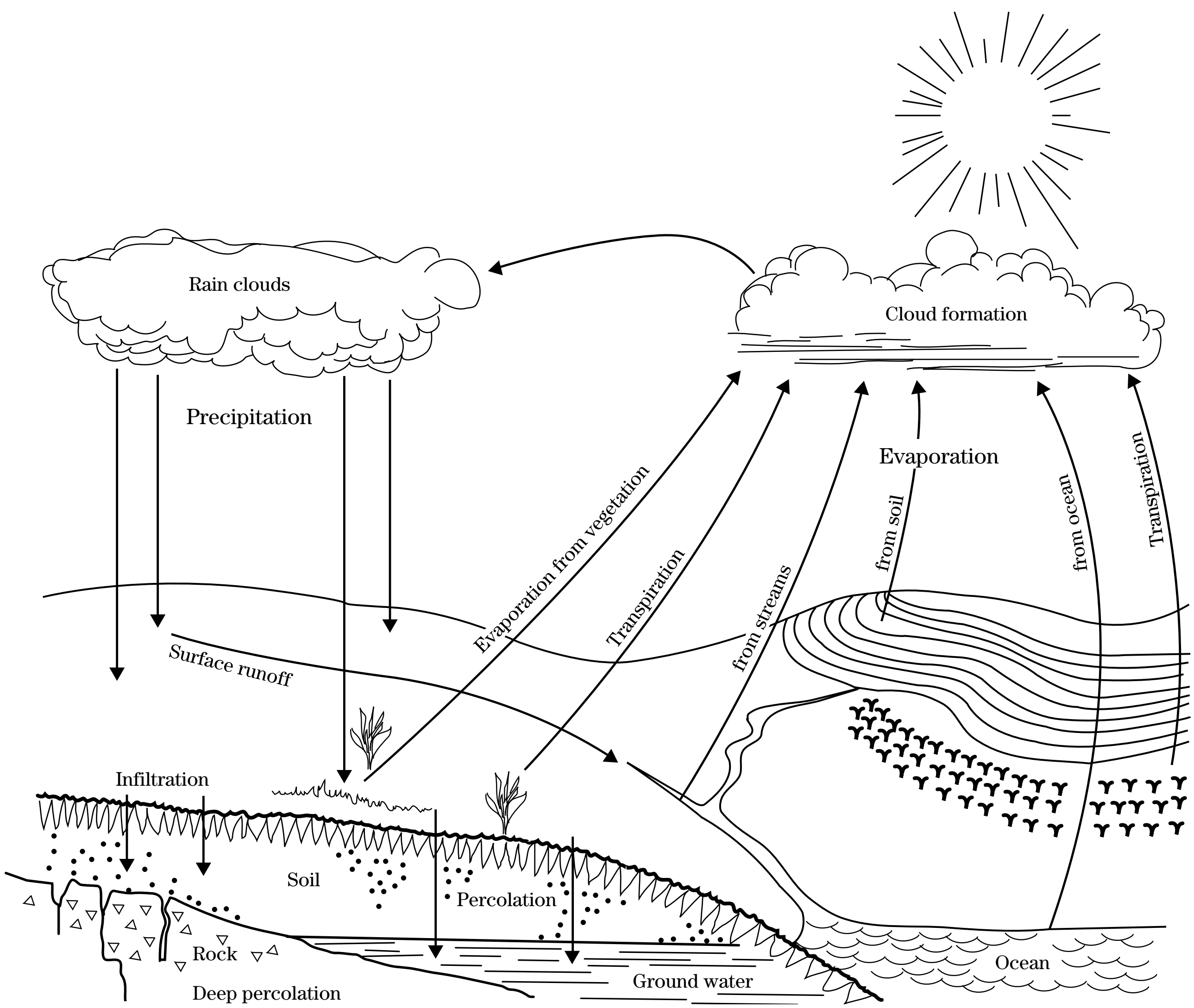
United States
Department of
Agriculture

**Natural
Resources
Conservation
Service**

Part 630 Hydrology
National Engineering Handbook

Chapter 21 Design Hydrographs



May 2019

Acknowledgments

Chapter 21, Design Hydrographs, was originally prepared by **Victor Mockus** (retired). A subsequent revision in 1965 was edited by **Vincent McKeever** (retired), **William Owen** (retired), and **Robert Rallison**, (retired) and was reprinted in 1972 with minor modifications. This version was prepared by **Edward J. Schmit** (retired) and **Wiley Scott**, hydraulic engineer, Natural Resources Conservation Service (NRCS), Nashville, TN, under the guidance of **Donald E. Woodward** (retired) and finalized under the guidance of **Claudia C. Hoeft**, national hydraulic engineer, Washington, DC.

Chapter 21 Design Hydrographs

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630.2100 Introduction

Chapter 21 (NEH630.21) presents a systematic approach to the development of hydrographs used to design earth dams that provide temporary storage for flood prevention and temporary or permanent storage for other uses. NEH630.21 is a companion document to Technical Release No. 60 (TR–60), Earth Dams and Reservoirs, which contains the NRCS minimum design criteria for earth dams. While NEH630.21 and TR–60 are very closely related, it is important that users understand TR–60 contains the design requirements while NEH630.21 describes technical methods for developing design hydrographs.

While the methodologies are based on data of actual storms and floods, they are not intended for reproducing hydrographs of historical floods. The general methodology for the development of flood hydrographs is found in NEH630.16.

Also included in NEH630.21 are methods for modifying design runoff to include effects of baseflow, channel losses, quick return flow (QRF) upstream releases, and methods for developing rainfall distributions associated with design hydrograph development. The SITES computer program may be used to develop design hydrographs for a particular project.

An earth dam generally has two spillways, a principal spillway and an auxiliary spillway, and perhaps a low flow outlet to meet downstream and instream needs. The design of a safe dam requires that the spillways be sized appropriately. This is done by routing several hydrographs through the spillways. Development of these design hydrographs takes into account storm return period and duration, which varies depending upon purpose, size, location and classification of the dam and types of spillways.

630.2101 Determining runoff volumes for design of earth dams and associated spillways

Any one of the following four methods to determine runoff volume is suitable for the design of principal spillway capacity, retarding storage, auxiliary spillway crest, and determination of top of dam elevation:

- runoff curve number procedure using rainfall data and watershed characteristics
- runoff volume maps covering specific areas of the United States
- regionalization and transposition of volume-duration-probability (VDP) analyses
- local streamflow data

Only the first two methods are described in the remainder of this chapter. NEH630.18, Statistical Methods, provides some details for the use of the last two methods.

(a) Runoff curve number procedure

The runoff curve number (CN) procedure uses certain climatic data and the characteristics of a watershed to convert rainfall data to runoff volume.

(1) Rainfall data sources
Rainfall data used in the determination of direct runoff may be obtained from the published sources listed in table 21–1. This table contains only a partial listing of potential rainfall data sources available and does not preclude the use of data sources, which may be required by State or other local law, or the use of special studies as appropriate.

(2) Runoff curve numbers
The runoff CN for the drainage area above a structure site is determined and runoff is estimated as described in NEH630.07 through NEH630.10. The CN is for the antecedent runoff condition II (ARC II) unless a special study shows that use of a different condition is justified or local requirements specify otherwise. ARC II applies to the 1-day storm used to develop design hydrographs.

Table 21–1 National Weather Service references for precipitation data [1/] [2/]

Durations to 1 day and return periods to 100 years

Technical Memorandum HYDRO–35. Durations 5 to 60 minutes for the Eastern and central States (1977)

Technical Paper 40. 48 contiguous States (1961) (Use for 37 contiguous States east of the 105th meridian)

Technical Paper 47. Alaska (1963)

NOAA Atlas 2. Precipitation Frequency Atlas of the United States (1973)

Vol. I, Montana	Vol. II, Wyoming	Vol. III, Colorado
Vol. V, Idaho	Vol. IX, Washington	Vol. X, Oregon
Vol. XI, California		

NOAA Atlas 14. Precipitation Frequency Atlas for the United States
Vol. 1 (2006), version 4, Semiarid Southwest (Arizona, Southeast California, Nevada, New Mexico, and Utah)
Vol. 2 (2004), version 3, Ohio River Basin and surrounding States (Delaware, District of Columbia, Illinois, Kentucky, Maryland, New Jersey, North Carolina, Ohio, Pennsylvania, South Carolina, Tennessee, Virginia, and West Virginia)
Vol. 3 (2006), version 4, Puerto Rico and the U.S. Virgin islands
Vol. 4 (2008), Hawaii

Durations from 2 to 10 days and return periods to 100 years

Technical Paper 49. 48 contiguous States (1965)

Technical Paper 52. Alaska (1965)

Probable maximum precipitation (PMP)

Hydrometeorological Report 36. California Pacific Drainage (1961)

Hydrometeorological Report 39. Hawaii (1963)

Hydrometeorological Report 43. Northwest States Pacific Drainage (1981)

Hydrometeorological Report 49. Colorado River and Great Basin Drainage (1977)

Hydrometeorological Report 51. United States East of the 105th meridian (1978)

Hydrometeorological Report 52. Application of probable maximum precipitation estimates, states east of the 105th meridian (1980)

Hydrometeorological Report 53. Seasonal variation of 10 square-mile probable maximum precipitation estimates, states east of the 105th meridian (1980)

Hydrometeorological Report 54. Probable maximum precipitation and snowmelt criteria for southeast Alaska (1963)

Hydrometeorological Report 55A. United States between the Continental Divide and the 103rd meridian (1988)

Technical Report 42. Puerto Rico and Virgin Islands (1961)

Technical Report 43. Hawaii (1962)

Technical Report 47. Alaska (1963)

1/ National Weather Service, National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Commerce

2/ This list is not all inclusive. Federal, State, Tribal, or other local laws may require the use of specific data sources other than those listed here.

(3) Methods of modifying design runoff

- **Baseflow**—Baseflow is a stream discharge derived from ground water sources. It is sometimes considered to include flows from regulated lakes or reservoirs depending on the situation. Baseflow fluctuates much less than storm runoff.
- **Channel losses—**Channel transmission losses may be important in arid and karst areas where a significant amount of streamflow is absorbed by the porous streambank and streambed material. Channel losses represent a net loss from the channel system. Runoff volume may be reduced to account for channel losses.

  If the drainage area above a structure site has a climatic index (equation 21–1) of less than 1, then the direct runoff from a rainfall may be decreased to account for channel losses of influent streams.
- **Climatic index, C_i—**The climatic index is used to estimate channel losses and for estimating QRF. The climatic index is:

$$C_i = \frac{100P_a}{\left(T_a\right)^2} \qquad \text{(eq. 21–1)}$$

  where:
  C_i = climatic index
  P_a = average annual precipitation in inches
  T_a = average annual temperature in inches

  Precipitation and temperature data are available in Station Temperature and Precipitation (TAPS) and Wetland Temperature and Precipitation (WETS) tables to NRCS Users of the electronic Field Office Technical Guide (eFOTG) in the AgACIS module, or by contacting the NRCS National Water and Climate Center in Portland, Oregon.
- **Quick return flow—**QRF is the rate of discharge that persists for some period beyond that for which the 10-day principal spillway hydrograph (PSH) is derived. It includes baseflow and other flows that become a part of the flood hydrograph such as:
  - rainfall that has infiltrated and reappeared soon afterwards as surface flow
  - drainage from marshes and potholes
  - snowmelt

  QRF is a contant rate of discharge which extends the falling or recession limb of the hydrograph from the point where QRF equals the PSH discharge to the end of the hydrograph.

  If the drainage area above a structure site has a climatic index (equation 21–1) greater than 1, then QRF is added to the hydrograph of direct runoff from rainfall (fig. 21–1a).
- **Combinations of channel loss, quick return flow**—For large watersheds, the topography may be such that two climatic indices are needed. For example, where mountains are adjacent to a semi-arid plain. In such simplified cases:
  - The design storm precipitation is determined for the watershed as a whole.
  - The direct runoff is estimated separately for the two parts by use of the appropriate CNs and then combined.
  - The channel loss reduction is based on the area of the semiarid plain and its climatic index.
  - The hydrograph or mass curve of direct runoff is constructed.
  - The QRF from the mountain area is added.
- Upstream releases—Releases from upstream structures must be accounted for in the runoff hydrograph, regardless of other additions or subtractions of low. Upstream release rates are determined from routings of applicable hydrographs through the upstream structures and the reaches downstream from them.

(b) Runoff volume maps procedure

The runoff volume and rate maps (figs 21–2 through 21–6) are provided for areas of the United States where measured runoff volumes vary significantly from those obtained by using the CN procedure for converting rainfall to runoff. The mapped areas are of two general types:

- areas where runoff from either snowmelt, dormant season rainfall, or a combination of the two produce greater runoff volumes than growing season rainfall
- deep snowpack areas of high mountain elevations

(1) Areas of mapped runoff volume

The 100-year, 10-day runoff volume maps (figs. 21–2 and 21–5) represent regionalized values derived from gaged streamflow data and supplemented with climatological data and local observations. These values should be used for estimating floodwater detention storage within the map area where local streamflow data are not adequate. Areal reduction should not be made on the 10-day runoff volumes shown in the maps. These amounts were derived from stream gage data, so baseflow and channel loss are automatically included in the map values.

QRF in this procedure is used as the rate of discharge expected to persist beyond the flood period described under the 10-day PSH. When using the Runoff Volume Maps procedure, the QRF rate (fig. 21–4) is an extension to the PSH before routing it through the reservoir (fig 21–1). The rates of discharge given in figure 21–4 were derived by averaging the accumulated depths of runoff between the 15th and 30th day on VDP accumulation graphs. They were obtained from the same VDP station data from which the 100-year, 10-day runoff volumes in figure 21–2 were obtained.

QRF is in units of cubic feet per second per square mile. It is converted to a discharge in cubic feet per second by multiplying by the drainage area of the site in square miles. On the falling limb of the PSH, all discharges less than the QRF are set equal to the QRF. The PSH may be extended at the QRF discharge beyond 10 days before routing the hydrograph through the reservoir (fig. 21–1b).

