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Characteristics of the April 2007 Flood at 10 Streamflow-Gaging Stations in Massachusetts

Scientific Investigations Report 2009–5068

U.S. Department of the Interior
U.S. Geological Survey

Front cover. Background image showing "Powerful Spring Storm." (From National Oceanic and Atmospheric Administration (NOAA) Geostationary Operational Environmental Satellite (GOES)-12 visible spectrum, April 16, 2007, at 13:15 p.m. Eastern Daylight Savings Time (EDT)).

Photograph of Shawsheen River upstream from Haverhill Street bridge in Andover, Massachusetts, on April 18, 2007, at 10:31 a.m. (EDT); stage at the time of the photograph was 1.33 feet below the storm-peak stage. Ironically, the yellow sign attached to the bridge warns of a downstream dam. (Photograph by Joseph Zanca, U.S. Geological Survey)

Back cover. Photograph shows same site under normal flow conditions.

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By Phillip J. Zarriello and Carl S. Carlson

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U.S. Geological Survey

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KEN SALAZAR, Secretary

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]

Vertical coordinate information is referenced to National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

ABBREVIATIONS

FEMA	Federal Emergency Management Agency
FIS	Flood-Insurance Study
MOVE-1	Maintenance of Variance Extension (version 1)
NWS	National Weather Service
RMSE	Root Mean Square Error
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Characteristics of the April 2007 Flood at 10 Streamflow-Gaging Stations in Massachusetts

By Phillip J. Zarriello and Carl S. Carlson

Abstract

A large "nor'easter" storm on April 15–18, 2007, brought heavy rains to the southern New England region that, coupled with normal seasonal high flows and associated wet soil-moisture conditions, caused extensive flooding in many parts of Massachusetts and neighboring states. To characterize the magnitude of the April 2007 flood, a peak-flow frequency analysis was undertaken at 10 selected streamflow-gaging stations in Massachusetts to determine the magnitude of flood flows at 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return intervals. The magnitude of flood flows at various return intervals were determined from the logarithms of the annual peaks fit to a Pearson Type III probability distribution. Analysis included augmenting the station record with longer-term records from one or more nearby stations to provide a common period of comparison that includes notable floods in 1936, 1938, and 1955.

The April 2007 peak flow was among the highest recorded or estimated since 1936, often ranking between the 3d and 5th highest peak for that period. In general, the peak-flow frequency analysis indicates the April 2007 peak flow has an estimated return interval between 25 and 50 years; at stations in the northeastern and central areas of the state, the storm was less severe resulting in flows with return intervals of about 5 and 10 years, respectively. At Merrimack River at Lowell, the April 2007 peak flow approached a 100-year return interval that was computed from post-flood control records and the 1936 and 1938 peak flows adjusted for flood control.

In general, the magnitude of flood flow for a given return interval computed from the streamflow-gaging station period-of-record was greater than those used to calculate flood profiles in various community flood-insurance studies. In addition, the magnitude of the updated flood flow and current (2008) stage-discharge relation at a given streamflow-gaging station often produced a flood stage that was considerably different than the flood stage indicated in the flood-insurance study flood profile at that station.

Equations for estimating the flow magnitudes for 5-, 10-, 25-, 50-, 100-, 200-, and 500-year floods were developed from the relation of the magnitude of flood flows to drainage area calculated from the six streamflow-gaging stations with the longest unaltered record. These equations produced a more conservative estimate of flood flows (higher discharges) than the existing regional equations for estimating flood flows at ungaged rivers in Massachusetts. Large differences in the magnitude of flood flows for various return intervals determined in this study compared to results from existing regional equations and flood insurance studies indicate a need for updating regional analyses and equations for estimating the expected magnitude of flood flows in Massachusetts.

Introduction

In mid-April 2007, a strong low-pressure system over southern New England produced heavy rainfall that, coupled with wet-antecedent conditions, produced extensive flooding in many streams and rivers in the region. This storm, known as the 2007 Patriots' Day Nor'easter, is one of the largest spring-time storms to hit New England in memory (FEMA, 2007). The flooding and the resulting flood damages were extensive enough to cause the Commonwealth of Massachusetts to declare a state of emergency and to prompt a Presidential disaster declaration on May 16, 2007.

The National Oceanic and Atmospheric Administration (NOAA) National Climatic Data Center (NCDC) provided the following description of the April 2007 storm for Essex County, Massachusetts (National Climatic Data Center, 2008d):

> *An unusually strong and slow moving coastal storm for mid April tracked to western Long Island Sound on April 16th before weakening slowly and drifting offshore. This storm brought a variety of impacts in southern New England, including heavy snow to the higher elevations of western Massachusetts, damaging winds in excess of 60 mph, widespread river and stream flooding, and significant coastal flooding through several high tide cycles. Rainfall totals of 3 to 5 inches, combined with wet antecedent conditions, resulted in widespread river and stream flooding, as well as significant flooding of urban areas. The worst flooding affected the Merrimack Valley,*

where moderate to major flooding occurred on the Merrimack, Nashua, and North Nashua Rivers. For many locations, this may have been the worst flooding since the May, 2006 or April, 1987 floods, but along the North Nashua, the preliminary crests recorded may have been the highest since the floods of September, 1938. Many small streams throughout the region also rose out of their banks and flooded nearby areas, including roadways. Major flooding occurred along the Mill River in Northampton, which required the evacuation of nearby residents.

Data collected and analyzed to document the magnitude and extent of flooding from this large storm provide important information for flood management, bridge and culvert design, and risk assessment. Streamflow-gaging stations with long periods of record are the single best tool for evaluating the magnitude and severity of flooding. Up-to-date information on the magnitude and frequency of flood flows and associated river stage is crucial for the development and guidance of mitigation measures to minimize flood losses in future disasters. The Federal Emergency Management Agency (FEMA), part of the Department of Homeland Security, is responsible for protecting life and property from all hazards, including natural disasters, through comprehensive emergency management preparedness, protection, response, recovery, and mitigation. To assist FEMA in its mission, the U.S. Geological Survey (USGS) entered into an agreement with FEMA in 2008 to characterize flooding from the April 2007 storm at 10 selected streamflow-gaging stations that experienced some of the most extensive flooding in Massachusetts.

Purpose and Scope

This report documents streamflow and river-stage conditions at 10 selected streamflow-gaging stations in west-central and northeastern Massachusetts during the flood of April 2007. The report describes the analysis of peak-flow magnitudes calculated for 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return intervals from currently available data to characterize the magnitude and return interval of the April 2007 storm. The results of this analysis are also compared to flood stages and discharges reported in flood-insurance studies done in the vicinity of the streamflow-gaging stations examined. The streamflow-gaging stations examined include (in order of the USGS identification number): North Nashua River at Fitchburg (01094400), Stillwater River near Sterling (01095220), Squannacook River near West Groton (01096000), Nissitissit River at Pepperell (01096503), Merrimack River at Lowell (01100000), Spicket River near Methuen (01100561), Shawsheen River at Andover (01100627), Mill River at Northampton (01171500), Sevenmile River near Spencer (01175670), and West Branch Westfield River near Huntington (01181000).

Study Area

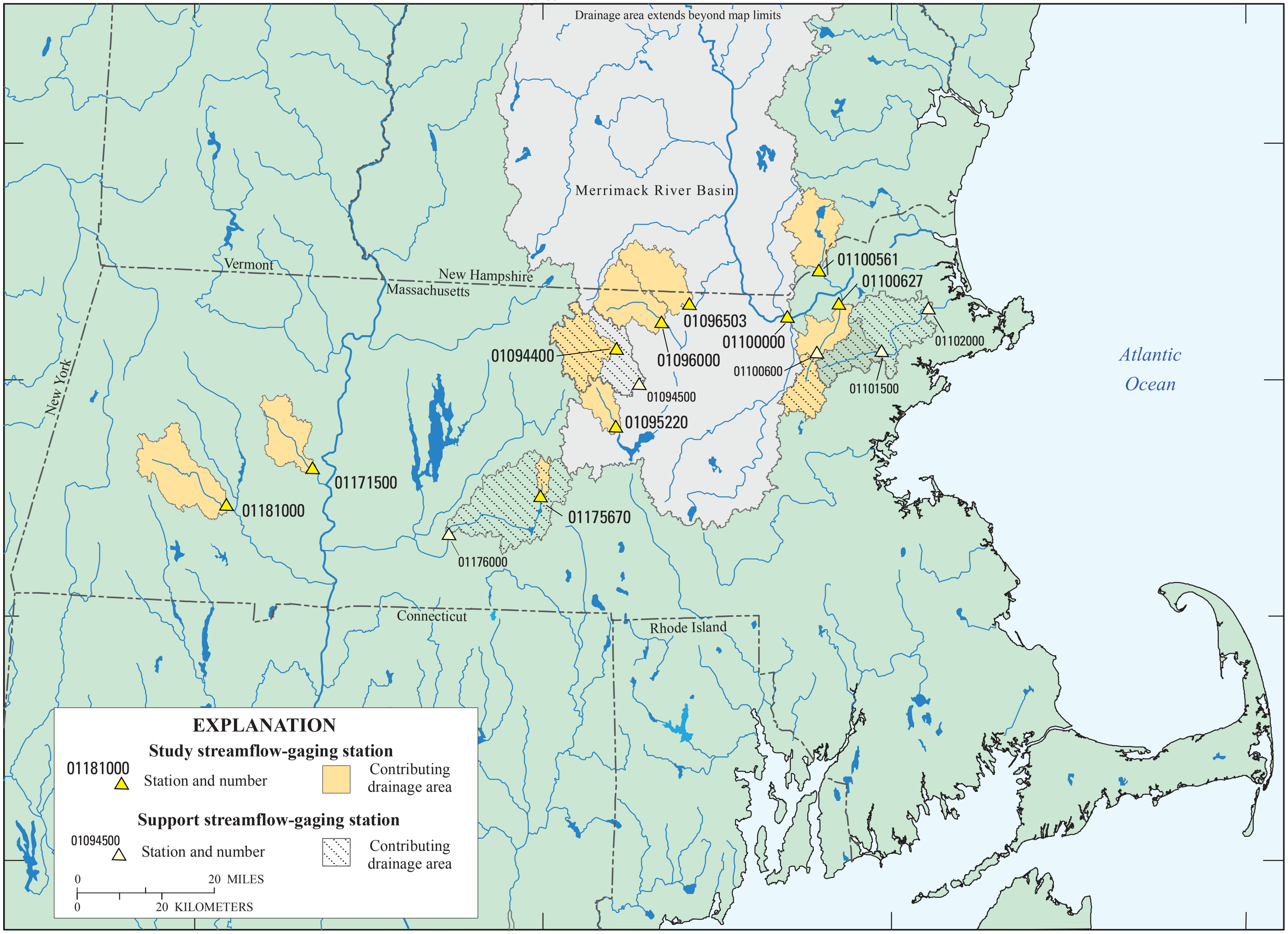
The 10 streamflow-gaging stations examined cover an area from west-central to northeastern Massachusetts (fig. 1). Drainage areas range from 8.81 to 4,635 mi^2 with a median drainage area of 63 mi^2 (fig. 1). Four of these streamflow-gaging stations have drainage areas that extend into New Hampshire: the Squannacook River near West Groton, Nissitissit River at Pepperell, Merrimack River at Lowell, and Spicket River near Methuen. Most of the drainage areas of the latter three stations are in New Hampshire. In addition to these 10 streamflow-gaging stations, records from 7 other stations were used to support the peak-flow analysis; these stations are referred to as support stations. Two of the support stations are in the northern part of the Merrimack River Basin and are beyond the map extent of figure 1.

The drainage basin characteristics vary (table 1). In general, elevation and steepness increase, while storage (water and wetland) and urban area decrease from the coast inland. Storage, as measured by the combined percent of the basin area classified as wetlands or open water, ranged from 1.9 percent at Mill River at Northampton to about 14 percent at Spicket River near Methuen. Urban areas (areas classified as high-density residential, multifamily, or commercial) ranged from 0.2 to 20 percent of the basin area (Sevenmile River near Spencer and Shawsheen River at Andover, respectively). Areas classified as “other” are mostly low-density residential lands and were largest in the Spicket and Shawsheen River Basins (about 22 and 40 percent of the basin area, respectively). The Spicket and Shawsheen River Basins have the highest percentage of combined urban land use.

Previous Studies

Numerous flood investigations have been made throughout Massachusetts as part of the FEMA’s Flood Insurance Program to delineate the expected flood elevation for large, infrequent events such as the 100- and 500-year flood. Flood-insurance studies relevant to the streamflow-gaging stations examined in this study are included in the sections of this report that describe flood flows at the individual stations. The discussion below is limited to specific flood events previously documented and to regional flood-flow analyses prepared by the USGS.

The USGS has documented flooding following major events, including the precipitation-snowmelt flood of 1936 (Grover, 1937), and hurricane floods of 1938 (Paulsen and others, 1940) and 1955 (Bogart, 1960) although these reports are broad in scope and cover an area extending far beyond Massachusetts. Jahns (1947) used the earlier flood information in the analysis of flooding to geologic features of the Connecticut River valley. Smaller flood events focused mainly in Massachusetts have been documented by Wood and others (1970), Swallow and others (1971), Swallow and Fogarty (1973), Swallow and Wood (1973), and Parker and



Base from U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 1. Location of selected streamflow-gaging stations in Massachusetts used to characterize the April 2007 flood.

Table 1. Generalized characteristics of the contributing area to selected streamflow-gaging stations in Massachusetts.

[Contributing area shown in figure 1; **Regulation code:** 0, none; 1, low flow only; 3, all flows. **Region code:** CU, Central Uplands; CL, Central Lowlands; WH, Western Highlands; --, not determined; basin characteristics from Zarriello and Socolow, 2003, unless otherwise noted; mi^2, square miles]

U.S. Geological Survey streamflow-gaging station		Drainage area (mi^2)	Regulation code	Region code	Mean elevation (feet)	Mean slope (percent)	Basin characteristics (percent of basin area)						
Name	Number						Water	Wetland	Forest	Urban	Agriculture	Other	Sand and gravel
North Nashua River at Fitchburg	01094400	64.2	1	CU	981	8.1	3.6	2.4	71	6.3	5.7	11	21
Stillwater River near Sterling	01095220	31.6	0	CL	766	7.7	1.9	2.5	77	1.2	10	7.4	18
Squannacook River near West Groton	01096000	63.7	0	CL	622	7.5	0.9	2.2	82	1.3	6.0	7.6	27
Nissitissit River at Pepperell[1]	01096503	59.6	0	CU	447	8.1	1.8	4.8	79	1.2	6.8	6.2	28
Merrimack River at Lowell	01100000	4,635	3	--	--	--	--	--	--	--	--	--	--
Spicket River near Methuen[1]	01100561	62.1	3	CL	246	6.1	4.1	9.4	49	8.6	7.0	22	--
Shawsheen River at Andover[1]	01100627	72.8	1	CL	146	4.3	0.8	3.8	32	20	3.0	40	64
Mill River at Northampton	01171500	52.6	1	WH	841	11.1	1.0	0.9	81	3.1	6.8	7.2	16
Sevenmile River near Spencer	01175670	8.81	1	CU	871	7.4	2.3	3.7	73	0.2	14	6.8	13
West Branch Westfield River near Huntington	01181000	94.0	0	WH	1,422	13.2	1.3	1.3	91	0.4	2.3	3.7	4.0

[1] Land use and land cover (LULC) from National Atlas cover grid, 2001, 30-square meter resolution, downloaded (http://nmviewogc.cr.usgs.gov/viewer.htm?BBOX=-88.23975,40.09448,-88.22655,40.1014&CLASSIDSON=39|6&LAYERSON=3380|10464|11787&LAYERSOFF=1652), July 10, 2008; elevation data from National Elevation Data (NED), 10-square meter resolution, downloaded (http://ned.usgs.gov/), July 10, 2008.

others (1998). Other reports that cover floods in the New England region include Kinnison (1930), Thomson and others (1964), and Gadoury (1979). A summary report of floods in Massachusetts done by Wandle and Lautzenheiser (1991) is included in the 1988–89 National Water Summary.

Several studies provide a regional analysis for the purpose of developing equations for determining flood flows at ungaged sites in Massachusetts. These studies began with Knox and Johnson (1965) and were followed by Johnson and Tasker (1974a), Wandle (1977), and Wandle (1983). Wandle's 1983 report in which regional equations were developed for estimating flood flows at 2-, 5-, 10-, 25-, 50-, and 100-year return intervals from annual peak flows at 95 sites is the most comprehensive of these studies. Wandle's analysis was made from systematic peak-flow records through the 1976 water year. These equations were used in a number of community flood-insurance studies to estimate flood flows at ungaged sites. Later work by Murphy (2001a, 2001b) provided equations for estimating flood flows from mixed probability distribution populations. The analysis was limited to peak-flow records through 1993 at 30 streamflow-gaging stations. More recent regional equations for estimating flood flows at ungaged sites in neighboring states have been developed for Connecticut (Ahearn, 2003), New Hampshire (Olson, 2009), New York (Lumia and others, 2006), and Vermont (Olson, 2002).

Antecedent and Storm Conditions

Antecedent moisture conditions can have a large effect on the magnitude of flows generated by a storm–for example, the highest recorded streamflow in south-central Massachusetts occurred following back-to-back Hurricanes Connie and Diane in August 1955 (National Weather Service Northeast River Forecast Center, 2008). Although either storm would have produced flood flows, the fact that Hurricane Diane (rainfall totals of about 15 in.) followed Hurricane Connie (rainfall totals of about 8 in.) within a 2-week period produced exceptionally high flows in parts of the state. This storm is used as an example because of its historical significance and its influence on the magnitude of peak flow in some of the sites examined in this report. In general, a given storm will produce higher flows if existing conditions are wet than if they are dry. Therefore, antecedent climatic and hydrologic conditions as well as the storm characteristics themselves are helpful in characterizing the April 2007 storm.

Streamflow

Streamflow prior to the April 16–18 flooding was in the normal range of the seasonal high flow at each of the stations examined. This is illustrated by the daily mean flow for the 2007 water year in relation to the 10th-, 25th-, 50th-, 75th-, and 90th-percentile flows for a given day calculated from the period-of-record daily mean flows at Squannacook River near West Groton and West Branch Westfield River near Huntington (fig. 2). These stations represent the geographic range of the stations examined in this study and the stations with the longest record. Antecedent flows at these two stations were between the median and 25th percentile for this time of year. Had flows been in the higher range of normal flows for this time of year, the 2007 Patriots' Day storm would likely have resulted in even greater flooding. If the storm had occurred at most other times of the year, however, flooding likely would have been less extensive.

Precipitation

Hourly precipitation data were compiled from three NOAA climate stations—Groveland and Worcester in Massachusetts and Hopkinton Lake in New Hampshire (fig. 3). Prior to the April 15–18 storm, the last precipitation was from a storm on April 12, 2007, which totaled 0.87, 1.03, and 0.90 in. at Groveland, Worcester, and Hopkinton Lake, respectively (table 2). As a result, hydrographs were receding prior to the April 15–18 storm (fig. 2).

The April 2007 nor'easter began as snowfall—1 to 3 in. were reported from northern Worcester County into northwestern Middlesex County, but changed to all rain as milder air was drawn into the interior (National Climatic Data Center, 2008d). Total precipitation from the nor'easter during April 15–18, 2007, was compiled from the three hourly climate stations and 290 daily climate stations in southern New England and contoured (fig. 3) using the ESRI spatial analyst inverse distance weighting technique. Precipitation in the region ranged from about 1.5 to 7 in. with the greatest amounts falling along a north-south line over the Berkshire Mountains in western Massachusetts and in an arc north from Worcester through Fitchburg, Massachusetts, into New Hampshire, and then northeastward (National Weather Service, 2008b). The streamflow-gaging stations examined in this study generally have drainage areas that lie in the areas of greatest precipitation from the April 2007 nor'easter.

