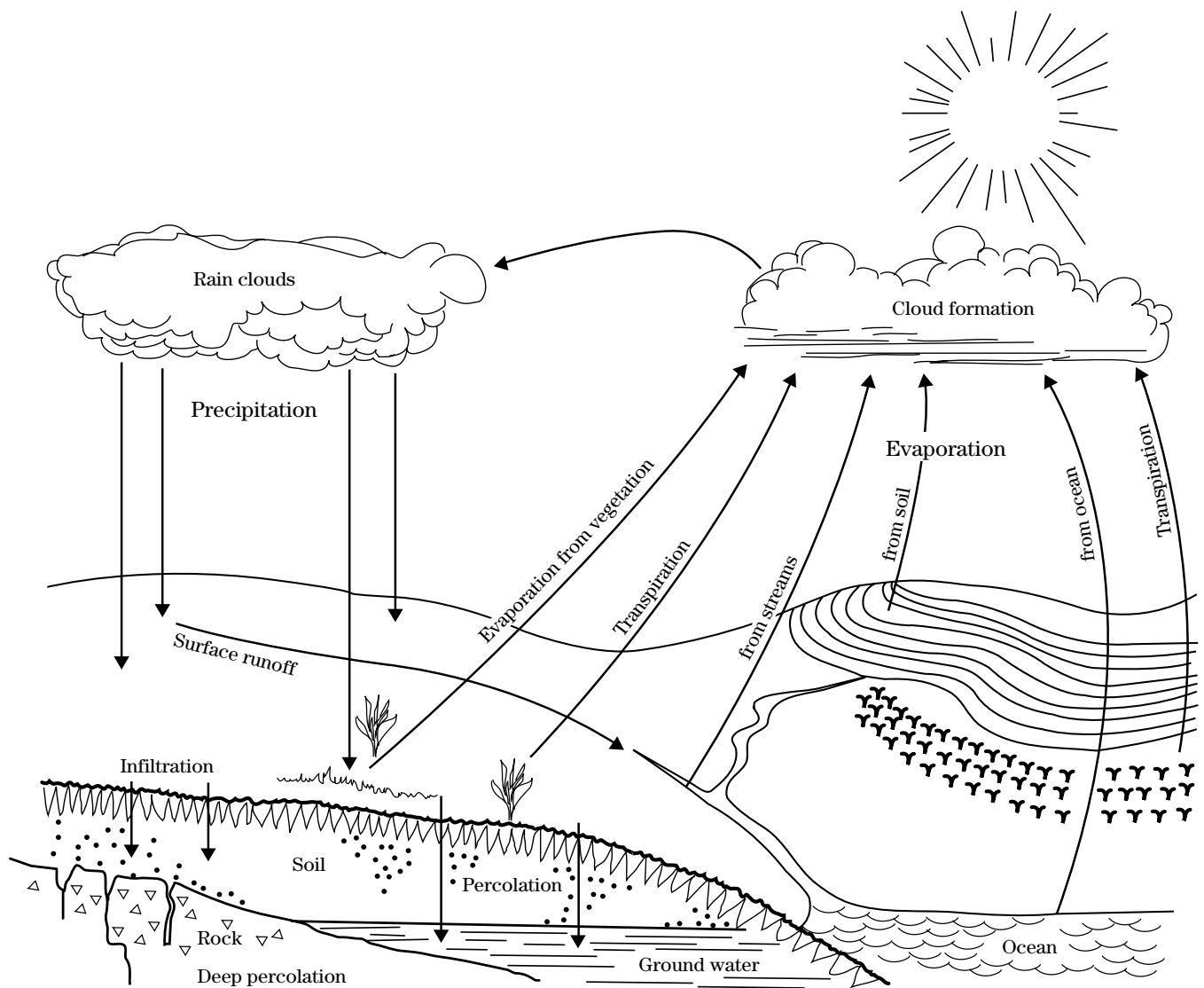


# Chapter 16 Hydrographs



March 2007

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# Acknowledgments

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Chapter 16 was originally prepared in 1971 by **Dean Snider** (retired) and was reprinted with minor revisions in 1972. This version was prepared by the Natural Resources Conservation Service (NRCS) under guidance of **Donald E. Woodward**, (retired), and **Claudia C. Hoefft**, national hydraulic engineer, Washington, DC. **William H. Merkel**, hydraulic engineer, prepared the section dealing with unit hydrograph development on gaged watersheds. **Katherine E. Chaison**, engineering aide, developed the dimensionless unit hydrograph tables and plots in appendix 16B, and **Helen Fox Moody**, hydraulic engineer, edited and reviewed the chapter and developed the tables and figures for example 16-1.



# Chapter 16

# Hydrographs

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## 630.1600 Introduction

Hydrographs or some elements of them, such as peak rates, are used in the planning and design of water control structures. They are also used to show the hydrologic effects of existing or proposed watershed projects and land use changes.

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## 630.1601 Development of hydrograph relations

Runoff occurring on uplands flows downstream in various patterns. These patterns of flow are affected by many factors including:

- spatial and temporal distribution of rainfall
- rate of snowmelt
- hydraulics of streams
- watershed and channel storage
- geology and soil characteristics
- watershed surface and cover conditions

The graph of flow (rate versus time) at a stream section is called a hydrograph, of which no two are exactly alike. Computation methods for computing peak rates of flow are based upon empirical relations, starting with the Rational Method for peak discharge in the 19th century, progressing to the unit hydrograph in the 1930s, and then to more recent use of dimensionless or index hydrographs. The empirical relations are simple elements from which a hydrograph may be made as complex as needed.

Difficulties with hydrograph development lie in the precise estimation of runoff from rainfall (NEH 630, chapter 10) and determination of flow paths (NEH 630, chapter 15).

### (a) Types of hydrographs

This classification of hydrographs is a partial list, suitable for use in watershed work.

- **Natural hydrograph**—obtained directly from the flow records of a gaged stream
- **Synthetic hydrograph**—obtained by using watershed parameters and storm characteristics to simulate a natural hydrograph
- **Unit hydrograph**—a discharge hydrograph resulting from 1 inch of direct runoff distributed uniformly over the watershed resulting from a rainfall of a specified duration

- **Dimensionless unit hydrograph (DUH)**—a hydrograph developed to represent several unit hydrographs; plotted using the ratio of the basic units time to peak and peak rate; also called an index hydrograph

## 630.1602 Unit hydrograph

In the 1930s, L.K. Sherman (Sherman 1932, 1940) advanced the theory of the unit hydrograph, or unit graph. The unit hydrograph procedure assumes that discharge at any time is proportional to the volume of runoff and that time factors affecting hydrograph shape are constant.

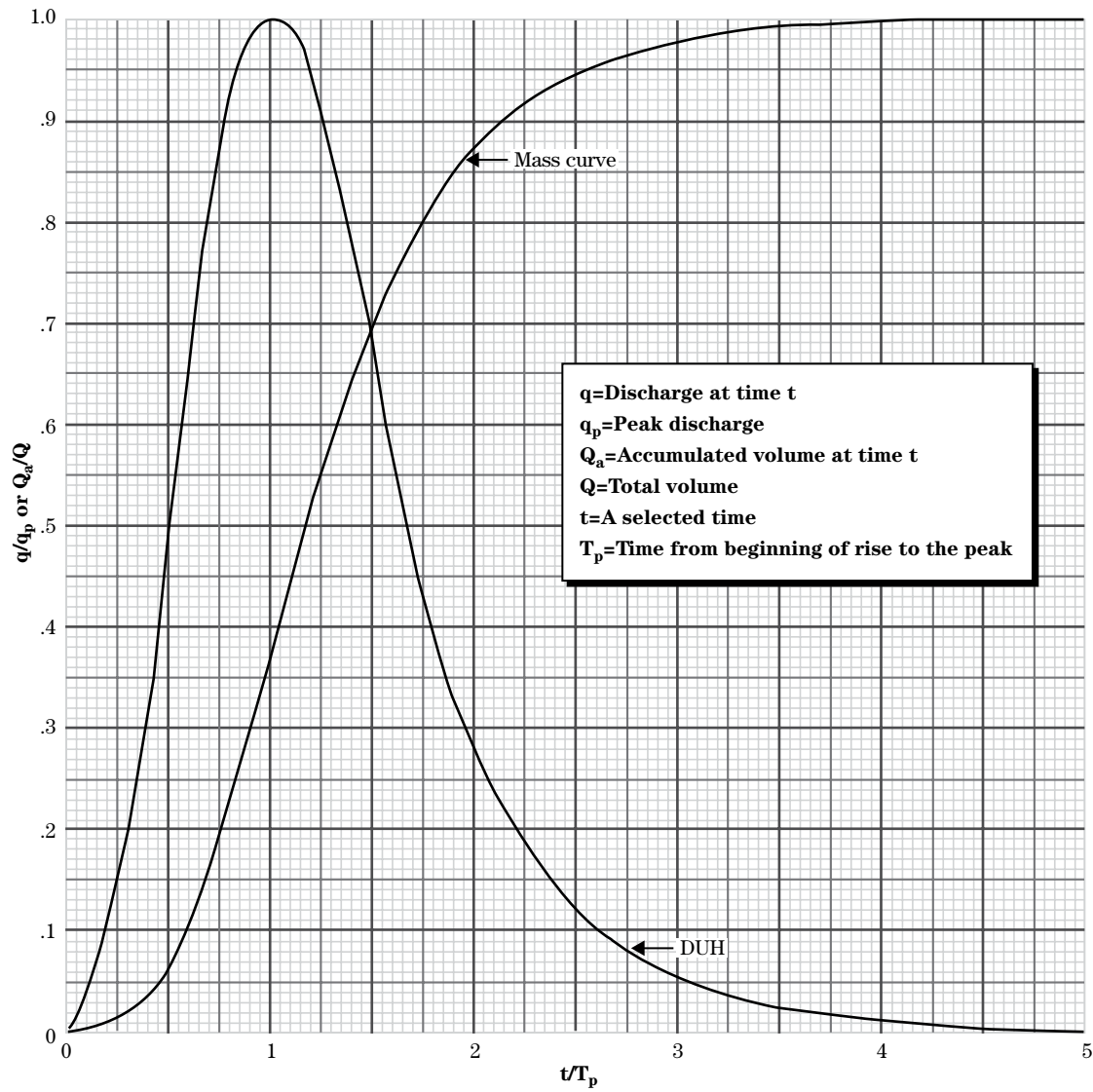
Field data and laboratory tests have shown that the assumption of a linear relationship among watershed components is not strictly true. The nonlinear relationships have not been investigated sufficiently to ascertain their effects on a synthetic hydrograph. Until more information is available, the procedures of this chapter will be based on the unit hydrograph theory.

The fundamental principles of invariance and superposition make the unit graph an extremely flexible tool for developing synthetic hydrographs. These principles are:

- Principle of Invariance—the hydrograph of surface runoff from a watershed resulting from a given pattern of rainfall is constant
- Principle of Superposition—the hydrograph resulting from a given pattern of rainfall excess can be built up by superimposing the unit hydrographs because of the separate amounts of rainfall excess occurring in each unit period; includes the principle of proportionality by which the ordinates of the hydrograph are proportional to the volume of rainfall excess

The unit time or *unit hydrograph duration* is the duration for occurrence of precipitation excess. The optimum unit time is less than 20 percent of the time interval between the beginning of runoff from a short duration, high-intensity storm and the peak discharge of the corresponding runoff.

The *storm duration* is the actual duration of the precipitation excess. The duration varies with actual storms. The dimensionless unit hydrograph used by the Natural Resources Conservation Service (NRCS) was developed by Victor Mockus (fig. 16–1) (Mockus 1957). It was derived from many natural unit hydrographs from watersheds varying widely in size and geographical locations. This dimensionless

**Figure 16-1** Dimensionless unit hydrograph and mass curve

curvilinear hydrograph, also shown in table 16–1, has its ordinate values expressed in a dimensionless ratio  $q/q_p$  or  $Q_a/Q$  and its abscissa values as  $t/T_p$ . This unit hydrograph has a point of inflection approximately 1.7 times the time to peak ( $T_p$ ). The unit hydrograph in table 16–1 has a peak rate factor (PRF) of 484 and is the default provided in the WinTR–20 program. See appendix 16A for derivation of the standard NRCS dimensionless hydrograph.

**Table 16–1** 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	.000	.000
.1	.030	.001
.2	.100	.006
.3	.190	.017
.4	.310	.035
.5	.470	.065
.6	.660	.107
.7	.820	.163
.8	.930	.228
.9	.990	.300
1.0	1.000	.375
1.1	.990	.450
1.2	.930	.522
1.3	.860	.589
1.4	.780	.650
1.5	.680	.705
1.6	.560	.751
1.7	.460	.790
1.8	.390	.822
1.9	.330	.849
2.0	.280	.871
2.2	.207	.908
2.4	.147	.934
2.6	.107	.953
2.8	.077	.967
3.0	.055	.977
3.2	.040	.984
3.4	.029	.989
3.6	.021	.993
3.8	.015	.995
4.0	.011	.997
4.5	.005	.999
5.0	.000	1.000

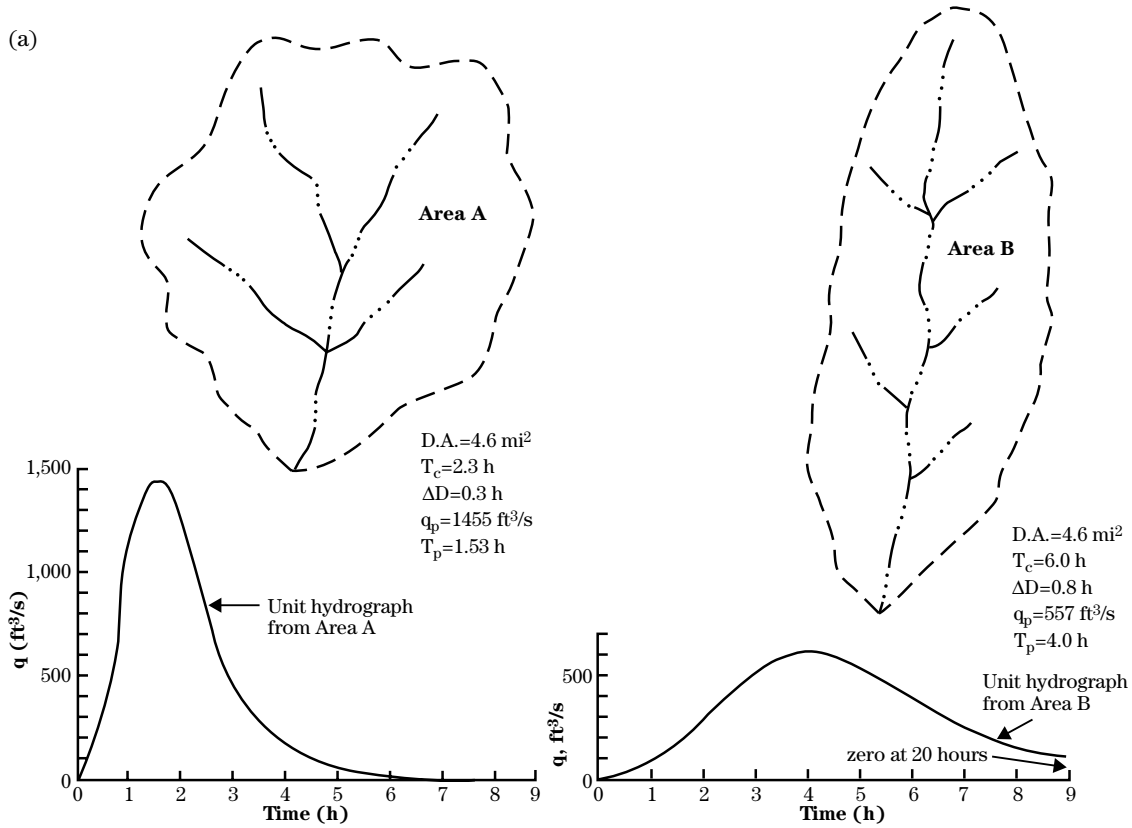
## 630.1603 Application of unit hydrograph

The unit hydrograph can be constructed for any location on a regularly shaped watershed, once the values of  $q_p$  and  $T_p$  are defined (fig. 16–2, areas A and B).

