

Water Resources Engineering Lecture 8

Hydrologic Analysis-
Rainfall-Runoff
Estimation Methods

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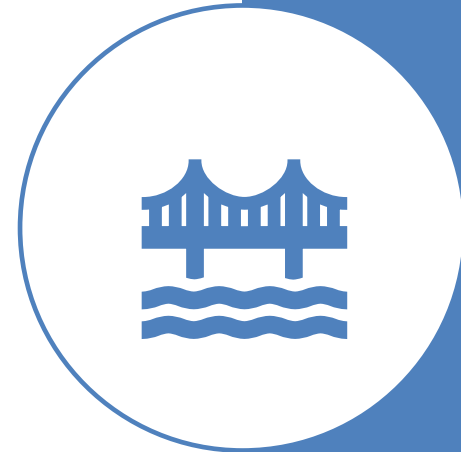
Runoff Estimation and Modeling

- To estimate the magnitude of a flood peak the following alternative methods are available:
 - 1. Time-Area Method
 - 2. Unit-hydrograph technique
 - 3. Semi-Empirical method (rational method).
 - 4. Empirical method (SCS curve number method)

Semi-Empirical formulae

There many empirical or Semi-Empirical formulae used to estimate the runoff discharge from catchment area. These formulae can be classify into three categories:

1. Formulae consider the area only into calculation, like **Dickens, Ryves, Ingles** and others. The formulae take forms as $Q=CA^n$; n exponent is almost <1 .
2. Formulae consider Area and some other factors such as **Craig , Lillie and Rhinds** (Taking velocity , and may be intensity, depth or max, depth of rainfall).
3. Formulae consider the recurrence interval ,like **Fullers , Hortons , Pettis** and other.



Which Method to Use

- Above all, two methods dependent on semi-empirical bases are preferable for storm design and have a wide use by the designer. The **Rational method** and the **SCS-CN method**. Further the Rational formula is only applicable to small-size (< 50 km²) catchments, and the **unit-hydrograph method** is normally restricted to moderate-size catchments with areas less than 5000 km²



Semi-Empirical Methods

Estimation of Runoff:

Runoff can be estimated by various methods. These can be classified under the following:

- Empirical Formulae (to find peak runoff)

- **Dicken's formula**

This formula was developed in the year 1865. It states that

$$Q_p = C_d A^{3/4}$$

Where,

Q_p = peak discharge rate (m³/s)

C_d = a constant (Dickens'), ranging from 6 to 30

A = Drainage basin area (km²).

For Indian conditions, suggested values for C_d are given as below:

Region	Topography	C_d
Northern states	Plains	6
	Hills	11-14
Central states	-	14.28
Coastal area	-	22.28.

- **Ryve's formula**

Ryve's formula was reported in the year 1884. It states that

$$Q_p = C_r A^{2/3}$$

Where,

Q_p = Peak discharge rate (m^3/s).

A = Drainage basin area (km^2).

C_r = A constant (Ryves), as shown below:

Region	C_r
Within 80 km from east coast	6.8
80-160 km from east coast	8.5
Hills	10.2

- **Igles's formula**

This formula was developed in areas of old Bombay state. It states that

$$Q_p = \frac{123 A}{\sqrt{A + 10.4}}$$

Where,

Q_p = Peak discharge in Cumecs (m^3/s).

A = Area of the catchment in sq km (km^2).