Methods

Characterization of the April 2007 flood flows consisted of three main parts. First, the April 2007 peak flow is described in relation to previously recorded annual peak flows and estimated annual peak flows dating back to 1936. Second, the April 2007 peak flow is put in the context of the magnitude and frequency of flood flows. Third, the April 2007 peak stage and discharge is examined in relation to existing flood-insurance-study information and the NWS flood-stage warnings. The general approach to each of these components is described below, but some of the specific details as they apply to individual streamflow-gaging stations are described later in the report for that station.

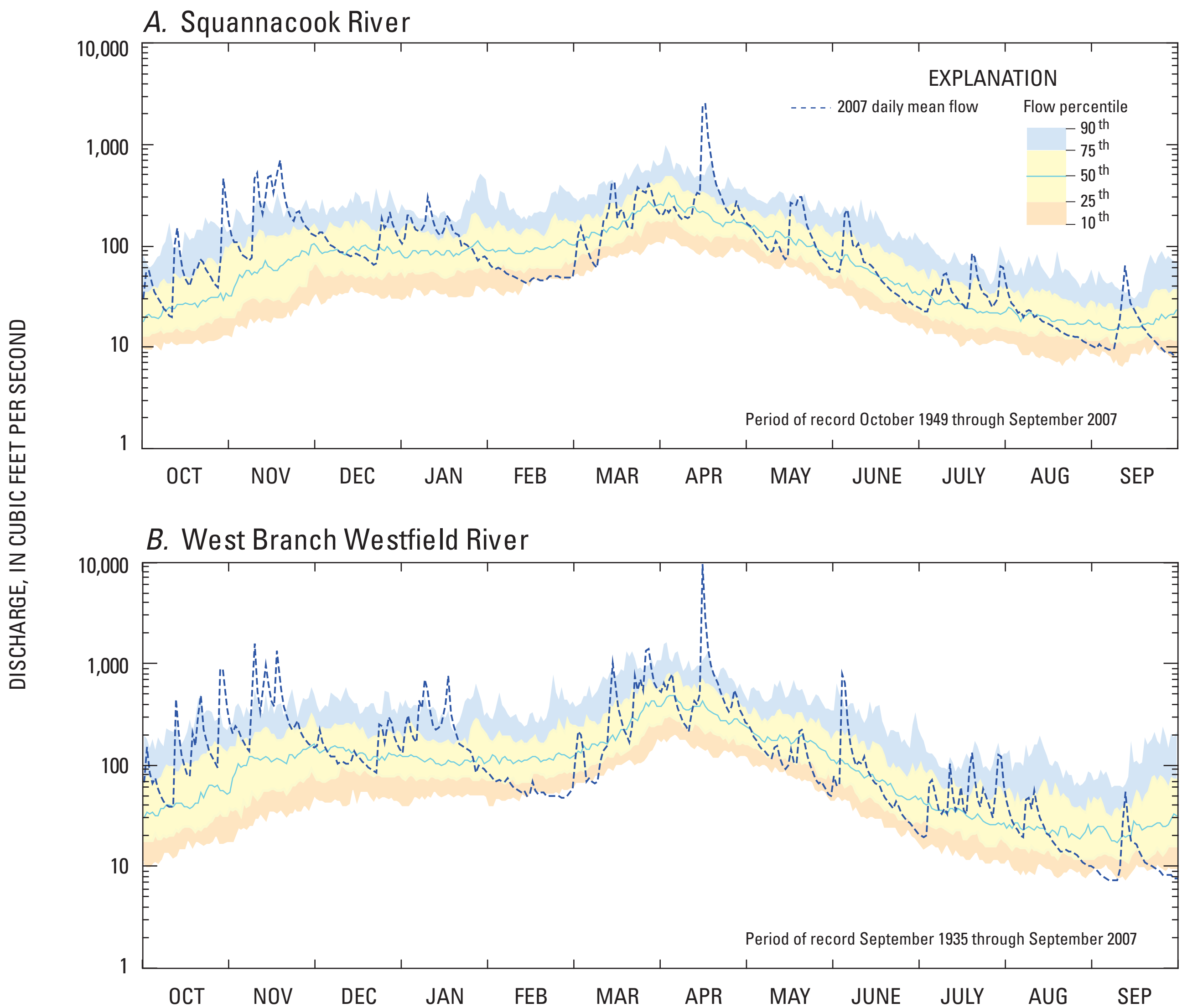
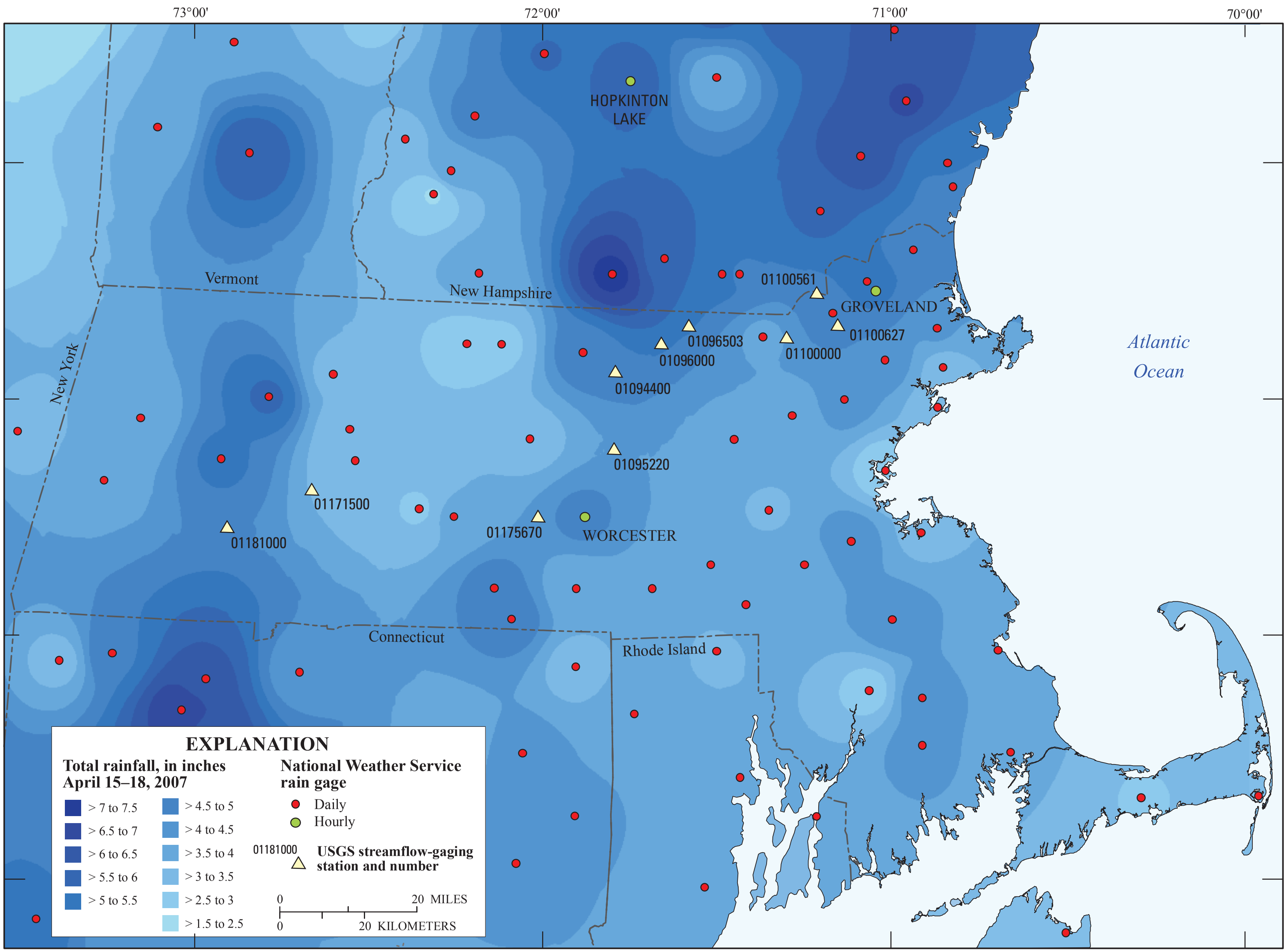


Figure 2. Daily mean period-of-record flow percentiles and 2007 flows at *(A)* Squannacook River near West Groton (01096000) and *(B)* West Branch Westfield River near Huntington (01181000), Massachusetts.



Base from U.S. Geological Survey and MassGIS data sources, Massachusetts State Plane Coordinate System, Mainland Zone.

Figure 3. Total precipitation from April 15 through 18, 2007, in and around Massachusetts.

Table 2. Precipitation and antecedent conditions associated with the April 2007 flooding at three climate stations in Massachusetts (MA) and New Hampshire (NH).

[EDT, Eastern Daylight Savings Time; hrs, hours; in, inches; in/hr, inches per hour; >, greater than; COOP-ID, National Weather Service station cooperative identification number; station location shown in figure 3]

Station	COOP-ID	Begin			Storm characteristics			
		Date	Time a.m. (EDT)		Duration (hrs)	Volume (in)	Average intensity (in/hr)	Maximum intensity (in/hr)
Groveland, MA	193276	4/15/2007	9:00		99	5.11	0.05	0.39
Worcester, MA	199923	4/15/2007	7:00		90	4.63	0.05	0.44
Hopkinton Lake, NH	274218	4/15/2007	11:00		68	5.70	0.08	0.40
Antecedent conditions								
Station	Time since total precipitation (hrs)				Antecedent rainfall (in)			
	>0 in	>0.2 in	> 0.5 in	>1.0 in	24 hrs	48 hrs	72 hrs	168 hrs
Groveland, MA	50	50	50	238	0.00	0.00	0.87	0.87
Worcester, MA	60	60	60	60	0.00	0.00	1.03	1.03
Hopkinton Lake, NH	60	60	60	236	0.00	0.00	0.90	1.00

Annual Peak Flows

Recorded and estimated annual peak flows at the streamflow-gaging stations provide a historical perspective on the magnitude of the April 2007 flood to prior flood flows. Systematic annual peak flows are recorded and maintained in the USGS National Water Information System (NWIS) Peak Flow File (PFF) available at http://nwis.waterdata.usgs.gov/usa/nwis/peak. The PFF provides key information necessary for the computation of the magnitude and frequency of flood flows, which in turn provide the foundation for flood insurance studies and other purposes such as bridge design.

Annual peak-flow data are generally limited to the period of streamflow-gaging station operation that varied from 1 to 84 years for the stations examined in this study. Occasionally, peak flow data outside the systematic streamflow record are entered into the PFF. These peaks are tagged as historical in the database and have special meaning in the way they are treated in peak-flow frequency analysis. Only one station, Merrimack River at Lowell (01100000), had a peak in the PFF outside the systematic record that occurred on April 23, 1852 (108,000 ft^3/s). Because of a special circumstance at this site, an analysis was made of post-flood control peaks treating the two highest peaks of record (1936 and 1938) as historical peaks adjusted for the effects of flood control as described later in the report.

To provide a common period of comparison, the variable-length peak-flow records for the streamflow-gaging stations were augmented by extending records from the beginning of the period of record back to the 1936 water year. The 1936 water year was chosen as a common starting base because it represents the highest known peak flow in some parts of the state, or includes the period of highest flow, notably the floods of 1938 and 1955. The 72 years of estimated and observed annual peak-flow record also provide a sufficient period of time to place the April 2007 peak discharge into historical context and to minimize the effects of the regional skew values used in the peak-flow frequency analysis.

Records that were extended were done so by a mathematical procedure developed by Hirsch (1982) known as Maintenance of Variance Extension (MOVE-1). MOVE-1 preserves the statistical moments of the data, namely the means and standard deviations of the log-transformed annual peaks at the short-term station to the long-term station. At two stations, Nissitissit River at Pepperell (01096503) and Shawsheen River at Andover (01100627), the record length was insufficient (1 year) to apply this method to annual peaks; therefore, selected independent storm peak flows were used in the MOVE-1 analysis.

Scatterplots of log-transformed concurrent annual peak-flows or independent storm-peak flows show the relation between the short-term and long-term streamflow-gaging station records. The long-term station, herein referred to as the index station, was selected on the basis of its proximity to the short-term station. In some instances, two or three index stations were used in the analysis because they spatially straddle the short-term station, and the results of these multiple station analyses reveal the range of potential discharges. In some cases, the estimated flows represent a weighted average of flows determined from each index station determined on the basis of the root mean square error (RMSE). The RMSE is determined by the square root of the average squared differences between observed and estimated peak flows for the period of concurrent record.

Magnitude and Frequency of Flood Flows

An important consideration in flood-risk management and in the development of local flood-insurance studies is the determination of the magnitude of peak flow for selected exceedance probabilities. The inverse of the exceedance probability is the expected return interval of a flood flow. For example, a flow with a 1-percent exceedance probability (0.01) has a 1-percent chance of being equaled or exceeded in a given year, or as more commonly expressed, an expected return interval of once every 100 years. For convenience, magnitude of flood flows are generally referred to in this report in terms of return interval and are given at 5, 10, 25, 50, 100, 200, and 500 years, which correspond to annual exceedance probabilities of 0.20, 0.10, 0.04, 0.02, 0.01, 0.005, and 0.002, respectively. However, as noted the flows associated with these return intervals can occur in any given year, but the likelihood of that flow occurring in a given year decreases as the return interval increases.

Although floods at low exceedance probabilities are rare and expected to occur infrequently, they can and often do occur with greater frequency than expected. This is partly because of the nature of probability theory, which represents the magnitude of a flood for a given exceedance probability over the long term defined around a stationary mean and variance. Milly and others (2008) have raised questions about the appropriateness of traditional probability methods in the midst of changing basin and climatic characteristics. Nevertheless, standard hydrologic methods were used to determine the magnitude and frequency of flood flows because they are still widely accepted and non-stationary methods are still in their infancy.

The magnitude and frequency of flood flows were determined at each of the streamflow-gaging stations by use of the computer program PeakFQ (Flynn and others, 2006). PeakFQ analyzes annual peak flows following guidelines in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). The period of systematic peak-flow data from six stations with records dating back to 1972 or earlier were analyzed with PeakFQ. The combined recorded and estimated annual peak flows estimated with MOVE-1 as described above were also analyzed with PeakFQ for all but one of the stations examined in this study. The exception is the West Branch of the Westfield River near Huntington (01181000), which has streamflow records dating back to 1935 and are not appreciably affected by regulation; hence, no record extension was necessary at this station.

In general, PeakFQ fits the logarithms of the annual peak flows to a Pearson Type III probability distribution function to calculate the discharge over a range of annual recurrence intervals from about 1 to 500 years (exceedance probabilities 0.995 to 0.002, respectively). PeakFQ also calculates the discharges at the 95-percent confidence limits over the range of annual recurrence intervals. Parameters of the Pearson Type III frequency curve are estimated from the logarithmic sample moments (mean, standard deviation, and coefficient of skewness). Adjustments to the Pearson Type III parameters are made for low outliers, high outliers, historic peaks, and generalized skew. No outliers were detected in the data sets examined, and therefore, no adjustment was needed for outliers. Historical peak adjustments were made only for the Merrimack River at Lowell analysis for post-flood control peak-flow analysis as described later in the report.

The skew calculated from the systematic station annual peak flows can greatly affect the shape of the probability distribution function. This is particularly true of stations with short records that are heavily leveraged by extreme events. To compensate, Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) specifies a weighting procedure calculated from the station skew and a generalized skew value to improve the accuracy of the probability distribution skew used in the peak-flow frequency analysis. Generalized skews have not been calculated for Massachusetts, and the program defaults to the skews determined from a national database of systematic peak-flow records up to 1973 (Interagency Advisory Committee on Water Data, 1982). Because these regional skew values are outdated, generalized skews for the stations used in this analysis were estimated from recent regionalized skew values determined for neighboring states (Ahearn, 2003; Lumia and Baevsky, 2000; Olson, 2002 and 2009). The generalized skews determined for the neighboring states do not always align with each other, but in general were less than the national skews for this region. The generalized skew specified for each station is given in the analysis section for that station. The effect of the specified skews on the station peak-flow frequency analysis increased as the period of record decreased, but their effect on the extended peak-flow record analysis was minimal.

At some stations, the two-station comparison method (Bulletin 17B, Appendix 7; Interagency Advisory Committee on Water Data, 1982) was used to adjust the logarithmic mean and standard deviation of the short-term station peak-flow record to a nearby long-term station peak-flow record. The skew used in this analysis was determined from the weighted station skew described above. The two-station comparison method was employed in the peak-flow frequency analysis at five streamflow-gaging stations. At the other five stations, the systematic annual peak-flow record was either too short or too long to warrant use of this method.

The Nissitissit River at Pepperell (01096503) and Spicket River near Methuen (01100561) streamflow-gaging stations began operation in March 2006 and March 2001, respectively. Their short records and the fact that most of these basins lie within southern New Hampshire made these sites suitable for estimating the magnitudes of floods using recently developed multiple linear-regression flood-flow equations for New Hampshire (Olson, 2009). The Shawsheen River at Andover station (01100627) began operation in October 2006; therefore, the upstream station on the Shawsheen River near Wilmington (01100600), which has been in operation since November 1963, was used in the peak-flow frequency analysis. The results of these analyses were then adjusted by the ratio of the drainage areas of the Andover and Wilmington stations to estimate the magnitude of flood flows for various return intervals at Andover.

Flood-Insurance Studies and Flood-Warning Levels

Flood-insurance studies provide water-surface profiles for 10-, 50-, 100-, and 500-year floods calculated from hydraulic analysis of the river's conveyance and other hydrologic properties. This analysis entails simulating the water-surface elevation, typically with an early version of the HEC-2 step-backwater program (Bonner, 1988) that was commonly in use at the time most of these studies were done. The peak flows at selected return intervals were used to simulate water-surface profiles. These flows were determined by one or more of the following methods—(1) log-Pearson Type III analysis of the available systematic peak-flows at streamflow-gaging stations at the time of the study, (2) interpolation on the basis of drainage area from calculated magnitudes of peak flows for given return frequencies at a nearby streamflow-gaging station, and (3) regional regression equations for estimating the magnitude of peak flows.

The April 2007 peak river stage was compared to the flood elevation reported in various flood-insurance studies and to the NWS flood-warning elevation, if available. Flood flows and flood elevations for various return intervals from the flood-insurance studies were compared to those determined as part of this study. These comparisons were made by determining the river elevation for flood flows at various return intervals on the basis of the current (2008) stage-discharge relation (rating curve) at the streamflow-gaging station. In some instances, flood flows were determined from the flood-insurance study flood-profile elevations at the streamflow-gaging station and the rating curve in use at the time of the study. If reported, the flood flows used in the flood-insurance study step-backwater analysis were compared to flood flows at various return intervals determined in this study.

Table 3. Streamflow-gaging stations and support stations used to characterize the April 2007 flood in Massachusetts.

