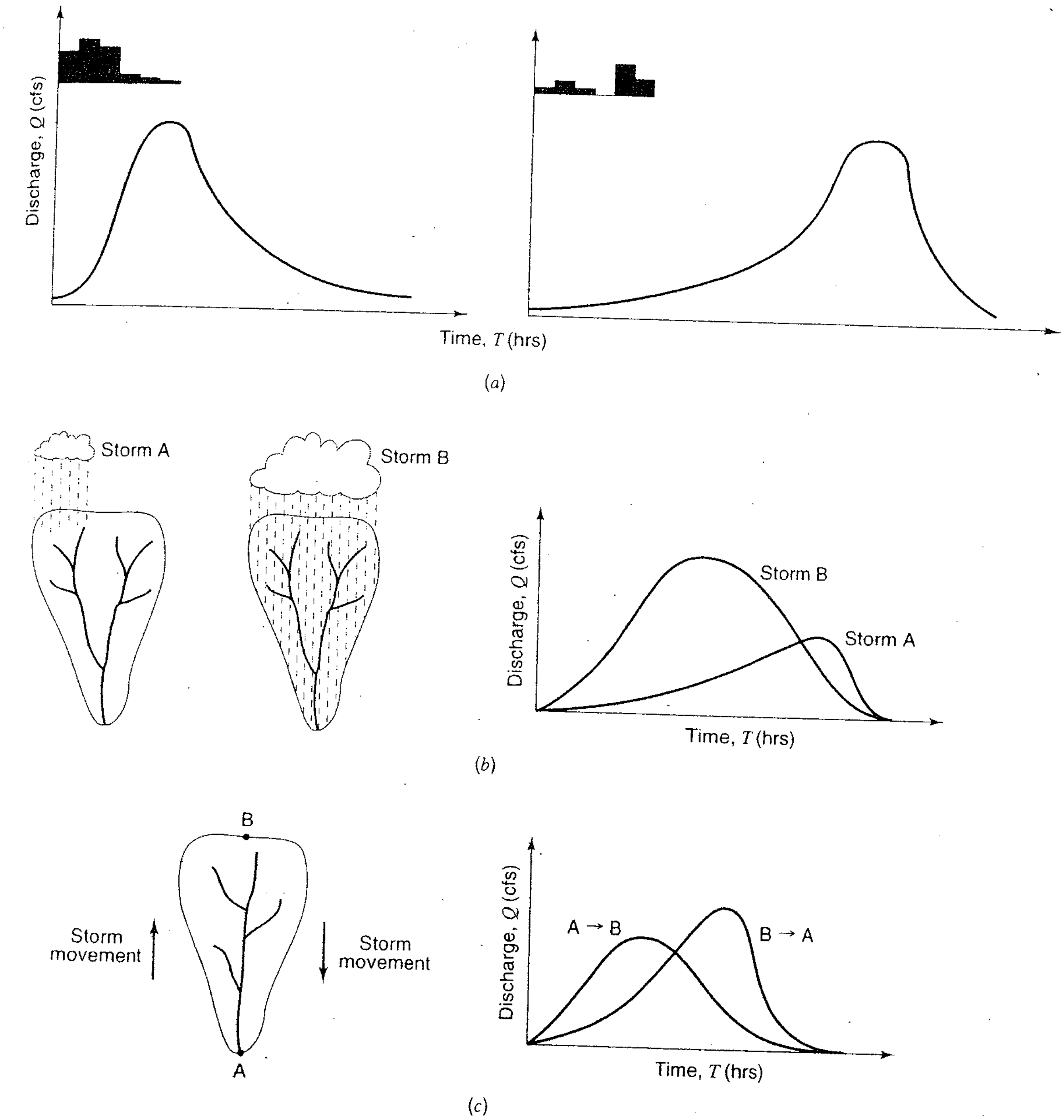


Figure 8.1.5 Effects of storm shape, size, and movement on surface runoff. (*a*) Effect of time variation of rainfall intensity on the surface runoff; (*b*) Effect of storm size on surface runoff. (*c*) Effect of storm movement on surface runoff (from Masch 1984)).

8.2 HYDROLOGIC LOSSES AND RAINFALL EXCESS

Rainfall excess, or *effective rainfall*, is that rainfall that is neither retained on the land surface nor infiltrated into the soil. After flowing across the watershed surface, rainfall excess becomes direct runoff at the watershed outlet. The graph of rainfall excess versus time is the rainfall excess hyetograph. As shown in Figure 8.2.1, the difference between the observed total rainfall hyetograph and the rainfall excess hyetograph is the *abstractions*, or *losses*. Losses are primarily water absorbed by infiltration with some allowance for interception and surface storage. The relationships of rainfall, infiltration rate, and cumulative infiltration are shown in Figure 8.2.2. Figure 8.2.2 illustrates the relationships for rainfall and runoff data of an actual storm that can be obtained from data recorded by the U.S. Geological Survey. Using the rainfall data, rainfall hyetographs can be computed.

The objective of many hydrologic design and analysis problems is to determine the surface runoff from a watershed due to a particular storm. This process is commonly referred to as *rainfall-runoff analysis*. The processes (steps) are illustrated in Figure 8.2.3 to determine the *storm runoff hydrographs* (or streamflow or discharge hydrograph) using the unit hydrograph approach.

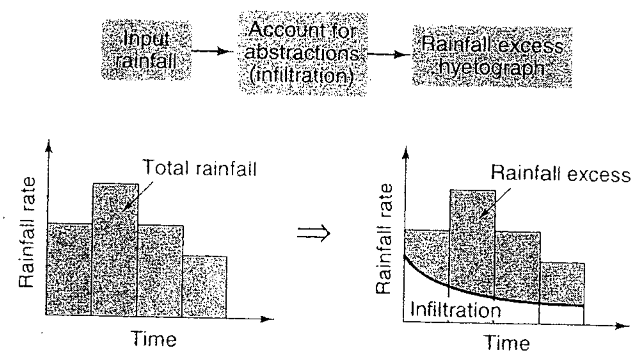


Figure 8.2.1 Concept of rainfall excess. The difference between the total rainfall hyetograph on the left and the total rainfall excess hyetograph on the right is the abstraction (infiltration).

