Unit - III Date:

Runoff and Hydrograph Analysis

Runoff:-

When rain falls on the surface of the earth a part of it's infiltrates into the soil, a part of it's intercepted by vegetation, a part gets evaporated into the atmosphere and remaining part flows on the surface of the earth to form small streams which ultimately joins the rivers and seas.

The part which flows on the surface of the earth and which runs away to join streams and rivers is termed as "Run off" on the catchment area.

The portion of precipitation which appears in the surface streams of either perennial of intermittent nature is called the "runoff".

The term runoff is used for water that is on the 'run' (or) in a flowing state, in contrast to the water held in depression storage and water evaporated in the atmosphere. The runoff of a catchment area in any specified period is the total quantity of water draining into a stream (or) into a reservoir in that period.

Runoff is usually expressed as volume per unit time (M^3/s). This can be expressed as,

(1) centimeter of water over a catchment

(2) Total water in cubic-metre.

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Catchment Area:-

The tract of land which contributes water into a stream or a reservoir is called as catchment basin and it's area is called "catchment area".

The runoff of a catchment area in a year is the volume of water discharged by the stream draining the area (or) into the reservoir recieving the discharge.

catchment area can be of three different types such as,

(1) Combined catchment area
(2) Intercepted catchment area
(3) Free catchment area.

Imp. Factor's Affecting Runoff:-

The principle factors affecting the flow from a catchment area are,

(1) Precipitation characteristics
(2) shape and size of the catchment
(3) Topography
(4) Geological characteristics
(5) Meteorological characteristics
(6) character of the catchment surface
(7) storage characteristics.

Precipitation characteristics:-

This is most important factor on which runoff depends. Important precipitation characteristic

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are,

(i) Intensity

(ii) Duration

(iii) Aerial distribution

(iv) Direction of storm movement

(v) form of precipitation

(vi) Evapo-Transpiration.

→ the more the rainfall, more will be run off. Runoff depends on the type of storm causing precipitation and also upon it's duration.

→ Runoff also increases with the intensity of rain.

→ Runoff also increases with the extent of storm over the catchment.

→ If intensity of rainfall is very less, and it rains as light showers, much of the water will be lost in information and evaporation etc. and the run off will be less.

→ Greater evapo-transpiration will resultinless runoff

→ similarly, If the precipitation is in the form of snow, (or) if water freezes as it falls, it will be retained in the catchment till temperature increas thus runoff will be less.

size and shape of the catchment:—

→ The Runoff from a catchment also depends upon size, shape and location of the catchment

→ More intersity of rainfall are generally distributed over a relatively smaller area, a stream collecting

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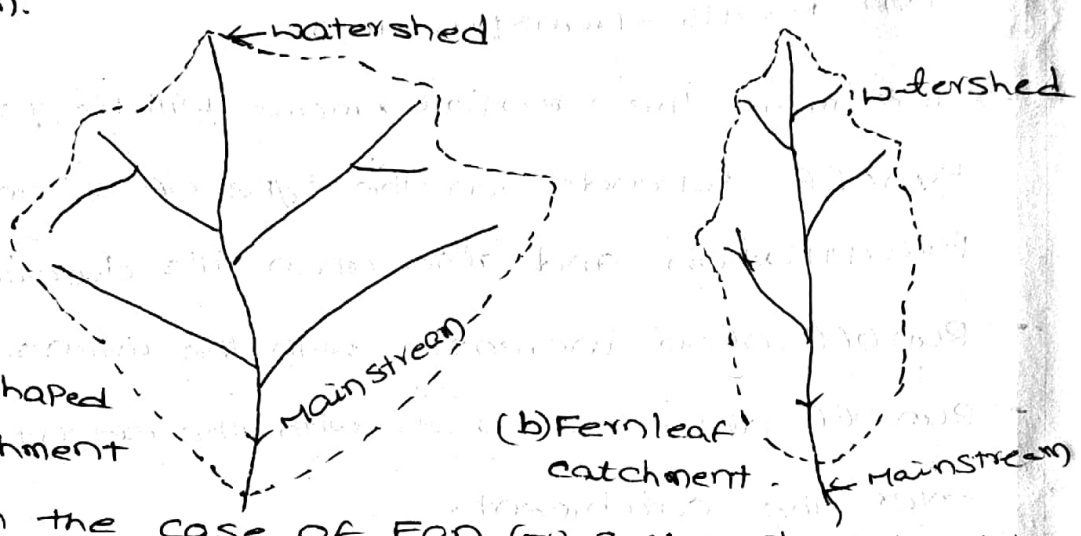
water from a small catchment area is likely to give greater runoff intensity per unit area.

→ In case of very big catchment, uniform rain seldom falls over the entire area, with the result that only very few tributaries of the stream feed water to main stream during a particular storm.



(a) Fan shaped Catchment

(b) Fernleaf catchment.

→ In the case of Fan (or) sector shaped catchment all the tributaries are approximately of the same size.

→ Such catchment gives greater runoff since the peak flood from the tributaries is likely to reach the main stream approximately at the same time.

→ In Fern leaf catchment the tributaries are generally of different lengths, and meet the main stream at the regular intervals.

→ In such a narrow catchment, the peak flood intensity is reduced. since discharge are likely to be distributed over a long period of time.

Topography of the catchment:-

→ The runoff depends upon whether the surface of the catchment is smooth (or) ragged.

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→ If the surface slope is steep, water will flow quickly, and absorption and evaporation losses will be less, resulting in greater runoff.

→ If the catchment is mountainous, and is on the windward side of the mountains, the intensity of rainfall will be more, and hence runoff will also be more.

4. Orientation of watershed:-

→ The orientation of watershed affects the evaporation and transpiration loss by influencing the heat recieved from the sun. The North and South orientation of watershed affects the melting time of collected snow and hence the runoff.

→ similarly, in mountaneous watershed, the windward side of the mountain recieves comparatively high intense rainfall than the leeward side.

Geological characteristics of basin:-

→ Geological characteristics of the catchment area is an important factor affecting the run-off.

→ This include the type of surface soil and sub-soil, type of rock and their permeability characteristics.

→ If the soil and subsoil is pervious, seepage will be more and this in turn reduces the

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the peak flood.

→ If the surface is rocky, the absorption will be practically nil, and runoff will be more. If the rocks have fissures, or if they are porous and have lava tunnels etc. most of the water will be lost by way of seepage, and surface run-off will be very small.

→ If this seeping water has the outlet in the stream of the catchment, most of the water flows back to the stream during its period of low flow.

Meteorological characteristics:-

→ Temperature, wind and humidity also affect the runoff. If the temperature is low and ground is saturated and frozen, it gives rise to greater run off.

→ If the whole of the stream freezes, the peak floods will be reduced. high temperature and greater wind velocity give rise to greater evaporation loss and reduce the run-off.

→ The peak flood depends upon the direction of movement of storm causing rainfall with relation to the direction of the stream

→ If the ~~stream~~ storm centre moves against the direction of the stream, the runoff from various points along the catchment reaches

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the stream at different timings, with the result that the peak flow is reduced.

Character of the catchment surface:-

→ The Runoff also depends upon the surface conditions whether the surface is drained (or) undrained, natural (or) cultivated, and whether it is bare (or) covered with vegetation etc.

→ If the surface has no natural drainage, absorption loss will be more. If more area of a catchment is cultivated, surface runoff will be less.

→ The presence of vegetal cover reduces the runoff specially during smaller streams.

→ For a bigger storm after the vegetal cover gets saturated, water runs from the surface freely as if there no vegetation.

Storage characteristics of the catchment:-

→ The artificial storage such as dams, weirs etc. and natural storage such as lakes, ponds tends to reduce the peak flow.

→ They also give rise to greater evaporation losses.

→ If the tributaries of a river discharge into a lake, and the river takes off from the lake, the peak floods in the river will be reduced.

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→ The storage into the Pervious surface soil and sub-soil tends to reduce the Peak flow and tend to regularise the flow of a stream.

Components of Runoff:-

Runoff is broadly classified into three types, such as,

1. Surface Runoff
2. Sub surface Runoff
3. Base flow.

} → Direct Runoff.

As discussed, the rainfall is disposed of the following manner.

(1) Basin Recharge

(2). Direct Runoff.

(3) Percolation down to ground water

(4) Evaporation and Transpiration.

Basin Recharge:-

It consists of,

→ Rain intercepted by leaves and stems of vegetation

→ Water held up in surface depressions, commonly known as the "depression storage".

→ Soil Moisture held as capillary water in pore spaces of soil (or) as hygroscopic water absorbed on the surface of soil particles.

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Direct Runoff:-

Direct Runoff is that water which reaches the stream shortly after it falls as rain is known as "Direct Runoff".

Direct Runoff consists of,

(1). surface Runoff (or) overland flow

(2) sub-surface Runoff (or) Interflow.

Surface Runoff:-

surface runoff is that portion of water which travels across the ground surface to the nearest stream.

→ If the soil is permeable, water percolates into it, and when it become saturated, flows laterally in the surface soil to a stream channel.

Sub surface Runoff:-

In sub surface Runoff is that the surface soil is permeable, but the sub soil is relatievely impermeable so that water does not percolate deep to meet the ground water.

Percolation down to ground water (or) Base flow:-

If the subsoil is also permeable, water percolates deep downwards to meet the ground water. Much of the low water flow of rivers is

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derived from the ground water. stream channel which are below the ground water table are called "effluent streams".

Computation of Runoff:-

The runoff from a catchment can be computed daily, Monthly (or) yearly. Following are some of the Methods of computing the Runoff are,

(1) By linear (or) exponential regression
(2) By empirical equations and tables
(3) By Infiltration Method
(4) By unit Hydrograph Method
(5) By Rational Method.

(1) Runoff by a linear (or) exponential regression:-

Factors affecting runoff resulting from a given rainfall, the relationship between these two is quite complex.

→ Straight line regression for small and Medium sized catchments.

→ Exponential from of regression for large catchments.

(i) Straight line regression between P and R:-

The equation of linear regression line between observed values of R and P

$$R = aP + b.$$

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(ii) Exponential regression between P and R:-

For large catchments, it is advantageous to use the following exponential Relationship,

$$R = B P^{m}.$$

(2) Run off by formulae and Tables:-

(i) Runoff co-efficient:-

The runoff and rainfall can be inter related by runoff co-efficient by the expression

$$R = KP.$$

Where,

R = Run off

P = Rainfall.

K = run off co-efficient

The runoff co efficient naturally depend upon all the factors which affect the runoff. This Method is used only for small water control project and should be avoided for the analysis of major storms.

Barlow's Table:-

TG. Barlow (1912) carried out studies of catchments mostly under 140 sq. km in the united provinces (U.P)

2. Strange's Tables and curves:-

W.L Strange (1928) gave tables and curves for runoff resulting from rainfall in the

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Plains of south India. The tables and graphs are for the konkan region of Maharashtra. Strange table and curves give runoff for daily rainfall, and take into account three type of catchments and three surface condition prior to the rain.

3. Inglis Formula:-

C.C Inglis gave the following formulae, derived from data collected from 37 catchments in the Bombay Presidency,

For ghat areas (western ghats)

$$R = 0.85P - 30.5$$

For Non-ghat areas (Plain ghats)

$$R = 0.00394P^2 - 0.0701P.$$

4. Lacey's formula:-

$$R = \frac{P}{1 + \frac{304.8F}{PS}}$$

where,

S = catchment factor

F = Monsoon duration factor.

5. Khosla's Formula (1960):-

$$R_m = P_m - 0.48\,T_m.$$

where,

R_m = Monthly runoff

T = Mean Temperature in °c

P_m = Monthly Precipitation. in cm.

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6. ICAR Formula (For Nilgiri hills):-

$$R = 1.511(P^{1.44})(T_m)^{-1.34}(A^{-0.0613})$$

7. Dhir, Ahuja and Majumdar Formulae:-

$R = 120P - 4945$ (For chambal, Rajasthan)

$R = 435P - 17200$ (For Tapi, Gujarat)

$R = 13400P - 575000$ (For damodar valley, west bengal)

$R = 34.6P - 1510$ (For Tawa, M.P)

$R = 13.18P + 86.5$ (For Machakund, A.P).

8. UP Irrigation Research Institute formula:-

$R = 5.45P^{0.6}$ (For Ganga, Haridwar)

$R = 0.35P^{1.1}$ (For Yamuna at Tajewala)

$R = 2.7P^{0.8}$ (For sarda at bana basa).

Stream Gauging:-

→ It is a technique used to measure the discharge (or) the volume of water moving through a channel per unit time of a stream.

→ The height of water in the stream channel, known as a stage (or) stage height, can be used to determine the discharge in a stream.

→ Streamflow representing the runoff phase of the hydrological cycle is the most important basic data for hydrologic studies.

→ Streamflow is the only part of hydrological cycle that can be measured accurately

→ Runoff from a catchment can be

by measuring the discharge of the stream draining it.

Necessity of stream gauging:-

→ By measuring the discharge in river the irrigation water can be distributed uniformly.

→ By measuring flow in rivers flood warning can be issued

→ By measuring flow in rivers flood warning can be issued in canal quantity losses may known.

Site selection for stream gauging:-

→ The bed and banks of the stream should be firm and stable so as to ~~measure~~ ensure consistency of area discharge relationship.

→ The bed and blanks should be free from vegetal growth, boulders or other obstructions like bridge, pier etc.

→ There should be no larger overflow section at flood stage.

→ The stream gauging station should be easily accessible.

Methods of stream gauging:-

Stream gauging as classified into two methods they are,

1. Conventional Method
2. Advanced Techniques.

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Conventional Method:-

Conventional Method is classied into two types they are.

→ Direct Method

→ In Direct Method.

Direct Method:-

Direct Method is classified into, such as,

→ velocity area Method using current Meter

→ velocity area Method using Floats

→ By Dilution Methods.

In Direct Method:-

In direct Method is again classified into, such as,

→ Slope area Method

→ Hydraulic structures.

Advanced techniques:-

Advanced techniques are classified into,

→ Moving boat Method

→ Ultrasonic Method

→ Electromagnetic Method.

1. Area-velocity Method:-

→

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performance [illegible] these are read each time the station is visited.

6.3 DISCHARGE MEASUREMENT BY AREA-VELOCITY METHOD

Though there are several methods of discharge measurement, perhaps the most accurate of all of them is the area-velocity method. In this method the discharge is obtained as the product of the cross-sectional area of flow in the river and the average velocity of flow. That is

$$Q = A \cdot V \qquad ...(6.1)$$

The measurement of discharge thus involves obtaining information at a number of points over the cross-section sufficient to determine the average velocity and also the area of flow. The number of points selected should be such that the measurements are completed within a reasonably quick time. This is essentially required when the stage in the river is changing rapidly at the time of discharge measurement. The procedure consists of dividing the flow area into a number of strips by means of *verticals* selected along the width of the river and measuring the depths at these verticals. The velocities are also measured at one or more points on the verticals to obtain the mean velocity for any vertical. The velocity at any point in the river is measured by inserting the *current meter* at that point facing the flow.

Current meter. There are mainly two types of current meters which are in common use, namely, *cup type* current meter (also known as the *price* current meter) and the *propeller type* current meter. The principle involved in both the meters is that the water flowing past the rotating element of the meter makes it revolve due to the unbalanced drag force acting on it and the speed of the rotating elements is directly proportional to the velocity of water. The cup type current meter consists of a wheel of six conical cups rotating about a vertical axis as shown in Fig. 6.3. The tail vanes (also known as the *fins*), will always align the meter along the direction of flow.

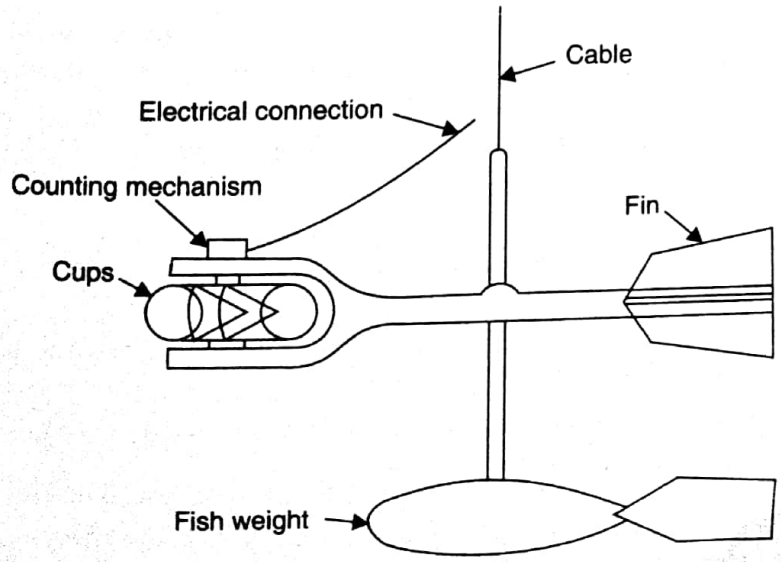

FIGURE 6.3 Cup type current meter.

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6.4 DISCHARGE MEASUREMENT BY MOVING-BOAT METHOD

The conventional area-velocity method of discharge measurement described in the previous section involves costly and tedius procedure and sometimes becomes impracticable especially during floods

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when facilities may be inundated or the site may be inaccessible, at site where no facilities exist, or at locations where unsteady flow conditions require that measurements be made as rapidly as possible. The moving-boat technique is a method applicable to the rapid measurement of discharge in large streams. It requires no fixed facilities and lends itself to the use of alternative sites if conditions make this desirable. This technique, the description of which now follows, has been developed by the United States Geological Survey in 1969.

The moving boat technique is similar to the conventional method as both use the area-velocity approach. The main difference is in the method of data collection. In the conventional method the data at each point in the cross-section are collected while the observer is in a stationary position. This may be called a *static* approach. In contrast, in the moving-boat method, the data are collected while the observer is on a boat which is rapidly traversing the cross-section which may be called a *dynamic* approach. The position of the current meter is fixed at a constant depth from the free surface unlike in the conventional method. Since the current meter moves with the same velocity as that of boat, the current meter records the resultant of boat and stream velocities which is the vectorial sum of these two. During a traverse of the boat across the stream, a sonic sounder records the depth of flow at different points which define the geometry of the cross-section. A continuously operating current meter measures the resultant of boat and stream velocities. A vertical vane aligns itself in a direction parallel to the movement of water past the current meter and an angle indicator attached to the vane assembly indicates the angle between the direction of the vane and the true course of the boat, that is, the angle between the resultant velocity and the boat velocity. The data from these instruments provide the information necessary for computing the discharge for the cross-section. The traverse is made without stopping along a preselected path that is normal to the streamflow, and the data are collected at regular intervals along the path, normally, at 30 to 40 observation points.