[NH, New Hampshire; mi², square miles; EOEEA, Massachusetts Executive Office of Energy and Environmental Affairs; --, not applicable]

U.S. Geological Survey streamflow-gaging station		Record begins	Drainage area (mi^2)	EOEEA basin	Support stations		
Name	Number						
North Nashua River at Fitchburg	01094400	Oct. 1972	64.2	Nashua	01094500		
Stillwater River near Sterling	01095220	Apr. 1994	31.6	Nashua	01094500		
Squannacook River near West Groton	01096000	Oct. 1949	63.7	Nashua	01094500		
Nissitissit River at Pepperell	01096503	Mar. 2006	59.6	Nashua	01094500	01096000	
Merrimack River at Lowell	01100000	Jun. 1923	4,635	Merrimack	01076500	01078000	01094500
Spicket River near Methuen	01100561	Mar. 2001	62.1	Merrimack	01094500	01101500	
Shawsheen River at Andover	01100627	Oct. 2006	72.8	Shawsheen	01094500	01100600	01102000
Mill River at Northampton	01171500	Oct. 1938	52.6	Connecticut	01176000	01181000	
Sevenmile River near Spencer	01175670	Feb. 1961	8.81	Chicopee	01094500	01176000	
West Branch Westfield River near Huntington	01181000	Sep. 1935	94.0	Westfield			
Support stations used in analysis							
Pemigewasset River at Plymouth, NH	01076500	Oct. 1903	622	--			
Smith River near Bristol, NH	01078000	May 1918	85.8	--			
North Nashua River near Leominster	01094500	Sep. 1935	110	Nashua			
Shawsheen River near Wilmington	01100600	Nov. 1963	36.5	Shawsheen			
Ipswich River at South Middleton	01101500	Jun. 1938	44.5	Ipswich			
Ipswich River near Ipswich	01102000	Jun. 1930	125	Ipswich			
Quaboag River at West Brimfield	01176000	Aug. 1909	150	Chicopee			

Characteristics of the April 2007 Flood at Selected Streamflow-Gaging Stations

The discharge characteristics at the selected streamflow-gaging stations are presented in order of their USGS identification number. Seven of the streamflow-gaging stations are in the Merrimack River Basin and three are in the Connecticut River Basin. The data available for the streamflow-gaging stations range from 1 to 84 years of record (table 3) and, thus, the methods used to characterize the April 2007 flood flows varied accordingly. For most streamflow-gaging stations, a nearby station or stations with records dating back to 1936 were used to extend the annual peak-flow records for analysis; the support stations are also listed in table 3 and shown in figure 1.

North Nashua River at Fitchburg–01094400

Annual peak flows recorded at North Nashua River at Fitchburg span a 35-year period, water years 1973 through 2007. The April 2007 peak discharge (3,930 ft^3/s) was the highest recorded and exceeded the previously recorded peak flow in the 1987 water year by about 12 percent. Annual peak flows at North Nashua River at Fitchburg were estimated from 1936 through 1972 by MOVE-1 using the 35 years of concurrent record with the downstream gaging station at North Nashua River at Leominster (01094500). The drainage area above the Leominster station is about twice that above the Fitchburg station (110 and 64.2 mi^2, respectively). MOVE-1 analysis indicates a strong relation between peak flows at the Fitchburg and Leominster stations (fig. 4), RMSE of 258 ft^3/s. Estimated peak flows from 1936–72 exceeded the April 2007 peak in water years 1936, 1938, 1944, and 1956 by about 98, 32, 7, and 16 percent, respectively (fig. 5).

The return period of the April 2007 peak discharge was determined from the period of record (1973–2007), the two-station comparison method, and the MOVE-1 extended record analyses (1936–2007). The peak-flow database indicates that discharge is affected to unknown degree by regulation. There are 11 dams with small to moderate-size impoundments on the river and its tributaries. None are known to be operated for flood control, but storage behind these impoundments could affect peak flows, particularly for small, frequent floods. The two-station comparison method utilized the 72-year peak-flow record for the North Nashua River at Leominster station (01094500). A generalized skew of 0.32 was specified in the PeakFQ analysis on the basis of region skew coefficients for southern New Hampshire (Scott Olson, USGS, written commun., 2008). A weighted skew of 0.38 computed by PeakFQ from the regional skew and the 1936–2007 systematic peak-flow record skew was specified in the two-station peak-flow analysis.

The return interval of the April 2007 peak discharge (3,930 ft^3/s) at North Nashua River at Fitchburg determined from the 1936–2007 record is about 25 years and is within the 95-percent confidence limits for discharges with a 25-year return interval (table 4; fig. 6). The two-station comparison method produced results similar to those produced by the extended record analysis. The period-of-record peak-flow analysis (1973–2007) indicates the April 2007 peak discharge has nearly a 50-year return interval and is within the 95-percent confidence limits for discharges with 25- to 100-year return intervals (table 4).

The flood-insurance study revised in 1991 for the City of Fitchburg area (FEMA, 1991) indicates that the April 2007 peak stage (403.48 ft) was between a 10- and 50-year flood stage (fig. 7A). During the April 2007 storm, the river remained above the NWS flood stage (401.39 ft) for about 1 day (fig. 7A) and exceeded the NWS flood stage by about 2.1 ft at its maximum stage (403.48 ft). The return interval of the April 2007 peak discharge determined from the extended-record peak-flow analysis made in this study was about 25 years and greatly exceeded the flood-insurance study 10-year flood (fig. 7B).

Although the flood-insurance-study stage and the peak-flow analysis return period of the April 2007 storm were in general agreement, there were appreciable differences between the studies. In general, the flood-insurance-study discharge and stage became increasingly greater relative to the findings in this study as the return interval increased (table 5). Discharges used in the flood-insurance study for the North Nashua River interpolated between the downstream corporate limits and the confluence with Baker Brook (FEMA, 1991, table 1) to estimate flow at the Fitchburg streamflow-gaging station were about 54, 130, 144, and 189 percent greater for return intervals of 10, 50, 100, and 500 years, respectively, than the discharges determined for the same return intervals in this study. Converting the flood-insurance study flood stage at various return intervals to discharge from the streamflow-gaging station stage-discharge rating in place at the time of the study (rating 9) also yielded discharges greater than those determined in this study except for the 10-year return interval, which was smaller. Likewise, converting discharges for various return intervals determined in this study into stage from the current stage-discharge rating (12.1) yielded flood stages that generally were lower than those shown in the flood profile at the streamflow-gaging station (FEMA, 1991, plate 03P, at 17,360 ft from corporate limit). Flood stage in this study is about 1.9 ft higher for a 10-year return interval and about 2.6, 3.9, and 9.2 ft lower for 50-, 100-, and 500-year return intervals, respectively, than the stage reported in the flood-insurance study. Ratings 9 and 12.1 are identical at high flows and are estimated above a stage of 401 ft (gage datum of 6 ft).

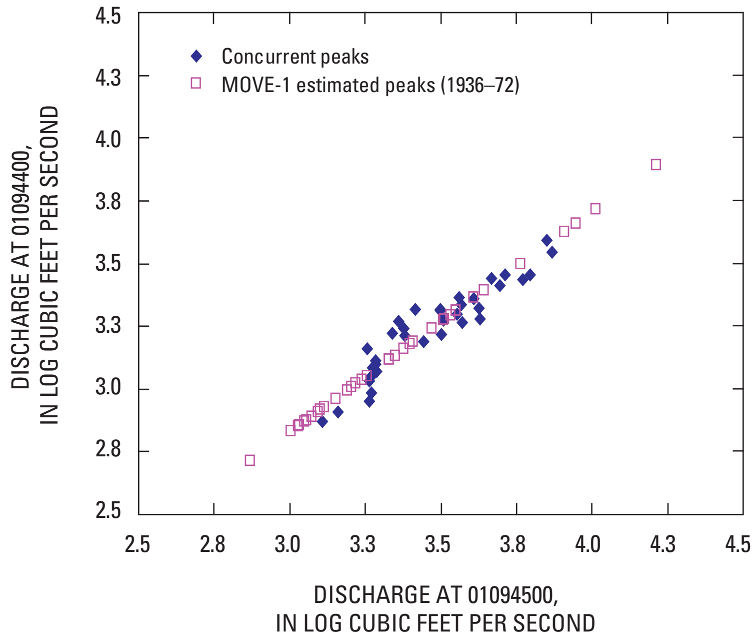


Figure 4. Relation between observed annual peak discharges for water years 1973 through 2007 at North Nashua River at Fitchburg (01094400) and North Nashua River at Leominster (01094500), Massachusetts.

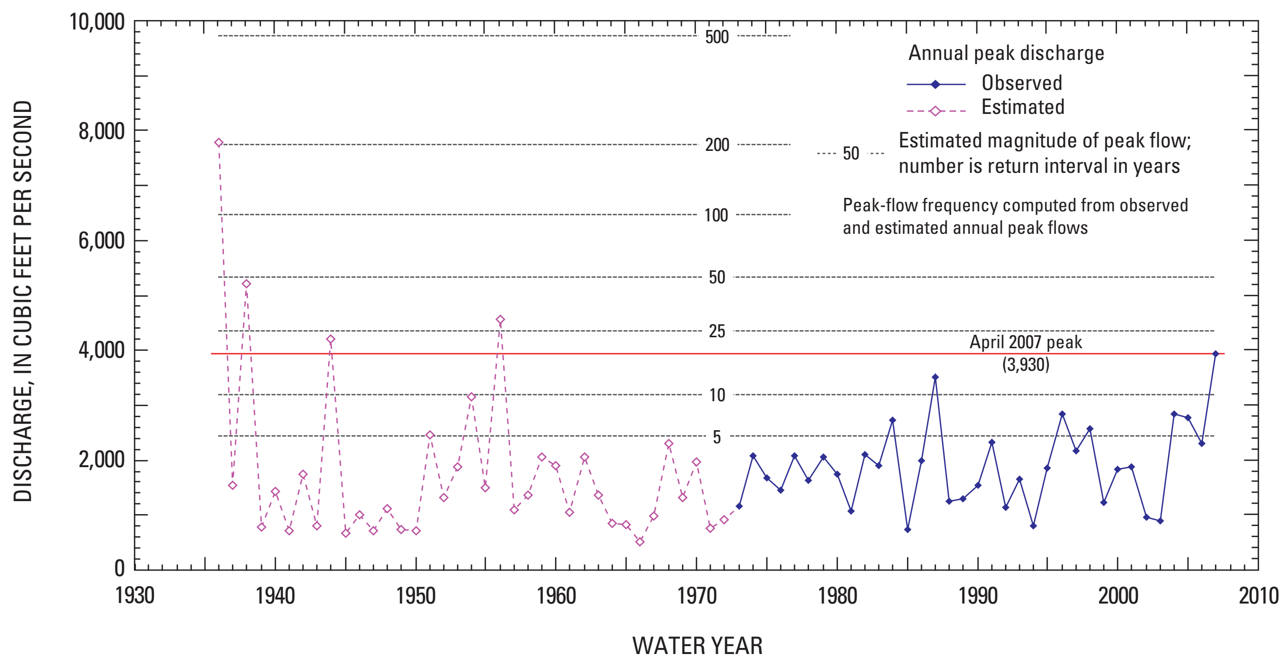


Figure 5. Observed and estimated annual peak discharge for water years 1936 through 2007 at North Nashua River at Fitchburg (01094400), Massachusetts.

Table 4. Magnitude and confidence limits of flood flows at selected return intervals at North Nashua River at Fitchburg (01094400), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second								
		Period-of-record analysis (1973–2007)			Extended-record analysis (1936–2007) with North Nashua River at Leominster (01094500)					
					Two-station comparison[1]			MOVE-1 extended record[2]		
		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit	
			Lower	Upper		Lower	Upper		Lower	Upper
5	0.2	2,460	2,170	2,870	2,420	2,150	2,780	2,430	2,160	2,780
10	0.1	2,940	2,560	3,540	3,160	2,750	3,730	3,200	2,790	3,760
25	0.04	3,560	3,030	4,450	4,240	3,600	5,220	4,340	3,700	5,310
50	0.02	4,030	3,370	5,170	5,180	4,310	6,560	5,340	4,450	6,720
100	0.01	4,500	3,710	5,920	6,240	5,090	8,130	6,470	5,290	8,370
200	0.005	4,980	4,050	6,700	7,430	5,940	9,940	7,750	6,220	10,300
500	0.002	5,620	4,490	7,790	9,240	7,210	12,800	9,720	7,600	13,400

[1] Computed following Bulletin 17B, Appendix 7 guidelines (Interagency Advisory Committee on Water Data, 1982).

[2] Estimated annual-peak flows 1936–72 using MOVE-1 method (Hirsch, 1982).

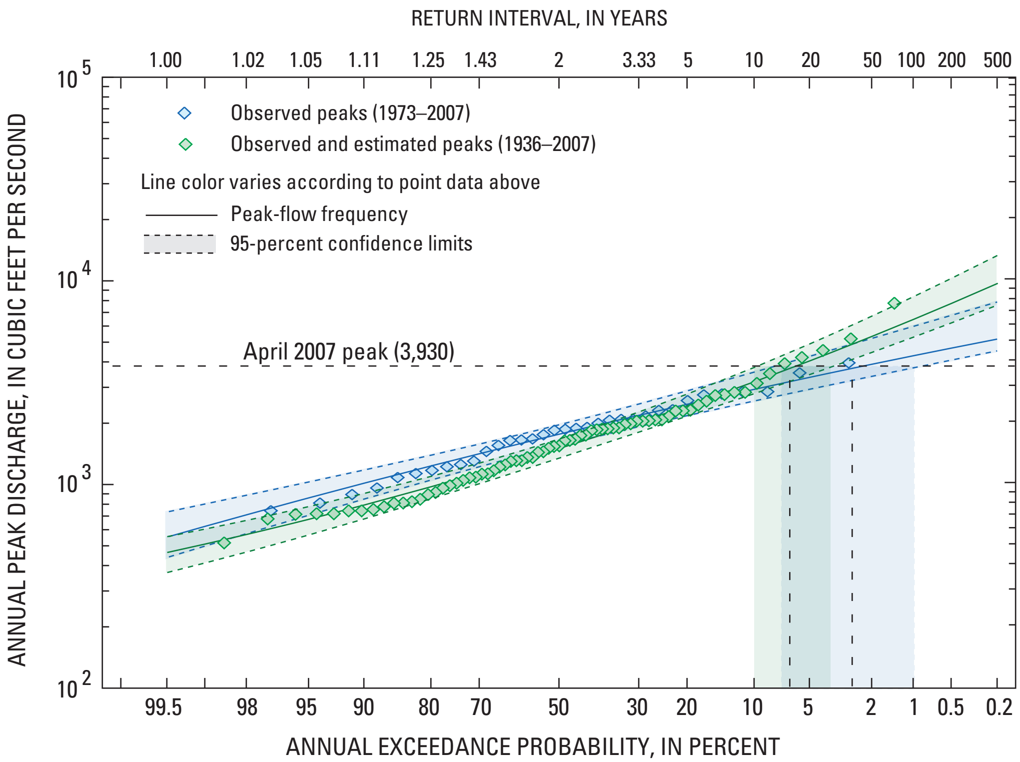


Figure 6. Peak-flow frequency computed from observed and estimated annual peaks at North Nashua River at Fitchburg (01094400), Massachusetts.

Table 5. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for North Nashua River at Fitchburg (01094400), Massachusetts.

[ft, feet NGVD 29; ft³/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft³/s)	[4]Discharge rating 12.1 (ft³/s)	[5]Discharge (ft³/s)	[4]Stage rating 12.1 (ft)	Stage (ft)	Discharge Table 1 (ft³/s)	Discharge Rating (ft³/s)
5	--	--	--	2,430	402.1	--	--	--
10	400.9	4,920	1,330	3,200	402.8	1.9	-1,720	1,870
25	--	--	--	4,340	403.8	--	--	--
50	407.1	12,260	8,200	5,340	404.5	-2.6	-6,920	-2,860
100	409.4	15,780	12,400	6,470	405.5	-3.9	-9,310	-5,930
200	--	--	--	7,750	406.2	--	--	--
500	416.9	28,080	23,000	9,720	407.7	-9.2	-18,360	-13,280

[1] Town of Fitchburg flood-insurance study (FEMA, 1991).

[2] Flood stages at streamflow-gaging station; 17,360 ft from corporate limit on flood profile (FEMA, 1991, pl. 03P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1991; table 1, weighted by drainage area ratio between values at corporate limit and confluence with Baker Brook).

[4] Stage determined from rating number 12.1; above 400 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record.

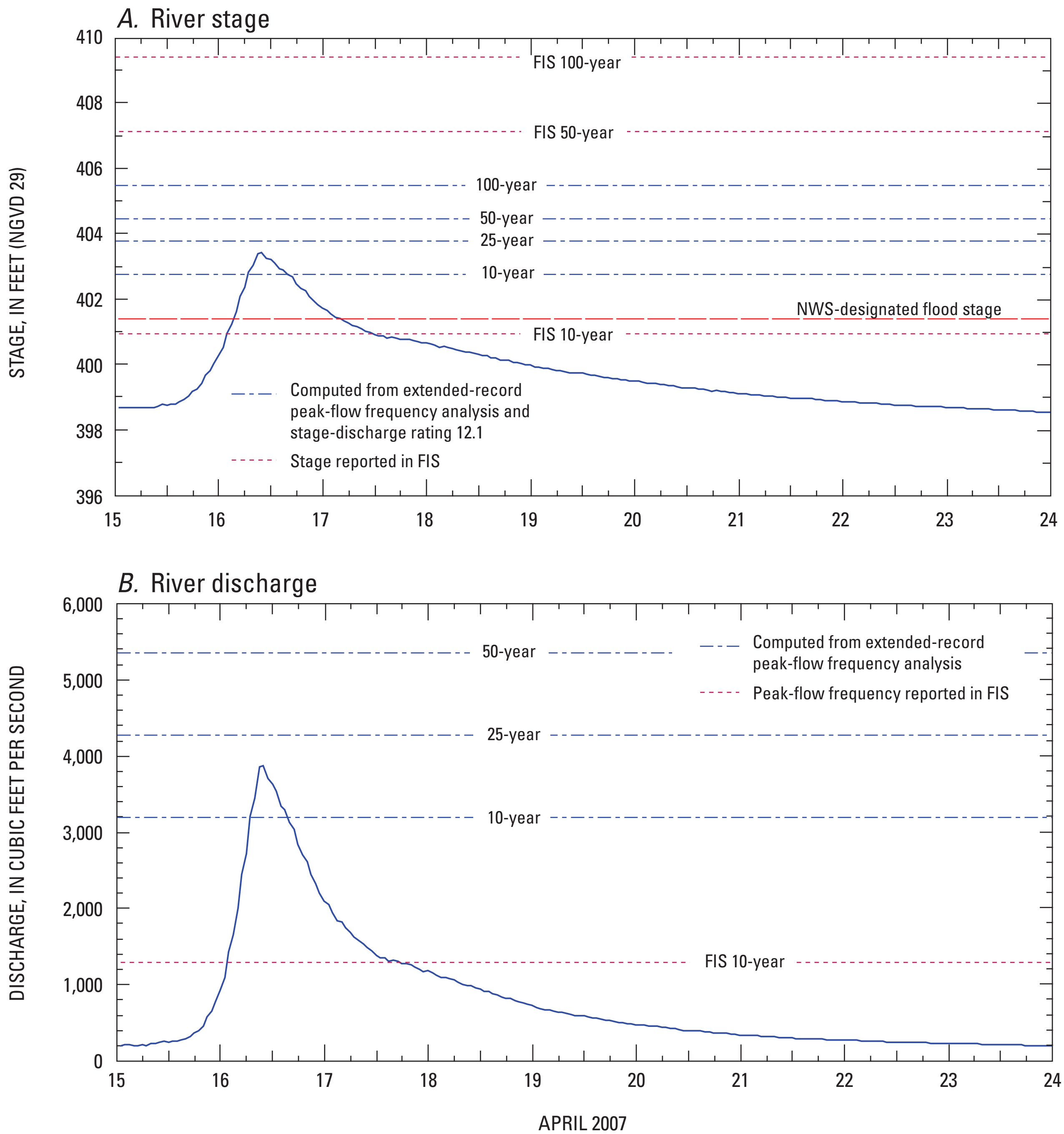


Figure 7. April 15–23, 2007, *(A)* stage and *(B)* discharge at North Nashua River at Fitchburg (01094400), Massachusetts. [NWS, National Weather Service; FIS, flood-insurance study by FEMA (1991)]

Stillwater River near Sterling–01095220

Annual peak flows recorded at Stillwater River near Sterling span a 13-year period, water years 1995 through 2007. The April 2007 peak discharge (1,850 ft^3/s) was the highest recorded and exceeded the previously recorded peak flow in the 2004 water year by about 35 percent. Annual peak flows at Stillwater River near Sterling from 1936 through 1994 were estimated by MOVE-1 using the 13 years of concurrent record with North Nashua River at Leominster (01094500); the basin centroid lies about 7.7 mi north of the Stillwater River Basin centroid (in this report, "basin centroid" refers to the geographic center of the streamflow-gaging station drainage basin depicted in figure 1). The MOVE-1 analysis indicates peak flows at Stillwater River and North Nashua River at Leominster are closely related (fig. 8, RMSE 770 ft^3/s). Estimated peak flows for 1936–94 exceeded the April 2007 peak in water years 1936, 1938, 1944, 1956, and 1987 by about 104, 35, 9, 18, and 1 percent, respectively (fig. 9).

