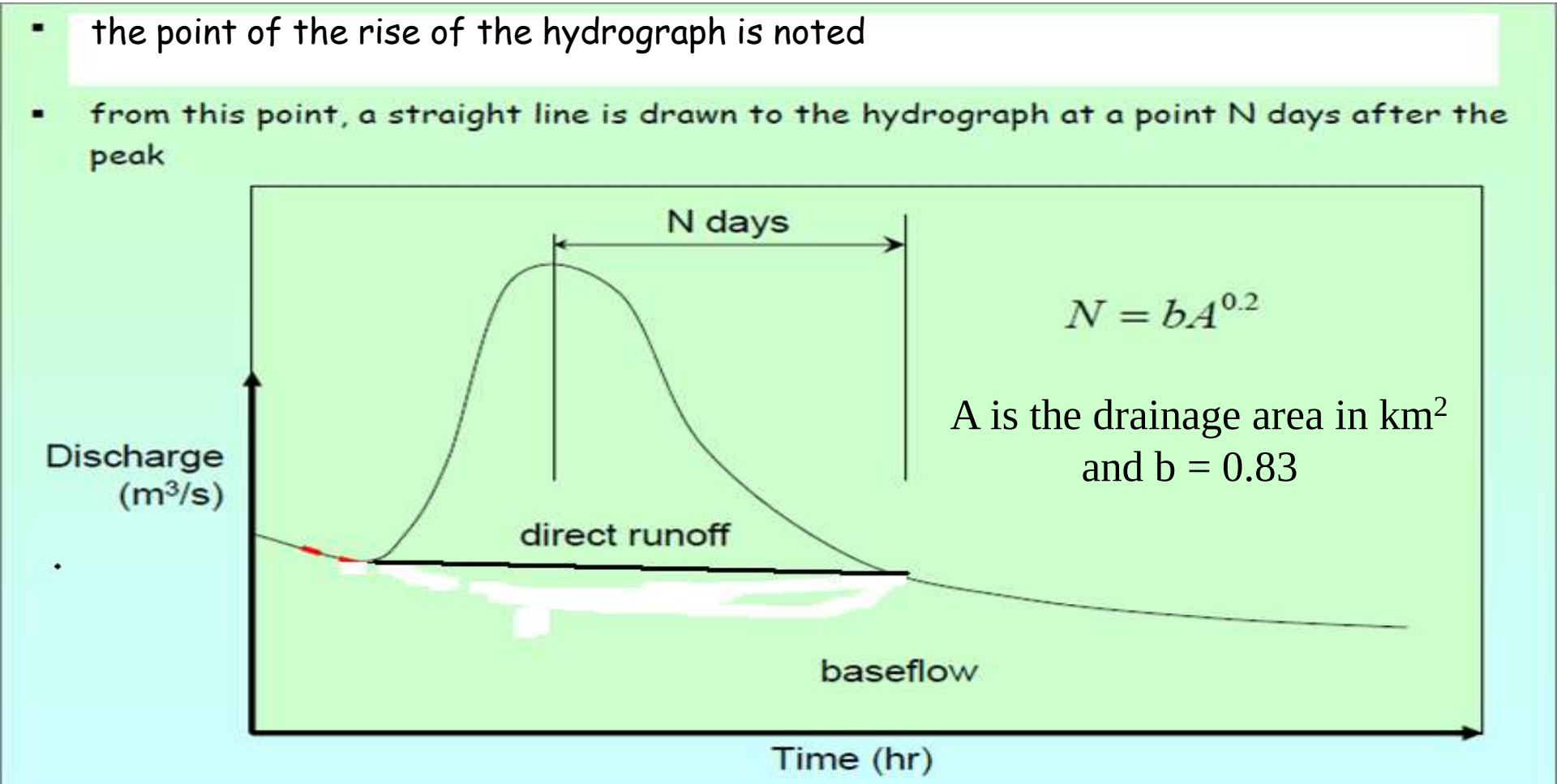
Runoff

Hydrograph Separation

The separation of direct runoff and base flow of a hydrograph is known as hydrograph separation or base flow separation. There are three methods of separating the base flow from the hydrograph. The methods are described below.

Method I

- the point of the rise of the hydrograph is noted
- from this point, a straight line is drawn to the hydrograph at a point N days after the peak

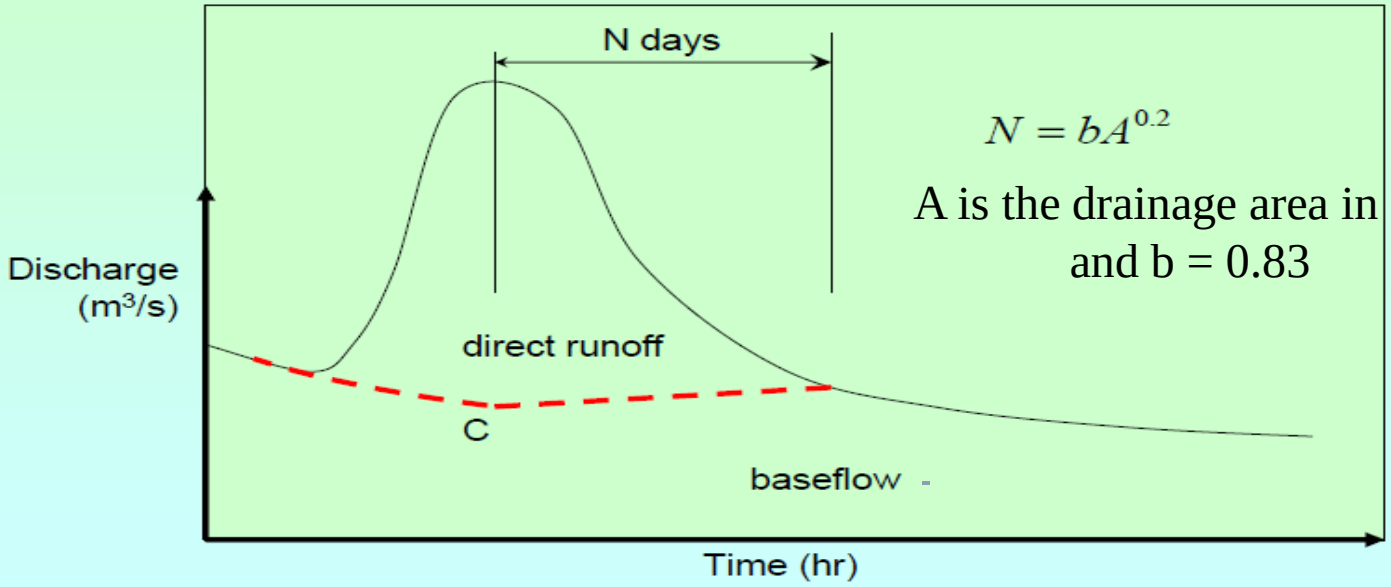


$$N = bA^{0.2}$$

A is the drainage area in km^2 and b = 0.83

Method II

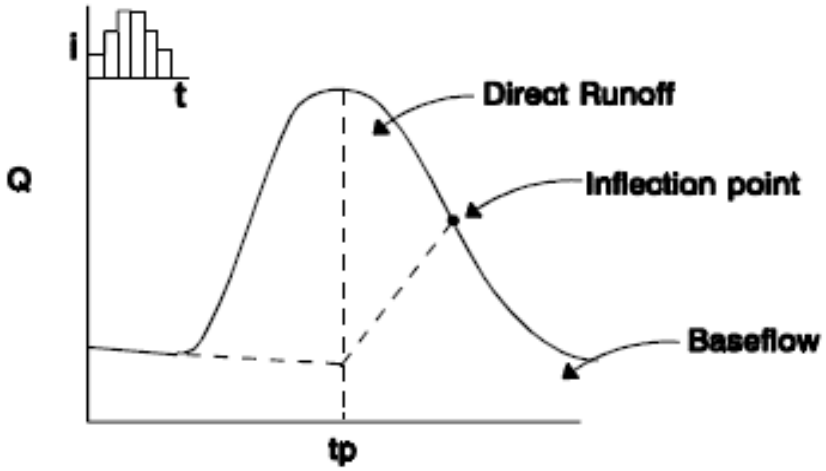
- an alternative approach is to project the initial recession curve downward to a point directly beneath the hydrograph peak (Point *C*)
- from this point, a straight line is drawn to the hydrograph at a point N days after the peak



