Engineering Hydrology

Week-4

CHAPTER -2 RAINFALL-RUNOFF RELATIONSHIPS

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Lecture contents of the last week (week-3)

CHAPTER -2 Rainfall-runoff Relationships

2.1 Hydrological Models

2.2 Rational Method

2.3 Rainfall intensity and Time of Concentration

Home assignment:

I hope you are sure you area able to exercise on:

1. Hydrological modeling: definition, importance and classification

2. Rainfall: Intensity, duration, frequency, effective rainfall and time of concentration

3. Rational method: symbols, units and problem analysis

Lecture contents of the week (Week-4)

CHAPTER -2 RAINFALL-RUNOFF RELATIONSHIPS

2.4 SCS Curve Number and Time-Area Methods

2.5 Stream Flow Hydrograph

2.5.1 Hydrograph

2.5.2 Factors Affecting Flood Hydrograph

2.5.3 Effective Rainfall

2.5.4 Separation of Base Flow and Runoff

Lecture Learning Outcomes

Course Learning Outcomes: After completion of this Lecture, you will be able to:

CLO-1: Apply measurement techniques of the components of the hydrologic cycle, water balance and filling of missed data;

CLO-2: Examine rainfall-runoff relationship and hydrograph;

- **Describe hydrographs**
- **Examine SCS-CN and indices runoff estimations**
- **Describe base flow separations**

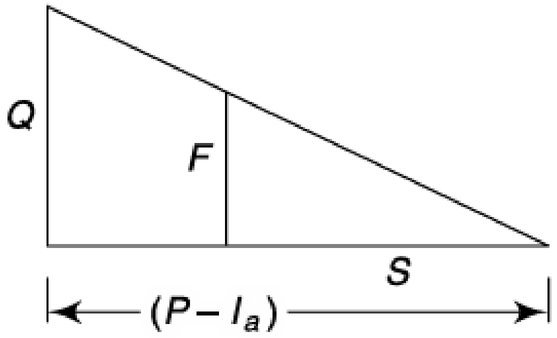
CLO-3: Examine the probability of occurrence;
CLO-4: Analyze the water movement in to, over, and through the soil surface;
CLO-5: Design capacity of reservoir;
CLO-6: Design runoff volume and time of distribution of the runoff hydrograph from urbanization effect.

SCS Curve Number

- It is generated by United State Department of Agriculture Soil Conservation Service (USDA-SCS) for estimating **yield** and **peak** rate of runoff to be applicable to small drainage area in the United State.
- For the simple storm the relation between rainfall, runoff, and retention at any point on the mass curve can be expressed as:

$$\frac{Q}{(P - I_a)} = \frac{F}{S}$$

where, $P = Q + I_a + F$



I_a = the initial abstraction on the surface

F = Actual retention **after runoff begin** (the additional loss occurred after runoff begins), or soil **infiltration**.

S =Potential maximum retention (after runoff begins, F increases with increasing rainfall up to some maximum retention S) or soil storage

Q = Actual runoff (excess rain fall, effective rain)

P = Rainfall

$$I_a = 0.2S$$

SCS Curve Number

- When substituted for I_a in the equation resulted in the more familiar equation as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad S = \frac{1000}{CN} - 10$$

where,

CN =Curve number is a parameter that combines **soil type** and **land use** to estimate runoff potential, based on the Hydrologic Soil Group (HSG), land use and condition.

CN ranges between 0 and 100.

- The greater the curve number, the lower the retention and the greater the potential for runoff.
- Impervious areas and water surfaces are assigned curve numbers of 98-100.

SCS Curve Number

Hydrologic Soil Groups

- SCS classified more than 4,000 soils into four general HSG (A, B, C, and D)
- Based on soils minimum infiltration rate when the soil is bare and after prolonged wetting.
  - A have the highest infiltration capacity and lowest runoff potential (sandy soils) and
  - D have lowest infiltration rates and highest runoff potential(clay soils)

HSG	*Soil textures*
A	Sand, loamy sand, or sandy loam
B	Silt loam or loam
C	Sandy clay loam
D	Clay loam, silty clay loam, sandy clay, silty clay, or clay

SCS Curve Number

Land Use	Cover: Treatment or practice	Cover: Hydrologic condition	Hydrologic soil group: A	B	C	D
Cultivated	Straight row		76	86	90	93
Cultivated	Contoured	Poor	70	79	84	88
		Good	65	75	82	86
Cultivated	Contoured &	Poor	66	74	80	82
	Terraced	Good	62	71	77	81
Cultivated	Bunded	Poor	67	75	81	83
		Good	59	69	76	79
Cultivated	Paddy		95	95	95	95
Orchards	With understory cover		39	53	67	71
	Without understory cover		41	55	69	73
Forest	Dense		26	40	58	61
	Open		28	44	60	64
	Scrub		33	47	64	67
Pasture	Poor		68	79	86	89
	Fair		49	69	79	84
	Good		39	61	74	80
Wasteland			71	80	85	88
Roads (dirt)			73	83	88	90
Hard surface areas			77	86	91	93

Source: Textbook, (Subramanya, 2008)

Hydrologic Soil Groups

Land Use and Condition;

- **Good condition** refers to areas for more potential for infiltration and less for runoff.

SCS Curve Number

Antecedent Moisture Conditions

- Runoff potential is dependent on antecedent moisture conditions so CN is dependent on that.
- The CN in the table are for antecedent moisture condition II which is **average soil moisture conditions** CN(II).
- CN(I) is used when there has been very little rainfall proceeding the rainfall in question (**dry soil**).
- CN(III) is used when there has been considerable rainfall before the rainfall in question (**wet soil**).

$$CN(I) = \frac{4.2CN(II)}{10 - 0.058CN(II)}$$

$$CN(III) = \frac{23CN(II)}{10 + 0.13CN(II)}$$

SCS Curve Number

Example 5:

Compute the runoff from 5 inches of rainfall on a 1000-acre watershed.

- The hydrologic soil group is 50 % Group B and 50 % Group C interspersed throughout the watershed.
- Antecedent moisture condition II is assumed.
- The land use is:
  - 40 % residential area that is 30 % impervious
  - 12 % residential area that is 65 % impervious
  - 18 % paved roads with curb sand storm sewers
  - 16 % open land with 50 % fair grass cover and 50 % good grass cover
  - 14 % parking lots, plazas ,schools, and so on (all im pervious)

SCS Curve Number

Given:

Land Use	Hydrologic soil group B %	B CN	B Product	Hydrologic soil group C %	C CN	C Product
Residential (30% impervious)	20	72	1440	20	81	1620
Residential (65% impervious)	6	85	510	6	90	540
Roads	9	98	882	9	98	882
Open land: Good cover	4	61	244	4	74	296
Fair cover	4	69	276	4	79	316
Parking lots, etc	7	98	686	7	98	686
	50		4038	50		4340

SCS Curve Number

Required:

Effective RF or RO

Solution:

$$\text{Weighted CN} = \frac{4038 + 4340}{100} = 83.8$$

$$S = \frac{1000}{CN} - 10$$

$$= \frac{1000}{83.8} - 10$$

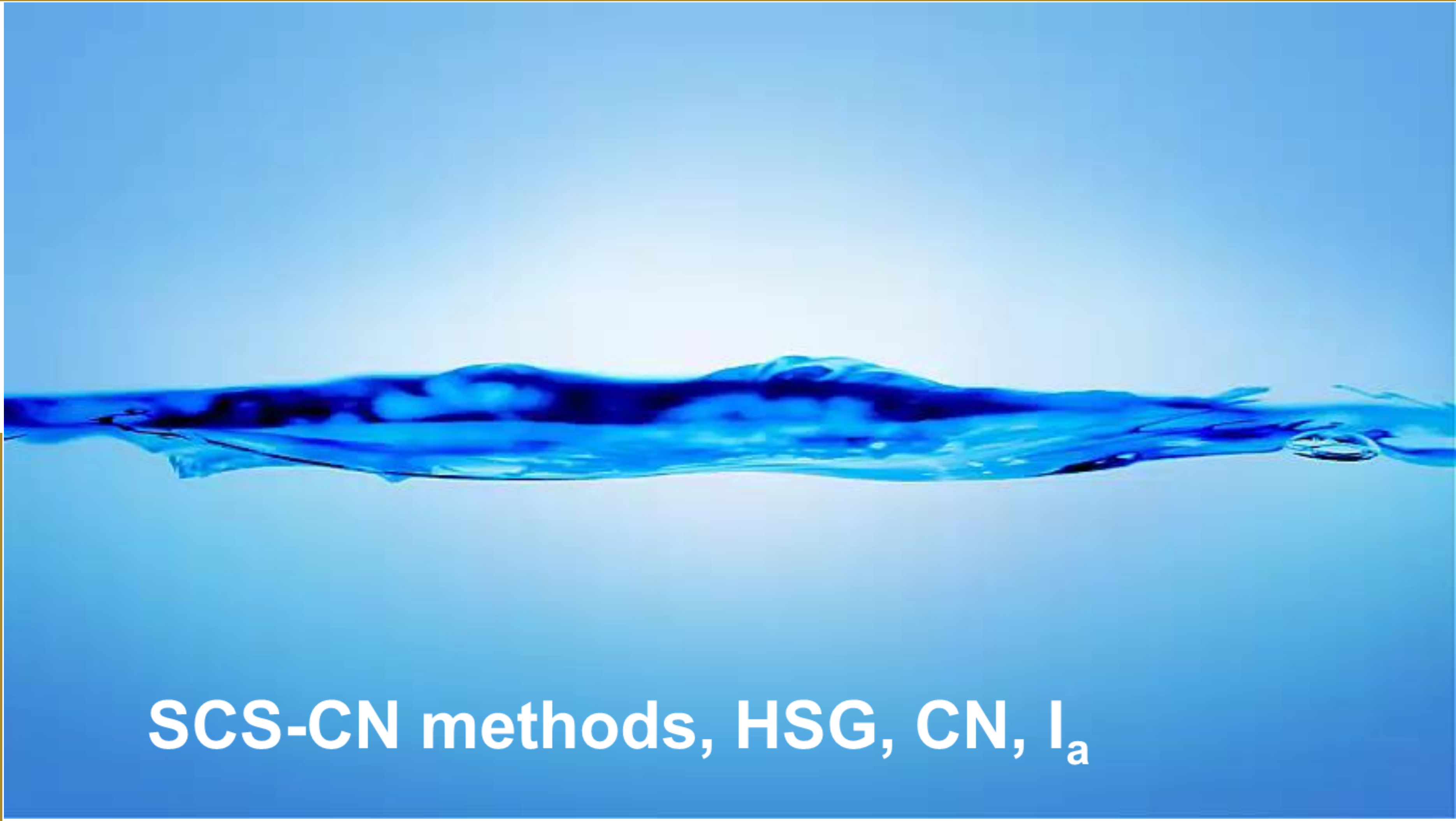
$$= 1.93 \text{ in}$$

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

$$= \frac{(5 - 0.2 \times 1.93)^2}{5 + 0.8 \times 1.93}$$

$$= 3.25 \text{ in}$$

Break:-
rehearsal on:



SCS-CN methods, HSG, CN, I_a

Rainfall-Runoff Correlation

- Plotting of R values against P and drawing a best fit line can adopted for very rough estimates.
  - A better method is to fit a linear regression line between R and P and to accept the result if the correlation coefficient is **nearer unity**.
  - The equation for straight-line regression between runoff R and rainfall P is:

$$\boldsymbol{R = a * P + b}$$

- the values of the coefficients a and b are given by:
- $$\boldsymbol{a = \frac{N(\Sigma PR) - (\Sigma P)(\Sigma R)}{N(\Sigma P^2) - (\Sigma P)^2}} \qquad \boldsymbol{b = \frac{\Sigma R - a\Sigma P}{N}}$$
  - in which N = number of observation sets R and P.

Rainfall-Runoff Correlation

- The coefficient of correlation r can be calculated as:

$$\boldsymbol{r = \frac{N(\Sigma PR) - (\Sigma P)(\Sigma R)}{\sqrt{[N(\Sigma P^2) \rightleftarrows -(\Sigma P) \rightleftarrows^2]} \times [N(\Sigma R^2) - (\Sigma R)^2]}}$$

- The value of r lies between 0 and 1 as R have only positive correlation with P.
- A value of $0.6 < r < 1.0$ indicates good correlation. Further it should be noted that $R \geq 0$.
- For large catchment, it is found advantageous to have an exponential relationship as: $\boldsymbol{R = \beta P^m}$

Infiltration Indices (index)

- a number of techniques are available for separating the losses from a rainfall hyetograph,
- The average infiltration (called infiltration indices) method is the simplest and the most popular technique.
- Two types of indices are in common use:
  - 1) ***Φ***-index
  - 2) ***W***-index
- ***Φ***- Index: is the average rainfall above which the excess rainfall value is equal to **the runoff volume** or the average (constant) value of losses per time duration.
- The amount of rainfall in excess of the index is called **rainfall excess (effective rainfall).**
- The initial losses are also considered as infiltration.

Infiltration Indices (index)

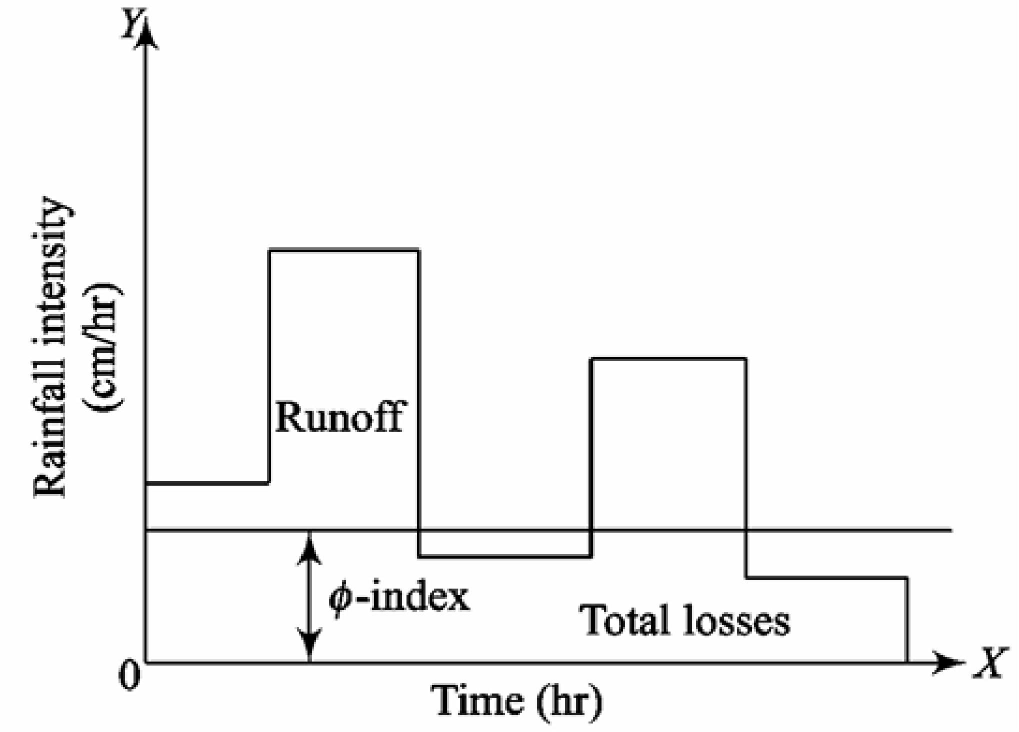
***Φ*- Index:**

- If the rainfall intensity is less than Φ, then the infiltration rate is equal to the rainfall intensity.
- Mathematically, the Φ-index can be expressed as:

$$\emptyset = \frac{P-R}{t_e}$$

where,

- ***P*** = total storm precipitation (mm or cm)
- ***R*** = total direct surface runoff (mm or cm)
- t_e= duration of the excess rainfall, ie., the total time in which the total intensity is greater than ∅ (in hours), and
- ∅ = uniform rate of infiltration (mm/hr or cm/hr)



Source: Textbook, (Ojha et al, 2008)

***Example 5, Φ*- Index:**

- A storm with 10 cm precipitation produced a direct surface runoff of 5.8 cm in the equivalent depth unit. The time distribution of the storm is given in the Table. Estimate the ***Φ***-index of the storm and the excess rainfall hyetograph.