The return period of the April 2007 peak flow was determined by the two-station comparison method and analysis of the extended record (1936–2007). The peak-flow analysis from the period of record (1995–2007) was not made because the record was considered to be of insufficient length. Streamflow at Stillwater River near Sterling is considered unregulated. The two-station comparison method utilized the 72-year peak-flow record at North Nashua River at Leominster (01094500). A generalized skew of 0.30 was specified in the PeakFQ analysis on the basis of the regional skews reported for southern New Hampshire and Connecticut. A weighted skew of 0.42 computed by PeakFQ from the regional skew and the systematic record for the 1936–2007 period was specified in the two-station peak-flow analysis.

The April 2007 peak discharge at Stillwater River near Sterling (1,850 ft^3/s) has a return interval of 10 to 25 years as determined from the 1936–2007 record analysis (fig. 10), but is within the 95-percent confidence limits for discharges with a 25-year return interval (table 6). Peak-flow analysis determined by the two-station comparison method produced similar results, with the exception that the April 2007 peak discharge is within the 95-percent confidence limits for discharges with a return interval 10 to 25 years (table 6).

The flood-insurance study completed in 1981 for the Town of Sterling (FEMA, 1981) indicates that the April 2007 peak stage (406.15 ft) was between a 50- and 100-year flood stage (fig. 11A). Stillwater River at Sterling is not part of the NWS Advanced Hydrologic Prediction network; therefore, a flood-warning stage is not available. The April 2007 peak discharge exceeded the discharge for a 50-year return interval flood as determined in the flood-insurance study (fig. 11B), whereas it was between a 10- and 25-year flood as determined from the extended record peak-flow analysis made in this study.

The flood-insurance-study stage and the peak-flow for various return intervals was lower than those determined from the extended-record peak-flow analysis made during this study (table 7). The extended-record peak-flow analysis values are similar to the results of the two-station analysis (table 6). In general, discharges for various return intervals used in the flood-insurance study at the location of the streamflow-gaging station (FEMA, 1981; table 1–Stillwater River at Muddy Pond Road) were about 25 percent less than the discharges for the same return intervals determined in this study. Converting the flood-insurance-study flood stage at various return intervals to discharge with the streamflow-gaging station rating 4 also yielded discharges that were lower than those determined in this study; as a percentage, the differences decreased as the return interval increased. Likewise, converting discharges for various return intervals determined in this study into stage from the stage-discharge rating (4) yielded flood stages that were higher than those shown in the flood profile at Muddy Pond Road (FEMA, 1981; plate 03P at the corporate limit). Flood stages as determined by the extended record analysis in this study relative to those reported in the flood-insurance study were about 1.4, 1.2, 1.0, and 0.7 ft higher for floods with return periods of 10-, 50-, 100-, and 500-years, respectively. The flood profile indicates the stage changes rapidly near the gage location, particularly for the 500-year return-interval flood profile, which may explain some of the differences. Rating 4 was used exclusively because it was best defined by high-flow measurements, but the rating was still estimated above 406 ft (gage datum of 9 ft).

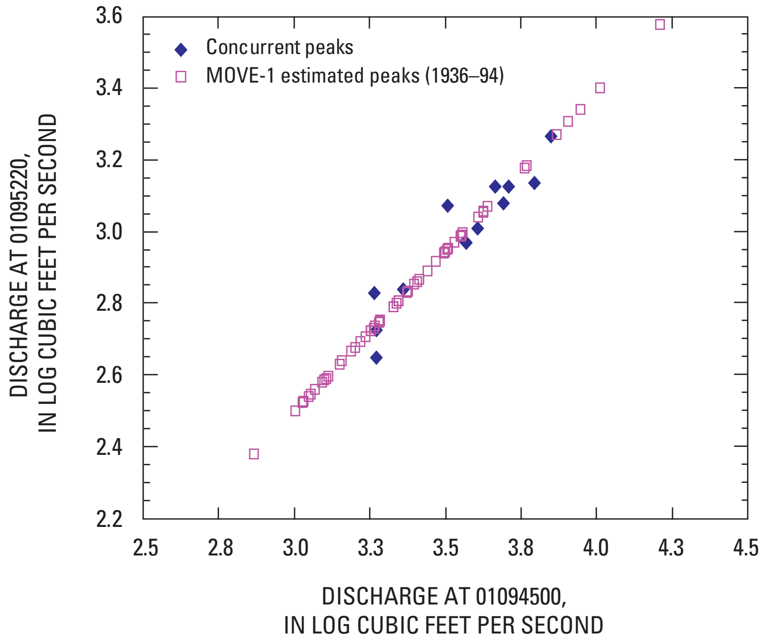


Figure 8. Relation between observed annual peak discharges for water years 1995 through 2007 at Stillwater River near Sterling (01095220) and North Nashua River at Leominster (01094500), Massachusetts.

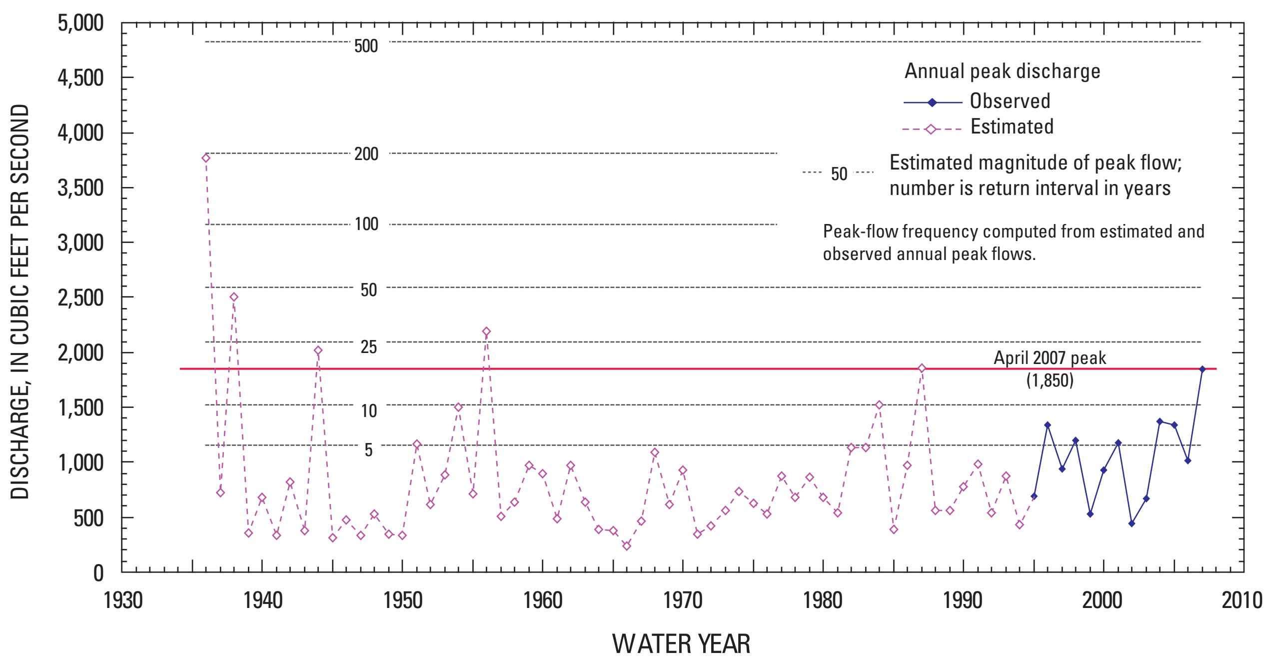


Figure 9. Observed and estimated annual peak discharge for water years 1936 through 2007 at Stillwater River near Sterling (01095220), Massachusetts.

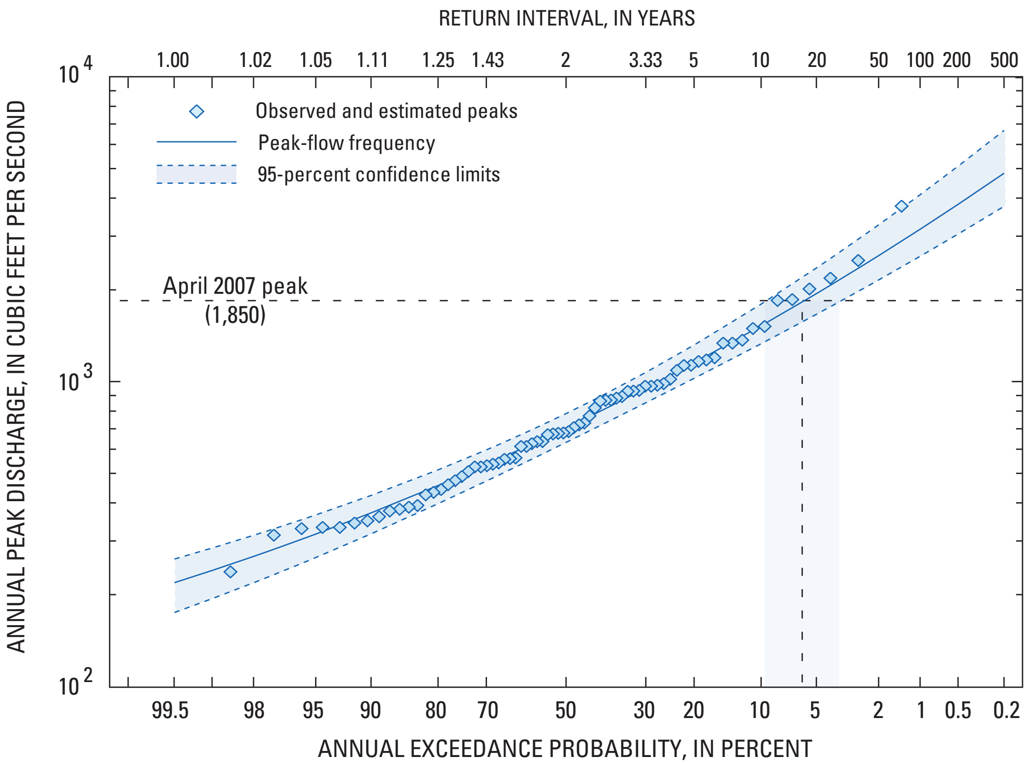


Figure 10. Peak-flow frequency computed from observed and estimated annual peaks for water years 1936 through 2007 at Stillwater River near Sterling (01095220), Massachusetts.

Table 6. Magnitude and confidence limits of flood flows at selected return intervals at Stillwater River near Sterling (01095220), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second — Extended-record analysis (1936–2007) with North Nashua River at Leominster (01094500) — Two-station comparison[1]: Expected peak	Two-station comparison[1]: 95-percent confidence limit, Lower	Two-station comparison[1]: 95-percent confidence limit, Upper	MOVE-1 extended record[2]: Expected peak	MOVE-1 extended record[2]: 95-percent confidence limit, Lower	MOVE-1 extended record[2]: 95-percent confidence limit, Upper
5	0.2	1,160	1,010	1,370	1,150	1,030	1,320
10	0.1	1,520	1,300	1,860	1,520	1,330	1,800
25	0.04	2,070	1,710	2,670	2,090	1,780	2,560
50	0.02	2,550	2,050	3,410	2,590	2,160	3,270
100	0.01	3,090	2,430	4,290	3,160	2,580	4,100
200	0.005	3,710	2,850	5,330	3,820	3,050	5,090
500	0.002	4,670	3,480	7,000	4,830	3,760	6,670

[1] Computed following Bulletin 17B, Appendix 7 guidelines (Interagency Advisory Committee on Water Data, 1982).

[2] Estimated annual-peak flows 1936–94 using MOVE-1 method (Hirsch, 1982).

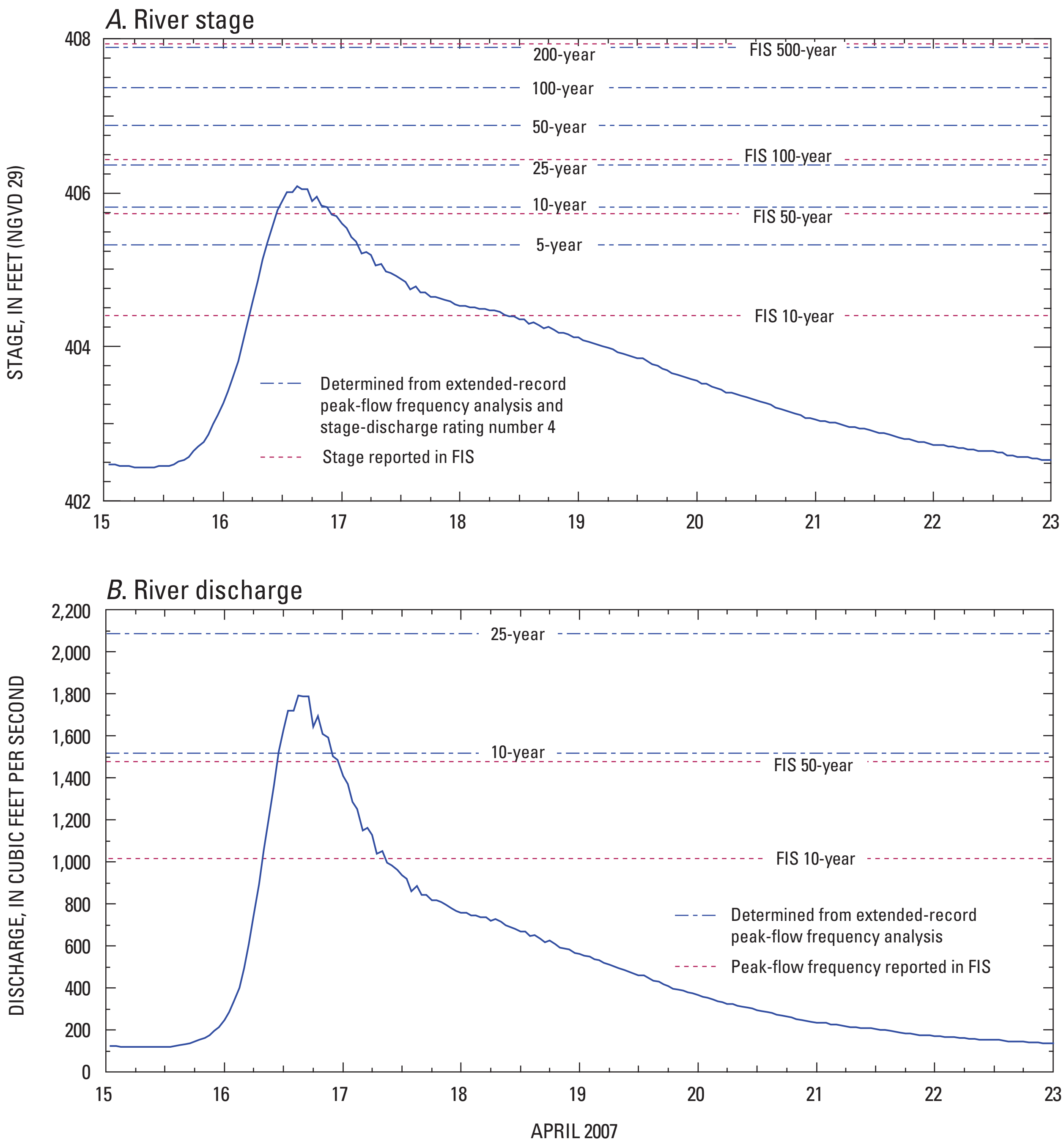


Figure 11. April 15–23, 2007, *(A)* stage and *(B)* discharge at Stillwater River near Sterling (01095220), Massachusetts. [FIS, flood-insurance study by FEMA (1981)]

Table 7. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Stillwater River near Sterling (01095220), Massachusetts.

[ft, feet NGVD 29; ft³/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft³/s)	[4]Discharge rating 4 (ft³/s)	[5]Discharge (ft³/s)	[4]Stage rating 4 (ft)	Stage (ft)	Discharge: Table 1 (ft³/s)	Discharge: Rating (ft³/s)
5	--	--	--	1,150	405.3	--	--	--
10	404.4	1,100	610	1,520	405.8	1.4	870	420
25	--	--	--	2,090	406.4	--	--	--
50	405.7	1,960	1,410	2,590	406.9	1.2	1,150	630
100	406.4	2,430	2,060	3,160	407.4	1.0	1,100	730
200	--	--	--	3,820	407.9	--	--	--
500	407.9	3,620	3,820	4,830	408.6	0.7	1,010	1,210

[1] Town of Sterling flood-insurance study (FEMA, 1981).

[2] Flood stages at streamflow-gaging station; at corporate limit on flood profile (FEMA, 1981, pl. 01P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1981; table 1, Stillwater River at Muddy Pond Road).

[4] Stage determined from stage-discharge rating number 4; above 406 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record.

Squannacook River near West Groton–01096000

Annual peak flows recorded at Squannacook River near West Groton span a 58-year period, water years 1950 through 2007. The April 2007 peak discharge (4,820 ft³/s) was the highest recorded and exceeded the highest previously recorded peak flow that occurred in the 1987 water year by about 14 percent. Annual peak flows from 1936 through 1949 were estimated by MOVE-1 using the 58 years of concurrent record with North Nashua River at Leominster (01094500); the basin centroid lies about 9.2 mi southwest of the Squannacook River Basin centroid. The MOVE-1 analysis indicates peak flows at Squannacook River and North Nashua River at Leominster are closely related (fig. 12; RMSE 1,513 ft³/s). Estimated peak flows during 1936–49 exceeded the April 2007 peak in water years 1936, 1938, and 1944 by about 118, 32, and 1 percent, respectively (fig. 13).

The return period of the April 2007 peak flow was determined from the period of record (1950–2007) by the two-station comparison method and by the extended-record (1936–2007) analyses. Streamflow at Squannacook River near West Groton is considered unregulated. The two-station comparison method utilized the 72-year peak-flow record at North Nashua River at Leominster (01094500). A generalized skew of 0.30 was specified in the PeakFQ analysis on the basis of regional skews reported for southern New Hampshire and Connecticut. The computed weighted skew of 0.38 was specified in the two-station peak-flow analysis.

The April 2007 peak discharge (4,820 ft³/s) at Squannacook River near West Groton determined from the 1936–2007 record has a return interval of about 25 years (fig. 14) and is within the 95-percent confidence limits for discharges with a 25-year return interval (table 8). Peak-flow analysis by the two-station comparison method produced results similar to those of the extended-record analysis. The 58-year period-of-record analysis places the April 2007 storm close to a 50-year return-interval discharge and within a much broader 95-percent confidence range of 25- to 100-year return interval (table 8).