$$N = bA^{0.2}$$

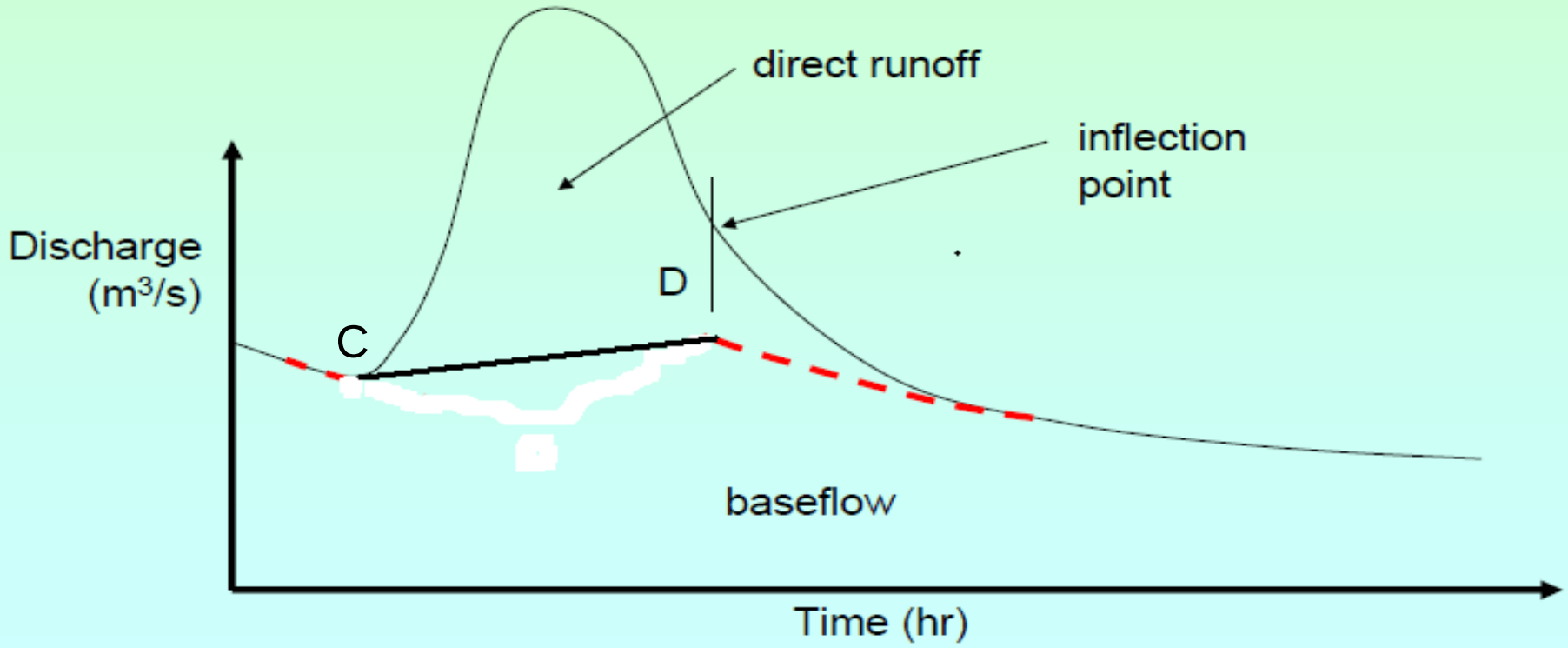
A is the drainage area in km^2 and b = 0.83

When N is too large, a modification is applied by connecting C with the point of inflection of the falling limb.



Method III

- the previous approach can be extended by making use of the baseflow recession curve
- we can project the recession curve backwards under the hydrograph to some point D, chosen somewhat arbitrarily below the inflection point of the hydrograph
- connecting points C and D allow us to separate the baseflow component



A modification of this method is to extend the recession curve up to the peak level and then connect the point with C.

Runoff

Runoff Estimation

Estimating the peak rate of runoff and the volume of runoff are basic to the design of hydraulic structures.

For a given hydrograph, the volume of direct runoff can be estimated by separating the base flow.

Example

A 8-hour storm with 6.6 cm of rainfall in a 27 sq. km watershed generated the following hydrograph. Estimate the volume of direct runoff and the Φ index.

Time (hrs)	0	6	12	18	24	30	36	42	48	54	60	66
Flow m^3/sec	5	13	26	21	16	12	9	7	5	5	4.5	4.5

In order to estimate the direct runoff it is necessary to find out the base flow.

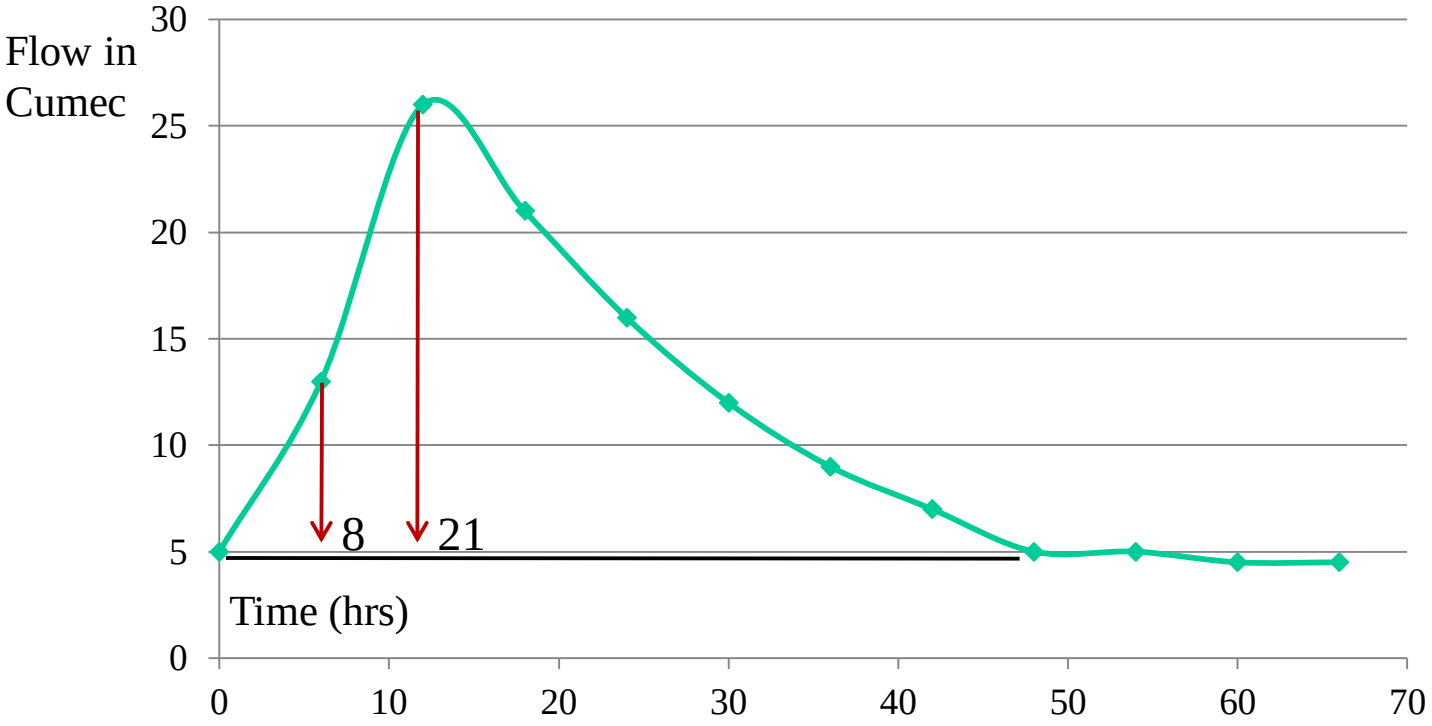
$N = 0.83\ A^{0.2} = 0.83\ (27)^{0.2} = 1.6$ days $= 38$ hours

From the figure, $N = 48 - 12 = 36$ hours ~ 38 hours

Thus, a straight line base flow separation gives base flow of 5 m^3/sec

Subtracting the base flow from the hydrograph, the total runoff volume is:

Runoff $= 6 \times 60 \times 60\ [\ (8)/2 + (8+21)/2 + (21+16)/2 + (16+11)/2 + (11+7)/2 + (7+4)/2 + (4+2)/2 + (2)/2] = 1.49 \times 10^6\ m^3$