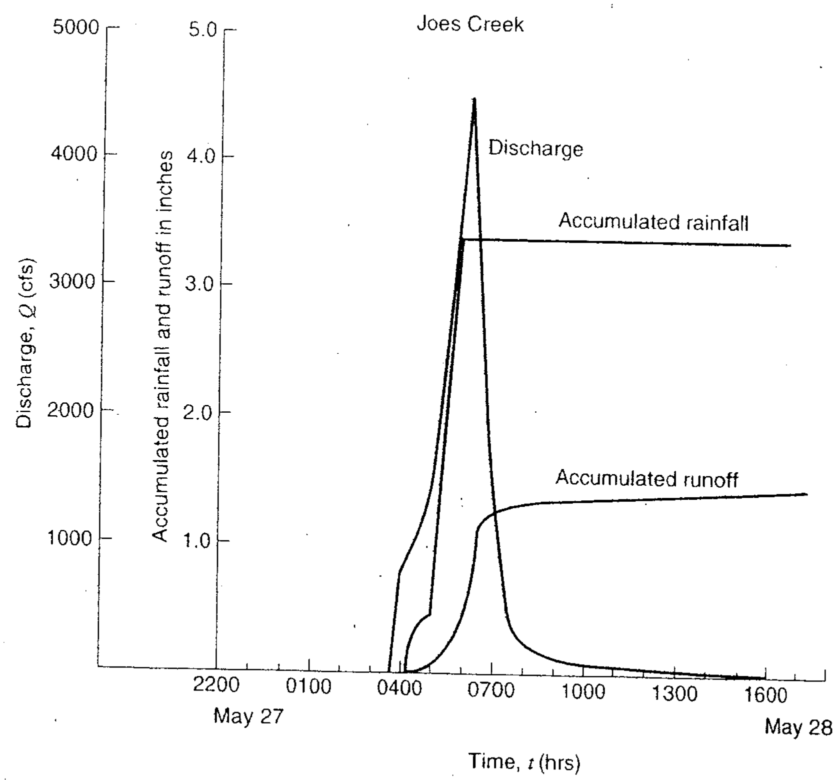


Figure 8.2.2 Precipitation and runoff data for Joes Creek, storm of May 27–28, 1978 (from Masch (1984)).

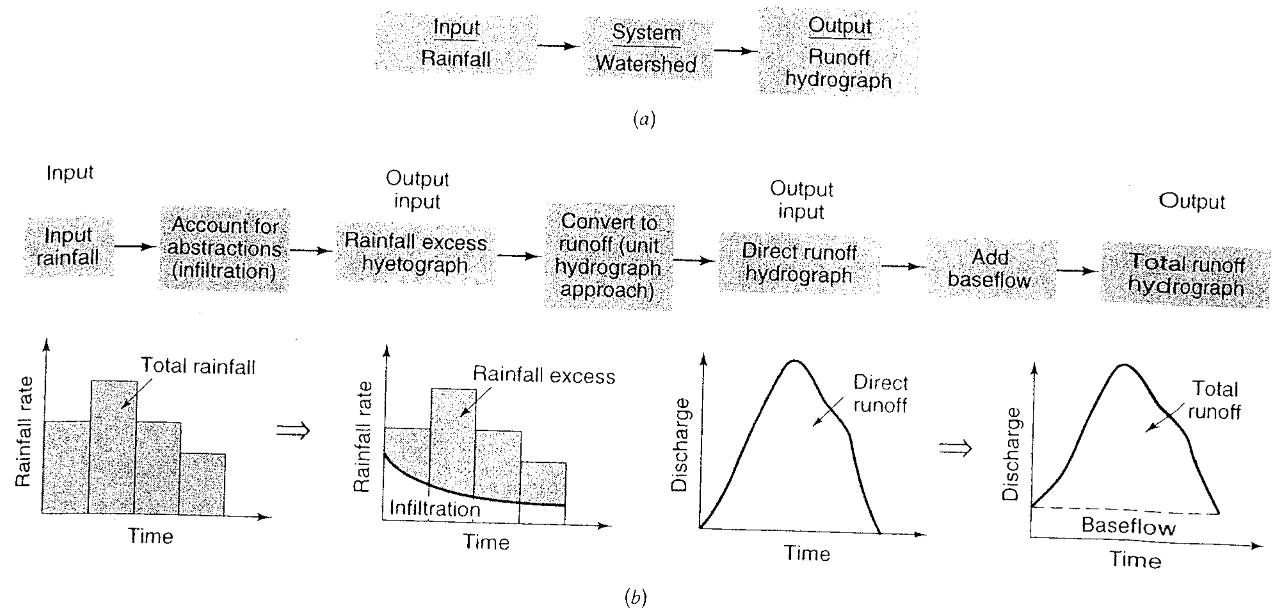


Figure 8.2.3 Storm runoff hydrographs. (*a*) Rainfall-runoff modeling; (*b*) Steps to define storm runoff.

8.3 RAINFALL-RUNOFF ANALYSIS USING UNIT HYDROGRAPH APPROACH

The objective of *rainfall-runoff analysis* is to develop the runoff hydrograph as illustrated in Figure 8.2.3*a*, where the system is a watershed or river catchment, the input is the rainfall hyetograph, and the output is the runoff or discharge hydrograph. Figure 8.2.3*b* defines the processes (steps) to determine the runoff hydrograph from the rainfall input using the *unit hydrograph approach*.

A *unit hydrograph* is the direct runoff hydrograph resulting from 1 in (or 1 cm in SI units) of excess rainfall generated uniformly over a drainage area at a constant rate for an effective duration. The unit hydrograph is a simple linear model that can be used to derive the hydrograph resulting from any amount of excess rainfall. The following basic assumptions are inherent in the unit hydrograph approach:

1. The excess rainfall has a constant intensity within the effective duration.
2. The excess rainfall is uniformly distributed throughout the entire drainage area.
3. The base time of the direct runoff hydrograph (i.e., the duration of direct runoff) resulting from an excess rainfall of given duration is constant.
4. The ordinates of all direct runoff hydrographs of a common base time are directly proportional to the total amount of direct runoff represented by each hydrograph.
5. For a given watershed, the hydrograph resulting from a given excess rainfall reflects the unchanging characteristics of the watershed.

The following *discrete convolution equation* is used to compute direct runoff hydrograph ordinates Q_n, given the rainfall excess values P_m and given the unit hydrograph ordinates U_{n-m+1} (Chow et al., 1988):

$$Q_n = \sum_{m=1}^{n \le M} P_m U_{n-m+1} \qquad \text{for } n = 1, 2, \ldots, N \tag{8.3.1}$$

where n represents the direct runoff hydrograph time interval and m represents the precipitation time interval ($m = 1, \ldots, n$).