In the velocity triangle at any point of observation as shown in Fig. 6.9, V V_b and V_v stand for the component of stream velocity normal to the cross- section at the sampling point, the velocity of boat and the resultant velocity respectively. Stream velocity V which is perpendicular to the boat path can be determined as

$$V = V_v \sin \theta \qquad \text{...(6.5)}$$

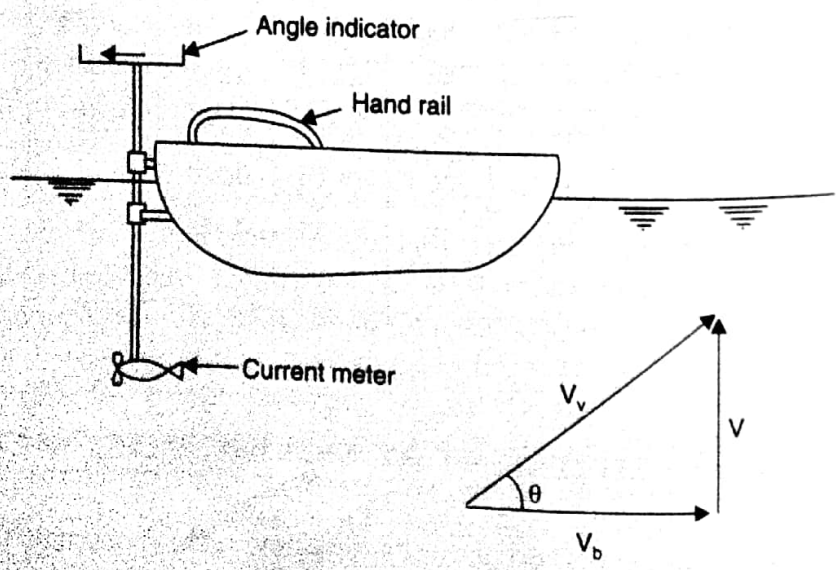

FIGURE 6.9 Moving-boat technique.

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points is about 30 to 40, it is only 9 in this example. The smaller number of sampling points uniform sampling time interval are adopted in this example only to reduce the computa may also be noted that the final discharge of 489.45 m^3/s should be multiplied by a coeffici get the true discharge.

Table 6.3. Discharge Measurement by Moving-boat Method

Time sec	Current meter reading	Angle from angle indicator	Depth from sonic sounder m	N rev/s	V_v m/s	Average θ	$L_b = V_v \cos\theta\, dt$ m	Average depth d m	$V = V_v \sin\theta$ m/s	$\Delta A = L_b \cdot d$
0	0	0	2.6							
30	26	21°	3.1	0.867	0.534	10.5	15.75	2.85	0.097	44.89
60	68	23°	4.6	1.400	0.800	22.0	22.25	3.95	0.300	85.66
90	130	27°	6.3	2.067	1.134	25.0	30.83	5.45	0.479	168.02
120	201	35°	8.1	2.367	1.284	31.0	33.02	7.2	0.661	237.74
150	265	31°	7.6	2.133	1.167	33.0	29.36	7.85	0.636	230.48
180	302	28°	6.5	1.233	0.717	29.5	18.72	7.05	0.353	131.98
210	335	20°	4.3	1.100	0.650	24.0	17.81	5.40	0.264	96.17
240	350	15°	1.8	0.500	0.350	17.5	10.01	3.05	0.105	30.53

Total

6.5 DISCHARGE MEASUREMENT BY OTHER METHODS

There are several other procedures employed for the measurement of discharge in streams none of them is comparable to the current meter method in reliability. The important of the described here.

Slope-Area Method. In this method the flow in the channel is computed by one of open channel formulae, namely Chezy's or Manning's given by

$$Q = AC\sqrt{RS}$$

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

where A is the cross-sectional area, S is the energy slope, R is the hydraulic radius, C is the C coefficient and n is the Manning's rugosity coefficient.

A fairly straight reach of the river which is free from disturbances like backwater drawdown curve or tributaries joining upstream or downstream is selected for the purpose length of the reach should be about 5 times the width of the river and not less than 300 m case. The drop in water surface in the reach selected must be at least 150 mm. The energy computed as

$$S = \frac{(h_1 - h_2) + \left(\frac{V_1^2}{2g} - \frac{V_2^2}{2g}\right)}{l} \quad ...(6.13)$$

where h_1 and h_2 are the gauge reading at the u/s and d/s sections of the reach V_1 and V_2 are the average velocities in the stream at u/s and d/s sections of the reach and l is the length of the reach. From the field surveys the cross - sectional area of flow and the wetted perimeter are obtained at the beginning, middle and end of the reach. Then A and R to be used in Eq. (6.11) or Eq. (6.12) are determined as

$$A = \frac{A_1 + 2A_3 + A_2}{4} \quad ...(6.14)$$

$$P = \frac{P_1 + 2P_3 + P_2}{4} \quad ...(6.15)$$

$$R = \frac{A}{P} \quad ...(6.16)$$

where the suffix 3 stand for the mid-section of the reach. The value of C or n has to be carefully selected from the field data. As a first approximation the energy slope is taken as the water surface slope neglecting the velocity terms in Eq. (6.13) and with this S, the discharge Q is obtained from Eq. (6.11) In the next trial using the Q from pervious trial and A_1, and A_2, the velocities V_1 and V_2 are determined and the energy slope is revised with these velocities in Eq. (6.13). The discharge Q is computed using Eq. (6.11) and the revised energy slope is computed. The computations are made by successive approximations like this, till the discharge obtained in any two successive trials is nearly the same.

This method of discharge measurement is used mainly for the estimation of flood discharge when actual measurement for the area-velocity method are not possible for various reasons or when the estimation of discharge is to be made after the flood has passed the site. Further details of the method can be obtained from IS : 1912–1964.

This method can give only an approximate estimate of the discharge due to the following limitations : (*i*) Difficulty in proper selection of the rugosity coefficient n, (*ii*) The cross-sectional areas used in the discharge equation may be differing from those which existed during the time the flood passed the reach, (*iii*) The slope used in the discharge estimation cannot be precise as the water surface during the flood may be markedly warped.

Hydraulic Structures. On small streams the flow can be measured with the help of hydraulic flow measuring devices such as rectangular, triangular and Trapezoidal weirs, or flumes like venturi-flume and Parshall flume. The discharge in all these cases is expressed as a function of geometry of the structure and some reference head. The discharge expression will also contain an empirical coefficient. The details about the theory of these devices can be obtained from text-books on open channel flow.

An existing dam across a stream, a bridge opening or a causeway may also be used as a means of determining discharge indirectly. In the case of a dam the discharge can be expressed as a function of length of dam and head of the flow over the dam. In the case of bridge opening the

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discharge is a function of the area of flow at the constriction and the drop in water surface near the bridge. This method is known as the *contracted-opening method*. The flow over a causeway may be approximated as the flow over a broad-crested weir and the discharge estimated using the broad-crested weir formula.

Floats. In this method the floats are used to measure the velocity at various verticals across the width of the stream. After the mean velocity for the vertical is determined the discharge is computed adopting the same procedure as in area-velocity method. A float is allowed to travel on the water surface and the time taken by it to travel a stipulated distance is noted. This enables the determination of the surface velocity. The mean velocity in the vertical is taken as 0.85 times the velocity of the float at the surface.

$$V = 0.85\, v_s \qquad \text{...(6.17)}$$

Several floats introduced into the stream at various points give the mean velocities for several verticals. The distance travelled by the float must be large enough to give reasonably accurate velocity. In general it should be at least 180 m.

The main objections to this method are that the floats may not travel along straight paths between the sections and that the travel of the floats may be influenced by the prevailing wind.

Dilution Method. In this method a solution of a stable chemical such as common salt or sodium dichromate or a radioactive chemical, known as the *tracer*, is injected into the stream at either a constant rate or all at once. When the tracer is introduced into the stream at a constant rate, it is called the *plateau* method and when it it introduced all at once it is called the '*gulp*' method.

The solution will be diluted by the discharge of the stream. The concentration of the tracer at a cross-section downstream (known as the sampling section) of the injection point is determined. Let the tracer with a concentration of C_1 be injected into the stream at a constant rate of q m^3/s. Let Q be the discharge in the stream which already contains the same tracer with a concentration of C_0. If the concentration of the tracer at the downstream section C_2, then from the mass balance equation written for the tracer, we have

$$Q\,C_0 + q\,C_1 = (Q + q)\,C_2 \qquad \text{...(6.18)}$$

which on rearrangement takes the form

$$Q = q\,\frac{(C_1 - C_2)}{(C_2 - C_0)} \qquad \text{...(6.19)}$$

If the concentration of the tracer initially present in the stream is negligible, that is when $C_0 = 0$, the discharge in the stream is given by

$$Q = q\left(\frac{C_1}{C_2} - 1\right) \qquad \text{...(6.20)}$$

When the injection of the trace into the stream is sudden, the discharge is given by

$$Q = \frac{C_1\,\forall}{\int_{t_1}^{t_2} (C_2 - C_0)\,dt} \qquad \text{...(6.21)}$$

where $\forall$ is the volume of injected solution, $(t_2 - t_1)$ is the time in which all the tracer passes the sampling section, and C_2 is the concentration of the tracer at sampling section monitored continuously with time.

In this method, there is no need to measure velocity, depth, cross-sectional area, or any other hydraulic factors. But the accuracy of the method critically depends on two factors : (*i*) complete mixing of the injected solution throughout the stream cross-section before the sampling section is reached and (*ii*) absorption of the added tracer by the stream bottom materials, sediments, plants, organisms and the decomposition of the added tracer in the water of stream. For this reason, the concentration of the tracer should be determined at least at one more section downstream of the sampling section to verify that there is no systematic difference in the mean concentration from one section to another. Also, the tracer material should be so selected that :

(*i*) it dissolves readily in stream water at ordinary temperature,

(*ii*) it is absent in the stream water, or present only in negligible concentrations,

(*iii*) it is not decomposed in the stream water and is not retained or absorbed by sediments, plants or organisms,

(*iv*) it can be detected by simple methods,

(*v*) it is harmless to man and animals in the concentrations it assumes in the stream, and

(*vi*) it is not expensive.

Although radioactive elements are ideal tracers for this method, the health hazard may limit their use.

Electromagnetic Induction Method. Notable among the recent developments in the river gauging are the electromagnetic induction method and the ultrosonic methods. In the electromagnetic induction method a long conductor is burried at the bottom of the channel covering the entire width of the river which carries a current I to produce a controlled vertical magnetic field. As the water flowing in the stream cuts this magnetic field, it produces an electromagnetic force (emf) which is related to the discharge in the river, depth of flow, and the current in the conductor at the bottom of the river. Electrodes provided at the sides of the channel section measure the emf produced due to the flow in the river. It has been shown that the relationship among the variables of interest can be expressed as

$$Q = k_1\left(\frac{Ed}{I} + k_2\right)^n \qquad \text{...(6.22)}$$

[illegible]e of flow in the river, d is the depth of flow, E is the emf induced, I is the current [illegible] and k_1, k_2, and n are the system constants to be obtained on calibration.

[illegible]od is particularly suitable for the rivers which undergo considerable change in [illegible]al properties due to sedimentation, weed growth etc., and also in tidal channels [illegible]anges rapidly with time both in magnitude and direction.

[illegible] Method. In this method certain reach of the river (of length at least equal to the [illegible] is made to have a rectangular lined cross-section. Two transducers which can [illegible]ive the ultrasonic signals are kept on either side of the reach such that the line [illegible] at 45° with the axis of the river as shown in Fig. 6.10.

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10.6 FLOW - DURATION CURVE

When the runoff rate observed at the catchment outlet is continuously measured, it can be plotted as the ordinate against time on abscissa to provide the runoff hydrograph. The variability in runoff is expressed is terms of the fluctuations of the runoff rate in the hydrograph. There are two other ways of evaluating the variability in the runoff. They are the *flow-duration* curve and the *flow-mass* curve which are described in this section and the next section respectively.

A graph representing the rate of runoff in the stream as the ordinate against the percentage of time such flow is equalled or exceeded as the abscissa is called the flow duration curve.

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To determine the flow duration curve for a particular location, it is necessary to obtain daily flow data for a certain period of time, either 1 year or a number of years. The length of the records indicate the total number of days in the series. The daily flows are then arranged in descending order of magnitude, from the highest to the lowest flow value, with each flow value being assigned a rank. The highest flow would get a rank of 1, the next highest flow a rank of 2, and so on, and lowest flow would get a rank n where n is the total number of days in the record. For each flow value, the percent of time is computed as $\frac{m}{n} \times 100$, where m is the rank assigned to the flow. The flow duration curve is obtained by plotting percent of time as the abscissa and the flow value as the ordinate. The flow duration curve can also be constructed using weekly, ten daily and monthly flow values. Flow duration curve determined from monthly flows is given in Example 10.5 and shown in Fig. 10.4. The flow duration curve is also known as the *discharge-frequency curve* or the cumulative frequency curve. The amount of work involved in preparing a flow duration curve can be reduced by dividing the flow data into class intervals instead of handling each individual observation. Thus, for example, if in a record length of 365 days the daily flow is between 40 m^3/s and 50 m^3/s on 73 days, then the mid value of class interval, *i.e.*, 45 m^3/s, is plotted against percent of time given by $\frac{73}{365} \times 100 = 20\%$, on the flow duration curve. A flow duration curve constructed based on daily flows will be steeper than the flow duration curve prepared from the monthly flow data for the same period of record. This is because the larger interval data will smoothen out the variation in the shorter interval data.

Uses of Flow Duration Curve

1. A flow duration curve allows the evaluation of low level flows. For example, from Fig. 10.4, the flow expected to be exceeded 75 percent of the time can be readily determined to be 20 m^3/s, and for 90 per cent of the time it is 16 m^3/s, etc. If the flow is regulated by providing storage to yield a minimum flow of 25 m^3/s all the time, the flow duration curve gets modified as shown by the broken line curve in Fig. 10.4.
2. The flow duration curve is highly useful in the planning and design of water resources projects. In particular, for hydropower studies, the flow duration curve serves to determine the potential for *firm power* generation. In the case of a run- of-the-river plant with no storage facilities, the firm power is usually computed on the basis of flow available 90 to 97 percent of the time. The firm power is also known as the *primary power*. *Secondary power* is the power generated at the plant utilising water other than that used for the generation of firm power.
3. If a sediment rating curve is available for the given stream, the flow duration curve can be converted into cumulative sediment transport curve by multiplying each flow rate by its rate of sediment transport. The area under this curve represents the total amount of sediment transported.
4. The flow duration curve also finds use in the design of drainage systems and in flood control studies.

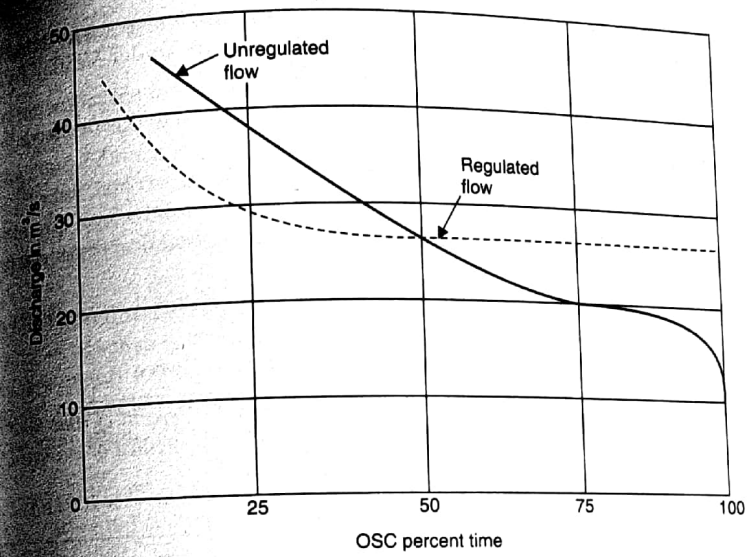

FIGURE 10.4 Flow duration curve.

5. A flow duration curve plotted on a log-log paper provides a qualitative description of the runoff variability in the stream. If the curve is having steep slope throughout, it indicates a stream with highly variable discharge. This is typical of the conditions where the flow is mainly from surface runoff. A flat slope indicates small variability which is a characteristic of the streams receiving both surface runoff and groundwater runoff. A flat portion at the lower end of the curve indicates substantial contribution from groundwater runoff, while the flat portion at the upper end of the curve is characteristic of streams with large flood plain storage, such as lakes and swamps, or where the high flows are mainly derived from snowmelt.
6. The shape of the flow duration curve may change with the length of record. This aspect of the flow duration curve can be utilised for extrapolation of short records. Suppose there is a catchment A with a long record (say 1941 to 1980) which also covers the period of the short record of catchment B (say 1971 to 1980) in the same region. Then it is assumed that relationship which existed during the concurrent period is also valid for the long period of catchment A for which catchment B has no record. First the flow duration curves are prepared for both the catchments for the concurrent period of record (1971 to 1980). Next the flow duration curve of A is constructed for the long period (1941 to 1980). Now the ordinates of flow duration curve of catchment B for the long period are obtained from the following equation.

$$Q_B = Q_A \frac{q_B}{q_A} \qquad ...(10.15)$$

where, for any given percent of time, q denotes the ordinate of flow duration curve based on short record, Q denotes the ordinate of flow duration curve based on long

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10.7 FLOW-MASS CURVE

For many water resources investigations it is important to know the total volumes of water that have to be dealt with over long periods of time. For such purposes the most convenient means of presenting the runoff data is the mass curve. When it is desired to use water at uniform or nearly uniform rate greater than the minimum discharge in the stream, it is necessary to provide storage where water is impounded during periods of high flow for use during periods of low flows. Mass curve serves as a very useful tool to determine the required storage capacity for any uniform rate of demand.