(2) Deep snowpack areas

Flood volume estimates from the deep snowpack areas may be calculated from local streamflow data or by regionalization and transposition of streamflow data. A standard procedure for making a regional analysis of volume of runoff for various durations and frequencies has not been developed at this time. Experience indicates that acceptable estimates can be made using multiple regression techniques. If watersheds can be selected that are reasonably homogeneous with regard to seasonal precipitation, range of elevation, aspect, cover, geology, soils, and other characteristics, estimating equations can be developed with a minimum number of interdependent variables.

Figure 21–1 Inflow design hydrograph with baseflow and QRF

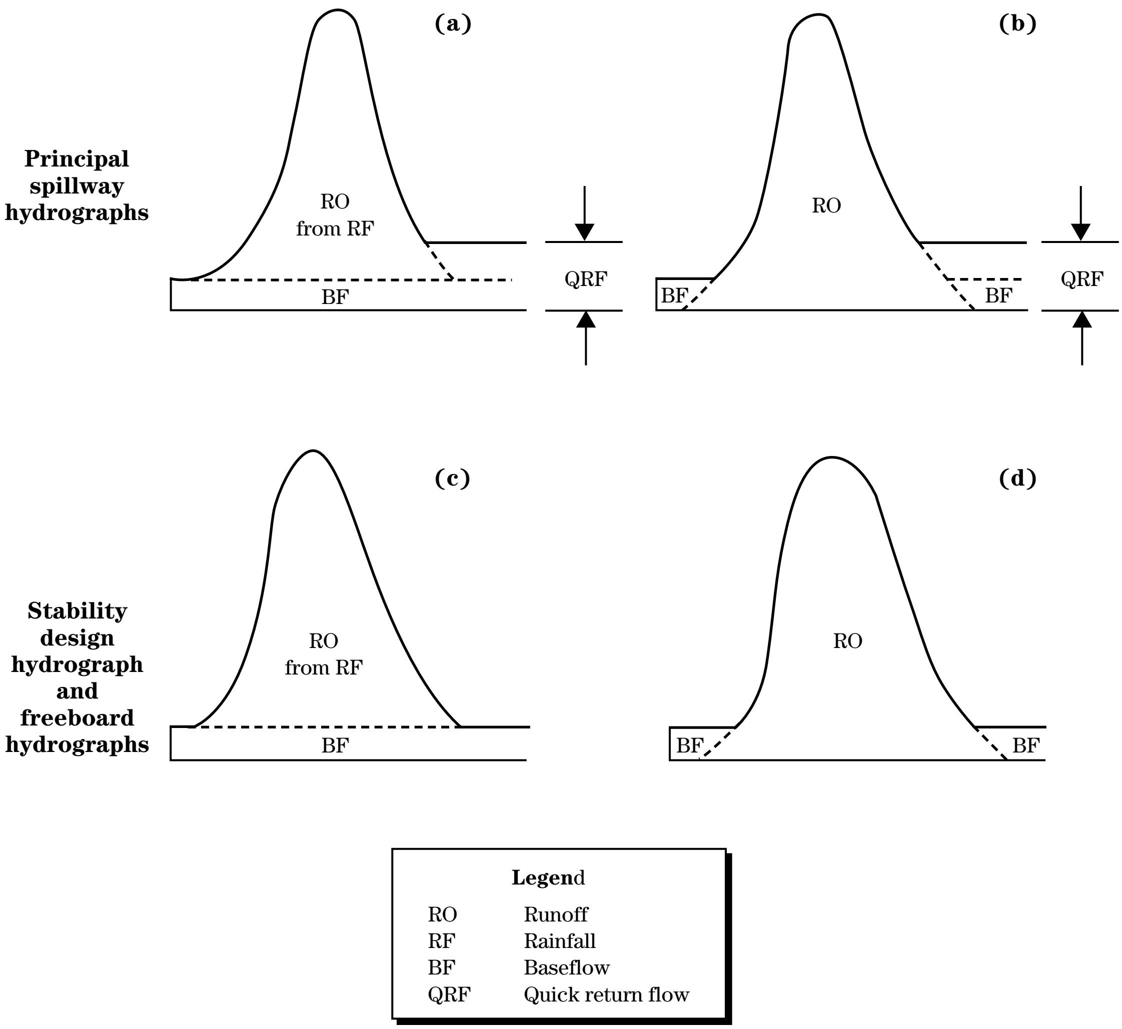
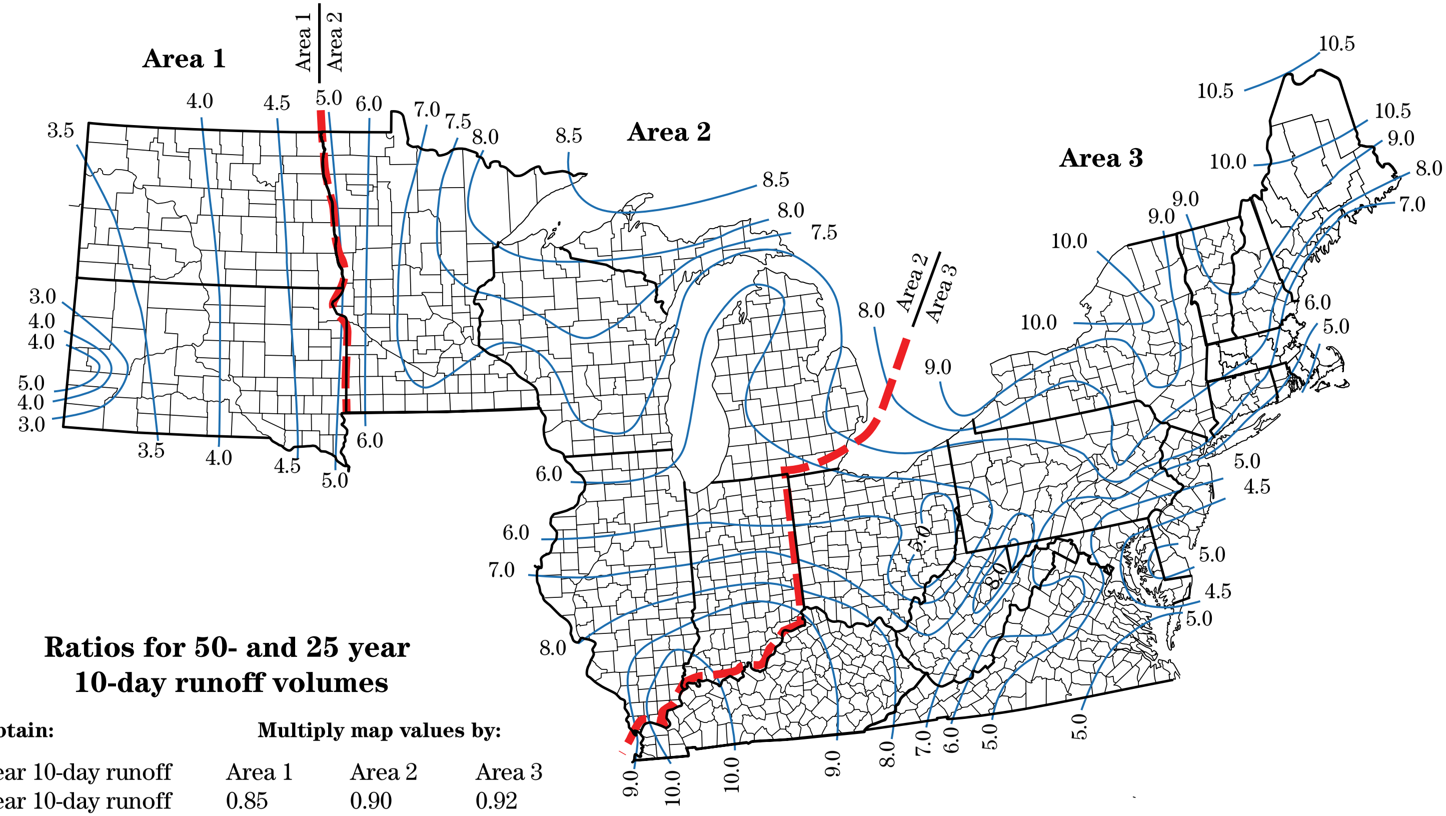


Figure 21–2 100-year, 10-day runoff volume (inches) for developing the PSH (Northeast States)

100-year 10-day runoff volumes (inches) for developing the principal spillway hydrograph



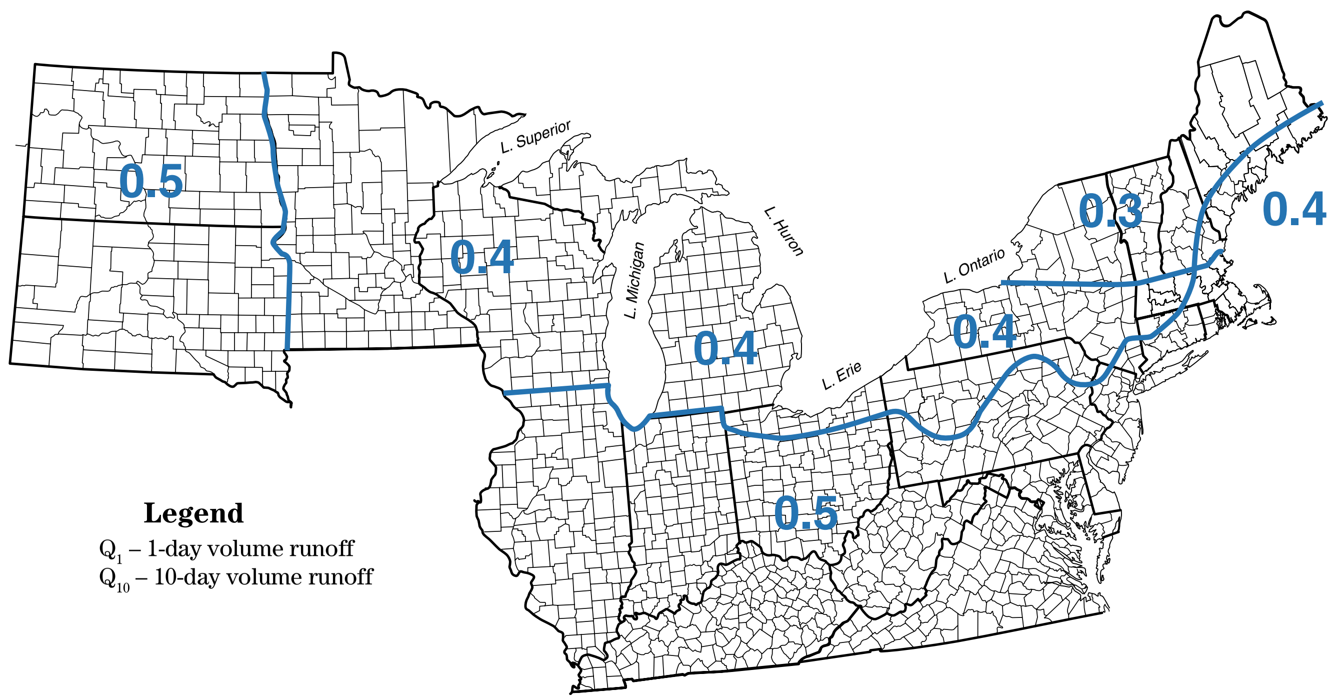
Ratios for 50- and 25 year 10-day runoff volumes

To obtain:	Multiply map values by: Area 1	Area 2	Area 3
50-year 10-day runoff	0.85	0.90	0.92
25-year 10-day runoff	0.70	0.80	0.90

Source:
United States Geological Survey streamflow data. Map prepared using automated map construction. National Cartography and Geospatial Center. Fort Worth, Texas. 1997

Figure 21–3 Ratios of volumes of runoff (Q_1/Q_{10}) for developing the PSH (Northeast States)

**Ratios of volumes of runoff (Q_1/Q_{10})
for developing the principal spillway hydrograph**



Legend

Q_1 – 1-day volume runoff
Q_{10} – 10-day volume runoff

0 200 400 600 MI

Source:
United States Geological Survey streamflow data. Map prepared using automated map construction. National Cartography and Geospatial Center. Fort Worth, Texas. 1997

Figure 21–4 Quick return flow (csm) for developing the PSH (Northeast States)

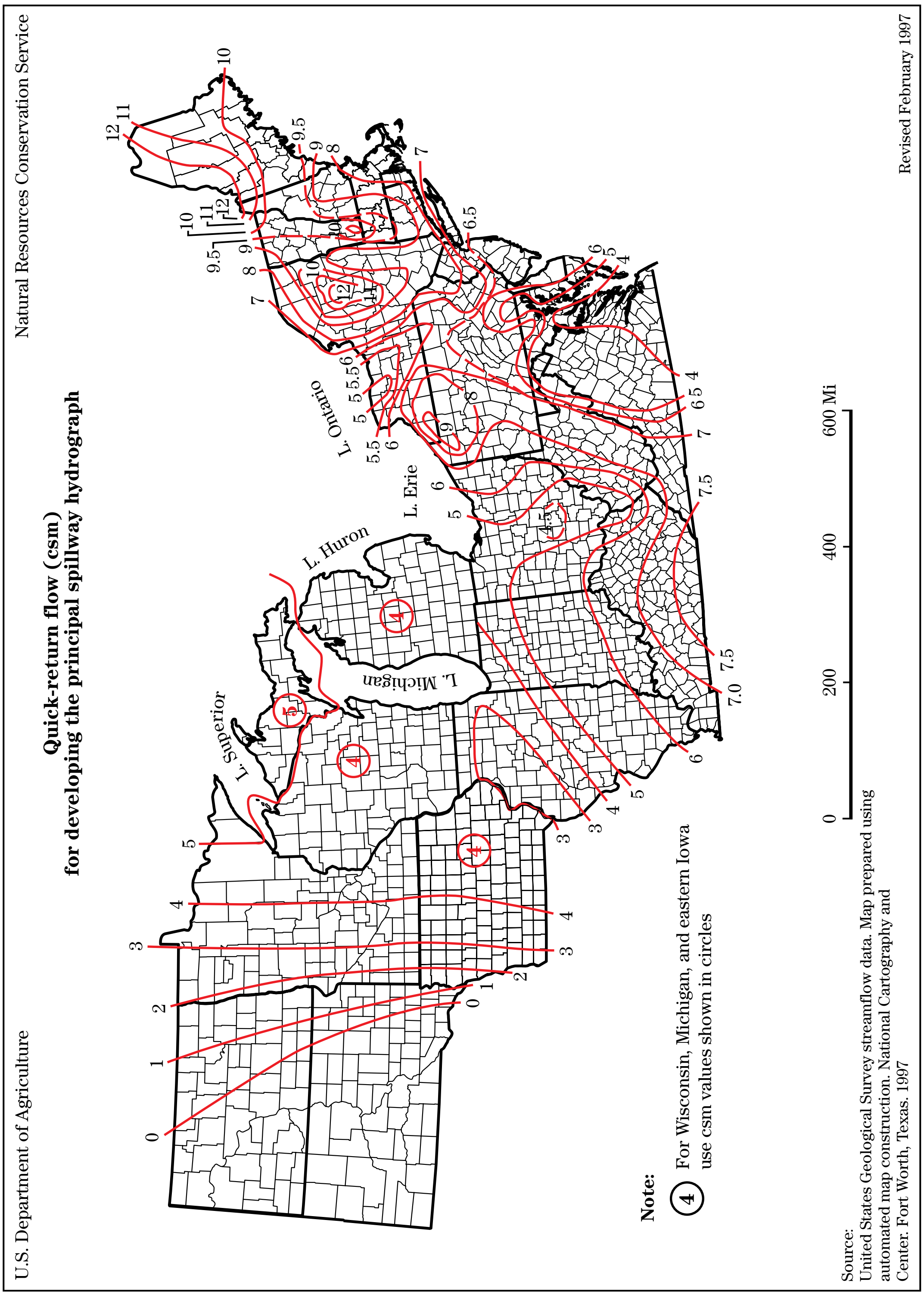


Figure 21–5 100-year, 10-day runoff volume (inches) for developing the PSH (Northwest States)

