use and topography	Soil type		
		Sandy loam	*Clay and silt loam*	*Tight clay*
1.	Cultivated land			
	(i) Flat	0.30	0.50	0.60
	(ii) Rolling	0.40	0.60	0.70
	(iii) Hilling	0.52	0.70	0.82
2.	Pasture land			
	(i) Flat	0.10	0.30	0.40
	(ii) Rolling	0.16	0.36	0.55
	(iii) Hilling	0.22	0.42	0.60
3.	Forest land			
	(i) Flat	0.10	0.30	0.40
	(ii) Hilling	0.30	0.50	0.60
4.	Populated land			
	(i) Flat	0.40	0.55	0.65
	(ii) Rolling	0.50	0.65	0.80

3.1.1 .2 Time of concentration (Tc)

– Time required to reach the surface runoff from remotest point of watershed to its outlet

– At Tc all the parts of watershed contribute to the runoff at outlet

– Have to compute the rainfall intensity for the duration equal to time of concentration

– Several methods to calculate Tc

– Kirpich equation

$$T_C = L^{0.77} S^{-0.385}$$

T_C = time of concentration (min)

L = Length of channel reach (m)
S = Average channel slope (m/m)

- Computation of rainfall intensity for the duration of Tc

$$I = \frac{Rainfall\ Depth}{T_C} = \frac{mm/cm}{\square}$$

- Assumptions of Rational Method

-Rainfall occur with uniform intensity at least to the Tc

–Rainfall intensity is uniform throughout catchment

- Limitations of Rational Method

–Uniform rainfall throughout the watershed never satisfied

–Initial losses (interception, depression storage, etc). are not considered

1.1.2 Cook's Method

Computes runoff based on 4 characteristics (relief, infiltration rate, vegetal cover and surface depression)

•Numerical values are assigned to each

Steps in calculation
•Step 1
–Evaluate degree of watershed characteristics by comparing with similar conditions

S. No.	Range	Numerical values assigned for runoff producing wateshed's characteristics			
		Relief	Soil infiltration	Vegetal cover	Surface storage
1.	Low	(10 to 0) Land is relatively flat, average slope ranges from 0 to 5%.	(5) Infiltration rate is more than 2 cm/hour, soil contains high sand and loamy sand.	(5) About 9% of total area is covered under good vegetation either by forest or equivalent.	(5) Land consists of high surface depression, drainage system is not very well.
2.	Normal	(20 to 10) The land is rolling in shape and slope ranges from 5% to 10%.	(10) Infiltration rate varies from 0.75 to 2 cm/ hour, the soil is in normal and deep permeable nature.	(10) About 50% of total area is under good grass land or any other equivalent cover.	(10) Considerable depression storage, lakes, ponds and marshes are less than 2% of entire drainage system.
3.	High	(30 to 20) Lands are hilly in nature, average slope ranges from 10% to 30%.	(15) Infiltration rate ranges from 0.25 to 0.75 cm/ hour, the soil is relatively hard such as clay soil.	(15) Vegetal cover varies from poor to fair, less than 10% of total area is under grass cover.	(15) Surface depression is very low and area is well drained.
4.	Extreme	(40 to 30) Lands are steep and rugged terrain, slope ranges upto 30%.	(20) Infiltration rate is less.	(20) Land is bare, no effective grass cover.	(10) Surface depressions are negligible, drainage of land is very well and no ponds or tanks are available.

Fig. (2) Numerical values for Cook's Method

Step 2

–Assign numerical value (W) to each of the characteristics

•Step 3

–Find sum of numerical values assigned

ΣW = total numerical value

R, I, V, and D are marks given to relief character, initial infiltration, vegetal cover and surface depression respectively

Step 4
–Determine runoff rate against ΣW using runoff curve (valid for specified geographical region and 10 year recurrence interval)
•Step 5
–Compute adjusted runoff rate for desired recurrence interval and watershed location

$$Q_{Peak} = P.R.F.S$$

Q_{Peak} = Peak runoff for specified geographical location and recurrence interval (m3/s)
P = Uncorrected runoff obtained from step 4
R = Geographic rainfall factor
F = Recurrence interval factor
S = Shape factor

1.1.1 Curve Number Method

• Calculates runoff on the retention capacity of soil, which is predicted by wetness status (Antecedent Moisture Conditions [AMC]) and physical features of watershed

• AMC - relative wetness or dryness of a watershed, preceding wetness conditions

• This method assumes that initial losses are satisfied before runoff is generated

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)^2}$$

$$CN = \frac{2540}{(25.4 + S)}$$

Q = Direct runoff
P = Rainfall depth
S = Retention capacity of soil
CN = Curve Number
•CN depends on land use pattern, soil conservation type, hydrologic condition, hydrologic soil group

Land use pattern	*Treatment/practice adopted*	*Hydrologic condition*	*Hydrologic soil group*			
			A	*B*	*C*	*D*
Fallow-row crops	Straight row	—	77	86	91	94
		Poor	72	81	88	91
		Good	67	78	85	89
	Contoured + terraced condition	Poor	70	79	84	88
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Contoured condition	Poor	63	74	82	85
		Good	63	75	83	87
	Contoured + terraced condition	Poor	61	72	79	82
		Good	59	70	78	81
Seeded	Straight row	Poor	66	77	85	89
Legumed		Good	55	69	78	83
Pasture land	Contoured condition	Poor	47	67	81	88
		Fair	25	59	75	83
		Good	6	35	70	79
Farm		Poor	45	66	77	83
Woodland		Fair	36	60	73.	79
		Good	25	55	70	77
Hard surface			74	84	90	92
Farm steads			59	74	82	86
Meadow			330	58	71	78

Fig (2) Curve Numbers

Procedure
•Step 1
–Find value of CN using table

–Calculate S using equation

–Use equation and calculate Q (AMC II)

–Use correction factor if necessary to convert to other AMCs)
•Three AMC conditions

Factors for converting AMC II to AMC I or AMR III

CN – AMC II	Conversion Factor	
	AMC I	AMC III
10	0.40	2.22
20	0.45	1.85
30	0.50	1.67
40	0.55	1.50
50	0.62	1.40
60	0.67	1.30
70	0.73	1.21
80	0.79	1.14
90	0.87	1.07
100	1.00	1.00

Fig (3) Conversion Factor

AMC I –Lowest runoff generating potential –dry soil
•AMC II –Average moisture status
•AMC III –Highest runoff generating potential –saturated soil
•Soil A –low runoff generating potential, sand or gravel soils with high infiltration rates
•Soil B –Moderate infiltration rate, moderately fine to moderately coarse particles
•Soil C –Low infiltration rate, thin hard layer prevents downward water movement, moderately fine to fine particles
•Soil D –High runoff potential due to very low infiltration rate, clay soils

