RUNOFF CALCULATIONS

To estimate the magnitude of a flood peak the following alternative methods are available:

1. Unit-hydrograph technique
2. Empirical method
3. Semi-Empirical method (such rational method).

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.

The use of a particular method depends upon (i) the desired objective, (ii) the available data, and (iii) the importance of the project.

Above all , two methods depend 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 km^2) catchments and the unit-hydrograph method is normally restricted to moderate-size catchments with areas less than 5000 km^2

RATIONAL METHOD

Consider a rainfall of uniform intensity and duration occurring over a basin in a time taken for a drop of water from the farthest part of the catchment to reach the outlet that called tc = time of concentration, it is obvious that if the rainfall continues beyond tc, the runoff will be constant and at the peak value. The peak value o f the runoff is given by;

$$Qp = C\,i\,A \, ; \qquad for\; t > tc \quad ----------(1)$$

Where,

C = coefficient of runoff = (runoff/rainfall), A = area of the catchment and i = intensity of rainfall.

The simulation of above equation is quoted from the following;

To quantify peak runoff discharge Qp, is examined in Figure 1.

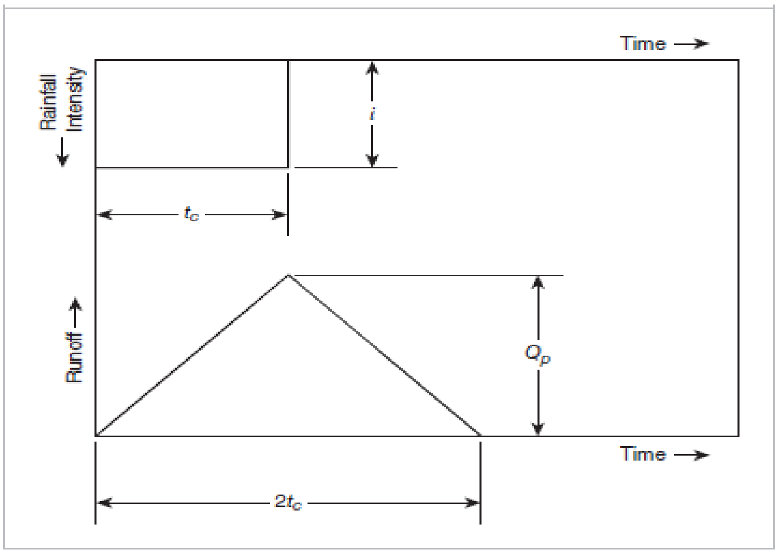


Fig.(1) *Relationship of rainfall intensity to runoff for an impervious drainage basin according to the Rational Method.*

The total volume of runoff equals the area under the graph of runoff versus time. Thus, volume is computed in (m^3) if tc in second Qp in (m^3/s) as;

$$Volume = \frac{1}{2}(2)(tc)(Qp)$$

$$= tc\,Qp$$

But remember that because the drainage basin is assumed hypothetically completely impervious, total runoff equals total rainfall. Total rainfall is computed simply as the depth of rainfall (m) times the area (m^2) over which the rainfall occurred. Depth of rainfall is the rainfall intensity (cm/hr) converted to (m/s) times the duration used in seconds. Thus,

$$\text{Depth} = \frac{i}{100(3600)}(\text{tc})$$

$$= \frac{i}{3.6 \times 10^5}\,tc$$

and rainfall volume is

$$Volume = Depth \times Area(\text{km}^2)$$

$$Volume = \frac{i}{3.6 \times 10^5} \times tc \times A \times 10^6$$

Finally, equating the volumes gives;

$$tc\ Qp = \frac{i}{3.6 \times 10^5} \times tc \times A \times 10^6$$

or;

$$Qp = 2.78\ i\ A \quad , \quad (\boldsymbol{A}\ in\ km^2\ and\ \boldsymbol{i}\ in\ (cm/hr)$$

This is the basic equation of the rational method for drainage basin that assumed completely impervious. Using the commonly used units, Eq. (1) is re-written for field application as;

$$Qp = 2.78\ C\ (i_{tc.p})A \text{------------------}(2)$$

Where

Qp = peak discharge (m^3/s)

C = Coefficient of runoff

$i_{tc.p}$ = the mean intensity of precipitation (*cm/ hr*) for a duration equal to tc and an exceedence probability P.