The direct runoff volume can also be obtained by adding all the ordinates as:

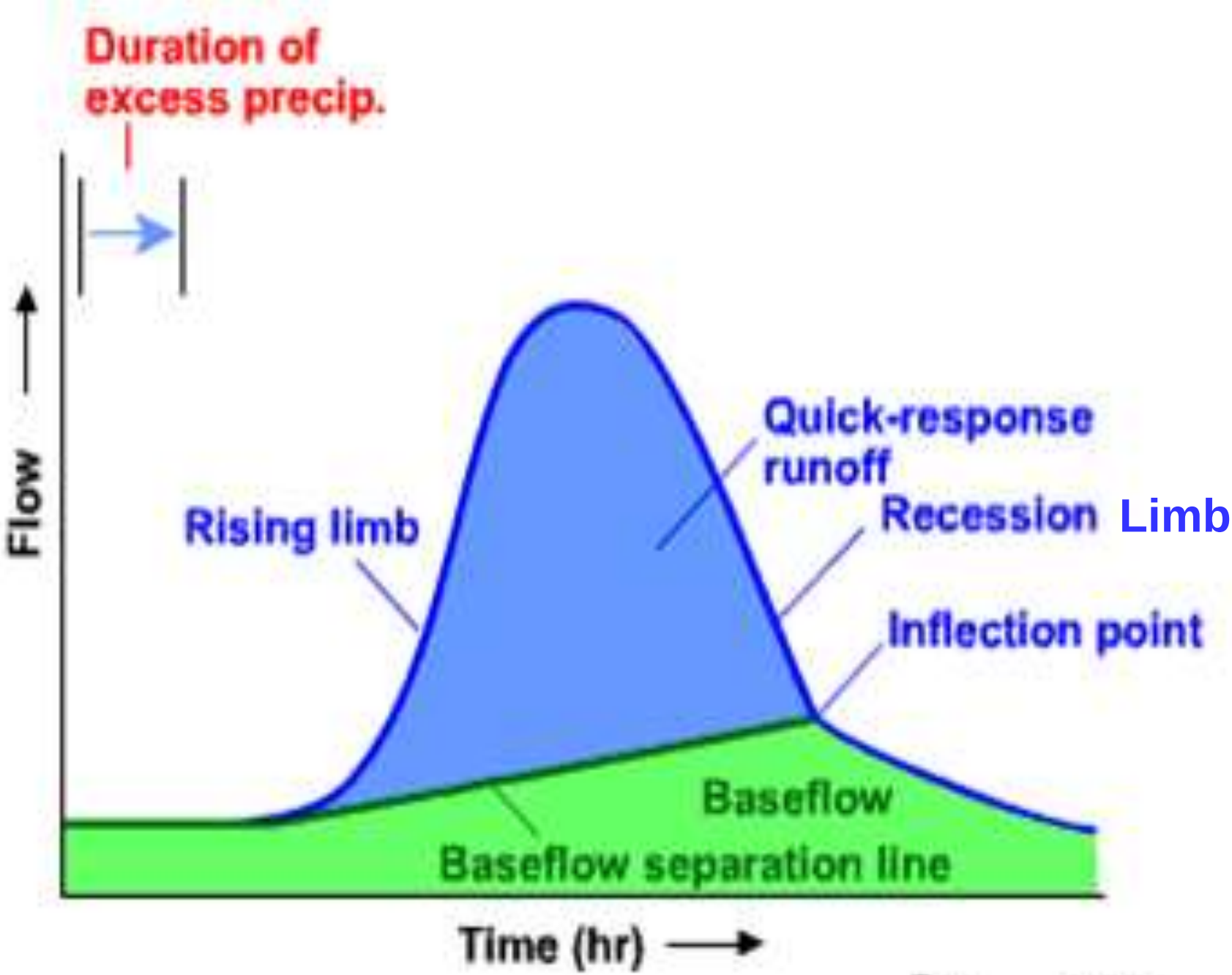
$$(8 + 21 + 16 + 11 + 7 + 4 + 2) = 69$$

Direct runoff volume $= 69 \times 3600 \times 6 = 1.49 \times 10^6\ m^3$

Direct runoff depth = Volume /Area = $1.49 \times 10^6 / 27 \times 10^6 = 0.055$ m = 5.5 cm

Subtracting the direct runoff from the rainfall: 6.6 – 5.5 = 1.1 cm = Total infiltration

Φ index = Average infiltration rate = 1.1/ 8 = 0.138 cm / hr


Duration of
excess precip.
Flow
Rising limb
Quick-response
runoff
Recession Limb
Inflection point
Baseflow
Baseflow separation line
Time (hr)

Runoff

Hydrograph Analysis

Lag Time (basin lag), T

- Time interval from the center of mass of the rainfall-excess to the centre of mass of the runoff hydrograph. Because of the difficulty if determining the centre of mass of the hyrdograph, usually the peak of the resultant hydrograph is taken as the centre.

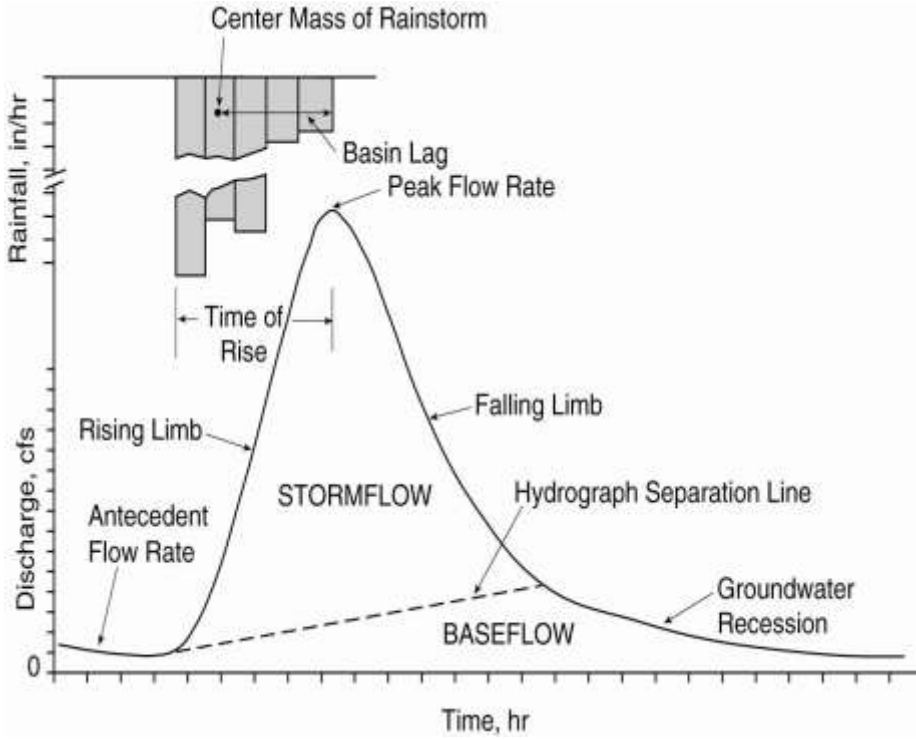
Time to Peak, T_P (Time of rise)

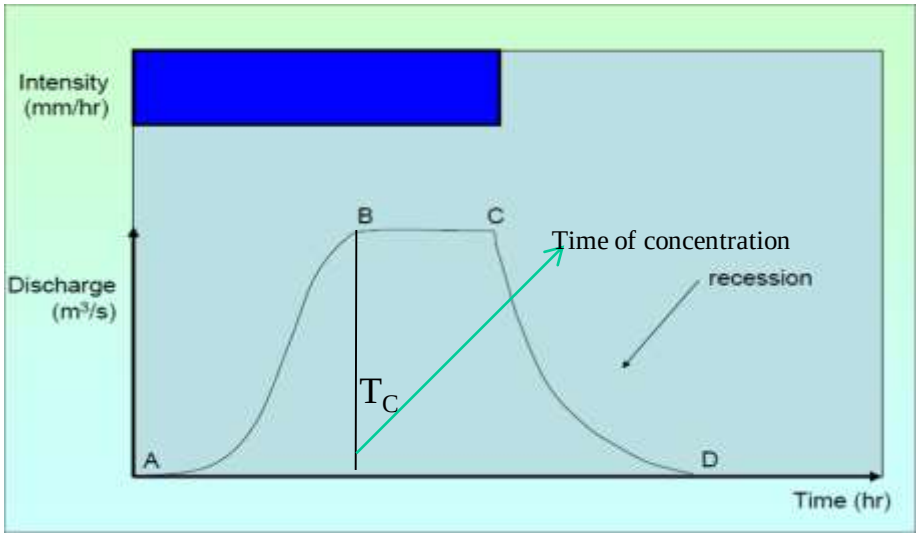
- Time interval from the start of the rainfall-excess (start of the rising limb) to the peak of the resultant hydrograph.

