United States Department of Agriculture
Natural Resources Conservation Service

Technical Note No. 301

September 2012

Runoff-Frequency: Peaks, Volumes, Timing for Low-Relief, Sandy “cranberry bog” Drainage Areas of Southeastern Massachusetts and Rhode Island

Issued September 2012

Cover photo: *Looking downstream from bridge over Wading River near Norton, Massachusetts, USGS gaging station 01109000 is on left bank lower left corner (not shown). Photo by Aaron Pugh, USGS.*

(Technical Note No. 301, draft September 2012)

Acknowledgments

This technical note was prepared by **Thomas J. Garday**, hydraulic engineer, U.S. Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS), at the National Water Management Center in Little Rock, Arkansas. The author would like to express appreciation for assistance from **Aaron L. Pugh**, hydrologist, U.S. Geological Survey (USGS), at the Arkansas Water Science Center, Little Rock, Arkansas, who assisted with data collection, field investigations, maps, analysis, and editing. The author appreciates the reviews and comments made by **William Merkel**, hydraulic engineer, NRCS, West National Technology Support Center, Beltsville, Maryland; **Claudia Hoeft**, national hydraulic engineer, NRCS, Washington DC; **John McClung**, hydraulic engineer, NRCS, National Water Management Center, Little Rock, Arkansas; and **Dr. Kerry Robinson**, hydraulic engineer, NRCS, East National Technology Support Center, Greensboro, North Carolina. The author would also like to express appreciation of the authors cited for their work is part of the basis upon which this report is based.

Preface

The original intent was to update Eng–Proc–MA–19 (Estimating Runoff for Cranberry Areas in Massachusetts) with additional years of record for the USGS gages cited and to add data from other gages within the study area that have 20 or more years of record. Eng–Proc–MA–19 dated June 19, 1974, became MA–TN–ENG–213 in April 1985. The USGS Instantaneous Data Archive (IDA) provided detailed runoff characteristics via 15-minute interval discharge measurements. Seven active gages within the study area are analyzed. After analyzing many storm events, the gathered runoff characteristics do not support all of the hydrologic assumptions stated in Eng–Proc–MA–19; therefore, this document was created with modified assumptions and procedures. Two of the original gages are included in this analysis with additional years of record. Some of the original text and information are also included.

Table of Contents

Runoff-Frequency: Peaks, Volumes, Timing for Low-Relief, Sandy “cranberry bog” Drainage Areas of Southeastern Massachusetts and Rhode Island

Abstract

Unit-area runoff hydrographs that characterize peak discharges, runoff volumes, and timing, proportional to drainage area were developed specifically for the “cranberry bog” areas of southeast Massachusetts and Rhode Island. Hydrograph relationships were derived from measured discharge data, collected at seven U.S. Geological Survey (USGS) stream gaging stations in Bristol, Norfolk, and Plymouth Counties of Massachusetts, and Providence and Washington Counties in Rhode Island. The regional hydrology is heavily influenced by the areal distribution and stratification of glacial drift, which affects surface and groundwater runoff; peaks and timing. Homogeneity of runoff responses amongst these seven low relief watersheds allowed successful use of regional stream gage analysis. The regional gage analysis incorporated the use of annual peak discharge data (Log Pearson III Distributions), 15-minute instantaneous stage data (converted into discharges for determining hydrograph shapes, volume distribution and runoff rates), and daily mean discharge data (unit-area flow duration curves). The thee datasets formed the basics to derive the most probable peaks, volumes, shapes, and timing of runoff at specific return intervals. The independent predictor variable required to solve for the runoff characteristics is drainage area.

Introduction

Runoff-frequency information is needed for the engineering design of conservation practices such as cranberry bog water management (CPS 356, Dike), erosion control, streambank protection (CPS 580, Streambank and Shoreline Protection), design of stream crossing (bridges and culverts) (CPS 578, Stream Crossing), and floodplain management. The objective of this technical note is to provide the U.S. Department of Agriculture (USDA), Natural Resources Conservation Service (NRCS) field and area engineers with an empirical technique to estimate the hydrologic regime including: peak discharges, runoff volumes, and the timing and duration of runoff on small rural ungaged stream sites in southeast Massachusetts (Bristol, Norfolk, and Plymouth Counties) and eastern Rhode Island (Providence and Washington Counties).

The NRCS has developed hydrologic analysis methods and software tools to estimate the volume of runoff and peak discharges for small watersheds. The technical references are within the NRCS National Engineering Handbook, Part 630, Hydrology (2004). The principal software tools that have been developed are EFH–2 (NRCS 2003), WinTR–55 (NRCS 2004), and WinTR–20 (NRCS 2004). These methods and software tools are based on rainfall/runoff relationships, which do not adequately account for the significant influence of groundwater and surface-water interactions observed in the surficial geology and topography of southeastern Massachusetts and Rhode Island.

Glaciation and the distribution of glacial deposits greatly influence the hydrologic characteristics of southern New England streams and rivers. Bog sites in low-lying southeastern coastal areas of Massachusetts and Rhode Island have significant areas (greater than 50%) of stratified sand and gravel glacial deposits and floodplain alluvium deposits. These stratified deposits are conducive to high infiltration rates, large storage capacities, and significant baseflow contributions to the surface water channels. The combination of stratified, highly conductive deposits and the low topographic relief allows water to move though the subsurface between surface water basins. Hence, peak discharges cannot be accurately computed by procedures based on direct surface runoff alone.

This technical note replaces ENG–PROC–MA–19 technical note (1974). Similar to the 1974 methodology, an analysis was made of streamflow data. This technical note presents design unit-area runoff hydrographs at specific annual exceedance probabilities for estimating peak discharges, runoff volumes, timing, durations of discharge, and rates of change of streamflow for ungaged drainage areas in low-lying rural “bog areas” of southeastern Massachusetts and Rhode Island. The method is empirical; runoff characteristics are based upon measured runoff from seven continuous long-term USGS stream gaging stations located within the five counties of the study area. Traditional rainfall to runoff methodologies use rainfall, rainfall distribution, land use/loss factors, unit hydrograph (UH) peak rate factors (PRF), and channel routing parameters as the dependent variables to calculate runoff and timing. This empirical method developed for a specific region where hydrologic response is homogeneous and uniform amongst drainage basins, uses drainage area as the only dependent variable.

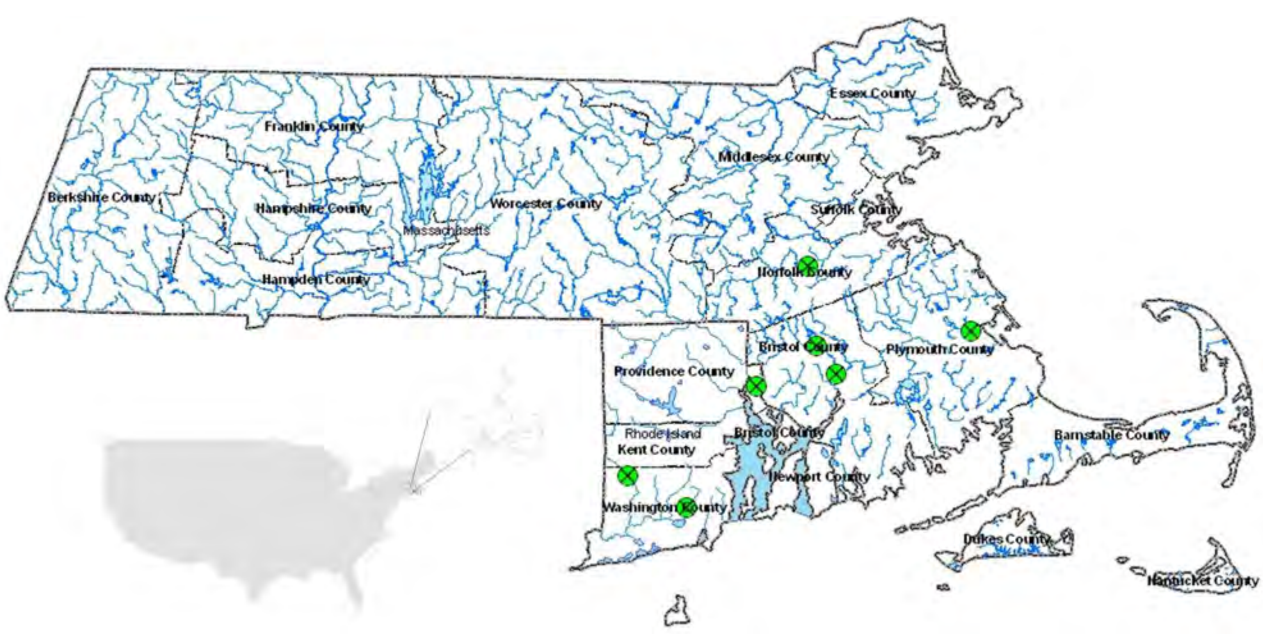
Description of study area

The study area (fig. 1) for this technical note is located in southeastern Massachusetts and Rhode Island. The landscape is characterized by low rolling topography and broad lowlands. The climate is temperate/maritime, with average annual precipitation ranging from approximately 48 to 50 inches per year (Randall 1996). High streamflows generally occur in the spring (March–May) and low streamflows generally occur in late summer (July–September). Areas where the procedures outlined in this technical note are applicable include the low-lying, sandy, forested, "cranberry bog" areas of Bristol, Norfolk, and Plymouth Counties in Massachusetts and Providence, and Washington Counties in Rhode Island.

The bog areas in southeastern Massachusetts and Rhode Island have drainage areas consisting of relatively low relief landscapes or low topographic relief underline by highly permeable loamy sands and organic (peat and muck) soils that are covered predominately by forest. For the four gaged basins examined in Massachusetts, the average basin slopes range from 0.95 to 1.83 percent; sand and gravel surficial deposits cover from 56.5 to 95.7 percent of the land area; and forested lands cover from 43.7 to 63.5 percent of the drainage areas.

Surficial deposits that overlie bedrock in southeastern Massachusetts and Rhode Island were deposited predominantly during the last glacial period, with recent floodplain alluvial deposits dissecting and overlying the older glacial deposits. Surficial glacial deposits are classified as either till (unsorted or poorly sorted, unstratified mixture of clay, silt, sand, gravel, cobbles, and boulders deposited by glaciers) or stratified deposits (glaciofluvial deposits), which includes sands and gravels, and deposits of floodplain alluvium (Bent et al. 2006). In southeast Massachusetts and Rhode Island, the surficial geology consists almost entirely of stratified glacial and recent alluvial deposits (Simcox (1992); Ries (1994a); Armstrong et al. (2008)).

Figure 1 Location of study area in relation to the United States and Massachusetts



Streamflow characteristics are greatly influenced by the local soils and surficial geology. The high hydraulic conductivity and storage of the surficial sands and gravels, combined with the low topographic relief, typically cause rivers in bog areas to have higher baseflows and lower runoff rates than rivers draining upland till areas. In these bog areas, surface runoff readily percolates into the ground though porous soils, which acts as a reservoir, eventually flowing back to the channel systems. Runoff characteristically peaks at low magnitudes with long periods of sustained flow. Infiltration and storage are so great in these areas that peak flows are attenuated sometimes by days. Epstein (2002), who studied rivers in the Pine Barrens on the coastal plain of New Jersey, wrote that peak flow typically occurs 2 days after a storm and is the result of augmented groundwater discharge.

In the seven gaged watersheds examined, the time to peak and the time to return to baseflow are longer than the standards assumed for the UH with a 484 PRF. Typical time to peak for the seven gaged watersheds (drainage areas range from 9.59 to 84.3 mi^2) is 35 to 48 hours. The hydrographs base time commonly lasts from 13 to 19 days. Due to the number of rainfall events thoughout the year, particularly in the winter and spring, it is likely for successive long-duration rains to produce "double peak hydrographs," where the second peak may occur anywhere on the recession limb of the first storm. This scenario of storm on storm can produce relatively high peaks from low amounts of additional rainfall due to previously saturated soil conditions.

Therefore, a special (empirical) procedure was developed to determine the timing elements such as time to peak (T_{Peak}) and base time (T_{Base}). The most probable hydrograph shape that results from this set of conditions is one with a long T_{Base} and slow rising peak or long T_{Peak}. Computed ratios of T_{Base}/T_{Peak} for 216 measured storm events indicate the average ratio of T_{Base}/T_{Peak} considering the entire spectrum of storm event return intervals is 12.1 with a standard deviation of 5.0. T_{Base} varies from 7.1 to 17.1 times longer than T_{Peak}. This ratio (T_{Base}/T_{Peak}) is 2.6 to 6.4 times greater than the upland assumption that $T_{Base} = 2.67 \times T_{Peak}$, which is the standard assumption for the UH shape in WinTR–55 and WinTR–20 computer models.

Previous studies

The USDA Soil Conservation Service (SCS) published an interim engineering procedure report: ENG–PROC–MA–19, dated June 19, 1974, which specifically addressed estimating runoff for cranberry (Bog) areas in Plymouth, Barnstable, Bristol, and Norfolk Counties in Massachusetts. The East Technical Service Center (ETSC) recognized that the soil cover of New England bog sites (described as mostly woods on loamy sands), being highly permeable soils with a great deal of "swamp storage" and seepage rates, greatly affected peak discharges. It was concluded that special procedures, not based solely on direct runoff, were required to properly estimate peak discharges. This technical note initially attempted to update the ENG–PROC–MA–19 with updated gage records. However, with the USGS Instantaneous Data Archive (IDA) available over the Internet, the analysis of 15-minute interval runoff hydrographs provided sufficient details to characterize the hydrologic runoff regime to describe peaks, runoff volume, and timing, hence design unit area runoff hydrographs were developed.

The USGS published Water-Supply Paper (WSP) 2214: Estimating Peak Discharges of Small, Rural Streams in Massachusetts (1983). Under Limitations of Method, it is specifically stated that the flood-estimating equations are not applicable in areas influenced by high infiltrations and storage capacities (see Description of Study Area) due to insufficient data. WSP 2214 includes two gages used in this technical note: Neponset River at Norwood, Massachusetts, and Wading River near Norton, Massachusetts. This technical note includes more years of annual peaks (1983–2008), which affects the Log Pearson III (LPIII) distribution. The instantaneous (60-, 30-, and 15-min. interval discharge) data archive, which started in 1990 and continued though 2006, provided measured streamflows sufficient to characterize the runoff in this study area.

Research hydraulic engineers from USDA Agricultural Research Service (ARS) Southeast Watershed Research Laboratory and NRCS National Water and Climate Center published Peak Rate Factors for Flatland Watersheds (2002), which addresses similar watershed characteristics as those found in the southeastern Massachusetts (SEMA) watersheds. The American Society of Agricultural Engineers (ASAE) paper addresses basin and runoff characteristics for defining synthetic UH for watersheds in the southeastern coastal regions of the United States (GA, NC, and FL). Watersheds characterized by low topographic relief, permeable surface soils, and low-gradient drainage networks. The authors note that mean PRF in the upper coastal plain range approximately between the SCS standard PRF of 484 and the SCS alternative UH DELMARVA PRF of 284; the mean PRF for the Florida Flatwoods watershed is 174, which is below the SCS alternative UH DELMARVA PRF of 284. In concluding remarks, the authors indicate that the use of a single regional synthetic UH is not a viable solution for estimating storm runoff response for all watersheds in coastal regions of the Southeastern United States. In looking at the runoff volume distributions under the rising and receding limbs for the SEMA gages, no single runoff volume distribution would represent all of the varied storms studied. Although PRFs for the SEMA gages were not developed in the same manner as performed by Sheridan, Merkel, and Bosch, the SEMA gages exhibit a ~17/83 percent runoff distribution under the rising and receding hydrograph limbs respectively. This distribution would equate to a PRF of 222, which falls between the PRF of the SCS UH DELMARVA (284) and the mean PRF for the Florida Flatwoods watershed (174).

Methods of analyses

To characterize the hydrologic regime (peaks, volumes, timing, duration, and rates), five different methods and three data types were utilized in the analysis. Analysis of annual peak discharges versus probability of annual exceedance relationships are developed using the LPIII distribution and annual peak discharge data. Runoff volumes above baseflow, partitioned under the rising limb and under the receding hydrograph limbs, were analyzed using 15-minute interval discharge data; runoff volumes above baseflow associated to peaks and hence associated to probability of annual exceedance were analyzed using 15-minute discharge data, annual peak discharges, and the LPIII distribution. Rates (cfs/hr) of discharge rise to peak and rates of recession (cfs/hr) from peak to baseflow are analyzed using the 15-minute discharge data, annual peak discharges, and the LPIII distribution. Unit flow duration curves (FDC) were constructed from mean daily discharge data to compare/screen watersheds with similar hydrologic regimes.

Annual peak-flow data

Annual peak-flow data, obtained from the USGS streamflow gaging network provides valuable information on characterizing the frequency of floods for a region. The annual peak flow is defined as the maximum instantaneous flow occurring in a water year (October 1 to September 30). Annual peak-flow data though water year 2008 from seven streamflow gaging stations in southeast Massachusetts and Rhode Island with at least 20 years of record were used to characterize the frequency of floods within the study area. Figure 1 shows the locations of the seven USGS gage stations (green circles marked with an X).