A = drainage area in km^2

The use of this method to compute Qp requires three parameters: tc, $i_{tc.p}$, and C .

Time of Concentration (tc)

There are a number of empirical equations available for the estimation of the time of concentration. One of these are described below:

Kirpich Equation (*1940*) This is the popularly used formula relating the time of concentration of the length of travel and slope of the catchment as;

$$tc = \frac{0.01947 L^{0.77}}{S^{0.385}} \text{------------------}(3)$$

tc in minutes.

Where;

L = maximum length of travel of water (m),

S = slope of the catchment = ΔH/L in which

ΔH =difference in elevation between the most remote point on the catchment and the outlet.

Rainfall Intensity $(i_{tc.p})$

The rainfall intensity corresponding to a duration *tc* and the desired probability of exceedence P, (i.e. return period T=1/P) is found from the rainfall-frequency-duration relationship for the given catchment area;

$$i_{tc.p} = \frac{KT^x}{(tc + a)^n}$$

in which the coefficients *K. a*, *x* and *n* are specific to a given area.

Runoff Coefficient (C)

The coefficient C represents the integrated effect of the catchment losses and hence depends upon the nature of the surface, surface slope and rainfall intensity. The effect of rainfall intensity is not considered in the available tables of values of *C*. Some typical values of *C* are indicated in *Table (1)* and *Table (2)*. Equation (2) assumes a homogeneous catchment surface. If however, the catchment is non-homogeneous but can be divided into distinct sub areas each having a different runoff coefficient, then the runoff from each sub area is calculated separately and merged in proper time sequence. Sometimes, a non-homogeneous catchment may have component sub areas distributed in such a complex manner that distinct sub zones cannot be separated. In such cases a weighted equivalent runoff coefficient Ce as below is used.

$$Ce = \frac{\sum_1^N C_i A_i}{A} \qquad ------------------- (4)$$

where A_i= the areal extent of the sub area *i* having a runoff coefficient *Ci* and N = number of sub areas in the catchment.

The rational formula is found to be suitable for peak-flow prediction in small catchments up to 50 km^2 in area. It finds considerable application in urban drainage designs and in the design of small culverts and bridges.

It should be noted that the word rational is rather a misnomer as the method involves the determination of parameters tc and C in a subjective manner.

Table (1) Value of the Coefficient C in Eq. (2)

Types of area	Value of *C*
A. *Urban area* (*P* = 0.05 to 0.10)	
Lawns: Sandy-soil, flat, 2%	0.05–0.10
Sandy soil, steep, 7%	0.15–0.20
Heavy soil, average, 2.7%	0.18–0.22
Residential areas:	
Single family areas	0.30–0.50
Multi units, attached	0.60–0.75
Industrial:	
Light	0.50–0.80
Heavy	0.60–0.90
Streets	0.70–0.95
B. *Agricultural Area*	
Flat: Tight clay;cultivated	0.50
woodland	0.40
Sandy loam;cultivated	0.20
woodland	0.10
Hilly: Tight clay;cultivated	0.70
woodland	0.60
Sandy loam;cultivated	0.40
woodland	0.30

Table (2) Values of C in Rational Formula for Watersheds with Agricultural an d Forest Land Covers

Sl. No	Vegetative cover and Slope (%)		Soil Texture: Sandy Loam	Soil Texture: Clay and Silty Loam	Soil Texture: Stiff Clay
1	Cultivated Land				
		0–5	0.30	0.50	0.60
		5–10	0.40	0.60	0.70
		10–30	0.52	0.72	0.82
2	Pasture Land				
		0–5	0.10	0.30	0.40
		5–10	0.16	0.36	0.55
		10–30	0.22	0.42	0.60
3	Forest Land				
		0–5	0.10	0.30	0.40
		5–10	0.25	0.35	0.50
		10–30	0.30	0.50	0.60

Example (1)

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 = $i_{tc.p} = \frac{depth}{duration} = \frac{47.4/10}{27.4/60} = 10.38\ cm/hr$

Recalling Eq. (2) :