Classification of Streams

•Based on flow duration, streams are classified into

–Perennial

•Streams carry flow throughout the year

•Appreciable groundwater contribution throughout the year

–Intermittent

•Limited groundwater contribution

•In rainy season, groundwater table rises above stream bed

•Dry season stream get dried

–Ephemeral

•In arid areas

•Flow due to rainwater only

•No base flow contribution

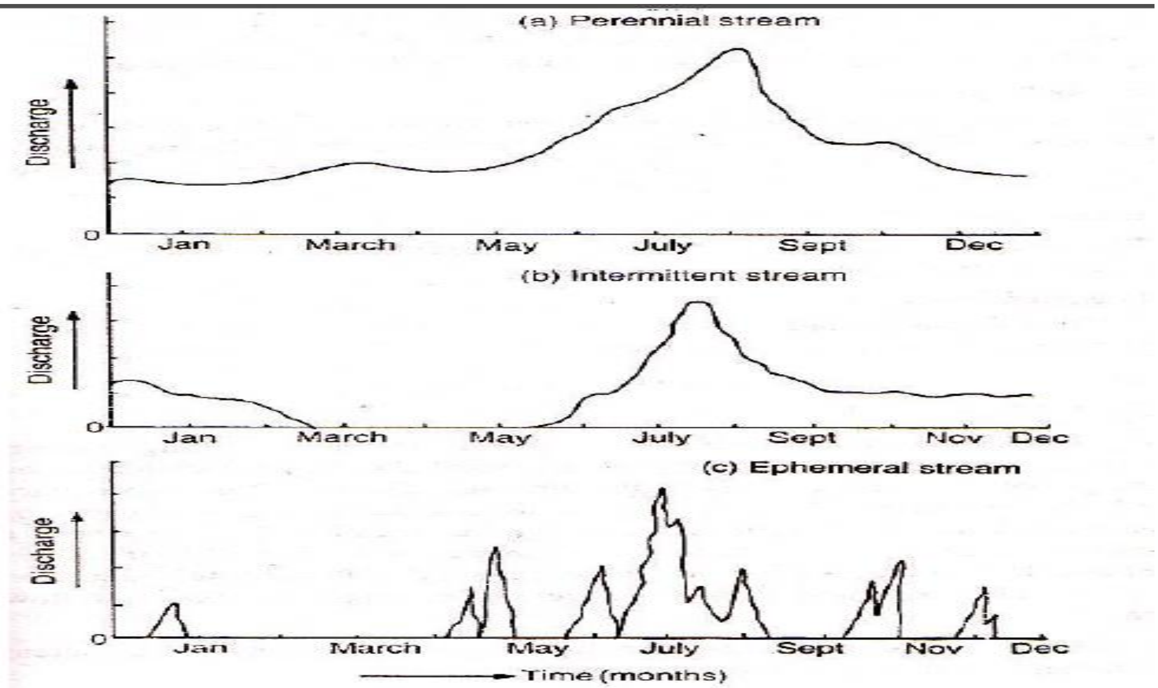


Fig (4) Classification of Stream

Flow Duration Curve

•Gives the variability of stream flow in a year

–Arrange stream flow data in descending order

–Assign rank number

–Calculate plotting position (Probability)

$$P = \left(\frac{m}{n+1}\right) 100$$

–Plot plotting position and discharge

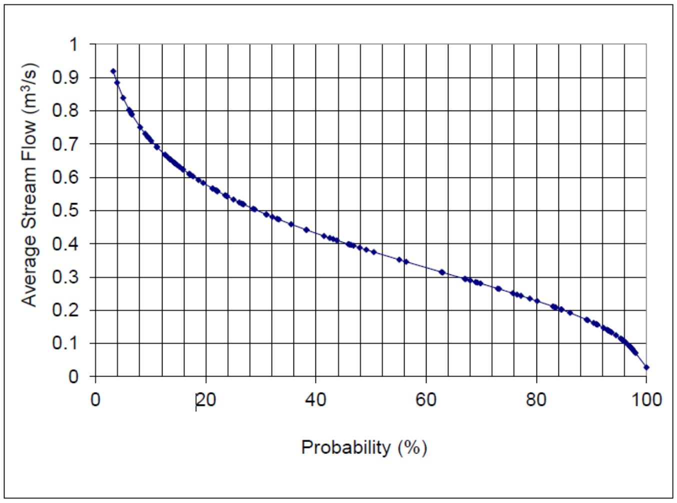


Fig (4) Flow Duration Curve

Characteristics of flow duration curve

–Steep slope –highly variable flow

–Flat slope –little variation in the flow

–Flat portion at top of curve –stream has large flood plain

–Flat portion at lower end –considerable baseflow

Uses of flow duration curve

–Discharge for any probability can be known

–Variation of flow within a year can be known

–Plan water resources projects

–Design of drainage structures

–Decide on flood control structures to be used

–Evaluate hydropower potential

–Determine sediment load carried by stream

Lecture Note 2

Streamflow Measurement

2.1 Introduction

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

2.2 Sources of Streamflow

Surface and subsurface sources: Stream discharge is derived from four sources: channel precipitation, overland flow, interflow, and groundwater.

- Channel precipitation is the moisture falling directly on the water surface, and in most streams, it adds very little to discharge. Groundwater, on the other hand, is a major source of discharge, and in large streams, it accounts for the bulk of the average daily flow.

- **Groundwater** enters the streambed where the channel intersects the water table, providing a steady supply of water, termed baseflow, during both dry and rainy periods. Because of the large supply of groundwater available to the streams and the slowness of the response of groundwater to precipitation events, baseflow changes only gradually over time, and it is rarely the main cause of flooding. However, it does contribute to flooding by providing a stage onto which runoff from other sources is superimposed.

- **Interflow** is water that infiltrates the soil and then moves laterally to the stream channel in the zone above the water table. Much of this water is transmitted within the soil itself, some of it moving within the horizons. Next to baseflow, it is the most important source of discharge for streams in forested lands. Overland flow in heavily forested areas makes negligible contributions to streamflow.

- In dry regions, cultivated, and urbanized areas, overland flow or surface runoff is usually a major source of streamflow. Overland flow is a stormwater runoff that begins as thin layer of water that moves very slowly (typically less than 0.25 feet per second) over the ground. Under intensive rainfall and in the absence of barriers such as rough ground, vegetation, and absorbing soil, it can mount up, rapidly reaching stream channels in minutes and causing sudden rises in discharge. The quickest response times between rainfall and streamflow occur in urbanized areas where yard drains, street gutters, and storm sewers collect overland flow and route it to streams straightaway. Runoff velocities in storm sewer piper can reach 10 to 15 feet per second.

2.3 Measurement

Streamflow is measured as an amount of water passing through a specific point over time. The units used in the United States are cubic feet per second, while in majority of other countries cubic meters per second are utilized. One cubic foot is equal to 0.028 cubic meters.

There are a variety of ways to measure the discharge of a stream or canal. A stream gauge provides continuous flow over time at one location for water resource and environmental management or other purposes. Streamflow values are better indicators than gage height of conditions along the whole river. Measurements of streamflow are made about every six weeks by United States Geological Survey (USGS) personnel. They wade into the stream to make the measurement or do so from a boat, bridge, or cableway over the stream. For each streamgaging station, a relation between gage height and streamflow is determined by simultaneous measurements of gage height and streamflow over the natural range of flows (from very low flows to floods). This relation provides the current condition streamflow data from that station.[2] For purposes that do not require a continuous measurement of stream flow over time, current meters or acoustic Doppler velocity profilers can be used. For small streams — a few meters wide or smaller — weirs may be installed.