Time from start (hr)	1	2	3	4	5	6	7	8
Incremental rainfall in each hour (cm)	0.4	0.9	1.5	2.3	1.8	1.6	1.0	0.5

Infiltration Indices (index)

***Example 5, Φ*- Index:**

Given: P=10 cm, R=5.8 cm, and hyetograph

Total infiltration = Total rainfall - Direct surface runoff = 10 - 5.8 = 4.2 cm

Required:

- Φ-index of the storm and
- the excess rainfall hyetograph.

Solution:

1. Assume duration of the excess rainfall (t_e) is equal to the total duration of the storm for the first trial, i.e., t_e = 8 hr
2. Compute the trial value of ***Φ*** as: $\phi=(P-R)/t_e = 4.2\,cm/8\,hr = 0.525\,cm/hr$
3. Compare the above ***Φ*** value with individual blocks of rainfall.

Infiltration Indices (index)

***Example 5, Φ*- Index:**

Solution:

4. The ***Φ*** value makes the rainfall of the first hour and the eighth hour ineffective as their magnitudes are less than 0.525 cm/hr. Therefore, value oft, is modified.
5. Assume t_e= 6 hour in the second trial and modified value of ***total rainfall*** for 6 hour duration will be 10 - (0.4 + 0.5) = 9.1 cm
6. Compute a modified value of infiltration, i.e., infiltration = 9.1- 5.8 = 3.3 cm
7. Compute second trial value of ***Φ***, i.e., ***Φ*** = 3.3/6= 0.55 cm/hr.
8. This value of ***Φ*** is satisfactory as it gives t_e = 6 hr
9. Calculate the excess rainfall, subtracting the uniform loss from each block.
10. The excess rainfall hyetograph is given below:

Time from start (hr)	1	2	3	4	5	6	7	8
Excess rainfall (cm)	0	0.35	0.95	1.75	1.25	1.05	0.45	0

Infiltration Indices (index)

W - Index: an average value of infiltration rate **treating the initial losses** separately called the W- index is defined as:

$$W = \frac{P - R - I_a}{t_e} = \frac{P - R}{t_e} - \frac{I_a}{t_e} = \emptyset - \frac{I_a}{t_e}$$

where, P = total storm precipitation (cm)

R = total storm runoff (cm)

I_a = initial losses (cm)

t_e = duration of the rainfall excess i.e. the total time in which the rainfall intensity is greater than W (in hours) and

W = average rate of infiltration (cm/h)

Effective Rainfall

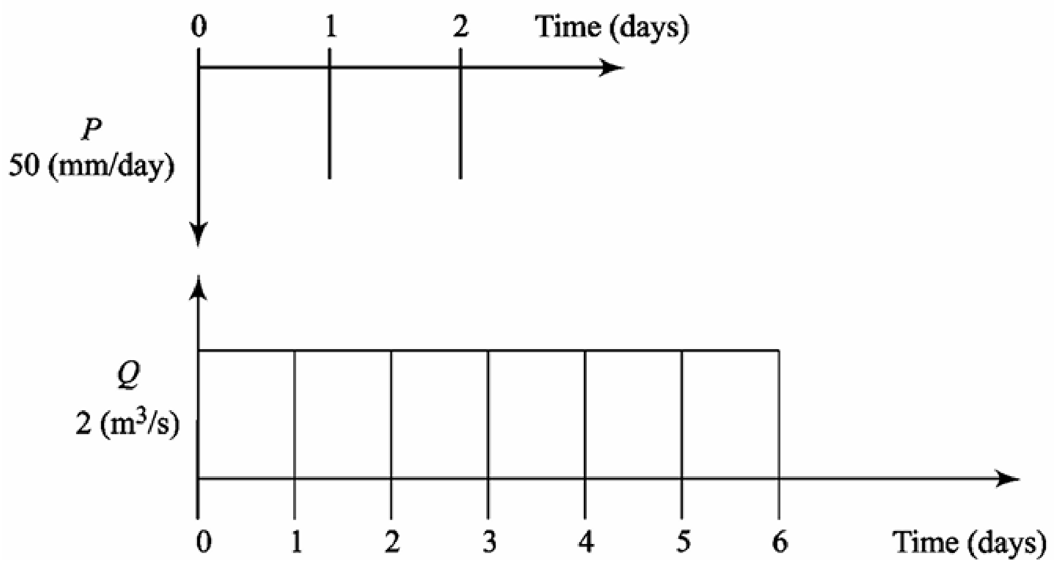
Example 5:

Over a period of two days, (50 + 50) mm rain fell over a catchment (A = 50 km^2). The runoff in the water course draining the area was Q = 0 at the start of rainfall; and over six days, Q_{mean}= 2 m^3/s; and thereafter Q = 0 again. Answer the following questions:

(a) How large was the effective rainfall (in mm)?

(b) How large were the total losses from the total precipitation (in mm)?

(c) What is the value of $\emptyset_{index}$(in mm/day)?



Source: Textbook, (Ojha et al, 2008)

Effective Rainfall

Given:

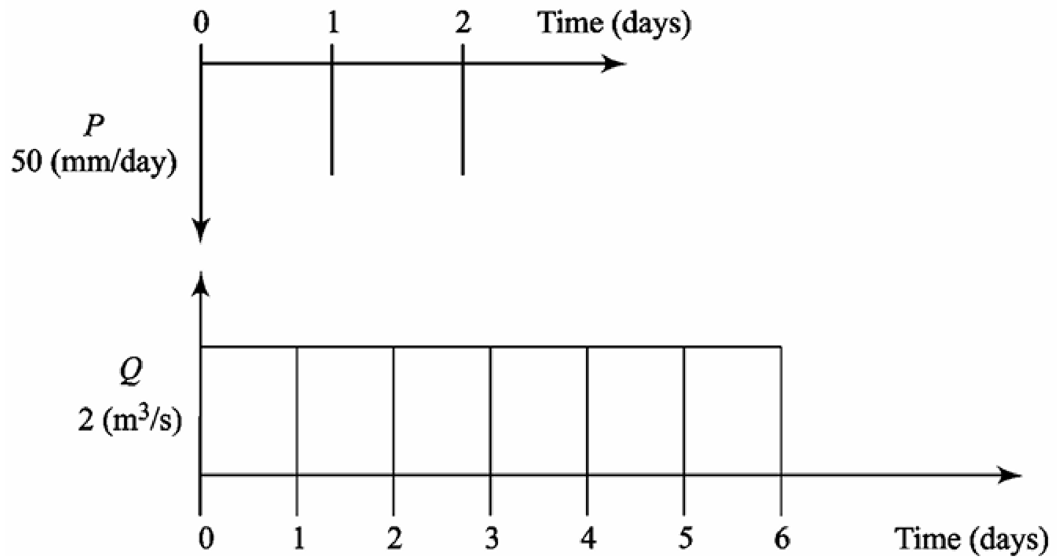
- P_{total} =50 mm + 50 mm=100 mm
- A = 50 km^2
- $Q_{initial} = Q_{final}$=0, $Q_{total} - Q_{base\ flow}$=0;
- Q_{mean}= 2 m^3/s over six days;

Require:

(a) $P_{effective}$ (in mm)?