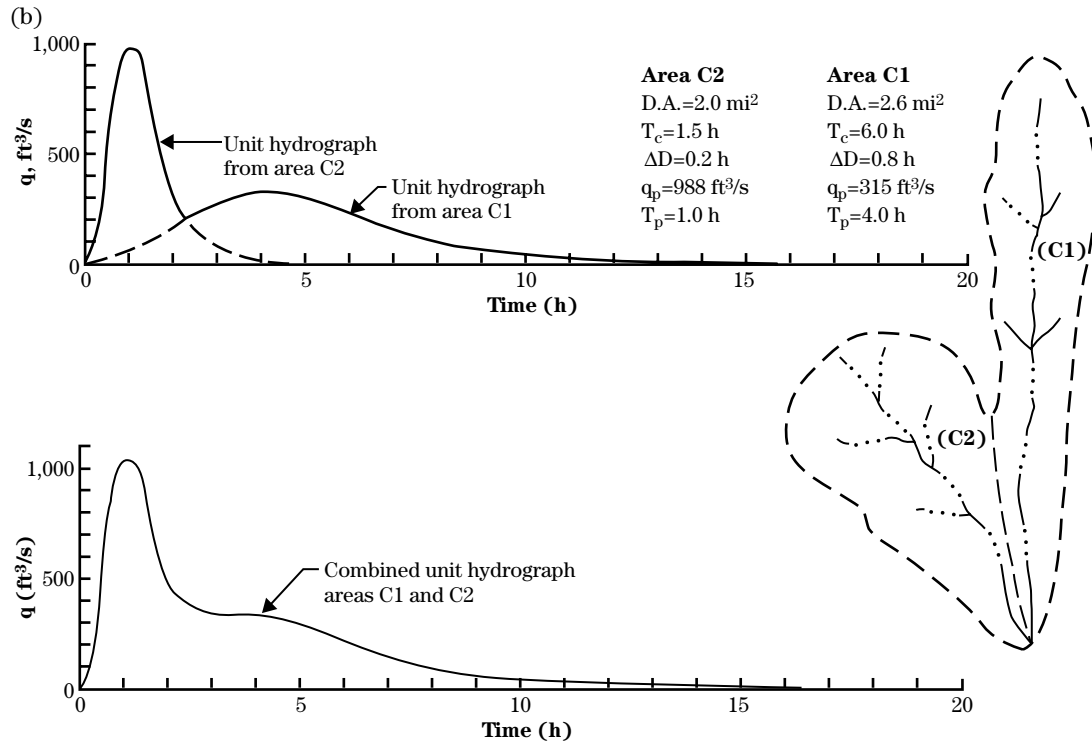
Area C in figure 16–2 is an irregularly shaped watershed having two regularly shaped areas (C2 and C1) with a large difference in their time of concentration. This watershed requires the development of two unit hydrographs that may be added together, forming one irregularly shaped unit hydrograph. This irregularly shaped unit hydrograph may be used to develop a flood hydrograph in the same way as the unit hydrograph developed from the dimensionless form (fig. 16–1) is used to develop the flood hydrograph. See example 16–1 which develops a composite flood hydrograph for area A shown in figure 16–2. Also, each of the two unit hydrographs developed for areas C2 and C1 in figure 16–2 may be used to develop flood hydrographs for the respective areas C2 and C1. The flood hydrographs from each area are then combined to form the hydrograph at the outlet of area C.

Many variables are integrated into the shape of a unit hydrograph. Since a dimensionless unit hydrograph is used and the only parameters readily available from field data are drainage area and time of concentration, consideration should be given to dividing the watershed into hydrologic units of uniformly shaped areas. These subareas, if at all possible, should have a homogeneous drainage pattern, homogeneous land use and approximately the same size. To assure that all contributing subareas are adequately represented, it is suggested that no subarea exceed 20 square miles in area and that the ratio of the largest to the smallest drainage area not exceed 10.

**Figure 16-2** Effect of watershed shape on the peaks of unit hydrographs (Equations, definitions, and units for variables are found in appendix 16A.)



**Figure 16-2** Effect of watershed shape on the peaks of unit hydrographs (Equations, definitions, and units for variables are found in appendix 16A.)—Continued



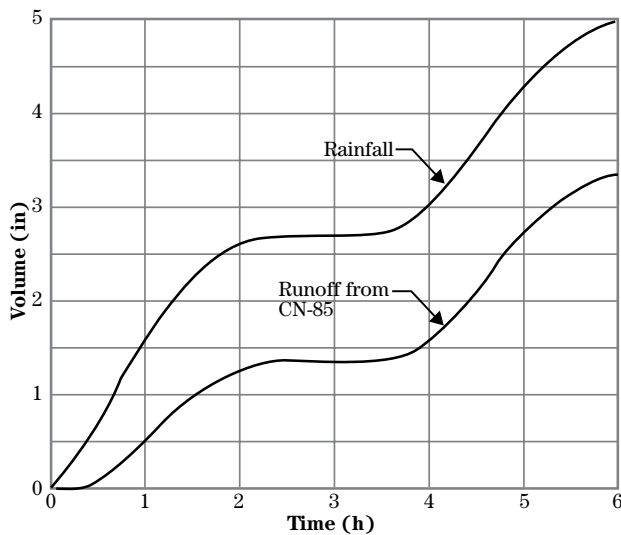
**Example 16-1** Composite flood hydrograph

**Given:** Drainage area ..... 4.6 square miles  
 Time of concentration..... 2.3 hours  
 CN ..... 85  
 Antecedent runoff condition ..... II  
 Storm duration ..... 6 hours

The equations used in this example are found in appendix 16A. It is recommended to read appendix 16A before reading the example.

**Problem:** Develop a composite flood hydrograph using the runoff produced by the rainfall taken from a recording rain gage (fig. 16-3) on watershed (area A) shown in figure 16-2.

**Figure 16-3** Accumulated or mass rainfall and runoff curves for CN 85 taken from a recording rain gage



**Example 16-1** Composite flood hydrograph—Continued**Solution:****Step 1**

Develop and plot unit hydrograph.

Using equation 16A-13 in appendix 16A, compute  $\Delta D$ :

$$\Delta D = 0.133 T_c$$

$$\Delta D = 0.133 \times 2.3 = 0.306, \text{ use } 0.3 \text{ hours}$$

Using equation 16A-7 from appendix 16A, compute  $T_p$ :

$$T_p = \frac{\Delta D}{2} + L$$

$$T_p = \frac{.30}{2} + (.6 \times 2.3) = 1.53 \text{ h}$$

Using equation 16A-6 from the appendix, compute  $q_p$  for volume of runoff equal to 1 inch:

$$q_p = \frac{484AQ}{T_p}$$

$$q_p = \frac{484 \times 4.6 \times 1}{1.53} = 1,455 \text{ ft}^3/\text{s}$$

The coordinates of the curvilinear unit hydrograph are shown in table 16-2, and the plotted hydrograph is figure 16-4.

**Step 2**

Tabulate the ordinates of the unit hydrograph from figure 16-4 in 0.3 hour increments ( $\Delta D$ ) (table 16-4a, column 2).

**Step 3**

Check the volume under the unit hydrograph by summing the ordinates (table 16-4a, column 2) and multiplying by  $\Delta D$ .

$$9,914 \times 0.3 = 2,974 \text{ (ft}^3/\text{s)h}$$

Compare this figure with the computed volume under the unit hydrograph:

$$\frac{645.33 \text{ (ft}^3/\text{s)h}}{\text{mi}^2 \times \text{in}} \times 4.6 \text{ mi}^2 \times 1 \text{ in} = 2,969 \text{ (ft}^3/\text{s) h}$$

The difference between the two volumes in this example is less than 1 percent, and can be considered negligible.

If the volumes fail to check closely, reread the coordinates from figure 16-4 and adjust if necessary until a reasonable balance in volume is attained.

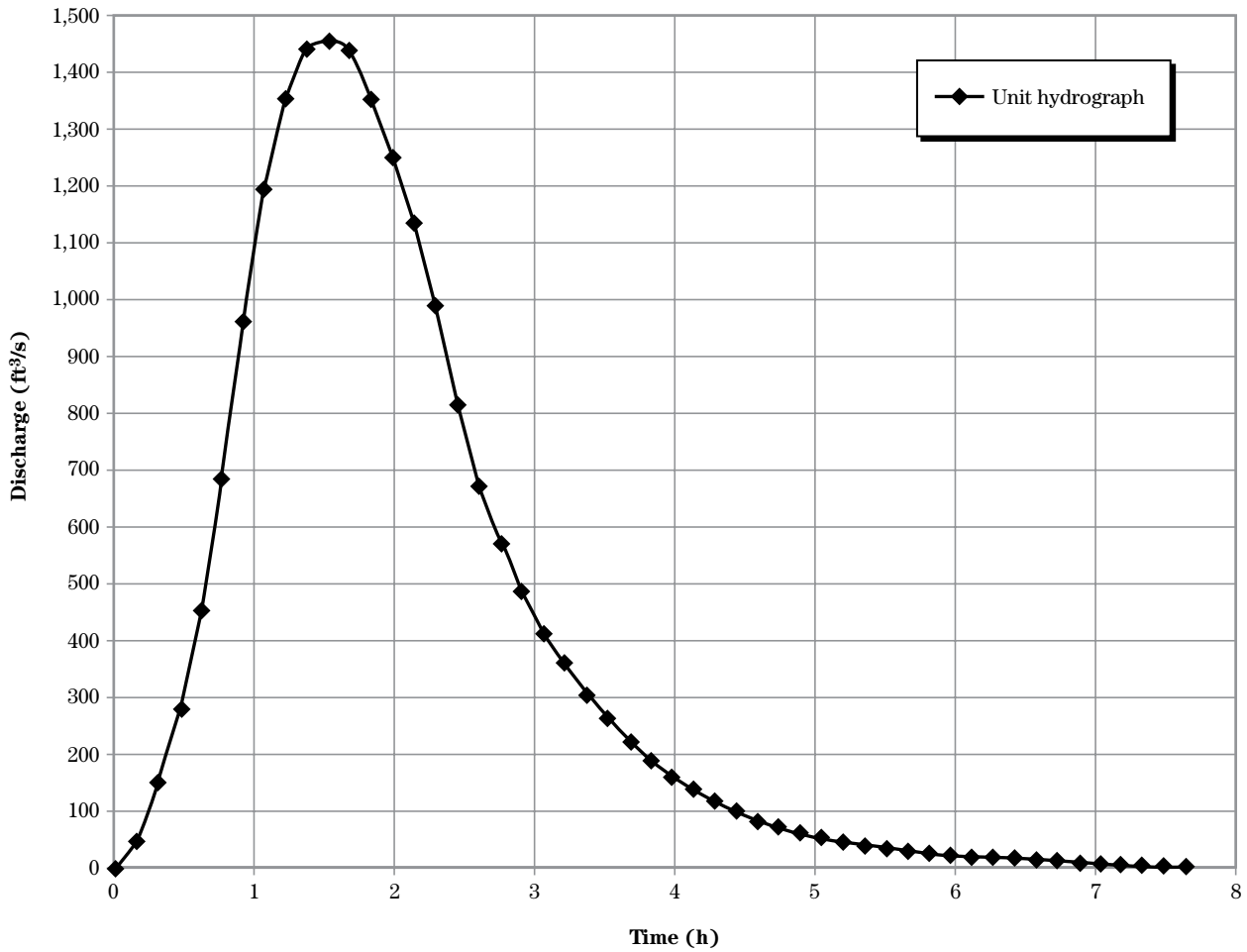


**Example 16-1** Composite flood hydrograph—Continued**Table 16-2** Computation of coordinates for unit hydrograph for use in example 16-1

Time ratios (table 16-1) ( $t/T_p$ )	Time (col 1 × 1.53) (h)	Discharge ratios (table 16-1) ( $q/q_p$ )	Discharges (col 3 × 1,455) ( $\text{ft}^3/\text{s}$ )	Time ratios (table 16-1) ( $t/T_p$ )	Time (col 1 × 1.53) (h)	Discharge ratios (table 16-1) ( $q/q_p$ )	Discharges (col 3 × 1,455) ( $\text{ft}^3/\text{s}$ )
(1)	(2)	(3)	(4)	(1)	(2)	(3)	(4)
0.000	0.000	0.0000	0	2.600	3.978	0.1070	156
0.100	0.153	0.0300	44	2.700	4.131	0.0920	134
0.200	0.306	0.1000	146	2.800	4.284	0.0770	112
0.300	0.459	0.1900	276	2.900	4.437	0.0660	96
0.400	0.612	0.3100	451	3.000	4.590	0.0550	80
0.500	0.765	0.4700	684	3.100	4.743	0.0475	69
0.600	0.918	0.6600	960	3.200	4.896	0.0400	58
0.700	1.071	0.8200	1193	3.300	5.049	0.0345	50
0.800	1.224	0.9300	1353	3.400	5.202	0.0290	42
0.900	1.377	0.9900	1440	3.500	5.355	0.0250	36
1.000	1.530	1.0000	1455	3.600	5.508	0.0210	31
1.100	1.683	0.9900	1440	3.700	5.661	0.0180	26
1.200	1.836	0.9300	1353	3.800	5.814	0.0150	22
1.300	1.989	0.8600	1251	3.900	5.967	0.0130	19
1.400	2.142	0.7800	1135	4.000	6.120	0.0110	16
1.500	2.295	0.6800	989	4.100	6.273	0.0098	14
1.600	2.448	0.5600	815	4.200	6.426	0.0086	13
1.700	2.601	0.4600	669	4.300	6.579	0.0074	11
1.800	2.754	0.3900	567	4.400	6.732	0.0062	9
1.900	2.907	0.3300	480	4.500	6.885	0.0050	7
2.000	3.060	0.2800	407	4.600	7.038	0.0040	6
2.100	3.213	0.2435	354	4.700	7.191	0.0030	4
2.200	3.366	0.2070	301	4.800	7.344	0.0020	3
2.300	3.519	0.1770	258	4.900	7.497	0.0010	1
2.400	3.672	0.1470	214	5.000	7.650	0.0000	0
2.500	3.825	0.1270	185				

**Example 16-1** Composite flood hydrograph—Continued

**Figure 16-4** Unit hydrograph from example 16-1



**Example 16-1** Composite flood hydrograph—Continued

- Step 4** Tabulate the accumulated rainfall in 0.3-hour increments (table 16-3, column 2).
- Step 5** Compute the accumulated runoff (table 16-3, column 3) using CN of 85 and moisture condition II.
- Step 6** Tabulate the incremental runoff (table 16-3, column 4).
- Step 7** Tabulate the incremental runoff in reverse order (table 16-3, column 5) on a strip of paper having the same line spacing as the paper used in step 2. A spreadsheet program may also be used to develop the composite hydrograph.
- Step 8** Place the strip of paper between column 1 and column 2 of table 16-4(a) and slide down until the first increment of runoff (0.12) on the strip of paper is opposite the first discharge (140) on the unit hydrograph (column 2). Multiplying  $0.12 \times 140 = 16.8$  (round to 17). Tabulate in column 3 opposite the arrow on the strip of paper.
- Step 9** Move the strip of paper down one line (table 16-4(b)) and compute  $(0.12 \times 439) + (.27 \times 140) = 90.48$  (round to 90). Tabulate in column 3 opposite the arrow on the strip of paper. Continue moving the strip of paper containing the runoff down one line at a time and accumulatively multiply each runoff increment by the unit hydrograph discharge opposite the increment.