The reverse process, called *deconvolution*, is used to derive a unit hydrograph given data on P_m and Q_n. Suppose that there are M pulses of excess rainfall and N pulses of direct runoff in the storm considered; then N equations can be written for Q_n, $n = 1, 2 \ldots, N$, in terms of $N - M + 1$ unknown values of the unit hydrograph, as shown in Table 8.3.1. Figure 8.3.1 diagramatically illustrates the calculation and the runoff contribution by each rainfall input pulse.

Table 8.3.1 The Set of Equations for Discrete Time Convolution

$$
\begin{aligned}
Q_1 &= P_1U_1 \\
Q_2 &= P_2U_1 + P_1U_2 \\
Q_3 &= P_3U_1 + P_2U_2 + P_1U_3 \\
&\ldots \\
Q_M &= P_MU_1 + P_{M-1}U_2 + \ldots + P_1U_M \\
Q_{M+1} &= 0 + P_MU_2 + \ldots + P_2U_M + P_1U_{M+1} \\
&\ldots \\
Q_{N-1} &= 0 + 0 + \ldots + 0 + 0 + \ldots + P_MU_{N-M} + P_{M-1}U_{N-M+1} \\
Q_N &= 0 + 0 + \ldots + 0 + 0 + \ldots + 0 + P_MU_{N-M+1}
\end{aligned}
$$

Once the unit hydrograph has been determined, it may be applied to find the direct runoff and streamflow hydrographs for given storm inputs. When a rainfall hyetograph is selected, the abstractions are subtracted to define the excess rainfall hyetograph. The time interval used in defining the excess rainfall hyetograph ordinates must be the same as that for which the unit hydrograph is specified.

EXAMPLE 8.3.1

CONVOLUTION

The 1-hr unit hydrograph for a watershed is given below. Determine the runoff from this watershed for the storm pattern given. The abstractions have a constant rate of 0.3 in/h.

Time (h)	1	2	3	4	5	6
Precipitation (in)	0.5	1.0	1.5	0.5		
Unit hydrograph (cfs)	10	100	200	150	100	50

SOLUTION

The calculations are shown in Table 8.3.2. The 1-hr unit hydrograph ordinates are listed in column 2 of the table; there are $L = 6$ unit hydrograph ordinates, where $L = N - M + 1$. The number of excess rainfall intervals is $M = 4$. The excess precipitation 1-hr pulses are $P_1 = 0.2$ in, $P_2 = 0.7$ in, $P_3 = 1.2$ in, and $P_4 = 0.2$ in, as shown at the top of the table. For the first time interval $n = 1$, the discharge is computed using equation (8.3.1):

$$Q_1 = P_1U_1 = 0.2 \times 10 = 2 \text{ cfs}$$

For the second time interval, n = 2,

$$Q_2 = P_1U_2 + P_2U_1 = 0.2 \times 100 + 0.7 \times 10 = 27 \text{ cfs}$$

and similarly for the remaining direct runoff hydrograph ordinates. The number of direct runoff ordinates is $N = L + M - 1 = 6 + 4 - 1 = 9$; i.e., there are nine nonzero ordinates, as shown in Table 8.3.2. Column 3 of Table 8.3.2 contains the direct runoff corresponding to the first rainfall pulse, $P_1 =$ 0.2 in, and column 4 contains the direct runoff from the second rainfall pulse, $P_2 = 0.2$ in, etc. The direct runoff hydrograph, shown in column 7 of the table, is obtained, from the principle of superposition, by adding the values in columns 3–6.

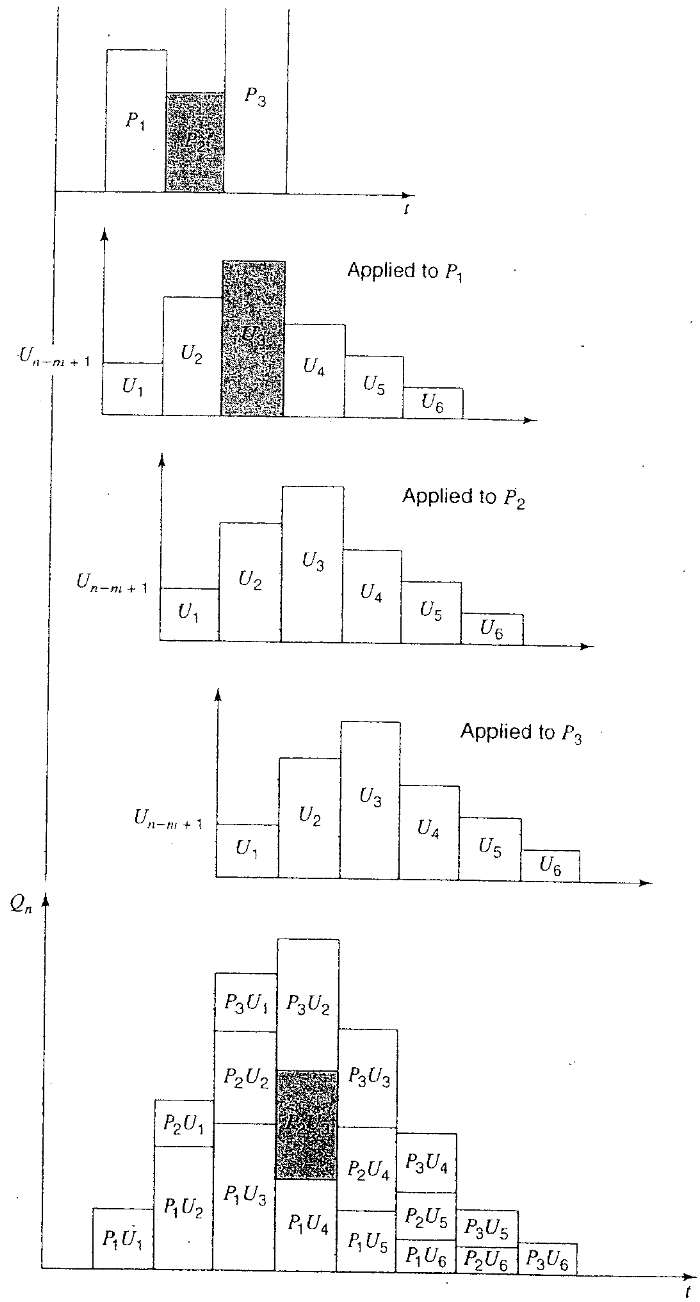


Figure 8.3.1 Application of unit hydrograph to rainfall input.

