Water Resources Engineering Lecture 9

Hydrologic Analysis-Rainfall-Runoff Estimation Methods 2

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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)

Rational Method Calcuations

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

$$Qp = 0.278\ C\ I\ A$$

Where,

- Qp = 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 Tc

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

$$Tc = 0.01947\, L^{0.77}\, S^{-0.385}$$

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 / Tc)

Example 2

Example

An urban catchment has an area o f 85 ha. The slope of the catchment is 0.006 and the maximum length o f travel o f 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 o f 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;

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

By interpolation,

Maximum depth of rainfall for 27.4 min duration:

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

- *Average intensity* = $i = \frac{Maximum\ Rainfall}{Tc}$

$$i = \frac{47.4 \times 60}{27.4} = 103.8 \text{ mm/hr}$$

$$Q_{p=0.278\ C\ I\ A}$$

$$Q_{p=0.278\ \times 0.3 \times 103.8 \times 85/100}$$

$$Q_{p=7.36\ m^3/s}$$

$$Km^2 = 100ha$$

Example 3

If in the urban area o f Example **2** *the land use o f the area and the corresponding runoff coefficients are as given below, calculate the equivalent runoff coefficient.*

Land use	Area (ha)	Runoff coefficient
Roads	8	0.70
Lawn	17	0.10
Residential area	50	0.30
Industrial area	10	0.80

Solution

The equivalent runoff coefficient $Ce = \frac{\sum_1^N C_i A_i}{A}$

$$Ce = \frac{0.7 \times 8 + 0.1 \times 17 + 0.3 \times 50 + 0.8 \times 10}{8 + 17 + 50 + 10} = \frac{30.3}{85} = 0.36$$

Example 4

An engineer is required to design a drainage system for an airport of area 2.5 km² for 35 year return period .if the equation of rainfall intensity is;

$i = \frac{T}{(t+10)^{0.38}}$ *; where i=rainfall intensity in cm/hr, and t=duration in minutes. T=return period in year.*

If the concentration time for the area is estimated as 50 minutes ,for what discharge the system must design?