$Qp = 2.78\ (0.3)(10.38)(0.85) = 7.35\ m^3/s$

Example (2)

If in the urban area o f Example (1), 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 (3)

An engineer is required to design a drainage system for an airport of area 2.5 km^2 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

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

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

HW1:

A watershed of 500 ha has the land use/cover and corresponding runoff coefficient as given below:

Land use/cover	Area (ha)	Runoff coefficient
Forest	250	0.10
Pasture	50	0.11
Cultivated land	200	0.30

The maximum length o f travel o f water in the watershed is about 3000 m and the elevation difference between the highest and outlet points o f the watershed is 25 m. The maximum intensity duration frequency relationship o f the watershed is given by;

$$i = \frac{6.311\,T^{0.1523}}{(D+0.5)^{0.945}}$$

Where;

i = intensity in cm/h, T = Return period in years and D = duration of the rainfall in hours.

Estimate the ***(i)*** *25 year peak runoff from the watershed and* ***(ii)*** *the 25 year peak runoff if the forest cover has decreased to 50 ha and the cultivated land has encroached upon the pasture and forset lands to have a total coverage of 450 ha.*

Solution of HW

SCS-CN Method to estimate Runoff

SCS-CN method, developed by Soil Conservation Services (SCS) of USA in 1969, is a simple, predictable, and stable conceptual method for estimation of direct runoff depth based on storm rainfall depth. It relies on only one parameter, *CN*. The details of the method are described in this section.

Basic Theory

The *SCS-CN* method is based on the water balance equation of the rainfall in a known interval of time Δt, referring to Fig.(2) and from the continuity principle it can be expressed as;

$$P = Ia + Fa + Pe \quad ------------------(5)$$

where

P = total precipitation,
Ia= initial abstraction,
Fa = Cumulative infiltration excluding Ia and,
Pe = direct surface runoff (all in units of volume occurring in time Δt).

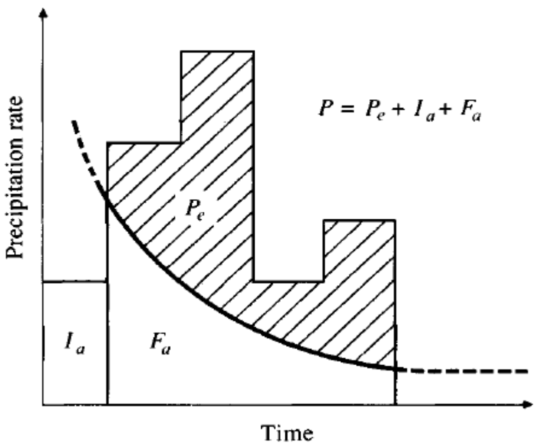


Fig.(2)
Variables in the SCS method of rainfall abstractions: I_a = initial abstraction, P_e = rainfall excess, F_a = continuing abstraction, P = total rainfall.

Two other concepts as below are also used with Eq. (5).

(i) The first concept is that the ratio of actual amount of direct runoff ,Pe to maximum potential runoff (= $P- Ia$) is equal to the ratio of actual infiltration (Fa) to the potential maximum retention (or infiltration), S. This proportionality concept can be schematically shown as in Fig.

$$\frac{Pe}{P-Ia} = \frac{Fa}{S} ----------- (6)$$

(ii) The second concept is that the amount of initial abstraction (Ia) is some fraction of the potential maximum retention (.S).

Thus *;*

$$Ia = \lambda S --------------- (7)$$

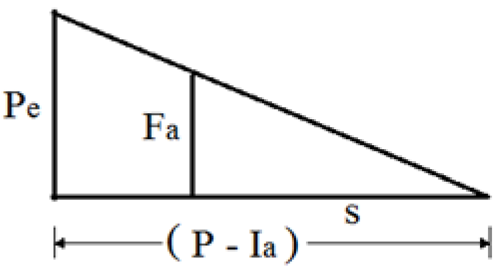


Fig. (3) Proportionality concept

Combining Eqs. (6) and (7), and using (5)

$$Pe = \frac{(P - Ia)^2}{P - Ia + S} = \frac{(P - \lambda S)^2}{P + (1-\lambda)S} \;\; ; \text{ for } P > \lambda S \;------- (8)$$

$$Pe = 0 \quad for\ P \le \lambda S$$

$$If\ P < Ia\ \ then\ Pe = 0\ while\ if\ P > Ia\ then\ Pe\ can\ be\ calculated\ .$$