Annual peak discharges were obtained from the USGS Web sites:
http://waterdata.usgs.gov/ma/nwis/sw
http://waterdata.usgs.gov/ri/nwis/sw

Cumulative length of gage records (including 2008) for the seven gages is 338 years; Tenmile River in Providence County, Rhode Island, has the shortest length of record (22 years), Chipuxet River in Washington County, Rhode Island, has 35 years record, Threemile River in Bristol County and Jones River in Plymouth County, Massachusetts, each have 42 years of record, Wood River in Washington County, Rhode Island, has 45 years of record, Neponset River in Norfolk County, Massachusetts, has 69 years of record, while the Wading River in Bristol County, Massachusetts, has the longest length of record of 83 years (table 1). Average record length of the seven stream gages is approximately 48 years.

Annual peak discharge versus probability of annual exceedance relationships were developed from annual peak-flow records using the LPIII distribution and a generalized skew coefficient of 0.70. The LPIII distribution accounts for high and low outliers as well as a generalized station skew. Table 1 lists each gage by gage number, county, stream name, drainage area, years of record, and period of record.

15-minute instantaneous discharge data: runoff hydrograph characteristics

The seven gages selected to represent the study area also have instantaneous discharge (15-, 30-, or 60-min. intervals) data for water years 1990 to 2006 available. A breakdown of record lengths (which gages were recording in 15-, 30- and 60-min. intervals) is presented in table 2. Instantaneous discharge measurements were obtained from the USGS IDA Web site: *http://ida.water.usgs.gov/ida/index_usgs.cfm*

This time-series data was essential for obtaining hydrograph characteristics such as time to peak, base time above baseflow discharge, rates of discharge rise (cfs/hr), rates of discharge recession (cfs/hr), runoff under the hydrograph above baseflow (watershed inches), and distribution of runoff under rising and under receding hydrograph limbs (percent). Hydrograph runoff characteristics were developed from an aggregation of measured discharges and time series from 216 storm events.

For each gage and for each water year, most instantaneous peaks greater than the 1.25-year return interval were selected for analysis. The analysis entailed finding the time and discharge, which represented baseflow for a particular storm and the time at which

Table 1 Seven USGS gages used in regional analysis of southeast Maine and Rhode Island

USGS gage number	County	Station name	Drainage area (mi^2)	Years of record [1/]	Period of annual peak discharges
01117350	Washington	Chipuxet River at West Kingston, RI	9.59	35	1973–2008
01105870	Plymouth	Jones River at Kingston, MA	19.8 (15.7)	42	1967–2008
01105000	Norfolk	Neponset River at Norwood, MA	34.7	69	1940–2008
01117800	Washington	Wood River near Arcadia, RI	35.2	45	1964–2008
01109000	Bristol	Wading River near Norton, MA	43.3	83	1926–2008
01109403	Providence	Ten Mile River Pawtucket Avenue at East Providence, RI	53.1	22	1987–2008
01109060	Bristol	Threemile River at North Dighton, MA	84.3	42	1967–2008

[1/] years of record for annual peak discharges

Table 2 Period of records of instantaneous discharges for the seven USGS gages

USGS gage number	County	Station name	Drainage area (mi^2)	15-minute records	30-minute records	60-minute records
01117350	Washington	Chipuxet River at West Kingston, RI	9.59	1991–2006		
01105870	Plymouth	Jones River at Kingston, MA	19.8 (15.7)	1991–2006		
01105000	Norfolk	Neponset River at Norwood, MA	34.7	1996–2006	1988–1995	
01117800	Washington	Wood River near Arcadia, RI	35.2	1991–2006		
01109000	Bristol	Wading River near Norton, MA	43.3	1996–2006		1988–1995
01109403	Providence	Ten Mile River Pawtucket Avenue at East Providence, RI	53.1	1991–2006		
01109060	Bristol	Threemile River at North Dighton, MA	84.3	1991–2006		

recession discharges returned back to baseflow. The peaked hydrograph event was extracted from the water year time series and replotted as an individual storm event with baseflow discharge at zero hour. Components of the runoff storm hydrograph developed from the 15-minute interval discharge data are: time to peak, base time, runoff volume above baseflow, runoff volume above baseflow under the rising limb to peak, runoff volume above baseflow under the receding limb back to baseflow discharge, and rates of rise (cfs/hr) between specific discharges (1.25-, 1.5-, 2-, 5-, 10-, 25-, 50-, and 100-yr). From the USGS IDA database, 216 storm events were obtained, and runoff characteristics were analyzed where each component is associated to the probability of exceedance associated to the peak discharge of the storm event.

Runoff volume above baseflow versus probability of annual exceedance

The runoff volume above baseflow for each of the 216 storm events was determined by calculating the area under the hydrographs and above the baseflow discharge (Q_{bf}). Incremental runoff volumes were calculated assuming the continuous runoff hydrograph is composed of a series of trapezoids whose base is the time increment (15, 30, or 60 minutes) between consecutive discharge readings. A typical calculation of incremental runoff volume follows:

$$\text{Incremental runoff volume } \left(\text{ft}^3\right) = \frac{1}{2} \times \left(T_{i+1} - T_i\right) \times \left\{\left(Q_{i+1} - Q_{bf}\right) + \left(Q_i - Q_{bf}\right)\right\} \times 3{,}600 \text{ sec/hr}$$

where:

T_i = time in hours at interval i
T_{i+1} = time in hours at next time interval
Q_i = discharge in cfs at time interval T_i
Q_{i+1} = discharge in cfs at time interval T_{i+1}
Q_{bf} = baseflow discharge, cfs

The USGS IDA time-series data (time, discharge) were plotted by water year (0 hour start time synchonized to beginning of water year to midnight on September 30). There were on occasion missing data of the time series records. Missing records were identified and overall cumulative hours were adjusted to be synchonized with calendar dates (end of water year to midnight of September 30 synchonized to cumulative hour 8,760 for nonleap years).

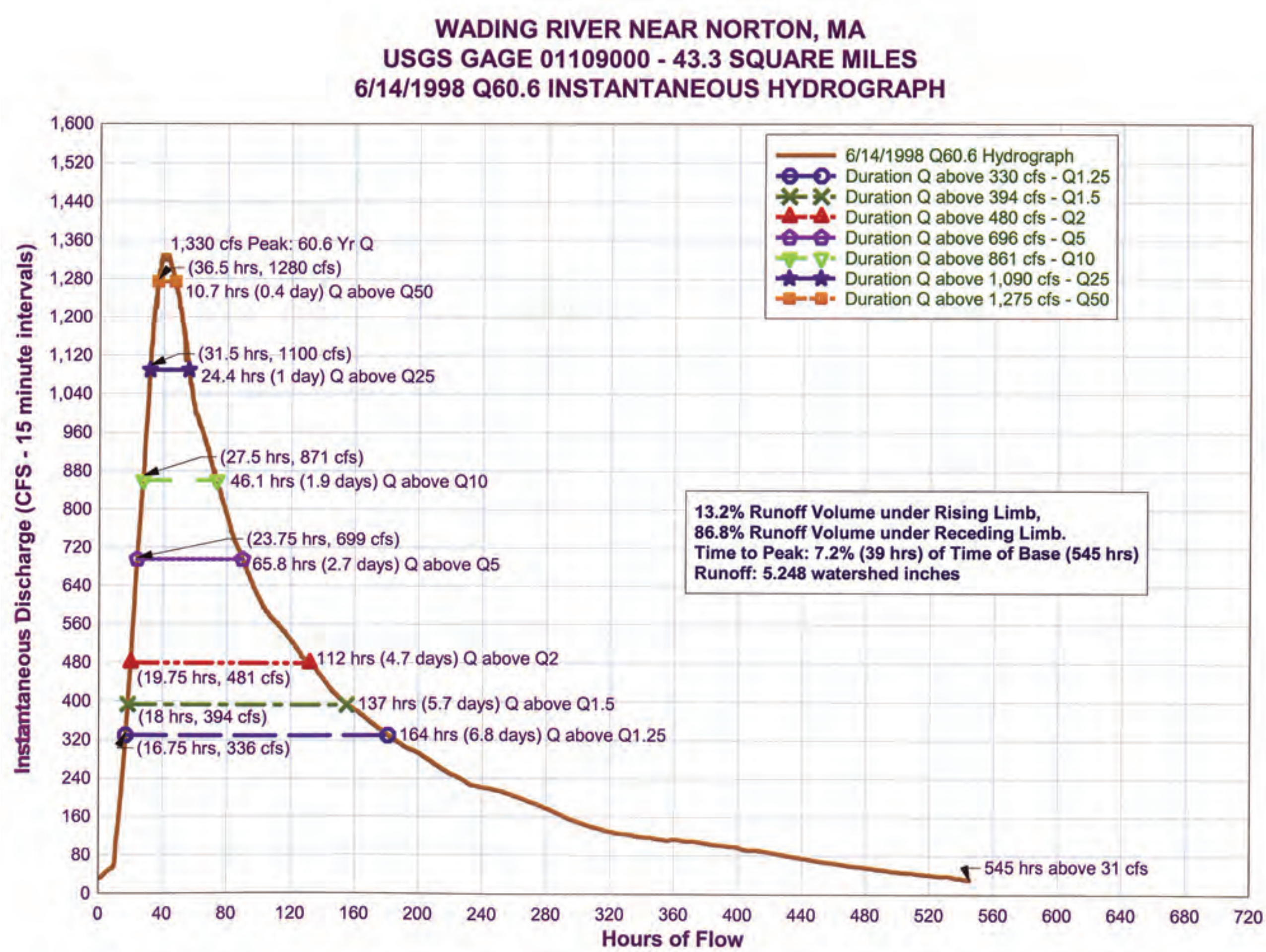
Rate of rise of hydrograph in cubic feet per second per hour and cubic feet per second per square mile per hour

An example calculation of rising discharge rates is illustrated in figure 2. The runoff hydrograph is on the Wading River, whose peak is associated to a ~61-year return interval event. The baseflow at the beginning of the storm was 31 cubic feet per second. The rates of rise (cfs/hr) were calculated based on the nearest 15-minute increments; from baseflow (31 cfs) to ~twice baseflow (63 cfs), from twice baseflow (63 cfs) to ~$Q_{1.25}$ (336 cfs), from ~$Q_{1.25}$ (336 cfs) to $Q_{1.5}$ (394 cfs), from $Q_{1.5}$ to ~Q_2 (481 cfs), from ~Q_2 to ~Q_5 (699 cfs), from ~Q_5 to ~Q_{10} (871 cfs), from ~Q_{10} to ~Q_{25} (1,100 cfs), from ~Q_{25} to ~Q_{50} (1,280 cfs), and finally from ~Q_{50} to Q_{peak} (1,330 cfs). These rates (change in discharge over change in time) in cubic feet per second per hour were then converted to cubic feet per second per square mile per hour by dividing by the drainage area. These rising rates could then be averaged with other gaged drainage areas for similar return intervals. For this storm event the rate of rise from ~Q_{10} to ~Q_{25} is (1,100–871)/(31.5–27.5) = 57.25 cubic feet per second per hour divided by 43.3 square miles equals 1.32 cubic feet per second per square mile per hour. The rate of 1.32 cubic feet per second per square mile per hour is then averaged with all other watershed events that had peaks above the 25-year return interval, specifically for the rate of rise from Q_{10} to Q_{25}.

Mean daily discharge data

Mean daily discharges are recorded at continuous streamflow gaging stations. Mean daily discharge expresses a uniform discharge rate for a 24-hour period (86,400 seconds, midnight to midnight) that is equivalent to the daily runoff volume flowing pass a gaging station for that day. Mean daily discharge is commonly expressed in cubic feet per second, but cubic feet per second-day is the correct unit to express runoff volume as opposed to expressing runoff discharge. One cubic foot per second-day is equivalent to 86,400 cubic feet per day, equivalent to 1.98 acre-feet per day. Mean daily discharges are used to construct FDCs, which express mean daily runoff volumes expected to be equaled or exceeded as a percent of time in a year. A mean daily discharge at one percent annum or one percent of time in a year is the mean daily discharge that could be expected to be equaled or exceeded for only 3.6525 days in an "average" year. Mean daily discharge (cfs-day) expressed as discharge per unit area (csm-day) is a measure of runoff volume per unit (drainage) area. This is a useful measure for illustrating either the variability or uniformity of annual runoff

Figure 2 Determining rates of rise between specific return intervals



volumes between drainage basins. Figure 16 shows all seven FDCs "collapsed" down to cubic feet per second per square mile per day. The eighth curve is an average of the seven unit area FDCs.

Results

Annual peak discharges versus probability of annual exceedance

The results of the LPIII frequency distribution analyses are presented for specific return intervals in table 3; gages are referenced by USGS gage number and drainage area. Return interval (T in years) is defined as the inverse of the probability of annual exceedance (P).

$$T = \frac{1}{P}$$

For example, the return interval **T** for a discharge that has a 4 percent chance of being equaled or exceeded (**P** = 0.04) in any given year is 1/0.04 = 25 years. A common misconception is that a discharge associated to a **T** return interval *occurs at a regular interval every* **T** years. It is more appropriate to say that a discharge with a return interval of 25 years has a one twenty-fifth (4%) probability of being equaled or exceeded in *any* given year.

Runoff volume above baseflow versus probability of annual exceedance

Two hundred and sixteen storm events were analyzed from seven USGS gages recording instantaneous discharges. Peak discharges were divided by the respective drainage area to derive unit-area peak discharge in cubic feet per second per square mile ($ft^3/s/mi^2$). Peak discharge per unit drainage area allows peak discharges of similar annual exceedance probability (%) to be compared across drainage areas. Unit-area peak discharge values for the seven gages are listed and sorted by return intervals. Averaged cubic feet per second per square mile values and runoff volumes are separated into 18 ranges of return interval (table 4). For example, there are 19 events of unit-area peaks (csm) within return intervals ranging from 1.30 years to 1.39 years that were averaged and plotted at the mean value: 9.31 cubic feet per second per square mile corresponding to an average return interval of 1.34 years or 100/1.34 = 74.6 percent probability. For the more frequent storms (small return intervals), there are a sufficient number of events to average and obtain a good representation for the interval being averaged. As the return interval increases (probability decreases), especially above the 6-year return interval, the number of storms representing the interval drops to four or five events (column 1 of table 4).