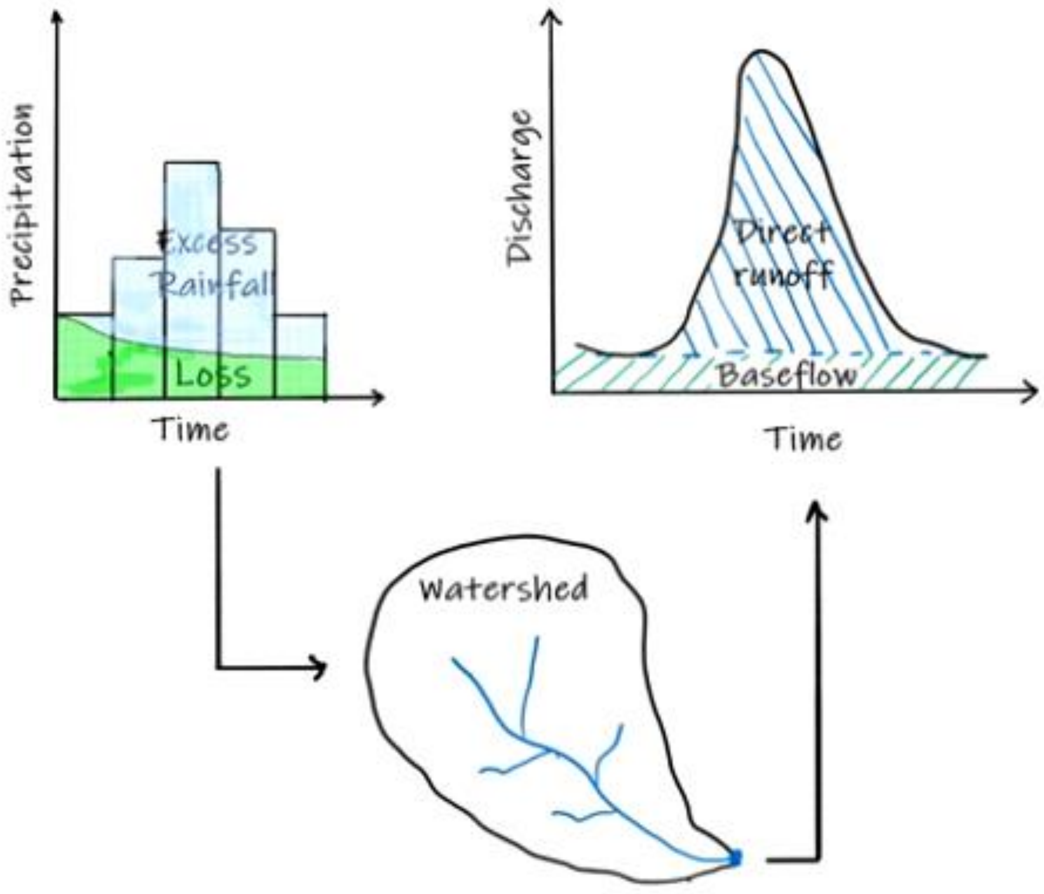
Solution

$$i = \frac{T}{(t+10)^{0.38}} = \frac{35}{(50+10)^{0.38}} = 7.385\ cm/hr$$

$$Qp = 2.78\,(1)(7.385)(2.5) = 51.32\ m^3/s$$

Unit Hydrograph Method

The Unit hydrograph (UH) of a catchment is defined as the hydrograph resulting from an effective rainfall of 1mm evenly distributed over the basin during the time



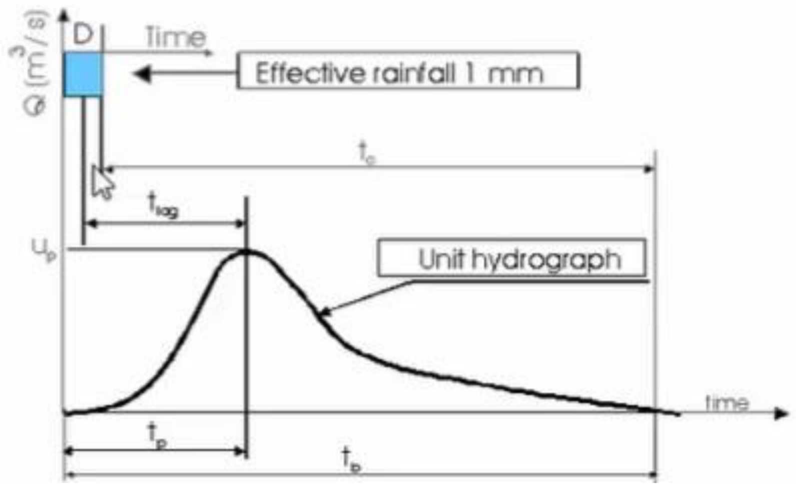
Unit Hydrograph

A simple linear model of rainfall excess and catchment hydrograph

- The amount of runoff resulting from 1 unit (inch, cm, etc.) of rainfall excess

- Principle: once you know a watershed's response to one storm, you can predict what its response for another storm will look like

- Assumes
  - Constant intensity
  - Uniformly distributed
  - Time increment is constant
  - Watershed is not changing



Application of Unit Hydrograph:

They are of great use in

- A unit hydrograph is used to estimate stream flow or discharge given a basin– averaged rainfall.
- The development of flood hydrographs for extreme rainfall magnitudes (for use in the design of hydraulic structures)
- Extension of flood flow records based on rainfall records
- Development of flood forecasting and warning systems based on rainfall

Example 1:

- Simplified Runoff Response (1 inch Rainfall Excess)

Time (hr)	Runoff (cfs/in)
0	0
1	5
2	15
3	30
4	45
5	35
6	25
7	15
8	8
9	3
10	0

For that same watershed, develop the runoff hydrograph for the following storm.

Time (hrs)	1 & 2	3 & 4	5 & 6
Rainfall (in/hr)	3.2	3.4	1.8
Abstractions (in/hr)	2.3	1.9	1.1

Solution

1) Rainfall excess (effective rainfall)