(b) $\emptyset_{index}$ (in mm)?

(c) $\emptyset_{index}$ (in mm/day)?



Effective Rainfall

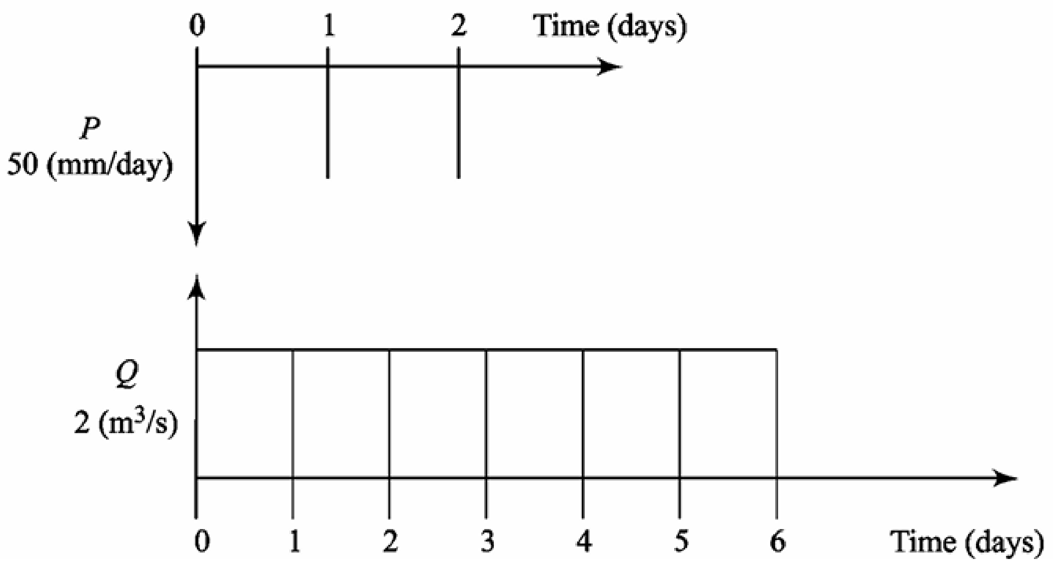
Solution:

(a) the effective rainfall per unit area is given by:

$$\boldsymbol{P_{effective}} = Q_{direct} = Q_{Mean} * 6days$$

$$= 2\frac{m3}{s} * 6days * 24\,\frac{hrs}{day}\; x\; 60\frac{min}{hr}\, x\; 60\,\frac{s}{min}$$

$$= \;\boldsymbol{1.0368\; x\; 10^{6}\; m^{3}}\;\; \boldsymbol{........\#}$$



- The effective rainfall per unit area, $P_{effective}$ (in mm), is given by:
- $\boldsymbol{P_{effective}} = Q_{direct}/A \;\; = \frac{1.0368\; x\; 10^{6}\; m^{3}}{50km^{2} * \frac{10^{4}m^{2}}{km^{2}}} = 0.0207\; m$

$$= \;\boldsymbol{20.7\; mm}\;\; \boldsymbol{......\#}$$

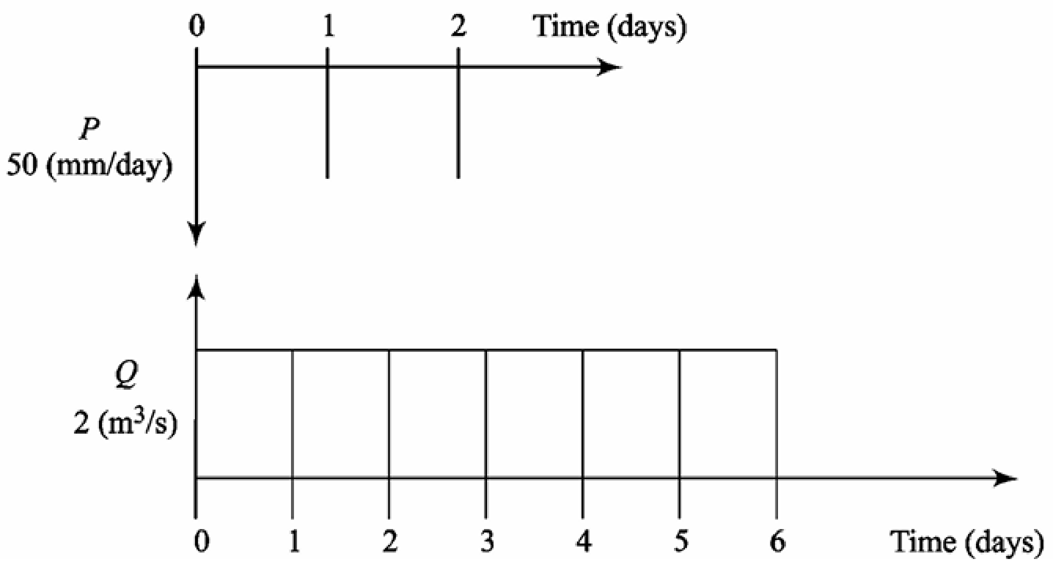
Effective Rainfall

Solution:

(b) The total losses, $\emptyset_{index}$ (in mm), were is given by:

$$\emptyset_{index} = P_{total} - P_{Eective}$$

$$= (100 - 20.7)\,mm = \underline{\underline{\mathbf{79.3\,mm}}}........\#$$



(c) $\emptyset_{index}$ (in mm/day)= total losses/days

$$\frac{79.3\,mm}{2\,days} = \underline{\underline{\mathbf{39.7\frac{mm}{day}}}}\,.......\#$$

Break:
Rehearse on:

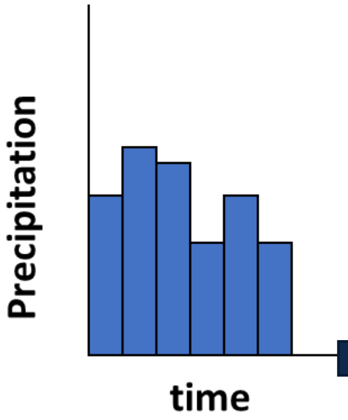
Stream Flow Hydrograph

Hyetograph:

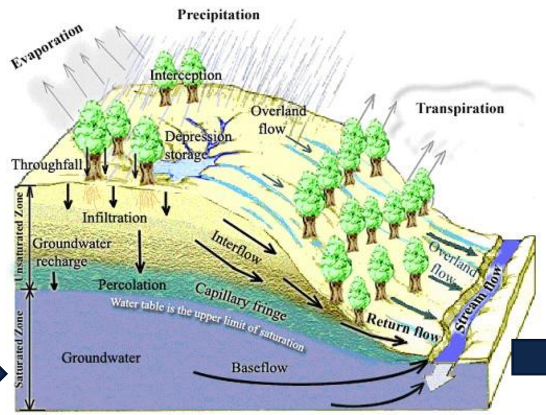
- The graph that plots the rainfall over the basin along a time scale

Hydrograph:

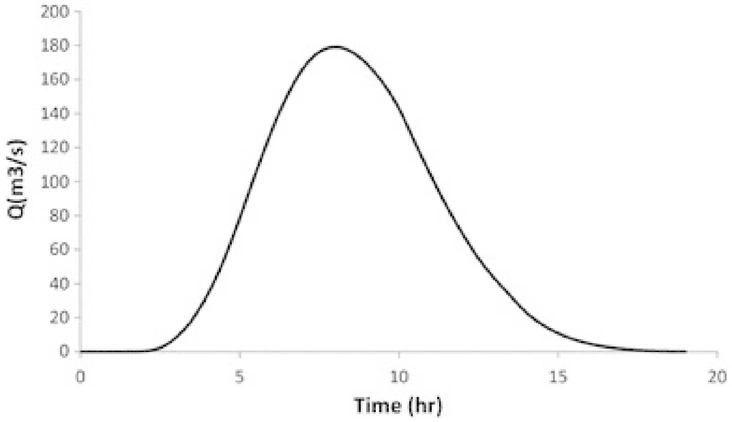
- is a graphical plot of discharge of a natural stream or river versus time



Hyetograph



Hydrologic Model



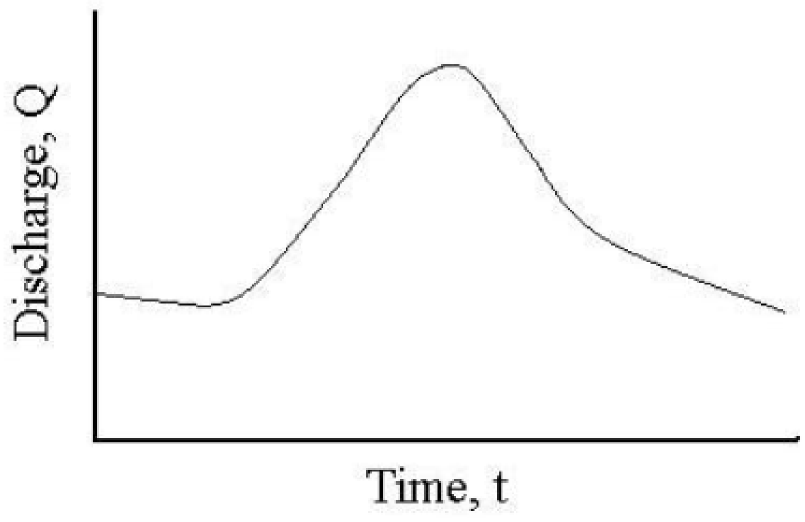
Hydrograph

Source: Schematic of runoff generation mechanism (Chalise, 2013)

Stream Flow Hydrograph

Hydrograph analysis:

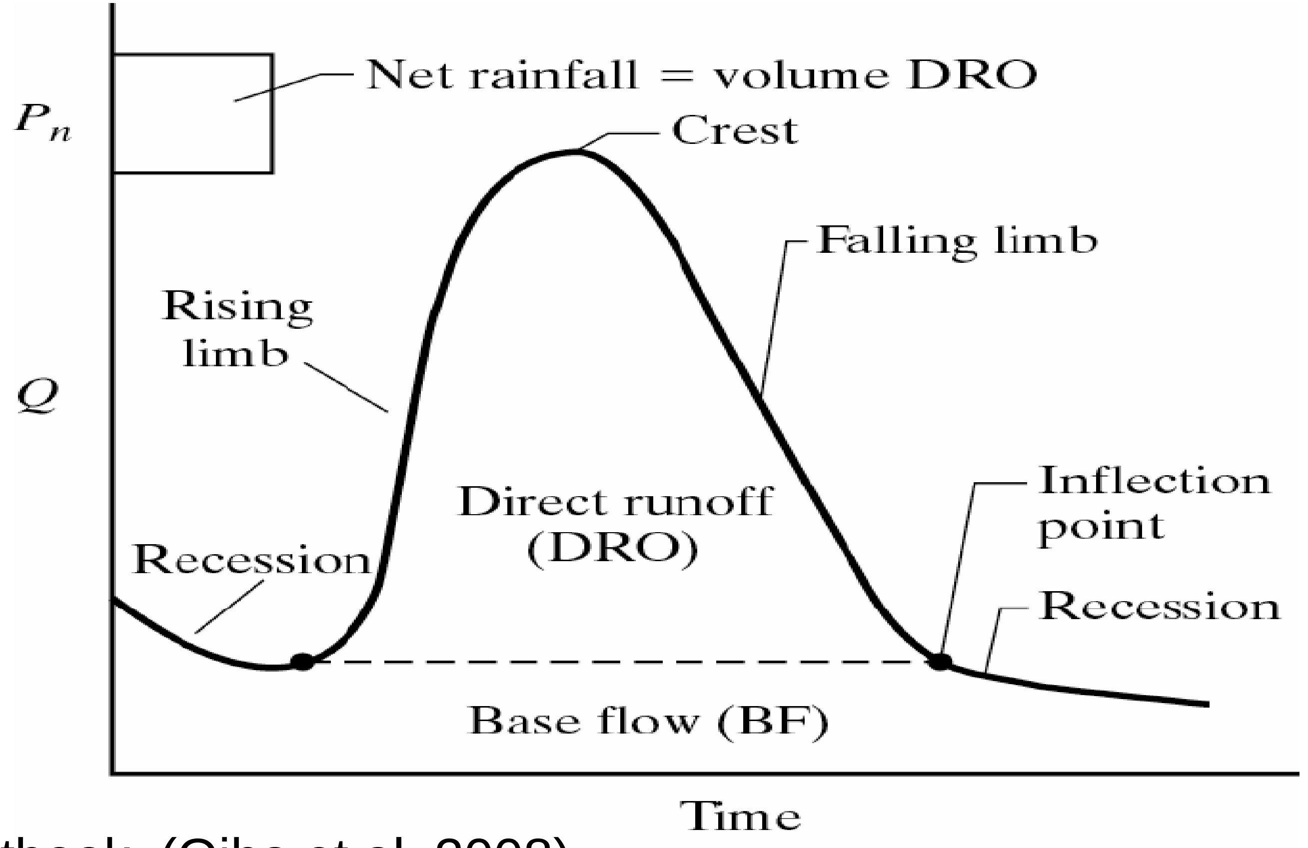
- is used to produce **rainfall-runoff** relationships for a catchment area.
- Hydrograph describes the **whole time history** of the changing rate of flow from a catchment due to rainfall event rather than predicting only the peak flow.



Stream Flow Hydrograph

Component of hydrograph:

- The rising limb,
- The crest(peak) segment ,
- The falling limb,
- The depletion (recession) curve.
  - Total recession
  - Base flow recission
- The Surface runoff, and
- The Base flow



Source: Textbook, (Ojha et al, 2008)