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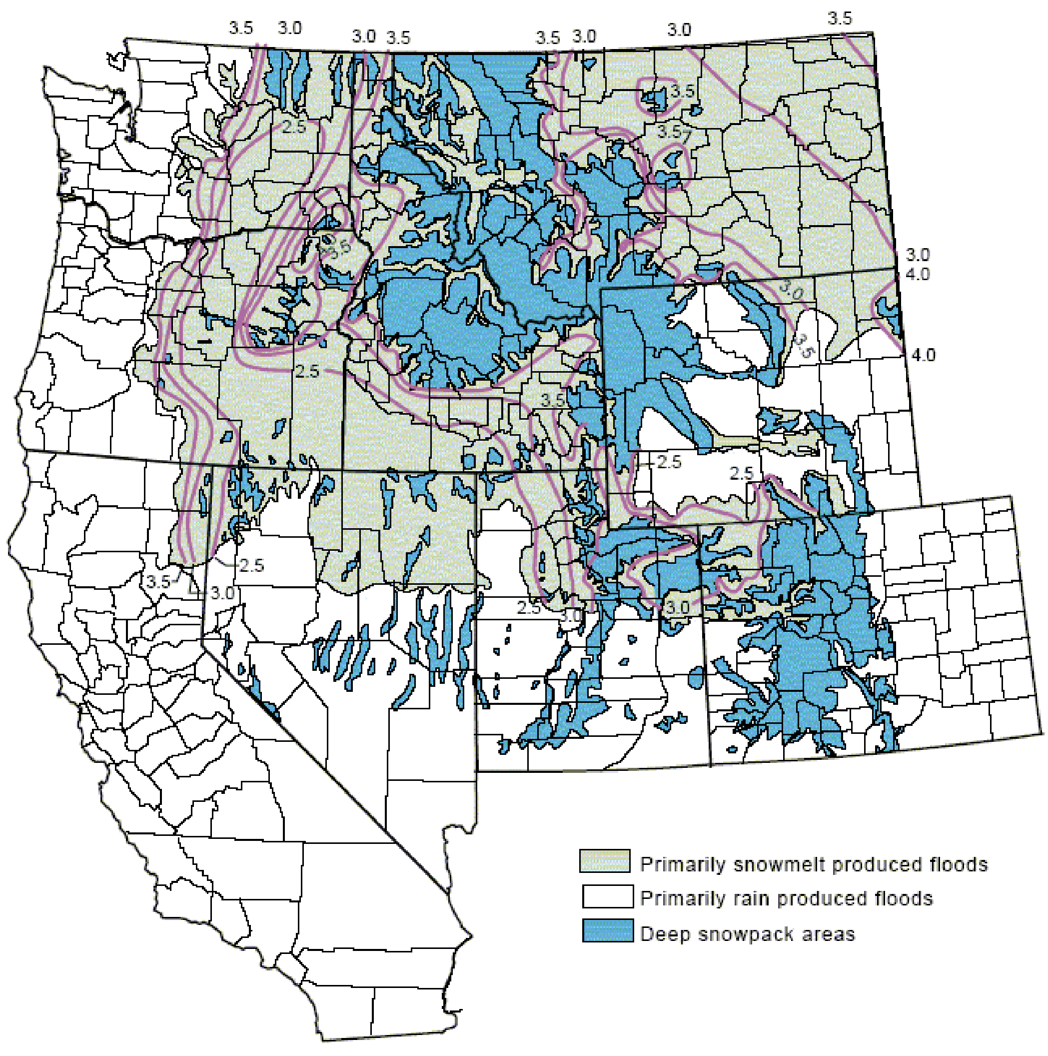
100-year, 10-day runoff (inches)
for developing the principal spillway hydrograph



50-year 10-day runoff—use 85% of map value
25-year 10-day runoff—use 70% of map value

Source:
U.S. Geological Survey streamflow data.
Map prepared using automated map construction. National Cartography and Geospatial Center. Fort Worth, Texas. 1995

0 200 400 600

Note:
Caution should be used in interpolating this map in mountainous area. Lines have been smoothed in mountianous areas of the Western States.

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Figure 21–6 Ratios of volumes of runoff (Q_1/Q_{10}) for developing the PSH (Northwest States)

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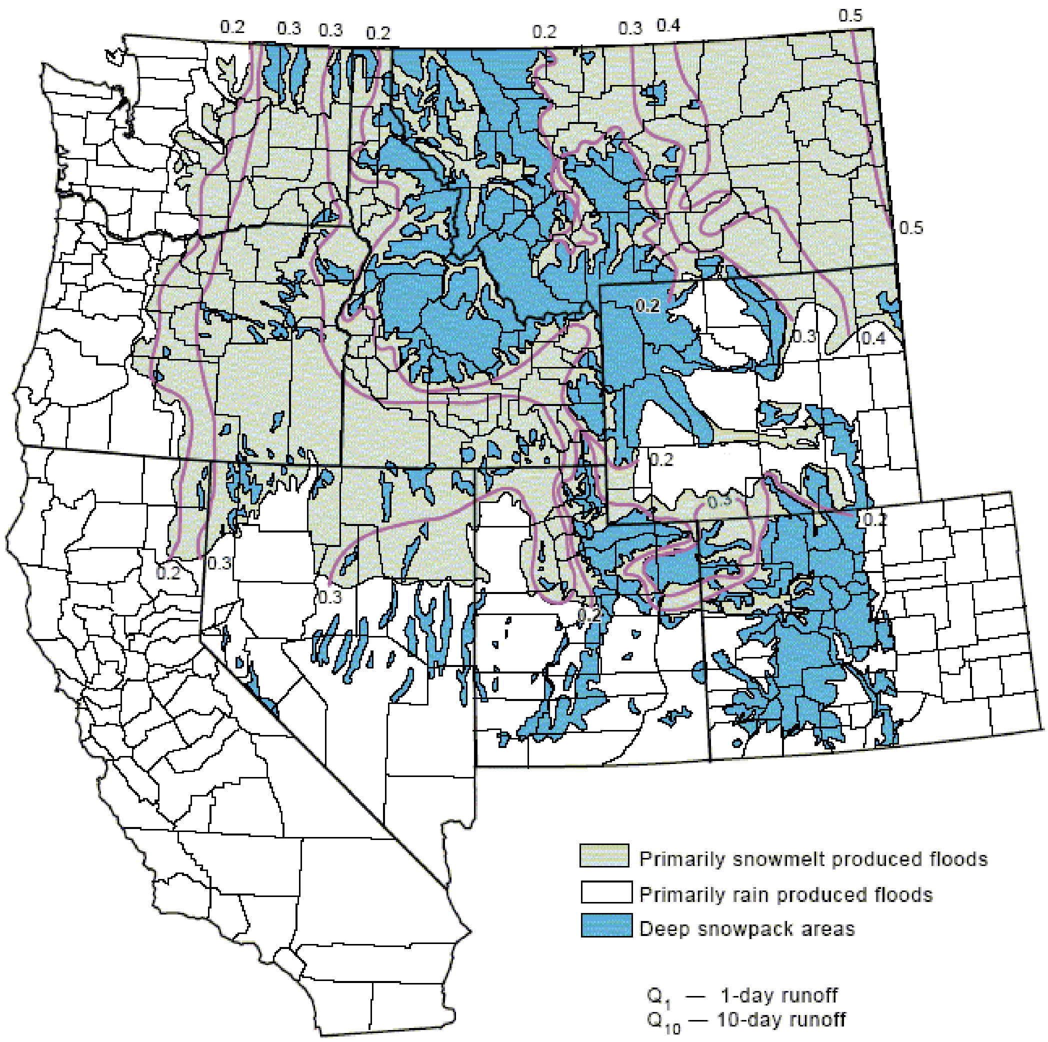
Ratios of volumes of runoff (Q_1/Q_{10})
for developing the principal spillway hydrograph
(Northwest States)



Source:
United State Geological Survey streamflow date.
Map prepared using automated map construction. National Cartography and Geospatial Center. Fort Worth, Texas. 1995

Note:
Caution should be used in interpolating this map in mountainous area. Lines have been smoothed in mountainous areas of the Western States.

0 200 400 600

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630.2102 Principal spillway hydrographs

The principal spillway provides the outlet capacity and storage required to meet the design objectives of the structure. The principal spillway is sized to limit the frequency of operation of the auxiliary spillway and to set the crest elevation of the auxiliary spillway so that it does not flow during the passage of the principal spillway storm. TR–60 criteria requires that the capacity of the principal spillway for flood retarding structures be determined using the 10-day hydrograph; while the principal spillway capacity for other structures are usually sized using the 1-day hydrograph.

(a) Rainfall and runoff volume considerations

(1) 10-day runoff curve number
In design of the principal spillway capacity, if the 100-year frequency, 10-day duration point rainfall for the structure site is 6 or more inches, the CN for the 10-day storm is adjusted using table 21–2. If the 100-year frequency, 10-day duration rainfall is less than 6 inches, the CN for the 10-day storm is the same as that for the 1-day storm. The 10-day CN is used only with the total 10-day rainfall.

(2) Areal adjustment of rainfall amount
TR–60 identifies the design storm to be used in development of the principal spillway design hydrograph. Values should be taken from the appropriate NWS publication, local designated data source, or special study.

If the drainage area above a proposed structure site is 10 square miles or less, no areal adjustment is made to the storm volume. If the drainage area is more than 10 square miles, the area-point ratios in table 21–3 may be used to reduce the rainfall volume. The table applies to all geographical locations serviced by the NRCS. The ratios are based on the 1- and 10-day depth-area curves of figure 10 in the U.S. Weather Bureau TP–49 (1965), but are modified to give a ratio of 1 at 10 square miles.

Table 21–2 PSH volume adjustment: 10-day runoff curve number adjustment*

------------------------Runoff curve numbers--------------------------					
1 day	10 days	1 day	10 days	1 day	10 days
100	100	80	65	60	41
99	98	79	64	59	40
98	96	78	62	58	39
97	94	77	61	57	38
96	92	76	60	56	37
95	90	75	58	55	36
94	88	74	57	54	35
93	86	73	56	53	34
92	84	72	54	52	33
91	82	71	53	51	33
90	81	70	52	50	32
89	79	69	51	49	31
88	77	68	50	48	30
87	76	67	49	47	29
86	74	66	47	46	28
85	72	65	46	45	28
84	71	64	45	44	27
83	69	63	44	43	26
82	68	62	43	42	25
81	66	61	42	41	24

* This table is used only if the 100-year frequency 10-day point rainfall is 6 or more inches. If it is less, the 10-day curve number is the same as that for the 1-day curve number.

Table 21–3 PSH volume adjustment: minimum areal adjustment ratios for precipitation

Area	--Area/point ratio--		Area	--Area/point ratio--	
(mi²)	1 day	10 days	(mi²)	1 day	10 days
≤10	1.000	1.000	45	0.951	0.976
15	0.977	0.991	50	0.948	0.974
20	0.969	0.987	60	0.944	0.972
25	0.965	0.983	70	0.940	0.970
30	0.961	0.981	80	0.937	0.969
35	0.957	0.979	90	0.935	0.977
40	0.954	0.977	100	0.932	0.966

(3) Adjusting for channel losses

Channel losses can be determined from local data, but losses must not be more than those determined by using table 21–4. When adequate local data are not available, table 21–4 may be used. A special study may be required if channel losses appear to be significant even though the climatic index is 1 or more, such as in karst areas.

Table 21–4 Channel loss factors for reduction of direct runoff

Drainage area	------------------Climatic index (C_i)-----------------------						
(mi²)	**1.0**	**0.9**	**0.8**	**0.7**	**0.6**	**0.5**	**0.4 or less**
1 or less	1.00	1.00	1.00	1.00	1.00	1.00	1.00
2	1.00	0.98	0.97	0.95	0.93	0.90	0.87
3	1.00	0.98	0.95	0.92	0.89	0.85	0.80
4	1.00	0.97	0.94	0.90	0.86	0.81	0.76
5	1.00	0.96	0.92	0.88	0.84	0.78	0.73
6	1.00	0.96	0.92	0.87	0.82	0.76	0.70
7	1.00	0.96	0.91	0.86	0.81	0.75	0.68
8	1.00	0.95	0.90	0.85	0.79	0.73	0.66
9	1.00	0.95	0.90	0.84	0.78	0.72	0.65
10	1.00	0.95	0.89	0.84	0.77	0.71	0.63
20	1.00	0.93	0.86	0.79	0.72	0.64	0.55
30	1.00	0.93	0.85	0.77	0.69	0.60	0.51
40	1.00	0.92	0.84	0.75	0.66	0.57	0.48
50	1.00	0.91	0.83	0.74	0.65	0.55	0.46
60	1.00	0.91	0.82	0.73	0.63	0.54	0.44
70	1.00	0.91	0.81	0.72	0.62	0.53	0.43
80	1.00	0.90	0.81	0.71	0.62	0.52	0.42
90	1.00	0.90	0.80	0.71	0.61	0.51	0.41
100	1.00	0.90	0.80	0.70	0.60	0.50	0.40
150	1.00	0.89	0.78	0.68	0.57	0.47	0.37
200	1.00	0.89	0.77	0.66	0.56	0.45	0.35
250	1.00	0.88	0.77	0.65	0.54	0.44	0.33
300	1.00	0.88	0.76	0.64	0.53	0.42	0.32
350	1.00	0.87	0.75	0.64	0.52	0.41	0.31
400	1.00	0.87	0.75	0.63	0.51	0.41	0.30

(4) Adjusting for quick return flow

QRF can be determined from local data, but it must not be less than the steady rate determined using table 21–5. When adequate local data are not available, table 21–5 may be used.

