19. If the infiltration continues at full capacity (i.e., the ponding effect continues throughout the period), the cumulative infiltration at the end of the period can be computed from the same equation of step 12 plotted in Figure 2.19. For $t =$ 50 min or 0.83 hr, $F = 1.60$ in.

20. Depression storage will reduce by 0.2 in. equal to $(i\,\Delta t - \Delta F)$.

F. Sixth and seventh rainfall periods

21. Computation continues similar to the fourth period by the application of the equation of step 12 as shown in Table 2.19.

2.14 HEC'S NONLINEAR LOSS-RATE FUNCTION APPROACH FOR DIRECT RUNOFF

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers has used the term *loss* for the precipitation not available to direct runoff and has indicated that the rate of loss is related nonlinearly to the rainfall intensity and a *loss-rate function* that decreases with increased ground wetness. The HEC studies indicated that a fairly definite quantity of water loss by interception and infiltration is required to satisfy initial moisture deficiencies before runoff can occur. An allowance for this initial loss or initial abstraction is made according to various antecedent soil moisture conditions. After the initial abstraction, the loss takes place at the following rate, which does not exceed the amount of precipitation for any time interval:

$$f = Kp^E \qquad [\mathrm{LT}^{-1}] \tag{2.47a}$$

with

$$K = K_0 C^{-0.1L} \qquad [\text{dimensionless}] \tag{2.47b}$$

where

$f =$ loss rate, in. or mm per hour

$K =$ loss rate function

$p =$ rainfall intensity, in. or mm per hour

$E =$ exponent ranging between 0.3 and 0.9, with a frequent value of 0.7

$K_0 =$ loss coefficient at start of a storm

$C =$ coefficient controlling the rate of decrease of the loss-rate function

$L =$ accumulated loss during the storm, in. or mm

A typical plot for the loss-rate function is shown in Figure 2.20. The loss-rate coefficients are determined from the rainfall and runoff data. The HEC has developed a loss-rate optimization program for this purpose (HEC, 1973).

EXAMPLE 2.17

Determine the rainfall excess for successive periods for the storm of Example 2.16 by the loss-rate function approach. Assume that Figure 2.20 applies for the loss-rate function. Use $E = 0.7$.

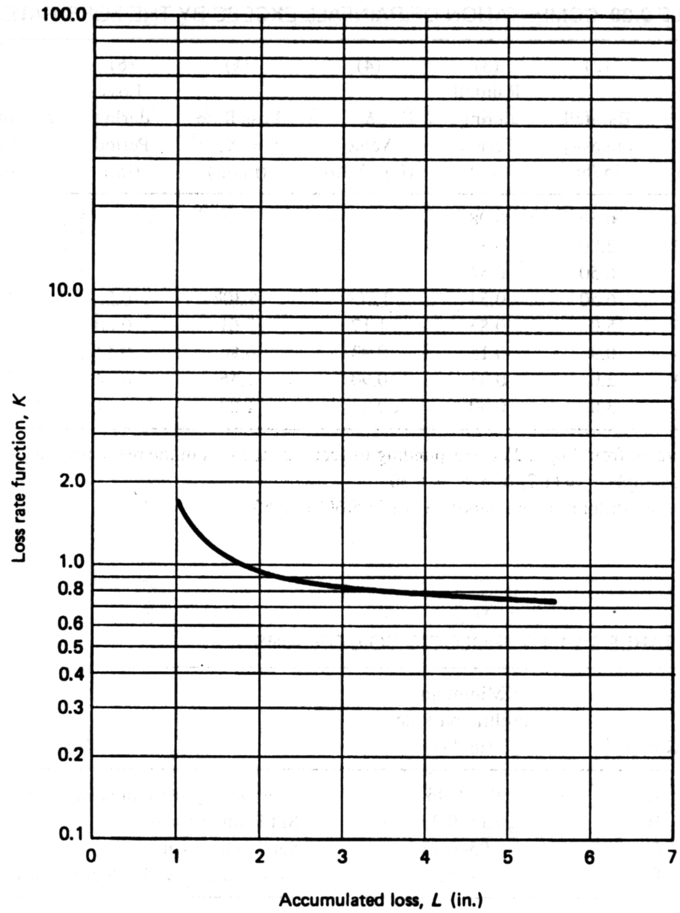

Figure 2.20 Loss-rate function.