A graph of the cumulative value of any hydrologic quantity, generally as the ordinate, plotted against the time as abscissa is known as a *mass* curve. When cumulative volume of runoff is taken as the hydrologic quantity, the mass curve may be called a *flow mass* curve or simply a mass curve. It is the integration of the hydrograph and therefore represents the area under the hydrograph from one time to another. Mathematically, the mass curve is expressed by

$$V(t) = \int_0^t Q(\tau).\, d\tau \qquad ...(10.16)$$

where $V(t)$ = cumulative volume of flow up to time t from the start of the record, that is, the ordinate of the mass curve at any time t.

$Q(\tau)$ = the discharge as a function of time, *i.e.*, the ordinate of the hydrograph, and

τ = a dummy variable.

A typical mass curve is shown in Fig. 10.5. The mass curve concept is believed to have been first suggested by Rippl in the year 1883.

Hence, the mass curve is also known by the name *Rippl curve* or *Rippl diagram*. The difference in the ordinates of any two points on the curve is the summation of the flow during the intervening period of time. Thus, if two points such as P and Q in Fig. 10.5 are joined by a straight line, the

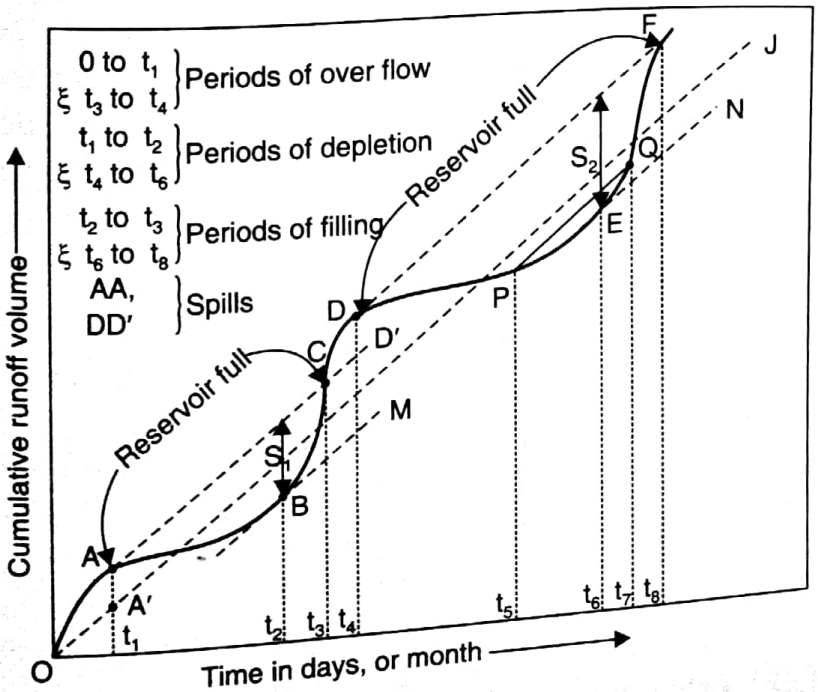

FIGURE 10.5 Flow mass curve.

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Hydrograph :-

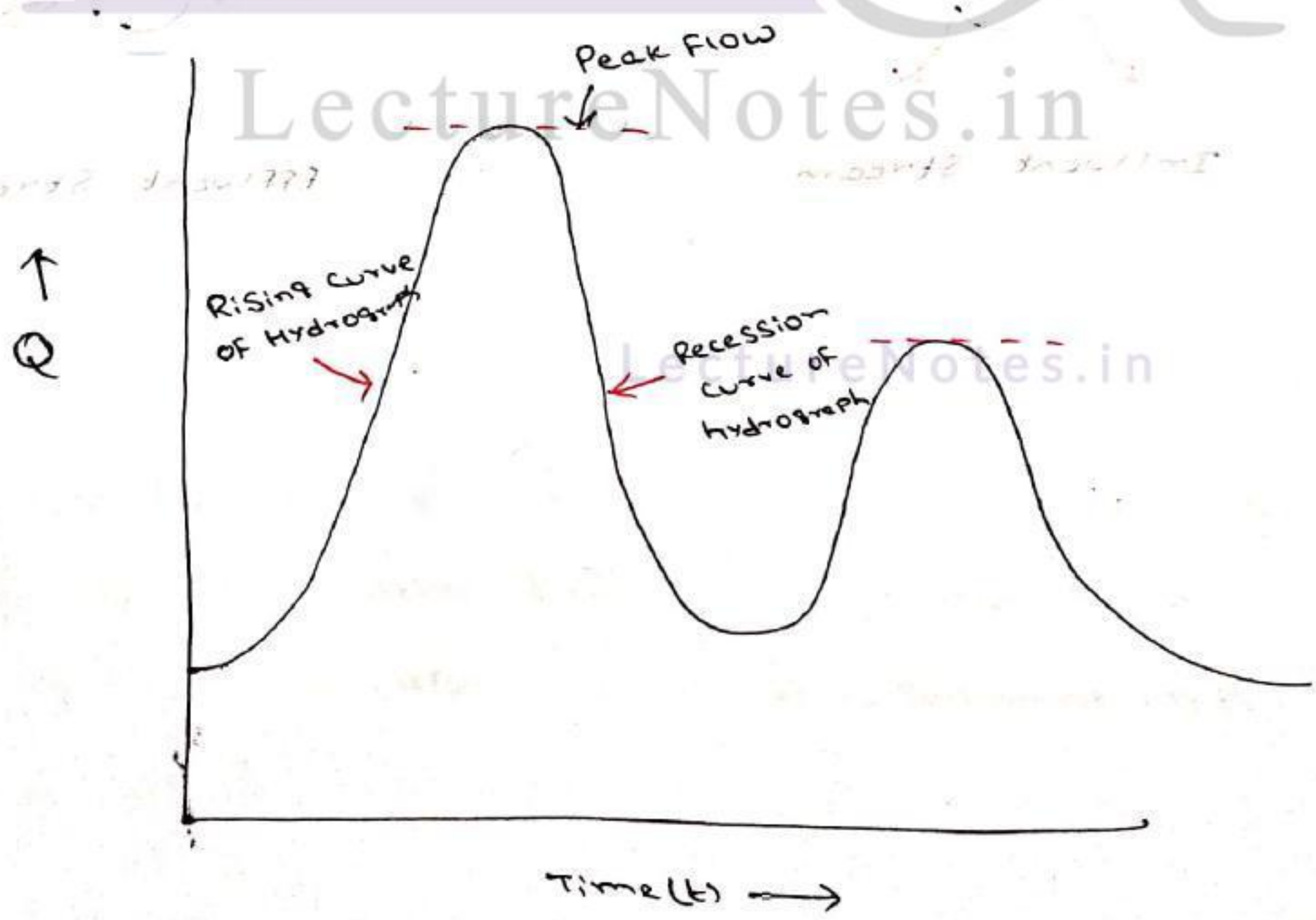
→ It is the graphical representation of the discharge flowing in a river at the given location with the passage of time.

→ A Hydrograph is capable of representing discharge fluctuation in the river at a given site over a given time period.

→ Hydrograph gives us the peak flow which is important for the design of hydraulic structure at that site.

→ The result of an hydrograph due to an isolated storm generally shows the single peak discharge and it is known as "Storm Hydrograph" or "Flood Hydrograph" or "simply Hydrograph".

→ Hydrograph consists of surface run-off, sub-surface run-off and base flow.



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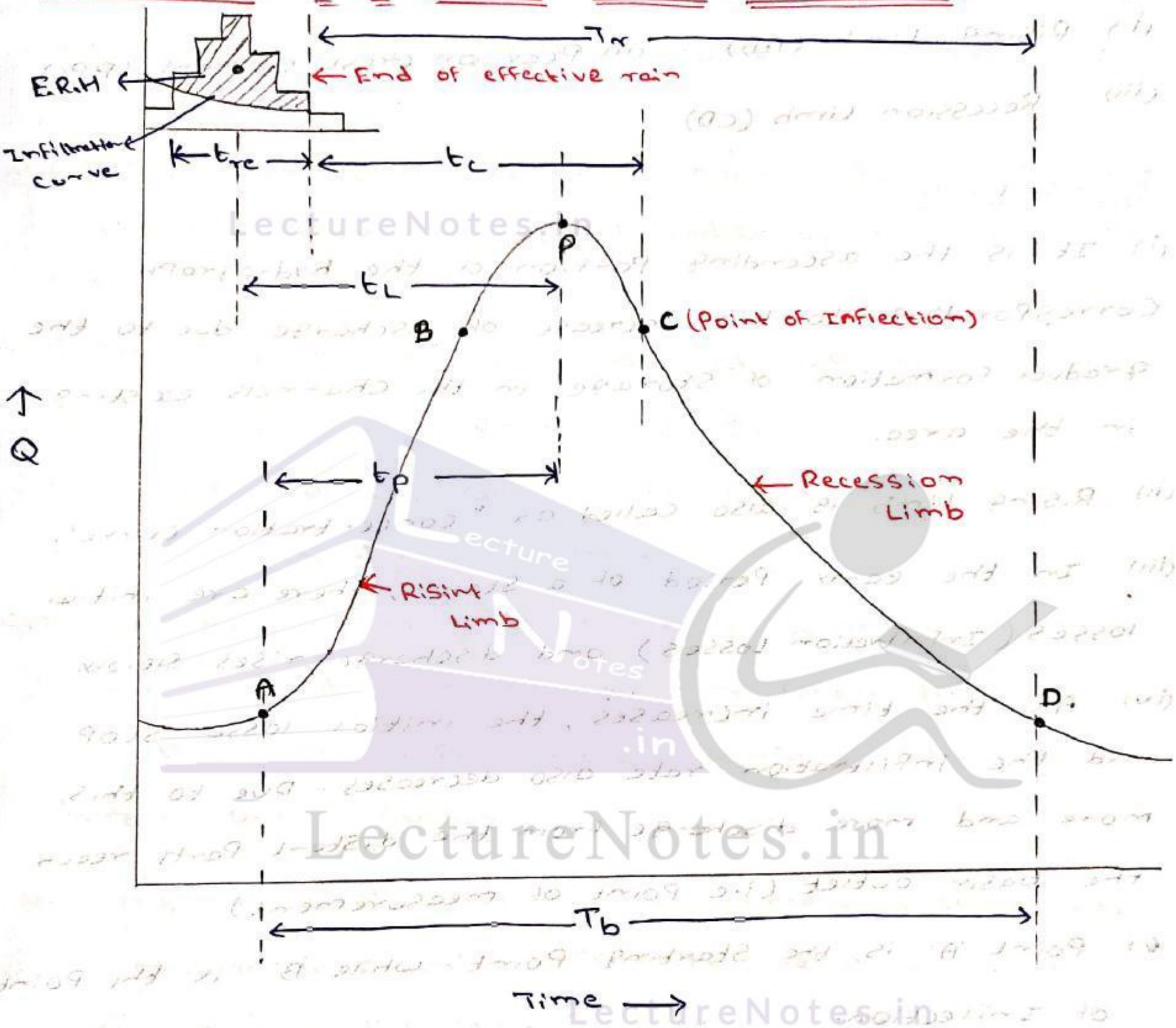
→ The hydrograph from a complex storm (more than one storm) will be a multi-peaked hydrograph.

Components of a Single Peaked Hydrograph:-



There are three essential components of a single peaked hydrograph resulting from an isolated storm:

(i) Rising limb (AB)

(ii) Crest segment (BPC)

(iii) Recession limb (CD)

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There are three essential components of a single peaked hydrograph resulting from an isolated storm. They are:-

(i) Rising limb (AB) (ii) Peak (or) crest element (BPC)
(iii) Recession limb (CD)

Rising limb:-

(i) It is the ascending portion of the hydrograph corresponding to the increase of discharge due to the gradual formation of storage in the channels existing in the area.

(ii) Rising limb is also called as "concentration curve".

(iii) In the early period of a storm, there are initial losses (Infiltration losses) and discharge rises slowly.

(iv) As the time increases, the initial losses stop and the infiltration rate also decreases. Due to this, more and more discharge from the distant parts reach the basin outlet (i.e point of measurement)

(v) Point 'A' is the starting point while 'B' is the point of inflection.

(vi) The shape of the rising limb is controlled by the characteristics of ~~basin~~ storm such as duration, intensity and uniformity of the rain.

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Peak (or) Crest Segment :- (BPC)

(i) The Peak or crest segment includes the Part of the hydrograph from the Inflection Point (B) on the rising limb to an inflection Point (C) on recession limb.

(ii) Crest segment is one of the most important component of the hydrograph because it indicates the Peak Flow rate.

(iii) The Peak may be Sharp or Flat depending upon the rainfall - catchment characteristics.

(iv) Multiple Peaked complex hydrographs in a basin can occur when two or more storms occur.

(v) The end of the crest segment corresponding to the inflection point 'c' marks the time when direct run-off from the overland flow (excess rainfall) into the stream outlet ceases.

(vi) The point of inflection 'c' represents the condition of maximum detention storage (depth of water built-up over the land surface).

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Recession limb :- (CD)

(i) The recession limb extends from the point of inflection "point C" of the crest segment to the point 'D' which is the point of commencement of the natural ground water flow.

(ii) The shape of the recession curve depends only on the basin characteristics and it is independent of rain-storm characteristics.

(iii) The equation of the recession curve may be expressed in following form by Barnes (1940)

$$Q_{rt} = Q_{ro} \cdot K_r^t$$

Q_{rt} : Discharge at any time interval t (days) after the point of inflection 'c'.

K_r^t = Recession constant with a value less than unity

→ Barne's observed that the above equation holds good for the lower portion of the curve where the contribution is mainly from ground water.

→ For upper portion of the curve where the contribution of discharge is from all the three phases i.e., surface storage, sub-surface flow & ground water flow) the recession constant K_r^t is composed of all the three components, and is given by

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$$K_r^t = K_{rs} \cdot K_{ri} \cdot K_{rg}$$

K_{rs} = Recession constant for Surface Storage (0.08 - 0.40)

K_{ri} = Recession constant for interflow (0.55 - 0.90)

K_{rg} = Recession constant for ground water (0.90 - 1.0)

Time Parameters used in hydrograph analysis:-

1 Effective Time Duration:- (t_{re})

It is the net duration of precipitation during which rainfall rates are more than infiltration rates.

2. Lag time or Basin Lag:- (t_L)

It is taken as the time lapse between the centre of mass of effective rainfall and the peak of the hydrograph.

3. Time to Peak:- (t_p)

It is the time interval between the starting of the rising limb (A) to the peak (P) of the hydrograph.

4. Time of Concentration :- (t_c)

It is defined in two ways.

(i) In terms of physical characteristics of watershed, it is defined as the travel time of a water particle from the hydraulically most remote point in the basin to the outflow location.

(ii) Based on rainfall and hydrograph characteristics, it is taken as the time from the end of net rainfall to the point of inflection (I) of falling limb of the

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hydrograph.

→ It is estimated by the following formula by Kirpich (1940)

$$t_c = \frac{0.000323 L^{0.77}}{S^{0.385}}$$

t_c = Time of concentration, in hours

L = Maximum length of travel of water in metres.

S = Slope of the channel = H/L

H = Difference in elevation between the remote point in channel and the outlet point.

5. Recession Time (T_r):

It is the time elapsed between the end of the effective rainfall and lowest point (D) of the recession limb.

6. Time base of hydrograph (T_b)

It is the time from the beginning point (A) to the end point (D) of the direct run-off.

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Computation of Direct Run-off from Storm hydrograph:

1. Find the ordinates of storm hydrograph, representing total discharge 'Q' at a given time interval say 't' hours.

2. Separate the ground water flow. Find the ordinates of the base flow at the same interval of time.

3. Find the ordinates of direct run-off by subtracting the ordinates of base flow from total discharge ordinates.

4. The direct run-off in depth of water (in cm) is found from the expression

$$\text{Direct Run-off} = \frac{\text{Total volume of Direct Run-off}}{\text{Area of basin}}$$

$$= \left[\frac{\Sigma \text{ ordinates} \times t \times 60 \times 60}{A \times 10^6}\right] \times 100$$

$$= 0.36 \frac{\Sigma \text{Ordinates} \times t}{A} \text{ cm}$$

t = Time interval between successive ordinates in hours.

A = Area of basin in sq.km

Q = Discharge in m^3/sec

Σ ordinates = Sum of discharge ordinates (Direct Run-off) in m^3/sec

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Direct Run-off Hydrograph:-

→ It is also called as surface run-off hydrograph which is obtained after separation of base flow from storm or flood hydrograph.

→ Area under D.R.H will give run-off volume over the catchment area. [It is equal to effective rainfall.]

→ It is a plot of direct run-off and time.

Q) A storm of 3 hour duration occur over a basin of an area 652.2 km² and the resulting flow measurement is given below. If the base flow is 10 m³/sec. What is the run-off over catchment in cms.

Time (hr)	0	3	6	9	12	15	18	
3 hr SHG ordinates m³/sec	10	310	510	410	260	85	10	
	1	2	3	4	5	6	7	A = 4780 × 3600
Base Flow m³/sec	10	10	10	10	10	10	10	= 180 × 3600
D.R.H m³/sec	0	300	500	400	250	75	0	

Area under D.R.H = $[0+300+500+400+250+75+0] \times 3\times60\times60$

$= 16.47 \times 10^6 \, m^3 \left[\rightarrow \frac{m^3}{sec} \times sec = m^3\right]$

Run-off Depth $= \frac{\text{Volume}}{\text{Area}} = \frac{16.47\times10^6}{652.2\times1000^2} = 0.0253 \, m$

$= 2.53 \, cm$

$= \frac{0.36\times1525\times3}{652.2} = 2.53 \, cm$

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Factors affecting flood hydrograph:

The factors that affect the shape of the hydrograph can be broadly grouped into two types. They are:

(i) Physiographic Factor (ii) Climate Factor

Physiographic Factors

1. Basin Characteristics
   a) Shape
   b) Size
   c) Slope
   d) Elevation
   e) Drainage Density
2. Infiltration Characteristics
   a) Land use and cover.
   b) Soil type
3. Channel Characteristics
   a) Cross-Section
   b) Roughness
   c) Storage Capacity

Climate Factors

1. Storm Characteristics
   a) Precipitation
   b) Intensity
   c) Duration
   d) Movement of Storm
2. Initial Loss
3. Evapo-Transpiration

→ Generally the rising limb is affected by climatic factor and recession limb is affected by the physiographic factor.