Value of $\boldsymbol{\lambda}$

On the basis of extensive measurements in small size catchments SCS (1985) adopted **λ = 0.2** as a standard value, then Eq. (8) becomes;

$$Pe = \frac{(P - 0.2\,S)^2}{P + 0.8S} \;\; ; \text{ for } P > 0.2S$$

For operation purposes a time interval Δt = 1 day is adopted. Thus P= daily rainfall and Pe= daily runoff from the catchment.

Curve Number (CN)

The parameter **S** representing the potential maximum retention depends upon :

1. The soil-vegetation-land use complex of the catchment.
2. the antecedent soil moisture condition in the catchment just prior to the commencement of the rainfall event.

For convenience in practical application the Soil Conservation Services (SCS) has expressed **S** (mm) in terms of a dimensionless parameter CN (the Curve number) as;

$$S = \frac{25400}{CN} - 254 = 254\left(\frac{100}{CN} - 1\right) ------------- (9)$$

The constant 254 is used to express S in mmThe curve number CN is now related to S as;

$$CN = \frac{25400}{S + 254}$$

and has a range of 0 < CN< 100.

CN = 100 represents zero potential retention (i.e. impervious catchment)

CN = 0 represents an infinitely abstracting catchment with S =∞.

Curve number CN depends upon:

a) Soil type , ***b)*** Antecedent moisture condition , ***c)*** Land use/cover

a) Soils:

In the determination of CN, the hydrological soil classification is adopted. Here, soils are classified into four classes A, B, C and D based upon the infiltration and other characteristics. The important soil characteristics that influence hydrological classification of soils are effective depth of soil, average clay content, infiltration characteristics and permeability.

- **Group-A**: (**Low Runoff Potential**): Soils having ***high infiltration rates*** even when thoroughly wetted. These soils have high rate of water transmission. [Example: ***Deep sand, Deep loess and Aggregated silt***].
- **Group-B:** (**Moderately Low runoff Potential**): Soils having ***moderate infiltration rates*** when thoroughly wetted. These soils have moderate rate of water transmission. [Example: ***Shallow loess, Sandy loam, Red loamy soil, Red sandy loam and Red sandy soil***].
- **Group-C:** (**Moderately High Runoff Potential**): Soils having ***low infiltration rates*** when thoroughly wetted. These soils have moderate rate of water transmission. [Example: ***Clayey loam, Shallow sandy loam, Soils usually high in clay, Mixed red and black soils***].
- **Group-D:** (**High Runoff Potential**): Soils having ***very low infiltration rates*** when thoroughly wetted and consisting chiefly of clay soils with a high swelling potential, soils with a permanent high-water table, soils with a clay layer near the surface.[Example: ***Heavy plastic clays, certain saline soils and deep black soils].***

b) Antecedent Moisture Condition

(*AMC*) refers to the moisture content present in the soil at the beginning of the rainfall-runoff event under consideration. It is well known that initial abstraction and infiltration are governed by AMC. For practical application three levels of AMC are recognized by SCS as follows:

AMC-I: Soils are dry but not to wilting point. Satisfactory cultivation has taken place.

AMC-II: Average conditions

AMC-III: Sufficient rainfall has occurred within the immediate past 5 days. Saturated soil conditions prevail.

T able (3) Antecedent Moisture Conditions (AMC) for Determining the Value of CN.

AMC Type	Total Rain in Previous 5 days	
	Dormant Season	**Growing Season**
I	Less than 13 mm	Less than 36 mm
II	13 to 28 mm	36 to 53 mm
III	More than 28 mm	More than 53 mm

c) Land Use/cover

The variation of *CN* under AMC-II, called CN_{II}, for various land use conditions commonly found in practice are shown in Table (4) (*a*, *b and c*).