The flood insurance study completed in 1982 for the Town of Groton (FEMA, 1982) indicates the April 2007 peak stage (252.77 ft) approached a 10-year flood stage (fig. 15A). The river stage was above the NWS-designated flood stage for nearly a day and peaked about 1.5 ft above the NWS flood stage. The return interval of the April 2007 peak discharge determined from the extended-record peak-flow analysis made in this study was between 10 and 25 years; the 10-year flood

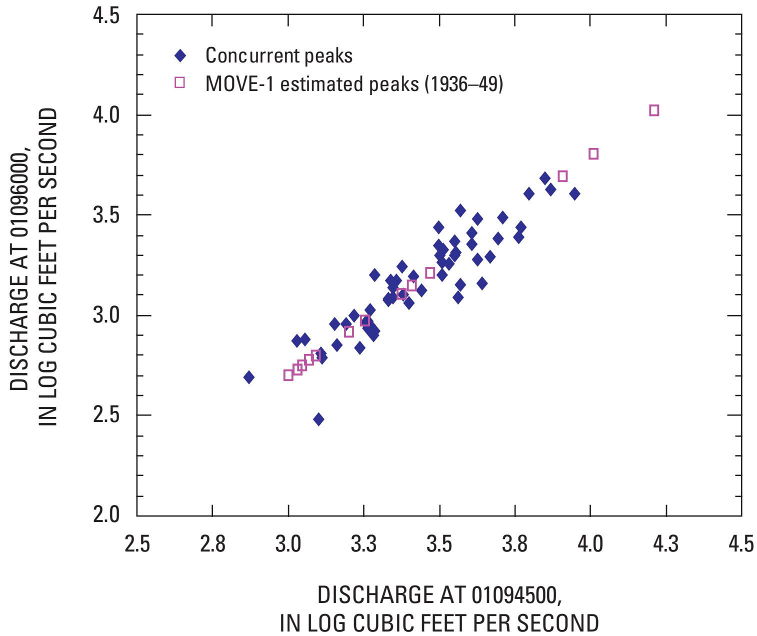


Figure 12. Relation between observed annual peak discharges for water years 1950 through 2007 at Squannacook River near West Groton (01096000) and North Nashua River at Leominster (01094500), Massachusetts.

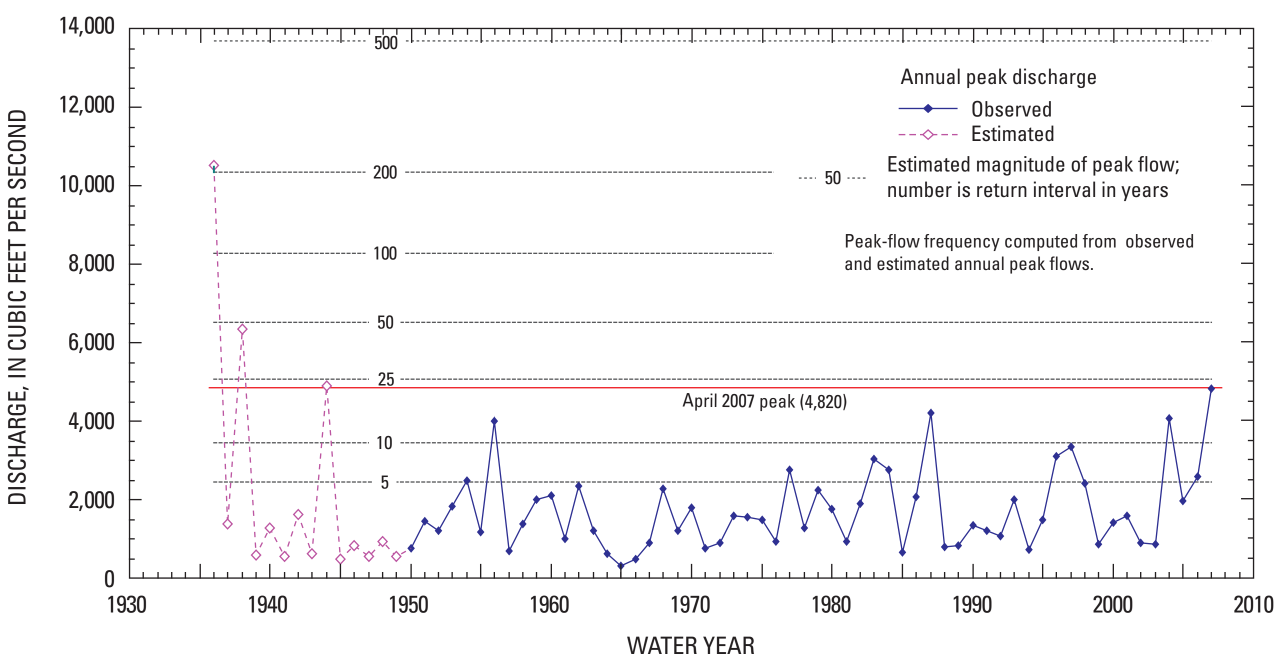


Figure 13. Observed and estimated annual peak discharge for water years 1936 through 2007 at Squannacook River near West Groton (01096000), Massachusetts.

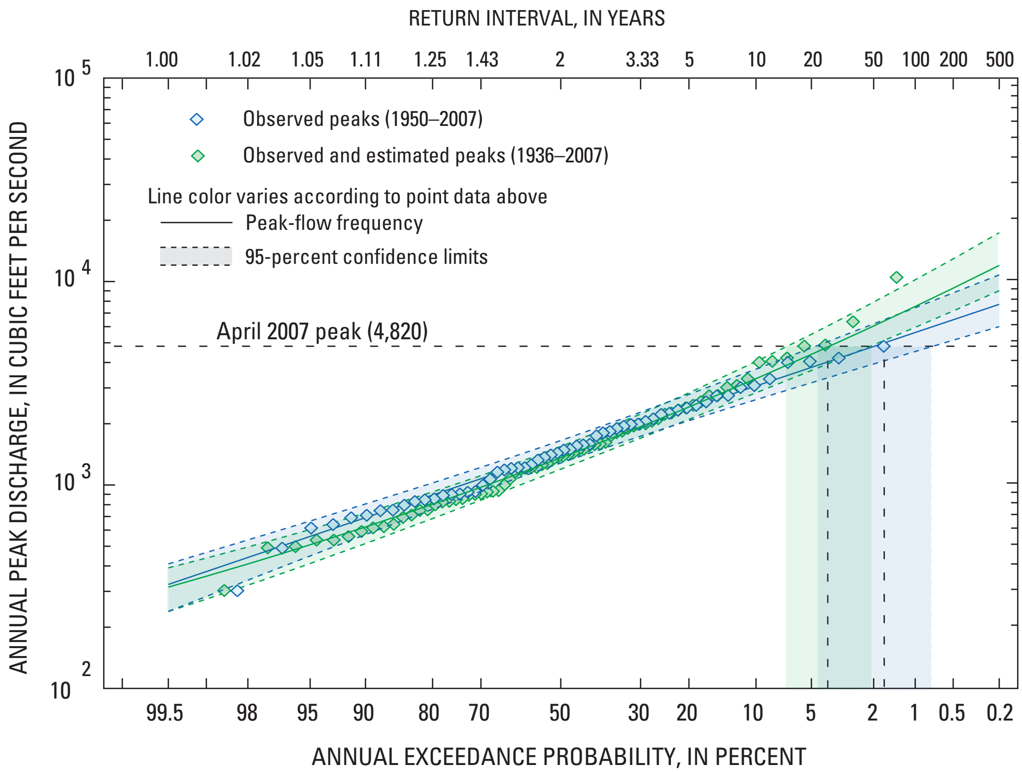


Figure 14. Peak-flow frequency computed from observed and estimated annual peaks for water years 1936 through 2007, Squannacook River near West Groton (01096000), Massachusetts.

discharge reported in the flood-insurance study is close to 10-year flood calculated in this study (fig. 11B).

The location of flood flows near the streamflow-gaging station reported in the flood-insurance study is uncertain (FEMA, 1982; table 1). The data row in the table indicates discharge in the Squannacook River was calculated at the confluence with the Nashua River, but the drainage area given at that location (62.8 mi^2) is about equal to the drainage area at the streamflow-gaging station (63.7 mi^2). The drainage area 0.2 mi upstream of the confluence is 73.0 mi^2, or about 16 percent more than stated; therefore, no adjustments were made to the discharge values reported in table 1. The flood-insurance-study stages and the peak flows at this location for various return intervals were slightly greater than those determined from the peak-flow analysis made during this study. The extended-record peak-flow analysis values are similar to the two-station-analysis values (table 8). The discharge values determined from the extended-record peak-flow analysis in this study are about 2 to 11 percent lower than the values given in the flood-insurance study for 10- and 500-year return intervals, respectively (table 9); the difference between discharges increases as the return interval increases.

Converting the flood-insurance-study flood stage at various return intervals to discharge with the streamflow-gaging station rating 22.1 yields discharges that were two or more times larger than those determined in this study. Conversely, converting discharges for various return intervals determined in this study into stage with the same rating yields lower flood stages for equivalent return intervals than those shown in the flood profile at the gage location (FEMA, 1982; plate 07P at 34,600 ft upstream from the confluence with the Nashua River). Flood stages in this study for 10-, 50-, 100-, and 500-year return intervals are about 1.8, 3.2, 3.7, and 5.1 ft lower, respectively, than in the flood-insurance study. Rating 22.1 was used exclusively because it was best defined by high-flow measurements, but the rating is still estimated above 252 ft (gage datum of 8.2 ft).

Table 8. Magnitude and confidence limits of flood flows at selected return intervals at Squannacook River near West Groton (01096000), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second: Period-of-record analysis (1950–2007)			Extended-record analysis (1936–2007) with North Nashua River at Leominster (01094500): Two-station comparison[1]			MOVE-1 extended record[2]		
		Expected peak	95-percent confidence limit: Lower	Upper	Expected peak	95-percent confidence limit: Lower	Upper	Expected peak	95-percent confidence limit: Lower	Upper
5	0.2	2,380	2,070	2,790	2,440	2,110	2,880	2,460	2,130	2,910
10	0.1	3,060	2,620	3,710	3,390	2,880	4,150	3,460	2,930	4,220
25	0.04	4,020	3,360	5,060	4,920	4,040	6,310	5,050	4,140	6,480
50	0.02	4,800	3,930	6,200	6,320	5,060	8,390	6,530	5,220	8,670
100	0.01	5,620	4,530	7,440	7,970	6,230	11,000	8,280	6,460	11,400
200	0.005	6,490	5,150	8,790	9,920	7,570	14,100	10,400	7,900	14,700
500	0.002	7,730	6,000	10,800	13,000	9,650	19,300	13,700	10,100	20,200

[1] Computed following Bulletin 17B, Appendix 7 guidelines (Interagency Advisory Committee on Water Data, 1982).

[2] Estimated annual-peak flows 1936–49 using MOVE-1 method (Hirsch, 1982).

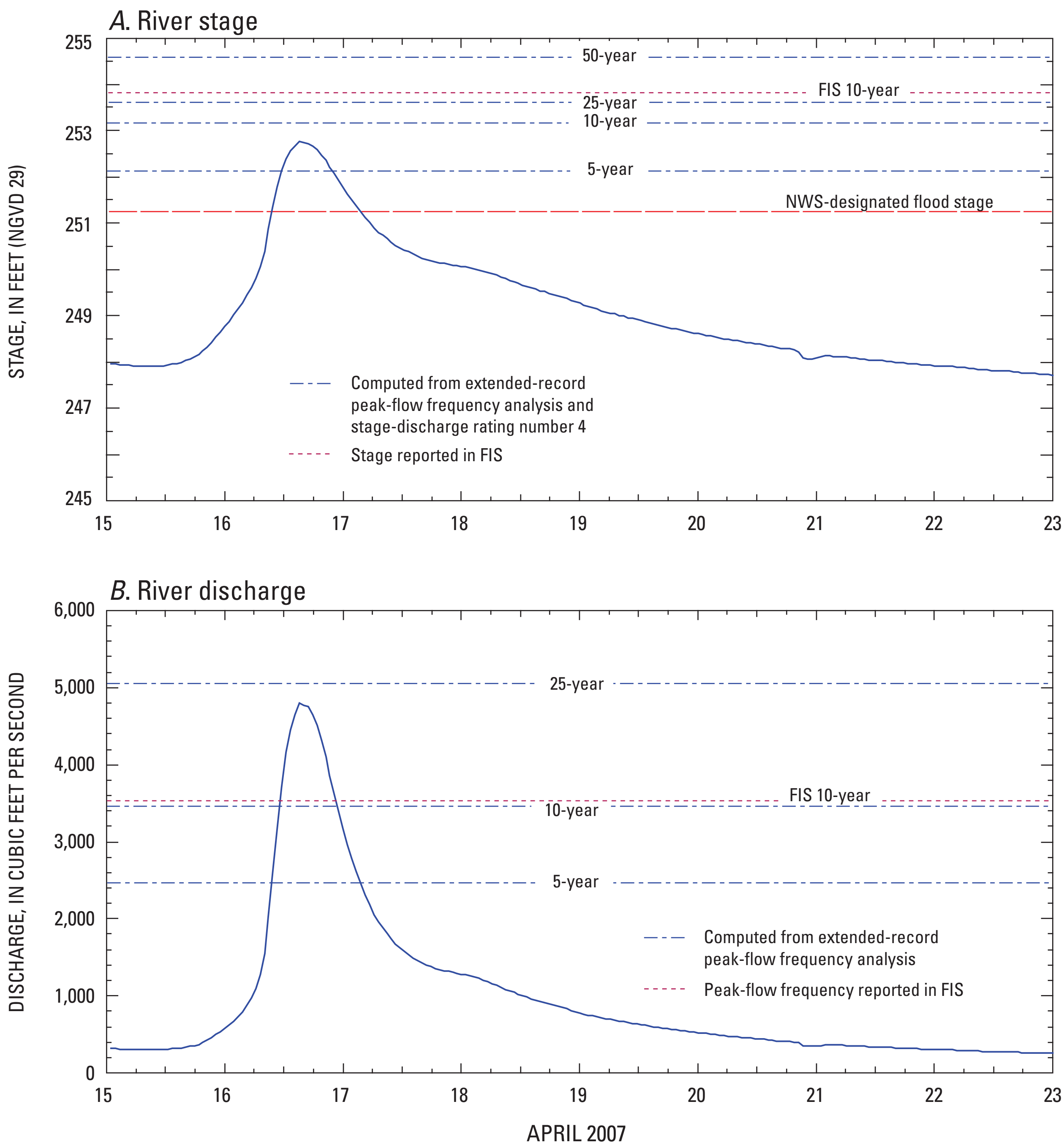


Figure 15. April 15–23, 2007, *(A)* stage and *(B)* discharge at Squannacook River near West Groton (01096000), Massachusetts. [NWS, National Weather Service; FIS, flood-insurance study by FEMA (1982)]

Table 9. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Squannacook River near West Groton (0109600), Massachusetts.

[ft, feet in NVGD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	[4]Discharge rating 4 (ft^3/s)	[5]Discharge (ft^3/s)	[3]Stage rating 4 (ft)	Stage (ft)	Discharge: Table 1 (ft^3/s)	Discharge: Rating (ft^3/s)
5	--	--	--	2,460	251.2	--	--	--
10	253.8	3,540	6,990	3,460	252.0	-1.8	-3,530	-80
25	--	--	--	5,050	252.9	--	--	--
50	256.8	6,880	17,100	6,530	253.6	-3.2	-10,570	-350
100	258.0	8,840	21,800	8,280	254.3	-3.7	-13,520	-560
200	--	--	--	10,400	255.0	--	--	--
500	261.1	15,160	30,000	13,700	256.0	-5.1	-16,300	-1,460

[1] Town of Groton flood-insurance study (FEMA, 1982).

[2] Flood stages at streamflow-gaging station; 34,600 ft above confluence with Nashua River on flood profile (FEMA, 1982; pl. 07P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1982; table 1, at confluence with Nashua River).

[4] Stage determined from stage-discharge rating number 22.1; above 252 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record.

Nissitissit River at Pepperell–01096503

The streamflow-gaging station on the Nissitissit River at Pepperell has been in operation since March 2006. To characterize the April 2007 storm, annual peak flows for the 1936 through 2006 water years were estimated using MOVE-1 and the Squannacook River near West Groton (01096000) streamflow-gaging station. The Squannacook River station was considered the most appropriate for estimating the Nissitissit River peak flows because the basins are nearly equal in size at their gages (63.7 and 59.6 mi^2, respectively) and the basin centroids are about 6.4 mi from each other (fig. 1). Note that part of the Squannacook River peak-flow record (1936–49) was estimated from the North Nashua River at Leominster station (01094500) record. The basin centroid of North Nashua River at Leominster lies about 14.5 mi southwest of the centroid of the Nissitissit River Basin. The available record at the Nissitissit River station limited the MOVE-1 analysis to five independent high-flow events in water years 2006 through 2008, which included the April 2007 peak (fig. 16). Three of the high flow events used in this analysis were from the 2008 water year, and although these data are provisional at the time of the analysis, a preliminary review of the data indicated that they were appropriate for use. Annual peak flows at Squannacook River near West Groton span a 58-year period; water years 1950 through 2007. Peak flows for water years 1936 through 1949 were estimated from a MOVE-1 analysis with the North Nashua River at Leominster station (01094500) (see Squannacook River peak-flow analysis for details).

Estimated annual peak flows from 1936–2006 exceeded the April 2007 peak (3,700 ft^3/s) in water years 1936, 1938, and 1944, by about 143, 44, and 10 percent, respectively (fig. 17). The annual peak discharge in water years 1956, 1987, and 2004 approached the April 2007 peak discharge.

The return interval of the April 2007 peak discharge was computed by (1) peak-flow frequency analysis of observed and estimated annual peak flows, and (2) regional regression equations developed for New Hampshire. Peak-flow frequency analysis of the observed and estimated annual peaks indicates the April 2007 peak has a return interval between 10 and 25 years and is within the 95-percent confidence limits for these return intervals (table 10, fig. 18). The New Hampshire regional regression equations place the April 2007 peak discharge near a 25-year return-interval discharge. Although these two methods produced comparable results for the April 2007 storm, the differences increase as the discharge increases (less frequent events); for example, storm discharges for 100- and 500-year return intervals calculated using the New Hampshire equations are about 27 and 41 percent less, respectively, than flows calculated by the peak-flow frequency analysis of mostly estimated annual peak-flow records.

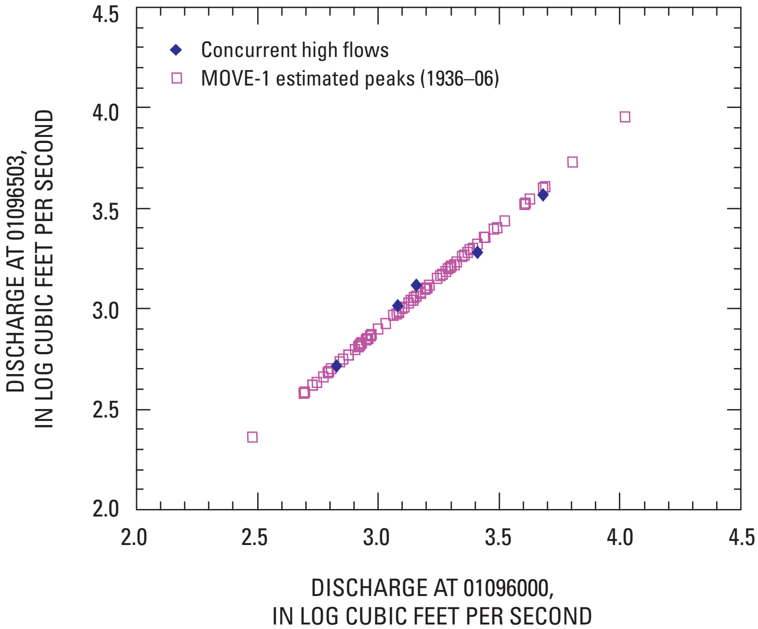


Figure 16. Relation between observed high flows for water years 2006 through 2007 at Nissitissit River at Pepperell (01096503) and Squannacook River near West Groton (01096000), Massachusetts.