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Factors affecting shape of a hydrograph:

Factors which affect the shape of hydrograph are as follows:

1. Climatic factors

   a) Form of precipitation

   b) Rainfall intensity

   c) Rainfall duration

   d) Direction of Rainfall (or) Storm movement

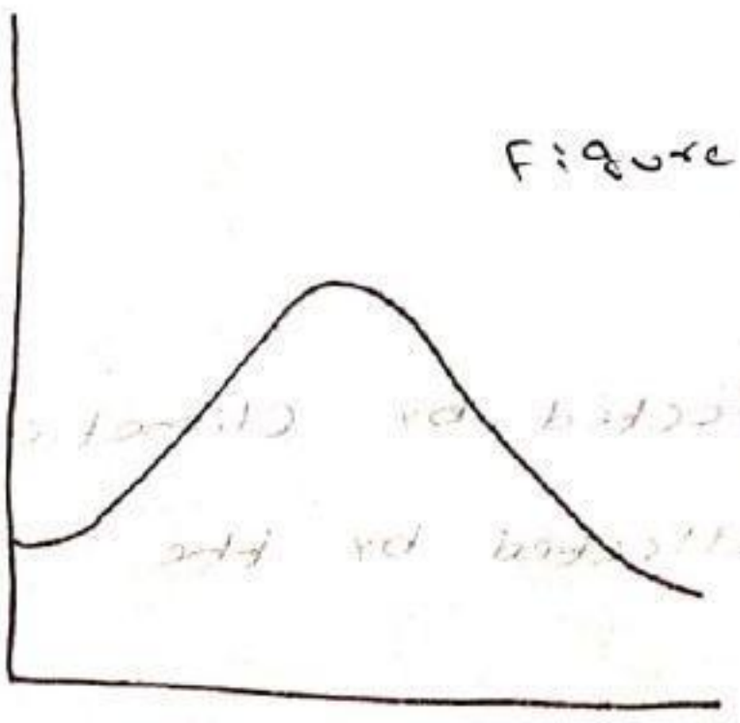
   e) Area distribution of rainfall

Among all the climatic factors, intensity, duration and direction of rainfall movement are the most important ones affecting the shape of a flood hydrograph.

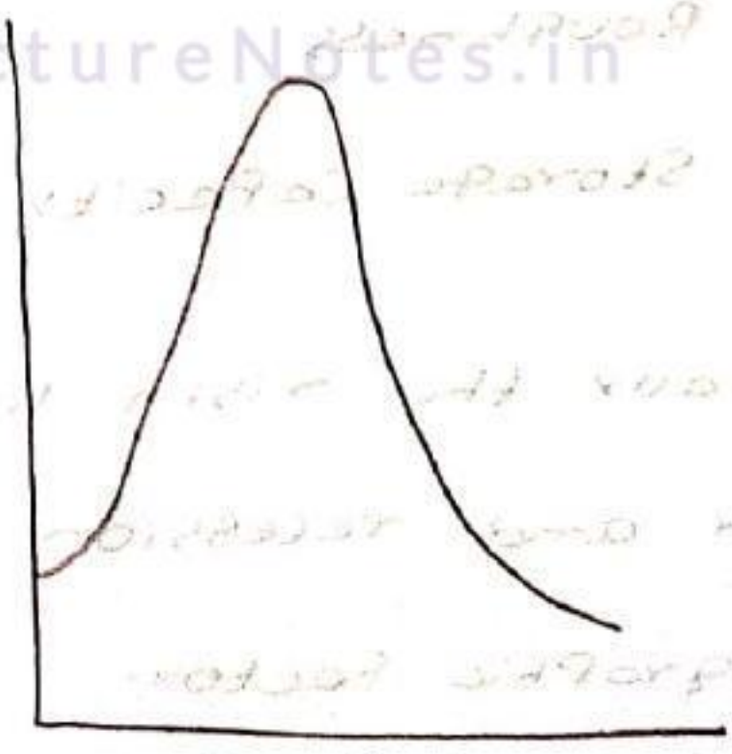
a) Form of precipitation:

→ Rainfall and snowfall – Rainfall tends to produce run-off rapidly generating hydrograph with high peak and narrow base.

Figure for



Snowfall



Rainfall

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b) Rainfall Intensity:-

→ For a given specified duration, the peak and volume of surface run-off are proportional to the intensity of rainfall.

→ Higher the intensity, quicker the peak flow.

Figure

c) Rainfall Duration:-

→ If the rainfall duration increases then the peak of hydrograph reduces.

→ Longer duration, peak flow occur after longer time and hydrograph is flatter with broad base.

Figure

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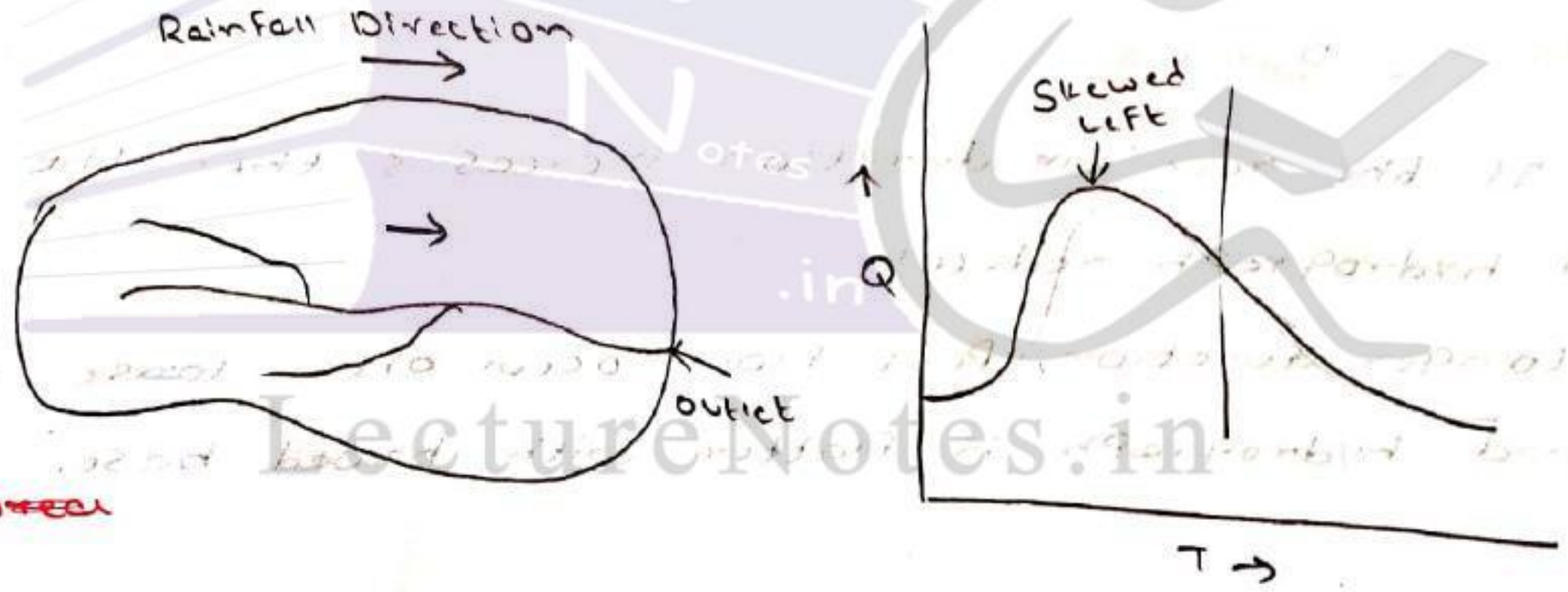
d) Direction of rainfall:

→ If the rainfall direction is in the direction of the outlet, then it gives left skewed hydrograph

→ If the rainfall direction is in the opposite direction of outlet, then it gives right skewed hydrograph.



e) Area

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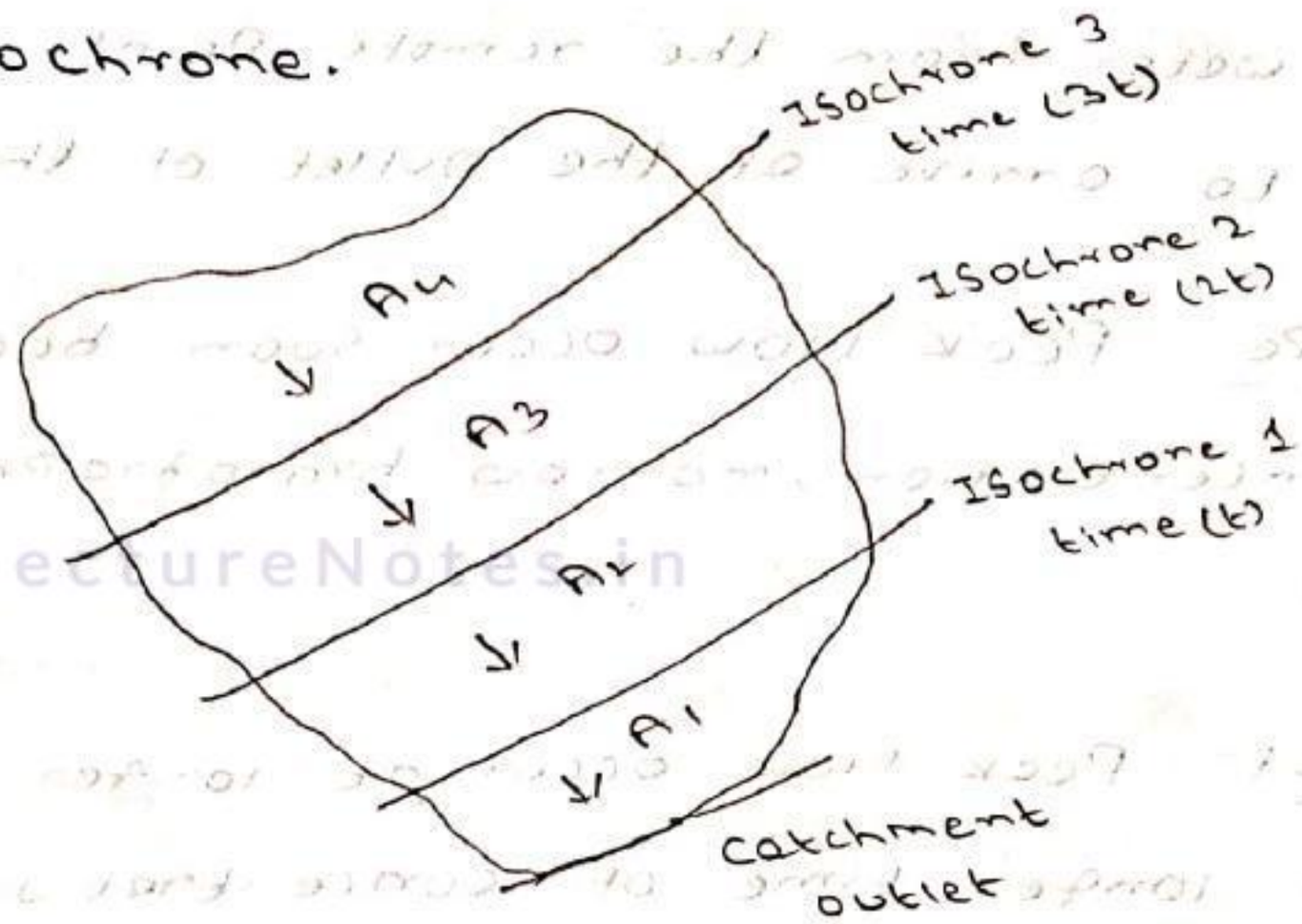
c) Areal distribution of rainfall:

Here is the catchment shown which are divided by three Isochrone.



→ If the rainfall occur only in area A_1, then we get peak immediately because this area is nearer to the outlet.

→ If rainfall occurs in area A_4, then we get peak later because this area is far away from the outlet.

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2. Shape of the Catchment:

→ The shape of the catchment influence the time taken for water from the remote points of the catchment to arrive at the outlet of the catchment.

→ Broad Shape: Peak flow occur soon because of less time of concentration, narrow hydrograph with high peak.

→ Fern (ferns) Fan Shaped- Peak flow occur at longer time interval because of longer time of concentration, broad base with lower peak hydrograph.

Figures

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3. Size of basin:-

→ Small basin - Flow dominated by overland flow that join channel quickly. Peak flow occur quickly.

4. Slope:-

→ The recession limb of hydrograph represent the depletion of storage.

→ Steeper slope give rise to quicker depletion of storage and hence results in steeper recession limbs of hydrograph with smaller time base.

5. Drainage Density:-

→ A large drainage density creates a situation for quick disposal of run-off. This response is reflected in a pronounced peak discharge.

→ In those catchments where the drainage density is less, the overland flow is predominant and resulting hydrograph with a slowly rising limb.

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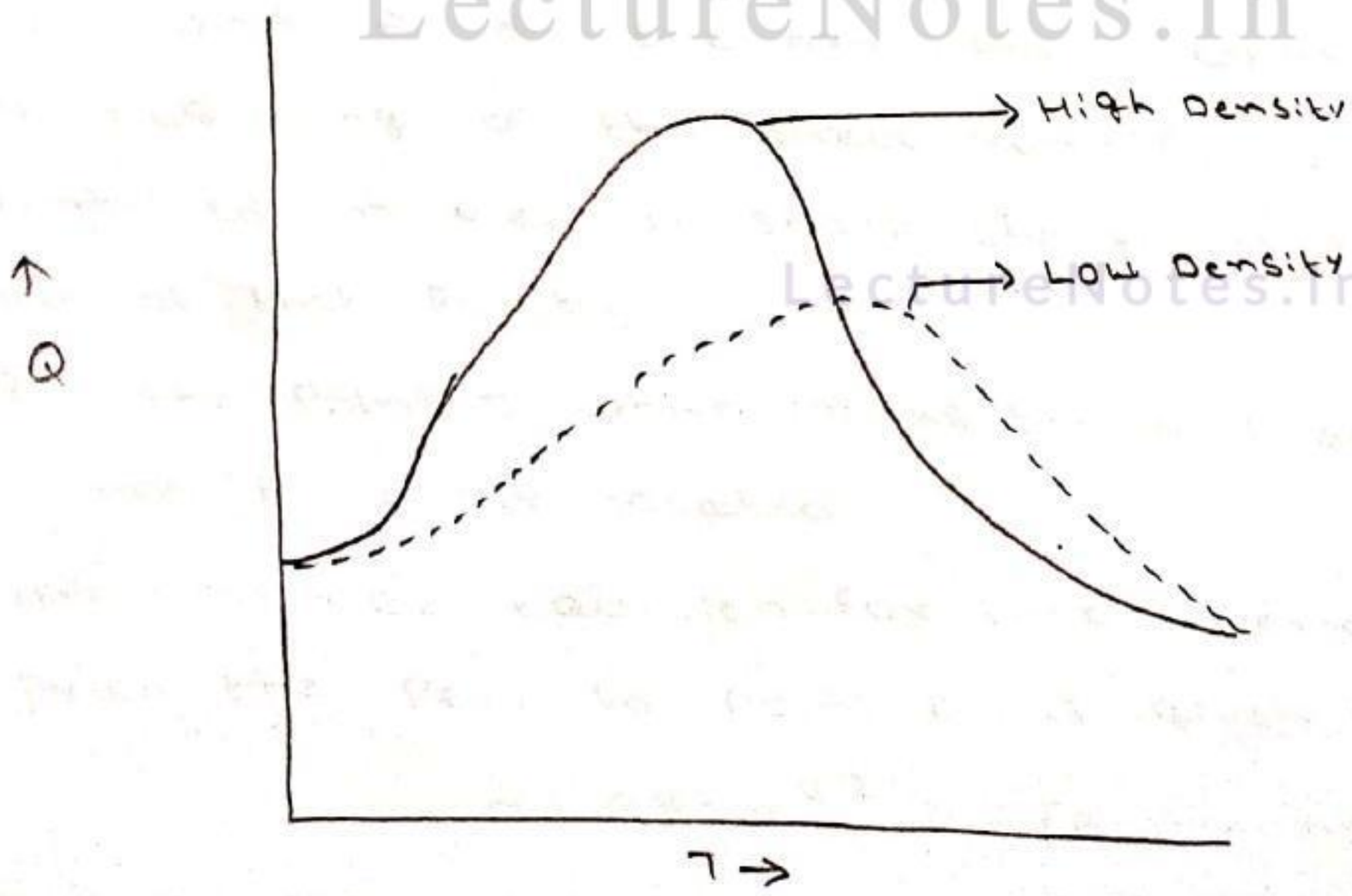

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6. Land use:-

→ An area covered by vegetation and forest shows increase in the infiltration and storage capacities of the soil.

→ The vegetation cause considerable retardance to overland flow, thus the vegetal cover reduces peak flow.

→ In general for two catchments of equal area, keeping other factors identical, the peak discharge is higher for a catchment that has a lower density of forest cover.

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Base Flow:-

→ If the sub-soil is also permeable, water percolates deep downwards to meet the ground water table. The delayed flow that reaches a stream generally as a ground water is called "Base Flow".

→ It is also called as "Drought Flow" or "Ground water recession flow" (or) "low flow" (or) "low water flow" or "low water discharge" or "fair weather run-off".

→ It has a very slow movement and takes months (or) years to reach streams.

Base Flow Separation:-

There are three types of base flow separation techniques. They are:-

1. Straight line method.
2. Fixed base method (or) Two lines method.
3. Constant slope method or curves extension method.

→ The point 'A' on the hydrograph which represents the beginning of the direct run-off, can be easily identified in view of sharp change in the run-off rate at that point

→ But, the point 'D' which marks the end of direct run-off cannot be easily located.