Table 8.3.2 Calculation of the Direct Runoff Hydrograph

(1)	(2)	(3)	(4)	(5)	(6)	(7)
		Total Precipitation (in)				
		0.5	1	1.5	0.5	
Time (hr)	Unit Hydrograph (cfs/in)	Excess Precipitation (in)				Direct Runoff (cfs)
		0.2	0.7	1.2	0.2	
0	0	0	0			0
1	10	2	0	0		2
2	100	20	7	0	0	27
3	200	40	70	12	0	122
4	150	30	140	120	2	292
5	100	20	105	240	20	385
6	50	10	70	180	40	300
7	0	0	35	120	30	185
8			0	60	20	80
9				0	10	10
10					0	0

EXAMPLE 8.3.2

DECONVOLUTION

Determine the 1-hr unit hydrograph for a watershed using the precipitation pattern and runoff hydrograph below. The abstractions have a constant rate of 0.3 in/hr, and the baseflow of the stream is 0 cfs.

Time (h)	1	2	3	4	5	6	7	8	9	10
Precipitation (in)	0.5	1.0	1.5	0.5						
Runoff (cfs)	2	27	122	292	385	300	185	80	10	0

SOLUTION

Using the deconvolution process, we get $Q_1 = P_1U_1$

so that for $P_1 = 0.5 - 0.3 = 0.2$ in and $Q_1 = 2$ cfs,

$U_1 = Q_1/P_1 = 2/0.2 = 10$ cfs.

$Q_2 = P_1U_2 + P_2U_1$, so that

$U_2 = (Q_2 - P_2U_1)/P_1$

where

$P_2 = 1.0 - 0.3 = 0.7$ in and $Q_2 = 27$ cfs.

$U_2 = (27 - 0.7(10))/0.2 = 100$ cfs and

$Q_3 = P_1U_3 + P_2U_2 + P_3U_1$

then

$U_3 = (Q_3 - P_2U_2 - P_3U_1)/P_1$, so that

$U_3 = (122 - 0.7(100) - 1.2(10))/0.2 = 200$ cfs.

The rest of the unit hydrograph ordinates can be calculated in a similar manner.

8.4 SYNTHETIC UNIT HYDROGRAPHS

When observed rainfall-runoff data are not available for unit hydrograph determination, a *synthetic unit hydrograph*, can be developed. A unit hydrograph developed from rainfall and streamflow data in a watershed applies only to that watershed and to the point on the storm where the streamflow data were measured. Synthetic unit hydrograph procedures are used to develop unit hydrographs for other locations on the stream in the same watershed or other watersheds that are of similar character.

One of the most commonly used synthetic unit hydrograph procedures is Snyder's synthetic unit hydrograph. This method relates the time from the centroid of the rainfall to the peak of the unit hydrograph to geometrical characteristics of the watershed. To determine the regional parameters C_t and C_p, one can use values of these parameters determined from similar watersheds. C_t can be determined from the relationship for the *basin lag:*

$$t_p = C_1 C_t (L \cdot L_c)^{0.3} \tag{8.4.1}$$

where C_1, L, and L_c are defined in Table 8.4.1. Solving equation (8.4.1) for C_t gives

$$C_t = \frac{t_p}{C_1 (L \cdot L_c)^{0.3}} \tag{8.4.2}$$

Table 8.4.1 Steps to Compute Snyder's Synthetic Unit Hydrograph

Step 0	Measured information from topography map of watershed: • L = main channel length in mi (km) • L_c = length of the main stream channel from outflow point of watershed to a point opposite the centroid of the watershed in mi (km) • A = watershed area in mi^2 (km^2) Regional parameters C_t and C_p determined from similar watersheds.
Step 1	Determine time to peak (t_p) and duration (t_r) of the standard unit hydrograph: $t_p = C_1 C_t (L \cdot L_c)^{0.3}$ (hours) $t_r = t_p/5.5$ (hours) where C_1 = 1.0(0.75 for SI units)
Step 2	Determine the time to peak t_{PR} for the desired duration t_R: $t_{PR} = t_p + 0.25(t_R - t_r)$ (hours)
Step 3	Determine the peak discharge, Q_{PR} in cfs/in ((m^3/s)/cm in SI units) $Q_{PR} = \frac{C_2 C_P A}{t_{PR}}$ where C_2 = 640 (2.75 for SI units)
Step 4	Determine the width of the unit hydrograph at $0.5Q_{PR}$ and $0.75Q_{PR}$. W_{50} is the width at 50% of the peak given as $W_{50} = \frac{C_{50}}{(Q_{PR}/A)^{1.08}}$ where C_{50} = 770 (2.14 for SI units). W_{75} is the width at 75% of the peak given as $W_{75} = \frac{C_{75}}{(Q_{PR}/A)^{1.08}}$ where C_{75} = 440 (1.22 for SI units)

Table 8.4.1 Steps to Compute Snyder's Synthetic Unit Hydrograph (*continued*)

Step 5 Determine the base, T_B, such that the unit hydrograph represents 1 in (1 cm in SI units) of direct runoff volume:

$$1\text{ in} = \left[\left(\frac{W_{50}+T_B}{2}\right)(0.5Q_{PR}) + \left(\frac{W_{75}+W_{50}}{2}\right)(0.25Q_{PR}) + \frac{1}{2}W_{75}(0.25Q_{PR})\right]\left(\text{hr}\times\frac{\text{ft}^3}{\text{sec}}\right)$$

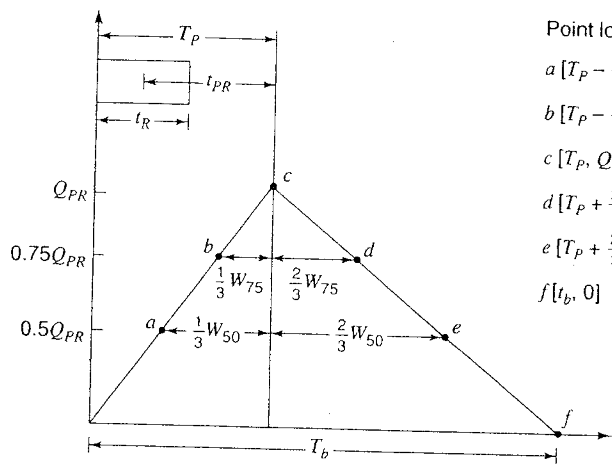
$$\left(\frac{1}{A(\text{mi})^2}\times\frac{1\text{ mi}^2}{(5280)^2\text{ ft}^2}\times\frac{12\text{ in}}{\text{ft}}\times\frac{3600\text{ sec}}{\text{hr}}\right)$$

Solving for t_b, we get

$$t_b = 2581\frac{A}{Q_{PR}} - 1.5W_{50} - W_{75}$$

for A in mi², Q_{PR} in cfs, W_{50} and W_{75} in hours.