Stream Flow Hydrograph

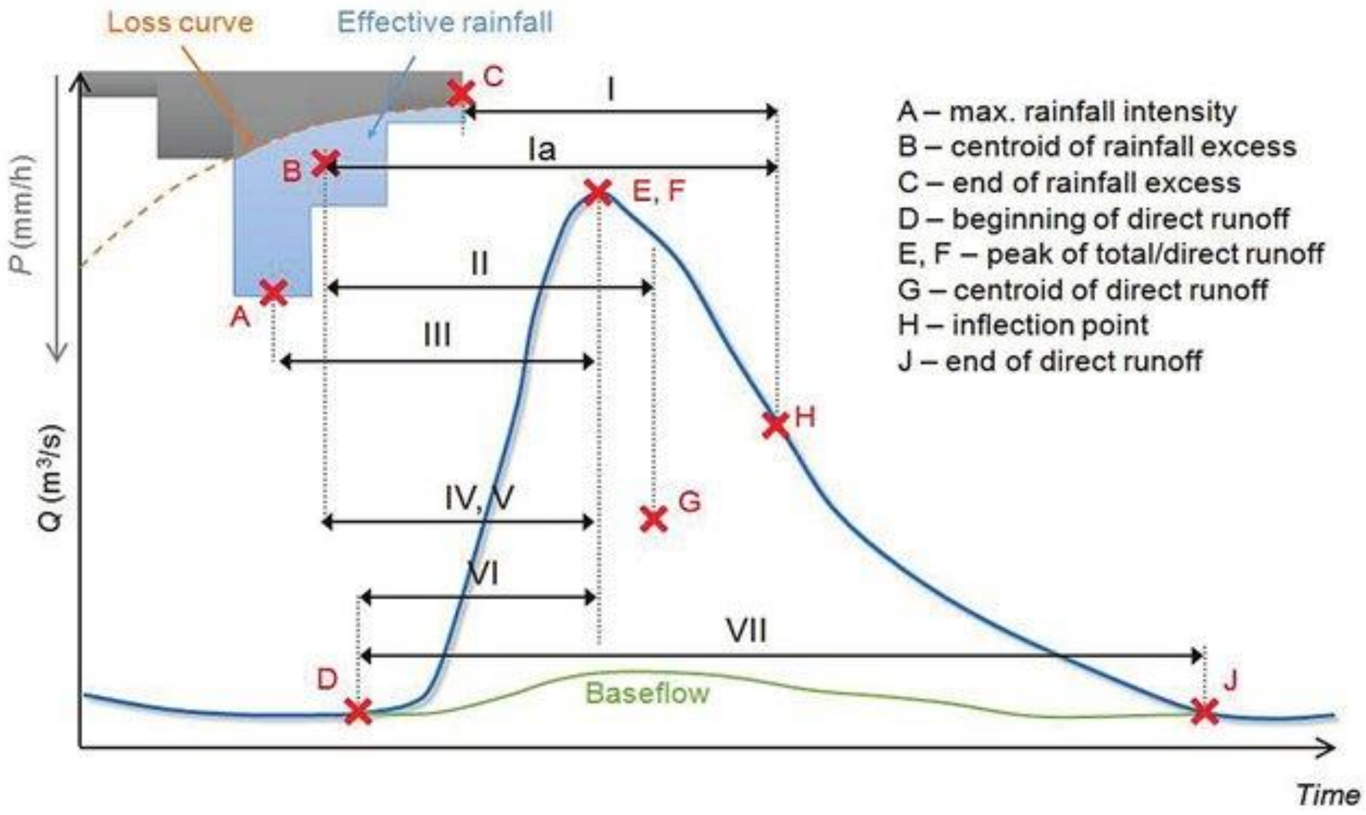
Hydrograph components:

- **Time base of a hydrograph, t_B,** is the time from the beginning to the end of the direct or unit hydrograph.
- **Lag time or basin lag, t_p**, is the difference in time between the center of mass of rainfall excess and center of mass of runoff (or peak rate of flow).
- **Time of concentration**, t_c , is defined in two ways:
  1. ***Based on physical characteristics of a watershed***, it is the travel time of a water particle from the hydraulically most remote point in the basin to the outflow location.
  2. ***Based on rainfall and hydrograph characteristics***, it is taken as the time from the end of the rainfall excess to the point of inflection on the falling limb of the DRH or the unit hydrograph. that signifies
- **Point of inflection**: the end of direct rainfall inflow into the stream and the start of the detention storage contribution.

Stream Flow Hydrograph

Different time parameters based on specific points of the hyetograph and hydrograph.

- I, I_a – Time of concentration;
- II, III, IV, V – lag time;
- VI – time to peak,
- VII – time base of the runoff.



Source: https://www.researchgate.net/profile/Peter-Torma/publication/312047380/figure/fig3/AS:451376942718977@1484628057770/nterpretation-of-different-time-parameters-based-on-specific-points-of-the-hyetograph-and.png

Stream Flow Hydrograph

Peak Discharge :

- It is the highest concentration of discharge of a stream or a river from its basin or catchment area that occurs
- The peak discharge is a function of:
  - Shape of the basin
  - Drainage Density
  - Rainfall Intensity
  - Soil Texture
  - Vegetation
  - Slope and
  - Geology

Stream Flow Hydrograph

Base flow:

- The flow during a period after direct runoff and not from a given rainfall event is called ***baseflow***.
- The base flow varies according to season and size of the catchment.
- The source of base flow is the water from **prior rainfalls** that have infiltrated into the soil.
- It represents the discharge of **aquifers**, changes occur slowly and
- The infiltrated groundwater slowly gets drained into the river.
- There is a lag between cause and effect that can easily extend to periods of **days** or **weeks**.
- The total runoff from a catchment as:

$$Q_{total} = Q_{direct} + Q_{base\ flow}$$

Effective Rainfall

- The rainfall that is not lost through any catchment losses, such as ***interception***, ***infiltration***, and ***evapotranspiration***.
- It is called the effective rainfall, P_{eff}.
- The effective rainfall must be equal to the **direct runoff**:

$$P_{eff} = Q_{direct}$$

- We can consider the total **losses** for the total rainfall:

$$P_{eff} = P_{total} - P_{losses}$$

- P_{eff} with respect to $\emptyset_{index}$:

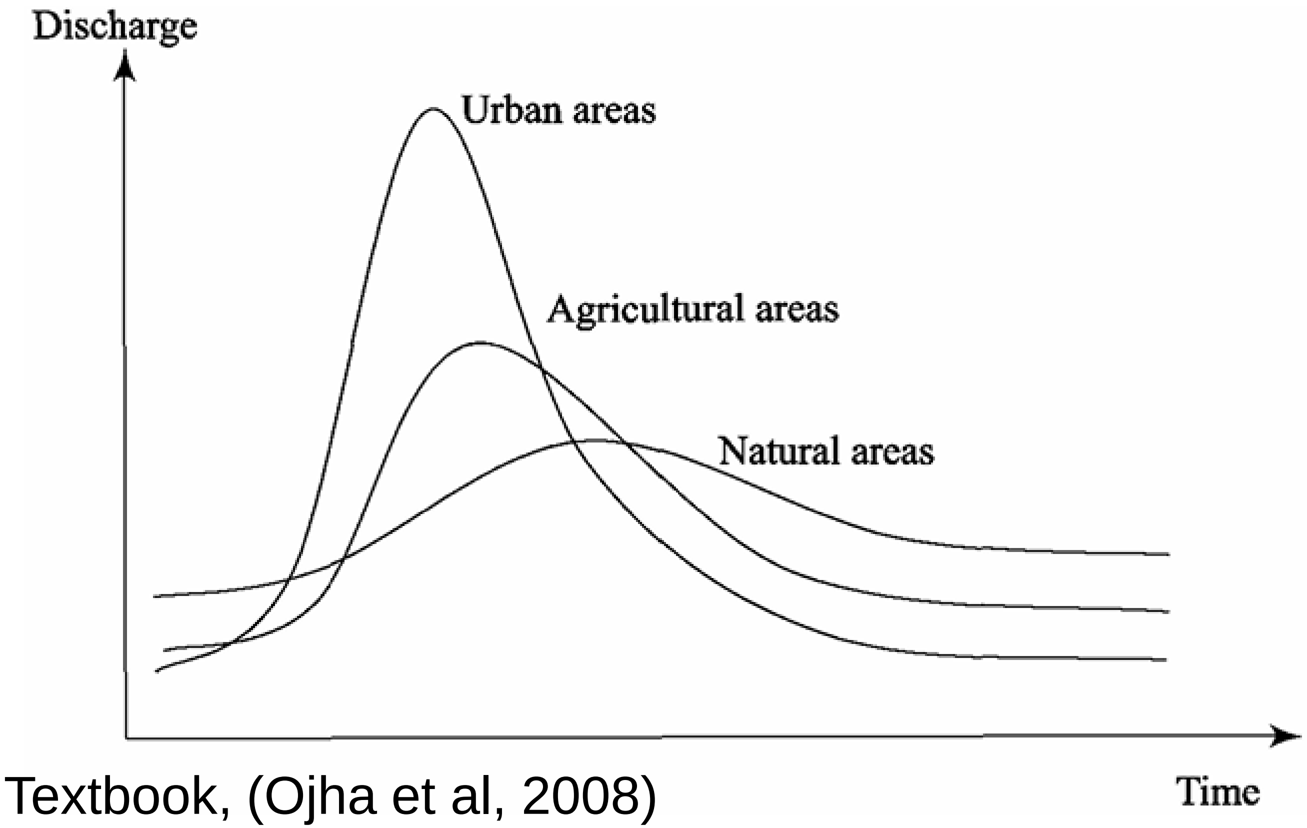
$$P_{eff} = P_{total} - \emptyset_{index}$$

- In terms of total runoff and base flow:

$$P_{eff} = Q_{total} - Q_{base\ flow}$$

Factors Affecting Flood Hydrograph

- Rainfall distribution over the catchment
  - Areal pattern of rainfall,
  - Rainfall duration, and
  - Intensity
- Physiographic elements of the catchment,
  - Shape,
  - Slope,
  - Vegetation,
  - Soil type, etc.