→ An empirical equation for time interval (N days) from the peak to point 'D' is given by

$$N = 0.83 A^{0.2}$$ [A = Drainage Area = km^2]

N = Time interval between peak and 'D' (in days)

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→ Another empirical equation to determine 'N' is given by

$$N = a.t_p$$

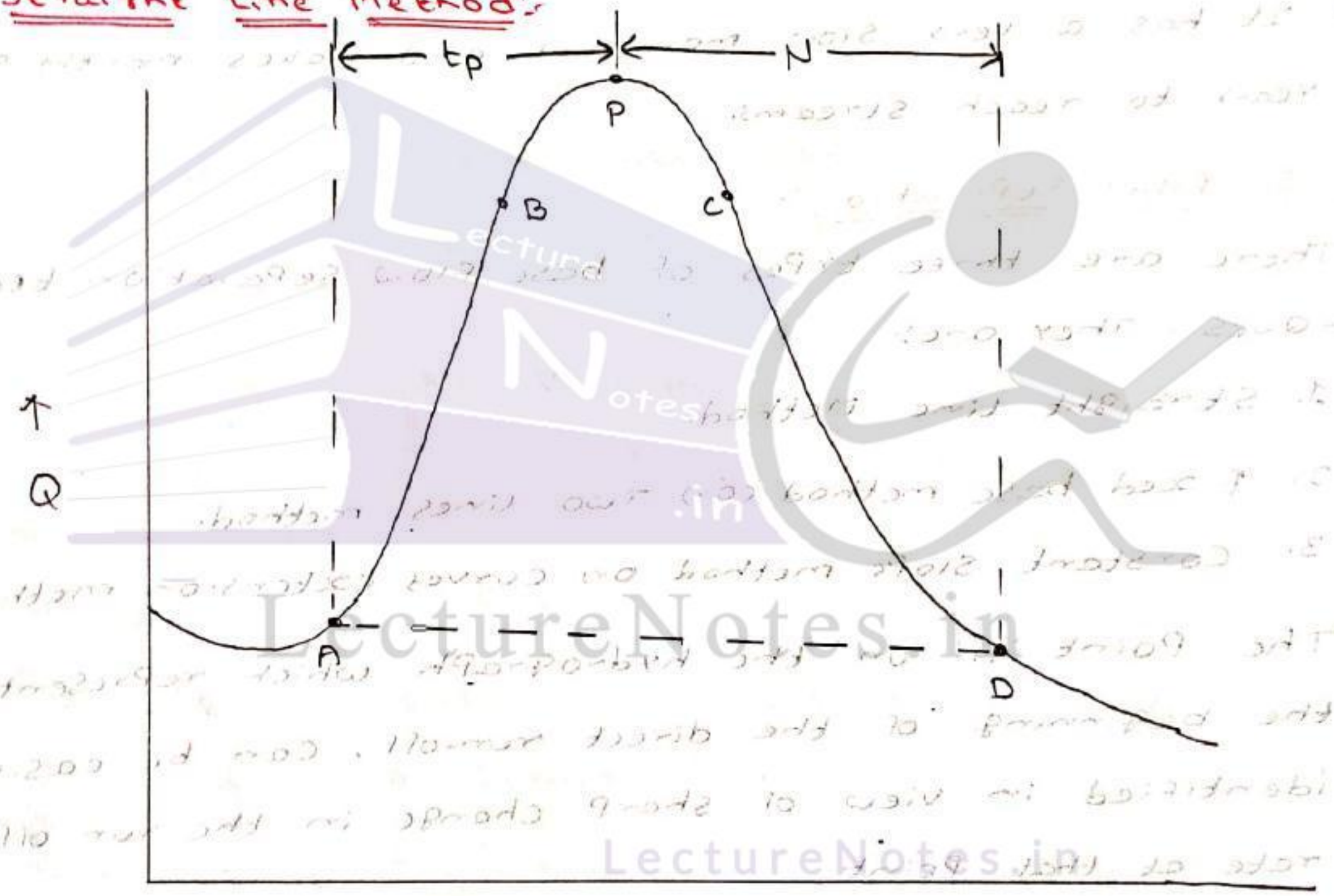
t_p = Time to Peak

= Time interval between beginning Point 'A' & Peak 'P'.

a = constant whose value may be taken between 2 to 4 for small basins and 4 for large basins.

Thus the two Points where the direct run-off begins (i.e., Point 'A') and run-off ceases (Point 'D') are identified.

1. Straight Line Method:-



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→ In this method, the separation of base flow is achieved by joining with a straight line the beginning of the surface run-off (Point 'A') on the rising limb to a point on the recession limb (Point 'D') which represents the end of the direct run-off.

→ This straight line which joins Point 'A' and Point 'D' demarcate the base flow and surface run-off.

→ This method is the simplest of all the three methods.

2. Two lines Method:-

→ This is most widely used method in which the base flow is separated from direct run-off by two lines.

→ The first line 'AE' is obtained by extending the base flow curve, existing prior to the commencement of the surface run-off, till it intersects a vertical line drawn from the peak (P) in a point 'E'.

→ Point 'E' so obtained and Point 'D' located earlier are joined by a straight line.

→ The segments marked by two line AE and ED demarcate the base flow and direct run-off.

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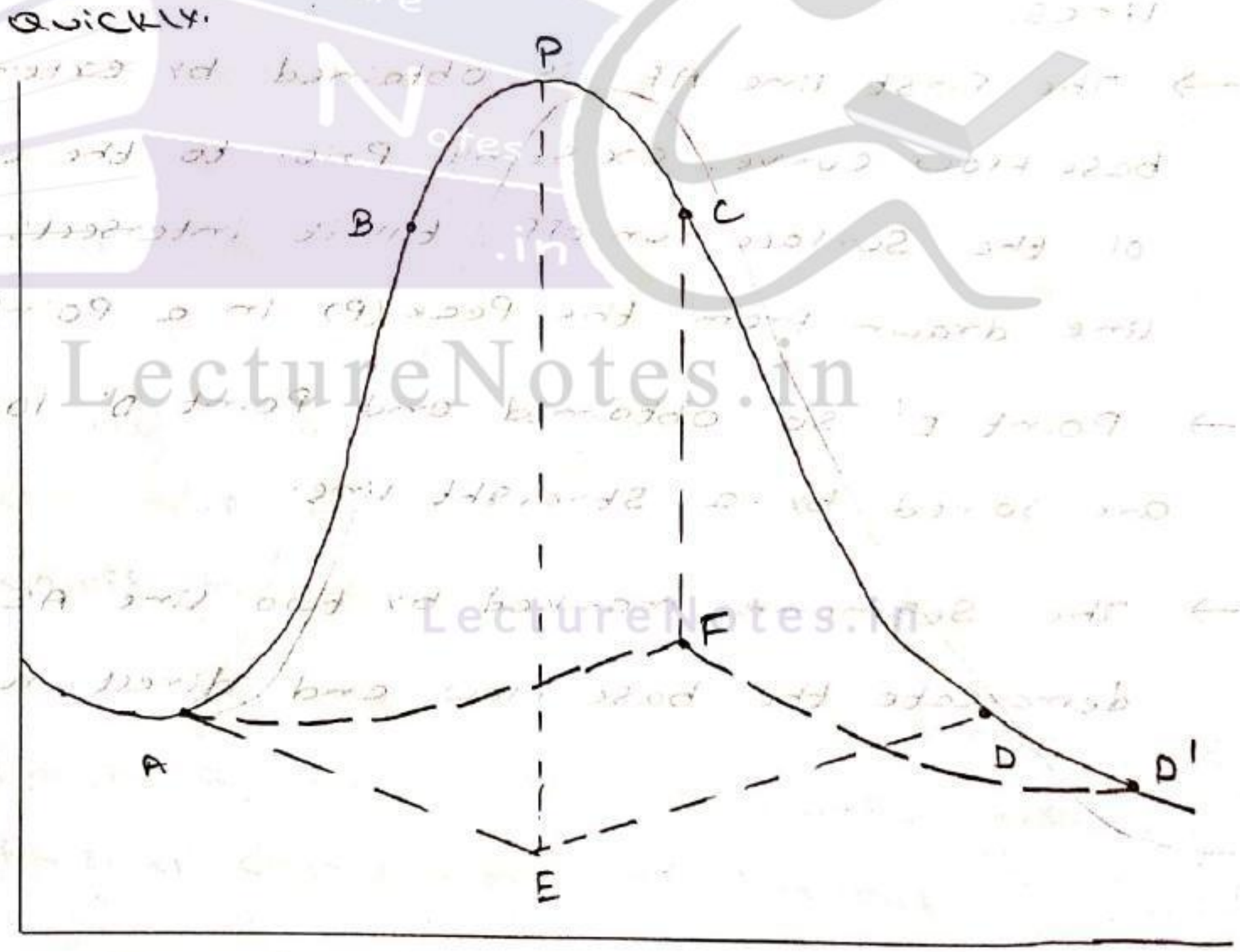
3. Curves Extension Method:-

→ This method consists of extendin the base flow curve on recession side backward till it intersects a vertical line through the "Point of Inflection (C) in a Point "F".

→ Points 'A' and 'F' are joined by a arbitrary smooth curve and D'F is the curve extended backwards.

→ Thus the two segments marked by two curves AF and FD' demarcate the base flow and direct run-off.

→ This method is preferred where the ground water contribution is significant and reach the stream quickly.



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Unit Hydrograph:-

→ The concept of a unit hydrograph initially called a unit graph was proposed by Mr. L.K. Sherman.

→ A unit Hydrograph is defined as the hydrograph of direct run-off resulting from one unit depth of rainfall excess occurring uniformly over the basin and at a uniform rate for a specified duration.

→ The term unit here refers to a unit depth of rainfall excess which is usually taken as 1 cm.

Assumptions of unit Hydrograph:-

1. The effective rainfall is uniformly distributed throughout the whole area of drainage basin.
2. Rainfall Intensity is constant during the Storm Period.
3. The base (or) time duration of the hydrograph of direct run-off due to an effective rainfall of unit duration is constant.
4. The ordinates of direct run-off of common base-time are directly proportional to the total amount of direct run-off represented by each hydrograph.
5. For a given catchment area, the hydrograph of run-off due to a given period of rainfall reflects all the physical characteristics of the basin.

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Construction of unit Hydrograph:- From Flood Hydrograph

1. From the Past records, select some unit Period of intense rainfall duration corresponding to an isolated storm uniformly distributed over the area.
2. From the Past records of the river discharge for that storm, Plot the storm hydrograph for some days before and after the Period of rainfall of that unit duration.
3. Separate the ground water flow (Base flow) from the hydrograph.
4. Subtracting the ordinates of base flow from the total ordinates, find the ordinates of direct run-off.
5. Calculate direct run-off n (in cm) by expression:

$$\text{Direct Run-off}, n = 0.36 \frac{(\Sigma O) \times t}{A} \text{ cm}$$

ΣO = Sum of direct run-off ordinates in cumecs.

t = Time interval between successive ordinates in hours.

A = Area of drainage basin in sq.km.

6. Calculate the ordinates of unit Hydrograph by the relation

$$\text{ordinate of unit Hydrograph} = \frac{\text{ordinate of direct run-off}}{\text{Direct run-off (n) in cm}}$$

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Q) Calculate the total depth of direct run-off and the ordinates of unit hydrograph of basin area of 25 km². (Class (E))

Date (1)	Hour (2)	Total (Q) m³/sec (3)	Base-Flow m³/sec (4)	Ordinates of direct run-off (5) m³/s	Ordinates of U.H (6) S/D.R.O
12 Aug	06:00	6	6	0	0
	08:00	8	6	2	0.08
	10:00	10	5.5	4.5	0.19
	12:00	16	5.0	11	0.46
	14:00	28	4.5	23.5	0.99
	16:00	42	4.0	38	1.61
	18:00	60	3.5	56.5	2.39
	20:00	80	3.0	77	3.25
	22:00	110	2.5	107.5	4.54
13 Aug	24:00	100	2.5	97.5	4.12
	02:00	90	2.5	87.5	3.70
	04:00	80	3.0	77	3.25
	06:00	68	3.0	65	2.75
	08:00	56	3.5	52.5	2.22
	10:00	45	3.5	41.5	1.75
	12:00	35	4.0	31	1.31
	14:00	26	4.0	22	0.93
	16:00	18	4.5	13.5	0.57
	18:00	11	4.5	6.5	0.27
	20:00	9	5.5	3.5	0.15
	22:00	8	5.5	2.5	0.105
14 Aug	24:00	7	5.5	1.5	0.06
	02:00	6	6.0	0	0

$\Sigma O = 821.5$ $\Sigma U = 34.695$

Direct Run-off $= 0.36 \times \frac{\Sigma O \times t}{A}$ cm

$= \frac{0.36 \times 821.5 \times 2}{25} = 23.66$ cm

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Check:-

Direct Run-off depth of unit Hydrograph $= \frac{0.36 \times \Sigma U.H \times t}{A}$

$= \frac{0.36 \times 34.695 \times 2}{25}$

$= 0.999 \simeq 1 cm$

Q) The following are the ordinates for a flood hydrograph resulting from an isolated storm of 6 hour duration.
Class (C)

Time (hr)	0	12	24	36	48	60	72	84	96
ordinates of Flood Hydrograph (m^3/sec)	5	15	40	80	60	50	25	15	5

Determine the ordinates of 1cm-6hr unit Hydrograph if the Catchment area is $450 km^2$. Assume Base flow as $5 m^3/sec$.

Time (hr) (1)	F.H (m^3/s) (2)	Base Flow (m^3/s) (3)	D.R.H (m^3/s) (4)	1cm U.H $= \frac{D.R.H}{D.R.D}$ (5)
0	5	5	0	0
12	15	5	10	4.17
24	40	5	35	14.58
36	80	5	75	31.25
48	60	5	55	22.92
60	50	5	45	18.75
72	25	5	20	8.33
84	15	5	10	4.17
96	05	5	0	0
			$\Sigma O = 250$	$\Sigma U.H = 104.17$

Direct Run-off depth, D.R.D $= \frac{0.36 \times \Sigma O \times t}{A} = \frac{0.36 \times 250 \times 12}{450} = 2.40 cm$

Check:-

Direct Run-off depth of unit Hydrograph $= \frac{0.36 \times \Sigma U.H \times t}{A}$

$= \frac{0.36 \times 104.17 \times 12}{450} = 1.00 cm$

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Q) The run-off data at a stream gauging station for a H.M Flood (m^3/sec) at three hourly intervals are as follows: The drainage area is 40 km^2. The duration of rainfall is 3 hour. Derive the three hour unit hydrograph for the basin. Assume a constant base flow of 50 m^3/s throughout the duration.

Time (hr)	ordinates of F.H (m^3/s)	Base Flow (m^3/s)	D.R.H (m^3/s)	3h-unit Hydrograph (m^3/s)
(1)	(2)	(3)	(4)	(5) = (4) ÷ D.R.D
0	50	50	0	0
3	50	50	0	0
6	75	50	25	0.93
9	125	50	75	2.79
12	225	50	175	6.51
15	290	50	240	8.92
18	270	50	220	8.18
21	145	50	95	3.53
24	110	50	60	2.23
27	90	50	40	1.49
30	80	50	30	1.11
33	70	50	20	0.74
36	60	50	10	0.37
39	55	50	5	0.18
42	51	50	1	0.04
45	50	50	0	0
			$\Sigma O = 996$	$\Sigma U.H = 37.02$

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Direct Run-off Depth $= \frac{0.36 \times \Sigma Q \times t}{A} = \frac{0.36 \times 996 \times 3}{40} = 26.89$ cm

(or) $= \frac{\text{Volume}}{\text{Area}}$

$= \frac{\text{Sum of ordinates} \times \text{time interval}}{\text{Area}}$

$= \frac{996 \times 3 \times 60 \times 60}{40 \times (10^3)^2} = 0.2689$ m

$= 26.89$ cm

LectureNotes.in

Check:-

Direct Run-off Depth of U.H $= \frac{0.36 \times \Sigma U.H \times t}{A}$

$= \frac{0.36 \times 37.02 \times 3}{40} = 0.999 \simeq 1.00$ cm

(or) $= \frac{\text{Volume}}{\text{Area}}$

$= \frac{\text{Sum of Ordinates of U.H} \times \text{Time Interval}}{\text{Area}}$

$= \frac{37.02 \times 3 \times 60 \times 60}{40} = 0.999$ cm $\simeq 1.00$ cm

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Q) a) The Peak of Flood hydrograph due to a 3 h duration isolated storm in a catchment is 270 m^3/s. The total depth of rainfall is 5.90 cm. Assuming an average infiltration loss of 0.30 cm/hr and had a constant base flow of 20 m^3/s. Estimate the Peak of the 3 hour U.H of this catchment.

b) If the area of the catchment is 567 km^2. Determine the base width of the 3-hour unit hydrograph by assuming it to be triangular in shape.

Loss @ 0.3 cm/hr = 0.3 × 3 = 0.90 cm ; Total rainfall depth = 5.90 cm

Rainfall Excess = 5.90 − 0.90 = 5.00 cm

Duration of rainfall Excess = 3 hour

Peak of Flood Hydrograph = 270 m^3/s ; Peak of D.R.H = 250 m^3/s

Base Flow = 20 m^3/s

Peak of 3hr unit Hydrograph = $\frac{\text{Peak of D.R.H}}{\text{Rainfall Excess}} = \frac{250}{5} = 50\ m^3/s$

b) Let B = Base width of the 3hour U.H in hours.

Vol. represented by area of U.H = Vol. of 1cm depth over catchment = Area of catchment × 1cm

$$\frac{1}{2} \times B \times 60 \times 60 \times 50 = 567 \times 10^6 \times \frac{1}{100}$$

B = 63 hours

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Unit Hydrograph of Different Duration:

If "Dhr" unit hydrograph is used to develop unit hydrograph of differing duration than D. For this purpose we have two methods:

(i) Method of super position (ii) S-curve method

Method of Super Position:

If we have a "D-hr" unit Hydrograph and we want to develop a unit Hydrograph of "nD" hour where 'n' is an integer, then this method is suitable.

→ we have a unit hydrograph of "D-hr" (Let D=3) and we want to make a unit hydrograph of "2D-hr" (2D=6).

→ Draw the unit hydrograph of D-hour and another unit hydrograph of D-hr is drawn by lagging D-hr (3hr).

→ Add the ordinate of both the hydrograph give us the hydrograph of 2 unit of 2D-hour.

→ Divide the ordinate by 2 gives the unit hydrograph of 2D-hour.