- **Khosla's formula**

In this method, the amount of mean annual runoff is calculated by following formula:

$$R = P - (T / 3.74)$$

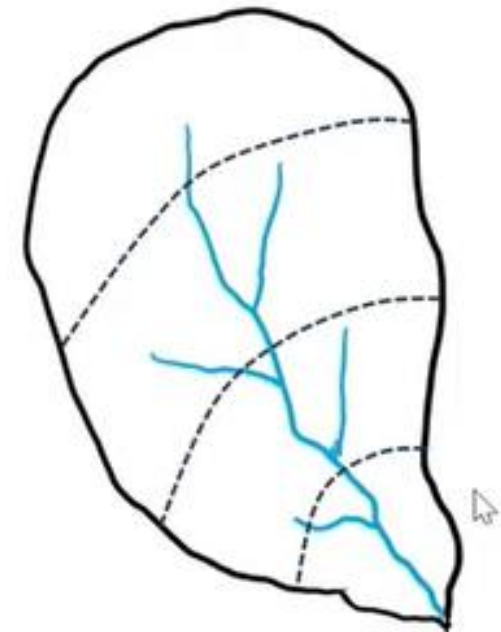
Where:

R = mean annual runoff of watershed by cm,

P = mean annual precipitation by cm, and

T = mean annual temperature by $^{\circ}C$.

Time-Area Method



$$Q_k = \sum_{j=1}^k A_j I_{k-j+1}$$

Where:

Q_k = the flow at time k ,

A_j = area of isochrone j ,

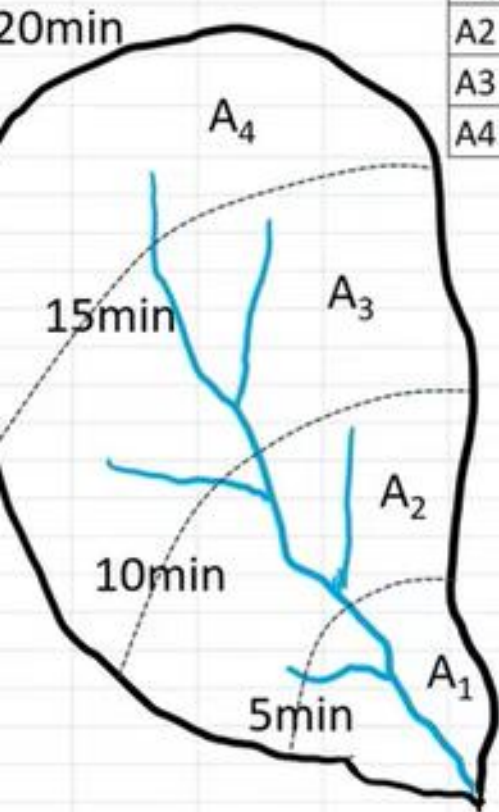
I_{k-j+1} = effective rainfall at time step $(k-j+1)$

Time-Area Method

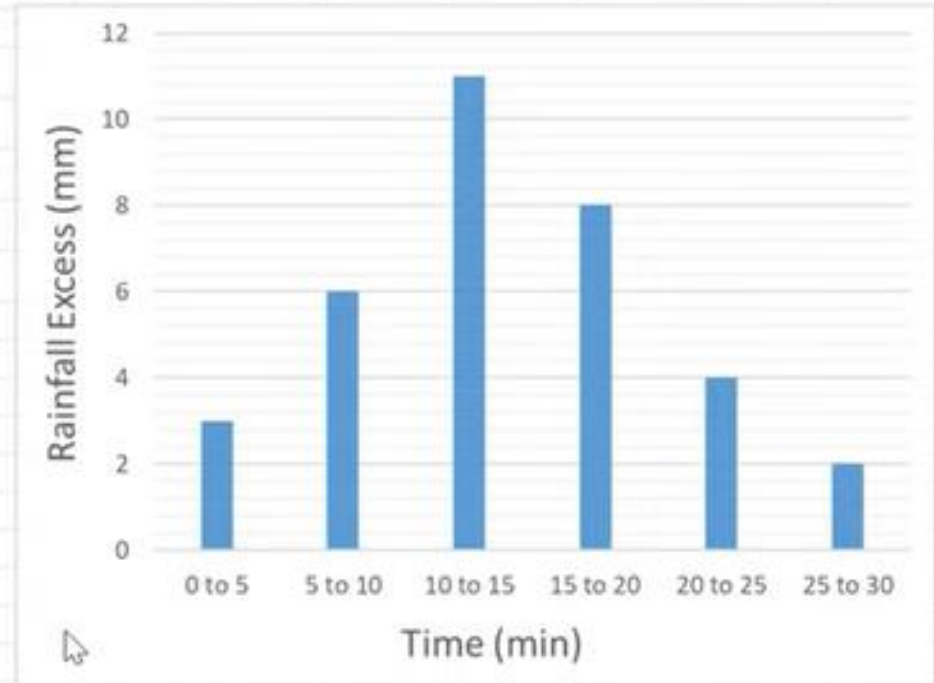
- **Core Concept:** It transforms effective rainfall into a runoff hydrograph by considering only the translation (movement) of water. It does not inherently account for storage effects, which are often added separately through **routing** the resulting hydrograph through a linear reservoir model.
- **Methodology:** The basin is divided into sub-areas by drawing lines of equal travel time (called isochrones) from all points to the outlet. A time-area histogram is then created, which plots the contributing area against the travel time. This histogram, combined with rainfall data, is used to calculate the flow at the outlet over time.
- **Application:** It is often used for larger catchments