Table (4-a) Runoff Curve Numbers (CN_{II}) for Hydrologic Soil Cover Complexes (Under AMC-II Conditions)

Land Use	Cover		Hydrologic soil group			
	Treatment or practice	**Hydrologic condition**	**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

Note: Sugarcane has a separate supplementary Table of CN_I values (Table 4-b) The conversion of CN_{II} to other two AMC conditions can be made through the use of following correlation equations.

For AMC-I: $CN_I = \frac{CN_{II}}{12.281 - 0.01281\, CN_{II}}$ ------ (11)

Table (4-b) CN_{II} Values for Sugarcane

Cover and treatment	Hydrologic soil group			
	A	B	C	D
Limited cover, Straight Row	67	78	85	89
Partial cover, Straight row	49	69	79	84
Complete cover, Straight row	39	61	74	80
Limited cover, Contoured	65	75	82	86
Partial cover, Contoured	25	59	45	83
Complete cover, Contoured	6	35	70	79

Table (4-c) CN_{II} Values for Suburban and Urban Land Uses

Cover and treatment	Hydrologic soil group			
	A	B	C	D
Open spaces, lawns, parks etc				
(i) In good condition, grass cover in more than 75% area	39	61	74	80
(ii) In fair condition, grass cover on 50 to 75% area	49	69	79	84
Commercial and business areas (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential, average 65% impervious	77	85	90	92
Paved parking lots, paved roads with curbs, roofs, driveways, etc	98	98	98	98
Streets and roads				
Gravel	76	85	89	91
Dirt	72	82	87	89

For AMC-III: $CN_{III} = \dfrac{CN_{II}}{0.427 + 0.00573\, CN_{II}}$ ------ (12)

The equations (11) and (12) are applicable in the CN_{II}, range of 55 to 95 which covers most of the practical range.

<u>Notes about λ</u>

λ=0.1 valid *for Black soils under AMC of Type II and III.*

λ=0.3 *valid for Black soils under AMC of Type I and for all other soils(excluding Black soil) having AMC of types I, II and III.*

Example (4)

In a 350 ha watershed the CN value was assessed as 70 for AMC-III.

a) Estimate the value o f direct runoff volume for the following 4 days of rainfall. The AMC on July 1st was of category III. Use standard SCS-CN equations.

Date	July 1	July 2	July 3	July 4
Rainfall (mm)	50	20	30	18

b) What would be the runoff volume if the CN_{III} value were 80?

Solution

a) Given CN$_{III}$ = 70 S = (25400/70) - 254 = 108.6mm

$$Pe = \frac{(P - 0.2\,S)^2}{P + 0.8S} \;;\; \text{for } P > 0.2S$$

$$Pe = \frac{[P - (0.2)108.6]^2}{P + 0.8(108.6)} = \frac{[P - 21.78]^2}{P + 87.09} \;;\; for\ P > 21.78 \text{ mm}$$

Date	P (mm)	Pe (mm)
July 1	50	5.81
July 2	20	0
July 3	30	0.58
July 4	18	0
Total	**118**	**6.39**

Total runoff volume over the catchment Vr = 350 × 10^4 × 6.39/1000

= 22,365 m^3

b) Given CN$_{III}$ = 80 S = (25400/80) - 254 = 63.5 mm

$$Pe = \frac{(P - 0.2\,S)^2}{P + 0.8S} \;;\; \text{for } P > 0.2S$$

$$Pe = \frac{[P - (0.2)63.5]^2}{P + 0.8(63.5)} = \frac{[P - 12.70]^2}{P + 50.80} \;;\; for\ P > 12.70 \text{ mm}$$

Date	P (mm)	Pe (mm)
July 1	50	13.80
July 2	20	0.75
July 3	30	3.70
July 4	18	0.41
Total	**118**	**18.66**

Total runoff volume over the catchment Vr = 350 × 10^4 × 18.66/1000

= 65,310m^3

Example (5)

A small watershed is 250 ha in size has group **C** soil. The land cover can be classified as 30% open forest and 70% poor quality pasture. Assuming AMC at average condition and the soil to be black soil, estimate the direct runoff volume due to a rainfall o f 75 mm in one day.