2.2 Methods of forecasting streamflow

For most streams especially those with small watershed, no record of discharge is available. In that case, it is possible to make discharge estimates using the rational method or some modified version of it. However, if chronological records of discharge are available for a stream, a short term forecast of discharge can be made for a given rainstorm using a hydrograph.

Unit Hydrograph Method. This method involves building a graph in which the discharge generated by a rainstorm of a given size is plotted over time, usually hours or days. It is called the unit hydrograph method because it addresses only the runoff produced by a particular rainstorm in a specified period of time- the time taken for a river to rise, peak, and fall in response to a storm. Once rainfall-runoff relationship is established, then subsequent rainfall data can be used to forecast streamflow for selected storms, called standard storms. A standard rainstorm is a high intensity storm of some known magnitude and frequency. One method of unit hydrograph analysis involves expressing the hour by hour or day by day increase in streamflow as a percentage of total runoff. Plotted on a graph, these data from the unit hydrograph for that storm, which represents the runoff added to the prestorm baseflow. To forecast the flows in a large drainage basin using the unit hydrograph method would be difficult because in a large basin geographic conditions may vary significantly from one part of the basin to another. This is especially so with the distribution of rainfall because an individual rainstorm rarely covers the basin evenly. As a result, the basin does not respond as a unit to a given storm, making it difficult to construct a reliable hydrograph.

Magnitude and frequency method. For large basins, where unit hydrograph might not be useful and reliable, the magnitude and frequency method is used to calculate the probability of recurrence of large flows based on records of past years' flows. In United States, these records are maintained by the Hydrological Division of the U.S. Geological Survey for most rivers and large streams. For a basin with an area of 5000 square miles or more, the river system is typically gauged at five to ten places. The data from each gauging station apply to the part of the basin upstream that location. Given several decades of peak annual discharges for a river, limited projections can be made to estimate the size of some large flow that has not been experienced during the period of record. The technique involves projecting the curve (graph line) formed when peak annual discharges are plotted against their respective recurrence intervals. However, in most cases the curve bends strongly, making it difficult to plot a projection accurately. This problem can be overcome by plotting the discharge and/or recurrence interval data on logarithmic graph paper. Once the plot is straightened, a line can be ruled drawn through the points. A projection can then be made by extending the line beyond the points and then reading the appropriate discharge for the recurrence interval in question.

2.5 Categorisation Of Streamflow Measurement

Stream flow techniques are broadly classified into two categories:-

(1) Direct determination of discharge

(2) Indirect determination of discharge

2.5.1 Direct Method

• Direct determination of stream discharge measurement includes :-
(a) Area velocity method
(b) Dilution techniques
(c) Electromagnetic method

(d) Ultrasonic method

2.5.2 Indirect Method

• Indirect method of stream discharge measurement includes :-

(a) Slope area method

(b) Hydraulic structures

- Continuous measurement of stream discharge is very difficult. As a rule direct measurement of discharge is a very time consuming and costly procedure.
- Hence a two step procedure is followed.
- At first the discharge in a given stream is related to the elevation of the water surface(stage) through avseries of careful measurement.
- In the next step, the stage of the stream is observedvroutinely in a relatively inexpensive manner and thevdischarge is estimated by using the previouslyvdetermined stage-discharge relationship.
- This method of discharge determination of streams is adopted universally.

2.5.3 Measurement Of Stage

• The stage of a river is defined as its water surface elevation measured above a datum(Mean Sea Level or any datum connected independently to MSL)
• For the measurement of stage we have:-
(1). Manual gauges
(2). Automatic stage recorder
• Under Manual gauges we have
(a). Staff gauge
(b). Wire gauge

2.5.4 Stage Data

• The stage data is often represented in the form of a plot of stage against chronological time.
• This is popularly known as stage hydrograph
• Stage data is of utmost importance in design of hydraulic structures, flood warning and flood protection work.
Abscissa- Time
Ordinate- Stage

2.6 Measurement Of Velocity

• For the accurate determination of velocity in a stream we have a mechanical device known as CURRENT METER.
• It is the most commonly used instrument in Hydrometry to measure the velocity at a point in the flow cross-section.
• It essentially consists of a rotating element which rotates due to the reaction of the stream current with an angular velocity proportional to the stream velocity.
• Robert Hooke(1663) invented a propeller type current meter for traversing the distance covered by ship.
• Later on it was Henry(1868) who invented present day cup- type instrument and the electrical make-and-break mechanism.

2.6.1 Types Of Current Meter

• VERTICAL AXIS METERS
• HORIZONTAL AXIS METERS
A current meter is so designed that its rotation speed varies linearly with the stream velocity v .
• A typical relationship is:-

$$v = a N_s + b$$

Where v= stream velocity at the instrument location.
Ns= no of revolutions per second of the meter
a, b= constants of the meter.

2.6.2 Calibration Equation

• Now we need to find out the relation between the stream velocity and revolutions per second of the meters which is nothing but the calibration equation.
• The calibration equation is unique to each instrument .
• It is determined by towing the instrument in a special tank
• A towing tank is a long channel containing still water with arrangements for moving a carriage longitudinally over its surface at constant speed.
The instrument to be calibrated is mounted on the carriage with the rotating element immersed to a specified depth in the water body in the tank.
• The carriage is then towed at a predetermined constant speed(v) and the corresponding avg value of revolutions per second is determined.
• In India we have an excellent towing tank facilities for calibration of current meters at CWPRS(Central Water And Power Research Station) and IIT MADRAS.

2.6.3 Value Of Velocity For Field Use

• The velocity distribution in a stream across a vertical section is logarithmic in nature.
• The velocity distribution is given by

$$v = 5.75v^* \log10 (30y/k_s)$$

• V= velocity at a point y above the bed
• V* = shear velocity
• K_s = equivalent sand grain roughness
• In order to determine the accurate avg velocity in a vertical section one has to measure the velocity at large no of points which is quite time consuming. So certain specified procedure have been evolved.
• For the streams of depth 3.0 m the velocity measured at 0.6 times the depth of flow below the water surface is taken as the average velocity.(single point observation model)

$$V(avg) = v_{0.6}$$

• For the depth between 3.0m to 6.0 m we have

$$V(avg) = (v_{0.2} + v_{0.8})/2$$

•For the river having flood flow we have

$$v(avg) = k^* v_s$$

where v_s(surface velocity) and k(reduction coefficient)
Value of k lies between 0.85 to 0.95

2.7. Sounding Weight

• Current meter is weighted down by lead weight called sounding weight.
• It is connected to the current meter with a hangar bar and pin assembly.
• These weights are of steramlined shapes with a fin in the rear
• The minimum weight of sounding weight is estimated as

$$w = 50^* v_{avg}{}^* d$$

Where d= depth of flow at vertical
v_{avg} = avg velocity

2.8. Vertical Axis Meters

• This instrument consist of a series of conical cups mounted around a vertical axis.
• The cups rotate in a horizontal plane .
• The cam attached to the vertical axial spindle records generated signals proportional to the revolutions of the cup assembly.
• Range of velocity is **0.155m/s to 2.0m/s**.
• **It can not be used in situations where there are appreciable vertical components of velocities.**
• **Price current meter and Gurley current meter** are some of its type.