Step 6 Define known points of the unit hydrograph. ($T_P = t_{PR} + \frac{t_R}{2}$)



Point location

$a\,[T_P - \frac{1}{3}W_{50},\ 0.5Q_{PR}]$

$b\,[T_P - \frac{1}{3}W_{75},\ 0.75Q_{PR}]$

$c\,[T_P,\ Q_{PR}]$

$d\,[T_P + \frac{2}{3}W_{75},\ 0.75Q_{PR}]$

$e\,[T_P + \frac{2}{3}W_{50},\ 0.5Q_{PR}]$

$f\,[t_b,\ 0]$

To compute C_t for a gauged basin, L and L_c are determined for the gauged watershed and t_p from the derived unit hydrograph for the gauged basin.

To compute the other required parameter C_p, the expression for peak discharge of the standard unit hydrograph can be used:

$$Q_p = \frac{C_2 C_p A}{t_p} \tag{8.4.3}$$

or for a unit discharge (discharge per unit area)

$$q_p = \frac{C_2 C_p}{t_p} \tag{8.4.4}$$

Solving equation (8.4.4) for C_p gives

$$C_p = \frac{q_p t_p}{C_2} \tag{8.4.5}$$

This relationship can be used to solve for C_p for the ungauged watershed, knowing the terms in the right-hand side.

Section 8.8 discusses the SCS-unit hydrograph procedure.

EXAMPLE 8.4.1 A watershed has a drainage area of 5.42 mi^2; the length of the main stream is 4.45 mi and the main channel length from the watershed outlet to the point opposite the center of gravity of the watershed is 2.0 mi. Using $C_t = 2.0$ and $C_p = 0.625$, determine the standard synthetic unit hydrograph for this basin. What is the standard duration? Use Snyder's method to determine the 30-min unit hydrograph parameter.

SOLUTION For the standard unit hydrograph, equation (8.4.1) gives

$$t_p = C_1 C_t (LL_c)^{0.3} = 1 \times 2 \times (4.45 \times 2)^{0.3} = 3.85 \text{ hr}$$

The standard rainfall duration $t_r = 3.85/5.5 = 0.7$ hr. For a 30-min unit hydrograph, $t_R = 30$ min $= 0.5$ hr. The basin lag $t_{PR} = t_p - (t_r - t_R)/4 = 3.85 - (0.7 - 0.5)/4 = 3.80$ hr. The peak flow for the required unit hydrograph is $= q_p t_p / t_{PR}$ and, substituting equation (8.4.4) in the previous equation, $q_{PR} = q_p t_p / t_{PR} = (C_2 C_p / t_p)\, t_p / t_{PR} = C_2 C_p / t_{PR}$, so that $q_{PR} = 640 \times 0.625/3.80 = 105.26$ cfs/(in · mi^2) and the peak discharge is $Q_{PR} = q_{PR} A = 105.26 \times 5.42 = 570$ cfs/in.

The widths of the unit hydrograph are computed next. At 75 percent of the peak discharge, $W_{75} = C_{W_{75}} q_{PR}^{-1.08} = 440 \times 105.26^{-1.08} = 2.88$ hr. At 50 percent of the peak discharge, $W_{50} = C_{W_{50}} q_{PR}^{-1.08} = 770 \times 105.26^{-1.08} = 5.04$ hr.

The base time t_b may be computed assuming a triangular shape. This, however, does not guarantee that the volume under the unit hydrograph corresponds to one inch (or one cm, for SI units) of excess rainfall. To overcome this, the value of t_b may be exactly computed taking into account the values of W_{50} and W_{75} by solving the equation in step 5 of Table 8.4.1 for t_b:

$$t_b = 2581\, A/Q_{PR} - 1.5\, W_{50} - W_{75}$$

so that, with $A = 5.42$ mi^2, $W_{50} = 5.04$ hr, $W_{75} = 2.88$ hr, and $Q_{PR} = 570$ cfs/in, $t_b = 2581(5.42)/570 - 1.5 \times 5.04 - 2.88 = 14.1$ hr.

8.5 S-HYDROGRAPHS

In order to change a unit hydrograph from one duration to another, the *S-hydrograph method*, which is based on the principle of superposition, can be used. An S-hydrograph results theoretically from a continuous rainfall excess at a constant rate for an indefinite period. This curve (see Figure 8.5.1) has an S-shape with the ordinates approaching the rate of rainfall excess at the time of equilibrium.

Basically the S-curve (hydrograph) is the summation of an infinite number of t_R duration unit hydrographs, each lagged from the preceding one by the duration of the rainfall excess, as illustrated in Figure 8.5.2.

A unit hydrograph for a new duration, t_R', is obtained by: (1) lagging the S-hydrograph (derived with the t_R duration unit hydrographs) by the new (desired) duration t_R', (2) *subtracting* the two S-hydrographs from one another, and (3) and *multiplying* the resulting hydrograph ordinates by the ratio t_R/t_R'. Theoretically the S-hydrograph is a smooth curve because the input rainfall excess is assumed to be a constant, continuous rate. However, the numerical processes of the procedures may result in an undulatory form that may require smoothing or adjustment of the S-hydrograph.

EXAMPLE 8.5.1 (Adapted from Sanders, 1980)

Using the 2-hr unit hydrograph in Table 8.5.1, construct a 4-hr unit hydrograph.

SOLUTION See computations in Table 8.5.1.