Q) Class (c) Given the ordinates of 4-hour unit Hydrograph below. Derive the ordinates of a 12-hour unit hydrograph for same catchment

Time (hr)	0	4	8	12	16	20	24	28	32	36	40	44
ordinate of 4-h U.H	0	20	80	130	150	130	90	52	27	15	5	0

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Time (hr)	Ordinates of 4-h U.H (m^3/s) A	B Lagged by 4h	C Lagged by 8-h	D.R.H of 3cm in 12-h (m^3/s)	Ordinate of 12-h U.H (m^3/s)
(1)	(2)	(3)	(4)	(5) = (2)+(3)+(4)	(6) = (5)/4.39
0	0	—	—	0	0
4	20	0	—	20	6.67
8	80	20	0	100	33.33
12	130	80	20	230	76.67
16	150	130	80	360	120
20	130	150	130	410	136.67
24	90	130	150	370	123.33
28	52	90	130	272	90.67
32	27	52	90	169	56.33
36	15	27	52	94	31.33
40	5	15	27	47	15.67
44	0	5	15	20	6.67
48		0	5	5	1.67
52			0	0	0
	699	699	699	2097	= 699.01
		↓		↓	↓
	$A = 1006.36\ km^2$	$\frac{0.36 \times 699 \times 4}{1006.36}$		$\frac{0.36 \times 2097 \times 4}{1006.36}$ = 3 cm	

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Application of the U.H to the construction of a F.H resulting from rainfall of unit duration

m = Eff. Rainfall (or) Rainfall Excess

Direct Run-off ordinates = ordinates of U.H × 'm' cm

Q) Construct a F.H from a U.H of 8 cm rainfall excess (or) direct run-off. P-31, P-33

Date	Hour	ordinates of U.H (m^3/s)	ordinates of Direct run-off m^3/s	Base-flow m^3/s	F.H m^3/s
(1)	(2)	(3)	(4)	(5)	(6)
			(4) = (3) × m		(6) = (4) + (5)
	06	0	0	4.0	4
29 Aug	09	0.12	0.96	3.5	4.46
	12	0.35	2.80	3.0	5.80
	15	0.88	7.04	2.5	9.54
	18	1.50	12.00	2.0	14.0
	21	2.80	22.40	1.5	23.90
	24	2.00	16.00	1.8	17.80
	03	1.85	14.80	2.1	16.90
	06	1.53	12.24	2.4	14.64
	09	1.26	10.08	2.7	12.78
	12	0.84	6.72	3.0	9.72
	15	0.50	4.00	3.3	7.30
	18	0.35	2.80	3.6	6.40
	21	0.12	0.96	3.8	4.76
	24	0.00	0.00	4.0	4.0
		14.10	112.80		

$$\text{Depth} = \frac{0.36 \times 112.8 \times 3}{15.23} = 8\ cm$$

A = 15.23 km^2

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(Q) Given below are observed flows from a storm of 6h duration on a stream with a catchment area of 500 km². P-11.M

Time (h)	0	6	12	18	24	30	36	42	48	54	60	66	72
Flow (m^3/s)	0	100	250	200	150	100	70	50	35	25	15	5	0

Assume Base Flow to be zero. Derive ordinates of 6hr U.H.

Time (hr) (1)	Flow (m^3/s) (2)	Base Flow (m^3/s) (3)	Direct Run-off Hydrograph (4)	ordinates of 6hr U.H (5) = (4)/D.R.O
0	0	0	0	0
6	100	0	100	23.15
12	250	0	250	57.87
18	200	0	200	46.30
24	150	0	150	34.72
30	100	0	100	23.15
36	70	0	70	16.20
42	50	0	50	11.57
48	35	0	35	8.10
54	25	0	25	5.79
60	15	0	15	3.47
66	5	0	5	1.16
72	0	0	0	0
			$\Sigma Q = 1000$	$\Sigma U.H = 231.48$

Direct Run-off depth $= \frac{0.36 \times \Sigma Q \times t}{A} = \frac{0.36 \times 1000 \times 6}{500} = 4.32$ cm

Check:

Direct Run-off depth of U.H $= \frac{0.36 \times \Sigma U.H \times t}{A} = \frac{0.36 \times 231.48 \times 6}{500} = 0.999 \simeq 1$ cm

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$A = 3889.73\ km^2$

$\frac{0.36 \times 1350.6 \times 8}{3889.73} = 1\ cm$

$\frac{0.36 \times 4051.8 \times 8}{3889.73} = 3\ cm$

$\frac{0.36 \times 1350.59 \times 8}{3889.73} = 1\ cm$

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Additional Answer Sheet

Q/ H.M Ordinates of short U.H for a drainage basin is given in table below. obtain a 24hr U.H. (23)

Time (hr)	1350.6 1st 8hr U.H	1350.6 2nd 8hr U.H	1350.6 3rd 8hr U.H	4051.8 Total 24hr hydrograph of 3cm run-off	1350.59 ordinates of 24 hr U.H
(1)	(2)	(3)	(4)	(5) = (2)+(3)+(4)	6) = (5)/3
0	0	–	–	0	0
4	5.5	–	–	5.5	1.83
8	13.5	0	–	13.5	4.50
12	26.5	5.5	–	32	10.67
16	45	13.5	0	58.5	19.5
20	82	26.5	5.5	114	38
24	162	45	13.5	220.5	73.5
28	240	82	26.5	348.5	116.17
32	231	162	45	438	146
36	165	240	82	487	162.33
40	112	231	162	505	168.33
44	79	165	240	484	161.33
48	57	112	231	400	133.33
52	42	79	165	286	95.33
56	31	57	112	200	66.67
60	22	42	79	143	47.67
64	14	31	57	102	34
68	9.5	22	42	73.5	24.5
72	6.6	14	31	51.6	17.2
76	4	9.5	22	35.5	11.83
80	2	6.6	14	22.6	7.53
84	1	4	9.5	14.5	4.83
88	0	2	6.6	8.6	2.87
92		1	4	5	1.67
96		0	2	2	0.67
			1	1	0.33
			0	0	0

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(Q) Pr. H.M Following are the ordinates of the hydrograph of flow from a catchment area of 770 km² due to 6h rainfall.

Derive 6hr U.H

Time (hr)	0	6	12	18	24	30	36	42	48	54	60	66	72
Discharge (m^3/s)	40	65	215	360	400	350	270	205	145	100	70	50	42

Time	Discharge	Base Flow	D.R.H	ordinates of U.H
0	40	40	0	0
6	65	40	25	4.97
12	215	40	175	34.79
18	360	40	320	63.62
24	400	40	360	71.57
30	350	40	310	61.63
36	270	40	230	45.72
42	205	40	165	32.80
48	145	40	105	20.87
54	100	40	60	11.93
60	70	40	30	5.96
66	50	40	10	4.99
72	42	40	2	0.40
			$\Sigma Q = 1792$	$\Sigma U.H = 356.25$

Direct Run-off Depth $= \frac{0.36 \times \Sigma Q \times t}{A} = \frac{0.36 \times 1792 \times 6}{770} = 5.03$ cm

Check:

Depth of U.H $= \frac{0.36 \times \Sigma U.H \times t}{A} = \frac{0.36 \times 356.25 \times 6}{770} = 0.999$ cm $\simeq 1$ cm

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Q) From the 4-hr U.H. Derive the 8-hr U.H.

4.M

Time (hr)	Ordinate of 4-hr U.H (m^3/s) without lag	lagged by 4h	Combined Hydrograph (m^3/s)	Ordinates of 8-hr U.H (m^3/s)
(1)	(2)	(3)	(4)	(5)
			(4) = (2)+(3)	(5) = (4) ÷ 2
0	0	–	0	0
2	12.52	–	12.52	6.26
4	21.32	0	21.32	10.66
6	23.54	12.52	36.06	18.03
8	17.84	21.32	39.16	19.58
10	14.79	23.54	38.33	19.165
12	12.18	17.84	30.02	15.01
14	10.04	14.79	24.83	12.415
16	8.26	12.18	20.44	10.22
18	6.51	10.04	16.55	8.275
20	4.98	8.26	13.24	6.62
22	3.95	6.51	10.46	5.23
24	3.05	4.98	8.03	4.015
26	2.26	3.95	6.21	3.105
28	1.60	3.05	4.65	2.325
30	1.07	2.26	3.33	1.665
32	0.53	1.60	2.13	1.065
34	0	1.07	1.07	0.535
36		0.53	0.53	0.265
38		0	0	0
	144.44	144.44	288.88	144.44
	↓		↓	↓
	$\frac{0.36 \times 144.44 \times 4}{208}$		$\frac{0.36 \times 288.88 \times 4}{208}$ (2cm)	$\frac{0.36 \times 144.44 \times 6}{208}$

A = 208 km^2

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(Q) The ordinates of a 3hr U.H are given below.

P-H.M

Time (hr)	0	3	6	9	12	15	18	21	24	27	30
Discharge (m^3/s)	0	10	25	20	16	12	9	7	5	3	0

Find the ordinates of a 6hr U.H for same basin. what is the Peak value of discharge in this U.H ; Catchment Area = 115.56 km^2

Time (hr)	3hr U.H ordinates (m^3/s)	3 hr U.H ordinates lagged by 3hr (m^3/s)	6hr U.H ordinates containing 2cm run-off (m^3/s)	ordinates of 6hr U.H (m^3/s)
(1)	(2)	(3)	(4)	(5)
				(5) = (4) ÷ 2
0	0	–	0	0
3	10	0	10	5
6	25	10	35	17.5
9	20	25	45	22.5
12	16	20	36	18
15	12	16	28	14
18	9	12	21	10.5
21	7	9	16	8
24	5	7	12	6
27	3	5	8	4
30	0	3	3	1.5
33	–	0	0	0
	107	107	$\Sigma O = 214$	$\Sigma O = 107$

$$\frac{0.36 \times 107 \times 3}{115.56} = 1\,cm$$

$$\frac{0.36 \times 214 \times 3}{115.56} = 2\,cm$$

$$\frac{0.36 \times 107 \times 3}{115.56} = 1\,cm$$

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Q/ Analysis of the Surface run-off records of a 1 day Storm over a Catchment yielded the following data.
class-C

Time (Days)	0	1	2	3	4	5	6	7	8	9
Discharge (m^3/s)	20	63	151	133	90	63	44	29	20	20
Base Flow (m^3/s)	20	22	25	28	28	26	23	21	20	20

If Catchment Area = 600 km^2, Determine depth of rainfall excess.

Time (Days)	Discharge (m^3/s)	Base Flow (m^3/s)	D.R.H (m^3/s)
0	20	20	0
1	63	22	41
2	151	25	126
3	133	28	105
4	90	28	62
5	63	26	37
6	44	23	21
7	29	21	8
8	20	20	0
9	20	20	0
			400

Depth of Direct Run-off (or) Excess Rainfall $= \frac{0.36 \times \Sigma Q \times t}{A}$

$= \frac{0.36 \times 400 \times 24}{600}$

$= 5.76 cm$

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Q) In a catchment, the average rainfall for a storm of two successive 6 hour intervals was 3 cm & 6 cm respectively. The abstraction losses Ø-Index were estimated to be 0.20 cm/hr. For the same catchment, the calculated data for a 6hr-U.H is available & is given below. Find D.R.H due to storm After (I)

Let R_1, R_2 be run-off at two successive 6 hour intervals.

Let P_1, P_2 be the average rainfall in cm.

Ø-Index = 0.20 cm/hr

$R_1 = P_1 - (Ø \times 6) = 3 - (0.2 \times 6) = 1.80 cm$

$R_2 = P_2 - (Ø \times 6) = 6 - (0.2 \times 6) = 4.80 cm$

Time (hr) (1)	U.H (m^3/s) (2)	R_1U (3)	R_2U (4)	D.R.H $R_1U + R_2U$ (5)
0	0	(3) = (2)×1.8 = 0	(4) = (2)×4.8 = 0	(5) = (3)+(4) = 0
6	10	18	48	0 18
12	25	45	120	48 93
18	40	72	192	120 192
24	100	180	480	192 372
30	150	270	720	480 750
36	100	180	480	720 900
42	75	135	360	480 615
48	25	45	120	360 405
54	15	27	72	120 147
60	0	0	0	72 72
				0

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Q) Find the ordinates of a storm hydrograph resulting from a 3hr storm with rainfall of 2, 6.75, 3.75 cm during subsequent 3 hours intervals. The ordinates of unit-3hour hydrograph are given below After (I)

$P_1 = 20$ mm; $P_2 = 67.5$ mm; $P_3 = 37.5$ cm

Rainfall excess during the first 3 hours = 20 − (2.5 × 3) − 5 = 7.5 mm = 0.75 cm

" " " " 2nd 3 hours = 67.5 − (2.5 × 3) = 60 mm = 6 cm

" " " " 3rd 3 hours = 37.5 − (2.5 × 3) = 30 mm = 3 cm

Time (hrs)	3hr U.H ordinates (m^3/s)	Surface run-off from rainfall excess during successive unit periods (m^3/s)				Base Flow (m^3/s)	Total Discharge (m^3/s)
		0.75	6.0	3	Total		
03	0	0	—	—	0	10	10
06	110	82.5	0	—	82.5	10	92.5
09	365	273.75	660	0	933.75	10	943.75
12	500	375	2190	330	2895	10	2905
15	390	292.5	3000	~~330~~ 1095	4387.5	10	4397.5
18	310	232.5	2340	~~1095~~ 1500	4072.5	10	4082.5
21	250	187.5	1860	~~1500~~ 1170	3217.5	10	3227.5
24	235	176.25	1500	~~1170~~ 930	2606.25	10	2616.25
03	175	131.25	1410	~~930~~ 750	2291.25	10	2301.25
06	130	97.50	1050	~~750~~ 705	1852.5	10	1862.50
09	95	71.25	780	~~705~~ 525	1376.25	10	1386.25
12	65	48.75	570	~~525~~ 390	1008.75	10	1018.75
15	40	30	390	~~390~~ 285	705	10	715
18	22	16.5	240	~~285~~ 195	451.50	10	461.50
21	10	7.50	132	~~195~~ 120	259.50	~~269.5~~ 10	269.50
24	0	0	60	~~120~~ 66	126	10	136
03	0	0	0	~~66~~ 30	30	10	40
06	0	0	0	30 0	0	10	10

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Limitations of Unit Hydrograph:-

1. Unit Hydrograph assumes uniform distribution of rainfall over the catchment and the intensity of rainfall is assumed constant for the duration of rainfall excess. In practice, these two conditions are never strictly satisfied.

2. Unit Hydrograph method cannot be used for a catchment area greater than 5000 km^2 and less than 2 km^2.

3. Precipitation must be from rainfall only. Snowmelt run-off cannot be satisfactory represented by unit Hydrograph.

4. The catchment should not have large storage which affects the linear relationship between storage and discharge.

Uses of Unit Hydrographs:-

The unit Hydrograph establish a relationship between effective rainfall and direct run-off for a catchment. This relationship is very useful in study of hydrology of a catchment of

(i) In the development of flood hydrograph for extreme rainfall magnitude.

(ii) In the extension of flood-flow records based on rainfall records.

(iii) In development of flood forecasting and warning system based on rainfall.

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S-Curve:-

→ If we want to develop a unit hydrograph of duration mD, here 'm' is not an integer, then we can't apply the method of Super-Position. Here we use S-Curve technique.

→ The S-curve is a hydrograph produced by a continuous (1) rainfall at a constant rate for an infinite period. It is also known as S-hydrograph.

→ It is a hydrograph by a continous effective rainfall at a constant rate for indefinite period.

→ It is a continuous rising curve, in the form of (2) letter 'S' till equilibrium is reached.

→ At time of equilibrium, it will represent a constant rate of continuous effective rainfall, say R_0 cm/hr.

$$Q_0 = \frac{A \times 100 \times 100}{100 \times 3600} \times R_0 = \frac{A \cdot R_0}{360} \text{ cumecs}$$

A = Catchment Area in Hectares

$$Q_0 = 2.778\, A \cdot R_0 \text{ cumecs} \quad [A = km^2] \Rightarrow Q = 2.778 \frac{A}{D}$$

R_0 = Rate of continuous effective rainfall cm per hour.

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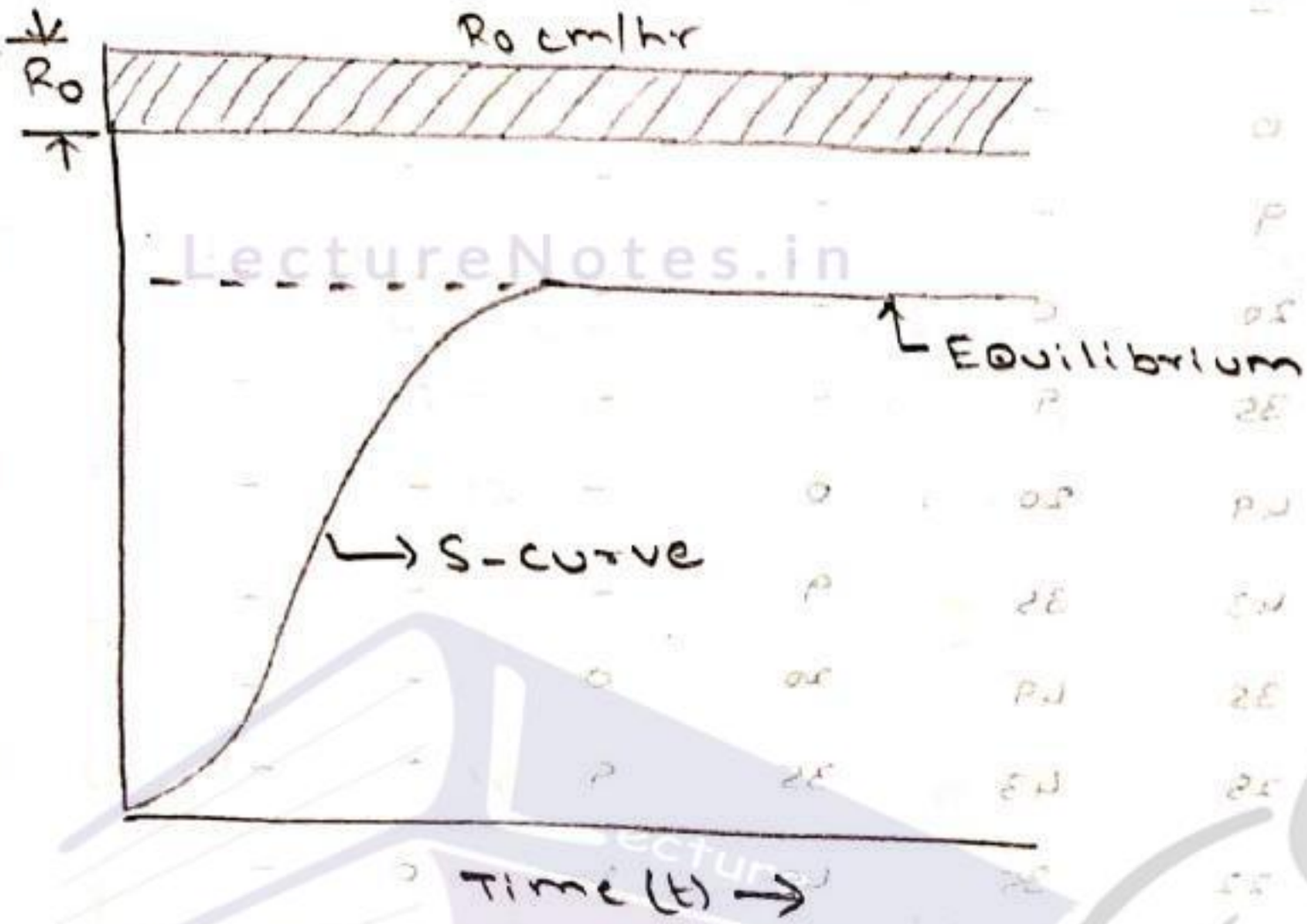
(3) The S-hydrograph (or) S-curve is constructed by adding together a number of unit hydrographs of unit time duration (T_0) spaced at a unit time duration (T_0) (i.e., duration of effective rainfall).