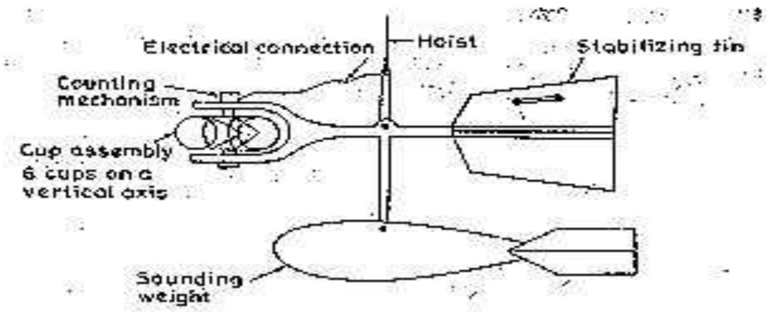


Fig (1) Vertical Axis Current Meter

2.9 Horizontal Axis Meters

• This instrument consist of a propeller mounted at the end of horizontal shaft .
• The propeller **diameter is in the range of 6 to 12cm**
• It can register velocities from **0.155m/s to 4.0m/s.**
• This meter is not affected by **oblique flows of as much as 150 .**
• **Ott, Neyrtec, Watt** type meters are typical instruments under this kind.

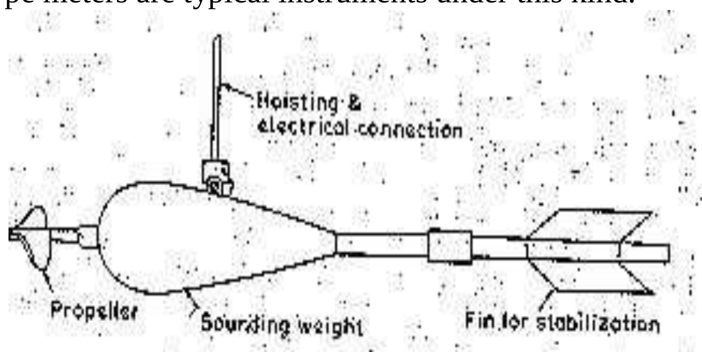


Fig (2) Propeller type Current Meter

2.10 Area Velocity Method

• This method of discharge measurement consists essentially of the area of cross section of the river at a selected section called the **gauging site** and measuring the velocity of flow through the cross sectional area.
• The gauging site must be selected with care to ensure that the stage discharge curve is reasonably constant over a long period over a few years. Toward the statement given in the previous slide the following criteria are adopted
• **(a)** The stream should have a well defined cross section which does not change in various seasons.
• **(b)** It should be easily accessible all through the year.
• **(c)** The site should be in straight, stable reach.
• **(d)** The gauging site should be free from backwater effects in the channel

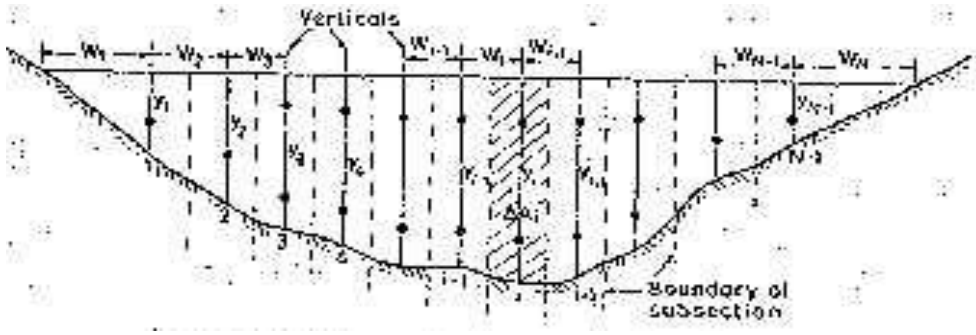


Fig (3) Stream section for area velocity method

➢ How basically the depth of a river is determined?

• . At the selected site, the section line is marked off by permanent survey markings and the cross section is determined.
Case 1 – when the stream depth is small.
• (The depth at various locations are measured by sounding rods or sounding weights.)
Case 2 – when the stream depth is large or when result is needed with higher accuracy.
• (An instrument named echo-depth recorder is used. In this, a high frequency sound wave is sent down by a transducer kept immersed in water surface and the echo reflected by the bed is recorded by the same transducer. By comparing the time interval between the transmission of the signal and the receipt of the echo the distance is measured and is shown . It is particularly advantageous in high velocity streams.)

➢ How cross section of a river is determined?

• The cross section is considered to be divided into large number of subsections by verticals. The average velocity in these subsections are measured by current meters or by floats.
• It is quite obvious that the accuracy of discharge estimation increases with the increase in number of subsections.
• The following are some of the guidelines to select the number of segments
• (a) the segment width should not be greater than 1/15 or 1/20 of the width of the river.
• (b) the discharge in each segment should be smaller than the 10% of the total discharge.
• (c) the difference of velocities in adjacent segments should not be more than 20%
• This is also called Standard Current Meter Method.

2.11 Moving Boat Method

• Discharge measurement of large alluvial rivers, such as the ganga by the standard current meter method is very time consuming even the flow is low or moderate.
• When the river is spate, it is impossible to use the standard current meter technique due to the difficulty in keeping the boat stationary on the fast moving surface of the stream .
• It is such circumstances that the moving boat techniques prove very helpful
• In this method, a special propeller- type current meter which is free to move about a vertical axis is towed in a boat at a velocity v_b at right angle to the stream flow . If the flow velocity is v_f, the meter will align itself in the direction of the resultant velocity vg making an angle θ with the direction of the boat . The meter will register the velocity v_r . If v_b normal to v_f then:-

$$\mathbf{v_b = v_r \cos\theta \text{ and } v_f = v_r \sin\theta}$$

• If the time of transit between two verticals is Δt then the width between the two verticals is

$$w = v_b \Delta t$$

• The flow in the sub-area between two verticals i and i+1 where the depths are y_i and y_{i+1} respectively by assuming the current meter to measure the average velocity in the vertical is :-

$$\Delta Q_i = [\{y_i + y_{i+}1\}/2] w_{i+1} v_f$$

$$\Delta Q_i = [\{y_i + y_{i+1}\}/2] v^2{}_r \sin\theta \cos\theta \Delta t$$

• Summation of the partial discharges ΔQi over the whole width of the stream gives the stream discharge.

2.12 Dilution Technique

• Also known as chemical method.
• Depends on the continuity principle. This principle is applied to a tracer which is allowed to mix completely with the flow.
• Two methods of dilution technique:-
(a) sudden injection method/ gulp / integration method.
(b) constant rate injection method/plateau gauging
NOTE
• Dilution method of gauging is based on the assumption of steady flow. If the flow is unsteady and the flow changes appreciably during gauging. There will be a change in the storage volume in the reach and the steady state continuity equation is not valid.