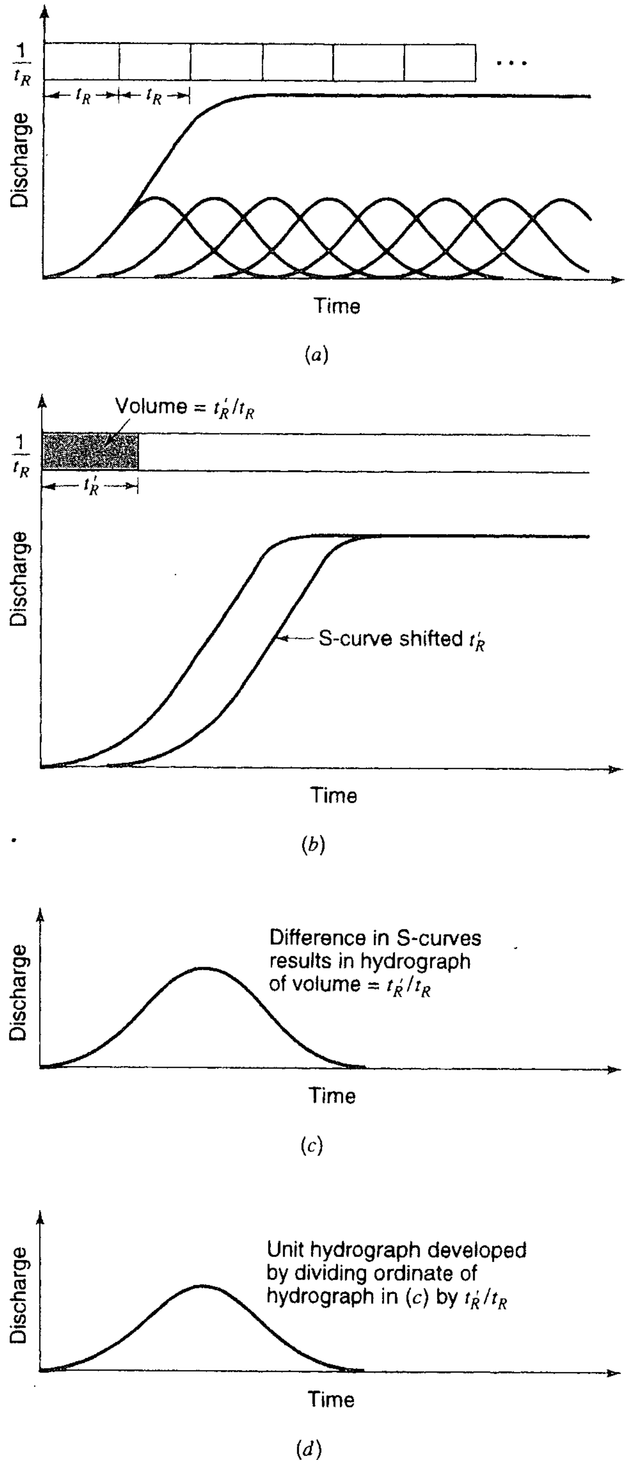


Figure 8.5.1 Development of a unit hydrograph for duration t'_R from a unit hydrograph for duration t_R.

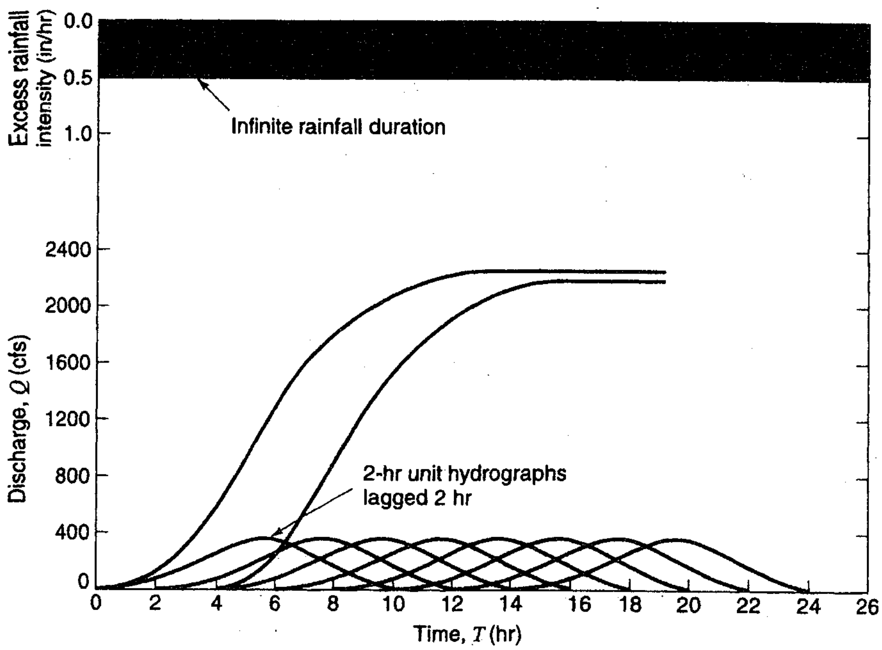


Figure 8.5.2 Graphical illustration of the S-curve construction (from Masch (1984)).

Table 8.5.3 S-Curve Determined from a 2-hr Unit Hydrograph to Estimate a 4-hr Unit Hydrograph

Time (hr)	2-hr unit hydrograph (cfs/in)	Lagged 2-hr unit hydrograph (cfs/in)		S-curve	Lagged S-curve	4-hr hydrograph	4-hr-unit hydrograph (cfs/in)
0	0			0	—	0	0
2	69	0		69	—	69	34
4	143	69	0 . . .	212	0	212	106
6	328	143	69 . . .	540	69	471	235
8	389	328	143 . . .	929	212	717	358
10	352	389	328	1281	540	741	375
12	266	352	389	1547	929	618	309
14	192	266	352	1739	1281	458	229
16	123	192	.	1862	1547	315	158
18	84	123	.	1946	1739	207	103
20	49	84	.	1995	1862	133	66
22	20	49	.	2015	1946	69	34
24	0	20	.	*2015	1995	20	10
26	0	0	. . . .	*2015	2015	0	0

*Adjusted values

Source: Sanders (1980).

For the third hour, $P_3 = 2 + 3 + 1 = 6$ in, so

$$F_{a,3} = \frac{1.63(6 - 0.33)}{6 + 1.3} = 1.27 \text{ in}$$

and $P_{e_3} = 6 - 0.33 - 1.27 = 4.40$ in (which compares well with the results of Example 8.7.2).

The results are summarized below, along with the rainfall excess hyetograph.

Time (hr)	Cumulative rainfall P_t (in)	Cumulative abstractions I_a (in)	$F_{a,t}$ (in)	Cumulative rainfall excess P_e (in)	Rainfall excess hyetograph (in)
1	2	0.33	0.82	0.85	0.85
2	5	0.33	1.21	3.46	2.61
3	6	0.33	1.27	4.40	0.94

8.8 NRCS (SCS) UNIT HYDROGRAPH PROCEDURE

The SCS dimensionless unit hydrograph and mass curve are shown in Figure 8.8.1 and tabulated in Table 8.8.1. The SCS dimensionless equivalent triangular unit hydrograph is also shown in Figure 8.8.1. The following section discusses how to develop a unit hydrograph from these dimensionless unit hydrographs.