Time of Concentration, T_C

- Time required for runoff to travel from the hydraulically most distant point on the watershed to the point of interest.

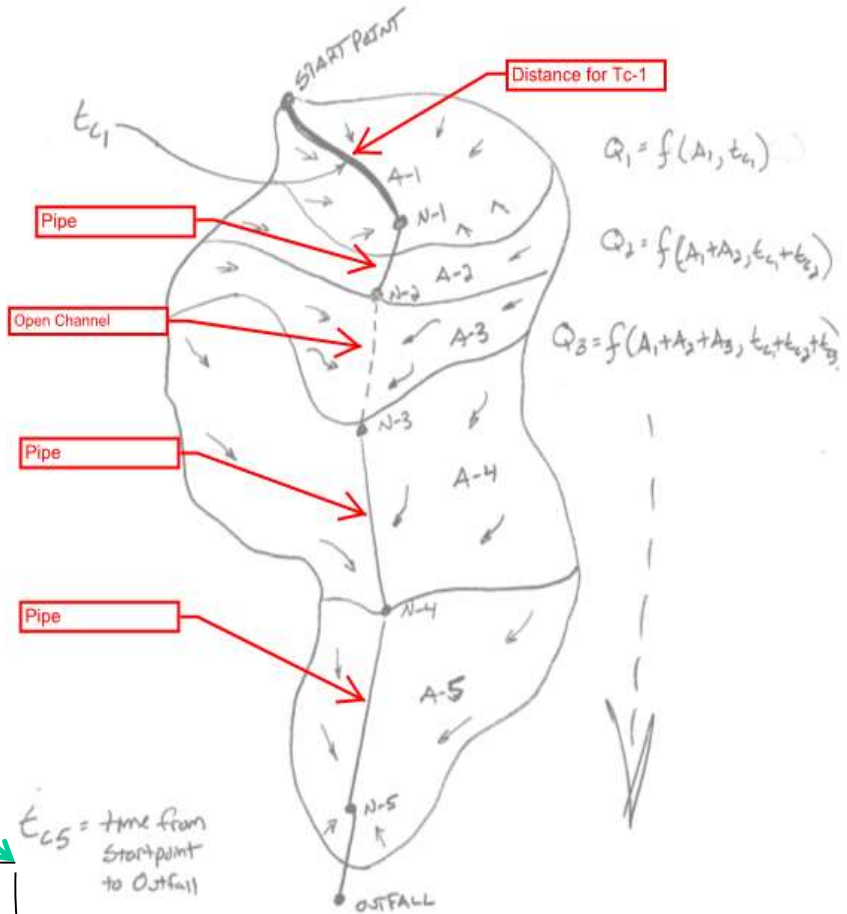
It is the time required for all portions of the basin to contribute runoff to the hydrograph. <u>Therefore if T_C is shorter than the rain duration, it represents the maximum discharge that can occur from a given storm intensity over the drainage basin.</u>

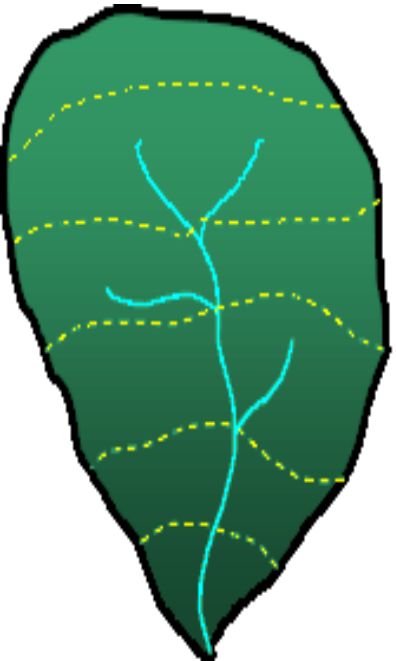


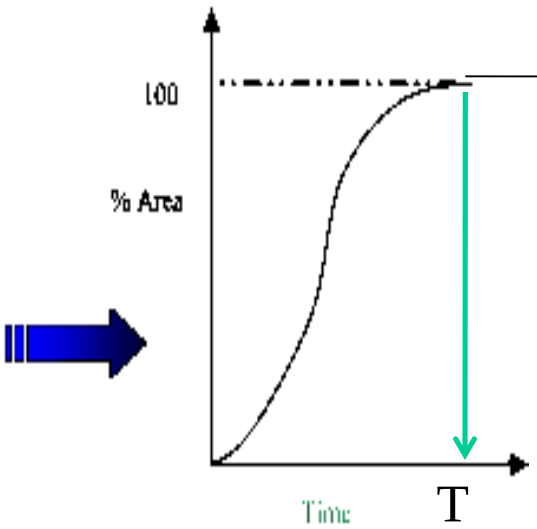


Time of Concentration

It is a function of the topography (slope), geology, and land use within the watershed.







Runoff

Determination of Peak Flow

For a given storm, the resulting peak flow (runoff or discharge) determines the size of the drainage structures. Peak flows mainly depend on rainfall characteristics, and basin characteristics (watershed size, shape and land use).

There are a number of acceptable methods of determining peak runoff for gaged and ungaged basins. The commonly used methods are:

1. Rational Method
2. Unit Hydrograph Method
3. Natural Resources Conservation Service Method (SCS Method)

The NRCS method (developed in the US) is more sophisticated hydrologically compared to Rational method and offers a more accurate approximation of runoff, particularly for areas larger than 10 hectares.

Runoff is related to the soil and land cover conditions of the watershed through the curve number (CN). CN has a range of 0 to 100.

4. Rainfall Runoff Models: HEC, HYMOS, MIKE 11- NAM etc.

HEC – Hydrologic Engineering Centre of US Corps of Engineers

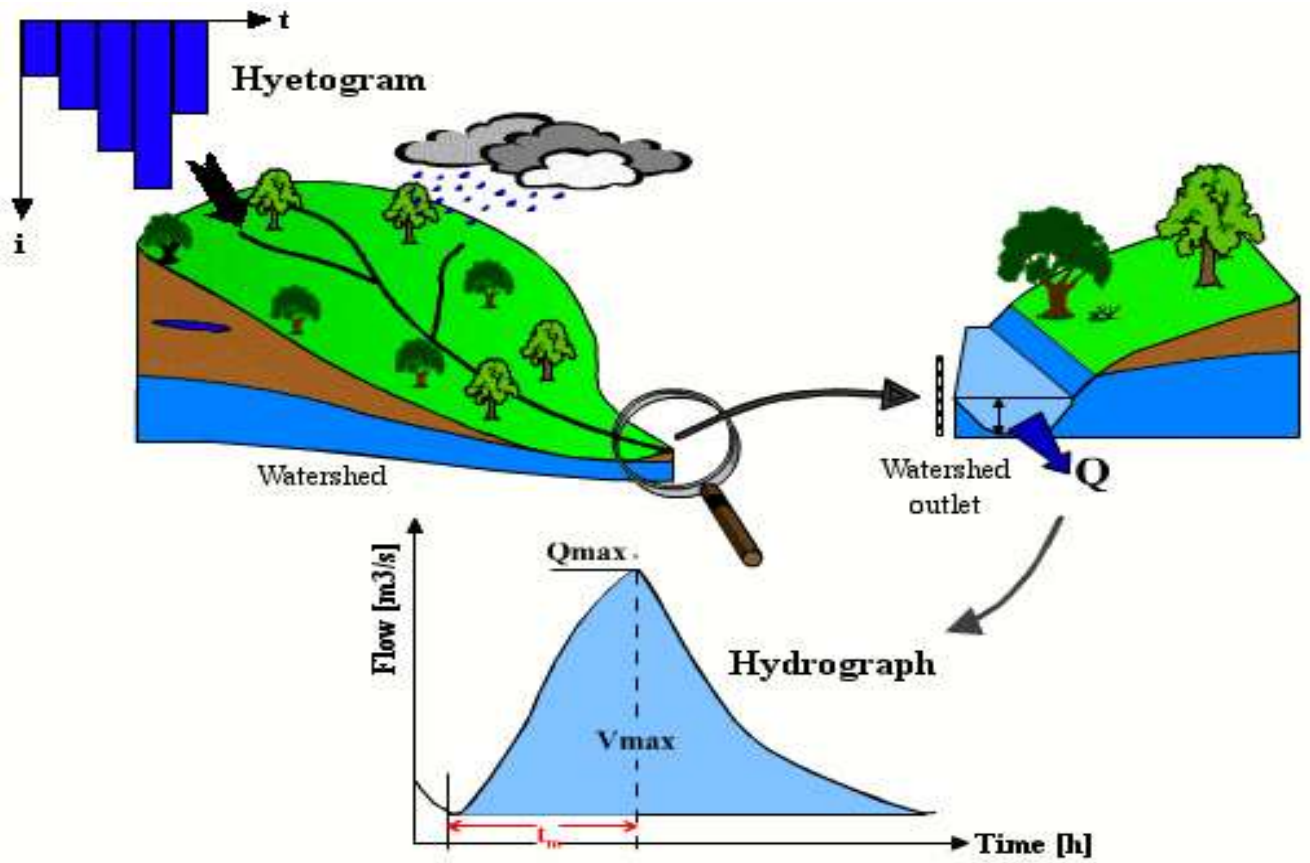
HYMOS – Sacramento Rainfall-runoff model