Q) Calculate the ordinates of a S-hydrograph.

Time (hrs)	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
6 hr U.H ordinates	0	9	20	35	49	43	35	28	22	17	12	9	6	3	0

Here $T_0 = 6$ hrs ; $A = 311\ km^2$

The summation is continued upto the time equal to the base of unit hydrograph minus one unit duration ($T_0 = 6$ hrs) to reach the equilibrium rate of discharge.

$Q_0 = 2.778\, A R_0$

$= 2.778 \times 311 \times \frac{1}{6}$

$Q_0 = 144$ cumecs

$R_0 = \frac{1}{T_0} = \frac{1}{6}$ cm/hr

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Time (hrs)	6hr U.H ordinates	ordinates of successive unit hydrographs						ordinates of S-Hydrograph
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0	0	-	-	-	-	-	-	0
3	9	-	-	-	-	-	-	9
6	20	0	-	-	-	-	-	20
9	35	9	-	-	-	-	-	44
12	49	20	0	-	-	-	-	69
15	43	35	9	-	-	-	-	87
18	35	49	20	0	-	-	-	104
21	28	43	35	9	-	-	-	115
24	22	35	49	20	0	-	-	126
27	17	28	43	35	9	-	-	132
30	12	22	35	49	20	0	-	138
33	9	17	28	43	35	9	-	141
36	6	12	22	35	49	20	0	144
39	3	9	17	28	43	35	9	144
42	0	6	12	22	35	49	20	144

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Q) Derive the S-curve for the 4hr U.H given below.
H.M-C

Time (hr)	0	4	8	12	16	20	24	28
Ordinates of 4hr U.H (m^3/s)	0	10	30	25	18	10	5	0

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Time (hrs)	Ordinate of 4hr U.H (m^3/s)	S-curve addition (m^3/s)	S_4-curve ordinate (m^3/s)
(1)	(2)	(3)	(4)
			(4) = (2)+(3)
0	0	-	0
4	10	0	10
8	30	10	40
12	25	40	65
16	18	65	83
20	10	83	93
24	5	93	98
28	0	98	98

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$Q_0 = 2.778\, A \cdot R_0$ $\left[R_0 = \frac{1}{T_0} = \frac{1}{4} \; (\because T_0 = 4)\right]$

$= 2.778 \times 141.11 \times \frac{1}{4} = 98\ m^3/s$

$Q_0 = 2.778 \cdot \frac{A}{D} = 2.778 \times \frac{141.11}{4} = 98\ m^3/s$

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Here $T_0 = 4$ hrs ; $A = 141.11\ km^2$

The summation is continued upto the time equal to the base of unit hydrograph minus one unit duration ($T_0 = 4$ hours) to reach the equilibrium rate of discharge

$$Q_0 = 2.778\, A R_0 \qquad R_0 = \frac{1}{T_0} = \frac{1}{4}$$

$$= 2.778 \times 141.11 \times \frac{1}{4}$$

$$Q_0 = 98\ m^3/s$$

Time (hrs)	4hr U.H ordinates	Ordinates of successive unit Hydrograph						Ordinates of S-Hydrograph
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0	0	–	–	–	–	–	–	0
4	10	0	–	–	–	–	–	10
8	30	10	0	–	–	–	–	40
12	25	30	10	0	–	–	–	65
16	18	25	30	10	0	–	–	83
20	10	18	25	30	10	0	–	93
24	5	10	18	25	30	10	0	98
28	0	5	10	18	25	30	10	98

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Q) Compute S-curve ordinates for the following 6hr U.H of a catchment area 300 km². H.M.

Time(hr)	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
Ordinates of 6hr U.H (m^3/s)	0	9	20	35	49	43	35	28	22	17	12	9	6	3	0

Time(hr)	Ordinates of 6hr U.H (m^3/s)	S-curve addition (or) Offset ordinates	Ordinates of S-hydrograph $R_0 = 1/6$ cm/hr
0	0	–	0
3	9	–	9
6	20	0	20
9	35	~~29~~ 9	~~55~~ 44
12	49	~~55~~ 20	~~103~~ 69
15	43	44	87
18	35	69	104
21	28	87	115
24	22	104	126
27	17	115	132
30	12	126	138
33	9	132	141
36	6	138	144
39	3	141	144
42	0	144	144

$Q_0 = 2.778 \cdot A \cdot R_0 = 2.778 \times 311 \times \frac{1}{6} = 144\ m^3/s$

$Q_0 = 2.778 \cdot \frac{A}{D} = 2.778 \times \frac{311}{6} = 144\ m^3/s$

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Synthetic unit Hydrograph:

1. To develop U.H for a catchment, we need detailed information about the rainfall and resulting flood hydrograph.
2. Majority of location in world, specially those which are at remote location, the data would normally be very scanty.
3. For those area we construct the unit hydrograph with the help of empirical equations or by relating the selected basin characteristics to U.H shape.
4. Such a unit hydrograph is called synthetic unit hydrograph.
5. There are several methods to derive synthetic unit hydrograph, one is given by Synder (1938) is widely used and it is discussed here.

Synder's Method:-

→ Synder studied the data of catchments of Appalachian Highlands of Eastern united states and then developed empirical equations for synthetic hydrograph.

→ Synder selected three parameters of unit hydrograph

(i) Base width (T_b).

(ii) Peak Discharge (Q_p).

(iii) Basin Lag [T_L]

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$$t_L = C_t [L_{ca} \cdot L]^{0.3}$$

t_L = Basin lag in hours [Basin Lag is the time between mass of centre of unit rainfall of 'T' hour duration and run-off Peak Flow]

C_t = A co-eff. depending on basin characteristics. [0.3-6]

L = Distance from Station to Catchment boundary measured along the main-Stream in km.

L_{ca} = Distance along the main-Stream from gauging Station to a Point opposite the centroid of the watershed in km.

T = Standard duration

$$Q_p = \frac{2.778\, C_p \cdot A}{t_L}$$

Q_p = Peak Discharge (m^3/s) ; A = Catchment Area (km^2)

C_p = a regional constant (0.59 - 0.69)

$$T = \frac{2}{11} t_L$$

Duration of Surface run-off or Base length (T_b) of U.H is given by

$$T_b = 3 + 3\left[\frac{t_L}{24}\right] \text{ days}$$

$$T_b = 72 + 3t_L \quad [T_b, t_L - \text{Hours}]$$

It is found that above equation gives unreasonably long base Periods for small catchments. Some of the investigators recommend that a base Period equal to five times the time to Peak should be taken as:

$$T_b = 5\left[\frac{T}{2} + t_L\right] = 5\left[\frac{2}{11} t_L \times 2 + t_L\right] = 5\left[\frac{t_L}{11} + t_L\right]$$

$$T_b = 5.455\, t_L$$

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Width of U.H at 50%, 75% Peak discharge given by

$$W_{50} = \frac{5.87}{q_p^{1.08}}$$

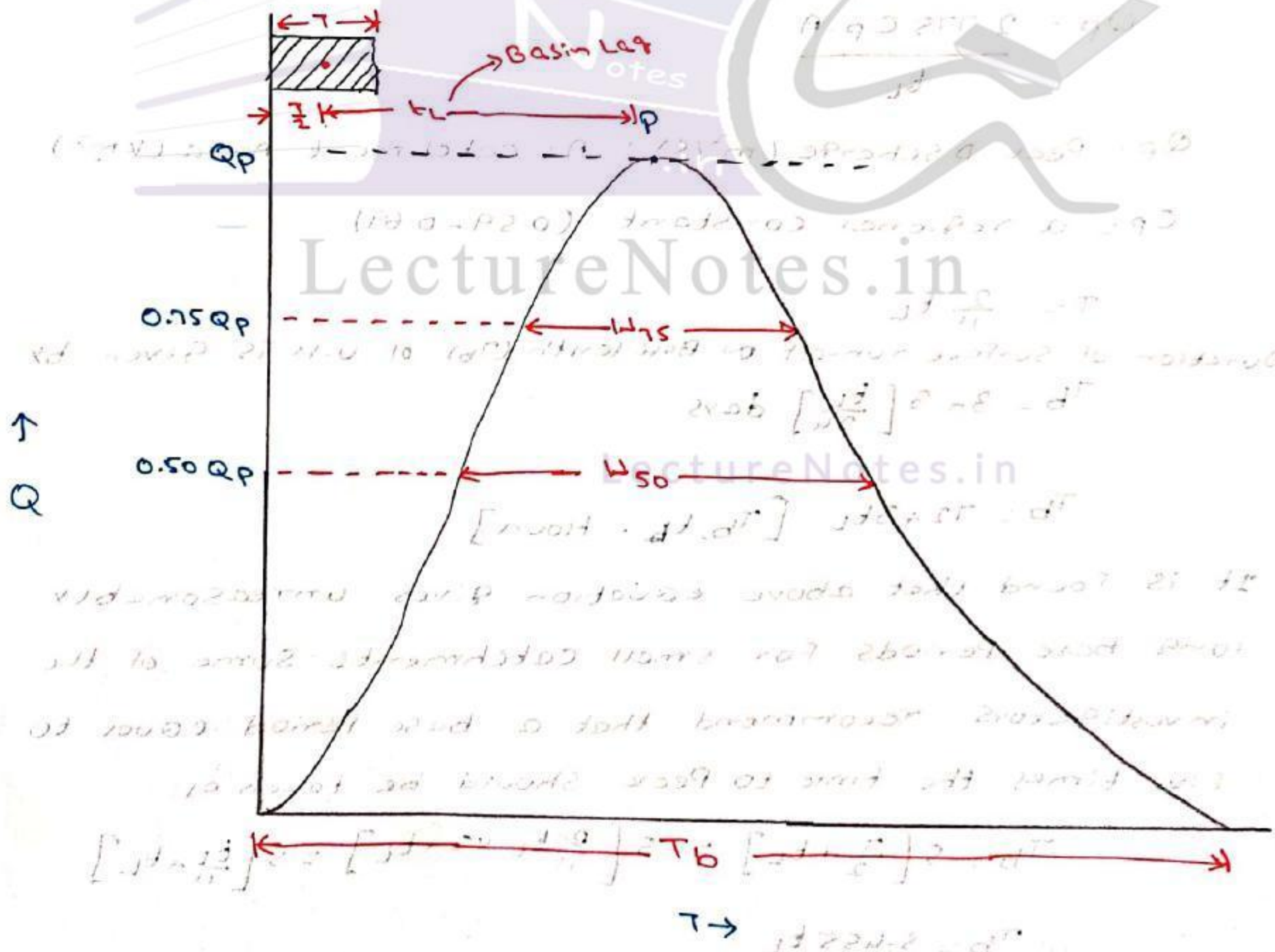
$$W_{75} = \frac{W_{50}}{1.75}$$

W_{50} = Width of U.H in hours at 50% Peak discharge.

W_{75} = Width of U.H in hours at 75% Peak discharge.

$q_p = \frac{Q_p}{A}$ = Peak discharge per unit area.

Usually, one third of this width is kept before the unit hydrograph peak and two thirds after the peak.



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Q) H.M.P A Peak of a Flood Hydrograph due to a Six-hour Storm is 470 m^3/s. The average depth of rainfall is 8 cms. Assume an infiltration loss of 0.25 cm/hr and a Constant base flow of 15 m^3/s. Estimate the Peak discharge of 6 hour unit Hydrograph for this Catchment.

Peak discharge of flood hydrograph = 470 m^3/s

Base Flow = 15 m^3/s

Peak discharge of Direct run-off hydrograph = 470 − 15
= 455 m^3/s

Average depth of rainfall = 8 cm

Rainfall Excess = 8 − (0.25 × 6) = 8 − 1.5 = 6.5 cm

Peak discharge of 6hr U.H = $\frac{455}{6.5}$ = 70 m^3/s

Q) P The ordinates of a 4-hour U.H of Catchment are given below. After (I)

Time (hr)	0	4	8	12	16	20	24	28	32	36	40	44
Ordinate of 4h U.H (m^3/s)	0	20	60	150	120	90	70	50	30	20	10	0

Determine the Flood Hydrograph in the Catchment due to the Storm given below.

Time from Start of Storm (h)	0	4	8	12
Accumulated Rainfall (cm)	0	5	5.8	8.8

The Ø-Index for the catchment can be assumed to be 0.25 cm/hr and a constant base flow of 20 m^3/s is

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	1st 4hr	2nd 4hr	3rd 4 hr
Rainfall	5.0	0.8	3.0
LOSS	1	1	1
EFF. Rainfall	4.0	0	2.0

Time (hrs)	Ordinate of 4hr U.H (m^3/s)	Surface run-off from rainfall excess during successive unit Periods $m_1=4$	$m_2=0$	$m_3=2$	Total	Base Flow	Ordinate of F.H
(1)	(2)	(3) = (2)×4	(4) = (2)×0	(5) = (2)×2	(6)	(7)	(8) = (6)+(7)
0	0	0			0	20	20
4	20	80	0		80	20	100
8	60	240	0	0	240	20	260
12	150	600	0	40	640	20	660
16	120	480	0	120	600	20	620
20	90	360	0	300	660	20	680
24	70	280	0	240	520	20	540
28	50	200	0	180	380	20	400
32	30	120	0	140	260	20	280
36	20	80	0	100	180	20	200
40	10	40	0	60	100	20	120
44	0	0	0	40	40	20	60
48			0	20	20	20	40
52				0	0	20	20

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Q) Using the given 6-h U.H derive F.H due to storm given

Time(h)	0	6	12	18	24	30	36	42	48	54	60	66
6hr UH ordinates	0	20	60	150	120	90	66	50	32	20	10	0

After (7)

Time from beginning of Storm (hr)	0	6	12	18
Accumulated Rainfall (cm)	0	4	5	10

The Ø-Index for storm can be assumed to be 0.167 cm/hr.

Assume Base Flow as 20 m³/s.

	1st 6hr	2nd 6hr	3rd 6hr
Rainfall	4	1	5
Loss	1	1	1
Eff. Rainfall	3	0	4

Time (hrs)	ordinate of 6hr U.H	Surface run-off from rainfall excess during successive unit periods $n_1=3$	$n_2=0$	$n_3=4$	Total	Base Flow	ordinates of F.H
0	0	0			0	20	20
6	20	60	0		60	20	80
12	60	180	0	0	180	20	200
18	150	450	0	80	530	20	~~550~~ 550
24	120	360	0	240	600	20	~~580~~ 620
30	90	270	0	600	870	20	~~850~~ 890
36	66	198	0	480	678	20	~~658~~ 698
42	50	150	0	360	510	20	~~490~~ 530
48	32	96	0	264	360	20	380
54	20	60	0	200	260	20	280
60	10	30	0	128	158	20	178
66	0	0	0	80	80	20	100
72			0	40	40	20	60
78				0	0	20	20

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(Q) H.M-P The 6hr U.H of a catchment area of 1000 km² can be approximated as a triangle with base of 69 hours. Calculate the Peak ordinate of this U.H.

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$$\text{Depth} = \frac{\text{Volume}}{\text{Area}}$$

$$\frac{1}{2} \times 69 \times 60 \times 60 \times Q_p = 1000 \times 10^6 \times \frac{1}{100}$$

$$1\,cm = \frac{\frac{1}{2} \times 69 \times 60 \times 60 \times Q_p}{1000 \times 1000^2}$$

$$Q_p = 80.52\ m^3/s$$

(Q) H.M-P The 6hr U.H of a basin is triangular in shape with a peak of 100 m³/s occurin at 24hr from the start. The base is 72hours. Calculate the Area of catchment.

$$\text{Depth} = \frac{\text{Volume}}{\text{Area}}$$

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$$0.01\,m\ (\text{or } 1\,cm) = \frac{\frac{1}{2} \times 100 \times 72 \times 60 \times 60}{A}$$

$$A = 1.296 \times 10^9\ m^2$$

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$$= 1.296 \times 10^9\ (10^{-3})^2\ km^2$$

$$A = 1296\ km^2$$

Depth = Volu / Area

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Q) The ordinates of a 6hr U.H are given below

Time(hr)	0	6	12	18	24	30	36	42	48	54	60	66
6hr U.H ordinates	0	20	60	150	120	90	66	50	32	20	10	0

If two storms each 1cm rainfall excess and 6hr duration occur in succession calculate the resulting hydrograph. Assume Base Flow as 10 m^3/s. After (I)

Time (hr)	6hr-U.H Ordinates	Surface run-off from rainfall excess during successive unit periods $n_1=1$	$n_2=1$	Total	Base Flow	F.H ordinates
0	0	0		0	10	10
6	20	20	0	20	10	30
12	60	60	20	80	10	90
18	150	150	60	210	10	220
24	120	120	150	270	10	280
30	90	90	120	210	10	220
36	66	66	90	156	10	166
42	50	50	66	116	10	126
48	32	32	50	82	10	92
54	20	20	32	52	10	62
60	10	10	20	30	10	40
66	0	0	10	10	10	20
72			0	0	10	10

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Q) Using the 6-hr U.H derive 12hr U.H for catchment.
H.H - P

Time (hr)	0	6	12	18	24	30	36	42	48	54	60	66
6hr U.H ordinates	0	20	60	150	120	90	66	50	32	20	10	0

Base Flow as $10 m^3/s$

Time (hr) (1)	6hr U.H ordinates (m^3/s) (2)	6hr U.H lagged by 6 hr (3)	Combined ordinates (4)	Ordinates of 12-hr U.H (5) = (4)/2
0	0		0	0
6	20	0	20	10
12	60	20	80	40
18	150	60	210	105
24	120	150	270	135
30	90	120	210	105
36	66	90	156	78
42	50	66	116	58
48	32	50	82	41
54	20	32	52	26
60	10	20	30	15
66	0	10	10	5
		0	0	0
	618	618	1236	618

A = 1334.88 km^2

$\frac{0.36 \times 618 \times 6}{1334.88} = 1 cm$

$\frac{0.36 \times 1236 \times 6}{1334.88} = 2 cm$

$\frac{0.36 \times 618 \times 6}{1334.88} = 1 cm$

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Q) The ordinates of 2hr U.H of a basin are given below.