2.13 Constant Rate Injection Method

• It is one particular way of using the dilution principle by injecting the tracer of a concentration c_1 at constant rate Q_1 at section1. At section 2 the concentration gradually rises from the background value of c_0 at time t_1 to a constant value c_2 .so at the steady state, the continuity equation for the tracer is :-

$$Q_t C_1 + Q C_0 = (Q+Q_t) C_2$$

$$Q = Q_t(C_1 - C_2)/(C_2 - C_0)$$

- **IMPORTANT POINTS REGARDING TRACERS**

• Tracers are of three main types:-
(a) chemicals (sodium chloride, sodium dichromate)
(b) fluorescent dyes (rhodamine- WT, sulpho-rhodamine)
(c) radioactive materials(bromine-82, sodium-22,iodine-132)
Tracers should ideally follow the following property:-
• 1 non-toxic
• 2 not be very expensive
• 3 should be capable of being detected even at a very small concentrations
• 4 should not get absorbed by the sediments or vegetation.
• 5 it should be lost by evaporation.
• 6 should not chemically react with any of the surfaces like channel boundary or channel beds

2.14 Length Of Reach

• It is the distance between the dosing section and sampling section which should be large enough to have the proper mixing of the tracer with the flow.

• The length depends on the geometric dimensions of the channel cross section , discharge and turbulence levels.
• Empirical formula suggested by **RIMMAR (1960**) for the estimation of the mixing length
.

L = 0.13B2C{0.7C+2(g1/2)}/gd

• L= MIXING LENGTH, B= AVG WIDTH, d= AVG DEPTH, C= CHEZY'S CONSTANT g = ACCLN DUE TO GRAVITY
The dilution method has the major advantage that the discharge is estimated directly in an absolute way. It is particularly attractive for small streams such as mountainous rivers
• It can be used occasionally for checking the calibration , stage discharge ,curves etc obtained by other methods.

2.15 Ultrasonic Methods

• It is essentially an area velocity method.
• The average velocity is only measured using ultrasonic signals.
• Reported by SWENGEL(1955)

2.16 Indirect Methods

• These category include those methods which make use of the relationship between the flow discharge and the depths at specified locations.
• Two broad categories under this method is:-
(**a**) flow measuring structures
(b) slope area method

2.17 Flow Measuring Structures

• Structures like notches, weir, flumes and sluice gates for flow measurements in hydraulic laboratories are well known.
• These conventional structures are used in the field conditions but their use is limited by the ranges of head, debris or sediment load of the stream and the backwater effects produced by the streams.
The basic principle governing the use of these structure is that these structure produce a unique control section in the flow. At these structure the discharge Q is the function of the water surface elevation measured from the specified datum.
$Q = f(H)$
H= water surface elevation measured from the specified datum
e.g. $Q = KH^n$ where[$K = 2/3\ c_d\ b(2g)^{1/2}$] used basically for weirs. K and n are system constants.
•The above red marked equation is valid as long the downstream water level is below a certain limiting water level known as modular limit.
•The flows which are independent of downstream water level are known as free flows.
• If the tail water conditions do affect the flow then the flow is called drowned flow /submerged flow.
• Discharges under drowned conditions are estimated by VILLEMONTE FORMULA.
$Q_s = Q_1\ [1-(H_2/H_1)^n]^{0.85}$
Q_s = submerged discharge
Q_1 = free flow discharge under H1
H_1 = Upstream water surface elevation measured above weir crest

H_2 = downstream water surface elevation measured above weir crest
n = for rectangular weir n = 1.5

CATEGORIZATION OF HYDRAULIC STRUCTURE

(a) thin plate structures

(b) long base weirs[broad crested structures]

(c) flumes[made of concrete, masonry, metal sheets etc]

SLOPE AREA METHOD

• Manning's formula is used to relate depth at either section with the discharge.
• Knowing the water surface elevation at the two section, it is required to estimate the discharge.
Applying the energy equation to sections 1 and 2,
• $Z_1 + Y_1 + \{V_1^{\ 2} / 2g\} = Z_2 + Y_2 + \{V_2^{\ 2} /2g\} + h_L$
• $h_L = h_e + h_f$ where h_e = eddy loss and h_f = frictional loss.
• $h_f = (h_1 - h_2) + \{(v_1^{\ 2}/2g) - (v_2^{\ 2}/2g)\} - h_e$
• If L = Length of the reach then $h_f / L = S_f = Q^2 / K^2$ = Energy slope
• K= conveyance of the channel =(1/n)A(R2/3)
• n= manning's roughness coefficients
• In non uniform flow $k = \{k_1 k_2\}^{1/2}$
• $H_e = K_e [(v_1^{\ 2}/2g) - (v_2^{\ 2}/2g)]$ where K_e = eddy loss coefficient .

2.18 Stage Discharge Relationship

• The stage discharge relationship is also known as **rating curve**.
• The measured value of discharges when plotted against the corresponding stages gives relationship that represents the integrated effects of a wide range of channel and flow parameters.
• The combined effects of these parameters is known as **control**.
• If the (G-Q) relationship for a gauging section is constant and does not change with time, the control is called **permanent**.
• If it changes with time , it is called **shifting control**

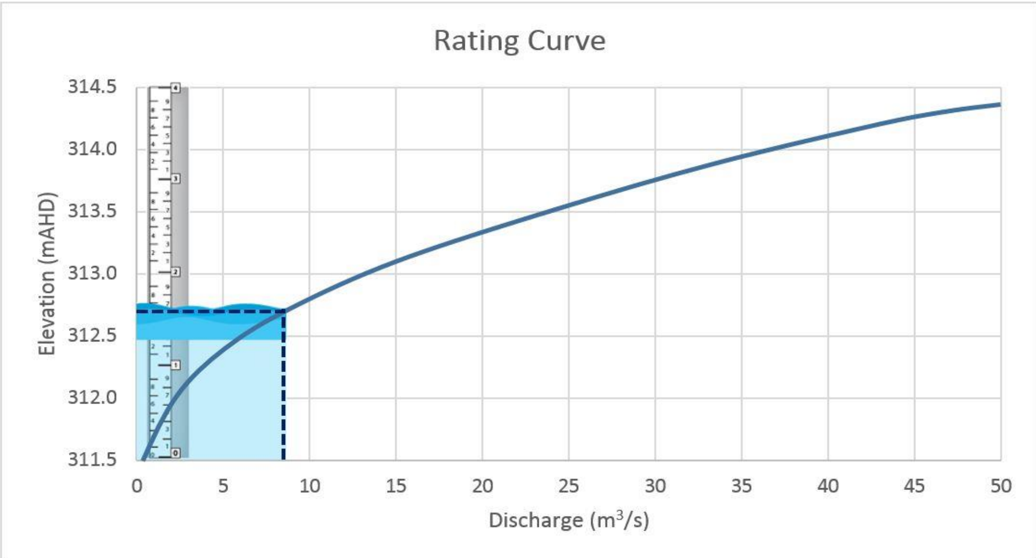


Fig (5) Rating Curve

2.19 Permanent Control

• Non alluvial rivers basically exhibit permanent control.
• Q= Cr (G-a) β
• Q= stream flow discharge
• Cr and β are rating curve constant
• a = constant representing the gauge reading corresponding to zero discharge.