MIKE 11- NAM- Danish Model used in Bangladesh

5. Synthetic Unit Hydrograph

Gauged and ungauged watersheds

- Gauged watersheds
  - Watersheds where data on precipitation, streamflow, and other variables are available
- Ungauged watersheds
  - Watersheds with no data on streamflow and other variables.



Runoff

Rational Method (Ungaged Basin)

The rational method is very simple in concept but relies on considerable judgment and experience to evaluate all factors properly. It is used primarily for small drainage areas (less than 250 hectares) and computes the peak discharge as:

$$Q_p = 0.278\ C\ i\ A$$

where Q_p = peak discharge (m^3/s);

C= runoff coefficient

i = average intensity of rainfall of selected frequency (return period) corresponding to the duration of time of concentration (mm/hr)

A = drainage area (km^2)

For Q_p to occur, the rainfall duration must be >= the time of concentartion. If the duration is less than the time of concentration, then the discharge is not the peak for that particular intensity.

The time of concentration can be obtained from Kirpich (1940) equation as:

$$t_c = 0.0195\ L^{0.77}\ S^{-0.385}$$

Where: t_c - time of concentration (minutes)

L - maximum length of travel (meters)

S - slope = (H/L) where H is the difference in elevation between the furthest point in the catchment and the outlet.

Table 8.03b
Value of Runoff Coefficient (C) for Rational Formula

Land Use	C
Business:	
Downtown areas	0.70-0.95
Neighborhood areas	0.50-0.70
Residential:	
Single-family areas	0.30-0.50
Multi units, detached	0.40-0.60
Multi units, Attached	0.60-0.75
Suburban	0.25-0.40
Industrial:	
Light areas	0.50-0.80
Heavy areas	0.60-0.90
Parks, cemeteries	0.10-0.25
Playgrounds	0.20-0.35
Railroad yard areas	0.20-0.40
Unimproved areas	0.10-0.30
Streets:	
Asphalt	0.70-0.95
Concrete	0.80-0.95
Brick	0.70-0.85
Drives and walks	0.75-0.85
Roofs	0.75-0.85

Land Use	C
Lawns:	
Sandy soil, flat, 2%	0.05-0.10
Sandy soil, ave., 2-7%	0.10-0.15
Sandy soil, steep, 7%	0.15-0.20
Heavy soil, flat, 2%	0.13-0.17
Heavy soil, ave., 2-7%	0.18-0.22
Heavy soil, steep, 7%	0.25-0.35
Agricultural land:	
Bare packed soil	
Smooth	0.30-0.60
Rough	0.20-0.50
Cultivated rows	
Heavy soil no crop	0.30-0.60
Heavy soil with crop	0.20-0.50
Sandy soil no crop	0.20-0.40
Sandy soil with crop	0.10-0.25
Pasture	
Heavy soil	0.15-0.45
Sandy soil	0.05-0.25
Woodlands	0.05-0.25

NOTE: The designer must use judgement to select the appropriate C value within the range for the appropriate land use. Generally, larger areas with permeable soils, flat slopes, and dense vegetation should have lowest C values. Smaller areas with slowly permeable soils, steep slopes, and sparse vegetation should be assigned highest C values.

Source: American Society of Civil Engineers

If the land use and soil cover is homogenous over the drainage area, a C value can be determined directly from the above Table. If there are multiple soil cover conditions, a weighted average must be calculated, or the area may be subdivided.

Runoff Coefficient for Rural Watersheds

	Extreme	High	Normal	Low
Relief - C_f	0.28-0.35 steep, rugged terrain with average slopes above 30%	0.20-0.28 hilly, with average slopes of 10-30%	0.14-0.20 rolling, with average slopes of 5-10%	0.08-0.14 relatively flat land, with average slopes of 0-5%
Soil Infiltration - C_i	0.12-0.16 no effective soil cover either rock or thin soil mantle of negligble infiltration capacity	0.08-0.12 slow to take up water, clay or shallow loam soils of low infiltration capacity or poorly drained	0.06-0.08 normal; well drained light or medium textured soils, sandy loams	0.04-0.06 deep sand or other soil that takes up water readily, very light well drained soils
Vegetal Cover - C_v	0.12-0.16 no effective plan cover, bare or very sparse cover	0.08-0.12 poor to fair; clean cultivation, crops or poor natural cover, less than 20% of drainage area over good cover	0.06-0.08 fair to good; about 50% of area in good grassland or woodland, not more than 50% of area in culitvated crops	0.04-0.06 good to excellent; about 90% of drainage area in good grassland, woodland, or equivalent cover
Surface - C_s	0.10-0.12 negligible; surface depression few and shallow, drainageways steep and small, no marshes	0.08-0.10 well defined system of small drainageways, no ponds or marshes	0.06-0.08 normal; considerable surface depression storage lakes and ponds and marshes	0.04-0.06 much surface storage, drainage system not sharply defined; large floodplain storage of large number of ponds or marshes

NOTE: The total runoff coefficient based on the four runoff components is $C = C_r + C_i + C_v + C_s$

Runoff

Example

A 20 ha (suburban area: 12 ha and woodland: 8 ha) catchment has an average slope of 3% and a maximum flow length of 400 m. What would be the peak runoff rate for a 10 mm/hr rainfall of 0.5 hr duration?

Solution:

For the catchment area of 20 ha, the calculated weighted average C is:

Suburban area C : 12 x 0.30 = 3.6

Woodland area C : 8 x 0.15 = 1.2

The weighted average C for the catchment is = 4.8/20 = 0.24

The time of concentration: $t_c = 0.0195\ L^{0.77}\ S^{-0.385}$

$= 0.0195\ (400)^{0.77}\ (0.03)^{-0.385} = 0.0195 \times (100.83) \times (3.857)$

= 7.58 minutes

Since the rainfall duration (0.5 hr) is greater than t_c, the peak runoff rate is: $Q_p = 0.278\ C\ i\ A = 0.278 \times 0.24 \times 10 \times 20/100 = 0.133$ cumec

Unit Hydrogarph

Unit Hydrograph (Gaged Basin)

The Unit Hydrograph (UH) of a watershed is defined as the **direct runoff (DRO)** hydrograph resulting from a unit volume of excess rainfall (1 cm) or **effective rainfall (ER) of constant intensity** and **uniformly distributed over the watershed**.

The **effective rainfall** is the portion of the rainfall which causes direct runoff. The direct runoff includes both the surface runoff and the interflow. But, as the interflow is usually small, the direct runoff and the surface runoff are approximately equal, and the two terms are sometimes used synonymously.

If the unit hydrograph can be developed for a watershed, then it is possible to find out the peak discharge for any amount of rainfall and for any duration for that particular watershed.

The duration of the unit volume of excess or effective rainfall, sometimes referred to as the effective duration, defines and labels the particular unit hydrograph (3-hr UH, 6-hr UH etc.). The 3, 6 here are not the duration for which the UH occurs (called base period), but it is the duration of the effective rainfall for which the UH is defined. Base period is the duration when UH/DRO occurs.