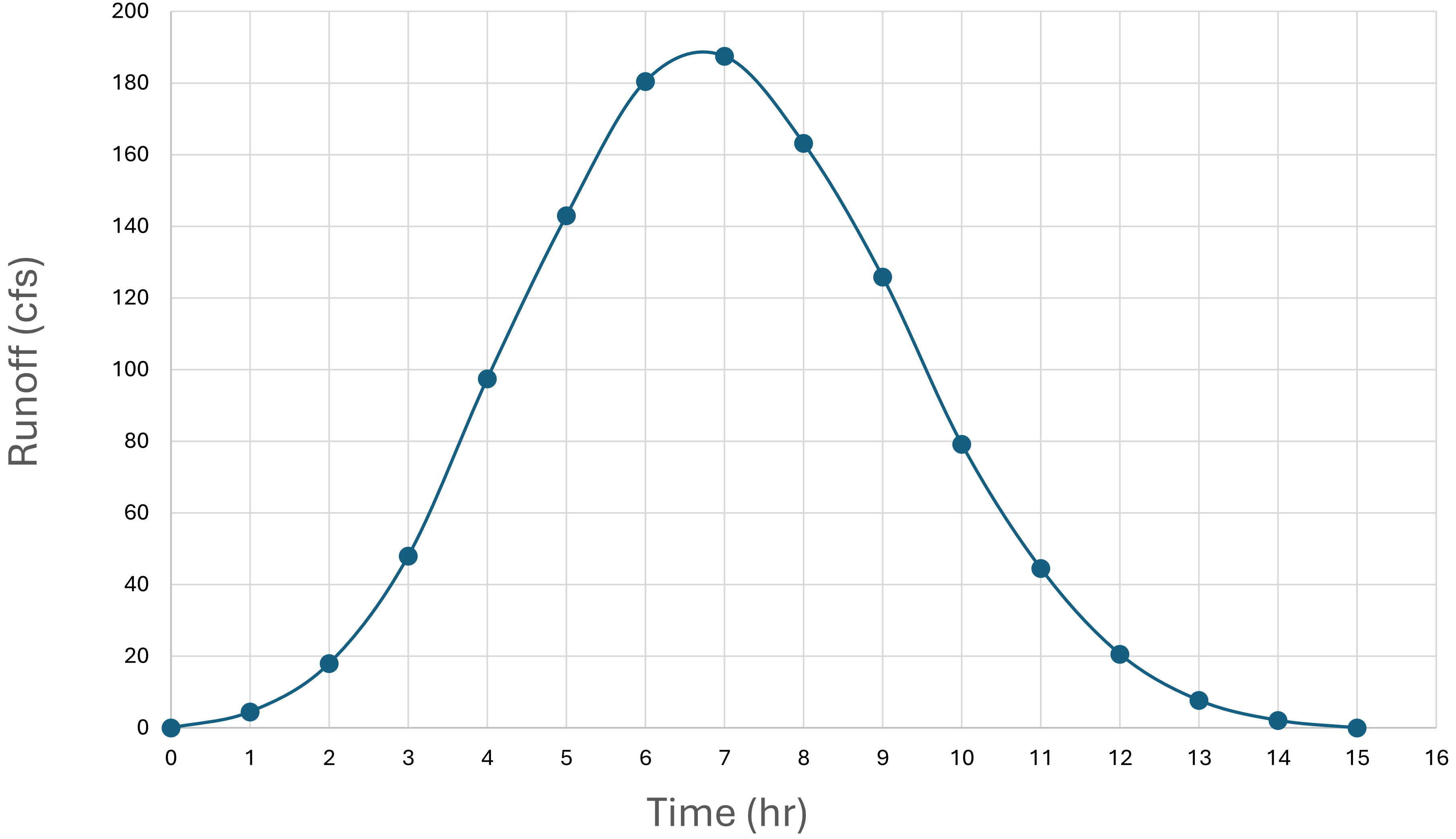
For each 2-hr block:

- Hours **1–2**: $3.2 - 2.3 = 0.9$ in/hr
- Hours **3–4**: $3.4 - 1.9 = 1.5$ in/hr
- Hours **5–6**: $1.8 - 1.1 = 0.7$ in/hr

- **Peak discharge Q_p = 187.5 cfs** at **t = 7 hr**.

Time (hr)	Runoff (cfs)
0	0
1	4.5
2	18
3	48
4	97.5
5	143
6	180.5
7	187.5
8	163.2
9	125.9
10	79.2
11	44.5
12	20.6
13	7.7
14	2.1
15	0

1 in-Unit Hydrograph



Example 2

- Simplified Runoff Response (1 inch Rainfall Excess)

Time (hr)	UH (cfs/in)
0	0
1	6
2	18
3	36
4	48
5	38
6	26
7	16
8	9
9	3
10	0

Time (hr)	1–2	3–4	5–6
Rainfall (in/hr)	2.6	3.0	1.4
Abstractions (in/hr)	1.6	1.2	0.7

Solution

1) Rainfall excess (effective rainfall)