(5) Adjusting for baseflow

When a PSH is developed from rainfall, the baseflow is added to the base of the entire hydrograph (fig. 21–1a). When the PSH is developed from runoff, all hydrograph discharge values less than baseflow should be increased to the baseflow value. The recession or tail of the PSH may be controlled by QRF if this is higher than the baseflow (fig. 21–1b).

Table 21–5 Minimum QRF for PSH derived from rainfall

C_i	------- QRF -------		C_i	------- QRF -------	
	in/d	csm		in/d	csm
1.00	0	0	1.50	0.233	6.28
1.02	0.011	0.30	1.52	0.239	6.42
1.04	0.022	0.60	1.54	0.244	6.56
1.06	0.033	0.90	1.56	0.249	6.70
1.08	0.045	1.20	1.58	0.254	6.83
1.10	0.056	1.50	1.60*	0.259	6.95
1.12	0.067	1.80	1.65	0.270	7.26
1.14	0.078	2.10	1.70	0.280	7.53
1.16	0.089	2.40	1.75	0.290	7.79
1.18	0.100	2.70	1.80	0.299	8.05
1.20	0.112	3.00	1.85	0.309	8.30
1.22	0.122	3.29	1.90	0.318	8.54
1.24	0.133	3.58	1.95	0.326	8.77
1.26	0.144	3.86	2.00	0.335	9.00
1.28	0.153	4.12	2.05	0.343	9.22
1.30	0.163	4.37	2.10*	0.351	9.44
1.32	0.171	4.61	2.20	0.367	9.86
1.34	0.180	4.83	2.30	0.382	10.26
1.36	0.188	5.05	2.40	0.396	10.65*
1.38	0.195	5.25	2.50	0.410	11.02
1.40	0.202	5.44	2.60	0.423	11.38
1.42	0.209	5.63	2.70	0.436	11.73
1.44	0.216	5.80	2.80	0.449	12.07
1.46	0.222	5.97	2.90	0.461	12.41
1.48	0.228	6.13	3.00**	0.473	12.73

* Change in tabulation interval
** For C_i greater than 3, use:

QRF (csm) = $9(C_i-1)^{0.5}$

QRF (in/d) = 0.03719 [QRF (csm)]

where:
QRF = quick return flow
csm = cubic feet per second per square mile
C = climatic index
in/d = inches per day

(b) Development of the 1-day/10-day hydrograph

PSHs are developed assuming a continuous 10-day period of runoff at the site for a given frequency. Choice of the 10-day period is based on NRCS experience using streamflow records. If the runoff in the 10-day period is arranged in order of decreasing values and then accumulated to form a mass curve, it has the appearance of curve A shown in figure 21–7. Such a curve is a straight line on log paper with the equation:

$$Q_D = Q_{10}\left(\frac{D}{10}\right)^a \qquad \text{(eq. 21–2)}$$

where:
Q_D = total runoff (in)
D = time (day)
Q_{10} = total runoff (in) at the end of 10 days
a = $\log(Q_{10}/Q_1)$
Q_1 = total runoff (in) at the end of 1 day

Using equation 21–2, a continuous mass curve can be developed for the entire 10-day period, knowing only the 1- and 10-day runoff amounts.

Examination of such mass curves of runoff from streamflow stations in many locations of the United States showed that exponent a varies from 0.1 to 0.5.

Figure 21–7 PSMC of runoff in various arrangements

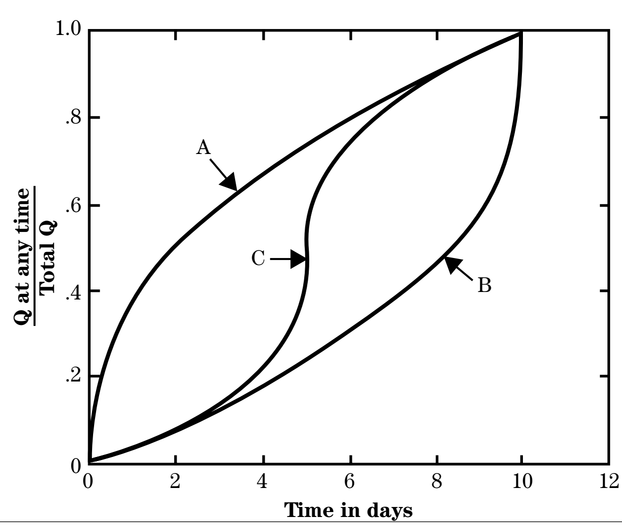


Table 21–6 Arrangement of half–day increments of PSMC for curve C in figure 21–7

Time (days)	Increment
0.0 to 0.5	19th largest 1/2 day
0.5 to 1.0	17th largest 1/2 day
1.0 to 1.5	15th largest 1/2 day
1.5 to 2.0	13th largest 1/2 day
2.0 to 2.5	11th largest 1/2 day
2.5 to 3.0	9th largest 1/2 day
3.0 to 3.5	7th largest 1/2 day
3.5 to 4.0	5th largest 1/2 day
4.0 to 4.5	3rd largest 1/2 day
4.5 to 5.0	Largest 1/2 day
5.0 to 5.5	2nd largest 1/2 day
5.5 to 6.0	4th largest 1/2 day
6.0 to 6.5	6th largest 1/2 day
6.5 to 7.0	8th largest 1/2 day
7.0 to 7.5	10th largest 1/2 day
7.5 to 8.0	12th largest 1/2 day
8.0 to 8.5	14th largest 1/2 day
8.5 to 9.0	16th largest 1/2 day
9.0 to 9.5	18th largest 1/2 day
9.5 to 10.0	20th largest 1/2 day

Arranging values obtained using equation 21–2 in increasing order and then accumulating, results in curve B as shown in figure 21–7.

Critically stacking the values obtained using equation 21–2 and then accumulating, results in curve C as shown in figure 21–7. Critically stacking involves placing the highest value at the middle time step, placing second highest value after the middle time step, the third highest value before the middle time step, and alternating back and forth until all values are accounted for. Table 21–6 illustrates such a critical stacking for a time step of 0.5 days.

Many modelers now use the SITES computer program which automatically computes the mass curve based on a 1-hour time step for watersheds having a time of concentration greater than 1 hour. Development of this mass curve is illustrated in the example problem in appendix A. For watersheds with a time of concentration less than 1 hour, SITES uses a 5,000 point mass curve which equates to a time step of approximately 2.9 minutes.

Development of the design hydrograph using the principal spillway mass curve follows general procedures outlined in NEH630.16, Hydrographs. Routing the hydrograph through the structure is described in NEH630.17, Flood Routing. Development of the composite PSH using the PSMC and unit hydrograph is illustrated in appendix A.

630.2103 Auxiliary spillway and freeboard hydrographs

The auxiliary spillway provides the necessary capacity to maintain the integrity of the earth dam when the capacity of the principal spillway is exceeded. A series of storm durations is needed to evaluate the auxiliary spillway system. According to TR–60 criteria, the duration that produces the highest water surface must be used to set the height of dam and the freeboard requirements for the structure.

Flows larger than those controlled by the principal spillway and retarding storage are safely conveyed past an earth dam by an auxiliary spillway designed using a stability design hydrograph (SDH).

The auxiliary spillway's minimum freeboard and integrity are determined using a freeboard hydrograph (FBH). The SDH and FBH are constructed by the same procedures of hydrograph development shown in NEH630.16, Hydrographs, with the rainfall temporal distribution developed using the methods described in this section.

(a) Rainfall and runoff volume considerations

(1) Precipitation amounts for stability design hydrographs (SDHs) and freeboard hydrographs (FBHs)

Typically, a storm duration greater than or equal to the time of concentration (T_c) for the watershed should be used for the SDH and FBH. Values should be taken from the appropriate NWS publication, local designated data source, or special study.

(2) Areal adjustment of rainfall

- **Areas with NWS Hydrometeorological Report (HMR) references for probable maximum precipitation (PMP)**—If the drainage area above a structure site is 10 square miles or less, the areal rainfall is taken from the appropriate HMR source. If the area is more than 10 square miles, but not over 100 square miles, the areal rainfall is obtained by using an adjustment factor as described in the applicable HMR.
- **Areas without an applicable NWS HMR for probable maximum precipitation (PMP)**—In areas without an applicable NWS HMR reference for spatial rainfall distribution, minimum areal adjustment ratios shown in figure 21–8 may be used. Special care must be taken in areas with special studies, since the rainfall amounts within the study area may have already been areally adjusted.

(3) Rainfall temporal distribution

In areas without applicable NWS references, locally designated guidance, or special studies for temporal distribution, the dimensionless auxiliary and freeboard storm distributions shown in figure 21–9 may be used.

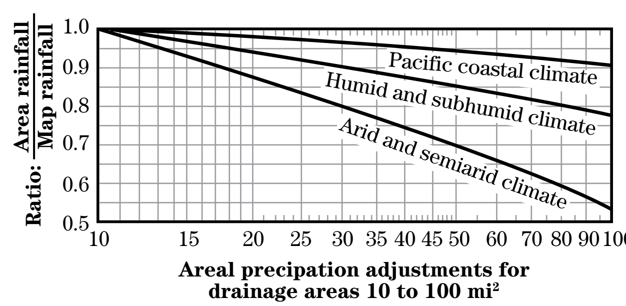
- **5-point rainfall distribution**—Alternately, the 24-hour storm distribution can be constructed by critically stacking incremental rainfall amounts of successive 6-, 12-, and 24-hour durations as described in HMR–52.

Step 1 From the appropriate data reference, obtain the 6-hour, 12-hour, and 24-hour PMP rainfall for the point location under consideration.

Step 2 Distribute the rainfall into four 6-hour increments as follows:

(a) First 6-hour block—Half of the difference between the 12-hour and the 24-hour PMP.

Figure 21–8 Areal adjustment for SDH and FBH design storms



(b) Second 6-hour block—6-hour PMP

(c) Third 6-hour block—Difference between the 12-hour and 6-hour PMP

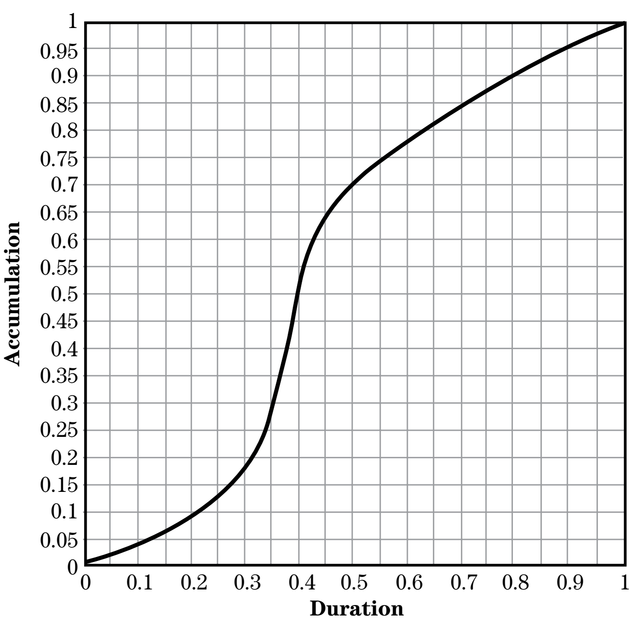
(d) Fourth 6-hour block—Half of the difference between the 12-hour and 24-hour PMP

Step 3 Divide each of the rainfalls in the four blocks by the 24-hour PMP rainfall to obtain the fractions for the 5-point distribution.

Step 4 Accumulate the fractions at the 6-hour intervals to obtain the 24-hour distribution.

Step 5 Development of a 5-point rainfall distribution is illustrated in appendix B.

Figure 21–9 Dimensionless design storm distribution for the SDH and FBH design storms



(4) Runoff CNs

The runoff CN and runoff volume for the drainage area above a structure site may be determined using any of the methods described in NEH630.10. Unless otherwise specified by criteria, the CN should be for an ARC II. This CN applies throughout the design storm, regardless of storm duration.

(5) Adjusting for channel losses

Runoff volumes and discharges for the SDH and FBH are typically so large that channel losses are insignificant in comparison and no reduction for channel losses is taken in the development of the SDH and FBH.

(6) Adjusting for QRF

QRF can be determined from local data, but it must not be less than the steady rate determined using table 21–5. When adequate local data are not available, table 21–5 may be used.

(7) Baseflow

When a SDH or FBH is developed from rainfall, the baseflow is added to the base of the entire hydrograph (fig. 21–1c). When the SDH or FBH is developed from runoff, all hydrograph discharge values less than baseflow should be increased to the baseflow value (fig. 21–1d). The recession or tail of the SDH or FBH may be controlled by QRF if this is higher than the baseflow (fig. 21–1d).

(b) Development of the stability design hydrograph (SDH) and the freeboard hydrograph (FBH)

Using the runoff volumes and rainfall distribution specific to the design event, the modeler develops an incremental mass curve of runoff and design hydrograph following the procedures outlined in NEH630.16. The step-by-step procedure for development of the incremental mass curve of runoff and design hydrograph for a freeboard hydrograph storm is illustrated in appendix B.