**Table 16-3** Rainfall tabulated in 0.3 hour increments from plot of rain gage chart in figure 16-3

Time (h)	Accum. rainfall (in)	Accum. runoff <sup>1/</sup> (in)	Incremental runoff (in)	Reversed incremental runoff	Time (h)	Accum. rainfall (in)	Accum. runoff <sup>1/</sup> (in)	Incremental runoff (in)	Reversed incremental runoff
(1)	(2)	(3)	(4)	(5)	(1)	(2)	(3)	(4)	(5)
	0.0	0.00							
0.3	0.37	0.00	0.00	0.09	3.3	2.71	1.35	0.01	0.00
0.6	0.87	0.12	0.12	0.19	3.6	2.77	1.40	0.05	0.00
0.9	1.40	0.39	0.27	0.24	3.9	2.91	1.51	0.11	0.06
1.2	1.89	0.72	0.33	0.31	4.2	3.20	1.76	0.25	0.12
1.5	2.24	0.98	0.26	0.42	4.5	3.62	2.12	0.36	0.18
1.8	2.48	1.16	0.18	0.36	4.8	4.08	2.54	0.42	0.26
2.1	2.63	1.28	0.12	0.25	5.1	4.43	2.85	0.31	0.33
2.4	2.70	1.34	0.06	0.11	5.4	4.70	3.09	0.24	0.27
2.7	2.70	1.34	0.00	0.05	5.7	4.90	3.28	0.19	0.12
3.0	2.70	1.34	0.00	0.01	6.0	5.00	3.37	0.09	0.00

<sup>1/</sup> Runoff computed using CN 85 moisture condition II.

**Example 16-1** Composite flood hydrograph—Continued

**Table 16-4** Computation of a flood hydrograph

16-4(a)			16-4(b)			16-4(c)			16-4(d)				
Reversed incremental runoff			Reversed incremental runoff										
(1) Time	(2) Unit hyd.	(3) Flood hyd.	(1) Time	(2) Unit hyd.	(3) Flood hyd.	(1) Time	Reversed incre. runoff	(2) Unit hyd.	(3) Flood hyd.	(1) Time	Reversed incre. runoff	(2) Unit hyd.	(3) Flood hyd.
0.09			0.09										
0.19			0.19										
0.24			0.24										
0.31			0.31										
0.42			0.42										
0.36			0.36										
0.25			0.25										
0.11			0.11										
0.05			0.05										
0.01			0.01										
0.00			0.00										
0.00			0.00										
0.06			0.06										
0.12			0.12										
0.18			0.18										
0.26	Unit		0.26	Unit		0.0	Reversed	0.	0.	0.0	Reversed	0.	0.
0.33	hyd.		0.33	hyd.		0.3	incre.	140.	140.	0.3	incre.	140.	140.
0.27	0.	0.	0.27	0.	0.	0.6	runoff	439.	17.	0.6	runoff	439.	17.
0.3	140.	0.	0.6	439.	17.	0.9		923.	90.	0.9		923.	90.
0.6	439.	17.	0.9	0.00→	90.	1.2		1,332.	275.	1.2		1,332.	275.
0.9	923.		1.2			1.5	0.24	1,332.	590.	1.5	0.31	1,455.	590.
1.2	1,332.		1.5	1,455.		1.8	0.42	1,378.	978.	1.8	0.42	1,378.	978.
1.5	1,455.		1.8	1,378.		2.1	0.36	1,166.	1,334.	2.1	0.36	1,166.	1,334.
1.8	1,378.		2.1	1,166.		2.4	0.25	873.	1,566.	2.4	0.25	873.	1,566.
2.1	1,166.		2.4	873.		2.7	0.11	601.	1,629.	2.7	0.11	601.	1,629.
2.4	873.		2.7	601.		3.0	0.05	436.	1,528.	3.0	0.05	436.	1,528.
2.7	601.		3.0	436.		3.3	0.01	324.	1,310.	3.3	0.01	324.	1,310.
3.0	436.		3.3	324.		3.6	0.00	235.	1,056.	3.6	0.00	235.	1,056.
3.3	324.		3.6	235.		3.9	0.00	171.	842.	3.9	0.00	171.	842.
3.6	235.		3.9	171.		4.2	0.06	124.	730.	4.2	0.06	124.	730.
3.9	171.		4.2	124.		4.5	0.12	90.	769.	4.5	0.12	90.	769.
4.2	124.		4.5	90.		4.8	0.18	65.	989.	4.8	0.18	65.	989.
4.5	90.		4.8	65.		5.1	0.26	47.	1,358.	5.1	0.26	47.	1,358.
4.8	65.		5.1	47.		5.4	0.33	35.	1,783.	5.4	0.33	35.	1,783.
5.1	47.		5.4	35.		5.7	0.27	25.	2,142.	5.7	0.27	25.	2,142.
5.4	35.		5.7	25.		6.0	0.12	18.	2,346.	6.0	0.12	18.	2,346.
5.7	25.		6.0	18.		6.3	0.00→	14.	2,356.	6.3	0.00→	14.	2,356.
6.0	18.		6.3	14.		6.6		11.		6.6		11.	2,179.
6.3	14.		6.6	11.		6.9		7.		6.9		7.	1,863.
6.6	11.		6.9	7.		7.2		4.		7.2		4.	1,494.
6.9	7.		7.2	4.		7.5		1.		7.5		1.	1,144.
7.2	4.		7.5	1.		7.8		0.		7.8	0.09	0.	845.
7.5	1.		7.8	0.		8.1				8.1	0.19		611.
7.8	0.		8.1			8.4				8.4	0.24		441.
8.1			8.4			8.7				8.7	0.31		320.
8.4			8.7			9.0				9.0	0.42		232.
8.7			9.0			9.3				9.3	0.36		168.
9.0			9.3			9.6				9.6	0.25		122.
9.3			9.6			9.9				9.9	0.11		89.
9.6			9.9			10.2				10.2	0.05		65.
9.9			10.2			10.5				10.5	0.01		47.
10.2			10.5			10.8				10.8	0.00		34.
10.5			10.8			11.1				11.1	0.00		25.
10.8			11.1			11.4				11.4	0.06		17.
11.1			11.4			11.7				11.7	0.12		11.
11.4			11.7			12.0				12.0	0.18		7.
11.7			12.0			12.3				12.3	0.26		4.
12.0			12.3			12.6				12.6	0.33		2.
12.3			12.6			12.9				12.9	0.27		1.
12.6			12.9			13.2				13.2	0.12		0.
12.9			13.2			13.5				13.5	0.00→		0.
13.2			13.5										0.
13.5													33,409
Total	9,914												

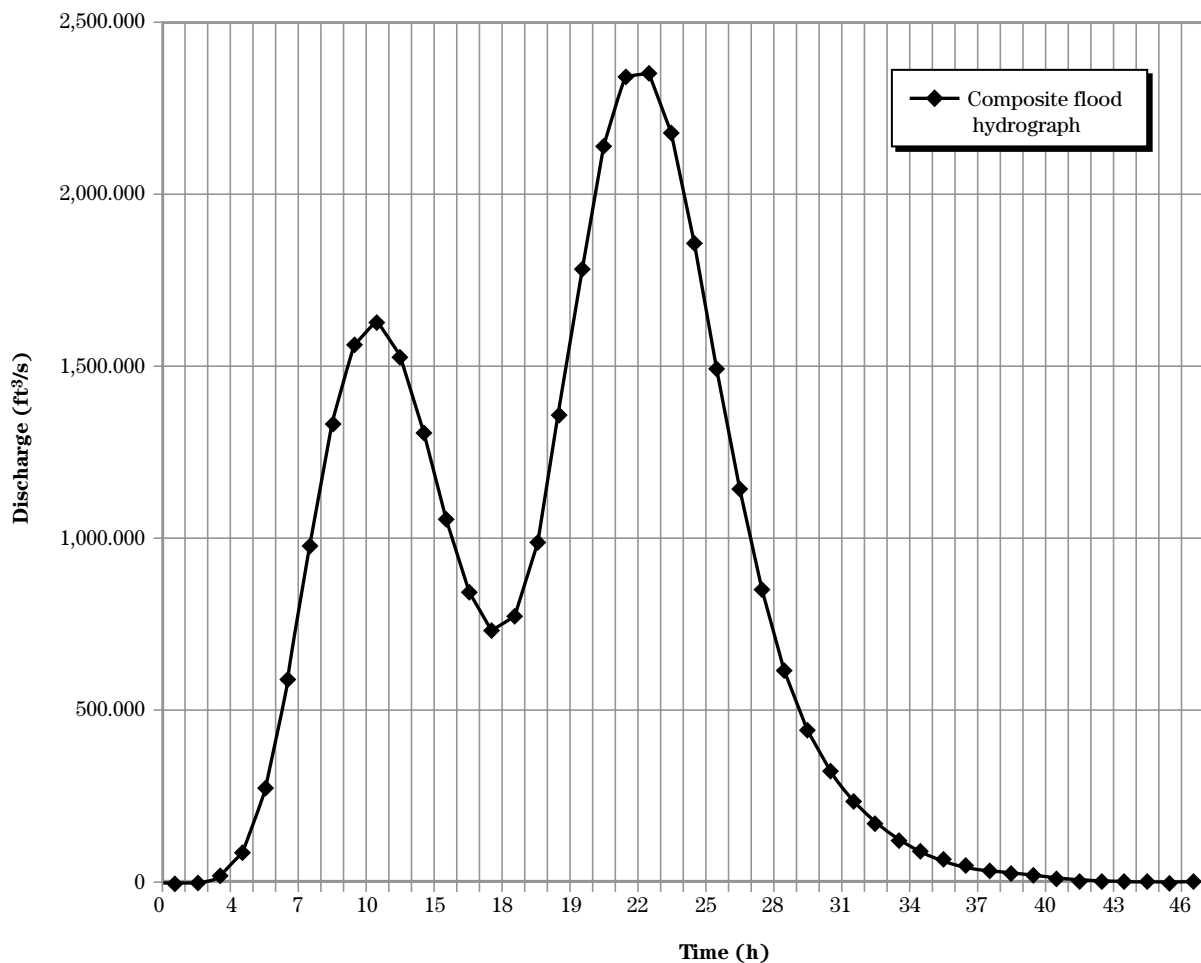
**Example 16-1** Composite flood hydrograph—Continued

Table 16-4(c) shows the position of the strip of paper containing the runoff when the peak discharge of the flood hydrograph (2,356 ft<sup>3</sup>/s) is reached. If only the peak discharge of the flood hydrograph is desired, it can be found by making only a few computations, placing the larger increments of runoff near the peak discharge of the unit hydrograph.

Table 16-4(d) shows the position of the strip of paper containing the runoff at the completion of the flood hydrograph. The complete flood hydrograph is shown in column 3. These discharges are plotted at their proper time sequence on figure 16-5, which is the complete flood hydrograph for example 16-1.

**Step 10** Calculate the volume under the flood hydrograph by summing the ordinates (table 16-4(d), column 3) and multiplying by  $\Delta D$ :  $33,409 \times 0.3 = 10,022.7 \text{ ft}^3/\text{s-h}$ .

**Figure 16-5** Composite flood hydrograph from example 16-1



## 630.1604 Unit hydrograph development for a gaged watershed

The dimensionless unit hydrograph varies from watershed to watershed based on a number of factors. Some of these factors are size of watershed, geomorphic characteristics, geologic characteristics, watershed slope, watershed length, amount of storage, degree of channelization of the stream network, and degree of urbanization. The dimensionless unit hydrograph (DUH) used as an NRCS standard for many years has a peak rate factor of 484 and is described earlier in this chapter. This DUH was developed by Victor Mockus (Mockus 1957) from analysis of small watersheds where the rainfall and streamflow were gaged. An alternative to the 484 DUH has been developed for the Delmarva region (Delaware, Maryland, Virginia peninsula) based on data from four gaged watersheds (Welle, Woodward, and Moody 1980).

Many reports have been published concerning development of the DUH for gaged watersheds in various parts of the country including Maryland (McCuen 1989), Georgia, Florida, and Texas (Sheridan and Merkel 1993). The DUH, as well as time of concentration, runoff curve number, stream Manning  $n$  values, and other key parameters, may be calibrated to gage data. Calibration of a hydrologic model may be based on actual measurements for the watershed or studies of nearby gaged watersheds, such as regional regression equations. A regional study of the DUH for gaged watersheds may reveal insights into what DUH to use for an ungaged watershed located within the region.

Various engineering textbooks, such as *Hydrology for Engineers* (Linsley, Kohler, and Paulhus 1982), have procedures for developing a unit hydrograph from gaged rainfall and streamflow data. The method presented in this chapter is somewhat different. It is a practical method using the NRCS WinTR-20 computer program. The primary concept upon which the method is based is that if the DUH is to be used in WinTR-20 for analysis of hypothetical storms (such as design storms, 100-year storm, probable maximum flood), the DUH should be developed by calibrating WinTR-20 for measured rainfall and streamflow data for the watershed. Furthermore, the WinTR-20 input data file should be organized in such a way as to represent the watershed stream network as determined by the

project purpose and degree of detail. The DUH is used in WinTR-20 to develop the incremental runoff hydrograph for a short duration of rainfall excess that results from rainfall assumed to be at uniform intensity. The rainfall distribution for the storm is divided into several short duration increments each with assumed uniform rainfall intensity and uniform depth over a watershed (or subarea). This is consistent with the assumption of unit hydrograph theory of spatial and temporal uniformity.

Williams (James, Winsor, and Williams 1987) and Meadows (Meadows and Ramsey 1991) developed computer programs that automate this process through optimization techniques. The only required data are rainfall distribution and magnitude, measured hydrograph data, and watershed drainage area. The output from these programs includes the event runoff curve number, unit hydrograph, peak rate factor, plots, and statistical analysis. These programs treat the watershed as a single unit (division of watershed into subareas is not simulated) assuming uniform rainfall and a single runoff curve number. They have been used to study unit hydrographs at many watersheds throughout the country (Woodward, Merkel, and Sheridan 1995). If the watershed is divided into subareas, the procedure above is recommended for developing a trial and error solution. The more subareas and reaches in the WinTR-20 input data, the more complicated this process becomes. However, if the steps are followed, a hydrologic model calibrated in such a manner will make the best use of limited gage information at other locations within the watershed.