SOLUTION

1. Initial accumulated loss from Figure 2.20 is 1.0 in.
2. Assuming a uniform distribution of the rain within 10-min observation periods, the rainfall of the first 25 min will be abstracted in the initial loss of about 1.0 in., as follows:

0–10 min	$0.5\left(\frac{10}{60}\right) = 0.08$ in.
10–20 min	$2\left(\frac{10}{60}\right) = 0.33$ in.
20–25 min	$6.5\left(\frac{5}{60}\right) = 0.54$ in.
	0.95 in.

3. The direct runoff will appear after 25 min. The computation is shown in Table 2.20.

2.15 THE NRCS APPROACH FOR DIRECT RUNOFF

By studying the infiltration behavior of different types of soils, the Natural Resources Conservation Service (formerly SCS) developed a method of computing the direct runoff

TABLE 2.20 COMPUTATION OF RAINFALL EXCESS BY THE LOSS-RATE FUNCTION METHOD

(1) Time (min)	(2) Rainfall Intensity (in./hr)	(3) Rainfall during Period (in.)	(4) K Value (Fig. 2.20)	(5) Loss Rate, $f = Kp^{0.7}$ (in./hr)	(6) Loss during Period (in.)	(7) Accumulated Loss (in.)	(8) Rainfall Excess (in.) (col. 3−col. 6)
0–10	0.50	0.08				0.95 initial loss (≈1)	
10–20	2.00	0.33					
20–25	6.50	0.54					
25–30	6.50	0.54	1.70[a]	6.30[b]	0.53[c]	1.48	0.01
30–40	5.0	0.83	1.17	3.61	0.60	2.08	0.23
40–50	0.9	0.15	0.93	0.86	0.14	2.22	0.01
50–60	2.0	0.33	0.90	1.46	0.24	2.46	0.09
60–70	3.0	0.50	0.87	1.88	0.31	2.77	0.19

[a] The value from Fig. 2.20 corresponding to accumulated loss in the preceding step.
[b] For example, $f = (1.7)(6.5)^{0.7} = 6.30$.
[c] (Column 5)(duration in hours): i.e., (6.3)(5/60) = 0.53.

TABLE 2.21 HYDROLOGIC SOIL GROUPS

Group	Minimum Infiltration Rate (in./hr)	Texture[a]
A	0.3–0.45	Sand, loamy sand, or sandy loam
B	0.15–0.30	Silt loam or loam
C	0.05–0.15	Sandy clay loam
D	0–0.05	Clay loam, silty clay loam, sandy clay, silty clay, or clay

[a]Reproduced from U.S. Soil Conservation Service (1986).

resulting from a rainfall storm (U.S. SCS, 1972). The factors affecting infiltration are: hydrologic soil group, type of land cover, hydrologic condition and antecedent (pre-storm) moisture condition, and cropping practice in the case of cultivated agriculture land. Each of these factors is subdivided into many classes. Hydrologically, soils are assigned four groups on the basis of intake of water on bare soil when thoroughly wetted, as shown in Table 2.21. With urbanization the soil profile is disturbed considerably. The group classification can be based on the texture of disturbed soil.