Values of unit peak discharge (table 4, column 3) were plotted against percent chance exceedance (table 4, column 4) to produce figure 3. The paired points were curve-fit with a first order least-squares regression routine (r^2 = 0.99). Unit peak discharges from the trend line were determined at specific exceedance probabilities and are shown in table 5, column 2. Similarly, aver-

Table 3 Log Pearson Type III peak discharges for the seven USGS gages of table 1

USGS gage number	Contributing drainage area	Log Pearson Type III frequency distribution					
		2-year (50% chance)	5-year (20% chance)	10-year (10% chance)	25-year (4% chance)	50-year (2% chance)	100-year (1% chance)
	mi^2	cfs	cfs	cfs	cfs	cfs	cfs
01117350	9.59	108	163	207	270	323	382
01105870	15.7	208	294	355	436	498	563
01105000	34.7	391	580	741	985	1,193	1,432
01117800	35.2	432	609	741	916	1,060	1,209
01109000	43.3	480	696	861	1,090	1,275	1,474
01109403	53.1	754	1,089	1,342	1,690	1,971	2,271
01109060	84.3	1,050	1,578	1,951	2,435	2,827	3,221

Table 4 Averaged unit peak discharge and runoff volume by averaged return interval

# of storms	Return intervals for averaging unit peaks and runoff volumes	Unit peak discharge	Average return interval (% chance exceedance) of columns 1 and 2	Runoff volume above baseflow
	Years	cfs/mi^2	RI Year (%)	Watershed inches
(column 1)	(column 2)	(column 3)	(column 4)	(column 5)
21	1.18 yr Q to 1.29 yr Q	8.35	1.24 (80.6%)	0.905
19	1.30 yr Q to 1.39 yr Q	9.31	1.34 (74.6%)	1.151
17	1.40 yr Q to 1.49 yr Q	9.65	1.45 (68.9%)	1.377
20	1.50 yr Q to 1.59 yr Q	10.10	1.54 (64.9%)	1.283
14	1.60 yr Q to 1.69 yr Q	10.76	1.65 (60.6%)	1.223
11	1.70 yr Q to 1.79 yr Q	10.80	1.75 (57.1%)	1.270
12	1.80 yr Q to 1.89 yr Q	11.19	1.85 (54.0%)	1.558
6	1.90 yr Q to 2.00 yr Q	12.03	1.95 (51.3%)	1.810
23	2.01 yr Q to 2.50 yr Q	12.60	2.27 (44.0%)	1.563
18	2.51 yr Q to 3.00 yr Q	14.32	2.77 (36.1%)	1.870
17	3.01 yr Q to 4.00 yr Q	16.00	3.49 (28.6%)	2.120
11	4.01 yr Q to 5.00 yr Q	17.27	4.53 (22.1%)	1.697
6	5.01 yr Q to 6.00 yr Q	18.43	5.38 (18.6%)	2.213
4	6.01 yr Q to 8.00 yr Q	19.32	7.01 (14.3%)	2.325
5	8.01 yr Q to 10.0 yr Q	21.83	9.03 (11.1%)	2.959
5	10.1 yr Q to 15.0 yr Q	24.47	12.55 (7.97%)	3.677
2	15.1 yr Q to 25 yr Q	24.63	18.94 (5.28%)	2.937
5	25.1 yr Q to 75 yr Q	32.78	46.39 (2.16%)	4.883
216 total		r^2 = 0.994 for Q (csm) vs. RI		r^2 = 0.917 for Q (in) vs. RI

Figure 3 Unit-peak discharge (csm) vs. probability of annual exceedance (%)

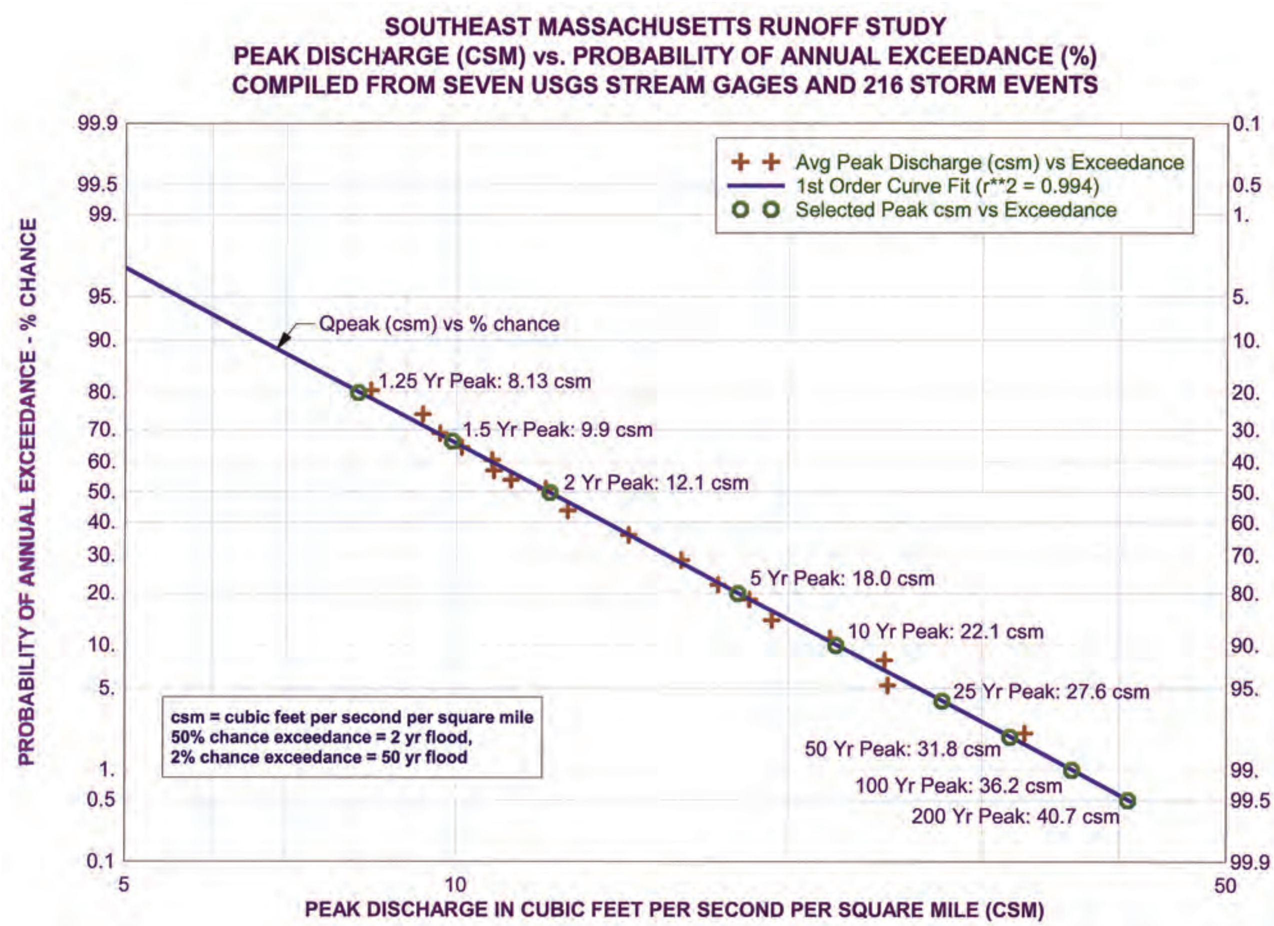


Table 5 Curve–fit values of unit-peak discharge and runoff volume above baseflow by return interval

Return interval (years) and probability of exceedance (percent) Column 1	Unit peak discharge (cfs/mi² or csm) Column 2 (from fig. 3)	Runoff volume above baseflow (watershed in) Column 3 (from fig. 4)	Averaged unit baseflow prior to storm (cfs/mi² or csm) Column 4
1.25 yr = 80% chance	8.13	0.95	1.65
1.5 yr = 66.7% chance	9.9	1.18	2.00
2.0 yr = 50% chance	12.1	1.50	2.45
5 yr = 20% chance	18.0	2.37	3.75
10 yr = 10% chance	22.1	3.00	2.25
25 yr = 4% chance	27.6	3.89	1.45
50 yr = 2% chance	31.8	4.57	1.15
100 yr = 1% chance	36.2	5.26	
200 yr = 0.5% chance	40.7	6.04	
Averaged unit baseflow (csm) all years:			2.31

age runoff volumes (table 4, column 5) were plotted against percent chance exceedance (table 4, column 4) to produce figure 4. The paired points were curve-fit with a first order least-squares regression routine ($r^2 = 0.91$) and runoff volumes determined from the least-squares trend line at specific exceedance probabilities are shown in table 5, column 3.

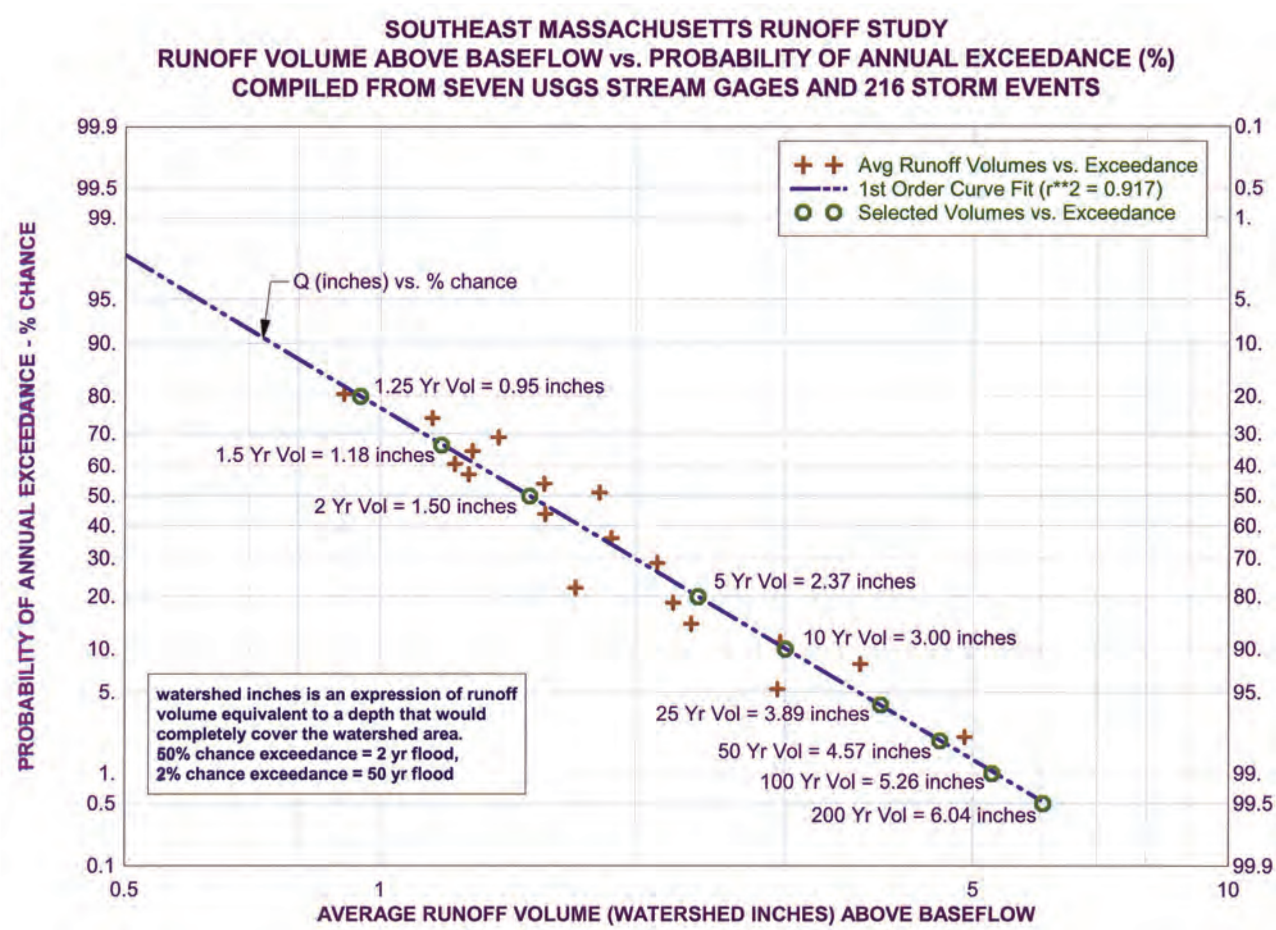
Values of unit peak discharge (fig. 3) and average runoff volumes (from fig. 4) determined from their respective least-squares trend lines at specific exceedance probabilities are summarized in table 5, columns 2 and 3 respectively. These values were used to construct the shapes of the unit-area design runoff hydrographs. Engineers performing a water management design for a cranberry bog would select corresponding unit peak discharges and runoff volumes for the desired probability of exceedance from table 5.

Unit-area baseflows were averaged within the return interval ranges shown in table 4. Averaged unit baseflows were plotted against percent chance exceedance, but the paired points did not produce a linear correlation on log-probability paper. Table 5, column 4 shows unit baseflow values at selected percent chance exceedances. It is interesting to note, empirically, that the 5-year storm or flood with a 20 percent chance is the most likely to have the largest baseflow prior to the flood event. The empirical weighted average unit baseflow regardless of return interval is 2.31 cubic feet per second per square mile.

Hydrograph characteristics—Rate of rise of hydrograph in cubic feet per second per hour and cubic feet per second per square mile per hour from baseflow to peak discharge

Determination of the time elements—time to peak (T_{Peak}) and base time (T_{Base}) of a hydrograph—were difficult to quantify based on drainage area as the independent variable; so, the time element is addressed indirectly by calculating average rates of discharge rise to peak and recession. These rates (slopes of the rising hydrograph limbs) have units of cubic feet

Figure 4 Runoff volume (watershed inches) above baseflow vs. probability of annual exceedance (%)



per second per square mile per hour. The number of storms analyzed varied from 21 to 43 storm events per gage across all return intervals. To compare and average rates for all storms with a similar probability of exceedance across drainage areas, discharge rates in cubic feet per second per hour were normalized to discharge rates in cubic feet per second per square mile per hour by dividing rising discharge rates by drainage area. Table 6 shows average rising discharge rates (csm/hr) for the major return intervals in years.

Hydrograph characteristics—time of baseflow in hours related to time of peak

Based on the results of the 216 storm events, the average ratio of base time to time to peak (T_{base}/T_{peak}) is 12.1. This ratio was applied in the construction of base times for all unit area design hydrograph return intervals.

Hydrograph characteristics—runoff volume distributions under rising and receding limbs

Averaged runoff volume distributions by selected return intervals are presented in table 7. Column 3 shows the percent of runoff volume under the rising

Table 6 Rates of runoff hydrograph rise in csm/hr by return interval (years)

Rate of rise—rising limb: csm/hr	Q at return interval (1) rising to Q at return interval (2)	Time to rise—hr	Cumulative time to peak—hr
0.10	0.5 csm to 1.0 csm (Q_{bf} to 2x Q_{bf})	5.0	5.0
0.15	1.0 csm to 2.0 csm (2x Q_{bf} to 4x Q_{bf})	6.67	11.67
0.20	2.0 csm to 4.0 csm (4x Q_{bf} to 8x Q_{bf})	10.0	21.67
0.60	4.0 csm to 8.13 csm (8x Q_{bf} to 1.25 yr RI)	6.88	28.55
0.70	8.13 csm to 9.9 csm (1.25 yr RI to 1.5 yr RI)	2.53	31.08
0.90	9.9 csm to 12.1 csm (1.5 yr RI to 2 yr RI)	2.44	33.52
1.40	12.1 csm to 18.0 csm (2 yr RI to 5 yr RI)	4.21	37.73
2.10	18.0 csm to 22.1 csm (5 yr RI to 10 yr RI)	1.95	39.68
3.00	22.1 csm to 27.6 csm (10 yr RI to 25 yr RI)	1.83	41.51
3.20	27.6 csm to 31.8 csm (25 yr RI to 50 yr RI)	1.31	42.82
3.40	31.8 csm to 36.2 csm (50 yr RI to 100 yr RI)	1.29	44.11
4.20	36.2 csm to 40.7 csm (100 yr RI to 200 yr RI)	1.07	45.18

Table 7 Runoff volume distributions under rising and receding hydrograph limbs

# of storms Col. 1	Return interval intervals Col. 2	% runoff volume under rising limb Col. 3	% runoff volume under receding limb Col. 4
59	1.18 to 1.50 yr	17.3	82.7
63	1.50 to 2.0 yr	17.2	82.8
59	2.0 to 4.0 yr	16.0	84.0
29	3.0 to 5.0 yr	16.5	83.5
16	5 to 10 yr	18.0	82.0
7	10 to 25 yr	17.0	83.0
5	25 to 50 yr	21.5	78.5
2	50 to 100 yr	18.1	81.9
216	**All years**	**17.1**	**82.9**

hydrograph limb (baseflow to peak discharge), and column 4 shows the percent of runoff volume under the receding hydrograph limb (peak to baseflow discharge). The runoff volume distributions represent the most probable hydrograph shape for the selected return intervals. Runoff distributions are shown in case there is a need to construct a runoff hydrograph at a specific return interval not provided (i.e., a 40-year event), these percentages can be used as guidelines. Note that the number of storms averaged for runoff distributions between the 2- and 5-year return intervals may have been averaged twice because of overlapping (2- to 4-year and 3- to 5-year) return intervals. Averaged runoff volume distributions varied from a 16/84 (16% rising/84% receding) distribution to a 21.5/78.5 distribution. In constructing the unit-area design runoff hydrographs, the overall average distribution of 17.1/82.9 was chosen to represent all return intervals.

Hydrograph characteristics—Hydrograph recession rates in cubic feet per second per hour and cubic feet per second per square mile per hour from peak discharge down to baseflow discharge

Time of recession is based on curve-fit recession rates from peak discharge to baseflow. Hydrograph recession limbs were plotted in t (hr) versus Q (cfs) on logarithmic scales and curve fit using a first-order least squares routine. The negative slope of the best fit linear equation is the exponent of the power relationship

$$Q(t) = T_O \times t^{-\text{slope}}$$

where

Q(t)	=	discharge at time t
T_O	=	peak discharge Q_{Peak} at time T_{Peak}
–slope	=	slope of the linear power relation

Figure 5 shows the Ten Mile River hydrograph recession limb plotted on logarithmic scale, and figure 6 shows the same recession on arithmetic scale. These figures exemplify the best-fit exponential decay rate satisfactorily matches the recession rate.