The shape of the DUH determines the peak rate factor. The higher the peak rate factor, the higher the peak discharge will be from the watershed. The 1972 version of this chapter stated: "This constant has been known to vary from about 600 in steep terrain to 300 in very flat, swampy country." Recent studies have shown the peak rate factor has a much wider range: from below 100 to more than 600. The standard 484 DUH was developed using graphical techniques and not an equation. The gamma equation, however, fits the shape of the 484 DUH fairly well. The gamma equation has the following form:

$$\frac{Q}{Q_p} = e^m \left[ \left( \frac{t}{t_p} \right)^m \right] \left[ e^{-m \left( \frac{t}{t_p} \right)} \right] \quad [16-1]$$

where:

- $\frac{Q}{Q_p}$  = ratio of discharge at a certain time to the peak discharge of the unit hydrograph (UH)  
 $e$  = constant 2.7183  
 $m$  = gamma equation shape factor  
 $\frac{t}{t_p}$  = ratio of the time of DUH coordinate to time to peak of the DUH

Since the equation has only one parameter,  $m$ , one value of  $m$  produces a unique DUH, and thus one unique peak rate factor. The peak rate factor (PRF) is calculated from the DUH coordinates using the equation 16-2.

$$\text{PRF} = \frac{645.33}{\sum \text{DUH}_{\text{coordinates}} \times \Delta T_{\text{DUH}}} \quad [16-2]$$

where:

- PRF = peak rate factor  
 $\sum \text{DUH}_{\text{coordinates}}$  = summation of the dimensionless unit hydrograph coordinates  
 $\Delta T_{\text{DUH}}$  = nondimensional time interval of the DUH  
 645.33 = unit conversion factor (see eq. 16-5, appendix 16A)

The gamma equation may be used to develop a DUH with any desired peak rate factor.

The PRF is calculated after the DUH coordinates are calculated. This means that various values of  $m$  must be tried in the equation until a desired PRF is reached. Table 16-5 shows the relationship of  $m$  and PRF. The general steps to develop the DUH follow.

**Table 16-5** Relationship of  $m$  and PRF for DUH developed from a Gamma equation

$m$	PRF
0.26	101
1	238
2	349
3	433
3.7	484
4	504
5	566

### DUH determination with WinTR-20

**Step 1**—Derive input to the WinTR-20 model, enter the data, and make preliminary simulations. If the stream gage is not at the watershed outlet, defining a subarea or end of reach at the location of the stream gage is recommended. The original WinTR-20 input file should be copied to create a separate file for each storm event to be analyzed. The object of this analysis is to model the storm event over the watershed and adjust parameters, such as runoff curve number, baseflow, time of concentration, and DUH, to provide the best match with the measured streamflow hydrograph at the gage.

**Step 2**—Examine rainfall and streamflow records to ensure there are periods of record where both rainfall and streamflow are measured. At the stream gage location, select several flood events to be analyzed representing a range of magnitudes and for which rainfall records are available. With respect to the time interval of the data, generally the smaller the time interval the better the results. At some point, the modeler needs to assess the quality of data being used, locations of gages (often a rain gage within the watershed boundary is not available), and whether the time interval of the data is satisfactory. For example, if the stream gage is a crest gage (only peak discharge is recorded) and the rain gage records daily precipitation, it is unlikely that a reasonable DUH can be developed. Other commonly available data are hourly and 15-minute precipitation; daily, hourly, and peak streamflow; and breakpoint data (available for many Agricultural Research Service (ARS) experimental watersheds). The ARS maintains the Water Data Center, <http://hydrolab.arsusda.gov/wdc/arswater.html> with an archive on experimental watersheds. The National Climatic Data Center (NOAA), <http://www.ncdc.noaa.gov/oa/ncdc.html> has archived National Weather Service rainfall records, and the U.S. Geological Survey (USGS), <http://water.usgs.gov/>) has also archived streamflow records.

**Step 3**—For storm events with both measured rainfall and streamflow, develop a cumulative rainfall distribution to be entered into the WinTR-20 data file. If the watershed is small enough or if rainfall data are limited, a single rain gage may be used to represent uniform rainfall over the watershed. If more than one rain gage is available, rainfall isohyets may be drawn over the watershed and rainfall varied for each subarea.

**Step 4**—Runoff volume may be determined for the streamflow hydrograph and is recommended to be the first parameter calibrated. Runoff volume is the volume of the hydrograph above the baseflow. Several baseflow separation methods are described in standard hydrology texts, but in many small watersheds, baseflow is relatively small and a constant baseflow can generally be assumed. The runoff curve number for the watershed (or its subareas if so divided) should be adjusted such that the storm event rainfall produces the storm event runoff.

**Step 5**—If the hydrograph at the gage has significant baseflow, the value may be entered in the appropriate location in the WinTR-20 input file. Consideration should also be given to prorating the baseflow value (based on drainage area) at other locations along the stream network.

**Step 6**—Timing of the peak discharge at the gage is dependent primarily upon the time of concentration and stream cross section rating tables. The value of Manning's  $n$  used for overland flow, concentrated flow, and channel flow is not known precisely. Using gage data may help in refining these estimates. If the times to peak of the measured and computed hydrographs are not similar, the timing factors of the watershed should be adjusted to bring the times to peak into closer agreement.

**Step 7**—After the runoff volume and timing have been adjusted, the DUH may be calibrated by entering different DUHs in WinTR-20 with various peak rate factors. The objective is to match the peak discharge and shape of the measured hydrograph as closely as possible.

Considerations to be made in selecting events to analyze should include single versus multiple peak hydrographs, long versus short duration rainfalls, high versus low event runoff curve numbers, and large versus small flood events. Rainfall events separated by a relatively short time span may not allow the streamflow hydrograph to return to baseflow. Use of a complete hydrograph that begins and ends at baseflow is recommended.

Consider rain gages close enough to the watershed location such that the rainfall measurements accurately represent the actual rainfall on the watershed.

Problems inevitably occur when working with rainfall and runoff data. Problems indicating that a particular event should not be included in the analysis may include:

- a significant flood event with minor rainfall and vice versa
- more runoff volume than rainfall (such as may happen with snowmelt events,) see NEH 630, chapter 11, Snowmelt
- timing of rainfall and runoff measurements may be out of synchronization (for example, the hydrograph may begin rising before there is any rainfall)

If more than one storm event is analyzed, a wide range of event peak rate factors may result. The causes of these kinds of problems include:

- poor data quality
- nonuniform rainfall over the watershed
- rainfall (magnitude and/or distribution) at the gage not representing rainfall over the watershed
- partial area hydrology
- runoff curve number procedure not representing the distribution of runoff over time
- frozen soil, snowmelt runoff, transmission loss, or physical changes in the watershed over time (urbanization, reservoir construction, channel modification)
- the DUH may even be sensitive to the magnitude of the storm and resulting flood

If the range of PRFs for the various storm events is wide, the data and watershed characteristics should be investigated to determine the reason. Judgment needs to be exercised in determining what DUH best represents the watershed. Example 16-2 shows the procedure to determine the dimensionless unit hydrograph for a gaged watershed.



**Example 16-2** Determining the DUH for a gaged watershed**Watershed and storm event description:**

The watershed selected for this example is Alligator Creek near Clearwater, Florida. Hourly discharge and rainfall data were provided by the U.S. Geological Survey. The watershed has a drainage area of 6.73 square miles. For simplicity, the watershed is treated as a single watershed and is not divided into subareas. The date of the storm event being analyzed is February 2, 1996. The storm had a duration of 15 hours and a total rainfall of 3.69 inches. The peak discharge at the stream gage was 436 cubic feet per second.

**Rainfall and runoff data:**

Columns 1 to 3 in table 16-6 show the time series of measured rainfall and stream discharge. The rainfall distribution for the storm event is plotted in figure 16-6. The baseflow of the hydrograph is 4.7 cubic feet per second. After subtracting the constant baseflow from the measured hydrograph, the runoff volume was computed to be 1.45 inches. The runoff curve number corresponding to 3.69 inches of rainfall and 1.45 inches of runoff is 75, which was used in WinTR-20 for the watershed runoff curve number.

**Time of concentration:**

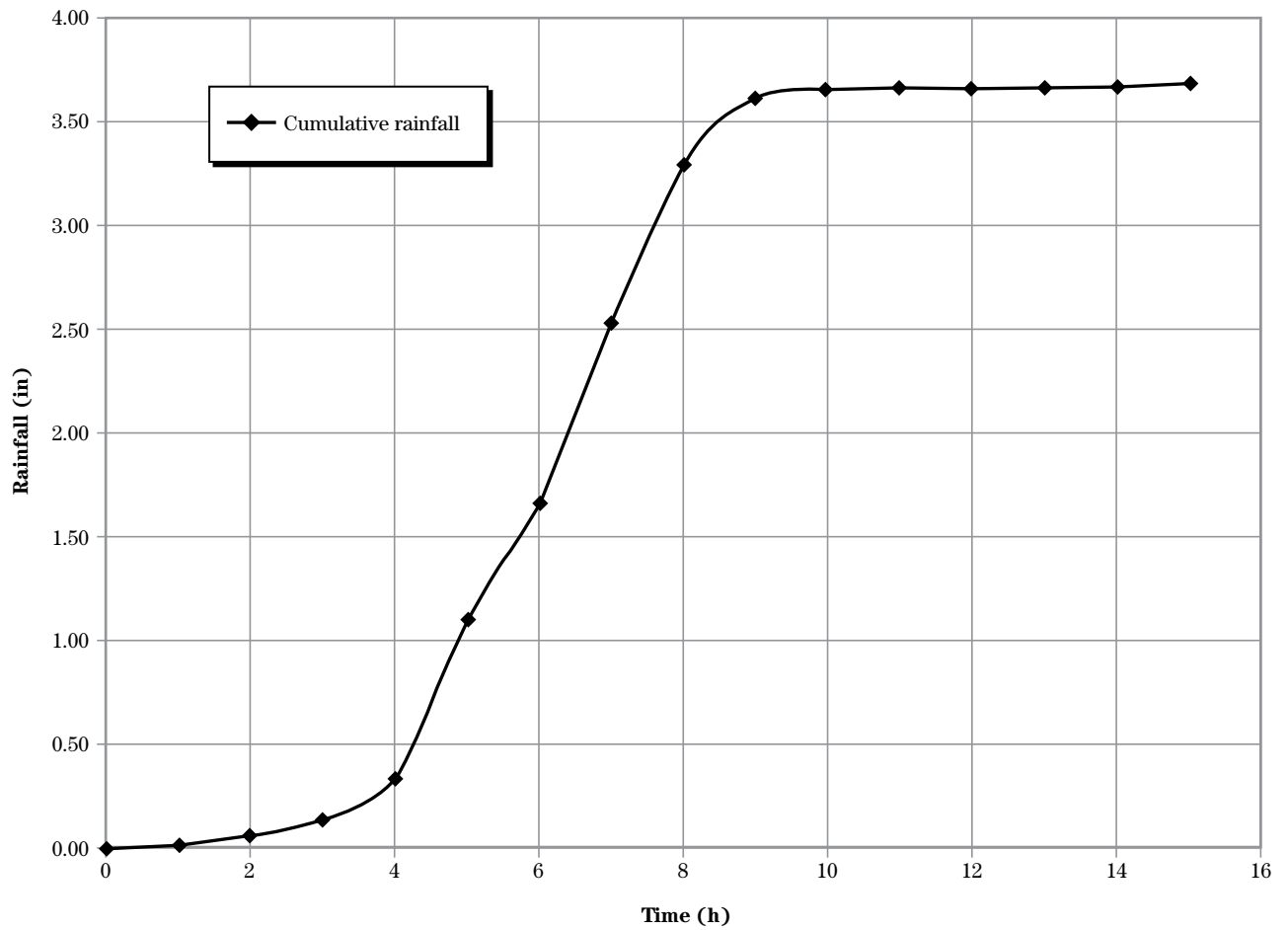
The time to peak of the measured hydrograph is 12 hours. Several trials of watershed time of concentration were made before arriving at the value of 8 hours. This resulted in the computed hydrograph having a time to peak of 12 hours.

**Dimensionless Unit Hydrograph:**

A DUH for any desired peak rate factor may be developed from the gamma equation (16-1) described in this section. Appendix 16B has standard tables that have been developed for a DUH based on the gamma equation for peak rate factors ranging from 100 to 600 (at increments of 50). The PRF for this individual storm event was between 200 and 250. The sum of the DUH coordinates in table 16-7 is 13.5361. Using the given nondimensional time step 0.2 and equation 16-2 results in a calculated PRF of 238.37, and is rounded to 238. The final peak rate factor of 238 was selected (which gave a good fit of hydrograph shape and peak discharge). The DUH is listed in table 16-7 and plotted in figure 16-7. The computed hydrograph for this PRF is in column 4 of table 16-6. The comparison of the measured and computed hydrographs is shown in figure 16-8.