Time-Area Method

Example: Calculate the runoff using Time-Area method and the given information



Sub-area	Area (ha)
A1	2.5
A2	5.4
A3	6.8
A4	6.1



Rational Method or Rain-fall Method

- This method was originally developed for urban catchments. Thus, the basic assumptions for development of this method were made for urban catchments. However, this method is fairly applicable to small agricultural **watersheds of 40 to 80 hectares size**.
- The rational method takes into account the following hydrological characteristics or processes:
 - (1) rainfall intensity
 - (2) rainfall duration
 - (3) rainfall frequency
 - (4) watershed area
 - (5) hydrologic abstraction
 - (6) runoff concentration.



Rational Method or Rain-fall Method

- The Rational method is based on the assumption that **constant intensity of rainfall** is uniformly spread over an area, and the effective rain falling on the most remote part of the basin takes a certain period of time, known as the **time of concentration (T_c)** to arrive at the basin outlet. If the input rate of excess rainfall on the basin continues for the period of time of concentration, then the part of the excess rain that fell in the most remote part of the basin will just begin its outflow at the basin outlet and with it, the runoff will reach its ultimate and the maximum rate. That is, the maximum rate of outflow will occur when the rainfall duration is equal to the time of concentration.

Rational Method Calculations

- The relationship for peak runoff Q_p is then expressed as:

$$Q_p = 0.278 C I A$$

Where,

- Q_p = Peak discharge in m^3/s .
- C = coefficient of runoff
- A = area of the catchment (drainage basin) in Km^2
- I = mean intensity of precipitation (mm/h) for a duration equal to time of concentration

Step 1: Find C

Runoff Coefficient Factor (C) for Different Soil Conditions in India:

Type of Vegetation	Slope Range (%)	Runoff Coefficient (C) in		
		Sandy Loam Soil	Loam / Loam Clay Soil	Stiff Clay Soil
Woodland and forests	0-5	0.1	0.3	0.4
	5-10	0.25	0.35	0.5
	10-30	0.3	0.5	0.6
Grassland	0-5	0.1	0.3	0.4
	5-10	0.16	0.36	0.55
	10-30	0.22	0.42	0.6
Agricultural land	0-5	0.3	0.5	0.6
	5-10	0.4	0.6	0.7
	10-30	0.52	0.72	0.82

Step 2: Find T_c

Time of Concentration (T_c):

For determination of the time of concentration, the most widely used formula is the equation given by Kirpich (1940). However, for small drainage basins, the lag time for the peak flow can be taken to be equal to the time of concentration. The lag time can be determined by the Snyder's equation.