Hydrograph characteristics—Design unit-area runoff hydrographs

In developing the design unit-area runoff hydrographs, the following criteria were met in the order shown:

1. Rates of rise from 0.5 cubic feet per square mile to unit-area peak discharge were standardized according to table 6.
2. Match unit-area peak discharge (csm) for every return interval according to figure 3, also summarized in table 5, column 2.
3. Match runoff volume (watershed inches above baseflow) for every return interval in accordance to figure 4, also summarized in table 5, column 3.
4. Runoff volume under the rising hydrograph limb equals ~17.1 percent of total runoff volume (above baseflow) from table 5. To satisfy this requirement, the unit area maximum peak discharge was extended in time to match a 17.1 percent runoff volume under the rising limb. These unit-area hydrographs are flat topped, which is not an unreasonable shape in comparison to actual runoff hydrographs.
5. The ratio of base time to time to peak is approximately 12.1 for all return intervals.
6. Runoff volume under the receding hydrograph limbs is approximately 82.9 percent of total runoff volume above baseflow from table 5. To satisfy this requirement, the receding limb is modeled as an exponential decay rate, and the exponent of the recession limb was iterated such that 82.9 percent runoff volume is under the receding limb within the specified time after peak (T_{Base}–T_{Peak}). At this point, discharge may not equal baseflow value at beginning of storm, and the hydrographs could be extended and more runoff could be calculated, but in trying to match peak, volume, distribution, and timing, it is not possible to match all constraints and still have a standardized design UH for the range of return intervals—the hydrograph tail being the least important hydrologic element in design is the least constrained. Many of the storms in the database were storm on storm, where runoff rose during the previous storm's recession producing a double peak. Table 5 shows averaged unit baseflow (csm) prior to storm event. It appears that many of the 5-year peaks may have been a result of storm on storm, as the 5-year return interval is likely to have the largest unit baseflow prior to the 5-year peaks. So, extending the design unit-area runoff hydrographs base time back to original baseflow conditions, it is likely a second storm will develop before these conditions are met.

Results: Mean daily discharge and unit-area flow duration curve

Average annual runoff volumes are useful for estimating long-term watershed yields for reservoir studies, fish habitat studies, sediment routing, and geomorphic analysis. Seven FDCs were constructed from USGS records of daily mean discharges. Daily mean discharges in cubic feet per second-day are plotted versus the per-

Figure 5 Hydrograph recession limb and best fit curve on logarithmic scale

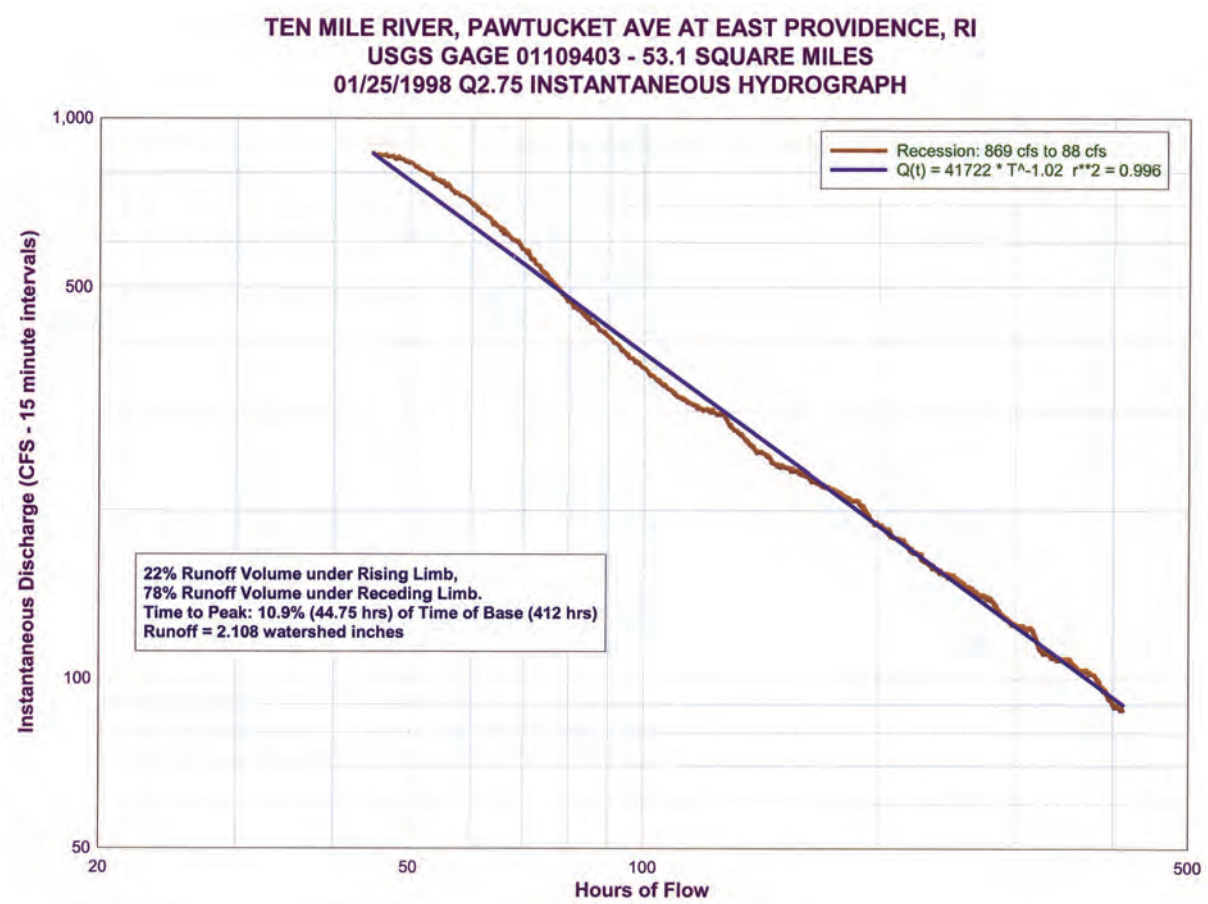
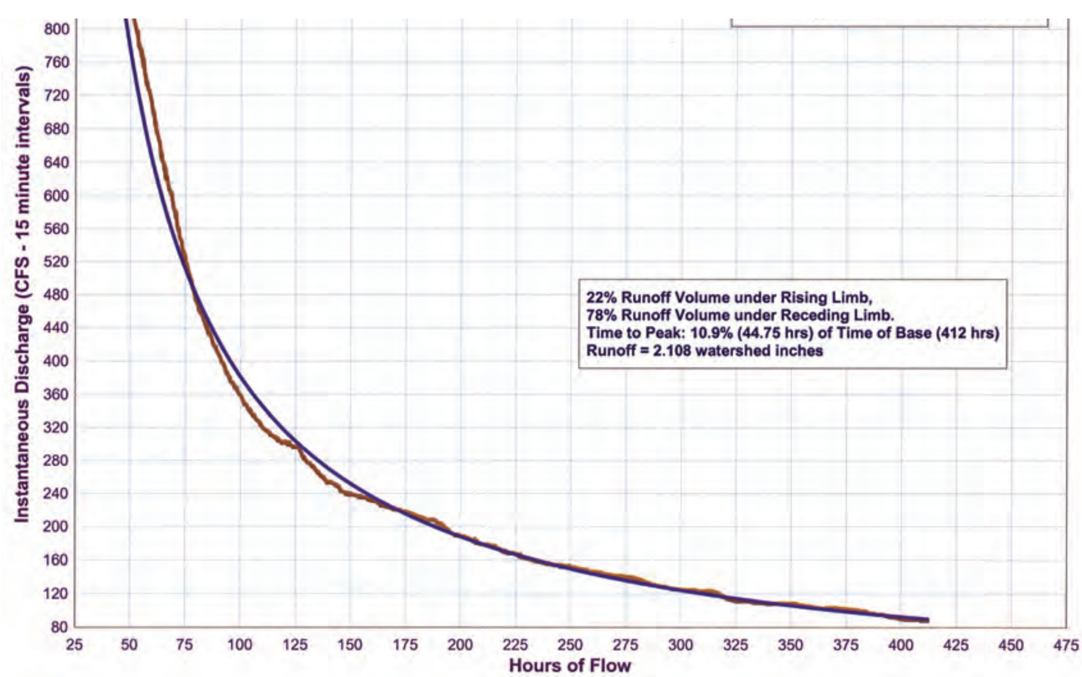


Figure 6 Hydrograph recession limb and best fit curve on arithmetic scale



cent of time (in a year) the daily mean discharge is expected to be equaled or exceeded. The FDC expresses the distribution of annual runoff volume expected in an "average year" assuming future rainfall/runoff conditions will be similar to the period of record used to construct the FDC. For the study area, more than 358 years and 131,703 days of daily mean discharges were used to construct the seven FDCs. The FDCs of various watersheds within the same hydro-physiographic province should parallel each other as shown in figure 16. Parallel curves indicate that these watersheds runoff respond in a similar manner with respect to drainage area and support using a regional analysis methodology.

Figure 16 shows eight unit-area FDCs, one developed for each gage and a regional unit-area FDC developed from averaging the seven gaged unit-area FDCs. Unit-area runoff volumes are expressed in cubic feet per-second per square mile-day, derived by dividing mean daily runoff volumes (cfs-day) by drainage area. At each specific interval of time (99% of year, 95% of year, 90% of year, etc.), the seven unit-area flow values are averaged and plotted (circle plot symbol) to develop the regional unit-area FDC. The regional (averaged) unit-area flow values are listed in table 17.

These unit-area runoff values could be used to estimate average annual or mean daily runoff volumes for ungaged drainages within the study area. The example (table 19) shows how to derive average annual runoff volumes from the regional unit-area FDC.

By inspection of figure 16, low runoff volumes exceeded more than 50 percent of the year are more variable than high runoff volumes exceeded less than 50 percent of the year. Caution is advised if the construction of a FDC is to determine minimum flows for fish passage for an ungaged area. Minimum flows to determine fish passage also take into account the chonological order of minimum flows (successive days), whereas FDC are constructed solely on magnitude of runoff

Figure 7 The 1.25-year design unit-area runoff hydrograph

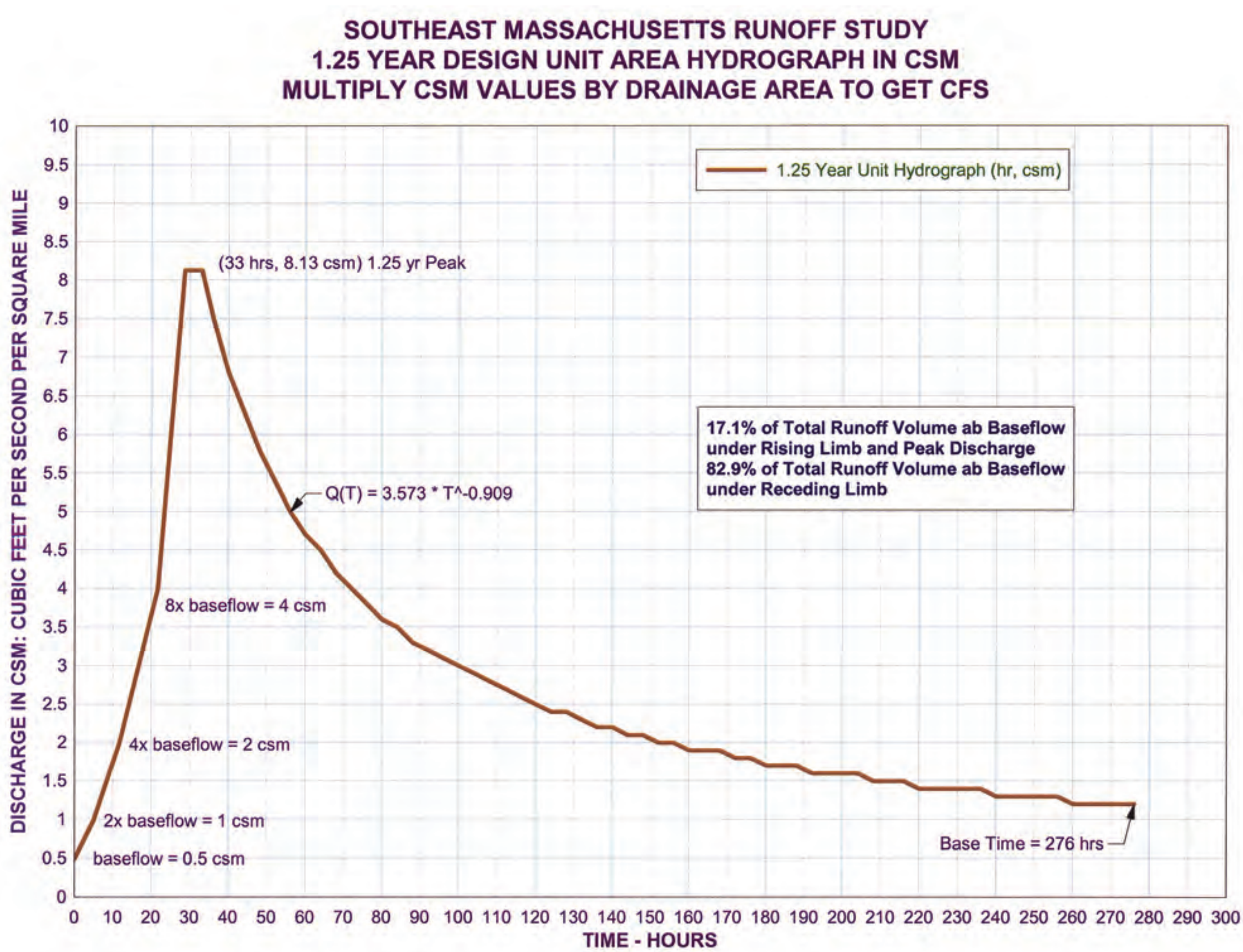


Table 8 1.25 year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	80	3.64	148	2.08	216	1.47
5	1.0	84	3.48	152	2.03	220	1.45
11.7	2.0	88	3.33	156	1.98	224	1.43
21.7	4.0	92	3.20	160	1.94	228	1.40
28.6	8.129	96	3.08	164	1.89	232	1.38
33.0	**8.13**	100	2.97	168	1.85	236	1.36
36	7.51	104	2.86	172	1.81	240	1.34
40	6.83	108	2.77	176	1.78	244	1.32
44	6.26	112	2.68	180	1.74	248	1.30
48	5.78	116	2.59	184	1.70	252	1.28
52	5.38	120	2.51	188	1.67	256	1.26
56	5.03	124	2.44	192	1.64	260	1.25
60	4.72	128	2.37	196	1.61	264	1.23
64	4.45	132	2.31	200	1.58	268	1.21
68	4.21	136	2.24	204	1.55	272	1.20
72	4.00	140	2.19	208	1.53	276	1.18
76	3.81	144	2.13	212	1.50		

Figure 8 The 1.5-year design unit-area runoff hydrograph

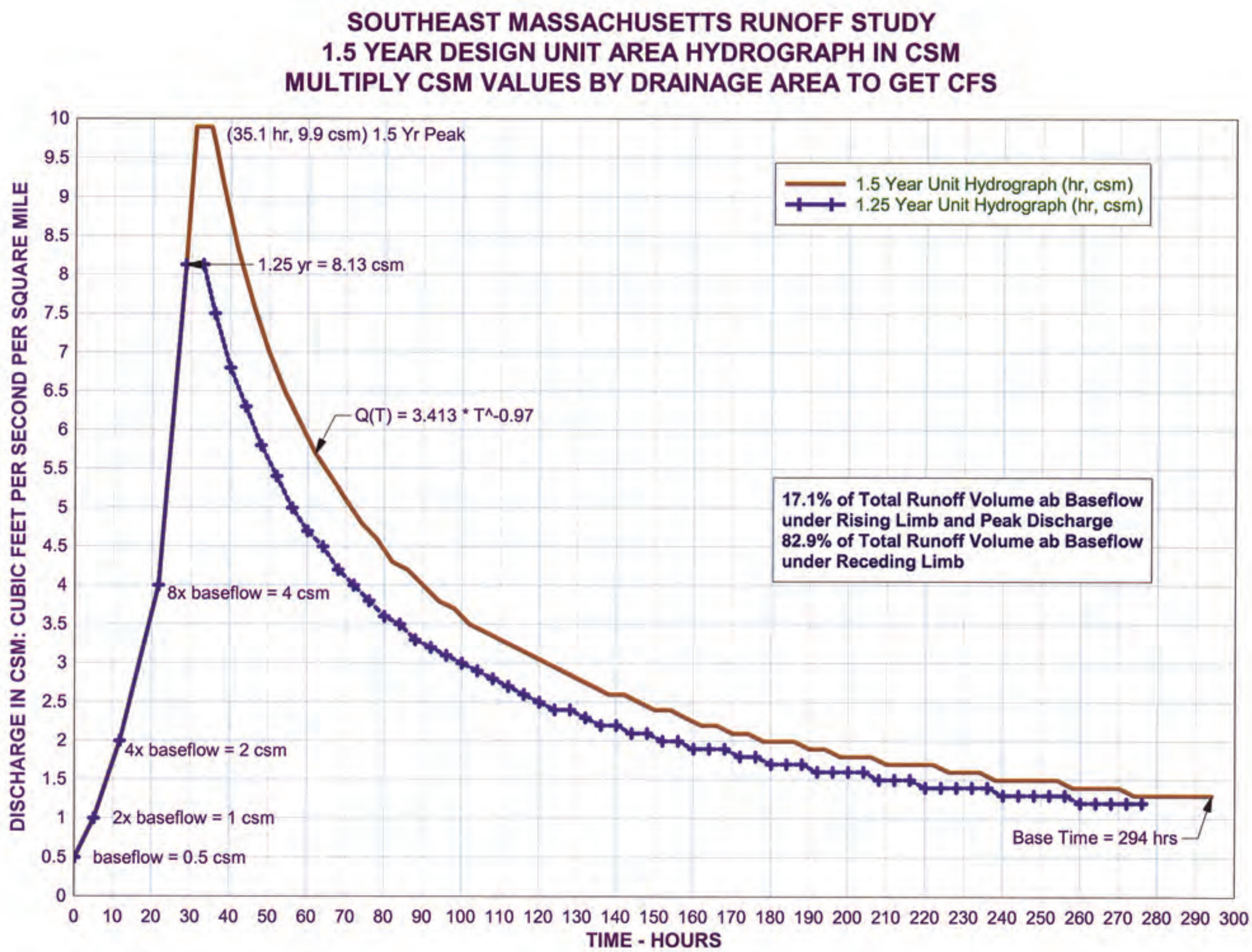


Table 9 1.5-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	82	4.35	158	2.30	234	1.57
5	1.0	86	4.15	162	2.25	238	1.55
11.7	2.0	90	3.97	166	2.19	242	1.52
21.7	4.0	94	3.81	170	2.14	246	1.50
28.6	8.13	98	3.66	174	2.10	250	1.47
31.1	9.89	102	3.52	178	2.05	254	1.45
35.1	**9.90**	106	3.39	182	2.01	258	1.43
36	9.66	110	3.27	186	1.96	262	1.41
38	9.17	114	3.16	190	1.92	266	1.39
42	8.32	118	3.05	194	1.89	270	1.37
46	7.62	122	2.96	198	1.85	274	1.35
50	7.02	126	2.87	202	1.81	278	1.33
54	6.52	130	2.78	206	1.78	282	1.31
58	6.08	134	2.70	210	1.75	286	1.29
62	5.70	138	2.62	214	1.71	290	1.28
66	5.37	142	2.55	218	1.68	294	1.26
70	5.07	146	2.48	222	1.65		
74	4.80	150	2.42	226	1.63		
78	4.56	154	2.36	230	1.60		