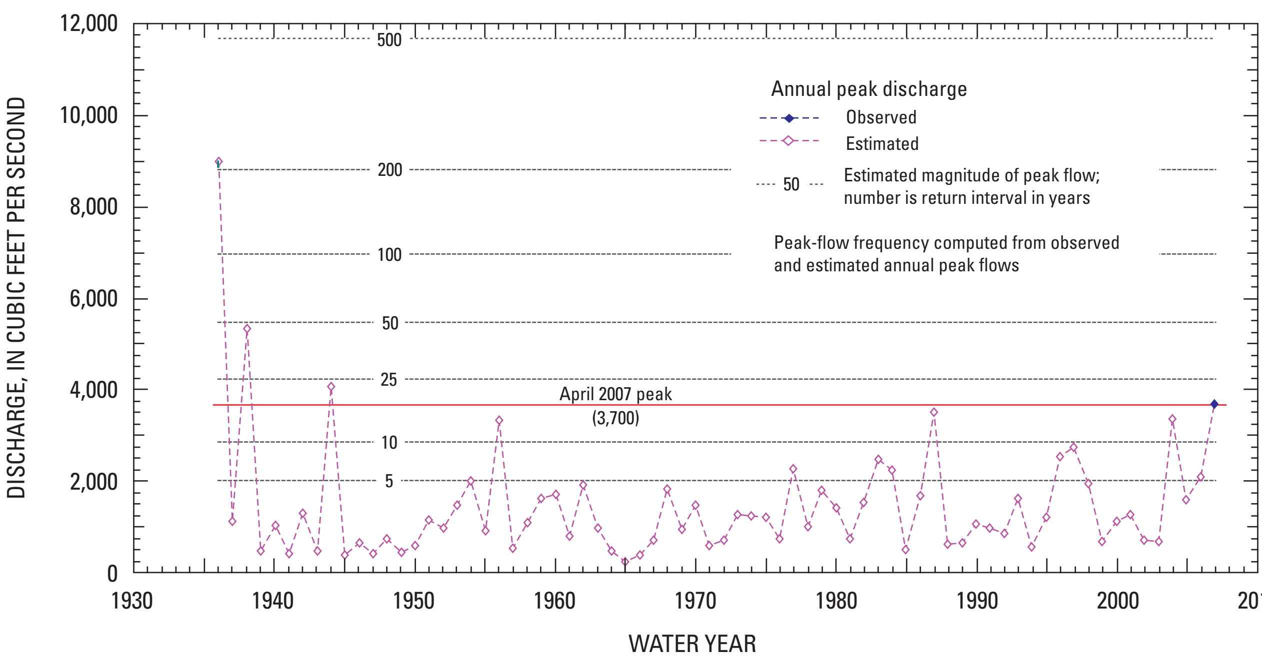


Figure 17. Observed and estimated annual peak discharge for water years 1936 through 2007 at Nissitissit River at Pepperell (01096503), Massachusetts.

Table 10. Magnitude and confidence limits of flood flows at selected return intervals at Nissitissit River at Pepperell (01096503), Massachusetts.

[--, not determined]

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second			
		NH regional regression equation[1]	MOVE-1 extended-record analysis (1936–2007) with Squannacook River near West Groton (01096000)[2]		
			Expected peak	95-percent confidence limit	
				Lower	Upper
5	0.2	2,200	2,000	1,730	2,380
10	0.1	2,830	2,840	2,390	3,490
25	0.04	3,640	4,200	3,420	5,420
50	0.02	4,140	5,460	4,340	7,310
100	0.01	5,070	6,980	5,400	9,670
200	0.005	--	8,780	6,640	12,600
500	0.002	6,880	11,700	8,580	17,500

[1] Olson, 2009.

[2] Estimated annual-peak flows 1936–2006 using MOVE-1 method (Hirsch, 1982).

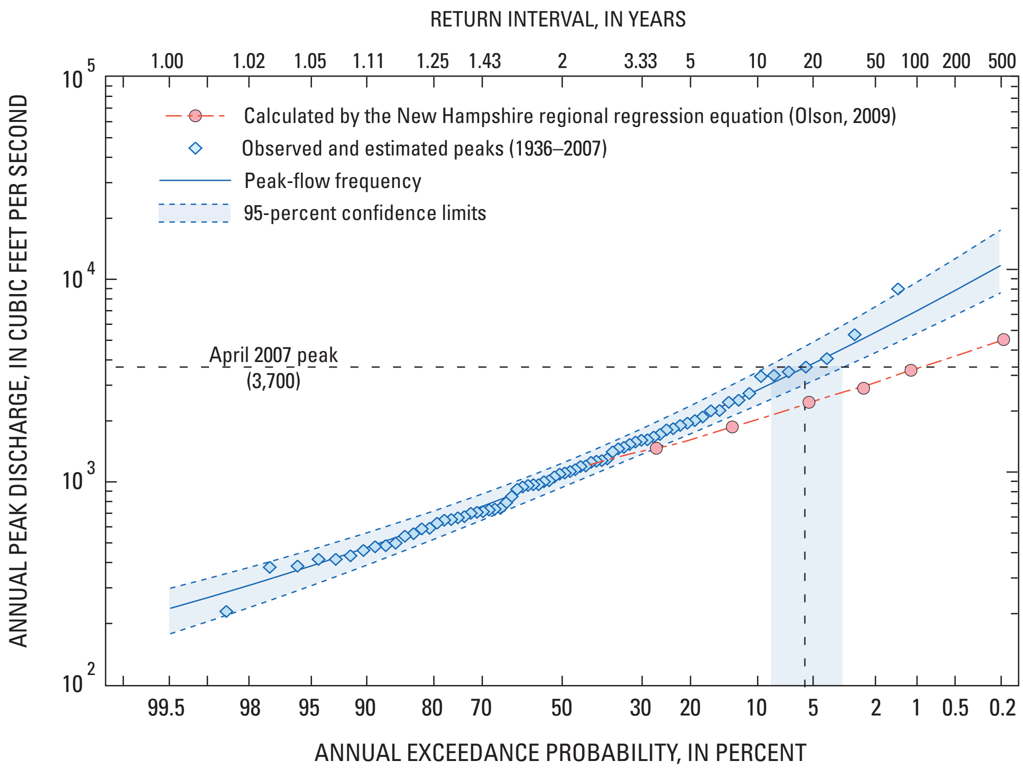


Figure 18. Peak-flow frequency computed from observed and estimated annual peaks at Nissitissit River at Pepperell (01096503), Massachusetts.

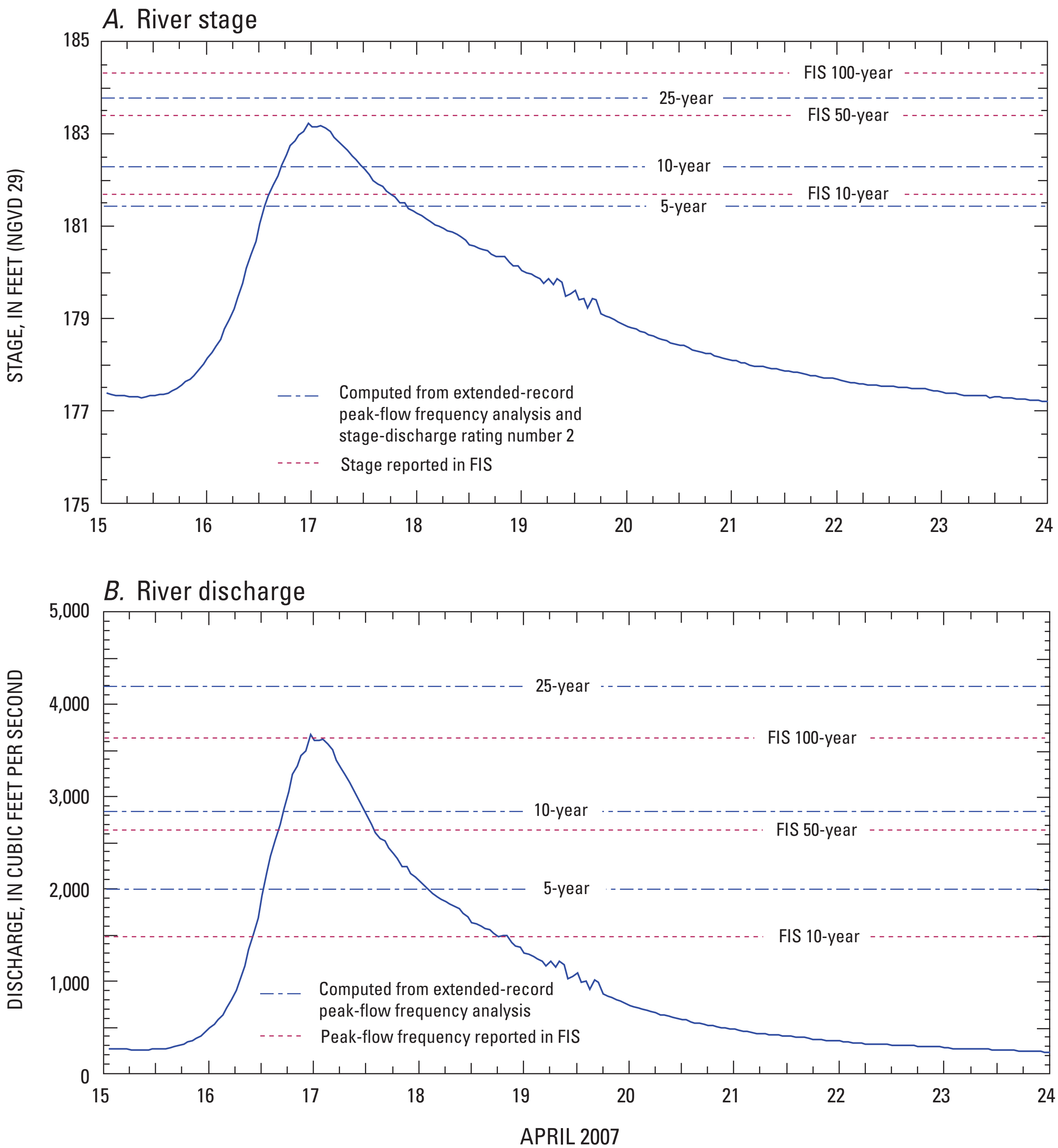


Figure 19. April 15–23, 2007, *(A)* stage and *(B)* discharge at Nissitissit River at Pepperell (01096503), Massachusetts. [FIS, flood-insurance study by FEMA (1993)]

The flood-insurance study revised in 1993 for the Town of Pepperell (FEMA, 1993) indicates the April 2007 peak stage (183.26 ft) approached a 50-year flood stage (fig. 19A). The Nissitissit River streamflow-gaging station is not part of the NWS Advanced Hydrologic Prediction network; therefore, a flood-warning stage is not available. The return interval of the April 2007 peak discharge was about equal to a 100-year return interval discharge reported in the flood-insurance study (fig. 19B), whereas the extended-record peak-flow analysis made in this study placed the April 2007 peak discharge between 10- and 25-year event.

The Town of Pepperell flood-insurance study (FEMA, 1993) reports the discharge frequency for the Nissitissit River was determined from regional equations developed by Johnson and Tasker (1974b) for Vermont streams; discharges of 1,500, 2,640, 3,640, and 5,000 ft^3/s were reported for 10-, 50-, 100- and 500-year return intervals, respectively (FEMA, 1993; table 1). These discharges are between 27 and 47 percent less than discharges determined from the peak-flow equations recently developed for New Hampshire (Olson, 2009) for similar return intervals (the difference decreased as discharge increased). The flood-insurance-study discharges for the Nissitissit River are 47 to 62 percent less than the discharges for similar return intervals determined from peak-flow frequency analysis of mostly estimated annual peaks (table 11).

Converting the flood-insurance-study flood stage at various return intervals to discharge from the station stage-discharge rating 2 also yielded discharges that were 17 to 39 percent less than those determined for similar return intervals in this study. Conversely, converting discharges for various return intervals determined in this study into stage by using rating 2 yielded higher flood stages for equivalent return intervals than those shown in the flood profile at the gage location (FEMA, 1993; plate 05P at 4,800 ft upstream from the confluence with the Nashua River). Flood stages in this study for 10-, 50-, 100-, and 500-year return intervals are about 0.6, 1.6, 1.9, and 1.3 ft higher, respectively, than in the flood-insurance study. The rating 2 stage-discharge relation is estimated above 181 ft (gage datum of 7 ft).

Table 11. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Nissitissit River near Pepperell (01096503), Massachusetts.

[ft, feet NGVD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	[4]Discharge rating 2 (ft^3/s)	[5]Discharge (ft^3/s)	[4]Stage rating 2 (ft)	Stage (ft)	Discharge: Table 1 (ft^3/s)	Discharge: Rating (ft^3/s)
5	--	--	--	2,000	181.5	--	--	--
10	181.7	1,497	2,350	2,840	182.3	0.6	1,343	490
25	--	--	--	4,200	183.8	--	--	--
50	183.4	2,642	3,800	5,460	185.0	1.6	2,818	1,660
100	184.3	3,642	4,700	6,980	186.2	1.9	3,338	2,280
200	--	--	--	8,780	187.6	--	--	--
500	187.3	5,000	7,100	11,700	188.6	1.3	6,700	4,600

[1] Town of Pepperell flood-insurance study (FEMA, 1993).

[2] Flood stages at streamflow-gaging station; 4,800,000 ft above confluence with Nashua River on flood profile (FEMA, 1993; pl. 05P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1993; table 1, at confluence with Nashoba River).

[4] Stage determined from stage-discharge rating number 2; above 181 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record.

Merrimack River at Lowell–01100000

The streamflow-gaging station on the Merrimack River below the confluence with the Concord River at Lowell has continuous flow records dating back to 1924. The flow records represent periods of various regulation, which complicate the peak-flow frequency analysis. Following major floods in 1936 and 1938, the U.S. Army Corps of Engineers (USACE) constructed five flood-control reservoirs in the Merrimack River Basin that were completed between 1941 and 1963–Hopkinton Dam, Everett Dam, Blackwater Dam, Edward MacDowell Dam, and Franklin Falls Dam. There are also a number of water-supply reservoirs, particularly in the Massachusetts portion of the basin, that have been in operation since the early 1900s or earlier. Although these supply reservoirs are not operated for flood-control purposes, they can still affect high flows in the lower Merrimack River, particularly for small, more frequent floods.

The USACE flood-control reservoirs were constructed on large tributaries in New Hampshire and are capable of storing from 2.8 to 6.8 in. of runoff upstream from the reservoir. Combined drainage area to these reservoirs affects about 36 percent of the total basin area above the Lowell streamflow-gaging station. The total available storage in these reservoirs represents about 1.9 in. of runoff over the entire basin. Storage in the flood-control reservoirs several days prior to the April 17, 2007, peak flow was fully available and was between 25 and 70 percent utilized with about 57 percent of the combined total storage utilized at the time of the peak (Paul Marinelli, USACE, written commun., 2008).

The April 17, 2007, peak discharge (89,900 ft^3/s, stage 63.27 ft) was the second highest recorded since the five USACE flood-control reservoirs became fully operational in 1964 (fig. 20). Peak discharges after flood-control reservoirs were built exceeded the April 2007 peak on May 15, 2006, (96,400 ft^3/s, stage 64.02 ft) by about 7 percent and was about equalled in April 1987 (84,700 ft^3/s, stage 62.34 ft). Prior to

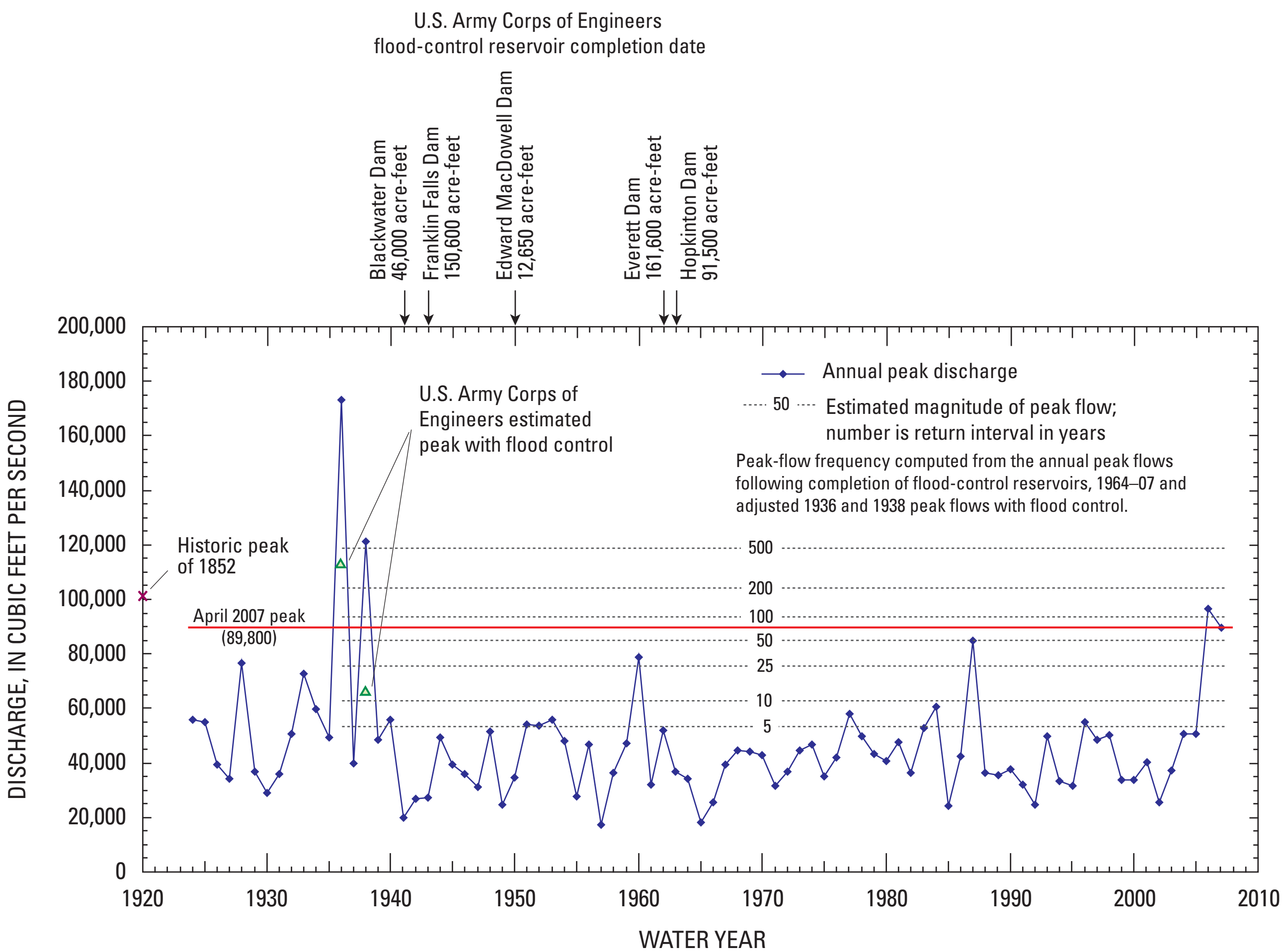


Figure 20. Observed and estimated annual peak discharge for water years 1924 through 2007 at Merrimack River at Lowell (01100000), Massachusetts.

the completion of the flood-control reservoirs, the recorded peak discharges in 1936 (173,000 ft^3/s, stage 73.58 ft) and in 1938 (121,100 ft^3/s, stage 72.75 ft) exceeded the April 2007 peak discharge by about 92 and 35 percent, respectively. If the flood-control reservoirs had been in operation, the USACE estimates that the peak flows in 1936 and 1938 would have been 113,000 and 66,000 ft^3/s, respectively (Paul Marinelli, USACE, written commun., 2008). The adjusted 1936 peak discharge still would have exceeded the April 2007 peak by about 26 percent, but the adjusted 1938 peak discharge would have been about 27 percent less than the April 2007 peak discharge.