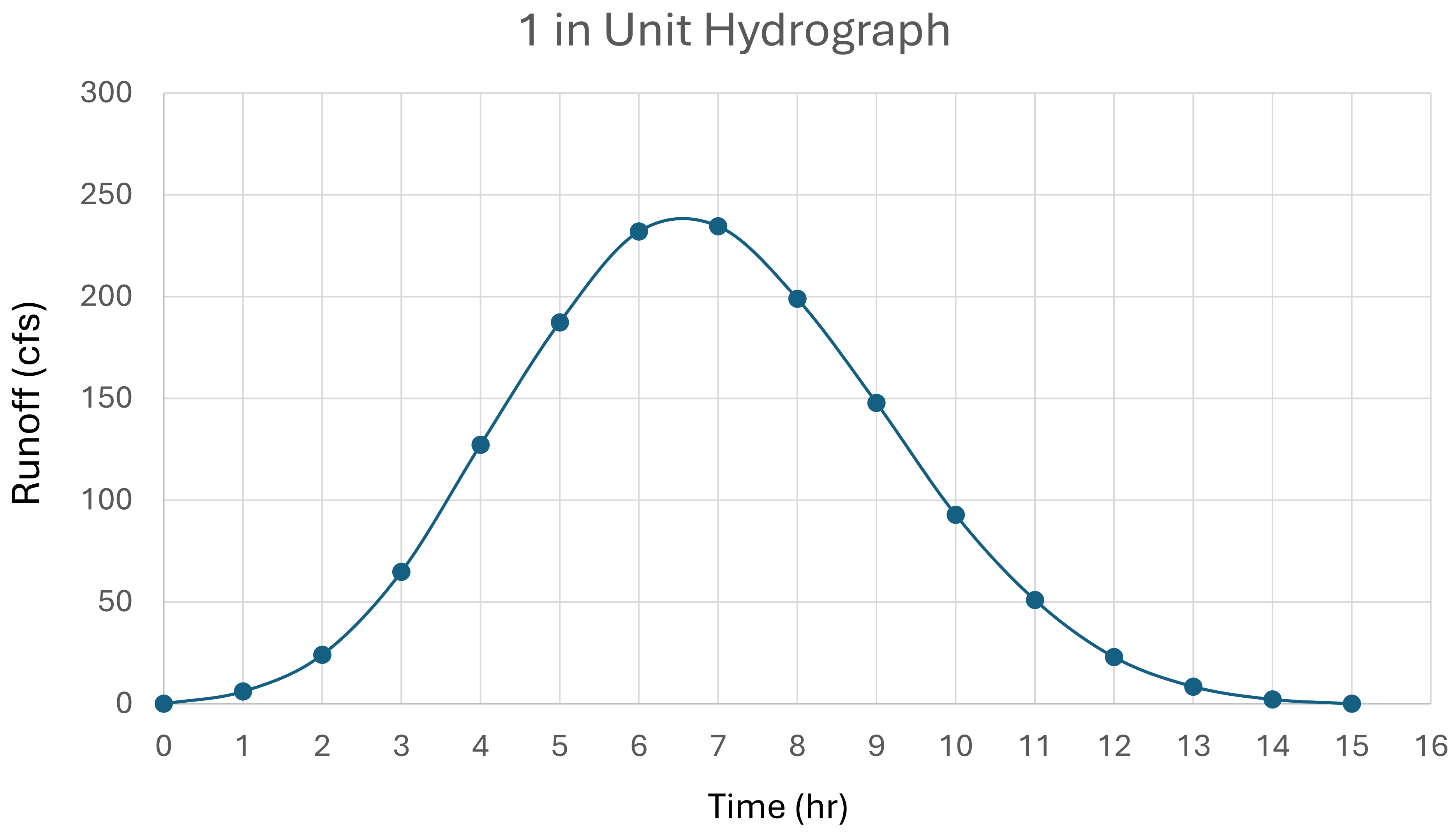
Excess (in/hr) = Rainfall − Abstractions:

- 1–2: $2.6 - 1.6 = 1.0$
- 3–4: $3.0 - 1.2 = 1.8$
- 5–6: $1.4 - 0.7 = 0.7$

Time (hr)	Runoff (cfs)
0	0
1	6
2	24
3	64.8
4	127.2
5	187.4
6	232
7	234.6
8	199
9	147.8
10	92.8
11	51
12	22.9
13	8.4
14	2.1
15	0

- **Peak discharge** = **234.6 cfs** at **t = 7 hr**.