**Example 16-2** Determining the DUH for a gaged watershed—Continued**Table 16-6** Storm event of February 2, 1996, at Alligator Creek near Clearwater, FL

Time (h) (1)	Cumulative rainfall (in) (2)	Measured discharge (ft <sup>3</sup> /s) (3)	Computed discharge (ft <sup>3</sup> /s) (4)	Time (h) (1)	Cumulative rainfall (in) (2)	Measured discharge (ft <sup>3</sup> /s) (3)	Computed discharge (ft <sup>3</sup> /s) (4)
0	0.00	4.7	4.7	28		87.4	92.5
1	0.01	4.7	4.7	29		81.4	81
2	0.06	4.7	4.7	30		76.7	70.9
3	0.14	5.0	4.7	31		71.6	62
4	0.34	5.5	4.7	32		66.6	54.2
5	1.10	7.8	13.9	33		63.4	47.4
6	1.66	24.8	48.5	34		59.2	41.4
7	2.54	98.8	121.1	35		56.2	36.1
8	3.30	199.5	211.2	36		53.2	31.4
9	3.62	292.9	315.3	37		50.8	27.6
10	3.66	362.5	379.6	38		47.5	24.4
11	3.67	416.1	414.1	39		45.7	21.7
12	3.67	436.4	425.9	40		44.3	19.2
13	3.67	424.9	421.6	41		42.5	17.1
14	3.68	395.0	407.2	42		40.8	15.3
15	3.69	357.8	386.2	43		39.1	13.8
16		316.8	360.8	44		37.8	12.4
17		279.1	333	45		36.5	11.3
18		244.6	304.3	46		35.3	10.3
19		215.0	275.9	47		34.5	9.4
20		187.1	248.4	48		33.7	8.7
21		165.9	222.4	49		32.5	8.1
22		146.7	198.2	50		31.8	7.6
23		132.2	175.8	51		31.0	7.1
24		119.9	155.2	52		30.2	6.7
25		110.4	136.6	53		29.5	6.4
26		100.8	120	54		28.8	6.1
27		93.0	105.4	55		27.7	5.8

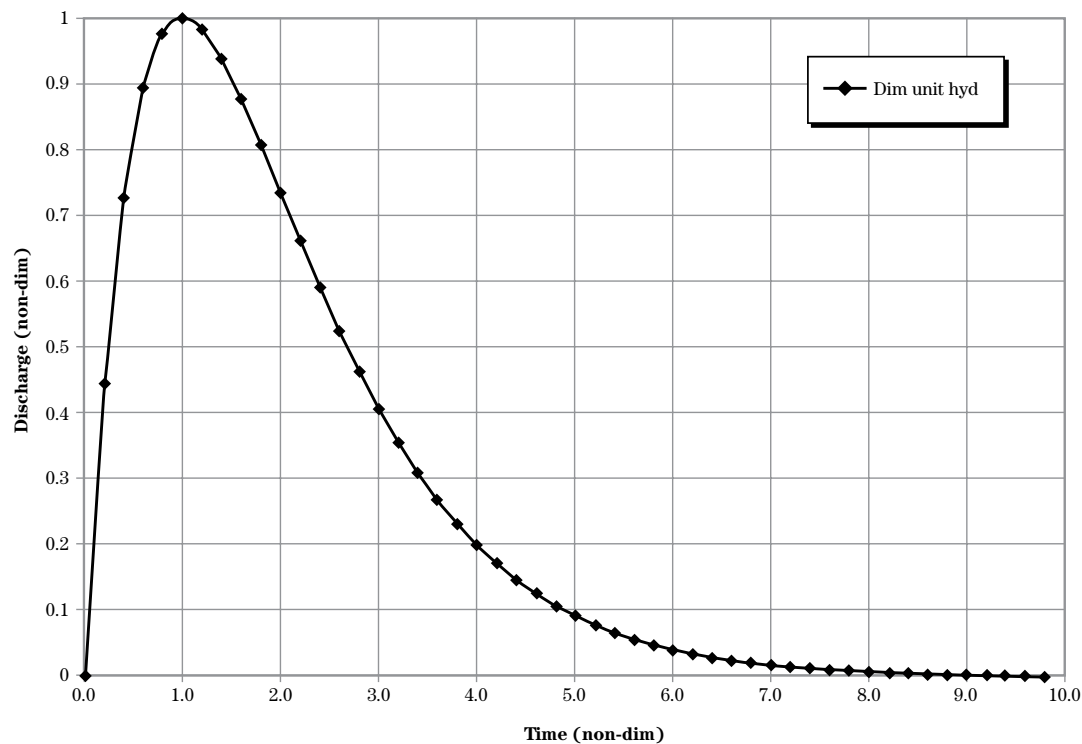
**Example 16-2** Determining the DUH for a gaged watershed—Continued**Figure 16-6** Cumulative rainfall used in example 16-2

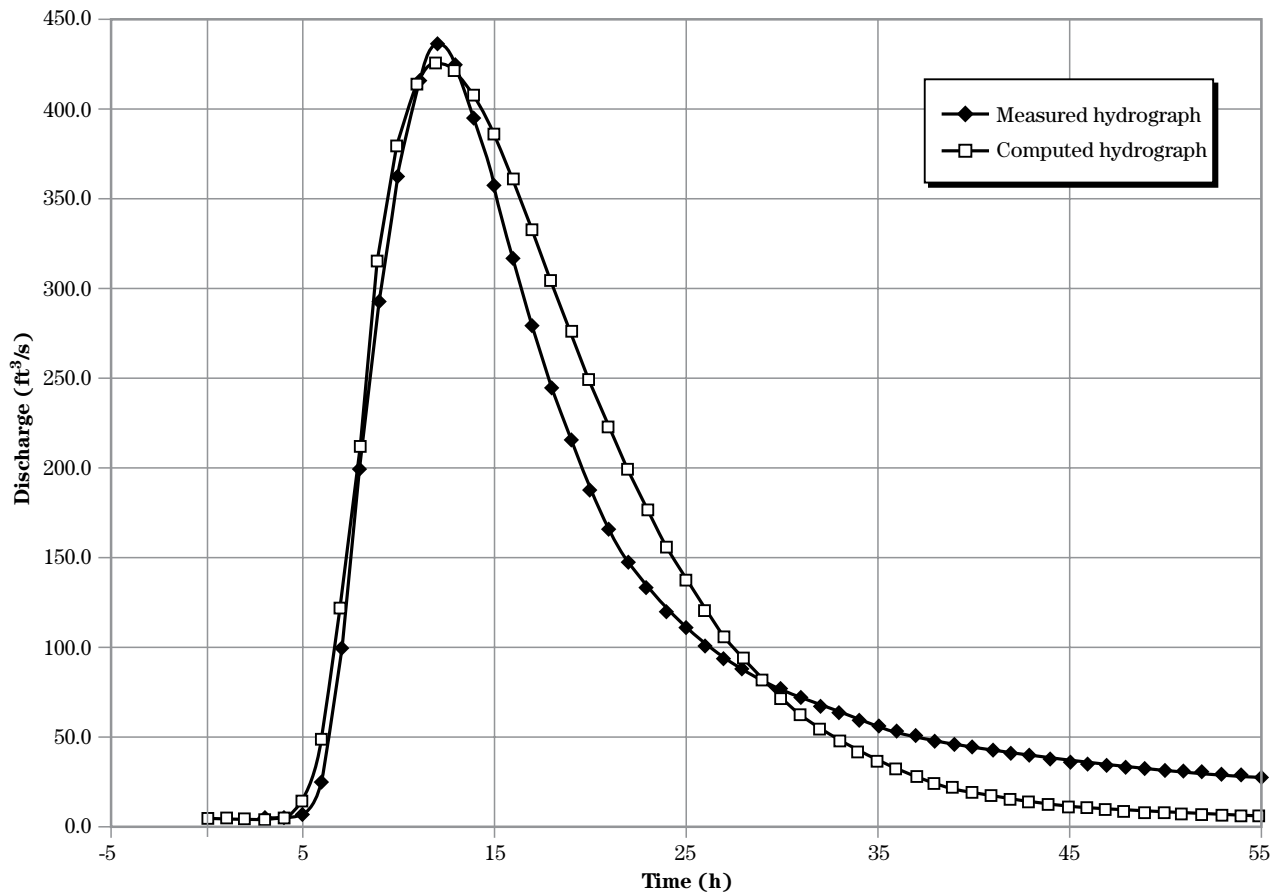
**Example 16-2** Determining the DUH for a gaged watershed—Continued

**Table 16-7** Dimensionless unit hydrograph for Alligator Creek at Clearwater, FL, used in example 16-2

Time non-dim	Discharge non-dim	Time non-dim	Discharge non-dim	Time non-dim	Discharge non-dim	Time non-dim	Discharge non-dim	Time non-dim	Discharge non-dim
0.0	0	2.0	0.736	4.0	0.199	6.0	0.04	8.0	0.007
0.2	0.445	2.2	0.663	4.2	0.172	6.2	0.034	8.2	0.006
0.4	0.729	2.4	0.592	4.4	0.147	6.4	0.029	8.4	0.005
0.6	0.895	2.6	0.525	4.6	0.126	6.6	0.024	8.6	0.004
0.8	0.977	2.8	0.463	4.8	0.107	6.8	0.021	8.8	0.0036
1.0	1	3.0	0.406	5.0	0.092	7.0	0.017	9.0	0.003
1.2	0.983	3.2	0.355	5.2	0.078	7.2	0.015	9.2	0.0025
1.4	0.938	3.4	0.308	5.4	0.066	7.4	0.012	9.4	0.002
1.6	0.878	3.6	0.267	5.6	0.056	7.6	0.01	9.6	0.001
1.8	0.809	3.8	0.231	5.8	0.048	7.8	0.009	9.8	0
sum DUH coordinates									13.5361
<b>PRF</b>									<b>238.</b>

**Figure 16-7** Dimensionless unit hydrograph used in example 16-2



**Example 16-2** Determining the DUH for a gaged watershed—Continued**Figure 16-8** Runoff hydrographs for example 16-2

**Example 16-2** Determining the DUH for a gaged watershed—Continued**Conclusion:**

This procedure outlines the steps of developing the DUH by trial-and-error using WinTR-20. The comparison of the measured and computed hydrographs shows a good match of the rising hydrograph limb and the peak discharge and a less accurate fit of the falling limb. The measured hydrograph shows a slower recession at the tail of the hydrograph, which may represent delayed release of water from storage or delayed hydrograph response as a result of subsurface flow. Representing this in the DUH would require a more complex mathematical representation, such as a gamma equation for the majority of the DUH shape and an exponential recession function to represent the tail of the DUH. If another shape of DUH is desired, it may be accommodated in the steps described above.

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## 630.1605 References

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The dimensionless curvilinear unit hydrograph (fig. 16-1) has 37.5 percent of the total volume in the rising side, which is represented by one unit of time and one unit of discharge. This dimensionless unit hydrograph also can be represented by an equivalent triangular hydrograph having the same units of time and discharge, thus having the same percent of volume in the rising side of the triangle (fig. 16A-1). This allows the base of the triangle to be solved in relation to the time to peak using the geometry of triangles. Solving for the base length of the triangle, if one unit of time  $T_p$  equals 0.375 per cent of volume:

$$T_b = \frac{1.00}{.375} = 2.67 \text{ units of time}$$

$$T_r = T_b - T_p = 1.67 \text{ units of time or } 1.67 T_p$$

where:

- $T_b$  = time from beginning to end of the triangular hydrograph
- $T_r$  = time from the peak to the end of the triangular hydrograph
- $T_p$  = time from the beginning of the triangular hydrograph to its peak

These relationships are useful in developing the peak rate equation for use with the dimensionless unit hydrograph.

**Peak rate equation**

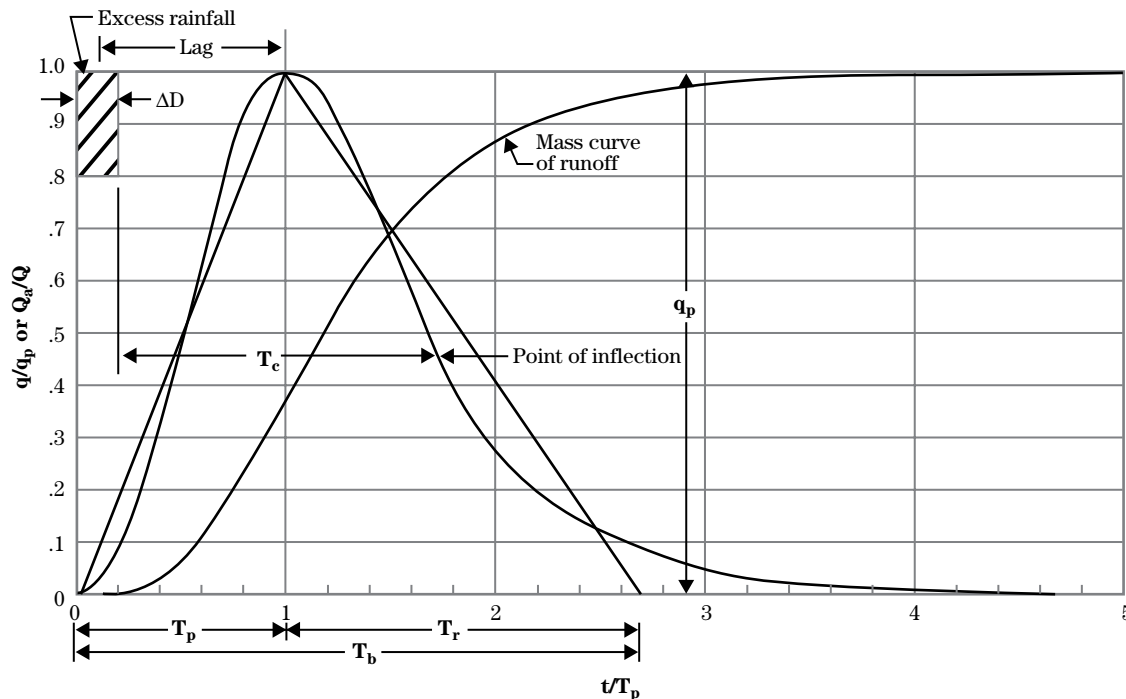
From figure 16A-1 the total volume under the triangular unit hydrograph is:

$$Q = \frac{q_p T_p}{2} + \frac{q_p T_r}{2} = \frac{q_p}{2} (T_p + T_r) \tag{16A-1}$$

With  $Q$  in inches and  $T$  in hours, solve for peak rate  $q_p$  in inches per hour:

$$q_p = \frac{2Q}{T_p + T_r} \tag{16A-2}$$

**Figure 16A-1** Dimensionless curvilinear unit hydrograph and equivalent triangular hydrograph



Let:

$$K = \frac{2}{1 + \frac{T_r}{T_p}} \quad [16A-3]$$

Therefore:

$$q_p = \frac{KQ}{T_p} \quad [16A-4]$$

In making the conversion from inches per hour to cubic feet per second and putting the equation in terms ordinarily used, including drainage area  $A$  in square miles and time  $T$  in hours, equation 16-4 becomes the general equation:

$$q_p = \frac{645.33 \times K \times A \times Q}{T_p} \quad [16A-5]$$

where:

- $q_p$  = peak discharge in cubic feet per second (ft<sup>3</sup>/s)
- 645.33 = conversion factor for the rate required to discharge 1 inch from 1 square mile in 1 hour, units of  $\frac{(\text{ft}^3/\text{s}) \times \text{h}}{\text{mi}^2 \times \text{in}}$
- $K$  = nondimensional factor
- $A$  = drainage area in square miles (mi<sup>2</sup>)
- $Q$  = runoff in inches (in)
- $T_p$  = time to peak in hours (h)

The relationship of the triangular unit hydrograph,  $T_r = 1.67$ , gives  $K = 0.75$ . Then substituting into equation 16-5 gives:

$$q_p = \frac{484AQ}{T_p} \quad [16A-6]$$

The peak rate factor for the triangular dimensionless unit hydrograph is 484. The curvilinear dimensionless unit hydrograph of table 16-1 has a peak rate factor of 483.4 due to rounding of the discharge ratios to either two or three decimal places. This discrepancy produces a negligible difference in the calculated peak discharges.

Any change in the dimensionless unit hydrograph reflecting a change in the percent of volume under the rising side would cause a corresponding change in the

shape factor associated with the triangular hydrograph and, therefore, a change in the constant 484. This constant has been known to vary from about 600 in steep terrain to 100 or less in flat, swampy country. The national hydraulic engineer should concur in the use of a dimensionless unit hydrograph other than that shown in figure 16A-1. If the dimensionless shape of the hydrograph needs to vary to perform a special job, the ratio of the percent of total volume in the rising side of the unit hydrograph to the rising side of a triangle is a useful tool in arriving at the peak rate factor.

Figure 16A-1 shows that:

$$T_p = \frac{\Delta D}{2} + L \quad [16A-7]$$

where:

- $\Delta D$  = duration of unit excess rainfall in hours
- $L$  = watershed lag in hours

The *lag* of a watershed is defined in NEH 630, chapter 15 as the time from the center of mass of excess rainfall ( $\frac{\Delta D}{2}$ ) to the time to peak ( $T_p$ ) of a unit hydrograph. Combining equations 16A-6 and 16A-7 results in equation 16A-8:

$$q_p = \frac{484AQ}{\frac{\Delta D}{2} + L} \quad [16A-8]$$

The average relationship of lag to time of concentration ( $T_c$ ) is  $L = 0.6 T_c$  (NEH 630, chapter 15).  $T_c$  is expressed in hours.