Source: Textbook, (Ojha et al, 2008)

Factors Affecting Flood Hydrograph

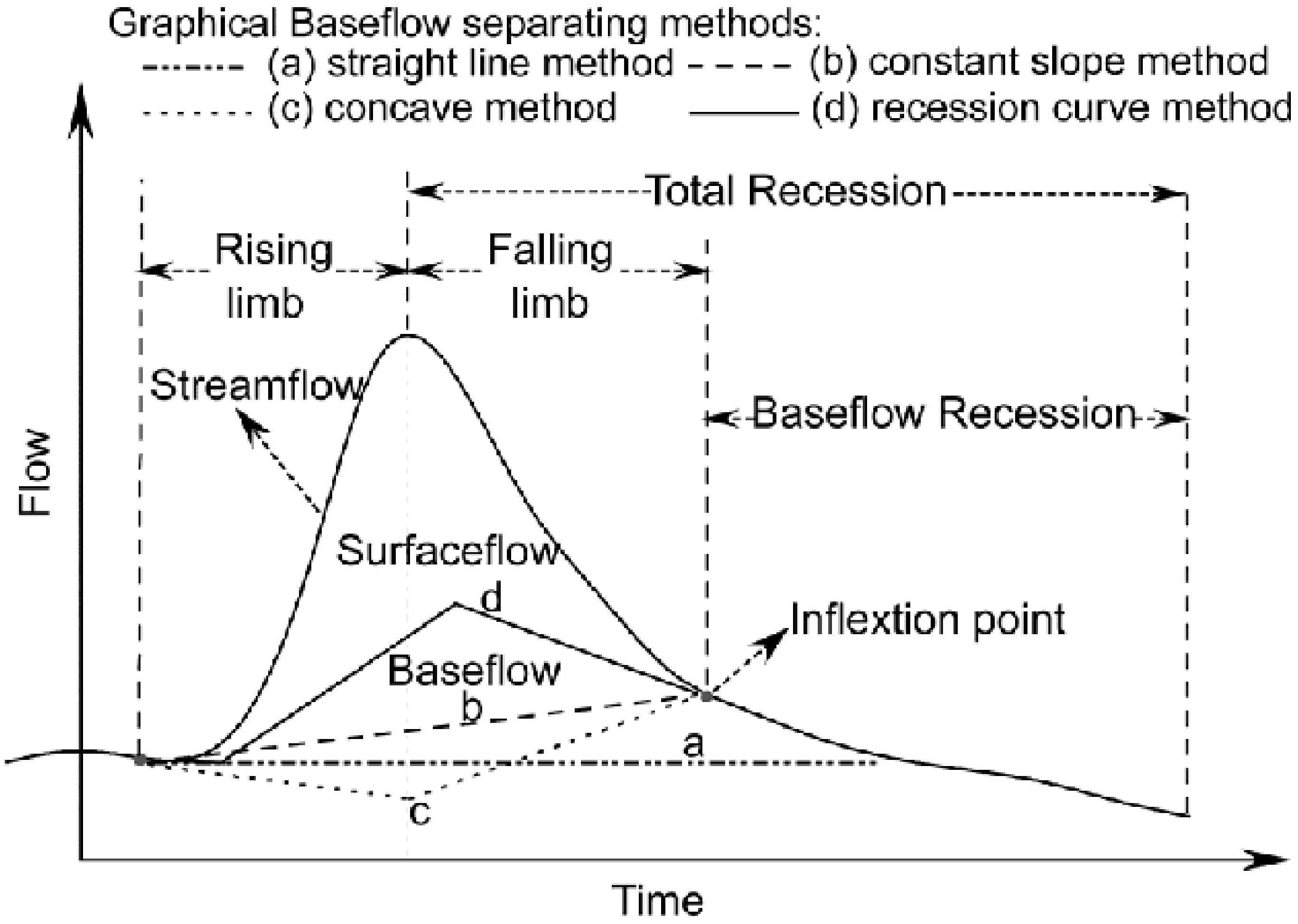
Physiographic factors:

1. Basin characteristics:
    - Shape, size, slope, nature of the valleys, elevation, drainage density,
2. Infiltration characteristics:
    - Land use land cover, soil type and geological conditions, lakes, swamps and other storages
3. Channel characteristics:
    - Cross-section, roughness and storage capacities

Climatic factors:

1. Storm characteristics:
    - Intensity, duration, magnitude and movement of storms
2. Initial losses
3. Evapotranspiration

Separation of Base Flow and Runoff

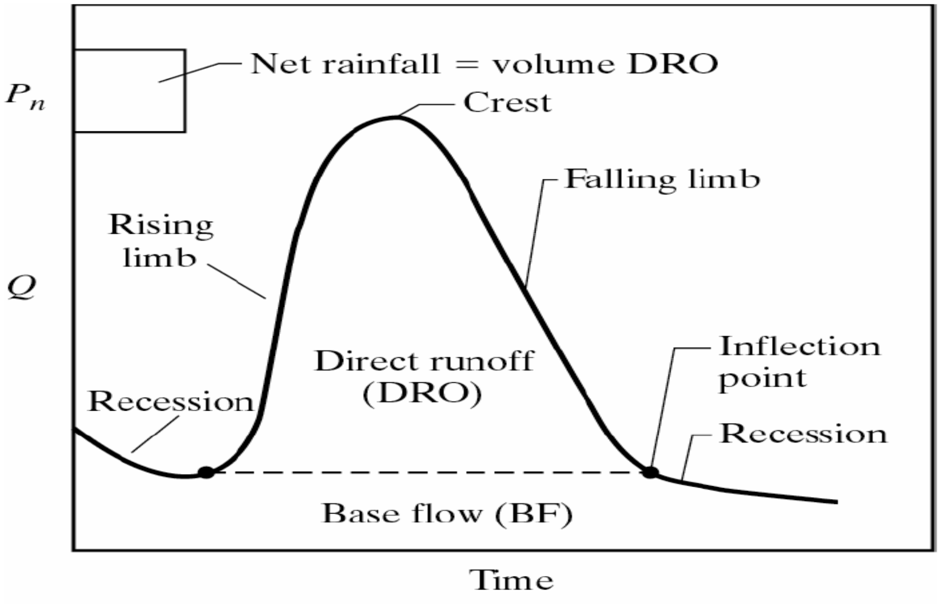


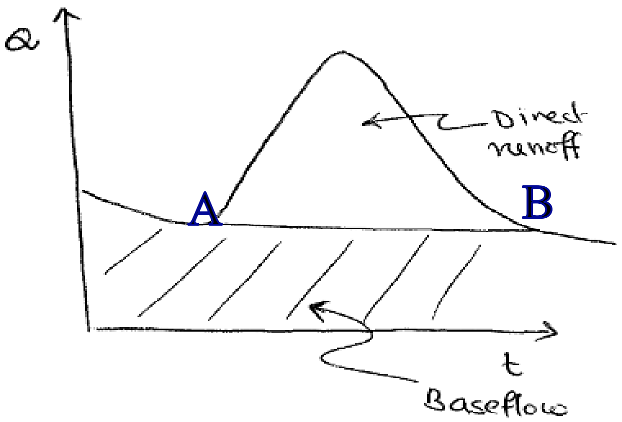
Source: Textbook, (Ojha et al, 2008)