NOTE
• Cr and β need not be the same for the full range of stages, Best possible way to find the value of cr and β(Rating curve constant)
• It is best obtained by the least square errorvmethod.
• Mathematically one can represent it in :-
• logQ = βlog(G-a) +logcr
• Y = βX+ b
β = {N(ΣXY)-(ΣX)(ΣY)}/{N(ΣX2)- (ΣX)2}
b= {ΣY – β(ΣX)}/N
•Pearson product moment correlation coefficient
. r = N(ΣXY)- (ΣX)(ΣY)/[{N(ΣX2)-(ΣX)2}{N(ΣY)2-(ΣY)2]1/2
If r = 0.6 to 1.0 , it is generally taken as a good Correlation

2.20 Shifting Control

• The control that exists in between stage discharge relationship changes due to:-
• (1). Changing characteristics caused by the weed growth, dredging or channel encroachment
• (2).aggradation or degradation phenomenon in an alluvial channel.
• (3). Variable backwater effects affecting the gauging station.
• (4). Unsteady flow effects of a rapidly changing stage.

Lecture Note 3

Hydrograph

3.1 Introduction

- A **hydrograph** is a graph showing the rate of flow (discharge) versus time past a specific point in a river, channel, or conduit carrying flow. The rate of flow is typically expressed in cubic meters or cubic feet per second (cms or cfs). It can also refer to a graph showing the volume of water reaching a particular outfall, or location in a sewerage network. Graphs are commonly used in the design of sewerage, more specifically, the design of surface water sewerage systems and combined sewers.

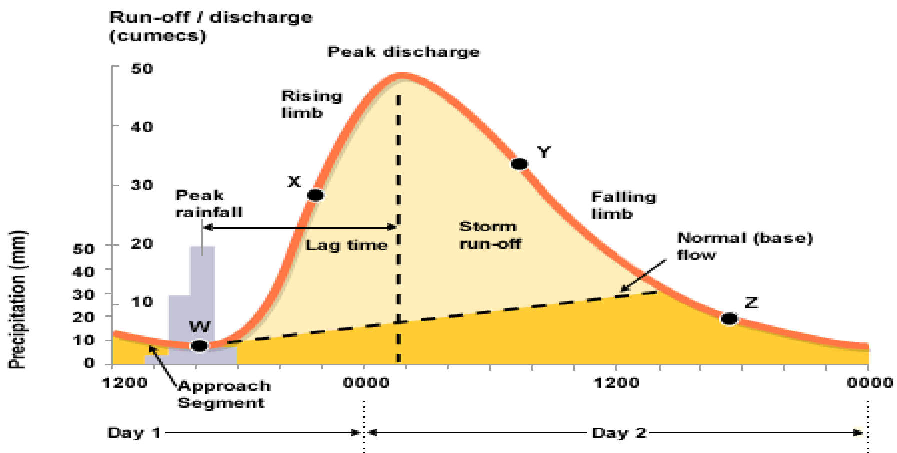


Fig (1) Hydrograph

3.2 Its Components

- **Discharge:** the rate of flow (volume per unit time) passing a specific location in a river, or other channel. The discharge is measured at a specific point in a river and is typically time variant.
- **Rising limb:** The rising limb of the hydrograph, also known as concentration curve, reflects a prolonged increase in discharge from a catchment area, typically in response to a rainfall event.
- **Peak discharge:** the highest point on the hydrograph when the rate of discharge is greatest.
- **Recession (or falling) limb:** The recession limb extends from the peak flow rate onward. The end of stormflow (a.k.a. quickflow or direct runoff) and the return to groundwater-derived flow (base flow) is often taken as the point of inflection of the recession limb. The recession limb represents the withdrawal of water from the storage built up in the basin during the earlier phases of the hydrograph.
- **Lag time:** the time interval from the center of mass of rainfall excess to the peak of the resulting hydrograph.
- **Time to peak:** time interval from the start of the resulting hydrograph.

3.3 Unit Hydrograph

- A unit hydrograph (UH) is the hypothetical unit response of a watershed (in terms of runoff volume and timing) to a unit input of rainfall. It can be defined as the direct runoff hydrograph (DRH) resulting from one unit (e.g., one cm or one inch) of effective rainfall occurring uniformly over that watershed at a uniform rate over a unit period of time. As a UH is applicable only to the direct runoff component of a hydrograph (i.e., surface runoff), a separate determination of the baseflow component is required.
- A UH is specific to a particular watershed, and specific to a particular length of time corresponding to the duration of the effective rainfall. That is, the UH is specified as being the 1-hour, 6-hour, or 24-hour UH, or any other length of time up to the time of concentration of direct runoff at the watershed outlet. Thus, for a given watershed, there can be many unit hydrographs, each one corresponding to a different duration of effective rainfall.
- The UH technique provides a practical and relatively easy-to-apply tool for quantifying the effect of a unit of rainfall on the corresponding runoff from a particular drainage basin. UH theory assumes that a watershed's runoff response is linear and time-invariant, and that the effective rainfall occurs uniformly over the watershed. In the real world, none of these assumptions are strictly true. Nevertheless, application of UH methods typically yields a reasonable approximation of the flood response of natural watersheds. The linear assumptions underlying UH theory allows for the variation in storm intensity over time (i.e., the storm hyetograph) to be simulated by applying the principles of superposition and proportionality to separate storm components to determine the resulting cumulative hydrograph. This allows for a relatively straightforward calculation of the hydrograph response to any arbitrary rain event.
- An instantaneous unit hydrograph is a further refinement of the concept; for an IUH, the input rainfall is assumed to all take place at a discrete point in time (obviously, this isn't the case for actual rainstorms). Making this assumption can greatly simplify the analysis involved in constructing a unit hydrograph, and it is necessary for the creation of a geomorphologic instantaneous unit hydrograph.

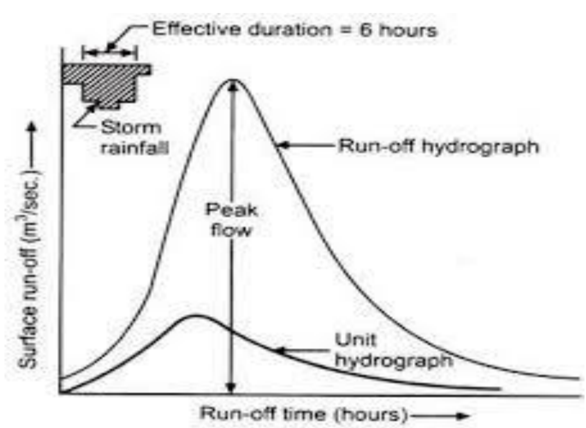


Fig (2) Unit Hydrograph

3.3.1 Basic Assumptions Of UH

(i) The effective rainfall is uniformly distributed over the entire drainage basin.
(ii) The effective rainfall occurs uniformly within its specifier duration.
This requirement calls for selection of storms of so small a duration which would generally produce an intense and nearly uniform effective rainfall and would produce a well defined single peak of hydrograph of short time base. Such a storm can be termed as “unit storm”.
(iii) The effective rainfalls of equal (unit) duration will produce hydrographs of direct runoff having same or constant time base.
(iv) The ordinates of the direct runoff hydrographs having same time base (i.e., hydrographs due to effective rainfalls of different intensity but equal duration) are directly proportional to the total amount of direct runoff given by each hydrograph. This important assumption is called principle of linearity or proportionality or superposition.
(v) The hydrograph of runoff from a given drainage basin resulting, from a given pattern of rainfall reflects all the combined physical characteristics of the basin. In other words the hydrograph of direct runoff resulting from a given pattern of effective rainfall will remain invariable irrespective of its time of occurrence. This assumption is called principle of time invariance.