Peak-flow analysis of the station record is complicated by three distinct periods of record with differing characteristics that affect peak flows—record from 1924 through 1940 represents pre-flood control flows, the record from 1940 through 1963 represents a transition as reservoirs were completed and brought into operation, and the record from 1964 to present represents present flood-controlled flows. As such, estimating the magnitude of floods from the period of record is not appropriate because of the changes in flood control over that time. Further, following completion of the flood-control reservoirs (1964–2007) peak flows have been influenced by their operation. For example, the available storage may be more or less utilized in anticipation of forecast predictions. Because of these factors, the estimates of peak flow magnitudes for various return periods are subject to a high degree of uncertainty. To quantify the possible range in flow magnitude for various return intervals, the peak-flow frequency analysis was made using the period-of-record data and data representing estimated and observed annual peaks with flood control for the period 1936–2007.

The period-of-record data (1924–2007) are heavily influenced by the unregulated peak discharges in 1936 and 1938, which are markedly higher than other peaks over the period of record. Data for the period with flood control (1964–2007) were combined with the peaks of 1936 and 1938 adjusted by the USACE as if the present flood-control reservoir system had been in operation. These two peaks were treated as historical peaks in the peak-flow frequency analysis. The peak-flow frequency analysis of historical peaks generally improves the frequency distribution of the systematic record by accounting for major floods and the intervening period of no data. The result of this analysis is dependent on the accuracy of the adjusted 1936 peak discharge and, to a lesser extent, the 1938 peak because it was exceeded by three other peaks in the record analyzed. Data representing the 17-year period of pre-flood control (1924–1940) also were examined, but the short record and the occurrence of the two largest peaks in the past century within this record greatly leverage the frequency distribution and cause misleading results. Therefore, these results were not reported. The magnitudes of peak flows for various return intervals were determined using skews calculated from the systematic record. Regional skew values were not considered appropriate because of the size of the basin, the period of record available for the analysis, and the extent of regulation in the basin.

The Merrimack River peak flow for the April 2007 storm (89,800 ft^3/s) has a return interval of about 25 years, as determined from the period-of-record analysis, and was within the 95-percent confidence limits for this return interval (table 12; fig. 21). The analysis representing post-flood-control data and the adjusted 1936 and 1938 peak discharges treated as historical peaks indicates the April 2007 peak flow was between a 50- and 100-year return interval and was within the 95-percent confidence limits for a 50-to 200-year return interval (table 12; fig. 21).

Additional peak-flow frequency analysis was made using a continuous record of peak flow from 1936 through 2007 by estimating the pre-flood-control period peaks (1936–1964) with flood control. The pre-flood-control peaks were adjusted by a MOVE-1 analysis of the post-flood-control data (1964–2007) to concurrent peak-flow records at three streamflow-gaging stations distributed throughout the Merrimack River Basin—Nashua River near Leominster, Mass. (01094500), Pemigewasset River at Plymouth, N.H. (01076500), and Smith River near Bristol, N.H. (01078000). These basins are in the southwestern, northern, and northwestern part of the Merrimack River Basin, respectively. The estimated adjusted peaks varied by station, but a weighted estimate using the records from the North Nashua and Smith River stations yielded the smallest RMSE of estimated peak flows to observed peak flows for the 1964–2007 period. The 1936 and 1938 peaks estimated by this technique were about 6 and 34 percent greater than the adjusted peaks estimated by the USACE, respectively, and about 31 and 27 percent less than the recorded peaks, respectively. The estimated 1938 peak was generally in agreement with comparable peaks in 1987, 2006, and 2007; however, the agreement depended on the station used in the analysis. This result suggests that the flood-control reservoir storage was fully utilized in the USACE adjusted 1938 peak, a condition that may not be realized in practice because reservoir operators may reserve some storage in anticipation of additional precipitation. Peak-flow analysis of the extended record (1936–1963) with flood control is subject to a large degree of uncertainty. The return interval of the April 2007 peak discharge, as determined from the extended- and observed-record data with flood control (1936–2007), is close to a 50-year flood and is within the 95-percent confidence limits for a 25- to 50-year flood.

Review of the peak-flow database and station historical file revealed that the stage-discharge rating in place at the time of the 1936 flood may have underrepresented the peak discharge. Correspondence between the USGS and the then Proprietors of Locks and Canals in Lowell, Mass., and the USACE indicates that a jetty in the river at the time of the flood may have been washed out or partially washed out during the flood. As a result, the stage-discharge rating may have shifted by as much as 2 ft on the basis of the rating developed after the jetty was removed; the peak flow determined from this rating would be about 190,000 ft^3/s, or about 11 percent greater than the recorded peak of 1936. No adjustments were made to the peak-flow database, however, because the

Table 12. Magnitude and confidence limits of flood flows at selected return intervals at Merrimack River at Lowell (01100000), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second								
		[1]Period-of-record analysis (1924–2007)			Analysis of data representing flood control					
					1936, [2]1938, 1964–2007			[3]MOVE-1 extended record (1936–2007)		
		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit	
			Lower	Upper		Lower	Upper		Lower	Upper
5	0.2	59,100	54,700	64,400	53,300	49,000	59,100	53,600	49,700	58,500
10	0.1	73,000	66,700	81,300	62,500	56,600	70,900	64,400	59,000	71,600
25	0.04	93,400	83,600	107,000	74,600	66,400	87,200	79,300	71,300	90,600
50	0.02	111,000	97,600	129,000	84,000	73,700	100,000	91,400	81,100	106,000
100	0.01	130,000	113,000	155,000	93,800	81,100	114,000	104,000	91,300	124,000
200	0.005	151,000	130,000	184,000	104,000	88,800	130,000	118,000	102,000	143,000
500	0.002	184,000	154,000	230,000	118,000	99,200	151,000	138,000	117,000	171,000

[1] Represents periods of no flood control (1924–40), transitional as flood-control reservoirs were built (1941–63), and post-flood control (1964–2007).

[2] Estimated 1936 and 1938 peak flows adjusted for flood control by the U.S. Army Corps of Engineers treated as historical peaks flood-frequency analysis.

[3] Weighted estimate of 1936–63 peak flows with flood control using Nashua River near Leominster, Mass. (01094500), Pemigewasset River at Plymouth, N.H. (01076500), and Smith River near Bristol, N.H. (01078000).

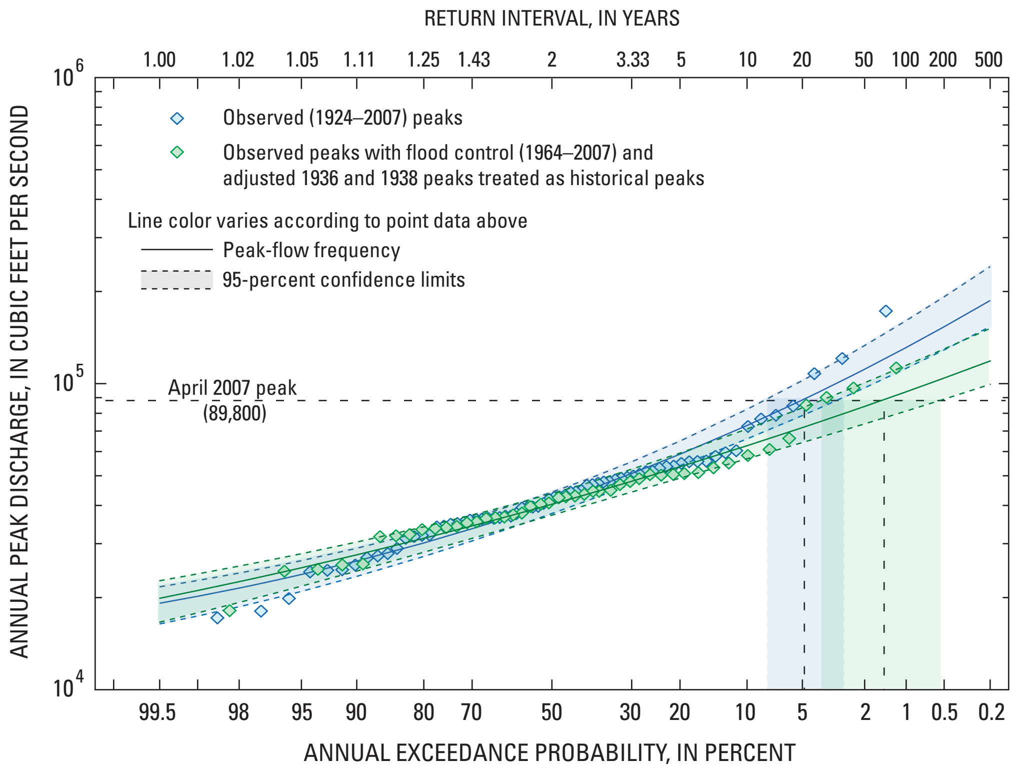


Figure 21. Peak-flow frequency computed from observed and estimated annual peaks for water years 1924 through 2007 at Merrimack River at Lowell (01100000), Massachusetts.

information was not sufficient to make this change permanent. Assuming an 11-percent increase in the USACE adjusted peak flow would cause the peak flows to increase from about 1 to 6 percent for 10- and 500-year return-interval peaks, respectively. Accounting for this change would still place the April 2007 peak discharge at about a 50-year return interval and within the 95-percent confidence limits of peak discharges for 25- and 100-year return intervals as determined by post-flood-control peaks (1964–2007) and historical 1936 and 1938 adjusted peaks.

The flood-insurance study revised in 1992 for the City of Lowell (FEMA, 1992) indicates the April 2007 peak stage (63.27 ft) was about 6 ft lower than the 50-year flood stage (fig. 22A). The river stage was above the NWS-designated flood stage (57.18 ft) for nearly 5 days and peaked about 6.1 ft above the NWS flood stage on April 17. The return interval of the April 2007 peak discharge determined from the peak-flow frequency analysis made from the post-flood-control annual peak-flow record and the 1936 and 1938 peaks flows adjusted for flood control was between a 50- and 100-year flood and was about equal to a 50-year discharge reported in the flood-insurance study (fig. 22B).

The City of Lowell flood-insurance study (FEMA, 1992) reports the discharge frequency for the Merrimack River about 8,300 ft downstream from the streamflow-gaging station of 58,000; 90,000; 111,000; and 156,000 ft^3/s for the 10-, 50-, 100- and 500-year return intervals, respectively (table 13). These discharges are about 7 percent less at a 10-year return interval to about 32 percent greater at a 500-year return interval than discharges computed from the peak-flow frequency analysis using post-flood-control annual peaks and adjusted 1936 and 1938 peaks treated as historical peaks.

Discharges and stage used in the flood-insurance study are comparable to the discharges and stage (as determined from the present rating, 25) determined in this study (table 13). Stages at the streamflow-gaging stations under the present stage-discharge rating are about 1.4 and 0.2 ft higher than the flood-insurance flood stages for flood flows with a 10- and 50-year return interval and about 1.2 and 3.2 ft lower for flood flows with a 100- and 500-year return interval (table 13). The stage-discharge relation is estimated above 65 ft (gage datum of about 60 ft).

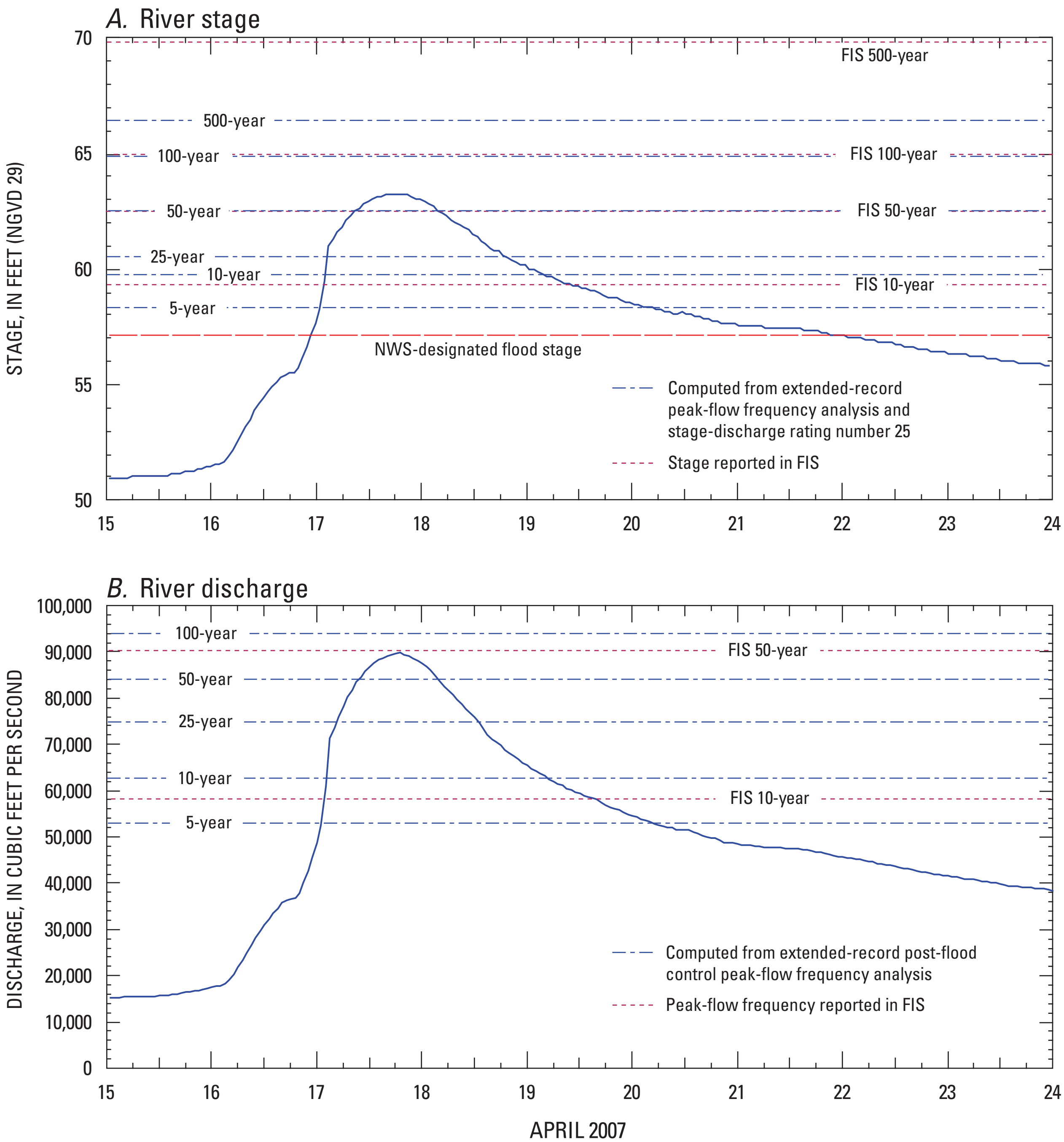


Figure 22. April 15–23, 2007, *(A)* stage and *(B)* discharge at Merrimack River at Lowell (01100000), Massachusetts. [NWS, National Weather Service; FIS, flood insurance study by FEMA (1992)]

Table 13. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Merrimack River at Lowell (01100000), Massachusetts.

[ft, feet in NVGD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	[4]Discharge rating 25 (ft^3/s)	[5]Discharge (ft^3/s)	[3]Stage rating 25 (ft)	Stage (ft)	Discharge Table 1 (ft^3/s)	Discharge Rating (ft^3/s)
5	--	--	--	53,300	58.4	--	--	--
10	58.4	58,000	53,300	62,500	59.8	1.4	4,500	9,200
25	--	--	--	74,600	61.5	--	--	--
50	62.5	90,000	83,700	84,000	62.7	0.2	-6,000	300
100	65.0	111,000	104,000	93,800	63.8	-1.2	-17,200	-10,200
200	--	--	--	104,000	65.0	--	--	--
500	69.6	156,000	152,000	118,000	66.4	-3.2	-38,000	-34,000

[1] City of Lowell flood-insurance study (FEMA, 1992).

[2] Flood stages at streamflow-gaging station; 8,300 ft from corporate limit on flood profile (FEMA, 1992; pl. 01P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1992; table 1, at corporate limit).

[4] Stage determined from stage-discharge rating number 25; above 65 ft rating is estimated.

[5] Determined from post-flood-contol flood-frequency analysis (1964–2007) and 1936 and 1938 adjusted peaks.

Spicket River near Methuen–01100561

The streamflow-gaging station on the Spicket River near Methuen has been in operation since March 2001, limiting the annual peak flow record to 7 years. In addition, peak flows were estimated in 2 of the years (2001–02), and all peaks are subject to an unknown degree of regulation from a reservoir in the basin making estimates of flood magnitudes difficult and uncertain. Two methods were used in the peak-flow frequency analysis—(1) estimation of annual series of peak flows from two nearby index sites and (2) computation by regionalized regression equations developed for New Hampshire.

In the first method, peak flows for 1936 through 2000 were estimated by MOVE-1 using concurrent peak-flow records at Spicket River with index stations at North Nashua River near Leominster (01094500) and Ipswich River at South Middleton (01101500). The centroids of the North Nashua River and Ipswich River Basins are about 35 mi southwest and 20 mi south of the Spicket River Basin centroid, respectively. Estimated peak discharges could vary considerably from the observed (fig. 23); the RMSEs of the estimated discharge determined from the North Nashua River and Ipswich River station records were 691 and 334 ft^3/s, respectively. Although the RMSE of estimated peaks from Ipswich River was about half that determined from North Nashua River the Ipswich River is not necessarily a more representative index station. For example, although the meterologic conditions during the period of concurrent record may be similar, this condition may not hold true in the long-term. The uncertainties associated with the estimated peaks are large because of an unknown degree of regulation and the differences between estimated peaks determined from different index stations are large (reflecting that the meteorologic conditions differ between basins). Therefore, the results of this analysis should be viewed with the uncertainties of these estimates in mind.

The recorded April 2007 peak discharge (1,360 ft^3/s) was the second highest annual peak recorded during the 7-year period of record; the 2006 water year peak (2,480 ft^3/s) exceeded the 2007 peak (fig. 24) by about 82 percent. The estimated peak flows (1936–2000) determined from the North Nashua River record exceeded the April 2007 peak seven times, most notably in 1936, 1938, 1944, and 1956 by about 310, 130, 76, and 96 percent, respectively. The estimated peak flows (1936–2000) determined from the Ipswich River record exceeded the April 2007 peak twice (1936 and 1987), but only by small amounts (about 3 and 12 percent, respectively). These differences underscore the uncertainty in the estimated peaks and the possible range of discharges that might have occurred during this period.