Type of land cover, such as bare soil, vegetation, impervious surface, and so on, establishes runoff production potential. Important cover types for urban areas, cultivated agriculture lands, other agriculture lands, and arid rangelands are given in Table 2.22. Cultivated agricultural lands are further subdivided by treatment or cropping practice, such as straight row, contoured, and contoured and terraced. The hydrologic conditions reflect the level of land management. Hydrologically poor conditions represent a state of land use that will provide higher runoff compared to good conditions. The antecedent moisture condition (AMC) is the index of the soil condition with respect to runoff potential before a storm event. It has three categories as shown in Table 2.23.

TABLE 2.22 CURVE NUMBERS FOR ANTECEDENT MOISTURE CONDITION II

Use	Cover Type	Treatment	Hydrologic Condition	Hydrologic soil group			
				A	B	C	D
Urban	Fully developed						
	Open space (lawns, parks)		Poor (cover < 50%)	68	79	86	89
			Fair	49	69	79	84
			Good (grass cover > 75%)	39	61	74	80
	Impervious areas (paved parking, roofs, driveways, paved roads)			98	98	98	98
	Dirt roads			72	82	87	89
	Urban districts						
	Commercial and business			89	92	94	95
	Industrial			81	88	91	93
	Developing areas			77	86	91	94
Cultivated agriculture lands	Fallow	Bare soil	. . .	77	86	91	94
	Row crops	Straight row	Poor	72	81	88	91
		Straight row	Good	67	78	85	89
		Contoured	Poor	70	79	84	88
		Contoured	Good	65	75	82	86
		Contoured and terraced	Poor	66	74	80	82
		Contoured and terraced	Good	62	71	78	81
	Small grain	Straight row	Poor	65	76	84	88
		Straight row	Good	63	75	83	87
		Contoured	Poor	63	74	82	85
		Contoured	Good	61	73	81	84
		Contoured and terraced	Poor	61	72	79	82
		Contoured and terraced	Good	59	70	78	81

continued

TABLE 2.22 *(cont.)*

Use	Cover Type	Treatment	Hydrologic Condition	Hydrologic soil group			
				A	B	C	D
	Close-seeded legumes or rotation meadow	Straight row	Poor	66	77	85	89
		Straight row	Good	58	72	81	85
		Contoured	Poor	64	75	83	85
		Contoured	Good	55	69	78	83
		Contoured and terraced	Poor	63	73	80	83
		Contoured and terraced	Good	51	67	76	80
Agriculture lands	Pasture or range		Poor	68	79	86	89
			Fair	49	69	79	84
			Good	39	61	74	80
	Meadow			30	58	71	78
	Woods		Poor	45	66	77	83
			Fair	36	60	73	79
			Good	30	55	70	77
	Farmsteads (building, lanes, driveways)			59	74	82	86
Arid and semiarid rangelands	Herbaceous (mixture of grass, weeds, and low-growing brush)		Poor (< 30% ground cover)		80	87	93
			Fair		71	81	89
			Good (> 70% cover)		62	74	85
	Oak–aspen (mountain brush mixture)		Poor		66	74	79
			Fair		48	57	63
			Good		30	41	48
	Pinyon–juniper		Poor		75	85	89
			Good		41	61	71
	Sagebrush with grass understory		Poor		67	80	85
			Good		35	47	55
	Desert shrub		Poor	63	77	85	88
			Fair	55	72	81	86
			Good	49	68	79	84

Source: Condensed from U.S. Soil Conservation Service (1986).

TABLE 2.23 ANTECEDENT MOISTURE CONDITION

Category	Condition
I	Dry soil but not to the wilting point
II	Average conditions
III	Saturated soils; heavy rainfall or light rainfall with low temperatures have occurred in the last 5 days

The NRCS (SCS) has evolved a system of curve numbers. A distinct curve number (CN) is assigned on the basis of the combination of the factors above. Table 2.22 gives curve numbers for antecedent moisture condition II. Table 2.24 provides conversion of CNs to other conditions. For an area with many different subareas, the composite CN is determined by adding the product of CN and respective area and dividing by the total area.