Substituting in equation 16A-8, the peak rate equation becomes:

$$q_p = \frac{484AQ}{\frac{\Delta D}{2} + 0.6T_c} \quad [16A-9]$$

The time of concentration is defined in two ways in chapter 15:

- The time for runoff to travel from the hydraulically most distant point in the watershed to the point in question.
- The time from the end of excess rainfall to the point of inflection on the receding limb of the unit hydrograph.

These two relationships are important because  $T_c$  is computed under the first definition and  $\Delta D$ , the unit storm duration, is used to compute the time to peak ( $T_p$ ) of the unit hydrograph. This in turn is applied to all of the points on the abscissa of the dimensionless unit hydrograph using the ratio  $t/T_p$  as shown in table 16-1.

The dimensionless unit hydrograph shown in figure 16A-1 has a time to peak at one unit of time and point of inflection at approximately 1.7 units of time. Using the relationships  $Lag = 0.6 T_c$  and the point of inflection =  $1.7 T_p$ ,  $\Delta D$  will be  $0.2 T_p$ . A small variation in  $\Delta D$  is permissible; however, it should be no greater than  $0.25 T_p$ . The standard NRCS dimensionless unit hydrograph is defined at an interval of  $0.1 T_p$  (table 16-1). If  $\Delta D$  is  $0.2 T_p$ , then during computations, every second point is used to develop the incremental flood hydrograph. If  $\Delta D$  is  $0.25 T_p$  or more, then the shape of the dimensionless unit hydrograph is not being represented accurately. Example 16-1 illustrates the development of a composite flood hydrograph as shown in figure 16-5.

Using the relationship shown on the dimensionless unit hydrograph in figure 16A-1, compute the relationship of  $\Delta D$  to  $T_c$ :

$$T_c + \Delta D = 1.7T_p \quad [16A-10]$$

$$\frac{\Delta D}{2} + 0.6T_c = T_p \quad [16A-11]$$

Combining these two equations results in a defined relationship between  $\Delta D$  and  $T_c$ :

$$T_c + \Delta D = 1.7 \left( \frac{\Delta D}{2} + 0.6T_c \right) \quad [16A-12]$$

$$0.15\Delta D = 0.02T_c$$

$$\Delta D = 0.133 T_c \quad [16A-13]$$



# Appendix 16B

# Dimensionless Unit Hydrographs with Peak Rate Factors from 100 to 600

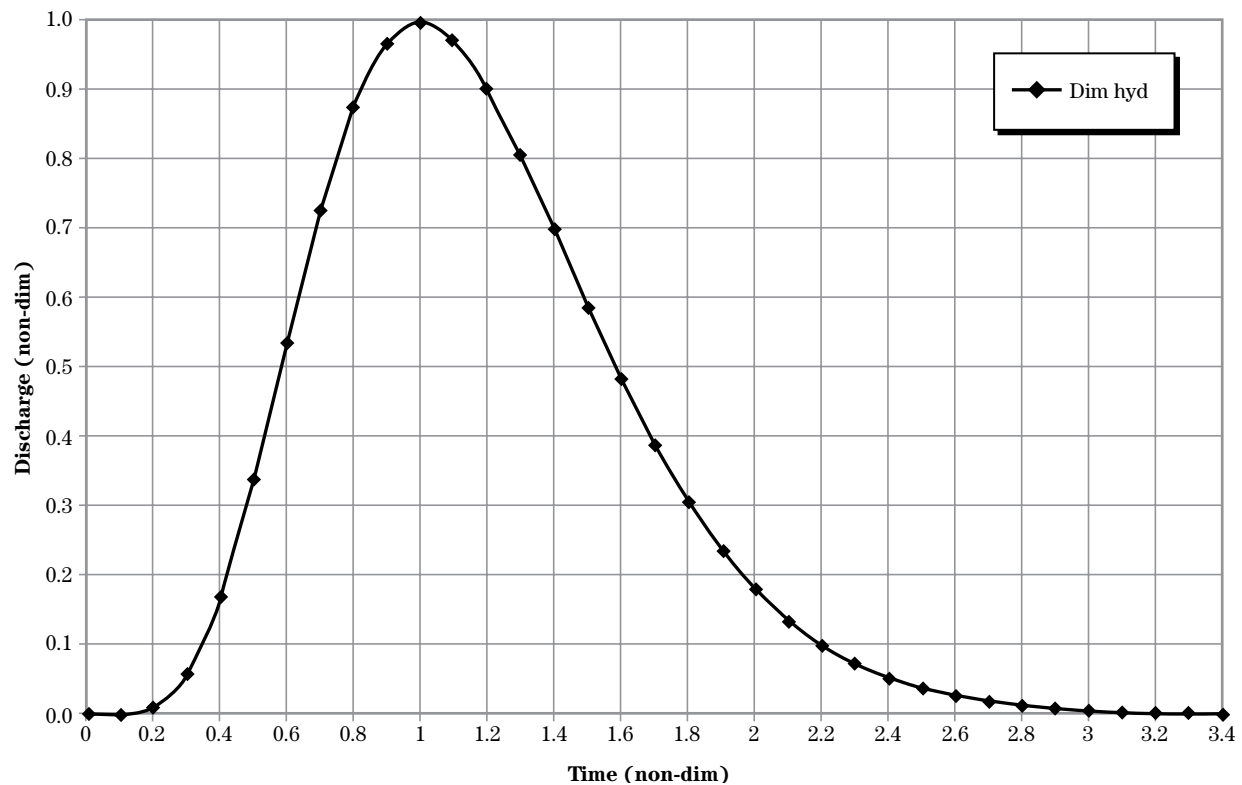
This appendix has standard dimensionless unit hydrographs developed using the gamma equation. For each peak rate factor from 100 to 600, in increments of 50, a table has been prepared in the format for the NRCS WinTR-20 computer program (see tables 16B-1 through 16B-11). A plot of each dimensionless unit hydrograph is included as figures 16B-1 through 16B-11. Refer to section 630.1604 for information on the development and use of these standard tables.

**Table 16B-1** Peak rate factor = 600

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.0004	0.0108	0.0596	0.1703
0.3392	0.5378	0.7282	0.8785	0.9704
1.0	0.9741	0.9058	0.8101	0.7008
0.5891	0.4831	0.3875	0.3049	0.2358
0.1795	0.1348	0.0999	0.0732	0.0531
0.0381	0.0271	0.0191	0.0134	0.0093
0.0064	0.0044	0.003	0.002	0.0014
0.0009	0.0006	0.0004	0.0003	0.0002
0.0001	0.0001	0.0001	0.0	

**Figure 16B-1** Peak rate factor = 600

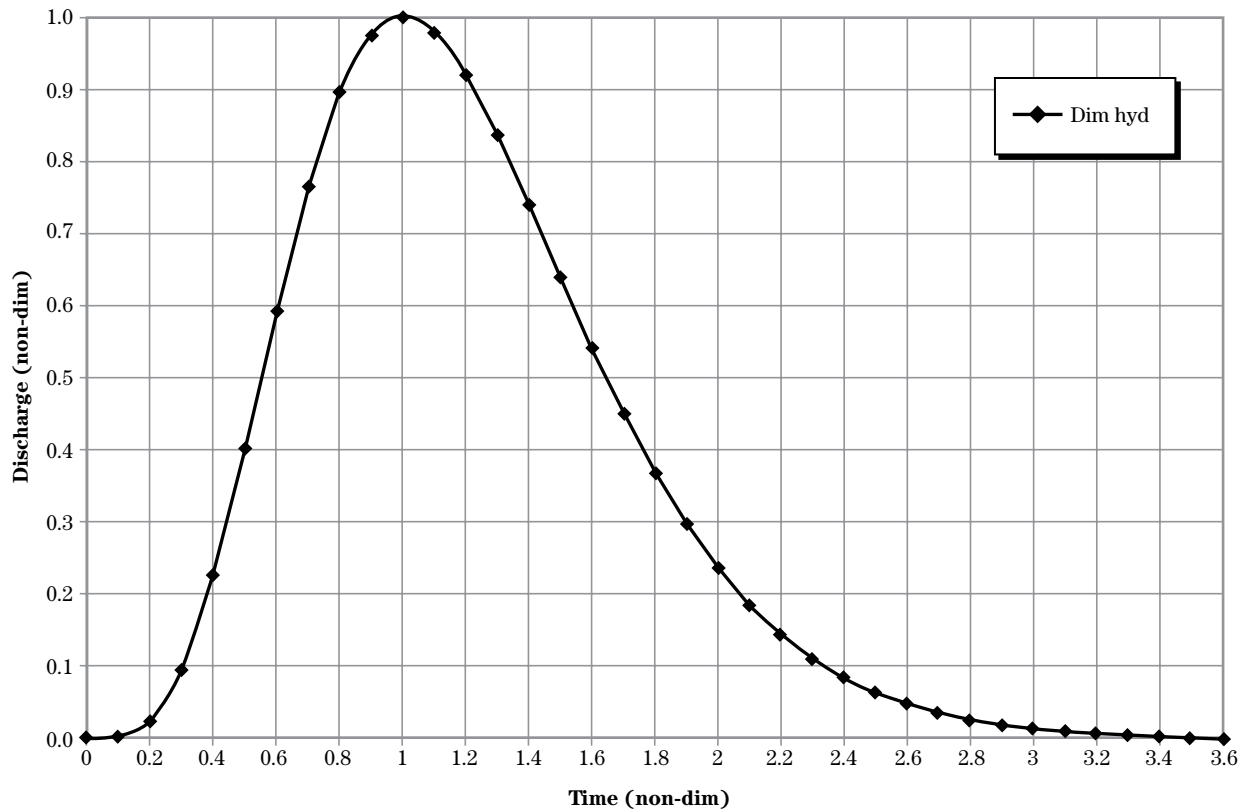


**Table 16B-2** Peak rate factor = 550

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.0013	0.0218	0.0923	0.2242
0.4012	0.5922	0.7649	0.8964	0.975
1.0	0.9781	0.9198	0.837	0.7405
0.6396	0.5408	0.449	0.3666	0.2951
0.2344	0.184	0.1429	0.1099	0.0837
0.0633	0.0475	0.0354	0.0262	0.0193
0.0141	0.0103	0.0074	0.0054	0.0038
0.0027	0.002	0.0014	0.001	0.0007
0.0005	0.0003	0.0002	0.0002	0.0001
0.0001	0.0001	0.0		

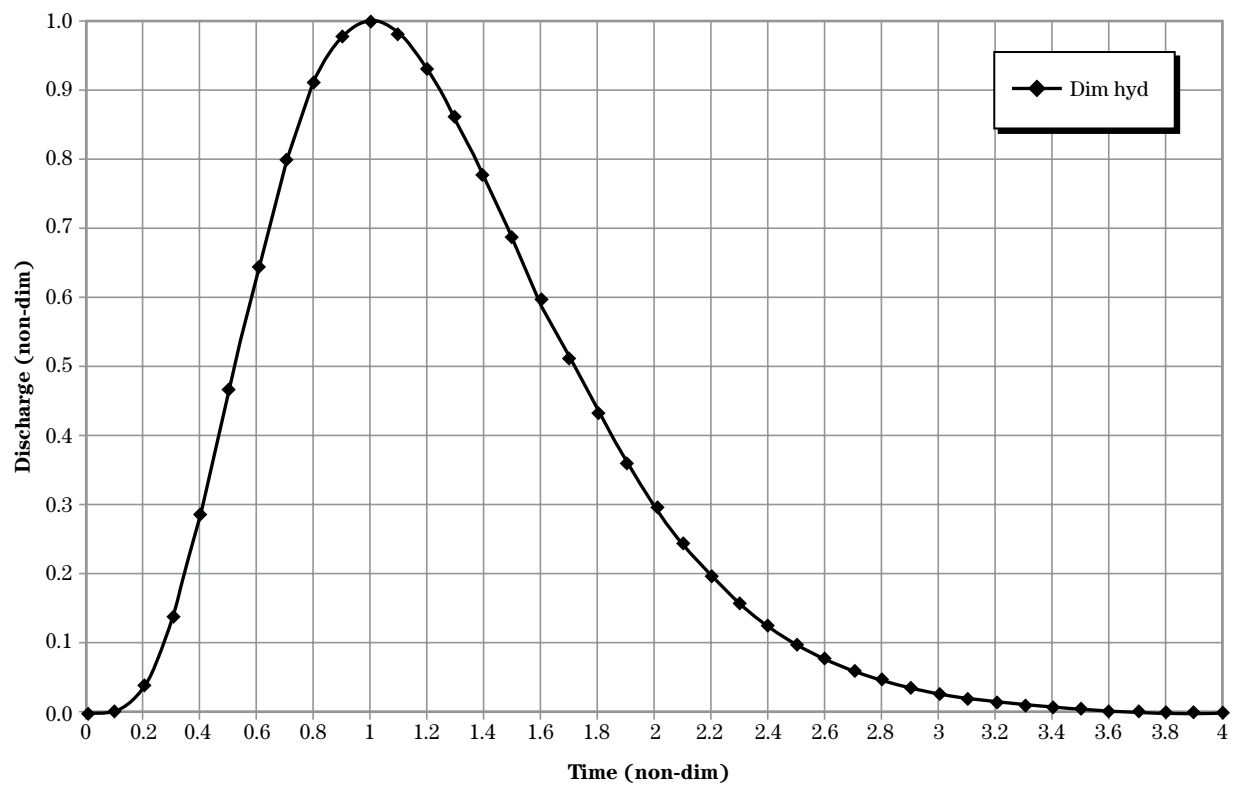
**Figure 16B-2** Peak rate factor = 550



**Table 16B-3** Peak rate factor = 500

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.004	0.0414	0.1376	0.2881
0.4677	0.6466	0.8001	0.913	0.9791
1.0	0.9817	0.9328	0.8623	0.7788
0.6893	0.5996	0.5135	0.4338	0.3621
0.2989	0.2444	0.198	0.1591	0.1269
0.1006	0.0792	0.062	0.0482	0.0374
0.0288	0.0221	0.0169	0.0129	0.0098
0.0074	0.0056	0.0042	0.0031	0.0023
0.0017	0.0013	0.001	0.0007	0.0005
0.0004	0.0003	0.0002	0.0002	0.0001
0.0001	0.0001	0.0		