630.2104 References

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Appendix A Example of PSH Development

Appendix 21A Example—Development of the Principal Spillway Hydrograph (PSH)

The principal spillway hydrograph (PSH) is one of the required design hydrographs needed to check that a dam's design meets NRCS design criteria. This example problem illustrates the development of the mass curve, unit hydrograph and the final spillway design hydrograph for the principal spillway design storm event for a dam on a watershed with the following characteristics.

This example illustrates the methodology for hydrograph development as used in the SITES computer program which varies only slightly from the hydrograph development methodology illustrated in National Engineering Handbook, Part 630, Chapter 16, Hydrographs (NEH630.16).

Watershed characteristics:

Drainage area, DA = 15.0 mi^2

Time of concentration, T_c = 7.1 h

Average annual precipitation, P_a = 22.8 in

Average annual temperature, T_a = 61.5° F

Runoff curve number, CN = 80

100-year, 1-day precipitation, $P_{100,1\text{-day}}$ = 6.8 in

100-year, 10-day precipitation, $P_{100,1\text{-day}}$ = 11.0 in

Structure hazard classification: High

Per the criteria for a high hazard dam found in Earth Dams and Reservoirs (TR–60), the principal spillway design storm for this structure is the 100-year storm.

PART A: Development of the principal spillway mass curve

Step 1 Determine the adjusted areal rainfall.

From table 21–2, adjustment factors for a drainage area of 15.0 square miles are 0.977 for the 1-day precipitation and 0.991 for the 10-day precipitation.

Adjusted rainfalls are:

$$
\begin{aligned}
P_{100,\text{1-day adjusted}} &= 0.977(6.8) \\
&= 6.64 \text{ in} \\
P_{100,\text{10-day adjusted}} &= 0.991(11.0) \\
&= 10.90 \text{ in}
\end{aligned}
$$

Step 2 Determine the curve number for the 10-day precipitation.

Since the 100-year frequency 10-day precipitation amount is greater than 6 inches, table 21–3 is used to determine the 10-day curve number.

For $CN_{1\text{ day}}$ = 80, from table 21–3, the $CN_{10\text{ day}}$ = 65

See the footnote for the table to determine when table 21–3 applies.

Step 3 Estimate the direct runoff for 1 and 10 days.

Use the runoff equation or use NEH630.10, appendix 10A to determine the direct runoff for the 1-day and 10-day events.

1-day runoff:

$$
Q_{1-\text{day}} = \frac{\left[P_{1\text{day}} - 0.2\times\left(\frac{1000}{CN_{1-\text{day}}} - 10\right)\right]^2}{\left[P_{1\text{day}} + 0.8\times\left(\frac{1000}{CN_{1-\text{day}}} - 10\right)\right]}
$$

$$
= \frac{\left[6.64 - 0.2\times\left(\frac{1000}{80} - 10\right)\right]^2}{\left[6.64 + 0.8\times\left(\frac{1000}{80} - 10\right)\right]}
$$

10-day runoff:

$$Q_{10-day} = \frac{\left[P_{10day} - 0.2\times\left(\frac{1000}{CN_{10-day}} - 10\right)\right]^2}{\left[P_{10day} + 0.8\times\left(\frac{1000}{CN_{10-day}} - 10\right)\right]}$$

$$= \frac{\left[10.9 - 0.2\times\left(\frac{1000}{65} - 10\right)\right]^2}{\left[10.9 + 0.8\times\left(\frac{1000}{65} - 10\right)\right]}$$

Step 4: Compute the climatic index.

Using the given data and equation 21–1, determine C_i.

$$C_i = \frac{100\times P_a}{(T_a)^2}$$
$$= \frac{100\times 22.8}{(61.5)^2}$$
$$= 0.603$$

Because the C_i is less than one the channel loss may be used to reduce direct runoff.

Step 5: Estimate the net runoff.

The net runoff is the direct runoff multiplied by the channel loss reduction factor determined from table 21–4.

Enter table 21–4 with the drainage area of 15.0 square miles and the C_i of 0.603 and by interpolation find a reduction factor of 0.75.

Multiply the runoff volumes by the channel loss reduction factor to get the net runoff volumes which will be used for the rest of the example.

$$Q_{1-day\ net} = Q_{1-day} \times \text{ Reduction Factor}$$
$$= 4.36\times 0.75$$
$$= 3.27 \text{ in}$$

$$Q_{10-day\ net} = Q_{10-day} \times \text{ Reduction Factor}$$
$$= 6.35\times 0.75$$
$$= 4.76 \text{ in}$$

Step 6: Determine the mass curve of runoff.

Equation 21–2 gives the distribution for developing the mass curve. The equation is

$$Q_D = Q_{10-day\ net}\left(\frac{D}{10}\right)^a$$

where:

Q_D	=	total runoff at time D
D	=	time in days
$Q_{10\text{-}day\text{-}net}$	=	net runoff at the end of 10 days = 4.76 inches
$Q_{1\text{-}day\text{-}net}$	=	net runoff at end of 1 day = 3.27 inches
a	=	log ($Q_{10\text{-}day\ net}/Q_{1\text{-}day\ net}$)
a	=	log (4.76/3.27) = 0.1631

Substituting gives:

$$Q_D = 4.76\left(\frac{D}{10}\right)^{0.1631}$$

Step 7: Calculate the mass curve.

A spreadsheet should be used to calculate the mass curve as the curve may then be quickly and easily plotted. The mass curve is calculated as follows:

- The equation from step 6 above is used to calculate the mass curve. The curve is tabulated on 1-hour (0.0417 days) time increments (column (a), labeled *Time*) and shown in column (b), labeled Q_D in table 21A–1.

  Note: SITES uses a 1-hour time increment for watersheds with Tc ≥ 1 hour. Therefore, the 1-hour time increment was chosen here for illustration purposes.

- Incremental volumes are tabulated in column (c), labeled *Incremental Volume* in table 21A–1.
- Columns (d), labeled *Rank*, and (e), labeled *Incremental Volume arranged Largest to Smallest*, show the computed *Incremental Volume* from column (c) sorted in value from highest to lowest and ranked accordingly.
- Column (g), labeled *Increment Arrangement*, column (h), labeled *Time*, and column (i), labeled *Incremental Volumes Rearranged* show the rearrangement process for the mass curve. In this process, the largest incremental volume

is placed at the middle time interval of the mass curve. As illustrated here, the largest incremental volume of 1.947 inches is placed at the time interval from hour 119 to hour 120. The next largest incremental volume, 0.2330 inches, is place at time interval from hour 120 to hour 121. The next largest incremental volume, 0.1490 inches, is placed at hour 118 to 119; the next largest, 0.1119 inches, at hour 121 to 122, the next largest, 0.0905 inches, at hour 117 to 118, and so on, until all incremental volumes have been used.

- The incremental volumes are reaccumulated in to develop the final mass curve. Shown in column (j), labeled *Principal Spillway Mass Curve*, in table 21A–1.
- If desired, a dimensionless mass curve can be tabulated by dividing each of the values in column (j) by the total net runoff volume as shown in column (k), labeled *Dimensionless PSM*, in table 21A–1.

The 10-day dimensionless PSMC is plotted in figure 21A–1. Because accumulating the principal spillway mass curve for the full 10-days requires 240 points. Table 21A–1 does not show all 240 points. Instead computations for the first half day, middle day and last half day are shown. The rows with stars indicate those time increments that are not shown.

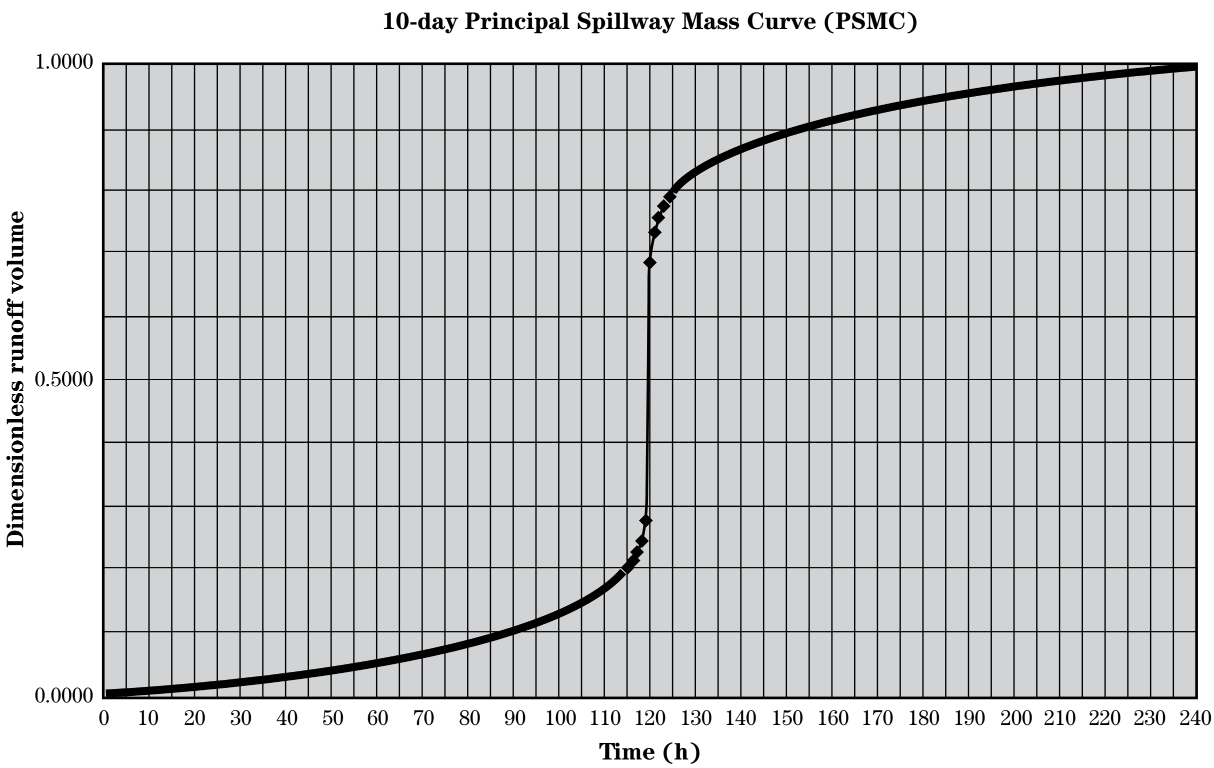
Table 21A–1 Step-by-step development of PSMC

(a) Time (days)	(b) Q_D (inches)	(c) Incremental volume (inches)	(d) Rank	(e) Incremental volume arranged largest to smallest	(g) Increment arrangement	(h) Time (hours)	(i) Incremental volumes rearranged	(j) PSMC	(k) Dimensionless PSMC
0.0000	0.0000					0		0.0000	0.0000
0.0417	1.9476	1.9476	1	1.9476	239th largest	1	0.0033	0.0033	0.0007
0.0833	2.1806	0.2330	2	0.2330	237th largest	2	0.0033	0.0065	0.0014
0.1250	2.3296	0.1490	3	0.1490	235th largest	3	0.0033	0.0098	0.0021
0.1667	2.4415	0.1119	4	0.1119	233rd largest	4	0.0033	0.0131	0.0028
0.2083	2.5320	0.0905	5	0.0905	231st largest	5	0.0033	0.0165	0.0035
0.2500	2.6084	0.0764	6	0.0764	229th largest	6	0.0034	0.0199	0.0042
0.2917	2.6748	0.0664	7	0.0664	227th largest	7	0.0034	0.0233	0.0049
0.3333	2.7337	0.0589	8	0.0589	225th largest	8	0.0034	0.0267	0.0056
0.3750	2.7867	0.0530	9	0.0530	223rd largest	9	0.0034	0.0301	0.0063
0.4167	2.8350	0.0483	10	0.0483	221st largest	10	0.0035	0.0336	0.0071
0.4583	2.8794	0.0444	11	0.0444	219th largest	11	0.0035	0.0371	0.0078
0.5000	2.9205	0.0411	12	0.0411	217th largest	12	0.0035	0.0406	0.0085
**********************									
4.5000	4.1789	0.0063	108	0.0063	25th largest	108	0.0218	0.7497	0.1575
4.5417	4.1852	0.0063	109	0.0063	23rd largest	109	0.0235	0.7732	0.1624
4.5833	4.1914	0.0062	110	0.0062	21st largest	110	0.0254	0.7986	0.1678
4.6250	4.1976	0.0062	111	0.0062	19th largest	111	0.0276	0.8262	0.1736
4.6667	4.2037	0.0061	112	0.0061	17th largest	112	0.0304	0.8566	0.1800
4.7083	4.2098	0.0061	113	0.0061	15th largest	113	0.0339	0.8905	0.1871
4.7500	4.2159	0.0061	114	0.0061	13th largest	114	0.0384	0.9288	0.1951
4.7917	4.2219	0.0060	115	0.0060	11th largest	115	0.0444	0.9732	0.2045
4.8333	4.2279	0.0060	116	0.0060	09th largest	116	0.0530	1.0263	0.2156
4.8750	4.2338	0.0059	117	0.0059	07th largest	117	0.0664	1.0926	0.2295
4.9167	4.2397	0.0059	118	0.0059	05th largest	118	0.0905	1.1831	0.2486
4.9583	4.2455	0.0058	119	0.0058	03rd largest	119	0.1490	1.3322	0.2799
5.0000	4.2513	0.0058	120	0.0058	largest	120	1.9476	3.2797	0.6890
5.0417	4.2571	0.0058	121	0.0058	02nd largest	121	0.2330	3.5128	0.7380
5.0833	4.2628	0.0057	122	0.0057	04th largest	122	0.1119	3.6247	0.7615
5.1250	4.2684	0.0057	123	0.0057	06th largest	123	0.0764	3.7011	0.7775
5.1667	4.2741	0.0056	124	0.0056	08th largest	124	0.0589	3.7599	0.7899
5.2083	4.2797	0.0056	125	0.0056	10th largest	125	0.0483	3.8082	0.8000