The NRCS runoff equation is

$$Q = \frac{(P - 0.2S)^2}{(P + 0.8S)} \quad [L] \tag{2.48}$$

where

$Q =$ accumulated runoff, in. or mm depth over the drainage area

TABLE 2.24 CROSS-LINKING OF CURVE NUMBERS FOR VARIOUS ANTECEDENT MOISTURE CONDITIONS

Curve Number for Condition II	Corresponding Curve Number for Condition: I	III
100	100	100
95	87	99
90	78	98
85	70	97
80	63	94
75	57	91
65	45	83
60	40	79
55	35	75
50	31	70
45	27	65
40	23	60
35	19	55
30	15	50
25	12	45
20	9	39
15	7	33
10	4	26
5	2	17
0	0	0

Source: U.S. Soil Conservation Service (1972).

$P =$ accumulated rainfall depth, in. or mm

$S =$ potential maximum retention* of water by the soil, in. or mm

The potential maximum retention, S, is related to the curve number, CN, by the following relation:

$$\text{CN} = \frac{1000}{10 + S} \quad \text{[unbalanced]} \tag{2.49}$$

Thus, once a curve number is ascertained from Tables 2.22 and 2.24 for the known conditions, the direct runoff can be computed from eqs. (2.48) and (2.49). The TR-55 (SCS, 1986) contains a graph and a table that solve eq. (2.48) directly. The tabular solution is reproduced in Table 2.25 for a certain range of CNs and rainfall values.

To use the method for sequential rainfall, the intensity is converted to the rainfall depth for each period of sequence and accumulated to the end of each period. From the

TABLE 2.25 RUNOFF DEPTH FOR SELECTED CNs AND RAINFALL AMOUNTS[a]

	Runoff Depth (in.) for Curve Number of:												
Rainfall	40	45	50	55	60	65	70	75	80	85	90	95	98
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.06	0.17	0.32
1.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.08	0.17	0.32	0.56	0.79
1.2	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.07	0.15	0.27	0.46	0.74	0.99
1.4	0.00	0.00	0.00	0.00	0.00	0.02	0.06	0.13	0.24	0.39	0.61	0.92	1.18
1.6	0.00	0.00	0.00	0.00	0.01	0.05	0.11	0.20	0.34	0.52	0.76	1.11	1.38
1.8	0.00	0.00	0.00	0.00	0.03	0.09	0.17	0.29	0.44	0.65	0.93	1.29	1.58
2.0	0.00	0.00	0.00	0.02	0.06	0.14	0.24	0.38	0.56	0.80	1.09	1.48	1.77
2.5	0.00	0.00	0.02	0.08	0.17	0.30	0.46	0.65	0.89	1.18	1.53	1.96	2.27
3.0	0.00	0.02	0.09	0.19	0.33	0.51	0.71	0.96	1.25	1.59	1.98	2.45	2.77
3.5	0.02	0.08	0.20	0.35	0.53	0.75	1.01	1.30	1.64	2.02	2.45	2.94	3.27
4.0	0.06	0.18	0.33	0.53	0.76	1.03	1.33	1.67	2.04	2.46	2.92	3.43	3.77
4.5	0.14	0.30	0.50	0.74	1.02	1.33	1.67	2.05	2.46	2.91	3.40	3.92	4.26
5.0	0.24	0.44	0.69	0.98	1.30	1.65	2.04	2.45	2.89	3.37	3.88	4.42	4.76
6.0	0.50	0.80	1.14	1.52	1.92	2.35	2.81	3.28	3.78	4.30	4.85	5.41	5.76
7.0	0.84	1.24	1.68	2.12	2.60	3.10	3.62	4.15	4.69	5.25	5.82	6.41	6.76
8.0	1.25	1.74	2.25	2.78	3.33	3.89	4.46	5.04	5.63	6.21	6.81	7.40	7.76
9.0	1.71	2.29	2.88	3.49	4.10	4.72	5.33	5.95	6.57	7.18	7.79	8.40	8.76
10.0	2.23	2.89	3.56	4.23	4.90	5.56	6.22	6.88	7.52	8.16	8.78	9.40	9.76
11.0	2.78	3.52	4.26	5.00	5.72	6.43	7.13	7.81	8.48	9.13	9.77	10.39	10.76
12.0	3.38	4.19	5.00	5.79	6.56	7.32	8.05	8.76	9.45	10.11	10.76	11.39	11.76
13.0	4.00	4.89	5.76	6.61	7.42	8.21	8.98	9.71	10.42	11.10	11.76	12.39	12.76
14.0	4.65	5.62	6.55	7.44	8.30	9.12	9.91	10.67	11.39	12.08	12.75	13.39	13.76
15.0	5.33	6.36	7.35	8.29	9.19	10.04	10.85	11.63	12.37	13.07	13.74	14.39	14.76