Figure 9 The 2-year design unit-area runoff hydrograph

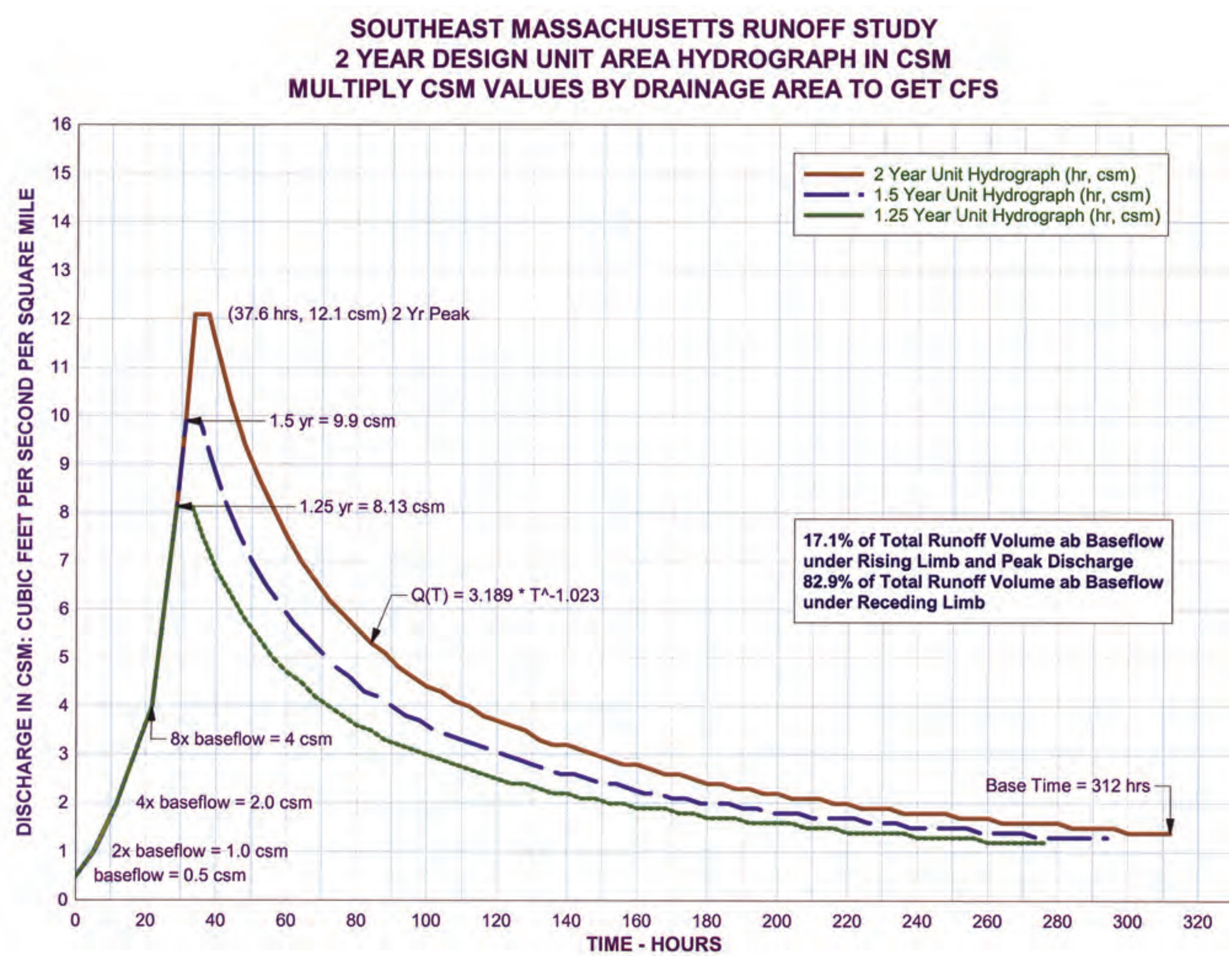


Table 10 2-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	88	5.07	168	2.62	248	1.76
5	1.0	92	4.84	172	2.55	252	1.73
11.7	2.0	96	4.64	176	2.49	256	1.70
21.7	4.0	100	4.45	180	2.44	260	1.67
28.6	8.13	104	4.27	184	2.38	264	1.65
31.1	9.90	108	4.11	188	2.33	268	1.62
33.6	12.09	112	3.96	192	2.28	272	1.60
37.6	**12.10**	116	3.82	196	2.23	276	1.57
40	11.36	120	3.69	200	2.19	280	1.55
44	10.30	124	3.57	204	2.15	284	1.53
48	9.43	128	3.46	208	2.10	288	1.51
52	8.68	132	3.35	212	2.06	292	1.49
56	8.05	136	3.25	216	2.02	296	1.47
60	7.50	140	3.15	220	1.99	300	1.45
64	7.02	144	3.06	224	1.95	304	1.43
68	6.60	148	2.98	228	1.91	308	1.41
72	6.23	152	2.90	232	1.88	312	1.39
76	5.89	156	2.82	236	1.85		
80	5.59	160	2.75	240	1.82		
84	5.32	164	2.68	244	1.79		

Figure 10 The 5-year design unit-area runoff hydrograph

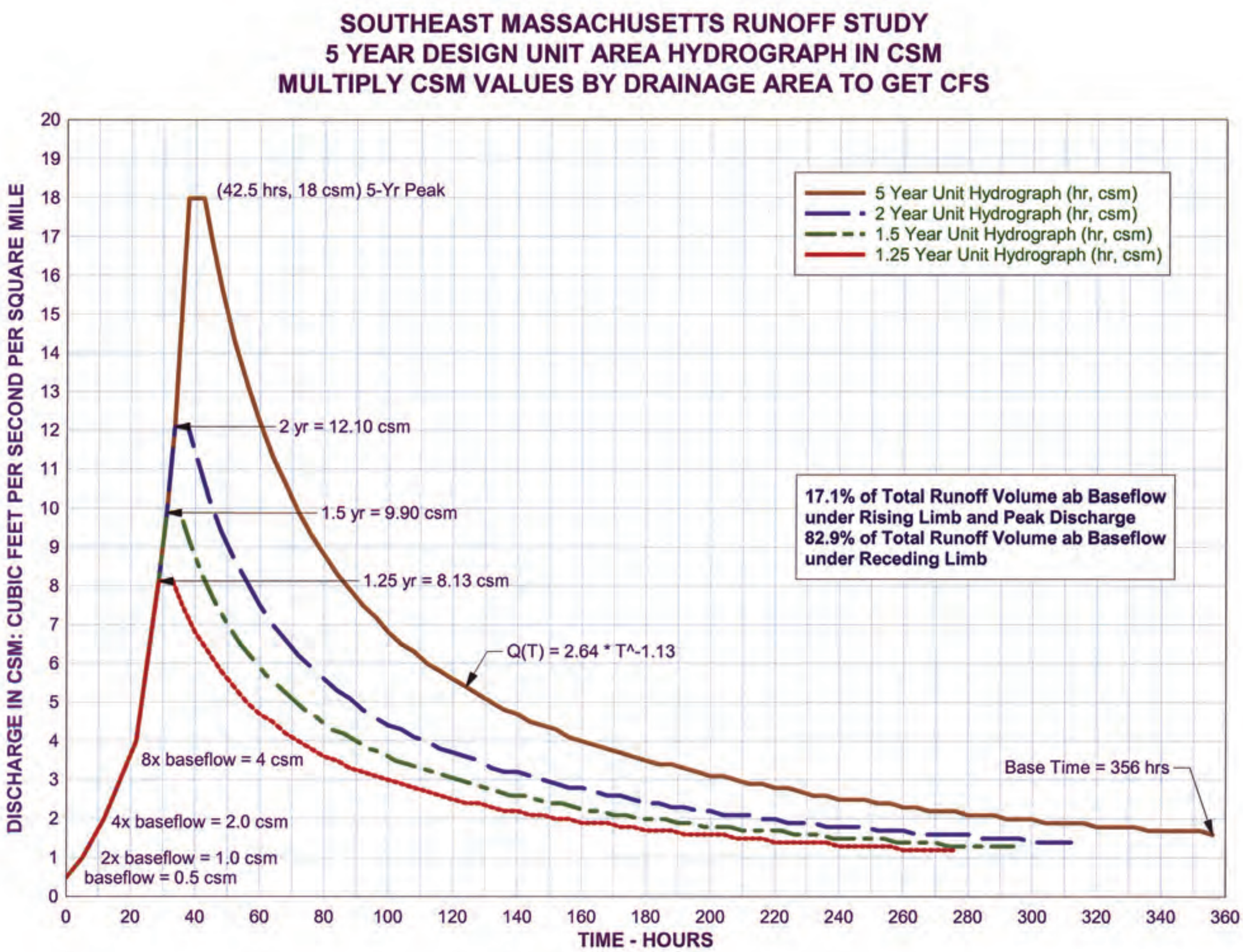


Table 11 5-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time h	Q (csm)	Time (hr)	Q (csm)
0	0.5	96	7.17	184	3.44	272	2.21
5	1.0	100	6.84	188	3.35	276	2.17
11.7	2.0	104	6.55	192	3.28	280	2.14
21.7	4.0	108	6.27	196	3.20	284	2.10
28.6	8.13	112	6.02	200	3.13	288	2.07
31.1	9.90	116	5.79	204	3.06	292	2.04
33.6	12.10	120	5.57	208	2.99	296	2.01
37.8	17.99	124	5.37	212	2.93	300	1.98
42.5	**18.00**	128	5.18	216	2.87	304	1.95
45	16.87	132	5.00	220	2.81	308	1.92
48	15.69	136	4.84	224	2.75	312	1.89
52	14.33	140	4.68	228	2.70	316	1.87
56	13.18	144	4.53	232	2.64	320	1.84
60	12.19	148	4.39	236	2.59	324	1.81
64	11.33	152	4.26	240	2.55	328	1.79
68	10.58	156	4.14	244	2.50	332	1.76
72	9.92	160	4.02	248	2.45	336	1.74
76	9.33	164	3.91	252	2.41	340	1.72
80	8.81	168	3.81	256	2.37	344	1.69
84	8.34	172	3.71	260	2.33	348	1.67
88	7.91	176	3.61	264	2.29	352	1.65
92	7.52	180	3.52	268	2.25	356	1.63

Figure 11 The 10-year design unit-area runoff hydrograph

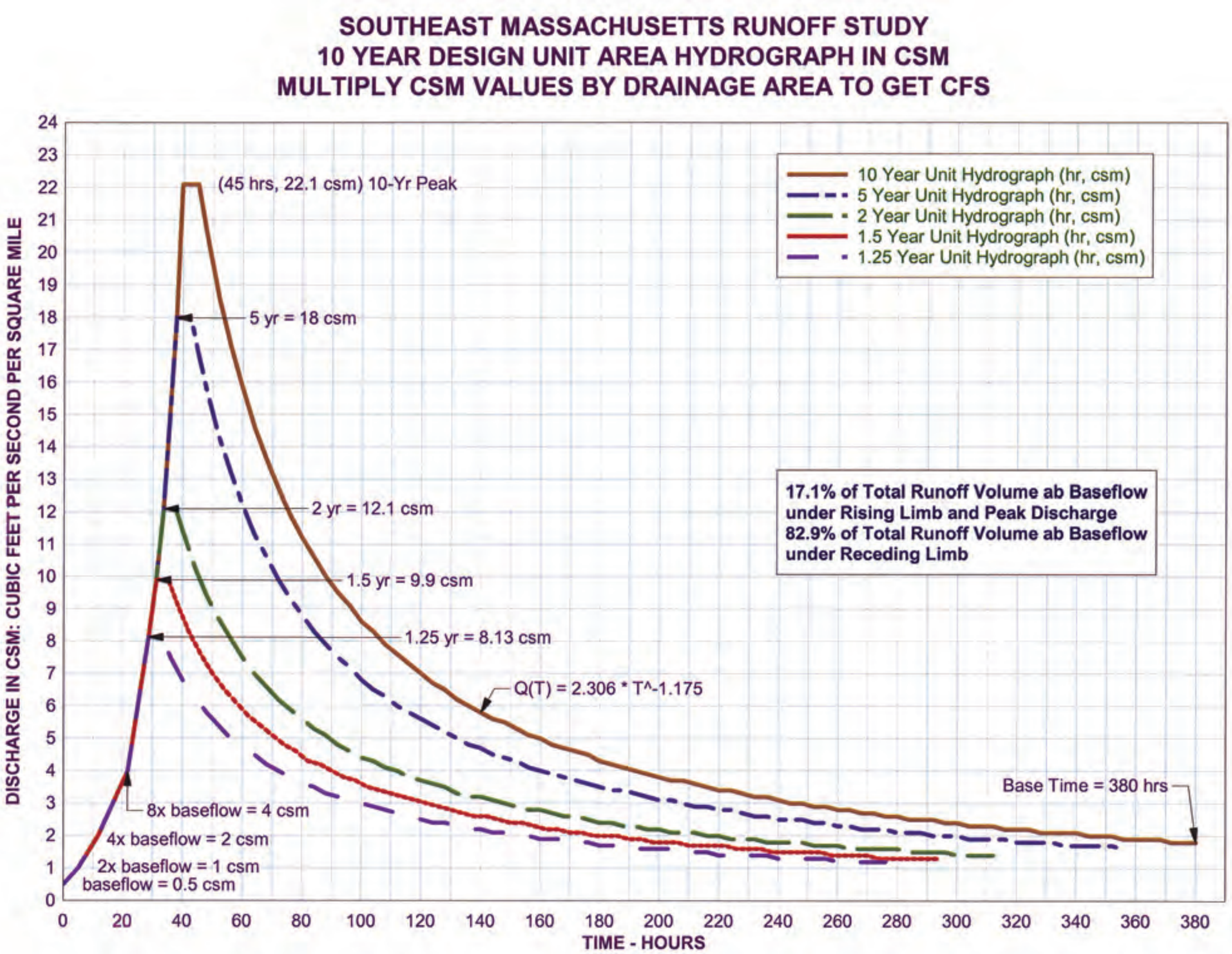


Table 12 10-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	104	8.26	200	3.83	296	2.42
5	1.0	108	7.90	204	3.74	300	2.38
11.7	2.0	112	7.57	208	3.66	304	2.34
21.7	4.0	116	7.26	212	3.58	308	2.31
28.6	8.13	120	6.98	216	3.50	312	2.27
31.1	9.90	124	6.72	220	3.42	316	2.24
33.6	12.10	128	6.47	224	3.35	320	2.20
37.8	18.00	132	6.24	228	3.28	324	2.17
39.7	22.09	136	6.03	232	3.22	328	2.14
45	**22.10**	140	5.82	236	3.15	332	2.11
48	20.49	144	5.63	240	3.09	336	2.08
52	18.65	148	5.46	244	3.03	340	2.05
56	17.09	152	5.29	248	2.97	344	2.03
60	15.76	156	5.13	252	2.92	348	2.00
64	14.61	160	4.98	256	2.87	352	1.97
68	13.61	164	4.84	260	2.81	356	1.95
72	12.72	168	4.70	264	2.76	360	1.92
76	11.94	172	4.57	268	2.72	364	1.90
80	11.24	176	4.45	272	2.67	368	1.87
84	10.61	180	4.33	276	2.62	372	1.85
88	10.05	184	4.22	280	2.58	376	1.82
92	9.54	188	4.12	284	2.54	380	1.80
96	9.07	192	4.02	288	2.50		
100	8.65	196	3.92	292	2.46		