The unit volume is usually considered to be associated with 1 cm of effective rainfall distributed uniformly over the basin area.

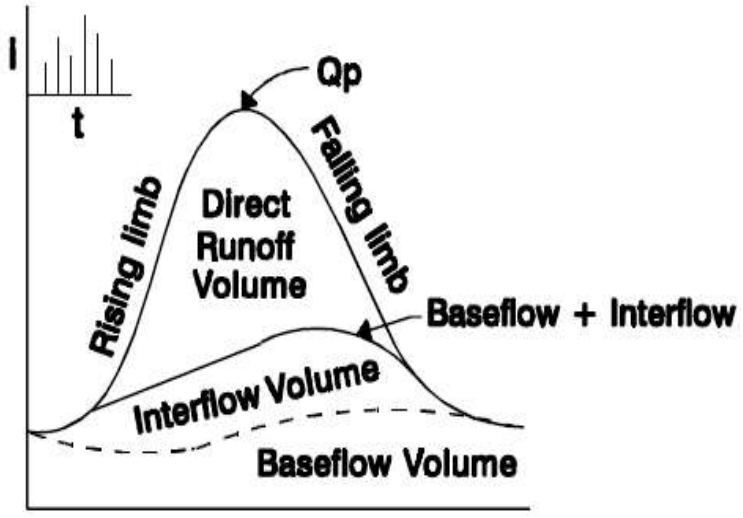
Effective Rainfall

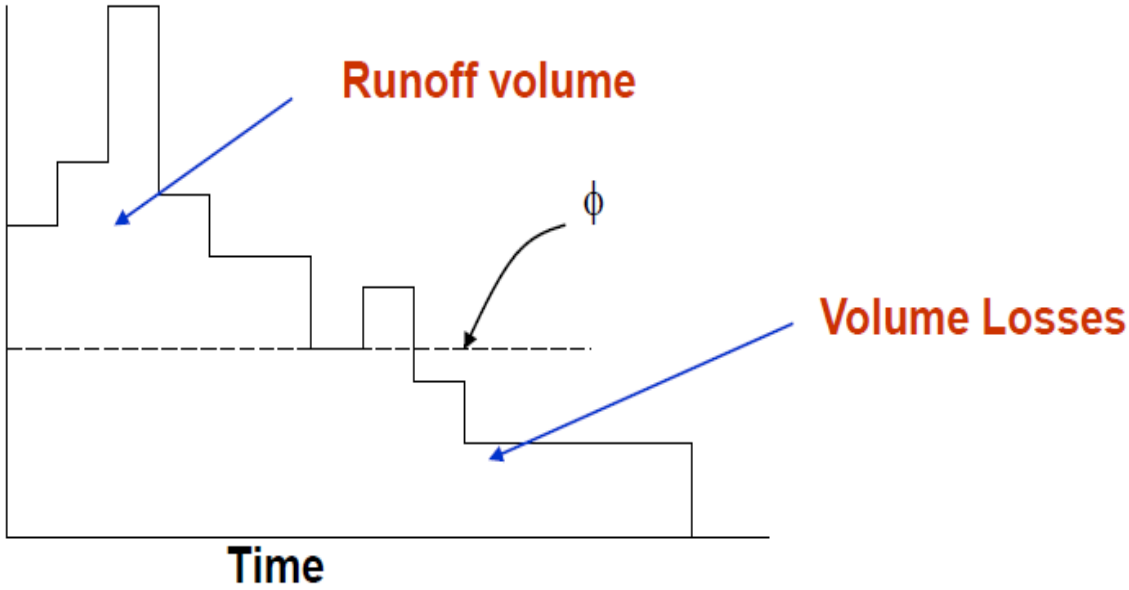
If the initial loss and infiltration losses are subtracted from the hyetograph, the resulting hyetograph is known as effective rainfall hyetograph (ERH). It is also known as hyetograph of rainfall excess. The Φ index separates the effective rainfall from the total rainfall.

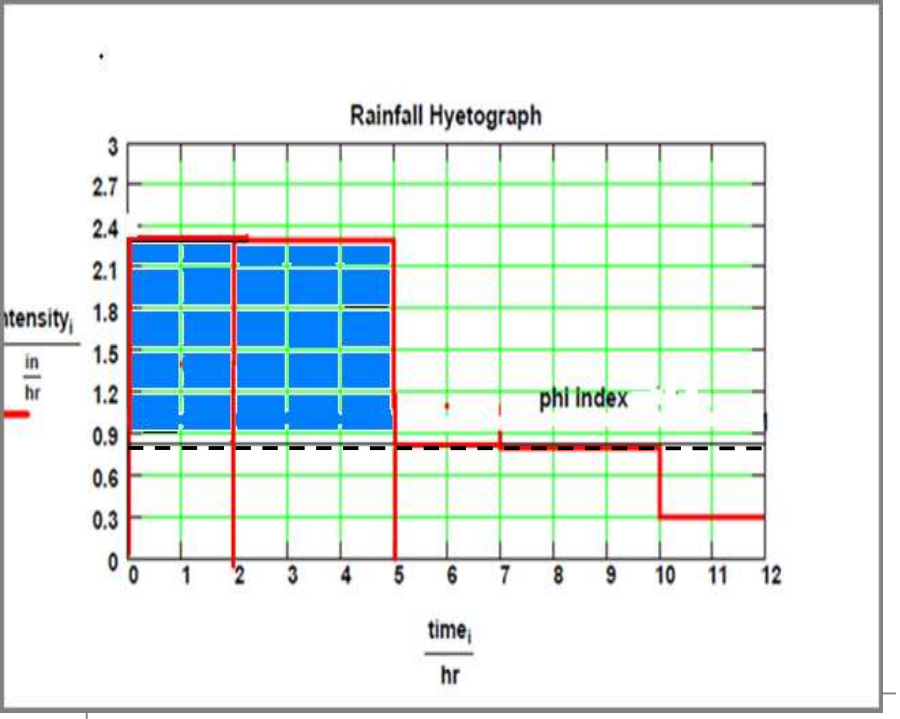
Both direct runoff (DRO) hydrograph and ERH represent the same total quantity of rainfall. The area of ERH multiplied by the catchment area gives the total volume of the direct runoff (total area of DRO hydrograph).

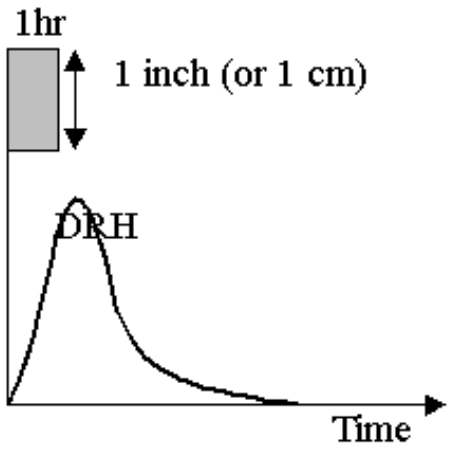
Purpose of Unit Hydrograph (UH)

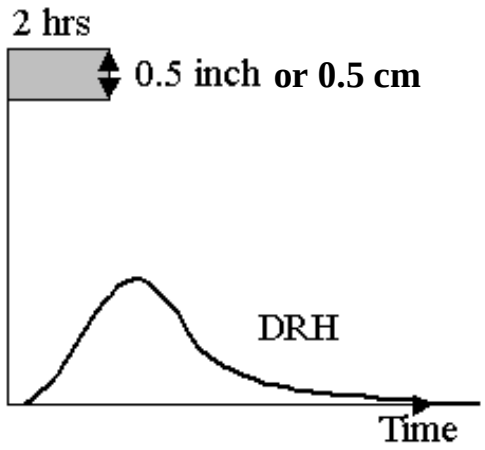
1. Develop hydrograph of any amount of rainfall
2. Convert UH of one duration to any another duration
3. Develop hydrograph of complex storm