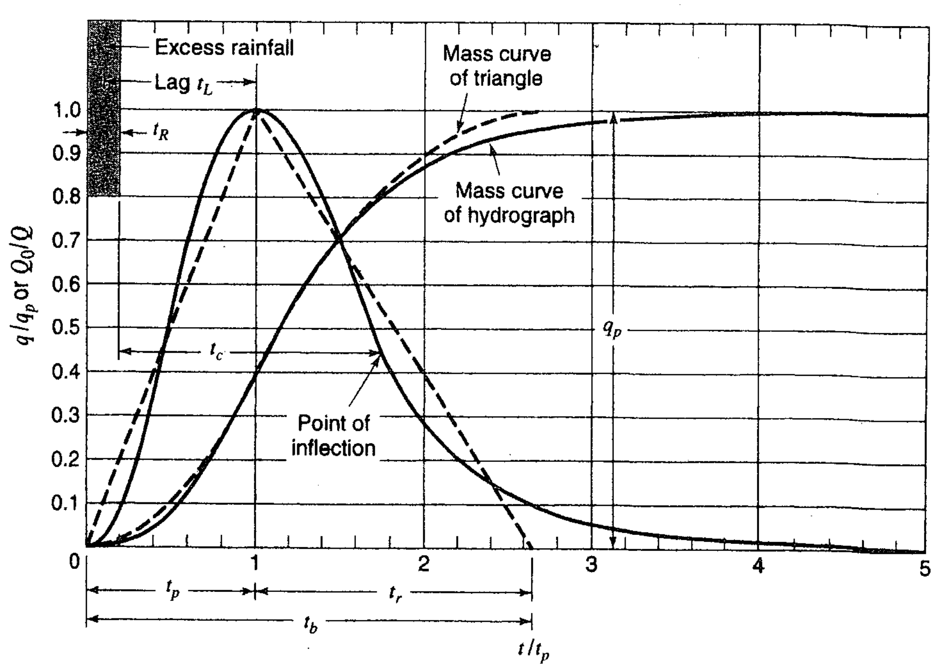


Figure 8.8.1 Dimensionless curvilinear unit hydrograph and equivalent triangular hydrograph (from U.S. Department of Agriculture Soil Conservation Service (1986)).

Table 8.8.1 Ratios for Dimensionless Unit Hydrograph and Mass Curve

Time ratios t/t_p	Discharge ratios q/q_p	Mass curve ratios Q_a/Q
0	0.000	0.000
0.1	0.030	0.001
0.2	0.100	0.006
0.3	0.190	0.012
0.4	0.310	0.035
0.5	0.470	0.065
0.6	0.660	0.107
0.7	0.820	0.163
0.8	0.930	0.228
0.9	0.990	0.300
1.0	1.000	0.375
1.1	0.990	0.450
1.2	0.930	0.522
1.3	0.860	0.589
1.4	0.780	0.650
1.5	0.680	0.700
1.6	0.560	0.751
1.7	0.460	0.790
1.8	0.390	0.822
1.9	0.330	0.849
2.0	0.280	0.871
2.2	0.207	0.908
2.4	0.147	0.934
2.6	0.107	0.953
2.8	0.077	0.967
3.0	0.055	0.977
3.2	0.040	0.984
3.4	0.029	0.989
3.6	0.021	0.993
3.8	0.015	0.995
4.0	0.011	0.997
4.5	0.005	0.999
5.0	0.000	1.000

Source: U.S. Department of Agriculture Soil Conservation Service (1972).

8.8.1 Time of Concentration

The *time of concentration* for a watershed is the time for a particle of water to travel from the hydrologically most distant point in the watershed to a point of interest, such as the outlet of the watershed. SCS has recommended two methods for time of concentration, the *lag method* and the *upland*, or *velocity method*.

The lag method relates the *time lag* (t_L), defined as the time in hr from the center of mass of the rainfall excess to the peak discharge, to the slope (Y) in percent, the hydraulic length (L) in ft, and the potential maximum retention (S), expressed as

$$t_L = \frac{L^{0.8}(S+1)^{0.7}}{1900Y^{0.5}} \tag{8.8.1}$$

The SCS uses the following relationship between the time of concentration (t_c) and the lag (t_L):

$$t_c = \frac{5}{3} t_L \tag{8.8.2}$$

or

$$t_c = \frac{L^{0.8}(S+1)^{0.7}}{1140Y^{0.5}} \tag{8.8.3}$$

where t_c is in hr. Refer to Figure 8.8.1 to see the SCS definition of t_c and t_L.

The velocity (upland) method is based upon defining the time of concentration as the ratio of the hydraulic flow length (L) to the velocity (V):

$$t_c = \frac{L}{3600V} \tag{8.8.4}$$

where t_c is in hr, L is in ft, and V is in ft/s. The velocity can be estimated knowing the land use and the slope in Figure 8.8.2. Alternatively, we can think of the concentration as being the sum of