The Kirpich's equation is given as

$$T_c = 0.01947 L^{0.77} S^{-0.385}$$

Where

T_c = time of concentration (min)

L = maximum length of travel of water (m)

S = slope of the drainage basin

Step 3: Find I

Intensity of Rainfall: (I = Rainfall depth / T_c)

Example

Example 1

A catchment has an area of 5.0 km². The average slope of the land surface is 0.006 and the maximum travel depth of rainfall in the catchment is approximately 1.95 km. The maximum depth of rainfall in the area with a return period of 25 years is as tabulated in Table 4.20.

Table 4.20 Maximum Depth of Rainfall in an Area with a Return Period of 25 Years.

Time duration (min)	5	10	15	20	25	30	40	60
Rain fall depth (mm)	15	25	32	45	50	53	60	65

Consider that 2.0 Km² of the catchment area has cultivated sandy loam soil (c=0.2) and 3.0 Km² has light clay cultivated soil (c = 0.7). Determine the peak flow rate of runoff by using the Rational method.

Solution: The time of concentration is given by Kirpich's equation.

$$\begin{aligned}T_c &= 0.01947 L^{0.77} S^{-0.385} \\ &= 0.01947 (1950)^{0.77} (0.006)^{-0.385} \text{ min} \\ &= 47.65 \text{ min.}\end{aligned}$$

~~min~~

40 → 60 mm

47.65 → X mm

60 → 65 mm

~~65 - 60~~

~~60 - 40~~

=

~~X - 60~~

47.65 - 40

Continue

The maximum rainfall depth for 47.65 min duration would fall between the periods of 40-60 min and is located at 7.65 min after the 40 min period at which the maximum rainfall depth is 60 mm, as per the available data.

The rainfall depth during the 7.65 min period = $\frac{65-60}{20} \times 7.65 = 1.9$ mm

Therefore, for 47.65 min duration, the rainfall depth = $60 + 1.9 = 61.9$ mm.

The average rainfall intensity = $\frac{\text{maximum rainfall depth}}{T_c}$
(During the period of time of concentration)

$$= \frac{61.9 \times 60}{47.65} = 77.96 \text{ mm/hr}$$

$$\text{Runoff coefficient, } C = \frac{(20 \times 0.2) + (3.0 \times 0.7)}{5.0}$$

$$= \frac{0.4 + 2.1}{5.0} = 0.5$$

$$\text{Peak runoff rate, } Q_p = \frac{CIA}{3.6} \text{ m}^3/\text{s}$$
$$= \frac{1}{3.6} \times 0.5 \times 77.96 \times 5.0$$

$$= 54.138 \text{ m}^3/\text{s}.$$

Example 2

Example

An urban catchment has an area of 85 ha. The slope of the catchment is 0.006 and the maximum length of travel of water is 950 m. The maximum depth of rainfall with a 25-year return period is as below:

Duration (min)	5	10	20	30	40	60
Max. Depth of rainfall (mm)	17	26	40	50	57	62

If a culvert for drainage at the outlet of this area is to be designed for a return period of 25 years, estimate the required peak-flow rate, by assuming the runoff coefficient as 0.3.

Solution:

The time of concentration is obtained by the Kirpich formula as;

$$t_c = \frac{0.01947L^{0.77}}{S^{0.385}} = \frac{0.01947(950)^{0.77}}{(0.006)^{0.385}} = 27.4 \text{ minutes}$$

By interpolation,

Maximum depth of rainfall for 27.4 min duration:

$$= \frac{(50 - 40)}{30 - 20} = \frac{(x - 40)}{27.4 - 20} \quad x = \frac{(50 - 40)}{30 - 20} \times 7.4 + 40 = 47.4 \text{ mm}$$

- *Average intensity* = $i = \frac{\text{Maximum Rainfall}}{T_c}$
 $i = \frac{47.4 \times 60}{27.4} = 103.8 \text{ mm/hr}$

$$Q_p = 0.278 C I A$$

$$Q_p = 0.278 \times 0.3 \times 103.8 \times 85 / 100$$

$$Q_p = 7.36 \text{ m}^3/\text{s}$$

$$Km^2 = 100ha$$