Table 21A–1 Step-by-step development of PSMC—continued

(a)	(b)	(c)	(d)	(e)	(g)	(h)	(i)	(j)	(k)
Time (days)	Q_D (inches)	Incremental volume (inches)	Rank	Incremental volume arranged largest to smallest	Increment arrangement	Time (hours)	Incremental volumes rearranged	PSMC	Dimensionless PSMC
5.2500	4.2853	0.0056	126	0.0056	12th largest	126	0.0411	3.8494	0.8087
5.2917	4.2908	0.0055	127	0.0055	14th largest	127	0.0360	3.8853	0.8162
5.3333	4.2963	0.0055	128	0.0055	16th largest	128	0.0320	3.9174	0.8230
5.3750	4.3017	0.0055	129	0.0055	18th largest	129	0.0289	3.9463	0.8291
5.4167	4.3071	0.0054	130	0.0054	20th largest	130	0.0264	3.9728	0.8346
5.4583	4.3125	0.0054	131	0.0054	22nd largest	131	0.0244	3.9971	0.8397
5.5000	4.3179	0.0054	132	0.0054	24th largest	132	0.0226	4.0197	0.8445
********************									
9.5000	4.7204	0.0034	228	0.0034	216th largest	228	0.0035	4.7195	0.9915
9.5417	4.7237	0.0034	229	0.0034	218th largest	229	0.0035	4.7230	0.9922
9.5833	4.7271	0.0034	230	0.0034	220th largest	230	0.0035	4.7265	0.9930
9.6250	4.7304	0.0033	231	0.0033	222nd largest	231	0.0035	4.7300	0.9937
9.6667	4.7338	0.0033	232	0.0033	224th largest	232	0.0034	4.7334	0.9944
9.7083	4.7371	0.0033	233	0.0033	226th largest	233	0.0034	4.7368	0.9951
9.7500	4.7404	0.0033	234	0.0033	228th largest	234	0.0034	4.7402	0.9958
9.7917	4.7437	0.0033	235	0.0033	230th largest	235	0.0034	4.7436	0.9965
9.8333	4.7470	0.0033	236	0.0033	232nd largest	236	0.0033	4.7469	0.9972
9.8750	4.7502	0.0033	237	0.0033	234th largest	237	0.0033	4.7502	0.9979
9.9167	4.7535	0.0033	238	0.0033	236th largest	238	0.0033	4.7535	0.9986
9.9583	4.7568	0.0033	239	0.0033	238th largest	239	0.0033	4.7568	0.9993
10.0000	4.7600	0.0032	240	0.0032	240th largest	240	0.0032	4.7600	1.0000

Figure 21A–1 PSMC of runoff



Part B: Development of the unit hydrograph

Step 1: Using equation 16A–13 in NEH630.16 appendix 16A, compute ΔD.

$$\Delta D = 0.133\ T_c$$
$$\Delta D = 0.133\ (7.1\ h)$$
$$\Delta D = 0.94\ h$$

For convenience, round to ΔD = 1.0 hour

Note: For watersheds with a Tc >1 hour, SITES defaults to a 1-hour time increment. For that reason, ΔD was rounded to 1-hour.

Step 2: Using equation 16A–7 from appendix 16A, compute T_p.

$$T_p = \frac{\Delta D}{2} + L$$
$$L = 0.6\,T_c$$
$$T_p = \frac{\Delta D}{2} + 0.6\,T_c$$
$$= \frac{1.0\ h}{2} + 0.6(7.1\ h)$$
$$= 4.75\ h$$

To simplify computations, and in keeping with the rounding of ΔD to 1 hour, round T_p to 5-hours for the dimensionless unit hydrograph computations.

Step 3: Using equation 16A–6 from appendix 16A, compute the unit hydrograph (runoff volume equal to 1 inch) peak discharge,q_p.

$$q_p = 484\frac{AQ}{T_p}$$
$$= 484(15.0\ mi^2)\left(\frac{1\ in}{5\ h}\right)$$
$$= 1452\ ft^3/s$$

Step 4: Using table 16–1, Ratios for dimensionless unit hydrograph and mass curve, compute the unit hydrograph.

- Tabulate the time and discharge ratios from NEH630.16, table 16–1 as shown in columns (a) and (b) of table 21A–3.
- Multiply the time ratios by the T_p computed in step 2 (use the rounded value), shown in column (c) of table 21A–2 (.1)(5)=.5 hour.
- Multiply the discharge ratios by the q_p computed in step 3, shown in column (d) of table 21A–2 (.03)(1492)=43.56.
- As shown in table 21A-3, Unit hydrograph ΔD equals 1 hour time increments, re-tabulate the unit hydrograph on ΔD equals 1 hour time increments (computed in step 1). Use simple linear interpolation for values which weren't computed directly in table 21A–2.
- If desired, plot the watershed dimensionless unit hydrograph as shown in figure 21A–2.

Step 5: Check the volume under the unit hydrograph.

- Sum the ordinates of the unit hydrograph (table 21A–3, column (b)) and multiply by ΔD.

$$9684.5\ ft^3/s \times 1\ h = 9684.5\ ft^3/s\text{-}h$$

- Compute the volume under the unit hydrograph using the drainage area and unit runoff volume, 1 inch.

$$15.0\ mi^2\,(1\ in)\left(\frac{1\ ft}{12\ in}\right)(43560\ ft^2/a)(640\ a/mi^2)$$
$$\left(\frac{1\ hr}{60\ min}\right)\left(\frac{1\ min}{60\ s}\right) = 9680\ ft^3/s\text{-}hr$$

The difference between the two volumes in this example is negligible at less than 0.5 percent.

Table 21A–2 Development of the unit hydrograph

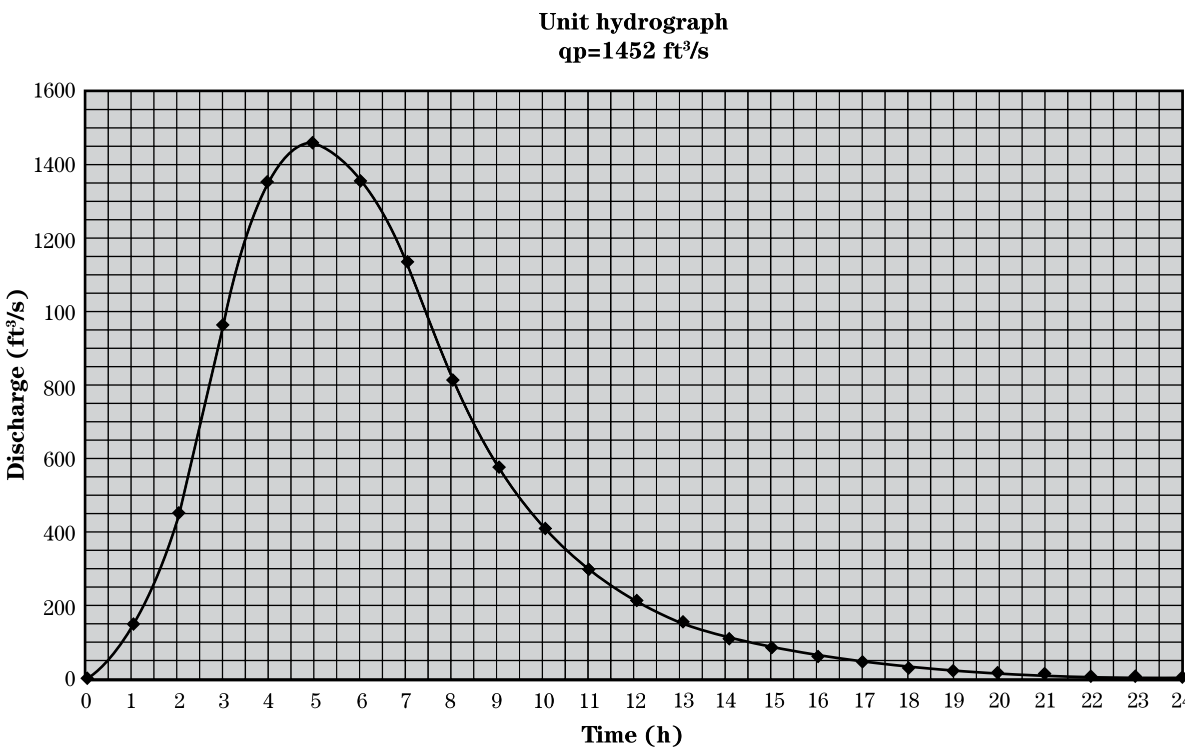
(a) Time ratios (t/T_p)[1/]	(b) Discharge ratios (q/q_p):[1/]	(c) Time (h)	(d) q (ft^3/s)
0.0	0.000	0	0
0.1	0.030	0.5	43.56
0.2	0.100	1	145.2
0.3	0.190	1.5	275.88
0.4	0.310	2	450.12
0.5	0.470	2.5	682.44
0.6	0.660	3	958.32
0.7	0.820	3.5	1190.64
0.8	0.930	4	1350.36
0.9	0.990	4.5	1437.48
1.0	1.000	5	1452
1.1	0.990	5.5	1437.48
1.2	0.930	6	1350.36
1.3	0.860	6.5	1248.72
1.4	0.780	7	1132.56
1.5	0.680	7.5	987.36
1.6	0.560	8	813.12
1.7	0.460	8.5	667.92
1.8	0.390	9	566.28
1.9	0.330	9.5	479.16
2.0	0.280	10	406.56
2.2	0.207	11	300.564
2.4	0.147	12	213.444
2.6	0.107	13	155.364
2.8	0.077	14	111.804
3.0	0.055	15	79.86
3.2	0.040	16	58.08
3.4	0.029	17	42.108
3.6	0.021	18	30.492
3.8	0.015	19	21.78
4.0	0.011	20	15.972
4.5	0.005	22.5	7.26
5.0	0.000	25	0

[1/] From table 16–1, NEH630.16

Table 21A–3 Unit Hydrograph on 1 hour time increments

(a) Time (hours)	(b) q (ft^3/s)
0	0.0
1	145.2
2	450.1
3	958.3
4	1350.4
5	1452.0
6	1350.4
7	1132.6
8	813.1
9	566.3
10	406.6
11	300.6
12	213.4
13	155.4
14	111.8
15	79.9
16	58.1
17	42.1
18	30.5
19	21.8
20	16.0
21	12.5
22	9.0
23	5.8
24	2.9
Summation	9684.5

Figure 21A–2 Plotted unit hydrograph



Part C Development of the principal spillway hydrograph.

Utilizing the incremental runoff volume (table 21A–1, column (i)) and the dimensionless unit hydrograph (table 21A–3, column (b)), compute the flood hydrograph as shown in table 21A–4. The unit hydrograph to the nearest cubic feet per second will be used in this example. It is also important that the incremental mass curve be reversed.

Step 1 Multiply the first ordinate of the incremental runoff volume by the first ordinate of the unit hydrograph to represent the runoff volume for the first time step.

$$(0.033)(0)=0$$

Step 2 Multiply the first ordinate of the incremental runoff volume by the second ordinate of the unit hydrograph and add to that the second ordinate of the incremental volume by the first ordinate of the unit hydrograph to represent the runoff volume for the second time step.

$$(0.0033)(145)=0.479 \quad \text{round to 0}$$

Step 3 Runoff volume for the third time step equals first ordinate of the incremental runoff volume multiplied by the third ordinate of the unit hydrograph plus the second ordinate of the incremental runoff volume multiplied by the second ordinate of the unit hydrograph plus the third ordinate of the incremental runoff volume multiplied by the first ordinate of the unit hydrograph.

$$(0.0033)(145)+(0.0033)(450)=1.9 \quad \text{round to 2}$$

Step 4 Continue in the same manner, until all values of both the incremental runoff volume and unit hydrograph are exhausted.

Table 21A–4 shows the computation of the final runoff hydrograph which is the design hydrograph for the principal spillway hydrograph storm event. This method differs slightly from that illustrated in NEH630.16. The methodology illustrated in NEH630.16 was intended for users computing the runoff hydrograph by hand using a separate strip of paper with the incremental runoff in reverse order. This is done to help the modeler track values as the computations were proceeding. As illustrated, the unit hydrograph is not reversed; however, the values are multiplied and added in the same order as would be done using the NEH630.16 methodology. However, an electronic spreadsheet was utilized in this example to help simplify the computations for the modeler.

Table 21A–4 shows portions of the composite principal spillway hydrograph. This example illustrates the computation of a 10-day flood hydrograph computed on 1-hour time increments. It takes approximately 256 hours for the flood hydrograph to return to zero discharge. Not all of the computations for all 256 time increments are shown in this table.

Figure 21A–3 shows a plot of the principal spillway hydrograph.