Solution

AMC = II . Hence *CN* = CNII . Soil = Black soil. Referring to Table (4-a) for **C**-group soil;

Land use	%	*CN*	Product
Open forest	30	60	1800
Pasture (poor)	70	86	6020
Total	**100**		**7820**

Average *CN* = 7820/100 = 78.2 S = (25400/78.2) - 254 = 70.81mm

The relevant runoff equation for Black soil and *AMC-II* is(λ=0.1) ;

$$Pe = \frac{(P - 0.1\,S)^2}{P + 0.9S} \;;\; \text{for } P > 0.1S$$

$$Pe = \frac{[P - (0.1)70.81]^2}{P + 0.9(70.81)} = 33.25 \;;\; for\ P > 7.08 \text{ mm}$$

Total runoff volume over the catchment Vr = $250 \times 10^4 \times 33.25/(1000)$

= 83,125 m^3

Example (5)

The land use and soil characteristics of a 5000 ha watershed are as follows:

Soil: Not a black soil.

Hydrologic soil classification: 60% is Group B and 40% is Group C

Land Use:

Hard surface areas = 10%

Waste Land = 5%

Orchard (without understory cover) = 30%

Cultivated (Terraced), poor condition = 55%

Antecedent rain: The total rainfall in past five days was 30 mm. The season is dormant season.

(a) Compute the runoff volume from a 125 mm rainfall in a day on the watershed

(b) What would have been the runoff if the rainfall in the previous 5 days was 10 mm?

(c) If the entire area is urbanized with 60% residential area (65% average impervious area), 10% of paved streets and 30% commercial and business area (85% impervious),
estimate the runoff volume under AMC-II condition for one day rainfall of 125 mm.

Solution

a) Calculation of weighted *CN;* From Table (3) *AMC* = Type III. Using Table (4-a) weighted CN_{II} is calculated as *below* ***;***

Land use	Total (%)	Soil Group B (60%)			Soil Group C (40%)		
		%	*CN*	Product	%	*CN*	Product
Hard surface	10	6	86	516	4	91	364
Waste land	5	3	80	240	2	85	170
Orchard	30	18	55	990	12	69	828
Cultivated land	55	33	71	2343	22	77	1694
Total				**4089**			**3056**

Weighted $CN = \frac{(4089 + 3056)}{100} = 71.45$

100

By Eq. (12) *;* $CN_{III} = \frac{71.45}{0.427 + 0.00573\,(71.45)} = 85.42$

Since the soil is not a black soil, λ=0.3 is used to compute the surface runoff.

$$Pe = \frac{(P - 0.3\,S)^2}{P + 0.7S}\ ;\ \text{for } P > 0.3S$$

$$S = 25400/CN - 254 = (25400/85.42) - 254 = 43.35 \text{ mm}$$

$$Pe = \frac{(125 - (0.3)\,43.35)^2}{125 + 0.7(43.35)} = 80.74\ mm$$

Total runoff volume over the catchment *Vr* = 5000 × 10^4 × 80.74/(1000)

= 4,037,000 m^3 = 4.037 Mm^3

b) Here AMC = Type I , and use Eq.(11) to get CN_I;

$$CN_I = \frac{71.45}{2.281 - 0.01281(71.45)} = 52.32$$

$$S = 25400/52.32 - 254 = 231.47$$

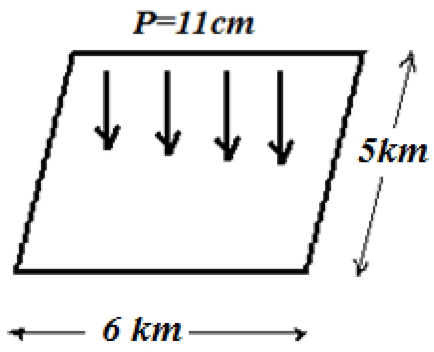
$$Pe = \frac{(125 - (0.3)\,231.47)^2}{125 + 0.7(231.475)} = 10.75\ mm$$

Total runoff volume over the catchment Vr = 5000 ×10^4 × 10.75/(1000)

= 537500 m^3

HW2

For Hydrological soil Group (HSG) type B for Pasture of Good cover(*Under AMC-II Conditions)*, calculate the runoff volume by SCS-CN method.



Solution of HW

From Table (4-a): CN_{II} =