3.3.2 Limitations

(i) In theory, the principle of unit hydrograph is applicable to a drainage basin of any size. In practice, however, uniformly distributed effective rainfall rarely occurs on large areas. Also on large areas effective rainfall is very rarely uniform at all locations, within its specified duration. Obviously bigger the area of the drainage basin lesser will be the chances of fulfilling the assumptions enunciated above. The limiting size of the drainage basin is considered to be 3000 km^2. Beyond it the reliability of the unit hydrograph method diminishes.
When the area of the drainage basin exceeds a few thousand km^2. The catchment has to be divided into sub-basins and the unit hydrographs developed for each sub-basin. The flood discharge at the basin outlet can then be estimated by combining the sub- basin floods adopting flood routing procedure.
(ii) The unit hydrograph method cannot be applied when appreciable portion of storm precipitation falls as snow because snow-melt runoff is governed mainly by temperature changes.
(iii) Also when snow covered area in the drainage basin is significant the unit hydrograph method becomes inapplicable. The reason is that the storm rainfall gets mixed up with the snow pack and may produce delayed runoff differently under different conditions of snow pack.
(iv) The physical basin characteristics change with seasons, man-made structures in the basin, conditions of flow etc. Obviously the principle of time invariance is really valid only when the time and condition of the drainage basin are specified.
(v) It is commonly seen that no two rain storms have same pattern in space and time. But it is not practicable to derive separate unit hydrograph for each possible time- intensity pattern. Therefore, in addition to limiting drainage basin area up to 5000 km^2 if storms of shorter duration say 1/3 to 1/4 of peaking time are selected it is seen that the runoff patterns do not vary drastically.

(vi) The principle of linearity is also not completely valid. This is so because due to variability in proportion of surface, subsurface and groundwater runoff components during smaller and larger storms of same duration, the maximum ordinate (peak) of the unit hydrograph derived from smaller storm is smaller than the one derived from larger storm. Obviously the character and duration of recession limb which is a function of the peak flow will also be different. When appreciable non-linearity is seen to exist it is necessary to use derived unit hydrographs only for reconstructing events of similar magnitude.

(vii) The unit hydrograph can be used theoretically to construct a flood hydrograph resulting from a storm having same unit duration. Obviously it necessitates construction of several unit hydrographs to cover different durations of storms. In practice however it is seen that a tolerance of ± 25% in unit hydrograph duration is acceptable. Thus a 2 hour unit hydrograph can be applied to storms of 1.5 to 2.5 hours duration.

Advantages of Unit Hydrograph Theory:

The limitation to the theory of unit hydrograph can be overcome to a large extent by remaining within the various ranges and restrictions indicated above.

The unit hydrograph theory has several advantages to its credit which can be summarised as below:

(i) Flood hydrograph can be calculated with the help of very short record of data.

(ii) In addition to peak flow unit hydrograph also gives total volume of runoff and its time distribution.

(iii) The unit hydrograph procedure can be computerised easily to facilitate calculations.

(iv) It is very useful in checking the reliability of flows obtained by using statistical methods.

3.3.3 Derivation Of Unit Hydrographs

1. A number of isolated storm hydrographs caused by short spells of rainfall excess, each of approximately the same duration (0.9 to 1.1D h) are selected from a study of continuously gauged runoff of the stream
2. For each of these surface runoff hydrographs, the base flow is separated
3. The area under DRH is evaluated and the volume of direct runoff obtained is divided by the catchment area to obtain the depth of ER
4. The ordinates of the various DRHs are divided by the respective ER values to obtain the ordinates of the unit hydrograph

- Flood hydrographs used in the analysis should be selected so as to meet the following desirable features with respect to the storms responsible for them:

1. The storms should be isolated storms occurring individually
2. The rainfall should be fairly uniform during the duration and should cover the entire catchment area
3. The duration of rainfall should be 1/5 to 1/3 of the basin lag
4. The rainfall excess of the selected storm should be high (A range of ER values of 1.0 to 4.0 cm is preferred)

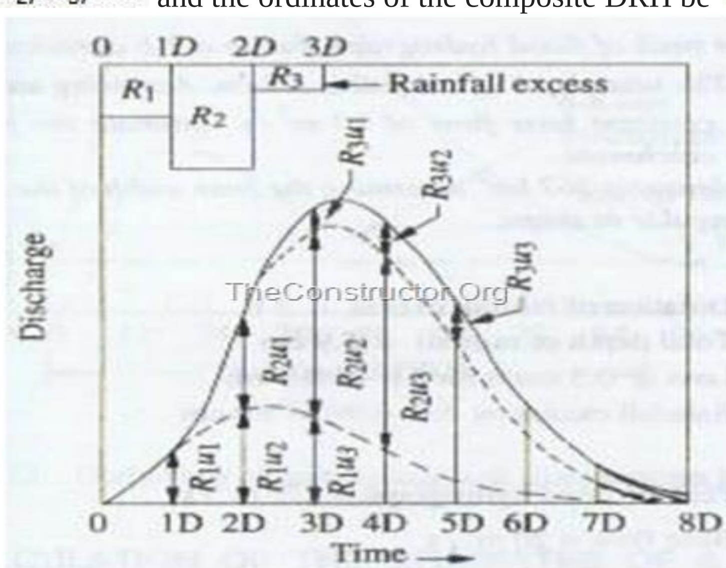
- A number of unit hydrographs of a given duration are derived as mentioned above and then plotted
- Because of spatial and temporal variations in rainfall and due to deviations of the storms from the assumptions in the unit hydrograph theory, the various unit hydrographs developed will not be exactly identical

• In general, the mean of these curves is adopted as the unit hydrograph of the given duration for the catchment
• The average of the peak flows and the time to peaks are computed first
• Then a mean curve of best fit (by eye judgment) is drawn through the averaged peak to close on an averaged base length
• The volume of the DRH is determined and any departure from unity is corrected by adjusting the peak value
• **Note** – It is customary to draw the averaged ERH of unit depth in the plot of the unit hydrograph to indicate the type and duration of rainfall creating the unit hydrograph.

• It is assumed that the rainfall excess occurs uniformly over the catchment during the duration D hours of a unit hydrograph
• An ideal duration for a unit hydrograph is one in which small fluctuations in rainfall intensity does not have any significant effect on the runoff
• The duration of the unit hydrograph should not exceed 1/5 to 1/3 of the basin lag
• In general, for catchments larger than 250 sq.km., 6 hour duration is satisfactory.