Table 21A–4 Ten-day composite principal spillway flood hydrograph

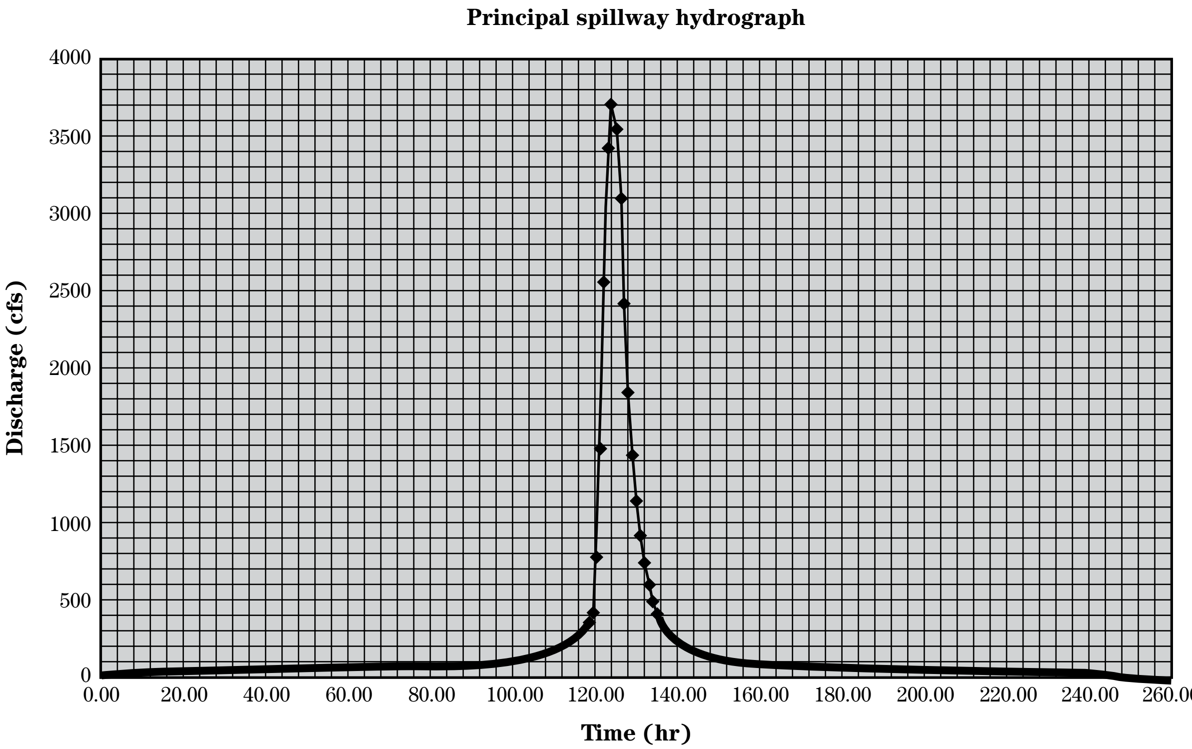
(a) Time (h)	(b) Incremental runoff volume (in)	(c) Unit hydrograph (ft^3/s)	(d) Composite PSH (ft^3/s)
0.00		0	0
1.00	0.0033	145	0
2.00	0.0033	450	2
3.00	0.0033	958	5
4.00	0.0033	1350	9
5.00	0.0033	1452	14
6.00	0.0034	1350	19
7.00	0.0034	1133	23
8.00	0.0034	813	25
9.00	0.0034	566	27
10.00	0.0035	407	29
11.00	0.0035	301	30
12.00	0.0035	213	31
13.00	0.0036	155	32
14.00	0.0036	112	32
15.00	0.0036	80	33
16.00	0.0036	58	33
17.00	0.0037	42	34
18.00	0.0037	30	34
19.00	0.0037	22	34
20.00	0.0038	16	35
21.00	0.0038	12	35
22.00	0.0038	9	35
23.00	0.0039	6	36
24.00	0.0039	3	36
25.00	0.0039	0	36
26.00	0.0040		37
27.00	0.0040		37
28.00	0.0040		37
29.00	0.0041		38
	**********		
95.00	0.0119		99
96.00	0.0123		102
97.00	0.0128		105
98.00	0.0133		108
99.00	0.0138		111
100.00	0.0143		115
101.00	0.0150		119
102.00	0.0156		123
103.00	0.0164		128
104.00	0.0172		133
105.00	0.0182		139
106.00	0.0192		145

(a) Time (h)	(b) Incremental runoff volume (in)	(c) Unit hydrograph (ft^3/s)	(d) Composite PSH (ft^3/s)
107.00	0.0205		152
108.00	0.0218		159
109.00	0.0235		168
110.00	0.0254		177
111.00	0.0276		188
112.00	0.0304		200
113.00	0.0339		215
114.00	0.0384		232
115.00	0.0444		253
116.00	0.0530		278
117.00	0.0664		311
118.00	0.0905		356
119.00	0.1490		425
120.00	1.9476		786
121.00	0.2330		1481
122.00	0.1119		2568
123.00	0.0764		3442
124.00	0.0589		3731
125.00	0.0483		3564
126.00	0.0411		3112
127.00	0.0360		2431
128.00	0.0320		1857
129.00	0.0289		1450
130.00	0.0264		1158
131.00	0.0244		918
132.00	0.0226		744
133.00	0.0211		608
134.00	0.0198		503
135.00	0.0187		425
136.00	0.0177		364
137.00	0.0168		317
138.00	0.0160		279
139.00	0.0153		249
140.00	0.0146		227
141.00	0.0140		207
142.00	0.0135		189
143.00	0.0130		173
144.00	0.0125		158
145.00	0.0121		150
146.00	0.0117		143
147.00	0.0114		137
148.00	0.0110		131
149.00	0.0107		126

Table 21A–4 Ten-day composite principal spillway flood hydrograph—continued

(a) Time (h)	(b) Incremental runoff volume (in)	(c) Unit hydrograph (ft^3/s)	(d) Composite PSH (ft^3/s)
150.00	0.0104		122
151.00	0.0101		117
152.00	0.0098		113
153.00	0.0096		110
154.00	0.0094		106
155.00	0.0091		103
	**********		
221.00	0.0037		38
222.00	0.0037		38
223.00	0.0037		37
224.00	0.0037		37
225.00	0.0036		37
226.00	0.0036		36
227.00	0.0036		36
228.00	0.0035		36
229.00	0.0035		36
230.00	0.0035		35
231.00	0.0035		35
232.00	0.0034		35
233.00	0.0034		34
234.00	0.0034		34
235.00	0.0034		34
236.00	0.0033		34
237.00	0.0033		33
238.00	0.0033		33
239.00	0.0033		33
240.00	0.0032		33
241.00			32
242.00			30
243.00			27
244.00			22
245.00			18
246.00			13
247.00			9
248.00			7
249.00			5
250.00			3
251.00			3
252.00			2
253.00			1
254.00			1
255.00			1
256.00			0

Figure 21A–3 Principal spillway hydrograph



Appendix 21B Example—Development of the Design Hydrograph: Freeboard Hydrograph (FBH) Storm

To check the capacity of the earthen spillway of a dam installed on the watershed described in appendix 21A, the 24-hour freeboard hydrograph must be developed.

To recap from the example in Appendix 21A, the watershed characteristics are as follows:

- Drainage area = 15.0 square miles
- Time of concentration = 7.1 hours
- Runoff curve number = 80
- Structure hazard class: High hazard

Development of the freeboard hydrograph for this example will use the 5-point rainfall distribution.

Step 1: Determine the appropriate time interval to use.

Both the unit hydrograph and rainfall distribution must be compiled on the same time interval for developing the final runoff hydrograph.

Using NEH630.16, appendix A, equation 16A–13, $\Delta D = 0.133T_c$ or 0.133(7.1) = 0.9443 hour. For convenience and to simplify computations, round this to ΔD = 1 hour.

Step 2: Develop the rainfall temporal distribution.

1. Determine the probable maximum precipitation (PMP) amounts using the appropriate hydrometeorological report (HMR) or other appropriate special study. For this example, the PMP values are as follows:

   $PMP_{6\text{-hour duration}}$: 29.0 inches

   $PMP_{12\text{-hour duration}}$: 34.0 inches

   $PMP_{24\text{-hour duration}}$: 38.0 inches

2. Distribute the rainfall into four 6-hour increments and determine the fraction of rainfall for each increment as described and shown in table 21B–1.

3. Accumulate the rainfall fractions for each time increment to develop the final 5-point rainfall distribution as shown in table 21B–2.

4. Using linear interpolation, tabulate the rainfall distribution on the time interval, ΔD = 1 hour which was determined in step 1, as shown in table 21B–3. Figure 21B–1 is a plot of the rainfall distribution from table 21B–3.

Step 3: Develop the mass curve of runoff for the design storm.

This follows the procedures outlined in NEH630.16.

Table 21B–1 Distribution of rainfall into time increments for the 5-point rainfall distribution

Time increment (h)	Incremental rainfall volume	Incremental rainfall volume (in)	Rainfall fractions for each time increment	
0 to 6	0.5 × (PMP 24-hour–PMP 12-hour) = 0.5 × (38.0-34.0) =	2.0	2.0 / 38.0 =	0.053
6 to 12	PMP 6-hour =	29.0	29.0 / 38.0 =	0.763
12 to 18	PMP 12-hour - PMP 6-hour = 34.0 - 29.0 =	5.0	5.0 / 38.0 =	0.131
18 to 24	0.5 x (PMP 24-hour - PMP 12-hour) = 0.5 x (38.0-34.0) =	2.0	2.0 / 38.0 =	0.053

Starting with the Rainfall Distribution on 1-hour time increments from Step 2, determine the incremental mass curve of runoff as shown in table 21B–4.

- Columns (a) and (b) show the hourly rainfall distribution as tabulated in step 2.
- Column (c) shows the accumulated rainfall distribution determined by multiplying the values in column (b) by $PMP_{24\text{-hour}}$ of 38.0 inches.
- Column (d) shows the accumulated runoff volume determined using the Curve Number Runoff equation (see NEH630.10) with an RCN=80 (assuming Antecedent Runoff Condition II).
- Column (e) shows the incremental runoff volume for each 1-hour time increment. Note that for RCN=80, runoff does not begin until rainfall is greater than the initial abstraction.

Initial abstraction:

$$I_a = 0.2S \qquad \text{(NEH630.10, eq. 10–10)}$$

where:

$$CN = \frac{1000}{10+S} \qquad \text{(NEH630.10, eq. 10–12)}$$

Rearranging equation 10–12 of NEH630.10

$$S = \frac{1000}{80} - 10$$
$$= 2.5 \text{ in}$$

$$CN = 80$$

$$I_a = 0.2S(2.5)$$
$$= 0.5 \text{ in}$$

Step 4: Develop the Unit Hydrograph.

The development of the freeboard hydrograph follows the procedures in NEH630.16.

- Determine the time to peak, T_p of the unit hydrograph.

Table 21B–2 Five-point rainfall distribution for 6-hour increments

Time ending (h)	Rainfall fraction	5-point rainfall distribution
0		0
6	0.053	0.053
12	0.763	0.816
18	0.132	0.947
24	0.053	1.000

Table 21B–3 Rainfall distribution for ΔD = 1 hour time increments

Time (h)	Rainfall distribution
0	0
1	0.009
2	0.018
3	0.026
4	0.035
5	0.044
6	0.053
7	0.180
8	0.307
9	0.434
10	0.561
11	0.689
12	0.816
13	0.838
14	0.860
15	0.882
16	0.904
17	0.925
18	0.947
19	0.956
20	0.965
21	0.974
22	0.982
23	0.991
24	1.000

Figure 21B–1 Plotted rainfall distribution

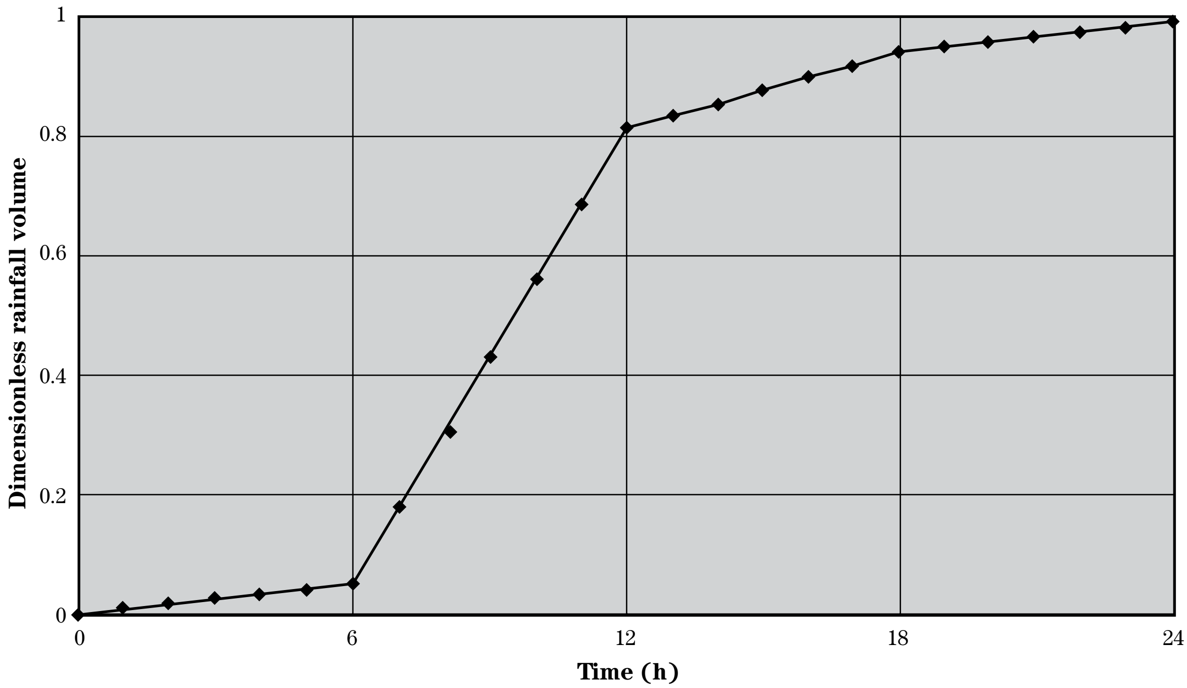
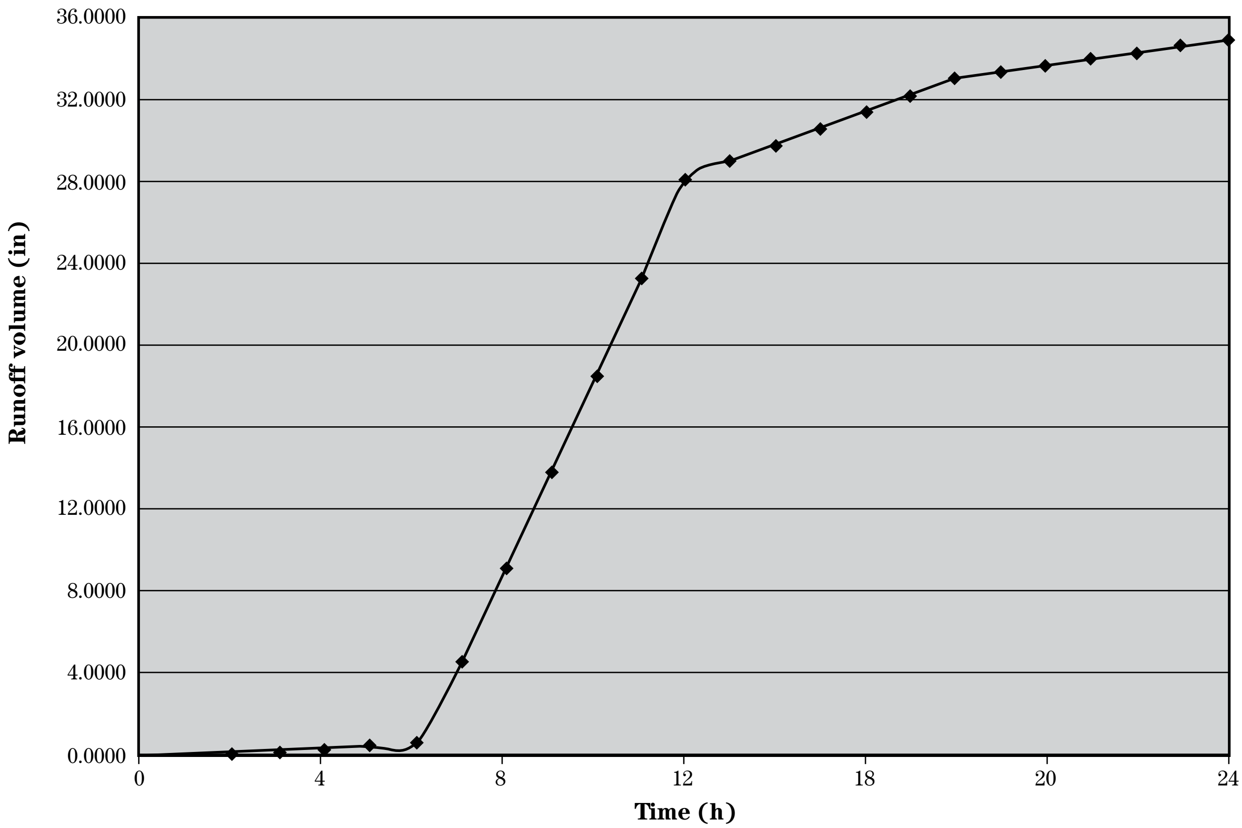