There are different methods of base flow separation in common:

a) Straight line method
b) Variable Slope Method
c) Fixed or constant base method
d) Concave method

Separation of Base Flow and Runoff





Source: Textbook, (Ojha et al, 2008)

1. Straight line method:

- It connects the beginning of the direct runoff to a point on the recession limb representing the end of the direct runoff.
- Point A represents the beginning of the excess rainfall (direct runoff), by looking sharp change of runoff.
- But point B, end of the direct runoff is **difficult** to exactly represents

Separation of Base Flow and Runoff

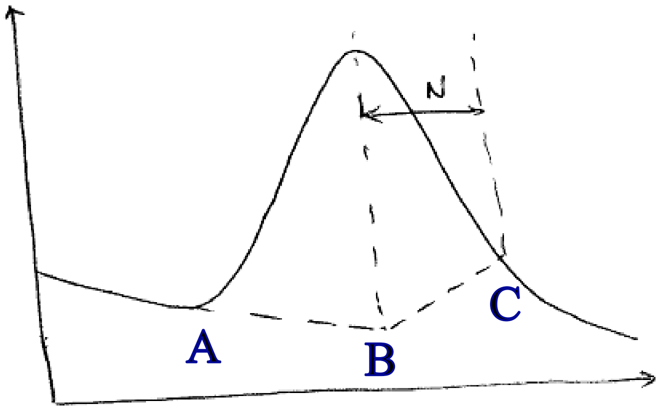
2. Fixed base method:

- Base-flow existing prior to the commencement of the surface runoff is extended until it intersects with the ordinate drawn at the peak point B.
- The base flow before the surface runoff began is projected ahead to the time of the peak.
- In this method the surface runoff is assumed to end a fixed time **N after** the hydrograph peaks.
- This point is joined to point C by a straight line.
- Empirical equation for time interval N days from the peak to the point C is

N=0.83*A 0.2

where A is drainage area in Km^2 and N in days

- Position of B should be decided by considering the **number of hydrographs**.

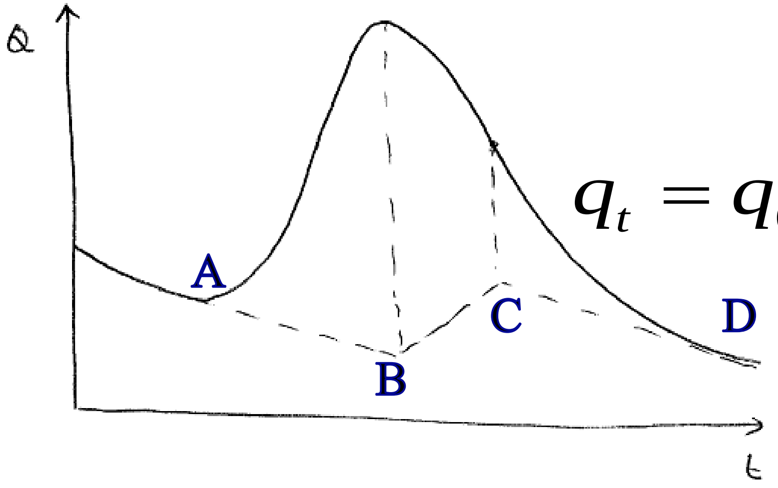


$$N=0.83*A^{0.2}$$

Separation of Base Flow and Runoff

3. Variable slope method:

- The base flow curve before the surface runoff began is **extrapolated forward** to the time of the peak discharge, and
- the base flow curve after the surface runoff ceases is **extrapolated backward** to the time of the point of **inflection** on the recession limb.
- A straight line is used to connect the end points of the extrapolated curves.



$$q_t = q_0 e^{-kt}$$

Hydrograph Analysis

Depending upon the unit of time involved, we have:

- **Annual hydrographs** showing the variation of daily or weekly or 10 daily mean flows over a year;
- **Monthly hydrographs** showing the variation of daily mean flows over a month;
- **Seasonal hydrographs** depicting the variation of the discharge in a particular season such as the monsoon season or dry season; and
- **Flood hydrographs** or hydrographs due to a storm representing stream flow due to a storm over a catchments.

Annual and seasonal hydrographs are of use in:

1. Calculating the ***surface water potential*** of stream,
2. ***Reservoir*** studies and
3. ***Drought*** studies.

Hydrograph Analysis

- **Flood hydrographs** are essential in analyzing stream characteristics associated with **floods**.
- A study of the annual hydrographs of streams enables one to classify streams into three classes as:
  1. Perennial,
  2. Intermittent and
  3. Ephemeral

A perennial stream is one which **always** caries some flow, there is considerable amount of groundwater flow throughout the year.

- Even during dry seasons the **water table**

will be able to reach the bed of the stream.

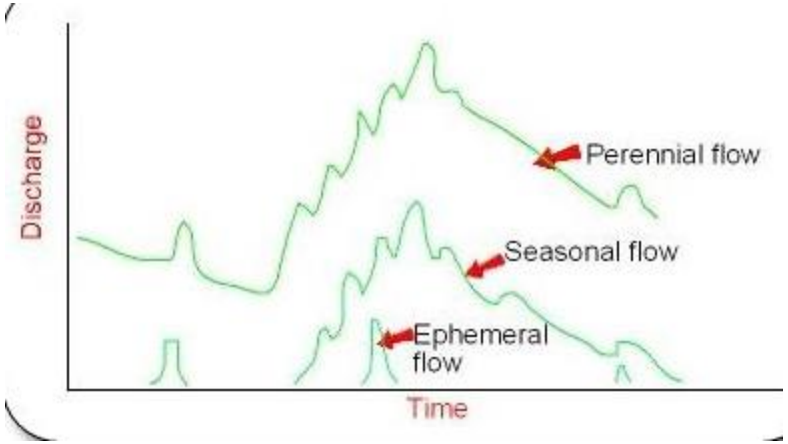
Hydrograph Analysis

An intermittent stream has limited contribution from the groundwater.

- **During the wet season**: there is a contribution of the base flow to the stream flow.
- **During dry seasons**: the streambed and the stream dries up.
  - can produce a short-duration flow,
  - the stream remains dry for the most part of the dry months.

An ephemeral stream does not have **any base-flow** contribution.

- The annual hydrograph shows series of **short duration peaks** marking flash flows in response to storms.
- The stream becomes dry soon after the end of the storm flow.
- does not have any **well-defined channel**.
- Most rivers in **arid zones** are of the ephemeral kind.



Source: Seasonal river.jpg

Home assignment:

Make sure that you can write, select, compare on the following topics:

- **SCS-CN methods**: symbols, units and problem analysis
  - Compare and contrast rainfall, effective rainfall and direct runoff.
    - Relate parameters under these methods
    - Try to solve mathematical expression and problem solving on these methods for effective rainfall
- **Baseflow separation**: definitions and methods
  - What does baseflow mean?
  - Why it is important?
  - Compare and contrast baseflow separation methods graphically.
- **Hydrograph**: Factors affecting,

References

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Subramanya, K. 2008. Engineering Hydrology, Tata McGraw-Hill Publishing Company Limited, New Delhi

Thank you very much for your active attendance!!

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