Figure 12 The 25-year design unit-area runoff hydrograph

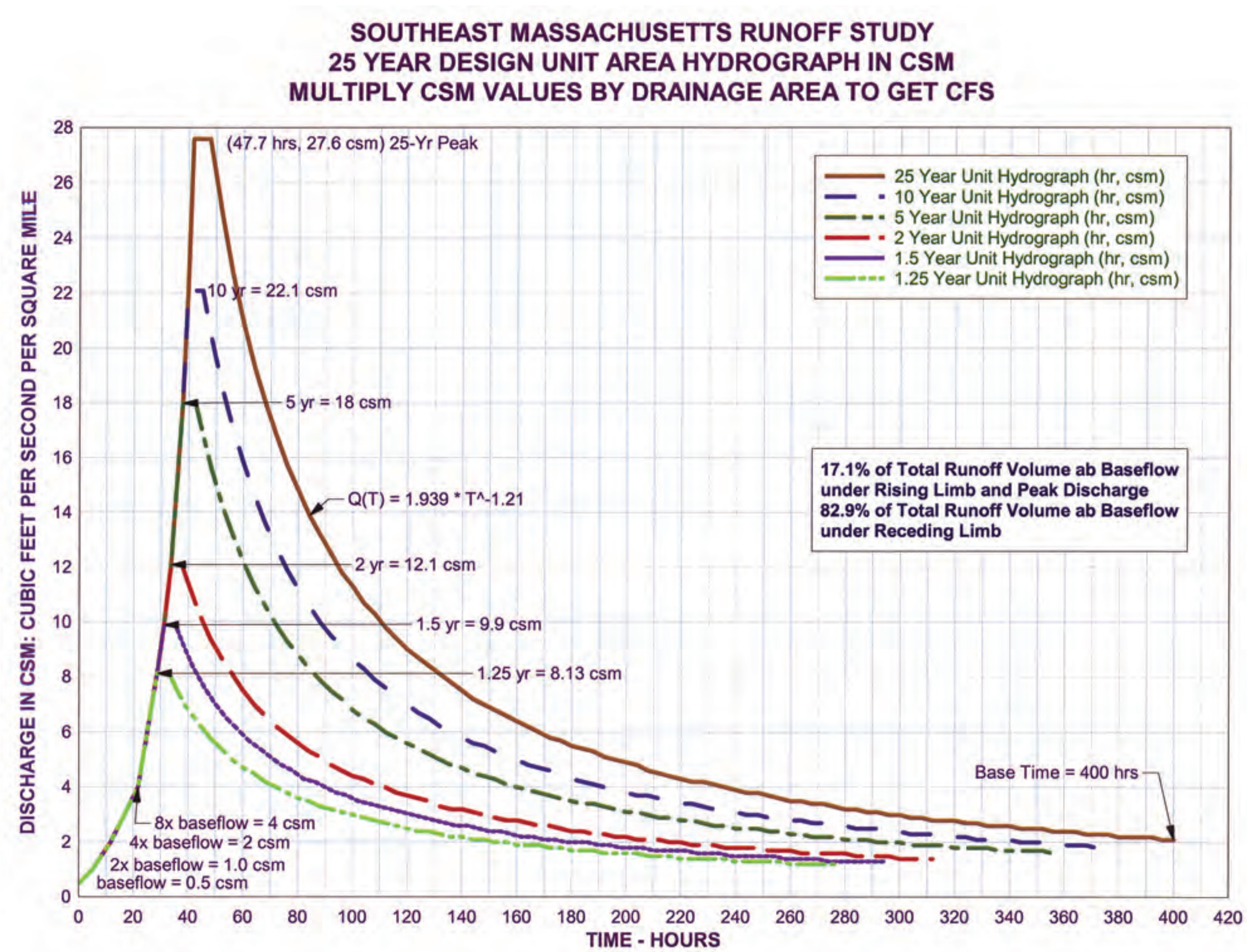


Table 13 25-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hs)	Q (csm)
0	0.5	112	9.83	216	4.44	320	2.76
5	1.0	116	9.42	220	4.34	324	2.72
11.7	2.0	120	9.04	224	4.25	328	2.68
21.7	4.0	124	8.69	228	4.16	332	2.64
28.6	8.13	128	8.36	232	4.07	336	2.60
31.1	9.90	132	8.05	236	3.99	340	2.56
33.6	12.10	136	7.77	240	3.91	344	2.53
37.8	18.00	140	7.50	244	3.83	348	2.49
39.7	22.10	144	7.25	248	3.76	352	2.46
41.6	27.59	148	7.01	252	3.68	356	2.42
47.7	**27.60**	152	6.79	256	3.61	360	2.39
52	24.86	156	6.58	260	3.55	364	2.36
56	22.73	160	6.38	264	3.48	368	2.33
60	20.91	164	6.19	268	3.42	372	2.30
64	19.34	168	6.02	272	3.36	376	2.27
68	17.97	172	5.85	276	3.30	380	2.24
72	16.77	176	5.69	280	3.24	384	2.21
76	15.71	180	5.53	284	3.19	388	2.18
80	14.76	184	5.39	288	3.13	392	2.16
84	13.92	188	5.25	292	3.08	396	2.13
88	13.16	192	5.12	296	3.03	400	2.11
92	12.47	196	4.99	300	2.98	404	2.08
96	11.84	200	4.87	304	2.94	408	2.06
100	11.27	204	4.76	308	2.89	412	2.03
104	10.75	208	4.65	312	2.84	416	2.01
108	10.27	212	4.54	316	2.80	420	1.99

Figure 13 The 50-year design unit-area runoff hydrograph

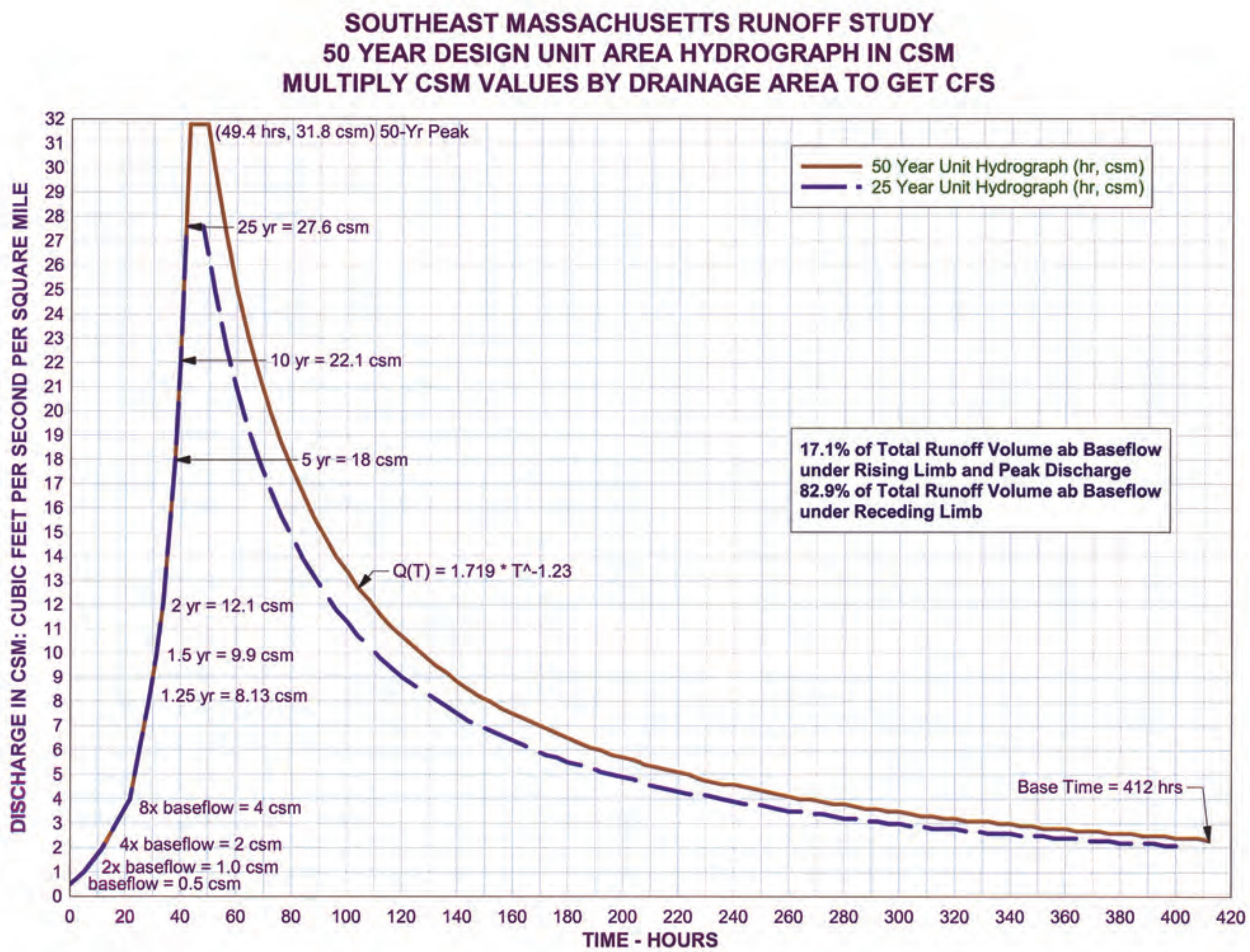


Table 14 50-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	116	11.13	228	4.85	340	2.96
5	1.0	120	10.67	232	4.74	344	2.92
11.7	2.0	124	10.25	236	4.65	348	2.88
21.7	4.0	128	9.86	240	4.55	352	2.84
28.6	8.13	132	9.49	244	4.46	356	2.80
31.1	9.90	136	9.15	248	4.37	360	2.76
33.6	12.10	140	8.83	252	4.29	364	2.73
37.8	18.00	144	8.53	256	4.20	368	2.69
39.7	22.10	148	8.25	260	4.12	372	2.65
41.6	27.60	152	7.98	264	4.05	376	2.62
42.9	31.79	156	7.73	268	3.97	380	2.59
49.4	**31.80**	160	7.49	272	3.90	384	2.55
52	29.86	164	7.27	276	3.83	388	2.52
56	27.25	168	7.06	280	3.76	392	2.49
60	25.04	172	6.86	284	3.70	396	2.46
64	23.13	176	6.66	288	3.64	400	2.43
68	21.46	180	6.48	292	3.58	404	2.40
72	20.01	184	6.31	296	3.52	408	2.37
76	18.72	188	6.14	300	3.46	412	2.34
80	17.58	192	5.99	304	3.40	416	2.31
84	16.55	196	5.84	308	3.35	420	2.29
88	15.63	200	5.69	312	3.30	424	2.26
92	14.80	204	5.56	316	3.24	428	2.23
96	14.04	208	5.43	320	3.19	432	2.21
100	13.36	212	5.30	324	3.15	436	2.18
104	12.73	216	5.18	328	3.10	440	2.16
108	12.15	220	5.06	332	3.05	444	2.14
112	11.62	224	4.95	336	3.01	448	2.11

Figure 14 The 100-year design unit-area runoff hydrograph

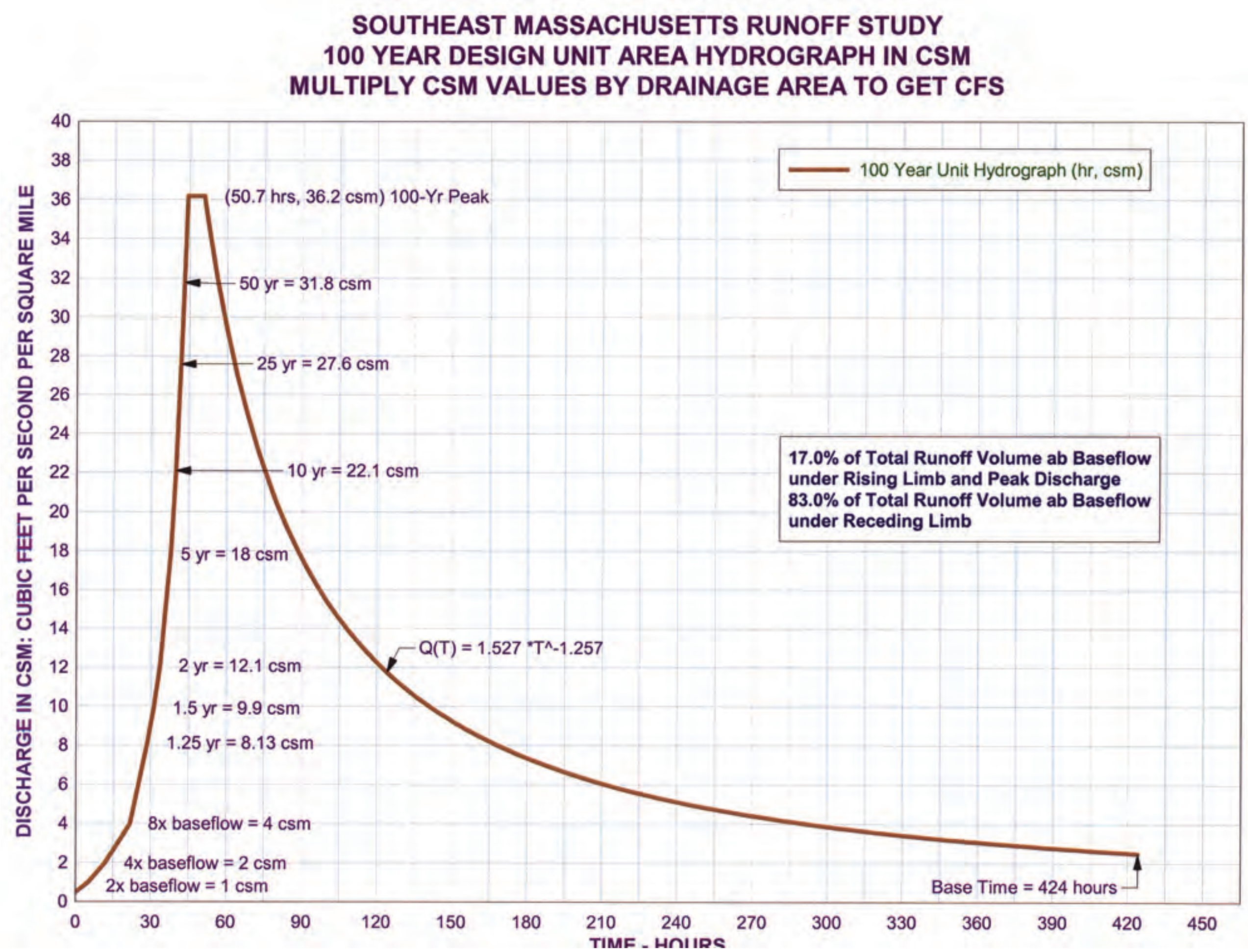


Table 15 100-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	108	13.99	216	5.85	324	3.52
5	1.0	112	13.37	220	5.72	328	3.46
11.7	2.0	116	12.79	224	5.59	332	3.41
21.7	4.0	120	12.26	228	5.47	336	3.36
28.6	8.13	124	11.76	232	5.35	340	3.31
31.1	9.90	128	11.30	236	5.24	344	3.26
33.6	12.10	132	10.87	240	5.13	348	3.21
37.8	18.00	136	10.47	244	5.02	352	3.17
39.7	22.10	140	10.10	248	4.92	356	3.12
41.6	27.60	144	9.75	252	4.82	360	3.08
42.9	31.80	148	9.42	256	4.73	364	3.04
44.2	36.19	152	9.11	260	4.64	368	3.00
50.7	**36.20**	156	8.81	264	4.55	372	2.96
52	35.07	160	8.54	268	4.46	376	2.92
56	31.95	164	8.28	272	4.38	380	2.88
60	29.29	168	8.03	276	4.30	384	2.84
64	27.01	172	7.80	280	4.22	388	2.80
68	25.03	176	7.57	284	4.15	392	2.77
72	23.29	180	7.36	288	4.08	396	2.73
76	21.76	184	7.16	292	4.01	400	2.70
80	20.40	188	6.97	296	3.94	404	2.66
84	19.19	192	6.79	300	3.87	408	2.63
88	18.10	196	6.62	304	3.81	412	2.60
92	17.12	200	6.45	308	3.75	416	2.57
96	16.23	204	6.29	312	3.69	420	2.54
100	15.41	208	6.14	316	3.63	424	2.51
104	14.67	212	5.99	320	3.57		