Table 21B–4 Incremental runoff

(a) Time (h)	(b) Rainfall distribution	(c) Total rainfall (in)	(d) Accumulated mass curve of runoff * (in)	(e) Incremental mass curve of runoff (in)
0	0.000	0.000		
1	0.009	0.342		0.000
2	0.018	0.684	0.013	0.013
3	0.026	0.988	0.080	0.067
4	0.035	1.330	0.207	0.127
5	0.044	1.672	0.374	0.167
6	0.053	2.014	0.571	0.197
7	0.180	6.840	4.547	3.976
8	0.307	11.666	9.123	4.576
9	0.434	16.492	13.830	4.707
10	0.561	21.318	18.586	4.756
11	0.689	26.182	23.404	4.818
12	0.816	31.008	28.197	4.794
13	0.838	31.844	29.029	0.831
14	0.860	32.680	29.860	0.832
15	0.882	33.516	30.692	0.832
16	0.904	34.352	31.524	0.832
17	0.925	35.150	32.318	0.794
18	0.947	35.986	33.151	0.832
19	0.956	36.328	33.491	0.341
20	0.965	36.670	33.832	0.341
21	0.974	37.012	34.172	0.341
22	0.982	37.316	34.475	0.303
23	0.991	37.658	34.816	0.341
24	1.000	38.000	35.156	0.341

* Runoff starts when $I_a = 0.2S = 0.2(2.5) = 0.5$ in

Figure 21B–2 Plotted freeboard storm mass curve



- Using NEH630.16, appendix A, equation 16A–10

$$T_c + \Delta D = 1.7\ T_p$$
$$T_p = \frac{(T_c + \Delta D)}{1.7} = \frac{(7.1+1)}{1.7} = 4.76 \text{ hr}$$

To simplify computations, and in keeping with the rounding of ΔD to 1 hour, round T_p to 5 hours for the dimensionless unit hydrograph computations.

- Determine the q_p for a volume of runoff equal to 1-inch.

Using equation 16A–6,

$$q_p = 484\frac{AQ}{T_p} = \frac{484(15.0\text{ mi}^2)(1\text{ in})}{(5\text{ hr})} = 1,452\text{ ft}^3/\text{s}$$

- Columns (a) and (b) in table 21B–5 are copied from table 16–1 and show the ratios of time to time to peak and unit discharge to unit peak discharge.
- Multiply the time ratios in column (a) by the computed time to peak, 4.76 hours, to obtain time increments, column (c) for the dimensionless unit hydrograph.
- Multiply the discharge ratios in column (b) by the computed unit peak discharge, 1452 cubic feet per second, to obtain the unit discharges, column (d), for the dimensionless unit hydrograph.
- Using linear interpolation between values shown in table 21B–5, tabulate the unit hydrograph so that the unit hydrograph and rainfall distribution are tabulated on the same interval. As determined in step 1, ΔD=1 hour should be used. Table 21B–6 shows the unit hydrograph recompiled on the 1-hour time interval.

Step 5: Check the volume under the unit hydrograph.

Table 21B–5 Unit hydrograph

(a) Time ratios (t/T_p)	(b) Discharge ratios (q/Q_p)	(c) Time (hr) $=5\times(t/T_p)$	(d) Unit hydrograph: (ft^3/s) $= 1,452\times(q/Q_p)$
0.0	0.000	0	0
0.1	0.030	0.5	43.56
0.2	0.100	1	145.2
0.3	0.190	1.5	275.88
0.4	0.310	2	450.12
0.5	0.470	2.5	682.44
0.6	0.660	3	958.32
0.7	0.820	3.5	1190.64
0.8	0.930	4	1350.36
0.9	0.990	4.5	1437.48
1.0	1.000	5	1452
1.1	0.990	5.5	1437.48
1.2	0.930	6	1350.36
1.3	0.860	6.5	1248.72
1.4	0.780	7	1132.56
1.5	0.680	7.5	987.36
1.6	0.560	8	813.12
1.7	0.460	8.5	667.92
1.8	0.390	9	566.28
1.9	0.330	9.5	479.16
2.0	0.280	10	406.56
2.2	0.207	11	300.564
2.4	0.147	12	213.444
2.6	0.107	13	155.364
2.8	0.077	14	111.804
3.0	0.055	15	79.86
3.2	0.040	16	58.08
3.4	0.029	17	42.108
3.6	0.021	18	30.492
3.8	0.015	19	21.78
4.0	0.011	20	15.972
4.5	0.005	22.5	7.26
5.0	0.000	25	0

- Sum the ordinates of the unit hydrograph (table 21B–6, column (b)) and multiply by ΔD.

$$9{,}685\ \text{ft}^3/\text{s} \times 1\ \text{h} = 9{,}683\ \text{ft}^3/\text{s-h}$$

- Compute the volume under the unit hydrograph using the drainage area and unit runoff volume, 1 inch.

$$15.0\ \text{mi}^2\,(1\ \text{in})\left(\frac{1\ \text{ft}}{12\ \text{in}}\right)\left(\frac{43560\ \text{ft}^2}{\text{ac}}\right)\left(\frac{640\ \text{ac}}{\text{mi}^2}\right)\left(\frac{1\ \text{h}}{3600\ \text{sec}}\right)$$

Table 21B–6 Unit hydrograph on ΔD =1-hour time increments

(a) Time (h)	(b) Unit hydrograph (ft^3/s)
0	0
1	145
2	450
3	958
4	1350
5	1452
6	1350
7	1133
8	813
9	566
10	407
11	301
12	213
13	155
14	112
15	80
16	58
17	42
18	30
19	22
20	16
21	12
22	9
23	6
24	3
Σ =	**9683**

$$\left(\frac{1\ \text{hr}}{60\ \text{min}}\right)\left(\frac{1\ \text{min}}{60\ \text{sec}}\right) = 9680\ \text{ft}^3/\text{s-hr}$$

The difference between the two volumes in this example is negligible at less than 0.5%.

Step 6: Compute the flood hydrograph.

- Utilizing the Incremental Runoff Volume (table 21B–4, column e) and the Unit Hydrograph (table 21B–6), compute the flood hydrograph.
  - Multiply the first ordinate of the incremental runoff volume by the first ordinate of the unit hydrograph to represent the runoff volume for the first time step.
  - Multiply the first ordinate of the incremental runoff volume by the second ordinate of the unit hydrograph and add to that the second ordinate of the incremental volume by the first ordinate of the unit hydrograph to represent the runoff volume for the second time step.
  - Runoff volume for the third time step = First ordinate of the incremental runoff volume multiplied by the third ordinate of the unit hydrograph PLUS the second ordinate of the incremental runoff volume multiplied by the second ordinate of the unit hydrograph PLUS the third ordinate of the incremental runoff volume multiplied by the first ordinate of the unit hydrograph.
  - Continue in the same manner, until all values of both the incremental runoff volume and unit hydrograph are exhausted.

Table 21B–7 shows the computation of the final runoff hydrograph which is the design hydrograph for the freeboard hydrograph storm event. This method differs slightly from that illustrated in NEH630.16. The methodology illustrated in NEH630.16 was intended for users computing the runoff hydrograph by hand using a separate strip of paper with the incremental runoff in reverse order. This is done to help the modeler track values as the computations were proceeding. The method illustrated here multiples and adds the values in the same order as would be done using the NEH630.16, Methodology. However, an electronic spreadsheet was utilized in this example to help simplify the computations for the modeler.

The next page shows the composite freeboard hydrograph.

Step 7 Check of runoff volume (OPTIONAL).

As an optional check, compare the runoff volume obtained by summing the ordinates of the unit hydrograph with the total volume of runoff for the $PMP_{24\text{-hour}}$ storm determined using the runoff eEquation with the total runoff volume from the principal spillway mass curve.

- Runoff volume from flood hydrograph ordinates equals:

$$340{,}677\ \text{ft}^3/\text{s} \times 1\ \text{h} = 340{,}677\ \text{cfs-h}$$

Converting that to watershed inches equals:

$$\frac{340{,}677\ \text{ft}^3/\text{s-h}(60\ \text{min/h})(60\ \text{s/min})}{15.0\ \text{mi}^2(640\ \text{ac/mi}^2)(43{,}560\ \text{ft}^2/\text{s})}\left(\frac{12\ \text{in}}{\text{ft}}\right) = 35.2\ \text{in}$$

- Runoff volume determined using the runoff equation,

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \qquad \text{(NEH630.10, eq. 10–11)}$$

where:
$P = PMP_{24\text{-hour}}$ = 38.0 inches; and

$$S = \frac{1000}{CN} - 10 \qquad \text{(NEH630.10, eq. 10–12)}$$

Figure 21B–3 Plot of unit hydrograph

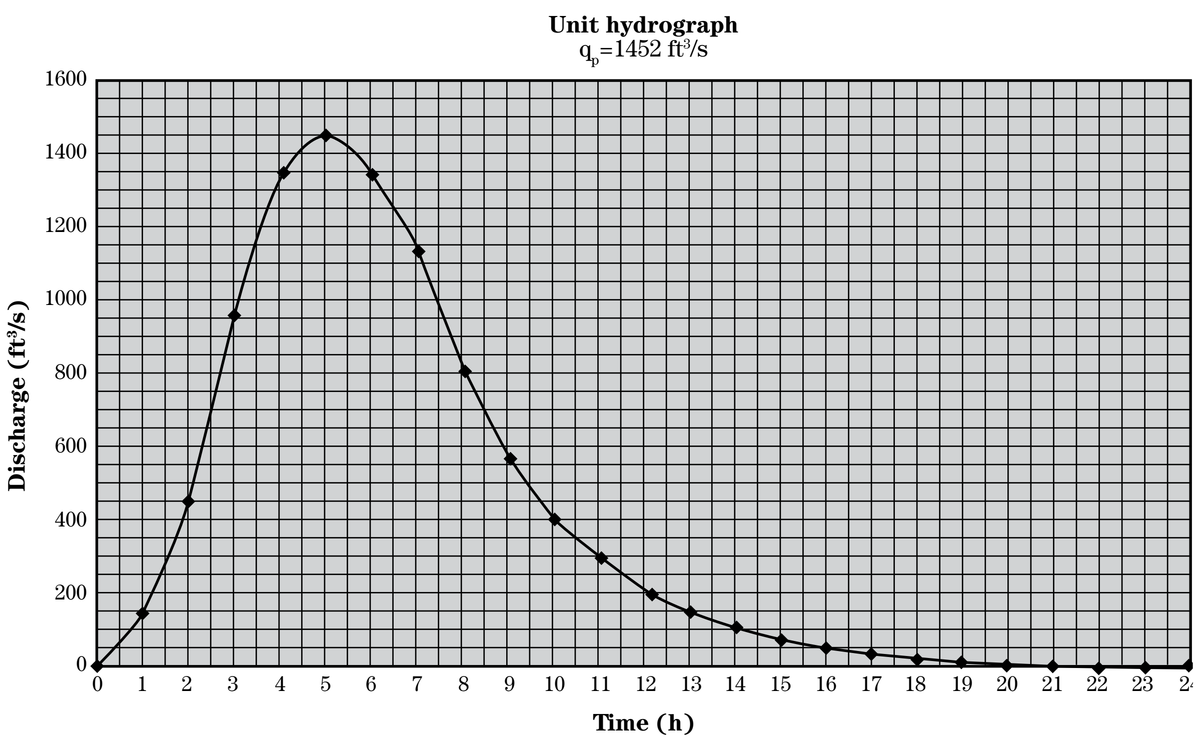


Table 21B–7 Design hydrograph—FBH storm event

(a) Time (h)	(b) Incremental runoff	(c) Unit hydrograph	(d) Freeboard hydrograph (discharge in ft^3/s)
0		0	0
1	0.000	145	0
2	0.013	450	2
3	0.067	958	16
4	0.127	1350	61
5	0.167	1452	163
6	0.197	1350	3335
7	3.976	1133	1111
8	4.576	813	3156
9	4.707	566	7317
10	4.756	407	13276
11	4.818	301	19900
12	4.794	213	26248
13	0.831	155	31160
14	0.832	112	33503
15	0.832	80	32652
16	0.832	58	29426
17	0.794	42	25225
18	0.832	30	20972
19	0.341	22	17194
20	0.341	22	14318
21	0.341	12	12017
22	0.303	9	10041
23	0.341	6	8350
24	0.341	3	6992
25		0	5880
26			4992
27			4143
28			3311
29			2547
30			1892
31			1353
32			939
33			664
34			464
35			318
36			220
37			158
38			110
39			77
40			53
41			36
42			25
43			17
44			10
45			6
46			3
47			1
48			0
Σ=			**340654**

with CN = 80 and rearranging equation 10–12 of NEH630.10

$$S = \frac{1000}{80} - 10$$
$$= 2.5 \text{ in}$$

and

Runoff volume from the mass curve (shown at time, t = 24.0 hours in column (d) of table 21B–6) = 35.16 inches.

All three runoff volumes agree.

Figure 21B–4 Plot of FBH