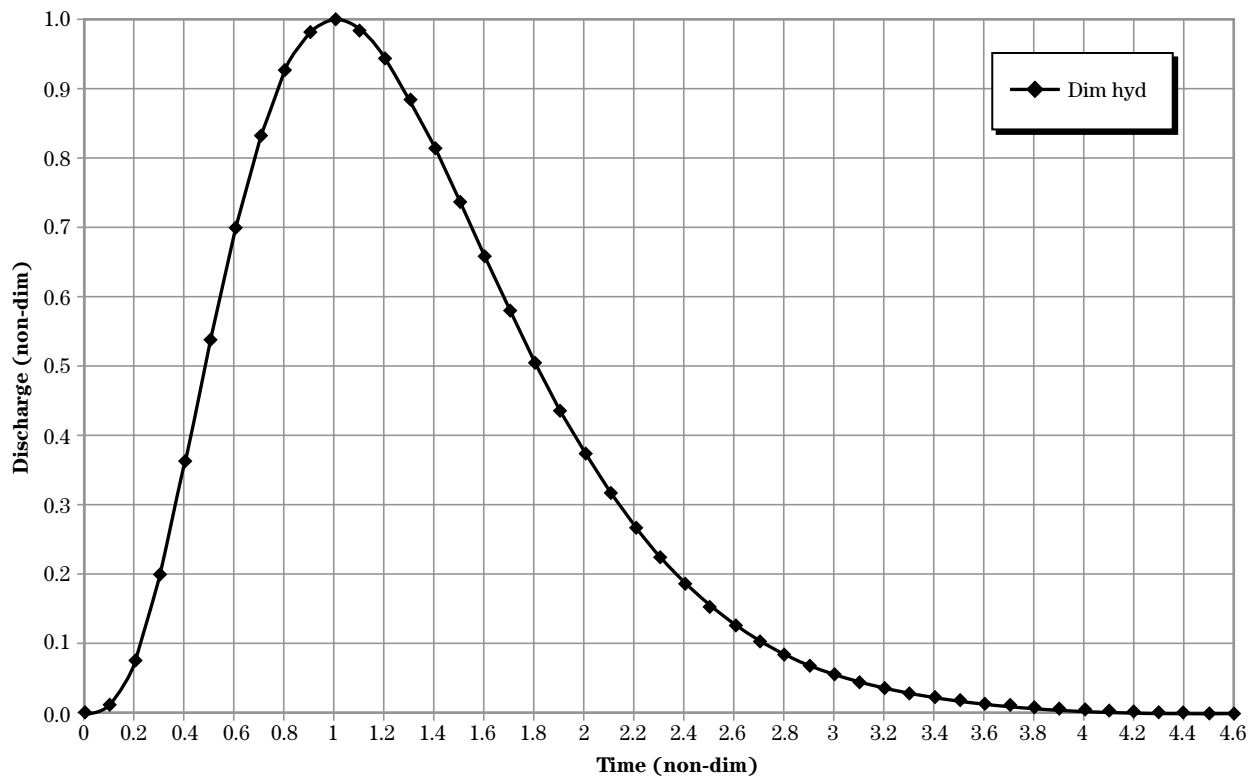
**Figure 16B-3** Peak rate factor = 500

**Table 16B-4** Peak rate factor = 450

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.011	0.0739	0.1975	0.3614
0.5371	0.7	0.8333	0.9282	0.9829
1.0	0.985	0.9447	0.8859	0.8151
0.7377	0.6581	0.5798	0.5051	0.4357
0.3725	0.3159	0.266	0.2224	0.1849
0.1528	0.1257	0.1029	0.0838	0.068
0.055	0.0443	0.0356	0.0285	0.0227
0.0181	0.0143	0.0114	0.009	0.0071
0.0056	0.0044	0.0034	0.0027	0.0021
0.0016	0.0013	0.001	0.0008	0.0006
0.0005	0.0004	0.0003	0.0002	0.0002
0.0001	0.0001	0.0001	0.0001	0.0

**Figure 16B-4** Peak rate factor = 450



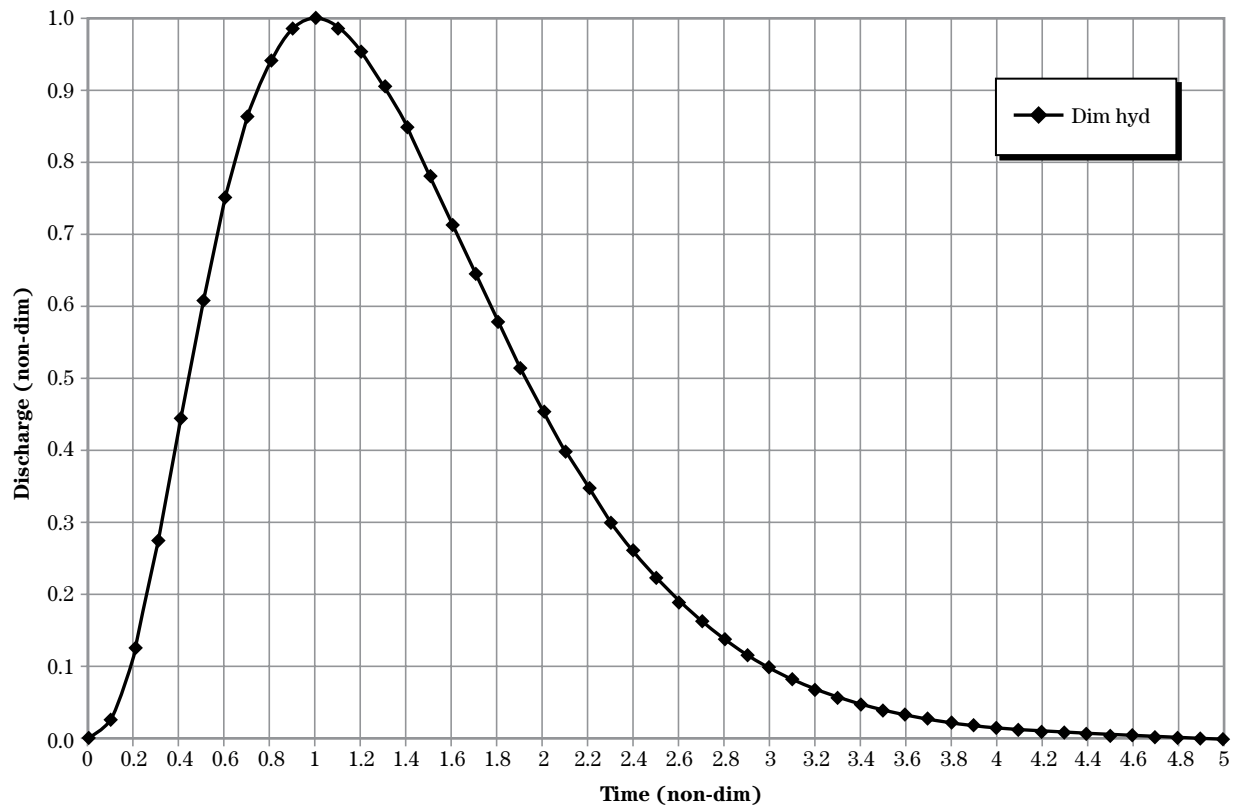


**Table 16B-5** Peak rate factor = 400

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.027	0.1244	0.2732	0.4429
0.6081	0.7517	0.8642	0.9421	0.9863
1.0	0.988	0.9555	0.9076	0.8491
0.7839	0.7155	0.6465	0.579	0.5144
0.4538	0.3977	0.3465	0.3004	0.2591
0.2224	0.1902	0.162	0.1376	0.1164
0.0982	0.0826	0.0693	0.0579	0.0484
0.0403	0.0335	0.0278	0.023	0.019
0.0157	0.0129	0.0106	0.0087	0.0072
0.0059	0.0048	0.0039	0.0032	0.0026
0.0021	0.0017	0.0014	0.0011	0.0009
0.0007	0.0006	0.0005	0.0004	0.0003
0.0003	0.0002	0.0002	0.0001	0.0001
0.0001	0.0001	0.0001	0.0	

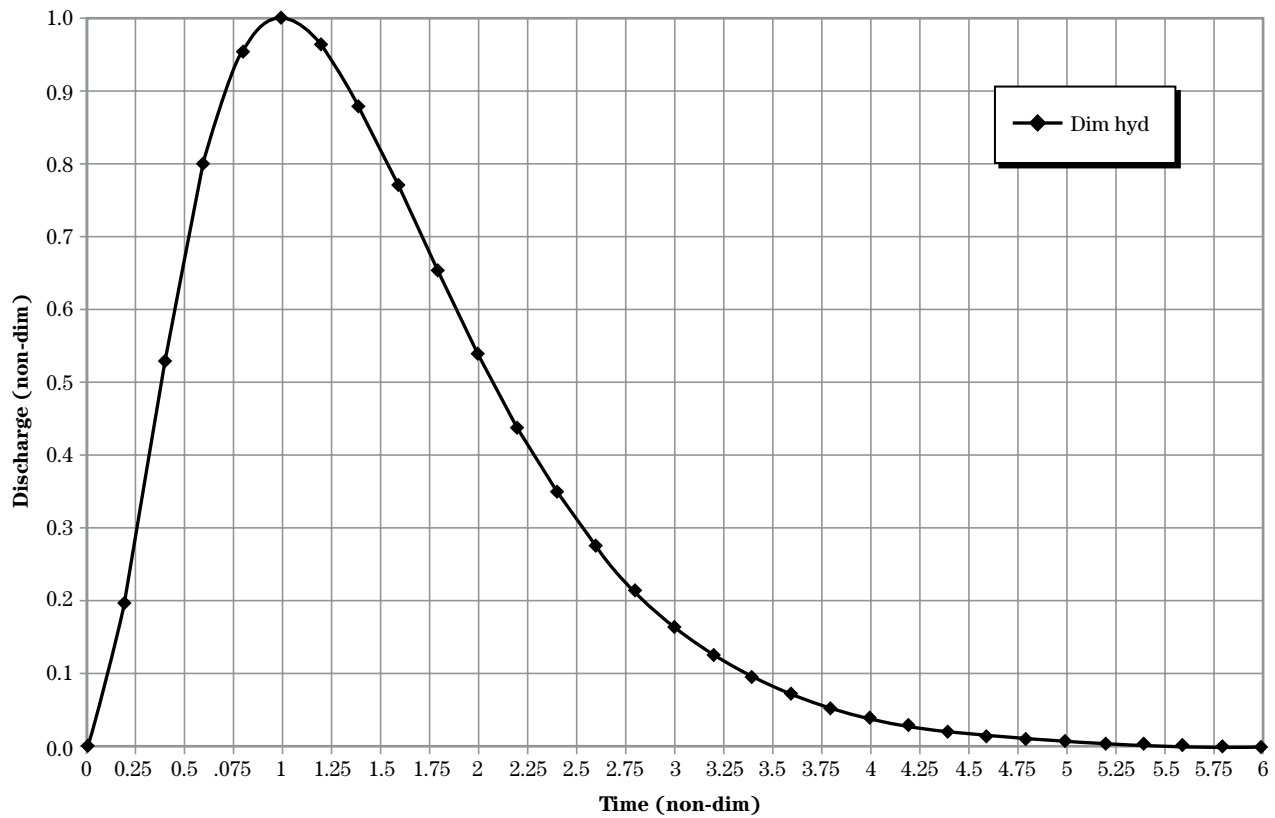
**Figure 16B-5** Peak rate factor = 400



**Table 16B-6** Peak rate factor = 350

DIMENSIONLESS UNIT HYDROGRAPH:

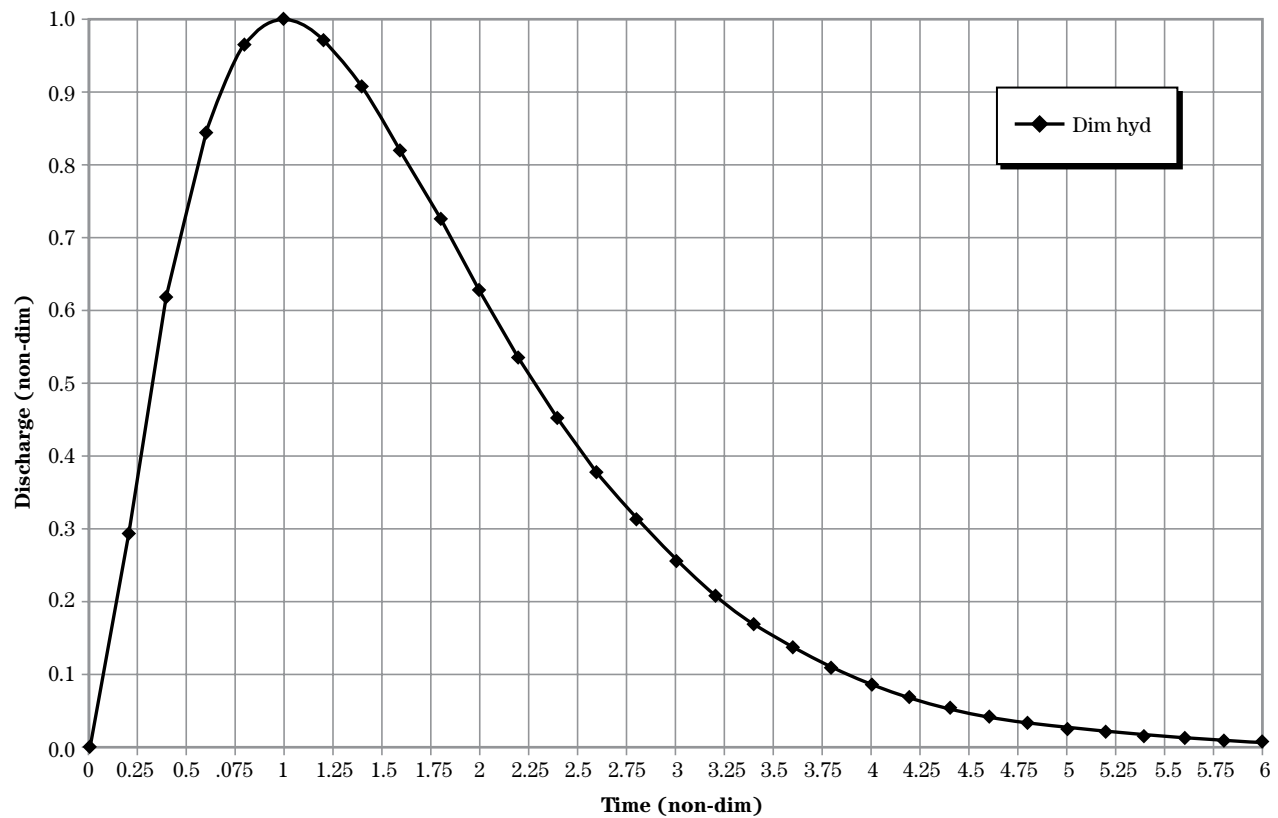
0.0	0.197	0.53	0.8006	0.9546
1.0	0.9651	0.8803	0.7703	0.6532
0.5402	0.4378	0.349	0.2743	0.2131
0.1638	0.1248	0.0944	0.0708	0.0529
0.0392	0.0289	0.0213	0.0156	0.0114
0.0082	0.006	0.0043	0.0031	0.0022
0.0016	0.0011	0.0008	0.0006	0.0004
0.0003	0.0002	0.0001	0.0001	0.0001
0.0001	0.0			

**Figure 16B-6** Peak rate factor = 350

**Table 16B-7** Peak Rate Factor = 300

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.2943	0.6201	0.8458	0.9656
1.0	0.9736	0.9085	0.8217	0.7257
0.629	0.5369	0.4527	0.3776	0.3122
0.2561	0.2087	0.1691	0.1363	0.1093
0.0873	0.0695	0.0551	0.0436	0.0343
0.027	0.0212	0.0166	0.0129	0.0101
0.0078	0.0061	0.0047	0.0037	0.0028
0.0022	0.0017	0.0013	0.001	0.0008
0.0006	0.0005	0.0003	0.0003	0.0002
0.0002	0.0001	0.0001	0.0001	0.0001
0.0				