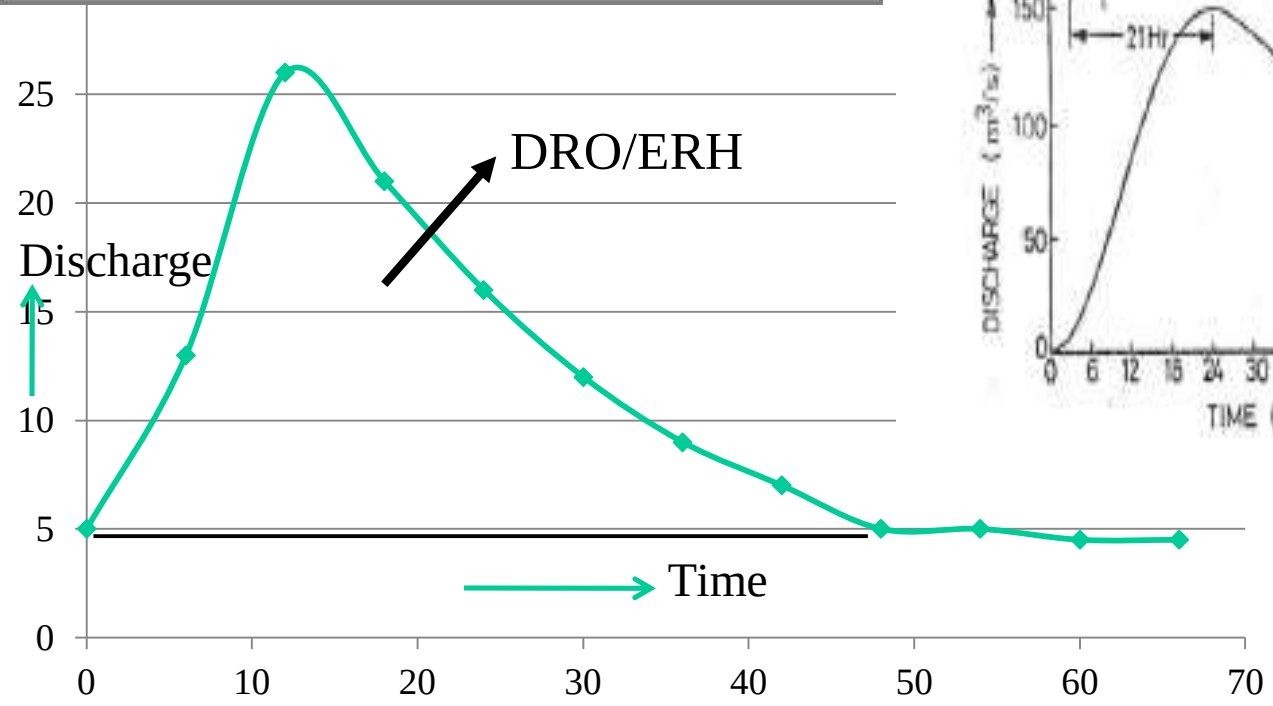


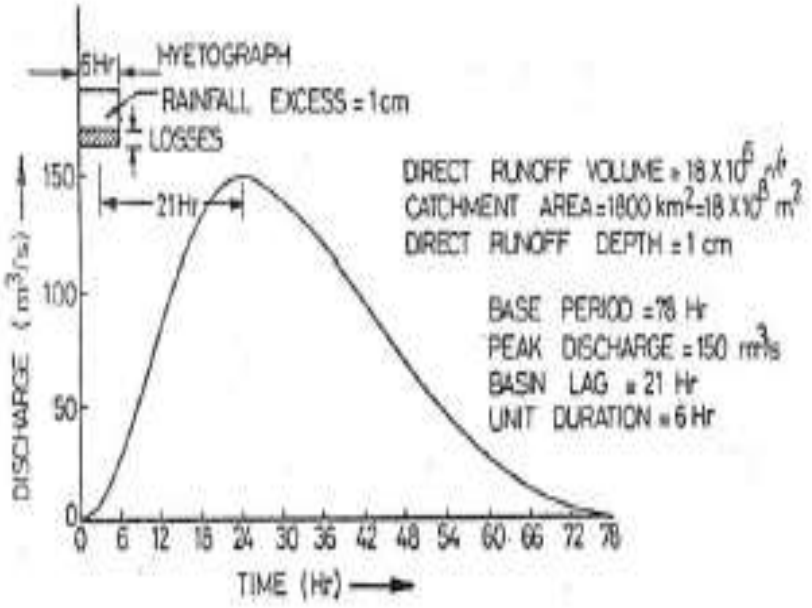



Rainfall Hyetograph
phi index
time
hr


1hr
1 inch (or 1 cm)
DRH
Time


2 hrs
0.5 inch or 0.5 cm
DRH
Time


DRO/ERH
Discharge
Time


6Hr
HYETOGRAPH
RAINFALL EXCESS = 1cm
LOSSES
21Hr
DIRECT RUNOFF VOLUME = 18 X 10^6 m^3
CATCHMENT AREA = 1800 km^2 = 18 X 10^8 m^2
DIRECT RUNOFF DEPTH = 1 cm
BASE PERIOD = 78 Hr
PEAK DISCHARGE = 150 m^3/s
BASIN LAG = 21 Hr
UNIT DURATION = 6 Hr
DISCHARGE (m^3/s)
TIME (Hr)

Unit Hydrogarph

Assumptions

There are four basic propositions of the unit hydrograph theory:

(i) Constant intensity and uniform distribution of effective rainfall

(ii) Time invariance

(iii) Linearity of response, and

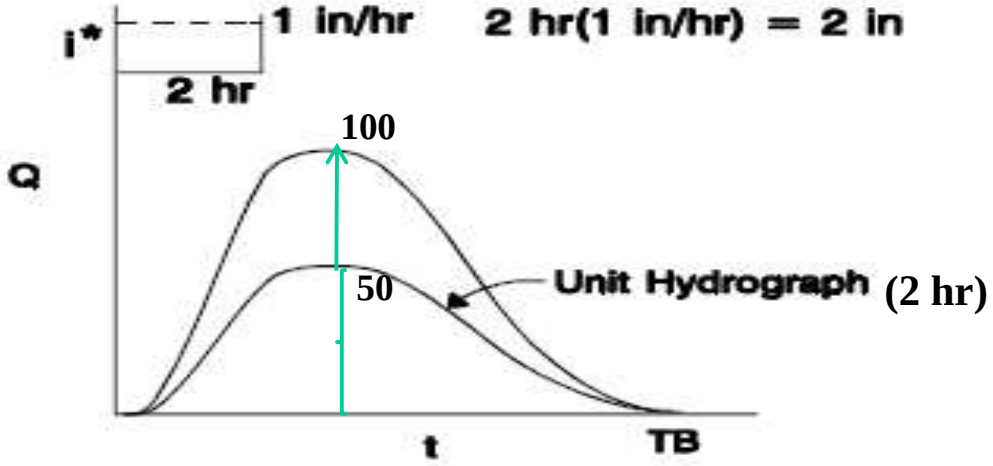
(iv) Fixed base period

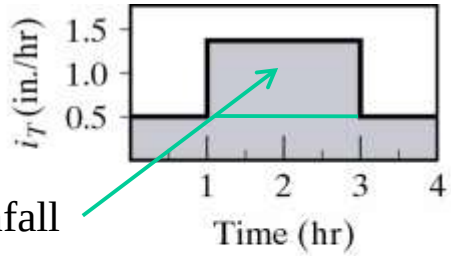
Constant intensity and uniform distribution of effective rainfall: The effective rainfall has a constant intensity within the effective duration. Moreover, the effective rainfall is uniformly distributed over the whole watershed.

Time invariance: It means that the direct runoff hydrograph does not depend upon the time when the storm occurs. In other words, the direct runoff hydrograph for a given effective rainfall of unit duration will be the same whenever such storm occurs on the catchment.