Unit Hydrograph



Rainfall-Runoff-NRCS Method

- Estimates runoff from rainfall
- Based on watershed characteristics

NRCS = Natural Resources Conservation Service

Used to estimate runoff from rainfall

Based on watershed characteristics (soil, land use, cover, slope)

Previously known as the SCS Curve Number Method

Rainfall-Runoff-NRCS Method

SCS runoff curve number method

The SCS Runoff Curve Number (CN) method is described in detail in NEH-4 (SCS 1985). The SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \quad \text{[eq. 2-1]}$$

where

Q = runoff (in)
P = rainfall (in)
S = potential maximum retention after runoff begins (in) and
I_a = initial abstraction (in)

Initial abstraction (I_a) is all losses before runoff begins. It includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but generally is correlated with soil and cover parameters. Through studies of many small agricultural watersheds, I_a was found to be approximated by the following empirical equation:

equation:

$$I_a = 0.2S \quad \text{[eq. 2-2]}$$

By removing I_a as an independent parameter, this approximation allows use of a combination of S and P to produce a unique runoff amount. Substituting equation 2-2 into equation 2-1 gives:

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad \text{[eq. 2-3]}$$

S is related to the soil and cover conditions of the watershed through the CN. CN has a range of 0 to 100, and S is related to CN by:

$$S = \frac{1000}{CN} - 10 \quad \text{[eq. 2-4]}$$

Figure 2-1 and table 2-1 solve equations 2-3 and 2-4 for a range of CN's and rainfall.

CN Depends On

- Soil type
- Land use
- Land condition
- Hydrologic soil group A–D
- CN represents watershed ability to absorb water
- Low CN → more infiltration → less runoff
- High CN → less infiltration → more runoff
- Depends on: Soil group (A, B, C, D)
- Land use (urban, agriculture, forest)
- Soil treatment/condition
- Hydrologic condition (poor/good)
- Low CN (e.g., forests, sandy soils) → water infiltrates easily
- High CN (e.g., urban areas, clay soils) → water runs off quickly

Soil Hydrologic Groups

Infiltration rates of soils vary widely and are affected by subsurface permeability as well as surface intake rates. Soils are classified into four HSG's (A, B, C, and D) according to their minimum infiltration rate, which is obtained for bare soil after prolonged wetting. Appendix A defines the four groups and provides a list of most of the soils in the United States and their group classification. The soils in the area of interest may be identified from a soil survey report, which can be obtained from local SCS offices or soil and water conservation district offices.

Soil Hydrologic Groups

- **A**: high infiltration (sand) → least runoff
- **B**: moderate infiltration
- **C**: low infiltration
- **D**: very low infiltration (clay) → most runoff