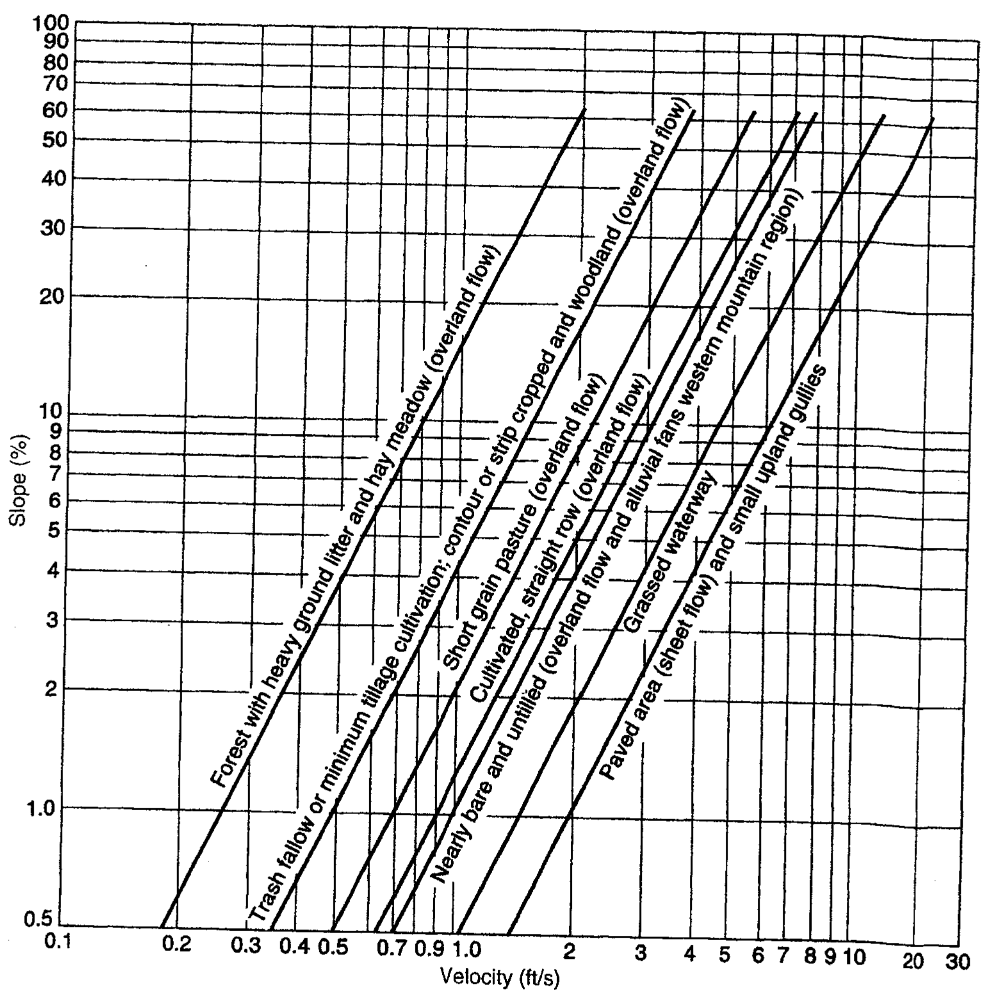


Figure 8.8.2 Velocities for velocity upland method of estimating t_c (from U.S. Department of Agriculture Soil Conservation Service (1986)).

travel times for different segments

$$t_c = \frac{1}{3600} \sum_{i=1}^{k} \frac{L_i}{V_i} \tag{8.8.5}$$

for k segments, each with different land uses.

8.8.2 Time to Peak

Time to peak (t_p) is the time from the beginning of rainfall to the time of the peak discharge (Figure 8.8.1)

$$t_p = \frac{t_R}{2} + t_L \tag{8.8.6}$$

where t_p is in hr, t_R is the duration of the rainfall excess in hr, and t_L is the lag time in hr. The SCS recommends that t_R be 0.133 of the time of concentration of the watershed, t_c:

$$t_R = 0.133 t_c \tag{8.8.7}$$

and because $t_L = 0.6t_c$ by Equation (8.8.2), then by Equation (8.8.6) we get

$$\begin{aligned} t_p &= \frac{0.133 t_c}{2} + 0.6 t_c \\ t_p &= 0.67 t_c \end{aligned} \tag{8.8.8}$$

8.8.3 Peak Discharge

The area of the unit hydrograph equals the volume of direct runoff Q, which was estimated by Equation (8.6.5). With the equivalent triangular dimensionless unit hydrograph of the curvilinear dimensionless unit hydrograph in Figure 8.8.1, the time base of the dimensionless triangular unit hydrograph is $8/3$ of the time to peak t_p, as compared to $5t_p$ for the curvilinear. The areas under the rising limb of the two dimensionless unit hydrographs are the same (37 percent).

Based upon geometry (Figure 8.8.1), we see that

$$Q = \frac{1}{2} q_p (t_p + t_r) \tag{8.8.9}$$

for the direct runoff Q, which is 1 in where t_r is the recession time of the dimensionless triangular unit hydrograph and q_p is the peak discharge. Solving Equation (8.8.9) for q_p gives

$$q_p = \frac{Q}{t_p} \left[\frac{2}{1 + t_r/t_p} \right] \tag{8.8.10}$$

Letting $K = \left[\frac{2}{1 + t_r/t_p} \right]$, then

$$q_p = \frac{KQ}{t_p} \tag{8.8.11}$$

where Q is the volume, equals to 1 in for a unit hydrograph.

The above equation can be modified to express q_p in ft^3/s, t_p in hr, and Q in inches:

$$q_p = 645.33K \frac{AQ}{t_p} \tag{8.8.12}$$

The factor 645.33 is the rate necessary to discharge 1 in of runoff from 1 mi^2 in 1 hr. Using $t_r = 1.67t_p$ gives $K = [2/(1 + 1.67)] = 0.75$; then Equation (8.8.12) becomes

$$q_p = \frac{484AQ}{t_p} \tag{8.8.13}$$

For SI units,

$$q_p = \frac{2.08AQ}{t_p} \tag{8.8.14}$$

where A is in km^2.

The steps in developing a unit hydrograph are:

Step 1 Compute the time of concentration using the lag method (Equation (8.8.3)) or the velocity method (Equation (8.8.4) or (8.8.5)).

Step 2 Compute the time to peak $t_p = 0.67t_c$ (Equation (8.8.8)) and then the peak discharge q_p using Equation (8.8.13) or (8.8.14).

Step 3 Compute time base t_b and the recession time t_r:
Triangular hydrograph: $t_b = 2.67t_p$
Curvilinear hydrograph: $t_b = 5t_p$
$t_r = t_b - t_p$

Step 4 Compute the duration $t_R = 0.133\ t_c$ and the lag $t_L = 0.6\ t_c$ by using Equations (8.8.7) and (8.8.2), respectively.

Step 5 Compute the unit hydrograph ordinates and plot. For the triangular only t_p, q_p, and t_r are needed. For the curvilinear, use the dimensionless ratios in Table 8.8.1.

EXAMPLE 8.8.1

For the watershed in Example 8.7.1, determine the triangular SCS unit hydrograph. The average slope of the watershed is 3 percent and the area is 3.0 mi^2. The hydraulic length is 1.2 mi.

SOLUTION

Step 1 The time of concentration is computed using Equation (8.8.1), with S = 1.63 from Example 8.7.2:

$$t_L = \frac{(6336)^{0.8}(1.63 + 1)^{0.7}}{1900\sqrt{3}} = 0.66\text{ hr}$$

and $t_c = \dfrac{5}{3}t_L = 1.1$ hr

Step 2 The time to peak $t_p = 0.67t_c = 0.67(1.1) = 0.74$ hr.
Step 3 The time base is $t_b = 2.67t_p = 1.97$ hr.
Step 4 The duration is $t_R = 0.133t_c = 0.133(1.1) = 0.15$ hr, and t_L is 0.66 hr.
Step 5 The peak is (for $Q = 1$ in)

$$q_p = \frac{484AQ}{t_p} = \frac{484(3)(1)}{0.74} = 1962\text{ cfs.}$$

In summary, the triangular unit hydrograph has a peak of 1962 cfs at the time to peak of 0.74 hr with a time base of 1.97 hr. This is a 0.15-hr duration unit hydrograph. ∎

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