Figure 15 The 200-year design unit-area runoff hydrograph

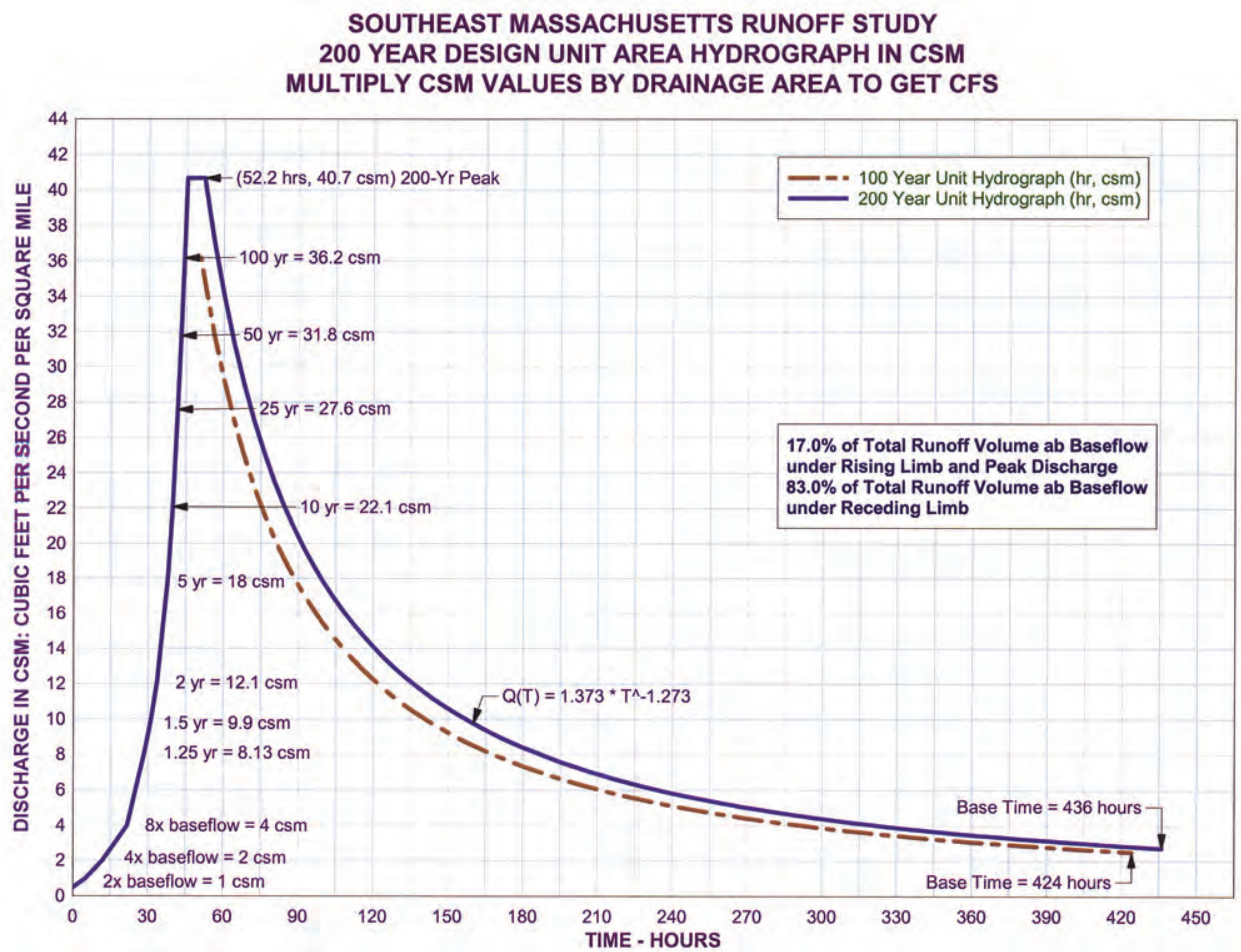


Table 16 200-year unit-area hydrograph ordinates

Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)	Time (hr)	Q (csm)
0	0.5	112	15.40	224	6.37	336	3.80
5	1.0	116	14.73	228	6.23	340	3.75
11.7	2.0	120	14.11	232	6.09	344	3.69
21.7	4.0	124	13.53	236	5.96	348	3.64
28.6	8.13	128	12.99	240	5.84	352	3.58
31.1	9.90	132	12.49	244	5.72	356	3.53
33.6	12.10	136	12.03	248	5.60	360	3.48
37.8	18.00	140	11.59	252	5.49	364	3.43
39.7	22.10	144	11.18	256	5.38	368	3.39
41.6	27.60	148	10.80	260	5.27	372	3.34
42.9	31.80	152	10.44	264	5.17	376	3.30
44.2	36.20	156	10.10	268	5.07	380	3.25
45.3	40.69	160	9.78	272	4.98	384	3.21
52.2	40.70	164	9.48	276	4.89	388	3.17
56	37.22	168	9.19	280	4.80	392	3.13
60	34.09	172	8.92	284	4.71	396	3.09
64	31.40	176	8.66	288	4.63	400	3.05
68	29.07	180	8.42	292	4.55	404	3.01
72	27.03	184	8.19	296	4.47	408	2.97
76	25.23	188	7.97	300	4.39	412	2.93
80	23.63	192	7.75	304	4.32	416	2.90
84	22.21	196	7.55	308	4.25	420	2.86
88	20.93	200	7.36	312	4.18	424	2.83
92	19.78	204	7.18	316	4.11	428	2.79
96	18.74	208	7.00	320	4.05	432	2.76
100	17.79	212	6.84	324	3.98	436	2.73
104	16.92	216	6.67	328	3.92		
108	16.13	220	6.52	332	3.86		

and not on chronology; therefore, FDCs by themselves should not be used for fish passage analysis.

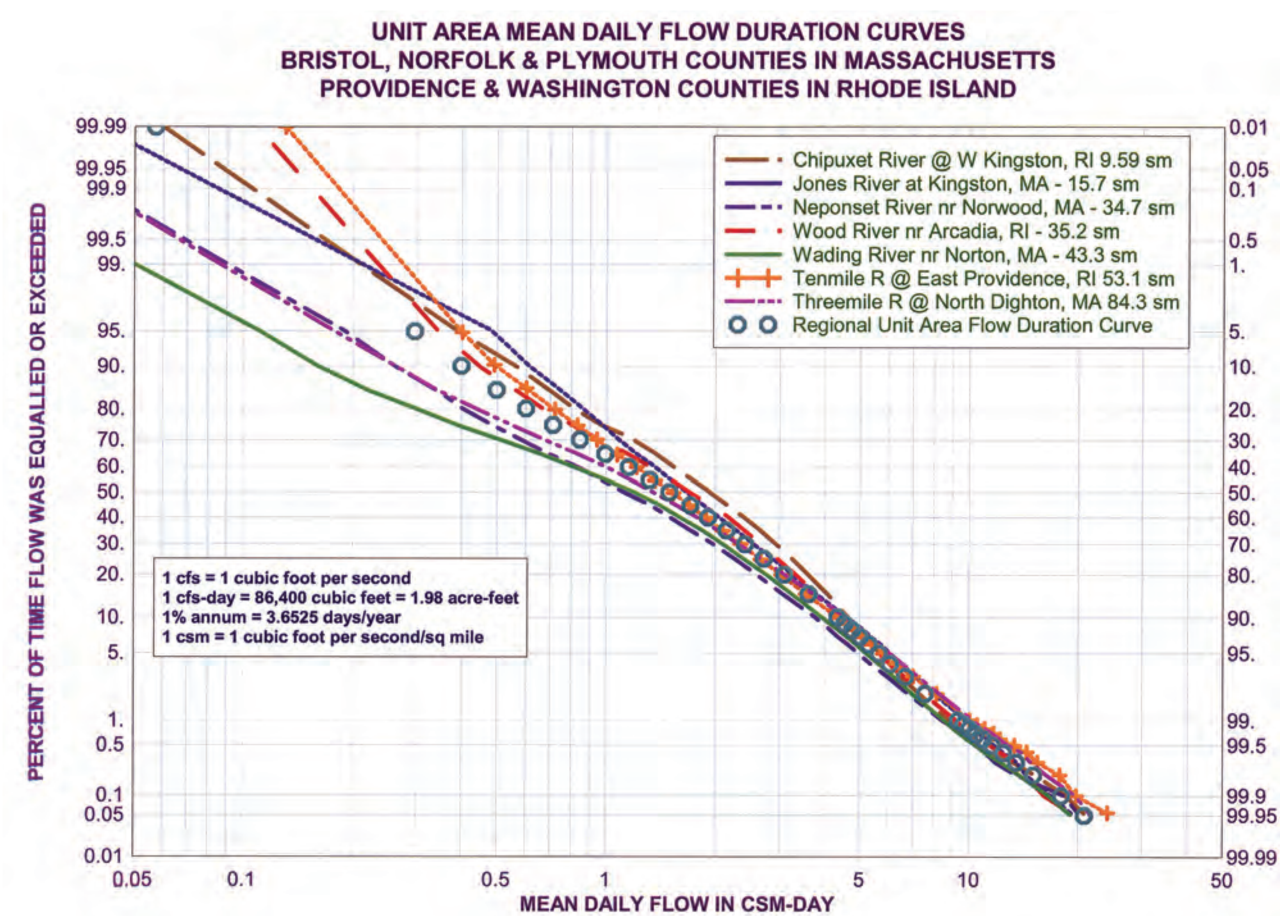
Geomorphic considerations of stream channels and effective discharge

Effective discharge is the range of discharges that over time moves the majority of suspended sediments and rock particles over the channel bed. Effective discharge maintains channel shape, in forming or removing sediment bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channel features (Dunne and Leopold 1978).

For design considerations of water control structures and canals, it would be hydraulically efficient and in terms of reducing channel maintenance, economical to design a pilot channel (within the overall design channel) at the discharge corresponding to the geomorphic effective duration. The pilot channel or inner berm passes and maintains the natural sediment movement within the watershed to prevent excessive erosion or aggradation of sediments. Pilot channel dimensions are not described in this technical note. Channel dimensions and hydraulic characteristics at effective and bankfull discharges are normally included in bankfull regional curve studies.

The ability for a given discharge to carry sediments is sometimes a concern to the engineer. The geomorphic effectiveness is the expected duration (days/year or hours/year) that discharges equal or exceed the channel forming discharge. Emmett (1975) found the geomorphic effectiveness in the Yampa River basin of Colorado and Wyoming to average ~1.59 percent of the year (annum), this equates to 5.8 days per year or 139 hours per year. Leopold (1994) found the geomorphic effectiveness of rivers on the Colorado front range to be around 1 percent annum (3.65 days/year or ~88 hours/year). On the coastal plains, effective

Figure 16 Unit-area FDCs from the counties of the study area



durations have a wider range in effective durations. For the East Gulf Coastal Plain in Alabama, Metcalf (2005) indicates effective durations for rivers average 1.55 percent annum (5.7 days/year or 136 hours/year), similar to what Emmett found in Colorado and Wyoming. In Florida, where the annual precipitation and annual runoff are higher than in Alabama, Metcalf (2004) indicates effective durations are as high as 3 to 5 percent of the year. Hudson and Mossa (1997) found "*The majority of sediment transport occurs during the moderate discharge events, having a duration of 2.4%, 1.5%, and 4.4% for the Rio Grande, Brazos, and Pearl Rivers, respectively.*" On the Atlantic Coastal Plains (Embayed section) of Maryland and Delaware, McCandless (2003) divided the coastal plain into eastern and western due to slope differences: The eastern Embayed section of the Atlantic coastal plain (Delmarva Peninsula) has a geomorphic effectiveness of 2.25 percent annum (8.25 days/year or 198 hours/year). Incorporating gages studied on the western coastal plain of Virginia and Maryland from Krstolic and Chaplin (2007), with the western dataset from McCandless (2003), the geomorphic effectiveness of the western Embayed section is 1.76 percent annum, (6.4 days/year or 154 hours/year). Both reports indicate individual effective durations vary between 1 and 4 percent on the coastal plains of Delaware, Maryland, and Virginia.

The geomorphic effective duration(s) within southeastern Massachusetts can be verified by field surveys on natural rivers of the stage of the inner berm and computation of the channel capacity at that stage. In observing the range of daily mean discharges amongst the seven gages shown in figure 16, the ranges are fairly tight for discharges exceeded less than 5 percent annum, which is within the expected geomorphic effectiveness range. For instance, at 5 percent annum, unit-area mean daily discharge range from 4.96 to 6.11 cubic feet per second per square mile-day, the mean value is 5.65 cubic feet per second per square mile-day. Table 18 shows expected ranges in unit area runoff volumes for known ranges of geomorphic effectiveness.

Example problem

Compute the average annual runoff for the regional unit-area FDC listed in table 17 and shown in figure 16.

Solution: The average annual unit-area runoff is the area under the unit-area regional FDC. Incremental areas are calculated using the mid-point of the class interval ($ft^3/(s\text{-}mi^2\text{-}day)$) multiplied by the duration of the class interval (days), the product is cubic feet per second per square mile, which is converted into

Table 17 Regional unit-area FDC—derived from averaging seven FDCs from gages

Class interval (csm-day)	% of year flow is equaled or exceeded	Class interval (csm-day)	% of year flow is equaled or exceeded	Class interval (csm-day)	% of year flow is equaled or exceeded
0.043	100.0	1.907	40.1	6.684	3.0
0.057	99.99	2.142	35.1	7.576	2.0
0.296	95.0	2.407	30.0	9.320	1.00
0.398	90.1	2.715	25.1	9.671	0.90
0.497	85.1	3.089	20.2	10.021	0.80
0.599	80.2	3.605	15.0	10.483	0.69
0.711	75.2	4.336	10.1	10.947	0.60
0.843	70.3	4.533	9.0	11.593	0.50
0.992	65.1	4.762	8.0	12.446	0.40
1.151	60.1	5.008	7.0	13.496	0.30
1.315	55.0	5.297	6.0	15.051	0.20
1.491	50.2	5.647	5.0	17.984	0.10
1.704	44.9	6.067	4.0	20.795	0.050

acre-feet per square mile. Incremental areas are then summed.

Table 19 column 1 shows unit-area flow values for the 39 class intervals that make up 1 year of time, and column 2 shows corresponding percent of time that flow values (class intervals) are equaled or exceeded. The corresponding number of days assigned to each class interval are shown in column 3, subsequent rows in column 2 were subtracted and the differences multiplied by 3.6525 days for every 1 percent annum of time. Column 4 shows the midpoint of the regional unit area class intervals, (consecutive class intervals were added together and divided by two). This midpoint of the class interval, (column 4) is multiplied by the number of days within the class interval (column 3) to produce an incremental unit area runoff volume (cubic feet per square mile), shown in column 5. Column 6 converts unit-area runoff volumes in cubic feet per square mile to acre-feet per square mile. Note that on an annual basis, every normalized square mile of drainage produces an average of 751.6 cubic feet per second-day of runoff per year. Using the conversion factor of 1.98 acre-feet per cubic feet per second-day, on an annual basis, there is ~1,488 acre-feet of runoff that flows past the outlet in one years time per square mile of drainage. To determine the estimated average annual runoff volume, 1,488 acre-feet per square mile per year should be multiplied by the ungaged drainage area.

For each of the seven gaged drainage basins, estimated average annual runoff volumes are computed on a per square mile basis, based on the regional unit-area FDC and gaged drainage area (table 20 column 3). For comparison to estimated runoff volumes, the average annual runoff volume computed from gage records is shown in column 4 of table 20. The percent differences between average annual runoff volumes and estimated annual runoff volumes are shown in column 5 of table 20. Estimated annual runoff varies from calculated average annual runoff by +13.6 to –21.7 percent. Note that columns 6 and 7 show recorded maximum and minimum annual runoff volumes (respectively) for each gage. The variance of annual runoff from year to year is greater than the long-term differences between average and estimated annual runoff volumes. Estimated average annual runoff predicts long term averages better than short-term averages.

Discussion

The design unit-area runoff hydrographs were constructed from averaged or most probable runoff characteristics derived from 216 measured runoff events. Runoff characteristics that were determined and replicated include: peak discharge versus annual exceedance, runoff volume above baseflow versus annual exceedance, rates of rise and rates of recession in cubic feet per second per hour and cubic feet per second per square mile per hour between specific annual exceedance probabilities, runoff volume distributions under rising and receding limbs, and base time versus time to peak. Analysis shows that the runoff from these gaged watersheds exhibit similar runoff characteristics when normalized by the drainage areas.

Ordinates of the design unit-area runoff hydrographs were multiplied by the drainage areas of the seven gages and compared to observed hydrographs for the same probability of annual exceedance. Estimated peaks varied from +11 percent over to –12 percent under actual peak discharges; rates of discharge rise and recession were in many instances parallel. Predicted and observed runoff volumes have the greatest variance. The variance is attributed to actual streamflow discharge at the beginning of the runoff event versus an assumed baseflow condition.