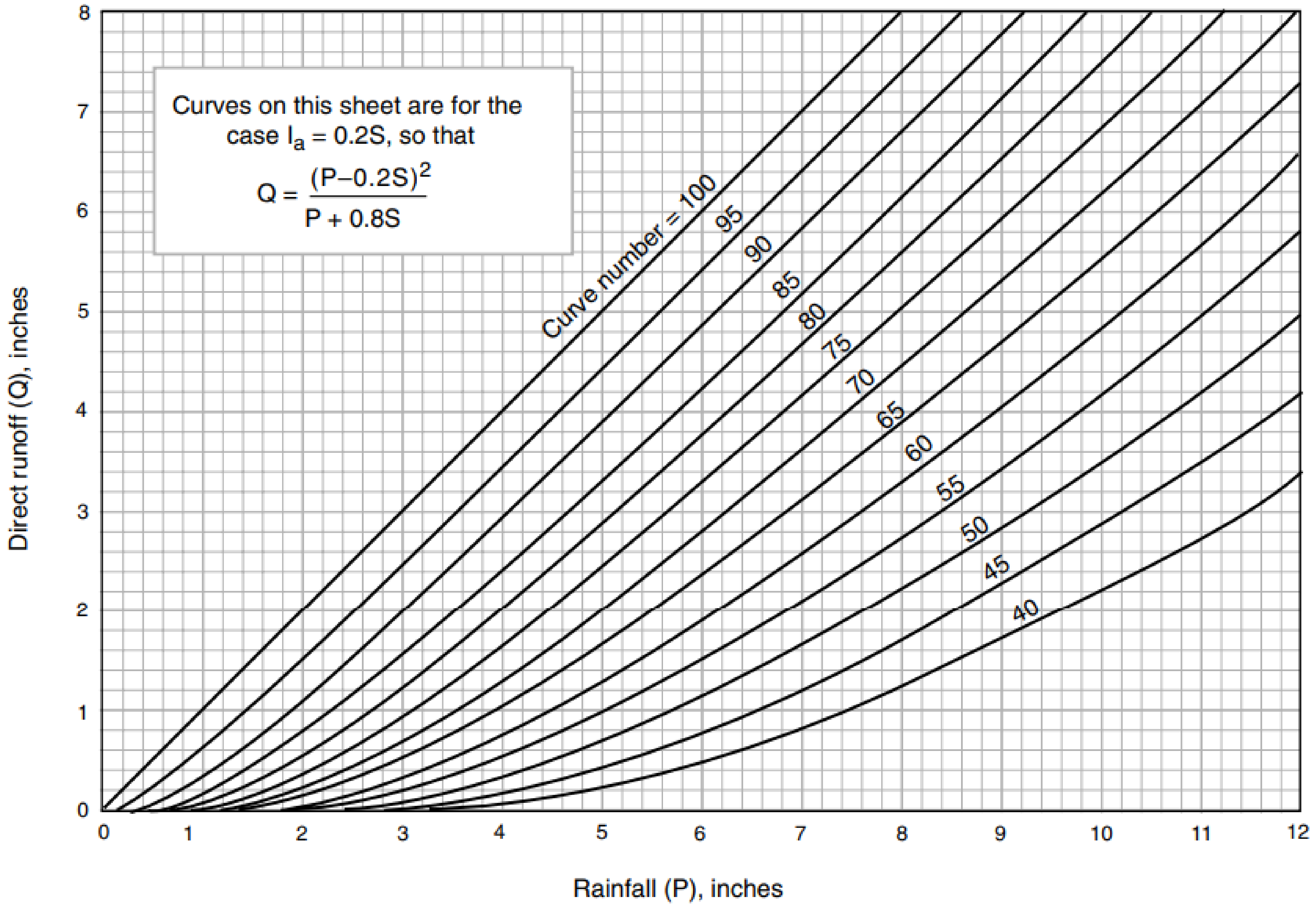
Curve Number

Curve number CN depends upon:

a) Soil type

b) Antecedent moisture condition

c) Land use/cover



Curves on this sheet are for the case $I_a = 0.2S$, so that
$$Q = \frac{(P-0.2S)^2}{P + 0.8S}$$
Curve number = 100
95
90
85
80
75
70
65
60
55
50
45
40
Direct runoff (Q), inches
Rainfall (P), inches
0
1
2
3
4
5
6
7
8
9
10
11
12

Table 2-2a Runoff curve numbers for urban areas [1/]

Cover description		Curve numbers for hydrologic soil group			
Cover type and hydrologic condition	Average percent impervious area [2/]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) [3/]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) [4/]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) [5/]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

Table 2-2c Runoff curve numbers for other agricultural lands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. [2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. [3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 [4]	48	65	73
Woods—grass combination (orchard or tree farm). [5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. [6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 [4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

Table 2-2d Runoff curve numbers for arid and semiarid rangelands [1]

Cover description		Curve numbers for hydrologic soil group			
Cover type	Hydrologic condition [2]	A [3]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

1 Average runoff condition, and I_a, = 0.2S. For range in humid regions, use table 2-2c.

Initial Abstraction (Ia)

- **Initial Abstraction (Ia)**
- Includes:
  - Surface storage
  - Interception
  - Infiltration before runoff starts

- Traditional assumption:
  Ia = 0.2 S
  (where S depends on CN)

Runoff Equation

- **Main Runoff Equation**
- $Q = \frac{(P-0.2S)^2}{P+0.8S}$
- Q = runoff depth
- P = total rainfall
- S = potential maximum retention
- $S = \frac{1000}{CN} - 10$

Time of Concentration (Tc)

- **Time of Concentration (Tc)**
- The time required for water to travel from the farthest point in watershed to outlet
- Determines **hydrograph peak time**
- Depends on:
  - Slope
  - Surface roughness
  - Flow path length
  - Land use

Summary: NRCS Unit Hydrograph

- **Watershed Response (Hydrograph)**
- NRCS uses **dimensionless unit hydrograph**
- Need:
  - Excess rainfall
  - Time of concentration
  - Watershed area
- Produces:
  - Peak discharge
  - Runoff volume
  - Hydrograph shape