5.3.4 Unit Hydrograph from a Complex Storm

• When suitable simple isolated storms are not available, data from complex storms of long duration will have to be used to derive the unit hydrograph
• The problem is to decompose a measured composite flood hydrograph into its component DRHs and base flow
• A common unit hydrograph of appropriate duration is assumed to exist
• This is the inverse problem of derivation of the flood hydrograph
• Consider a rainfall excess made up of three consecutive durations of D hours and ER values of R_1, R_2 and R_3.
• After base flow separation of the resulting composite flood hydrograph, a composite DRH is obtained. Let the ordinates of the composite DRH be drawn at a time interval of D hours.
• At various time intervals 1D, 2D, 3D, ……. from the start of the ERH let the ordinates of unit hydrograph be $u_1, u_2, u_3, \ldots$ and the ordinates of the composite DRH be $Q_1, Q_2, Q_3 \ldots$



Fig(3)

Then
$Q_1 = R_1u_1$
$Q_2 = R_1u_2+R_2u_1$
$Q_3 = R_1u_3+R_2u_2+R_3u_1$
$Q_4 = R_1u_4+R_2u_3+R_3u_2$
$Q_5 = R_1u_5+R_2u_4+R_3u_3+$.................. and so on

• The values of $u_1, u_2, u_3,$ ...... can be determined from the above
• Disadvantage of this method – Errors propagate and increase as computation proceeds

3.4 S-Hydrograph

• It is the hydrograph of direct surface discharge that would result from a continuous succession of unit storms producing 1cm(in.)in t_r –hr
• If the time base of the unit hydrograph is Tb hr, it reaches constant outflow (Q_e) at T hr, since 1 cm of net rain on the catchment is being supplied and removed every tr hour and only T/tr unit graphs are necessary to produce an S-curve and develop constant outflow given by,

$$Q_e = (2.78 \cdot A) / t_r$$

where Q_e = constant outflow (cumec)
t_r = duration of the unit graph (hr)
A = area of the basin (km2 or acres)
• In India, only a small number of streams are gauged (i.e., stream flows due to single and multiple storms, are measured)
• There are many drainage basins (catchments) for which no stream flow records are available and unit hydrographs may be required for such basins
• In such cases, hydrographs may be synthesized directly from other catchments, which are hydrological and meteorologically homogeneous, or indirectly from other catchments through the application of empirical relationship
• Methods for synthesizing hydrographs for ungauged areas have been developed from time to time by Bernard, Clark, McCarthy and Snyder. The best known approach is due to Snyder (1938).

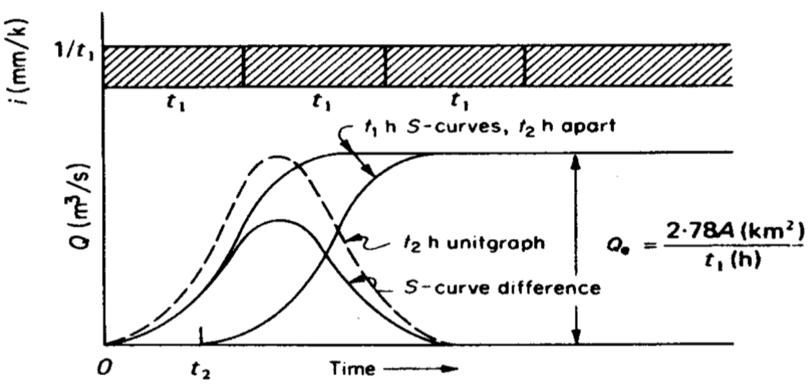


Fig (4) S-Hydrograph

3.5 Snyder's method

Snyder (1938) was the to develop a synthetic UH based on a study of watersheds in the Appalachian Highlands. In basins ranging from 10 – 10,000 mi.^{2}
Snyder relations are

$$t_p = Ct\ (LL_C)0.3$$

where
t_p= basin lag (hr)
L= length of the main stream from the outlet to the divide (mi)
L_c = length along the main stream to a point nearest the watershed centroid (mi)
C_t = Coefficient usually ranging from 1.8 to 2.2

$$Q_p = 640\ C_pA/t_p$$

where Qp = peak discharge of the UH (cfs)
A = Drainage area (mi^2)
C_p = storage coefficient ranging from 0.4 to 0.8, where larger values of cp are associated with smaller values of C_t

$$T_b = 3+t_p/8$$

where T_b is the time base of hydrograph
Note: For small watershed the above eq. should be replaced by multiplying tp by the value varies from 3-5
• The above 3 equations define points for a UH produced by an excess rainfall of duration

$$D= t_p/5.5$$

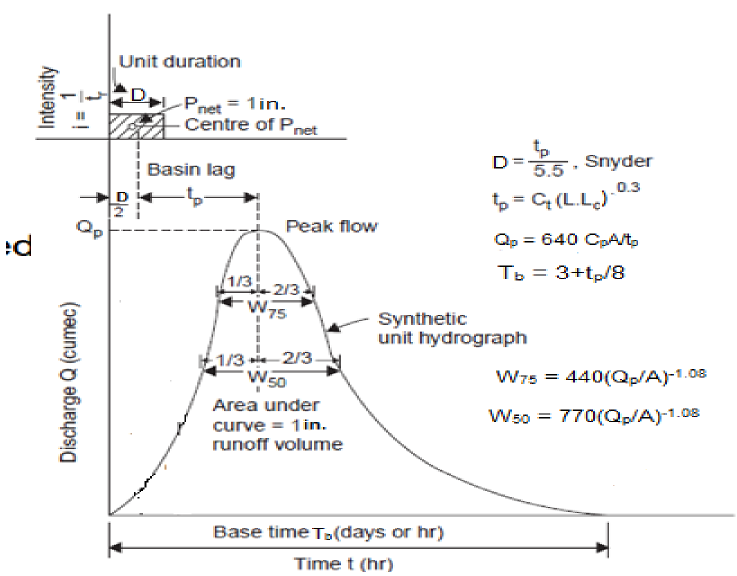


Fig (5) Snyder's hydrograph parameter

3.6 Instantaneous Unit Hydrograph (IUH).

• The instantaneous unit hydrograph is defined as a unit hydrograph produced by an effective rainfall of 1 mm and having an infinitesimal reference duration (in other words the duration tends towards zero).

• IUH is the direct runoff hydrograph resulted from an impulse function rainfall i.e., one unit of effective rainfall at a time instance.

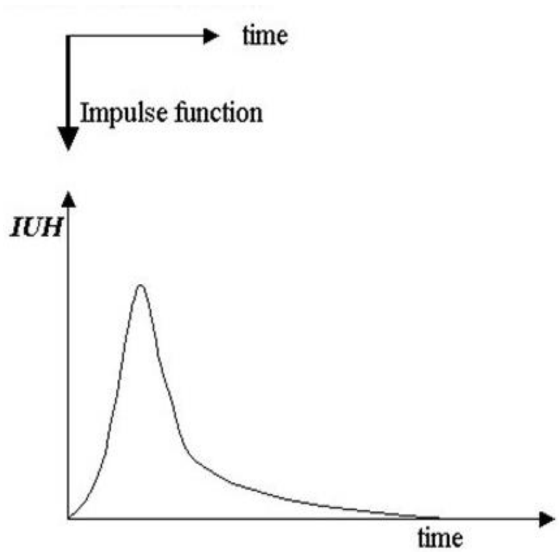


Fig (6) IUH

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