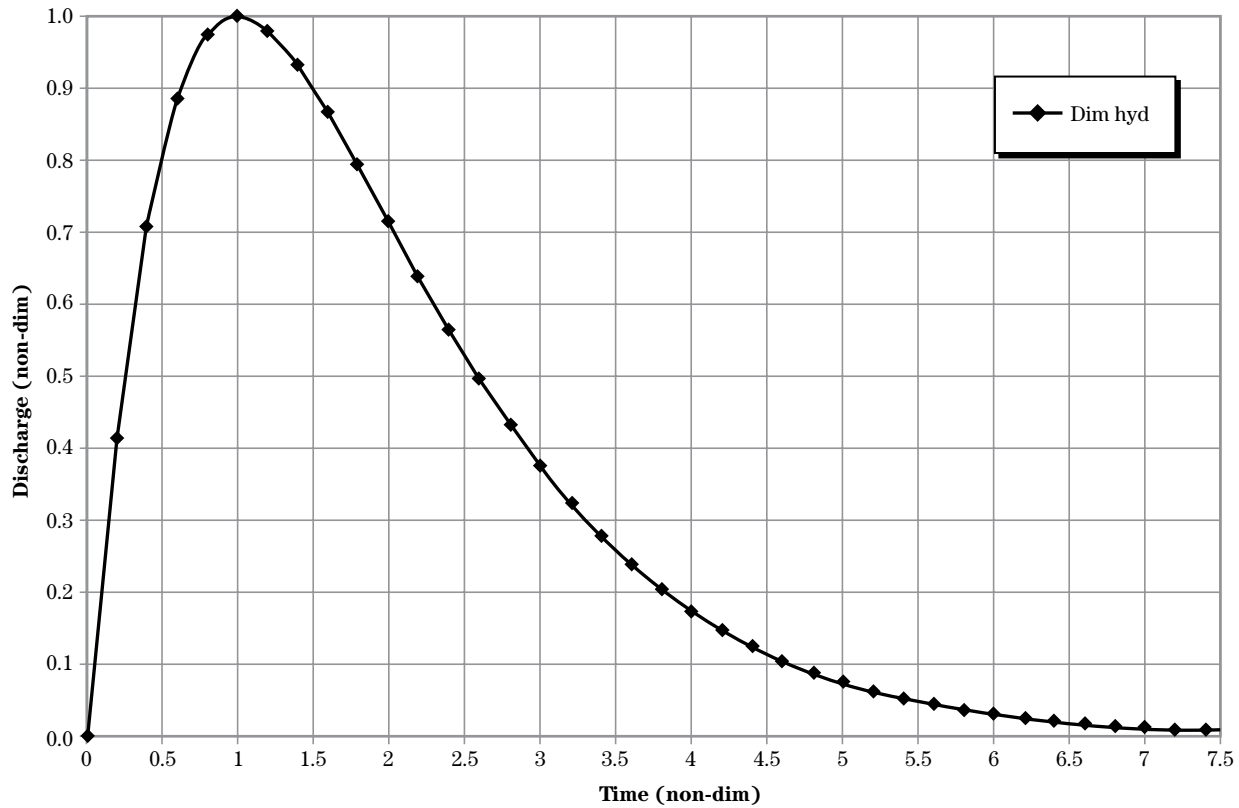
**Figure 16B-7** Peak rate factor = 300

**Table 16B-8** Peak rate factor = 250

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.4142	0.7086	0.8863	0.9751
1.0	0.9809	0.9332	0.868	0.7937
0.7159	0.6388	0.5648	0.4957	0.4322
0.3747	0.3233	0.2778	0.2378	0.2028
0.1725	0.1463	0.1238	0.1045	0.088
0.074	0.0621	0.0521	0.0436	0.0364
0.0304	0.0253	0.0211	0.0175	0.0146
0.0121	0.01	0.0083	0.0069	0.0057
0.0047	0.0039	0.0032	0.0027	0.0022
0.0018	0.0015	0.0012	0.001	0.0008
0.0007	0.0006	0.0005	0.0004	0.0003
0.0003	0.0002	0.0002	0.0001	0.0001
0.0001	0.0001	0.0001	0.0001	0.0

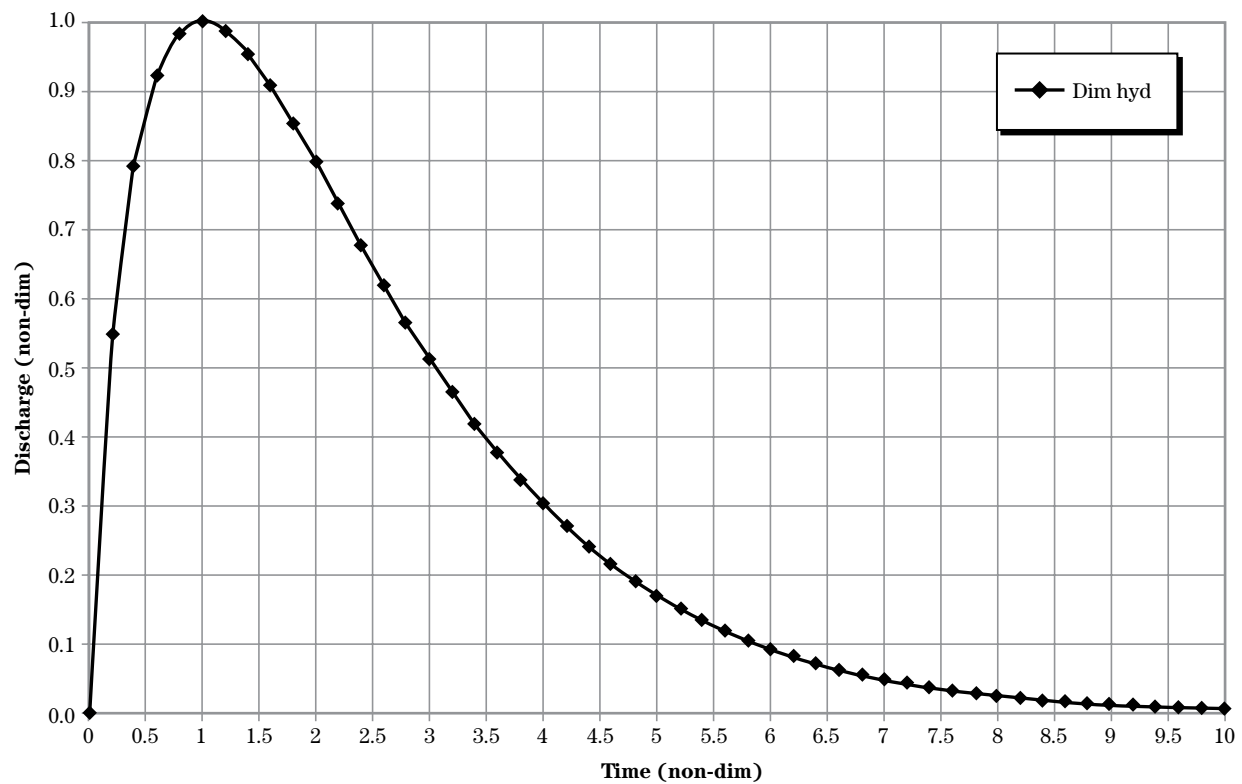
**Figure 16B-8** Peak rate factor = 250



**Table 16B-9** Peak rate factor = 200

DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.5489	0.7911	0.9212	0.983
1.0	0.987	0.954	0.9082	0.8545
0.7966	0.7372	0.6779	0.6203	0.565
0.5128	0.4638	0.4183	0.3763	0.3377
0.3025	0.2704	0.2413	0.2151	0.1914
0.1701	0.151	0.1339	0.1186	0.105
0.0928	0.082	0.0724	0.0638	0.0563
0.0496	0.0437	0.0384	0.0338	0.0297
0.0261	0.0229	0.0201	0.0176	0.0155
0.0136	0.0119	0.0104	0.0091	0.008
0.007	0.0061	0.0054	0.0047	0.0041
0.0036	0.0031	0.0027	0.0024	0.0021
0.0018	0.0016	0.0014	0.0012	0.0011
0.0009	0.0008	0.0007	0.0006	0.0005
0.0005	0.0004	0.0004	0.0003	0.0003
0.0002	0.0002	0.0002	0.0002	0.0001
0.0001	0.0001	0.0001	0.0001	0.0001
0.0001	0.0001	0.0		

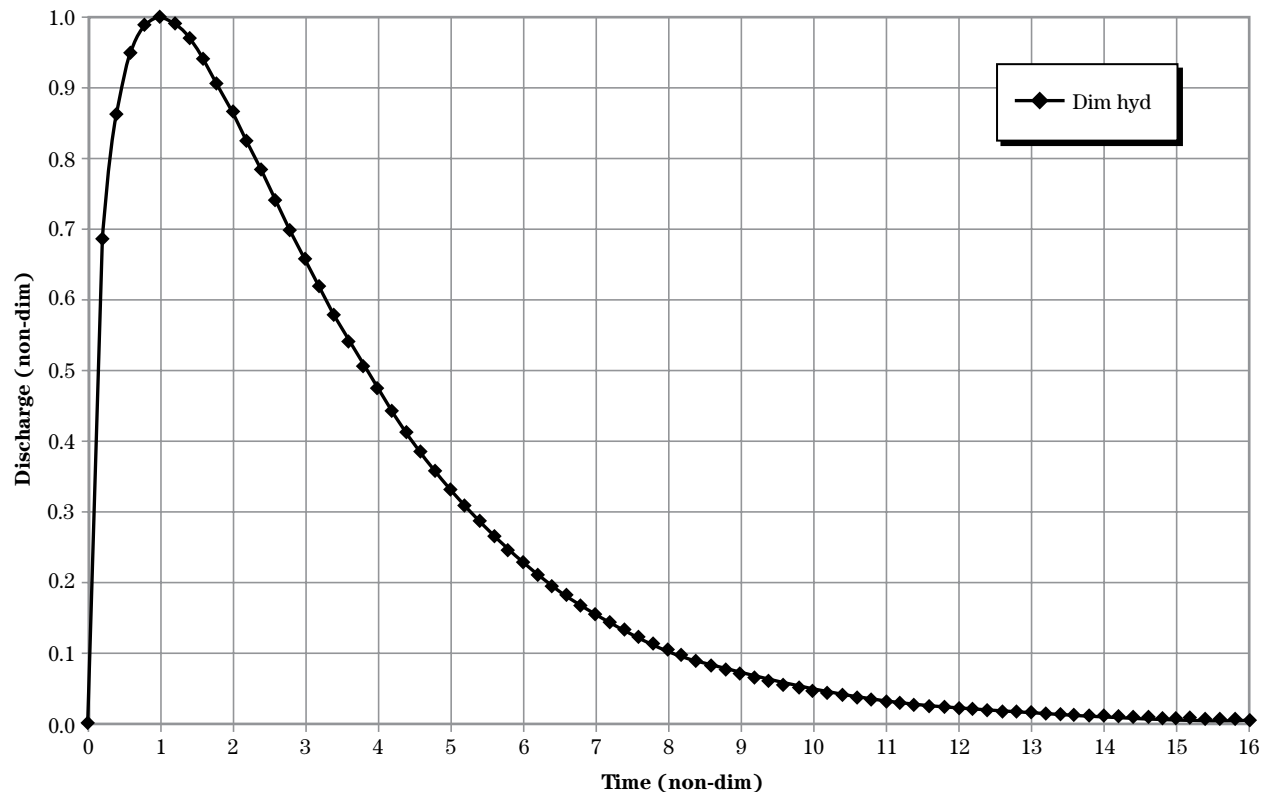
**Figure 16B-9** Peak rate factor = 200

**Table 16B-10** Peak rate factor = 150

## DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.6869	0.8635	0.9499	0.9893
1.0	0.9918	0.971	0.9415	0.9062
0.8673	0.8262	0.784	0.7415	0.6994
0.6582	0.6181	0.5794	0.5422	0.5067
0.4729	0.4409	0.4106	0.382	0.3551
0.3298	0.3061	0.2839	0.2631	0.2438
0.2257	0.2088	0.1931	0.1786	0.165
0.1524	0.1407	0.1299	0.1199	0.1106
0.102	0.094	0.0866	0.0798	0.0735
0.0677	0.0623	0.0574	0.0528	0.0486
0.0447	0.0411	0.0378	0.0348	0.032
0.0294	0.027	0.0248	0.0228	0.0209
0.0192	0.0177	0.0162	0.0149	0.0137
0.0126	0.0115	0.0106	0.0097	0.0089
0.0082	0.0075	0.0069	0.0063	0.0058
0.0053	0.0049	0.0045	0.0041	0.0037
0.0034	0.0031	0.0029	0.0026	0.0024
0.0022	0.002	0.0019	0.0017	0.0016
0.0014	0.0013	0.0012	0.0011	0.001
0.0009	0.0008	0.0008	0.0007	0.0007
0.0006	0.0005	0.0005	0.0005	0.0004
0.0004	0.0004	0.0003	0.0003	0.0003
0.0002	0.0002	0.0002	0.0002	0.0002
0.0002	0.0001	0.0001	0.0001	0.0001
0.0001	0.0001	0.0001	0.0001	0.0001
0.0001	0.0001	0.0001	0.0	

**Figure 16B-10** Peak rate factor = 150



**Table 16B-11** Peak rate factor = 100

## DIMENSIONLESS UNIT HYDROGRAPH:

0.0	0.8142	0.9228	0.9722	0.9941
1.0	0.9955	0.984	0.9675	0.9475
0.925	0.9007	0.8753	0.849	0.8223
0.7954	0.7685	0.7417	0.7153	0.6893
0.6637	0.6387	0.6143	0.5905	0.5674
0.5449	0.5231	0.5019	0.4815	0.4618
0.4427	0.4243	0.4065	0.3894	0.3729
0.3571	0.3418	0.3272	0.3131	0.2996
0.2866	0.2741	0.2621	0.2506	0.2396
0.229	0.2189	0.2092	0.1999	0.191
0.1825	0.1743	0.1665	0.159	0.1519
0.145	0.1385	0.1322	0.1262	0.1205
0.115	0.1098	0.1048	0.1	0.0954
0.091	0.0869	0.0829	0.0791	0.0754
0.072	0.0686	0.0655	0.0624	0.0596
0.0568	0.0542	0.0517	0.0493	0.047
0.0448	0.0427	0.0407	0.0388	0.037
0.0353	0.0336	0.0321	0.0306	0.0291
0.0278	0.0265	0.0252	0.024	0.0229
0.0218	0.0208	0.0198	0.0189	0.018
0.0172	0.0164	0.0156	0.0148	0.0141
0.0135	0.0128	0.0122	0.0117	0.0111
0.0106	0.0101	0.0096	0.0091	0.0087
0.0083	0.0079	0.0075	0.0072	0.0068
0.0065	0.0062	0.0059	0.0056	0.0054
0.0051	0.0049	0.0046	0.0044	0.0042
0.004	0.0038	0.0036	0.0035	0.0033
0.0031	0.003	0.0028	0.0027	0.0026
0.0025	0.0023	0.0022	0.0021	0.002
0.0019	0.0018	0.0017	0.0017	0.0016
0.0015	0.0			



**Figure 16B-11** Peak rate factor = 100