Table 18 Mean and range in unit-area runoff associated with geomorphic effectiveness

Geomorphic effectiveness	Lower range (csm-day)	Mean value (csm-day)	Upper range (csm-day)
5% annum	4.96	5.647	6.11
4% annum	5.36	6.067	6.58
3% annum	5.97	6.684	7.24
2% annum	6.80	7.576	8.28
1% annum	8.47	9.320	10.27

Table 19 Example of estimating annual runoff from southeast MA regional unit-area FDC

Class interval csm-day	% of year flow is equaled or exceeded	# of days between class intervals	Mid-point of class interval csm-day	Estimated average annual runoff volume (csm-day) or ft^3/sec-day /mi^2	Estimated average annual runoff volume acre-ft/mi^2
Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**	**Column 6**
0.043	100.0				
0.057	99.99	0.04	0.050	0.002	0.004
0.296	95.0	18.18	0.177	3.211	6.357
0.398	90.1	17.94	0.347	6.232	12.338
0.497	85.1	18.11	0.448	8.107	16.052
0.599	80.2	18.19	0.548	9.966	19.734
0.711	75.2	18.20	0.655	11.920	23.603
0.843	70.3	17.95	0.777	13.947	27.615
0.992	65.1	18.71	0.917	17.166	33.989
1.151	60.1	18.50	1.071	19.821	39.246
1.315	55.0	18.40	1.233	22.681	44.908
1.491	50.2	17.78	1.403	24.955	49.411
1.704	44.9	19.39	1.598	30.983	61.347
1.907	40.1	17.33	1.806	31.294	61.963
Class interval csm-day	**% of year flow is equaled or exceeded**	**# of days between class intervals**	**Mid-point of class interval csm-day**	**Expected average runoff volume (csm-day) or ft^3/sec-day /mi^2**	**Expected average annual runoff volume acre-ft/mi^2**
Column 1	**Column 2**	**Column 3**	**Column 4**	**Column 5**	**Column 6**
2.142	35.1	18.49	2.025	37.425	74.102
2.407	30.0	18.41	2.274	41.865	82.893
2.715	25.1	18.01	2.561	46.111	91.299
3.089	20.2	17.99	2.902	52.195	103.346
3.605	15.0	18.88	3.347	63.184	125.104
4.336	10.1	18.01	3.971	71.517	141.604
4.533	9.0	3.72	4.435	16.484	32.637
4.762	8.0	3.75	4.647	17.422	34.495
5.008	7.0	3.81	4.885	18.606	36.841
5.297	6.0	3.58	5.152	18.432	36.496
5.647	5.0	3.73	5.472	20.417	40.426
6.067	4.0	3.48	5.857	20.407	40.406
6.684	3.0	3.71	6.376	23.685	46.897
7.576	2.0	3.64	7.130	25.977	51.435
9.320	1.00	3.66	8.448	30.905	61.192
9.671	0.90	0.39	9.496	3.662	7.252
10.021	0.80	0.34	9.846	3.355	6.642
10.483	0.69	0.40	10.252	4.102	8.122
10.947	0.60	0.34	10.715	3.593	7.114
11.593	0.50	0.37	11.270	4.139	8.196
12.446	0.40	0.38	12.020	4.539	8.986
13.496	0.30	0.36	12.971	4.665	9.237
15.051	0.20	0.37	14.274	5.287	10.468
17.984	0.10	0.36	16.518	5.934	11.748
20.795	0.050	0.18	19.390	3.576	7.081
		0.18	20.795	3.833	7.589
Totals		**365.25**		**751.60**	**1488.18**

Because this analysis is based on empirical methods and the probabilities of annual exceedance are based on a limited sample set, there is some error inherent to the methodology (as is the case for all discharge vs. probability relationships). With a larger sample set (more gages, more years), the confidence of the statistics becomes more refined. But on the practical side, a methodology is needed to estimate peaks, volumes. and timing for low relief sandy-bog areas, where groundwater plays a significant role in the timing, collection, and movement of runoff in these watersheds.

Recommendations for future updates

Few, if any, areas in southern New England are without any human alterations; even areas classified as forestland may have roads and low-density housing or remnants of historic alterations to the land or to the waterways. Coastal areas and river valleys were settled first; mankind has gradually converted the landscape from forest to farmland to suburban to urban. During the industrial revolution, manufacturing centers required water power; small dams and impoundments were built on many rivers to power sawmills and gristmills. In the mid 1900s, growth expanded around metropolitan areas; surrounding rural lands changed over to suburban use. The mosaic of forest, agricultural, suburban, and urban lands reflect the settlement and economic history of the area. There is no doubt that the landscape and runoff patterns will continue to change into the future. The changing land uses coincide and reflect the changes in runoff and streamflows. Therefore, updates to the hydrologic regime should occur as the land use changes.

With time and continued operation of the USGS stream gaging network, extra years of records would improve the LPIII frequency distributions, which would increase the confidence of peak discharge to frequency relationships. For the seven gages studied, the 15-minute interval discharge data (1990–2006) provided valuable timing and volume characteristics that annual peak data could not. The largest storm event studied in the dataset has a return interval of ~61 years, extra years of 15-minute data could eventually provide peaks, timing, and average runoff volumes to exemplify an actual 100-year storm event. The USGS IDA Web site now provides instantaneous discharge data up to the end of water year 2009.

Table 20 Percent differences between estimated and actual average annual runoff volumes

Gage number	Drainage area	Average annual runoff volume estimated from regional unit area FDC	Average annual runoff volume calculated from gaged FDC	% difference = 100% × (calculated–estimated)/ calculated =100% × (column 4– column 3)/ (column 4)	Maximum annual runoff volume calculated from gage record	Minimum annual runoff volume calculated from gage record
	mi^2	acre-ft	acre-ft	%	acre-ft	acre-ft
Column 1	Column 2	Column 3	Column 4	Column 5	Column 6	Column 7
01117350	9.59	14,272	16,519	13.6	26,301	4,985
01105870	15.7	23,364	25,702	9.10	47,167	10,769
01105000	34.7	51,640	42,435	–21.7	77,193	15,721
01117800	35.2	52,384	56,023	6.50	82,225	24,080
01109000	43.3	64,438	54,257	–18.8	89,602	20,881
01109403	53.1	79,022	81,326	2.83	120,698	39,646
01109060	84.3	125,454	123,023	–1.98	193,144	46,657

An update to this empirical dataset every 10 years adding new hydrologic records, recalculating most probable averages, and updating the runoff characteristics is recommended. Updates every 10 years would reflect changes in land use as well as corresponding changes in runoff. At some point, however, extra years of data collection may only show changes of increased runoff due to conversion from forest or agriculture land to urban land use.

Limitations of method

This empirical procedure which estimates flood peaks, runoff volumes, and timing is applicable on drainage areas representative of the seven USGS stream gaging stations watersheds, bog sites with similar basin characteristics of forested land cover, slopes, stratified glacial drift deposits, and drainage areas (9.59 to 84.3 mi^2). The critical question, however, is how far outside these ranges (especially how small of a drainage area) is also represented. If the drainage area soil-cover is greater than 50 percent forestland and at least 50 percent of the land areal coverage is stratified sand and gravel deposits and the stream (or branch) is classified as perennial, then the methodology should apply. Studies by Bent and Steeves (2006) concluded that drainage areas greater than 2 square miles are likely to flow perennially. For drainage areas less than 2 square miles, visual observations of flows during low-flow periods (late July though early September) would need to be ascertained to determine whether the stream or branch is perennial or intermittent.

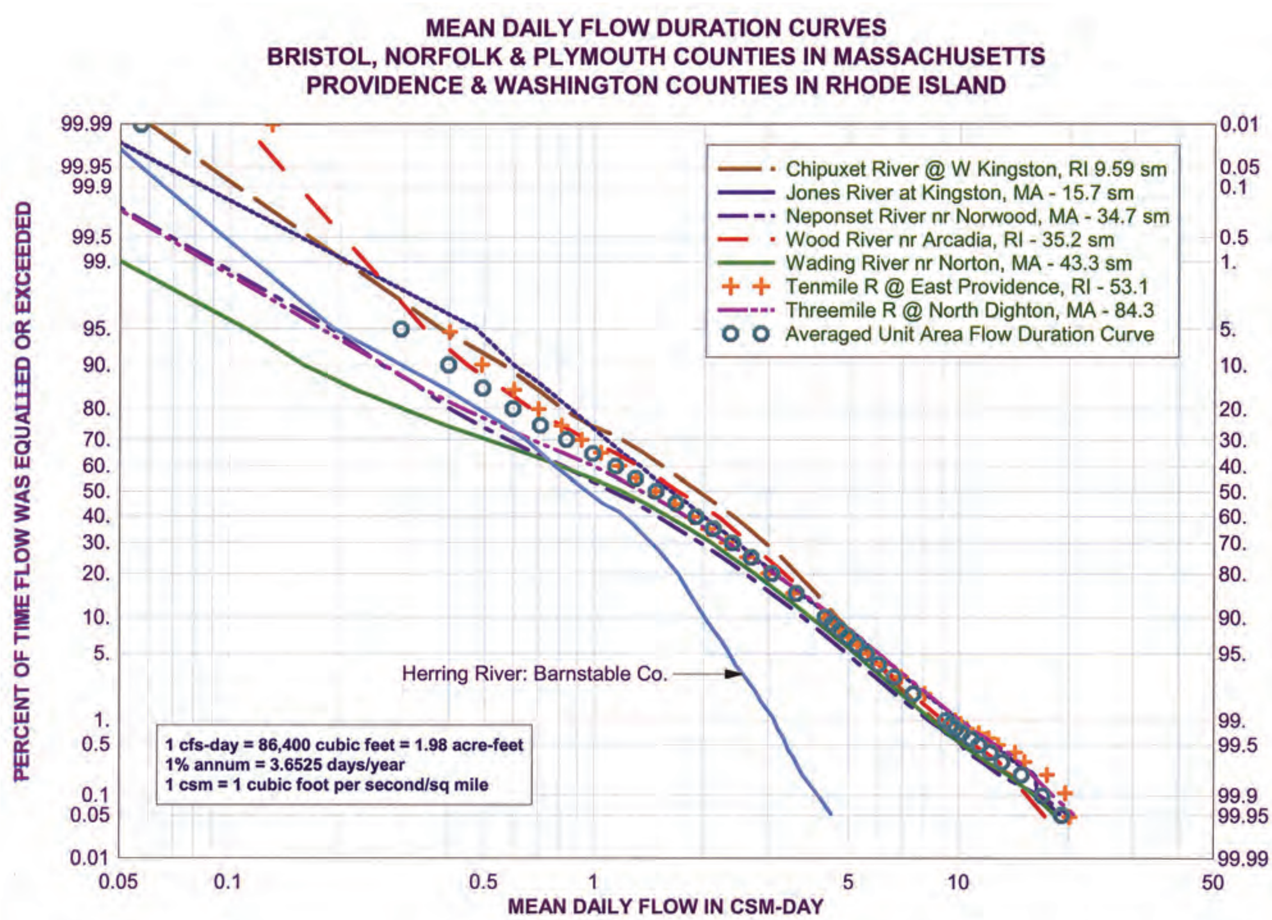
NRCS technical document Eng–Proc–MA–19 was developed for bog sites in Plymouth, Barnstable, Bristol, and Norfolk Counties in Massachusetts. In this technical note, Barnstable County was omitted from the study area because the two gages in Barnstable County had peak flow and mean daily flow characteristics unlike the seven gages used in the analysis. In Barnstable County, unit-peak discharge per square mile for a given return interval is generally lower than the unit-peak discharges generated from the study area. Had the two gages in Barnstable County been incorporated into the regional gage analysis, overall peak discharges would be lower, and time to peak and base time would have been longer. Figure 17 shows the unit FDC of the Herring River (Barnstable County), which did not "collapse" like the seven gages used. Geology, stratified drift, and topography may be the influencing factor on runoff differences.

There are cranberry bog sites in Barnstable County. This procedure could be used to predict peaks and runoff and timing, with the understanding that designs are likely to be conservative; estimated design peaks are likely to be higher than actual.

Conclusions

Empirical hydrologic data of storms within the 50- to 100-year return intervals are the least represented. Therefore, confidence of estimating runoff rates and volumes for a 100-year storm is less than the confidence of estimating runoff rates and volumes for the more frequent 10-year storm. However, the relationships of peak discharge per unit drainage area (csm) and runoff volumes per unit drainage area (watershed inches) to probability of annual exceedance (figs. 3 and 4) are quite good. The strong correlations of the frequent storms and high r^2 values support using these empirical averaged rates and volumes to estimate beyond the 10-year storm event, normalizing peaks and volumes to drainage area support the use in small drainage basins. Combining all runoff elements in the hydrograph generation calibration process, such as peaks, volumes, average rates of changing discharge by return intervals with proportions of runoff volumes under the rising and receding hydrograph limbs, should give a good representation of the most probable runoff hydrographs by return interval.

Figure 17 Unit-area FDCs for study area compared to Herring River in Barnstable County



References

Armstrong, D.S., G.W. Parker, and T.A. Richards. 2008. Characteristics and classification of least altered streamflows in Massachusetts: U.S. Geological Survey Scientific Investigations Report 2007–5291.

Bent, G.C., and P.A. Steeves. 2006. A revised logistic regression equation and an automated procedure for mapping the probability of a stream flowing perennially in Massachusetts. U.S. Geological Survey Scientific Investigations Report 2006–5031.

Dunne, T, and L.B. Leopold. 1978. Water in environmental planning. W.H. Freeman and Company, San Francisco, CA.

Epstein, C.M. 2002. Application of Rosgen analysis to the New Jersey pine barrens. J. of AWRA Vol. 38:1 pp 69–78.

Emmett, W.W. 1975. The channels and waters of the upper Salmon River area, Idaho: U.S. Geological Survey Professional Paper 870A.

Hudson, P.F., and J. Mossa. 1997. Suspended sediment transport effectiveness of three large impounded rivers. U.S. Gulf Coastal Plain. Environmental Geology 32 (4), pp 263–273.

Krstolic, J.L., and J.J. Chaplin. 2007. Bankfull regional curves for streams in the non-urban, non-tidal coastal plain physiographic province, Virginia and Maryland. USGS Scientific Investigations Report 200–5162, Reston, VA.

Leopold, L.B. 1994. A view of the river. Harvard University Press, Cambridge, MA.

McCandless, T.L. 2003. Maryland stream survey: bankfull discharge and channel characteristics of streams in the coastal plain hydrologic region. US Fish and Wildlife Service Chesapeake Bay Field Office, Annapolis, MD.

Metcalf, C. 2004. Regional channel characteristics for maintaining natural fluvial geomorphology in Florida streams: U.S. Fish and Wildlife Service, Panama City Fisheries Resource Office, Panama City, FL.

Metcalf, C. 2005. Alabama riparian reference reach and regional curve study. U.S. Fish and Wildlife Service, Panama City Fisheries Resource Office, Panama City, FL.

Ries, K.G. 1994. Estimation of low-flow duration discharges in Massachusetts: U.S. Geological Survey Water-Supply Paper 2418.

Simcox, A.C. 1992. Water resources of Massachusetts. U.S. Geological Survey Water-Resources Investigation Report 90–4144.

Sheridan, J.M., W.H. Merkel, and D.D. Bosch. 2002. Peak rate factors for flatland watersheds. American Society of Agricultural Engineers ISSN 0883–8542.

U.S. Department of Agriculture, Natural Resources Conservation Service. 1974. Estimating runoff for cranberry areas in Massachusetts Eng–Proc–MA–19.

U.S. Department of Interior. 1982. Guidelines for determining flood flow frequency. Bulletin #17B. Geological Survey, Reston, Virginia, Revised 1981, editorial corrections, 1982.

List of Units Symbols

List of Units	Symbols
annum	% of time in a year (1% annum = 3.6525 days/year)
ARS	Agriculture Research Service
ASAE	American Society of Agricultural Engineers
acre-feet	volume that covers 1 acre (43,560 ft^2) 1 foot deep
ft^3/s	units of discharge in cubic feet per second (cfs)
ft^3/s /hr	rate at which discharge varies—increasing or decreasing
ft^3/s-day	mean daily volume, 1 ft^3/s-day = 86,400 cubic feet = 1.98 acre feet
csm	flow rate per unit drainage area, $ft^3/s/mi^2$
csm-day	volume based on a daily flow per unit drainage area
EFH	Engineering Field Handbook
FDC	flow duration curve
IDA	Instantaneous Data Archive (USGS)
LPIII	Log Pearson III distribution
NRCS	Natural Resources Conservation Service
P	probability (0.04 = 4%)
PRF	peak rate factor
Q	discharge
$Q_{1.25}$	discharge at the 1.25-year return interval
Q_{100}	discharge at the 100-year return interval
Q_{bf}	baseflow discharge
SCS	Soil Conservation Service
SEMA	southeast Massachusetts
T	return interval (years)
T_{Base}	duration of baseflow in hours
T_{Peak}	time in hours from baseflow to peak discharge
TR	Technical Release
UH	unit hydrograph
USGS	U.S. Geological Survey
Watershed inches	runoff equivalent to a uniform depth that would cover the watershed area uniformly
WY	water year: October 1 to September 30 of water year