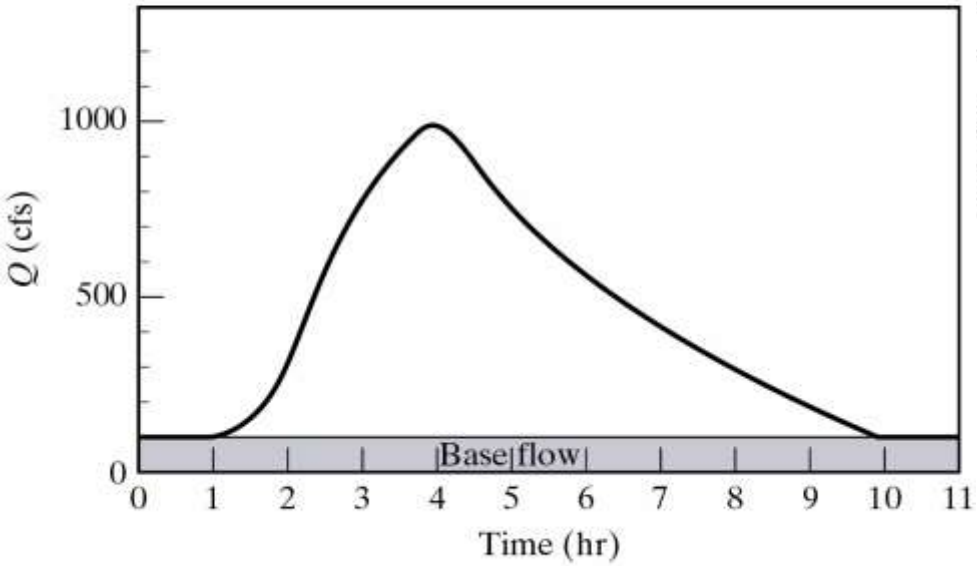
Linearity of response : It means that the relation between the direct runoff discharge and the effective rainfall is linear. Therefore, **the principle of superposition** can be applied. Thus, if the effective rainfall is 2 cm, all the discharge ordinates of the unit hydrograph would be doubled.

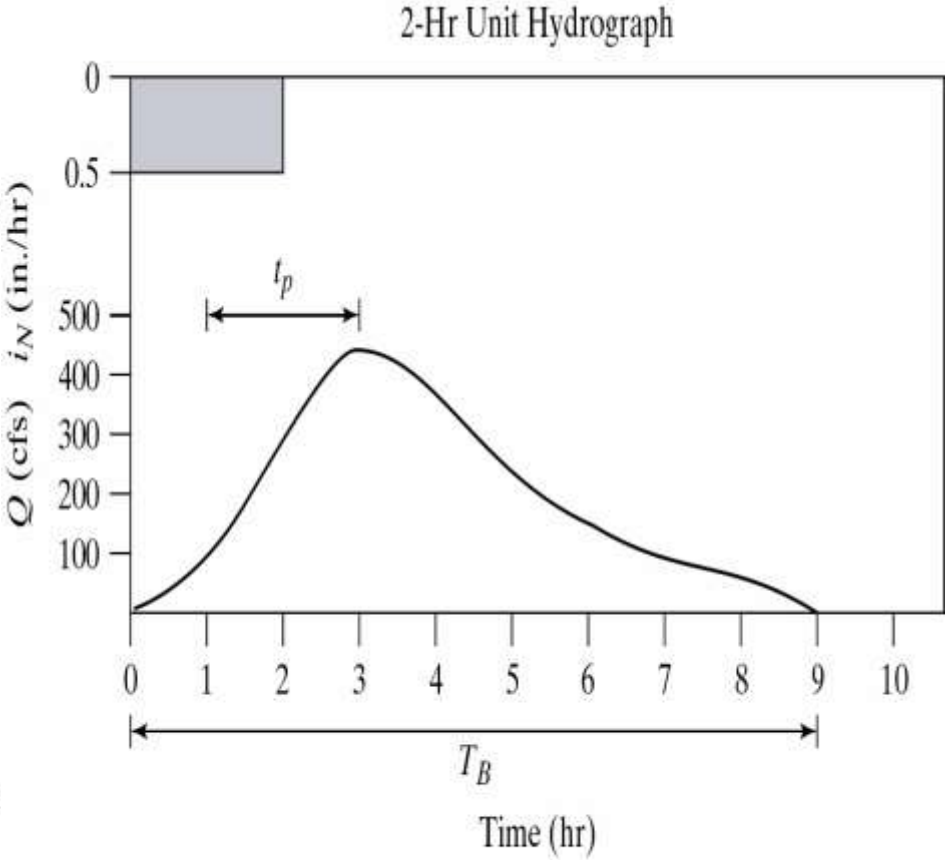
Fixed base period : The period during which the direct runoff occurs is called the base period. The base period of the direct runoff hydrograph remains the same whatever may be the magnitude of the effective rainfall, provided the duration of the unit rainfall remains the same.





Effective rainfall





Limitations of Unit Hydrograph

In theory, the principle of unit hydrograph is applicable to a basin of any size. However, in practice, to meet the basic assumption in the derivation of the unit hydrograph as closely as possible, the limit is generally considered to be about 5000 sq. km. beyond which the reliability of the unit hydrograph method diminishes.

When the basin area exceeds this limit, it has to be divided into sub-basins and the unit hydrograph is developed for each sub-basin.

UH concept is not valid for very large basins because:

1. Rainfall is never uniformly distributed over large basins
2. Except for small durations, the rainfall is never uniformly distributed over the total duration.
3. Antecedent soil moisture condition would affect the amount of direct runoff.

Thus, it is essential to use storms which are uniformly distributed over the basin and producing rainfall excess at uniform rate as such storms rarely occur over large areas.

However, when the hydrologic data used in the unit hydrograph analysis are carefully selected so that they meet the assumptions closely, the results obtained by the unit hydrograph theory have been found to be acceptable for all practical purposes.

Unit Hydrograph

Derivation of Unit Hydrograph

The following steps are applied for deriving the UH from each individual storm hydrograph:

1. Separation of the measured hydrograph into direct runoff hydrograph and baseflow.
2. Calculation of direct runoff volume by integrating the direct runoff hydrograph.
3. Calculation of direct runoff depth by dividing the direct runoff volume by the catchment area.
4. Calculation of unit hydrograph ordinates by dividing the ordinates of the direct runoff hydrograph by the direct runoff depth.
5. Estimation of the unit hydrograph duration.

The ordinates of all hydrographs from identical rainfalls of the same duration are proportional to the volume of rainfall-excess. That is, if unit hydrographs were obtained from a 2 cm and 3 cm rainfall excess by dividing ordinates of each hydrographs by 2 and 3, respectively, the unit hydrographs would be identical in shape.

Example: The following runoff from a 6 hr rainfall was recorded on a 4300 km^2 watershed. Find the unit hydrograph. **What is the peak flow from 6 hr of 30 cm of rainfall?**

Date	Hour	Total flow m^3/s	B
Feb 16	0600	500	
	0800	5600	
	1000	9200	
	1200	10100	
	1400	7800	
	1600	6600	
	1800	5550	
	2000	4700	
	2200	4000	
	2400	3300	
Feb 17	0200	2700	
	0400	2300	
	0600	1950	
	0800	1650	
	1000	1400	
	1200	1200	
	1400	1000	
	1600	800	

Date	Hour	Total flow m^3/s	Base flow m^3/s
Feb 16	0600	500	500
	0800	5600	450
	1000	9200	400
	1200	10100	400
	1400	7800	450
	1600	6600	450
	1800	5550	500
	2000	4700	550
	2200	4000	600
	2400	3300	600
Feb 17	0200	2700	600
	0400	2300	650
	0600	1950	650
	0800	1650	700
	1000	1400	700
	1200	1200	750
	1400	1000	750
	1600	800	800

Base flow separation:

1. By any method
2. Data given (may be a constant value)

Date	Hour	Total flow	Base flow	DRO	6hr UHG	6hr DRO for 30 cm
		m^3/s	m^3/s		(divided by 10)	x 30
Feb 16	0600	500	500	0	0	0
	0800	5600	450	5150	515	15450
	1000	9200	400	8800	880	26400
	1200	10100	400	9700	976	29100
	1400	7800	450	7350	735	22050
	1600	6600	450	6150	615	18450
	1800	5550	500	5050	505	15150
	2000	4700	550	4150	415	12450
	2200	4000	600	3400	340	10200
	2400	3300	600	2700	270	8100
Feb 17	0200	2700	600	2100	210	6300
	0400	2300	650	1650	165	4950
	0600	1950	650	1300	130	3900
	0800	1650	700	950	95	2850
	1000	1400	700	700	70	2100
	1200	1200	750	450	45	1350
	1400	1000	750	250	25	750
	1600	800	800	0	0	0

				59850		



Total volume of flow = 59850 m^3/s x 2 hrs = 59850 m^3/s x 2 x 3600 s

= 430.9 x 10^6 m^3

Area of catchment = 4300 km = 4300 x 100 ha = 4300 x 100 x 10000 m^2

= 4300 x 10^6 m^2

Effective rainfall per unit area = 430.9 x 10^6 / 4300 x 10^6 = 0.1 m = 10 cm

To obtain 1 cm i.e. 1 unit hydrograph, divide DRO column ordinates by 10.

If 6 hr DRO for 30 cm is required, multiply UHG ordinates by 30.