Time(hr)	0	2	4	6	8	10	12	14	16	18	20	22
2hr-U.H ordinates (m^3/s)	0	25	100	160	190	170	110	70	30	20	6	0

Determine the ordinates of S_2-curve hydrograph and using this S_2-curve, determine ordinates of 4hr U.H of basin

$$O = \Delta y \cdot \frac{T_o}{t_o} = \Delta y \cdot \frac{2}{4} \Rightarrow O = \Delta y \cdot \frac{2}{4}$$

Time(hr) (1)	2hr U.H ordinates (m^3/s) (2)	offset ordinates (m^3/s) (3)	ordinates of S-hydrograph (m^3/s) (4)	ordinates of offset S-curve (5)	Δy (6) (6)=(4)-(5)	$O = \Delta y \cdot \frac{2}{4}$ (7)
0	0		0		0	0
2	25	0	25		25	12.5
4	100	25	125	0	125	62.5
6	160	125	285	25	260	130
8	190	285	475	125	350	175
10	170	475	645	285	360	180
12	110	645	755	475	280	140
14	70	755	825	645	180	90
16	30	825	855	755	100	50
18	20	855	875	825	50	25
20	6	875	881	855	26	13
22	0	881	881	875	6	3
24		881	881	881	0	0
26		881	881	881	0	0
						494

A = 634.32 km^2

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Application of unit hydrograph to construction of a flood hydrograph resulting from two (or) more periods of rainfall:

1. A unit hydrograph of some specific unit duration can also be utilised for construction of flood hydrograph resulting from the rainfall lasting for a long duration.

2. As an example, let us say that a 3-hours unit hydro-graph is available and it is required to compute the flood hydrograph resulting from a rainfall lasting for 9 hours with variable intensities of rainfall.

3. The intensity rates having n_1 cm/3 hours for the first period of 3 hours, n_2 cm/3 hours for the second period of 3 hours and n_3 cm/3 hours for the last 3 hours.

4. The storm is divided into 3 parts and the flood hydro-graph of each part is computed separately and added.

5. The hydrographs for the second part of the storm starts 3 hours later than that for the first part.

6. Similarly, the hydrograph for the third part of the storm starts 6 hours later than that for the first (or) 3 hours later than that for the second part.

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Derivation of Unit Hydrograph from Complex Storms:-

1. Let the direct run-off ordinates of the given complex hydrograph be represented by $Q_1, Q_2, Q_3, \ldots Q_m$ in successive periods during the storm.

2. Let the ordinates of the unit hydrograph be designated by $U_1, U_2, U_3 \ldots U_m$ at the successive time intervals.

3. For the purpose of illustration, we shall assume that the whole period of complex storm has three storms, each of effective duration equal to unit duration for which unit hydrograph is to be drawn.

4. On the hyetographs of rainfall, super-impose the infiltration rate curves and find the "rainfall excess" rates. Let R_1, R_2 and R_3 be the respective rainfall-excess for the three storms

5. Thus, for the whole duration, there will be three similar unit hydrographs, each operating at a time lag equal to the 'unit duration'

$[N < m]$

$$Q_1 = R_1 U_1$$

$$Q_2 = R_1 U_2$$

$$Q_3 = R_1 U_3 + R_2 U_1$$

$$Q_4 = R_1 U_4 + R_2 U_2$$

$$Q_5 = R_1 U_5 + R_2 U_3 + R_3 U_1$$

$$Q_N = R_1 U_N + R_2 U_{N-2} + R_3 U_{N-4}$$

The ordinates $U_1, U_2, U_3 \ldots$ of the U.H are known.

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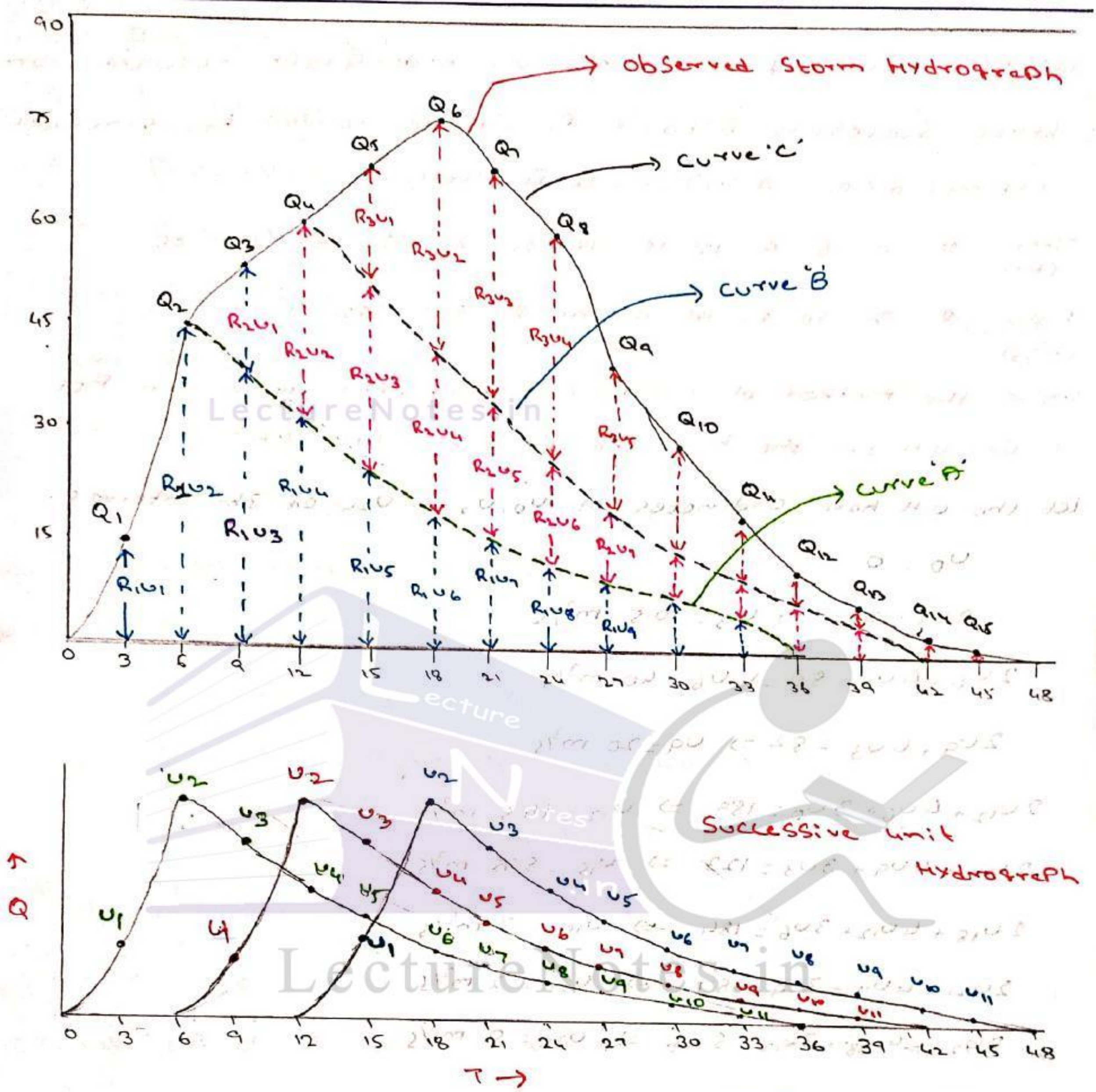

Ordinates of Curve A = R_1 × Successive ordinates of 1st U.H

Ordinates of curve B = (Successive ordinates of curve A) + (R_2 × Successive ordinates of 2nd U.H)

Ordinates of curve C = (Successive ordinates of curve A + B) + (R_3 × Successive ordinates of 3rd U.H)

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Q) The following direct run-off hydrograph resulted from three successive 6 hours periods of rainfall having run-off estimated as 2, 4, 3 cm respectively.

Time (hr)	0	3	6	9	12	15	18	21	24	27	30	33	36
Flow (m^3/s)	0	21	80	82	189	123	184	87	55.5	25.25	9	6	0

Using the method of complex hydrographs, derive and plot a 6hr U.H for the basin having area = 103.4 km^2.

Let the U.H have ordinates of $U_0, U_3 \ldots U_{24}$ at 3hr intervals.

$U_0 = 0$

$2U_3 = 21 \Rightarrow U_3 = 10.5\ m^3/s$

$2U_6 + 4U_0 = 80 \Rightarrow U_6 = 40\ m^3/s$

$2U_9 + 4U_3 = 82 \Rightarrow U_9 = 20\ m^3/s$

$2U_{12} + 4U_6 + 3U_0 = 189 \Rightarrow U_{12} = 14.5\ m^3/s$

$2U_{15} + 4U_9 + 3U_3 = 123 \Rightarrow U_{15} = 5.75\ m^3/s$

$2U_{18} + 4U_{12} + 3U_6 = 184 \Rightarrow U_{18} = 3\ m^3/s$

$2U_{21} + 4U_{15} + 3U_9 = 87 \Rightarrow U_{21} = 2\ m^3/s$

$2U_{24} + 4U_{18} + 3U_{12} = 55.5 \Rightarrow U_{24} = 0\ m^3/s$

Ordinates of U.H are

Time	0	3	6	9	12	15	18	21	24	
Flow	0	10.5	40	20	14.5	5.75	3	2	0	= 95.75

Direct Run-off: $\frac{\Sigma Q \times t \times 0.36}{A}$

$= \frac{95.75 \times 3 \times 0.36}{103.4} = 1\ cm$

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Time

0 hr $R_1 U_1 = Q_1 \Rightarrow 2U_1 = 0 \Rightarrow U_1 = 0$

3 hr $R_1 U_2 = Q_2 \Rightarrow 2U_2 = 21 \Rightarrow U_2 = 10.5$

6 hr $R_1 U_3 + R_2 U_1 = Q_3 \Rightarrow 2U_3 + 4U_1 = 80 \Rightarrow U_3 = 40$

9 hr $R_1 U_4 + R_2 U_2 = Q_4 \Rightarrow 2U_4 + 4U_2 = 82 \Rightarrow U_4 = 20$

12 hr $R_1 U_5 + R_2 U_3 + R_3 U_1 = Q_5 \Rightarrow 2U_5 + 4U_3 + 3U_1 = 189 \Rightarrow U_5 = 14.5$

15 hr $R_1 U_6 + R_2 U_4 + R_3 U_2 = Q_6 \Rightarrow 2U_6 + 4U_4 + 3U_2 = 123 \Rightarrow U_6 = 5.75$

18 hr $R_1 U_7 + R_2 U_5 + R_3 U_3 = Q_7 \Rightarrow 2U_7 + 4U_5 + 3U_3 = 184 \Rightarrow U_7 = 3$

21 hr $R_1 U_8 + R_2 U_6 + R_3 U_4 = Q_8 \Rightarrow 2U_8 + 4U_6 + 3U_4 = 87 \Rightarrow U_8 = 2$

24 hr $R_1 U_9 + R_2 U_7 + R_3 U_5 = Q_9 \Rightarrow 2U_9 + 4U_7 + 3U_5 = 55.5 \Rightarrow U_9 = 0$

27 hr $R_1 U_{10} + R_2 U_8 + R_3 U_6 = Q_{10} \Rightarrow 2U_{10} + 4U_8 + 3U_6 = 25.25 \Rightarrow U_{10} = 0$

30 hr $R_1 U_{11} + R_2 U_9 + R_3 U_7 = Q_{11} \Rightarrow 2U_{11} + 4U_9 + 3U_7 = 9 \Rightarrow U_{11} = 0$

33 hr $R_1 U_{12} + R_2 U_{10} + R_3 U_8 = Q_{12} \Rightarrow 2U_{12} + 4U_{10} + 3U_8 = 6 \Rightarrow U_{12} = 0$

36 hr $R_1 U_{13} + R_2 U_{11} + R_3 U_9 = Q_{13} \Rightarrow 2U_{13} + 4U_{11} + 3U_9 = 0 \Rightarrow U_{13} = 0$

Ordinates of U.H are,

Time (hr)	0	3	6	9	12	15	18	21	24	27	30	33	36
Ordinates of U.H (m^3/s)	0	10.5	40	20	14.5	5.75	3	2	0	0	0	0	0

$\Sigma O = 95.75$

Direct Run-off Depth of U.H $= \dfrac{0.36 \times D \times \Sigma O}{A}$

$= \dfrac{0.36 \times 3 \times 95.75}{103.4}$

$= 1.00$ cm

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Q) The ordinates of a 6hr U.H of a basin are given below

Time (hr)	0	3	6	9	12	15	18	21	24	27	30	33	36	39	42
6hr U.H ordinates (m^3/s)	0	9	20	35	49	43	35	28	22	17	12	9	6	3	0

Determine ordinates of S-curve hydrograph & also in this S-curve

$T_0 = 6hr$; $t_0 = 3hrs$ determine ordinates of 3hr U.H.

$$O = \Delta y \cdot \frac{T_0}{t_0} = \Delta y \cdot \frac{6}{3} \Rightarrow O = (\Delta y) \cdot 2$$

Time (hr) (1)	6hr U.H ordinates (m^3/s) (2)	Offset ordinates (m^3/s) (3)	ordinates of S-Hydrograph (m^3/s) (4) (4) = (2)+(3)	ordinates of Offset S-Hydrograph (m^3/s) (5)	Δy (m^3/s) (6) (6) = (4)-(5)	ordinates of 3 hr U.H (m^3/s) $O = \Delta y \cdot \frac{T_0}{t_0}$ (7) (7) = (6)×2
0	0	–	0	–	0	0
3	9	–	9	0	9	18
6	20	0	20	9	11	22
9	35	9	44	20	24	48
12	49	20	69	44	25	50
15	43	44	87	69	18	36
18	35	69	104	87	17	34
21	28	87	115	104	11	22
24	22	104	126	115	11	22
27	17	115	132	126	6	12
30	12	126	138	132	6	12
33	9	132	141	138	3	6
36	6	138	144	141	3	6
39	3	141	144	144	0	0
42	0	144	144	144	0	0

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Q) The ordinates of a flood hydrograph, resulting from two successive storms each of 1cm rainfall excess and 6 hour duration are tabulated below. Find a 6 hour unit hydrograph.

Time (hr)	0	6	12	18	24	30	36	42	48	54	60	66	72
6hr F.H ordinates (m^3/s)	10	30	90	220	280	220	166	126	92	62	40	20	10

Let R_1, R_2 be rainfall excess. $R_1 = R_2 = 1cm$; Base flow $= 10\ m^3/s$

$Q_1, Q_2 --- Q_{13}$ be the ordinates of direct run-off hydrograph

$U_1, U_2 --- U_{13}$ be the ordinates of 6 hours unit hydrograph.

Time (hr)	ordinate of 6hr F.H (m^3/s)	Base Flow (m^3/s)	ordinates of Direct Run-off	Equation for direct runoff hydrograph	ordinate of 6 hr unit Hydrograph
0	10	10	0 (Q_1)	$Q_1 = R_1U_1$	$U_1 = 0$
6	30	10	20 (Q_2)	$Q_2 = R_1U_2 + R_2U_1$	$U_2 = 20$
12	90	10	80 (Q_3)	$Q_3 = R_1U_3 + R_2U_2$	$U_3 = 60$
18	220	10	210 (Q_4)	$Q_4 = R_1U_4 + R_2U_3$	$U_4 = 150$
24	280	10	270 (Q_5)	$Q_5 = R_1U_5 + R_2U_4$	$U_5 = 120$
30	220	10	210 (Q_6)	$Q_6 = R_1U_6 + R_2U_5$	$U_6 = 90$
36	166	10	156 (Q_7)	$Q_7 = R_1U_7 + R_2U_6$	$U_7 = 66$
42	126	10	116 (Q_8)	$Q_8 = R_1U_8 + R_2U_7$	$U_8 = 50$
48	92	10	82 (Q_9)	$Q_9 = R_1U_9 + R_2U_8$	$U_9 = 32$
54	62	10	52 (Q_{10})	$Q_{10} = R_1U_{10} + R_2U_9$	$U_{10} = 20$
60	40	10	30 (Q_{11})	$Q_{11} = R_1U_{11} + R_2U_{10}$	$U_{11} = 10$
66	20	10	10 (Q_{12})	$Q_{12} = R_1U_{12} + R_2U_{11}$	$U_{12} = 0$
72	10	10	0 (Q_{13})	$Q_{13} = R_1U_{13} + R_2U_{12}$	$U_{13} = 0$

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Construction of shorter or longer Period unit hydrograph from a given unit hydrograph

1. Let it be required to obtain a unit hydrograph of unit Period "t_0" from a given unit hydrograph of unit Period (T_0) where t_0 can be greater or smaller than T_0. For this S-curve method is used.

2. From the given unit hydrograph of unit Period (T_0), S-curve can be derived. The S-curve will represent a constant effective rainfall of $R_0 = 1/T_0$ cm/hr. An offset curve is then drawn by advancing or offsetting the position of original S-curve for a period equal to the desired unit Period (t_0) hours.

3. The difference between the ordinates of original S-curve and offset curve divided by $R_0 t_0$ will give the ordinates of desired unit hydrograph.

4. Thus at any time Period t, if difference between the ordinates of the two S-curves is Δy, then the ordinates of the desired unit hydrograph of t_0 unit Period is given by

$$= \frac{\Delta y}{R_0 t_0} = \frac{\Delta y}{\left(\frac{1}{T_0}\right) \cdot t_0} = \Delta y \cdot \frac{T_0}{t_0}$$

5. Thus ordinates at various time intervals can be computed and the desired unit hydrograph may be obtained.

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