[a]Interpolate the values shown to obtain runoff depths for CNs or rainfall amounts not shown.
Source: U.S. Soil Conservation Service (1986).

*This is mostly the infiltration. The term is distinct from the surface retention, which does not include the infiltration.

accumulated rainfall to the end of successive rain periods, the accumulated direct runoff or rainfall excess is derived for each time period using the NRCS equation (2.48). The accumulated direct runoff is then converted to the increments of the runoff.

EXAMPLE 2.18

Determine the direct runoff (rainfall excess) for successive 10-min periods of the storm of Example 2.16. The soil in the basin belongs to hydrologic group B. The basin is mostly wooded in good hydrologic condition. The saturated soil condition (condition III) exists in the basin.

SOLUTION

1. For given hydrologic characteristics and for moisture condition II, CN = 55, from Table 2.22.
2. Corresponding CN = 75 for condition III, from Table 2.24.
3. Computations for accumulated rain and runoff are given in Table 2.26.

2.16 INFILTRATION-INDEX APPROACH FOR DIRECT RUNOFF

The index approach is the simplest procedure to estimate the total volume of storm runoff. The object of this method is to obtain a coefficient that may be applied to an entire rain period, or to an entire storm if it is made up of several rain periods, to arrive at an estimate of the direct runoff (Cook, 1946). Three types of indices are common: (1) the ϕ index, which represents a level (horizontal line) of intensity that divides the rainfall intensity diagram in such a manner that the depth of rain above the index line is equivalent to surface runoff depth over the basin, as illustrated in Figure 2.21; (2) the f_{av} index, which indicates the average rate of infiltration during a period in which the rainfall intensity is equal to or more than the infiltration capacity, f_p; and (3) the W index, which is a mean of f_{av} when it varies across a watershed. The value of W for a rain occurring after the watershed is wetted and the infiltration capacity is reduced to the minimum is known as the W_{min} index.

The ϕ index is the simplest of these indices. For its determination, the rainfall due to a storm is measured and the amount of runoff is obtained from the corresponding direct

TABLE 2.26 COMPUTATION OF RUNOFF BY THE NRCS (SCS) METHOD

(1) Time (min)	(2) Rainfall Intensity (in./hr)	(3) Amount of Rain[a] (in.)	(4) Accumulated Rainfall (in.)	(5) Accumulated Direct Runoff (Table 2.25) (in.)	(6) Runoff Increments[b] (in.)
0–10	0.5	0.08	0.08	0	0
10–20	2.0	0.33	0.41	0	0
20–30	6.5	1.08	1.49	0.16	0.16
30–40	5.0	0.83	2.32	0.55	0.39
40–50	0.9	0.15	2.47	0.65	0.10
50–60	2.0	0.33	2.80	0.84	0.19
60–70	3.0	0.50	3.30	1.17	0.33

[a]For example, (0.5 in./hr × 10 min)(1 hr/60 min).
[b]Difference between successive values, 0.55 − 0.16 = 0.39.