The Spicket River near Methuen April 2007 peak discharge was slightly greater than the discharge for a 5-year flood flow determined by the regional equations for New Hampshire (table 14; fig. 25). The April 2007 flood flow was about midway between a 5- and 10-year return interval for discharges computed from records extended with the North Nashua River data and midway between a 10- and 25-year

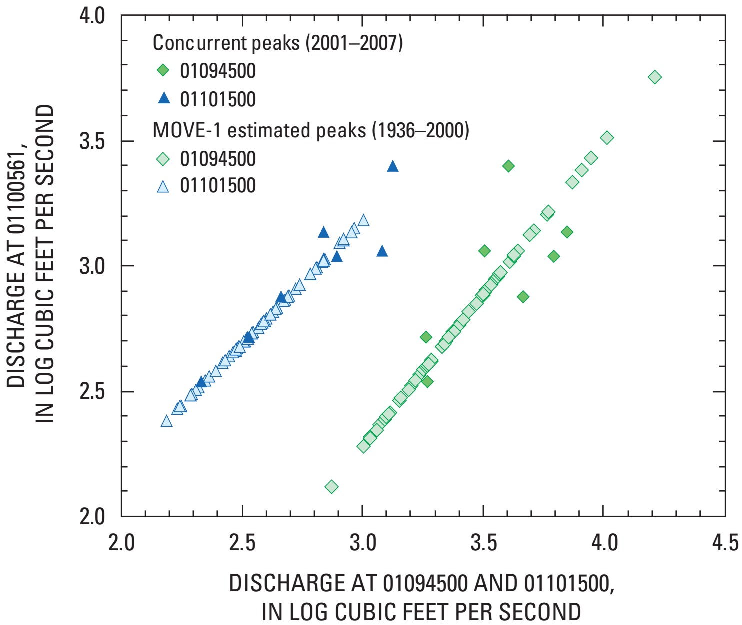


Figure 23. Relation between observed annual peak discharges for water years 2001 through 2007 at Spicket River near Methuen (0110561) and Nashua River at Leominster (01094500) and to Ipswich River at South Middleton (01101500), Massachusetts.

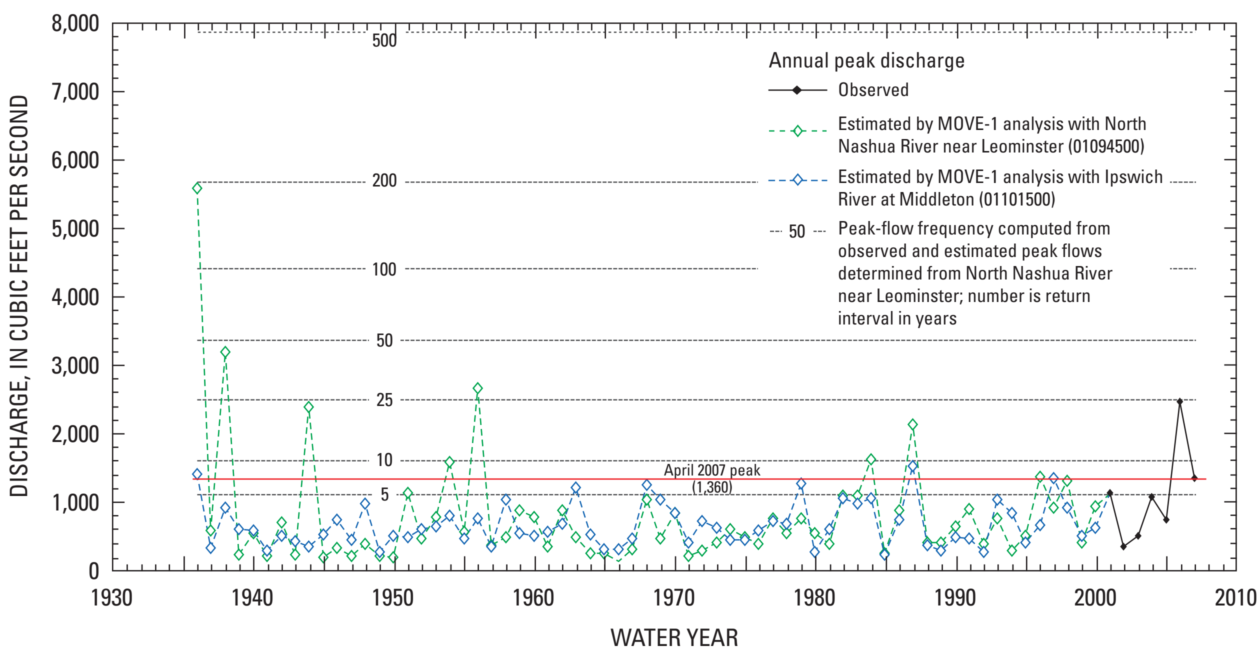


Figure 24. Observed and estimated annual peak discharge for water years 1936 through 2007 at Spicket River near Methuen (01100561), Massachusetts.

Table 14. Magnitude and confidence limits of flood flows at selected return intervals at Spicket River near Methuen (01100561), Massachusetts.

[NH, New Hampshire; --, not determined]

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second						
		NH regional regression equation[1]	Extended-record analysis (1936–2007)[2]					
			with North Nashua River at Leominster (01094500)			with Ipswich River at South Middleton (01101500)		
			Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit	
				Lower	Upper		Lower	Upper
5	0.2	1,270	1,120	953	1,340	939	846	1,060
10	0.1	1,630	1,630	1,360	2,040	1,190	1,050	1,370
25	0.04	2,090	2,510	2,010	3,310	1,540	1,330	1,830
50	0.02	2,380	3,360	2,620	4,610	1,820	1,560	2,220
100	0.01	2,920	4,400	3,340	6,280	2,130	1,790	2,660
200	0.005	--	5,690	4,190	8,420	2,470	2,040	3,150
500	0.002	3,980	7,830	5,580	12,200	2,960	2,400	3,880

[1] Olson, 2009.

[2] Estimated annual-peak flows 1936–2000 using MOVE-1 method (Hirsch, 1982).

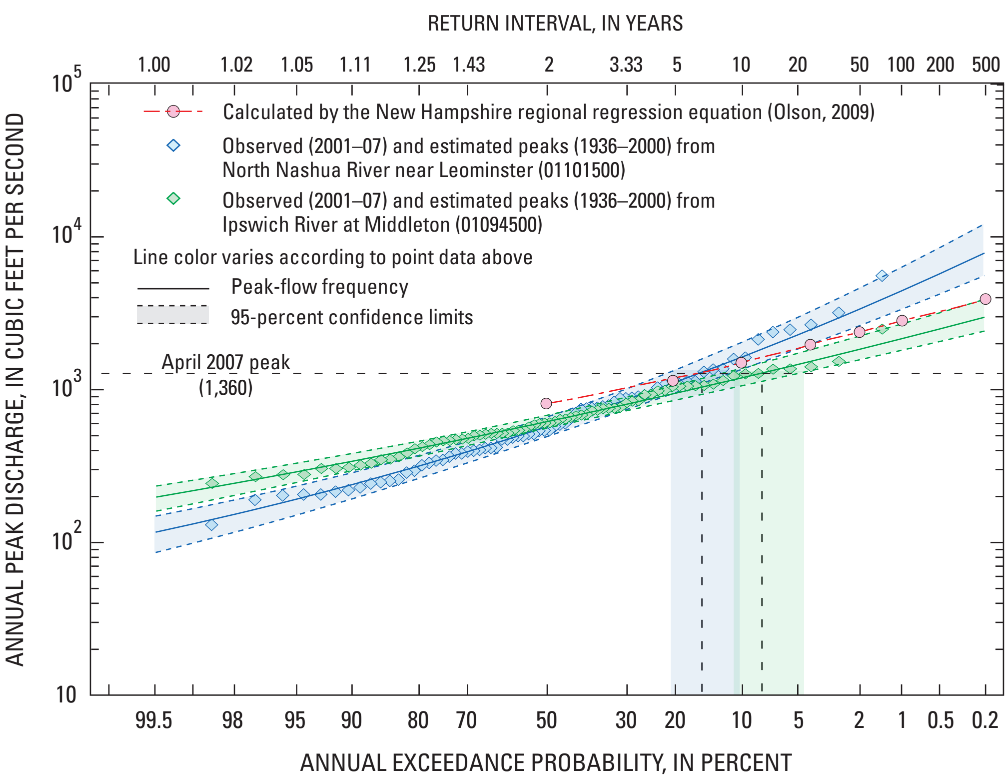


Figure 25. Peak-flow frequency computed from observed and estimated annual peaks for water years 1936 through 2007 at Spicket River near Methuen (01100561), Massachusetts.

return interval for discharges computed from records extended with the Ipswich River data (table 14). At the 95-percent confidence limit the April 2007 flood flow was between these return intervals for the corresponding extended record used in the analysis. Although the difference in the return period of the April 2007 peak flow determined by the various methods was not large, the differences between methods increase as discharge increases. The peak discharge for a 100-year return interval determined from records extended with the North Nashua River data was about twice that determined from records extended with the Ipswich River data. The 100-year peak discharge determined from the New Hampshire regional regression equation was about midway between the discharges computed from the records extended with the North Nashua River and Ipswich River data for a 100-year peak discharge (fig. 25).

The flood-insurance study completed in 1987 for the City of Methuen (FEMA, 1987) indicates the April 2007 peak stage (63.27 ft) was between a 10- and 50-year flood stage (fig. 26A). The river stage was above the NWS-designated flood stage (108.91 ft) for nearly 3.5 days and peaked about 1 ft above the NWS flood stage on April 18. The return interval of the April 2007 peak discharge determined from the extended-record peak-flow analysis made in this study was between 5 and 10 years and between a 10- and 50-year return interval as reported in the flood-insurance study (fig. 26B).

The City of Methuen flood-insurance study (FEMA, 1987) reports the discharge of the Spicket River near the streamgage (about 16,300 ft upstream of the corporate limit) for 10-, 50-, 100- and 500-year return intervals of 900; 1,600; 1,900; and 2,900 ft^3/s, respectively (table 15). These discharges, obtained from an upstream flood-insurance study for Salem, New Hampshire (U.S. Department of Housing and Urban Development, 1978), appear to have been determined from a flow-frequency analysis of 30 years of record from the Parker River in northeastern Massachusetts adjusted by drainage-area ratio. As previously described, the discharges determined from the peak-flow analysis of extended record made with the Ipswich River at South Middleton station (basin just south of the Parker River Basin) results in a much lower discharge than that calculated from the North Nashua River data. Hence, the peak flows for various return intervals reported in the flood-insurance study were similar to those determined from the extended-record analysis with the Ipswich River at South Middleton data but were considerably lower than the peak flows for those return intervals determined from the extended-record analysis with the North Nashua River data.

Peak flows calculated from extended records using the North Nashua River differed most from the flood flows for the Spicket River reported in the flood-insurance study (table 15). The magnitude of flood flows estimated from records extended with the North Nashua River were about 1.8 to 2.7 times greater than those in flood-insurance study; the differences increased as the return interval increased. Converted to stage (rating 2.1), the peak flows calculated from the extended record using North Nashua River were about 2.7, 3.8, 5.9, and 6.6 ft greater than the flood stages shown on the flood-insurance-study profile (FEMA, 1987; plate 04) for return intervals of 10, 50, 100, and 500 years, respectively. The rating is estimated above 113 ft (gage datum of about 11.3 ft).

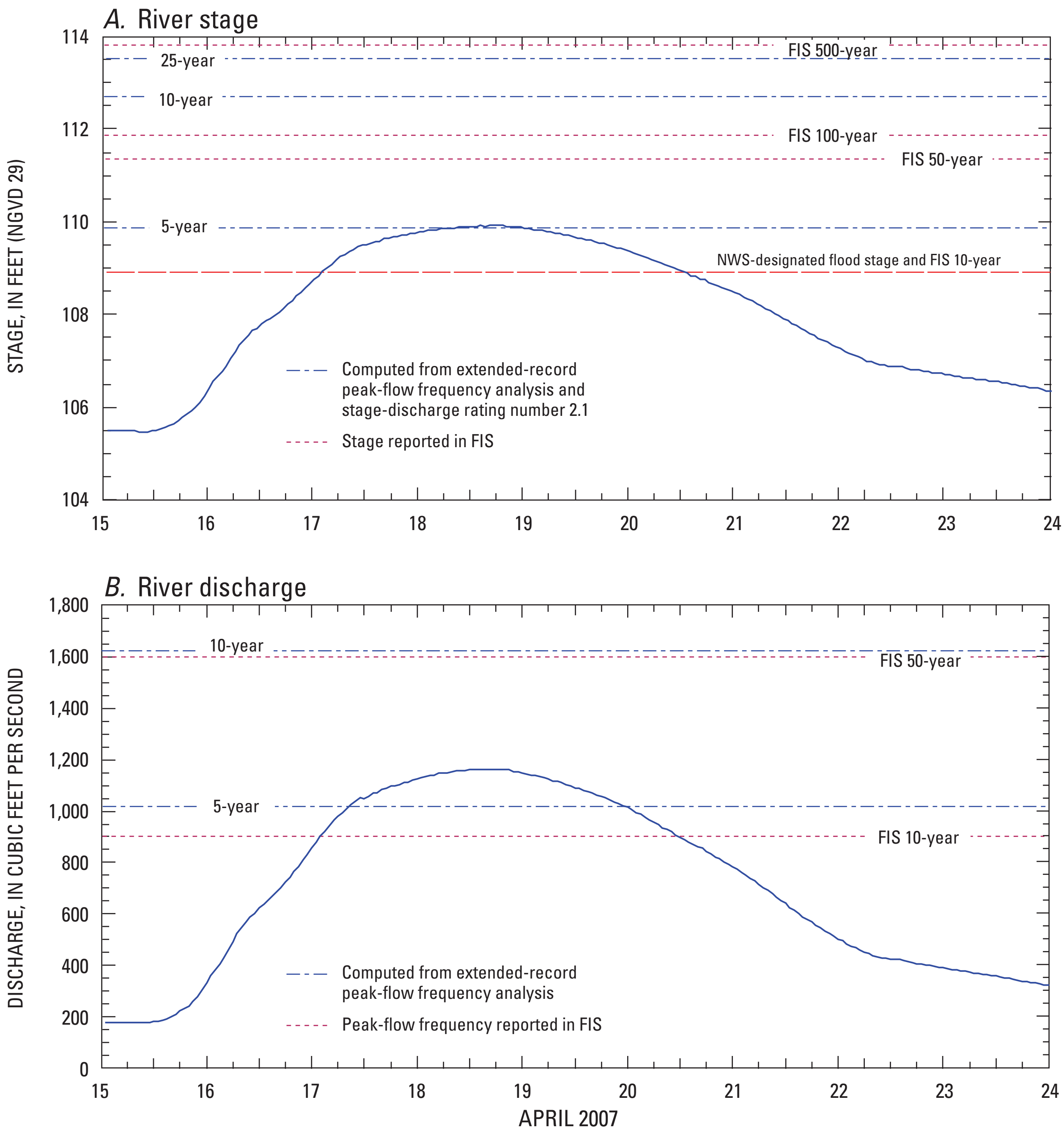


Figure 26. April 15–23, 2007, *(A)* stage and *(B)* discharge at Spicket River near Methuen (01100561), Massachusetts. [NWS, National Weather Service; FIS, flood-insurance study by FEMA (1987)]

Table 15. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Spicket River near Methuen (01100561), Massachusetts.

[ft, feet in NVGD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	[4]Discharge rating 2.1 (ft^3/s)	[5]Discharge (ft^3/s)	[3]Stage rating 2.1 (ft)	Stage (ft)	Discharge Table 1 (ft^3/s)	Discharge Rating (ft^3/s)
5	--	--	--	1,120	109.9	--	--	--
10	108.9	900	850	1,630	111.6	2.7	780	780
25	--	--	--	2,510	113.7	--	--	--
50	111.4	1,600	1,550	3,360	115.2	3.8	1,760	1,810
100	111.8	1,900	1,700	4,400	117.7	5.9	2,500	2,700
200	--	--	--	5,690	118.2	--	--	--
500	113.8	2,900	2,500	7,830	120.4	6.6	4,930	5,330

[1] City of Methuen flood-insurance study (FEMA, 1987).

[2] Flood stages at streamflow-gaging station; 16,200 ft from corporate limit on flood profile (FEMA, 1987; pl. 04P).

[3] Flood-insurance-study summary of discharges used in determining flood elevations (FEMA, 1987; table 1, at state line).

[4] Stage determined from stage-discharge rating number 2.0 and 2.1; above 113 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record with North Nashua River at Leominster (01094500).

Shawsheen River at Andover–01100627

The streamflow-gaging station on the Shawsheen River at Andover has been in operation since October 2006 limiting annual peak-flow data to 1 year. Therefore, the upstream streamflow-gaging station on the Shawsheen River at Wilmington (01100600) was used as a surrogate to characterize high flows in relation to the April 2007 storm at Andover (01100627). Peak flows from 14 independent storms with concurrent record at Andover and Wilmington were used to evaluate the relation of peak flows from the long-term site to those at the recently installed streamflow-gaging station. Although a drainage-area ratio with an exponent of 0.688 yielded the smallest RMSE between observed peaks for these 14 storms, a drainage-area ratio with an exponent of 1.0 best fit the observed April 2007 peak. Therefore, a simple drainage-area ratio (exponent of 1.0) was used to estimate peak flows at Andover from peak flows at Wilmington. The drainage area of the Shawsheen River at Andover and at Wilmington is 72.8 and 36.5 mi^2, respectively. Additional data are needed to determine whether modification of the ratio exponent is warranted.

Annual peak flows at Shawsheen River at Wilmington for water years 1936 through 1963 were estimated by MOVE-1 using the 44 years of concurrent record (1964–2007) with North Nashua River at Leominster (01094500) and Ipswich River near Ipswich (01102000). The centroids of the drainage basins to the North Nashua River at Leominster and Ipswich River near Ipswich are about 31 mi west and 14 mi east of the basin centroid of Shawsheen River at Wilmington, respectively. The relation of concurrent peak-flow data at Shawsheen River at Wilmington with North Nashua River at Leominster varied widely (fig. 27; RMSE of 368 ft^3/s). The relation of concurrent peak-flow data at Shawsheen River at Wilmington and the Ipswich River near Ipswich was better (less scatter; RMSE 222 ft^3/s); however, the relation of peak flows between sites is not as strong as it was at other sites where MOVE-1 was used to estimate peak flows. Therefore, the estimated peak-flow record from 1936–63 at Shawsheen River at Wilmington generally has a larger degree uncertainty than at other sites where peak-flows were estimated. This uncertainty is exemplified by the difference in estimated peaks at Andover derived from the North Nashua River relation as opposed to those derived from the relation with the Ipswich River, particularly in water years 1936, 1938, 1944, and 1956; estimated peaks for these years derived from the North Nashua River data greatly exceeded the peaks derived from

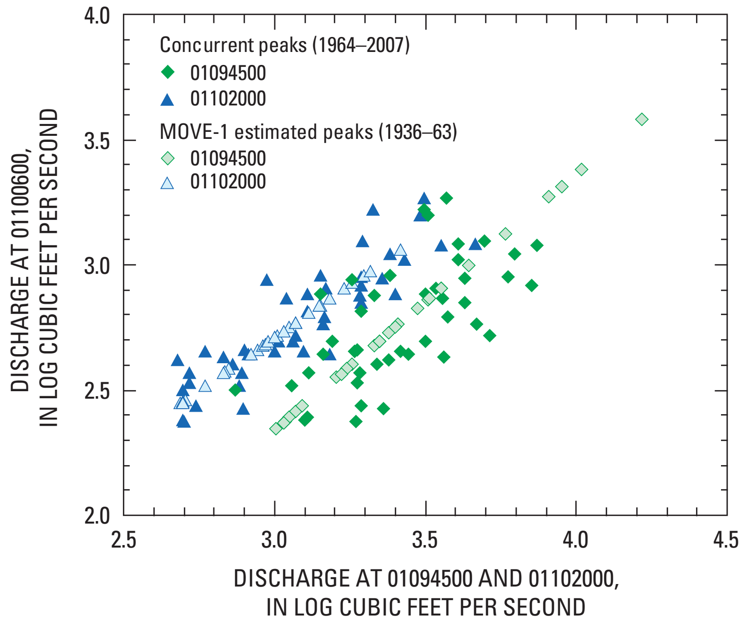


Figure 27. Relation between observed annual peak discharges for water years 1964 through 2007 at Shawsheen River near Wilmington (0110600) and North Nashua River at Leominster (01094500) and to Ipswich River near Ipswich (01102000), Massachusetts.

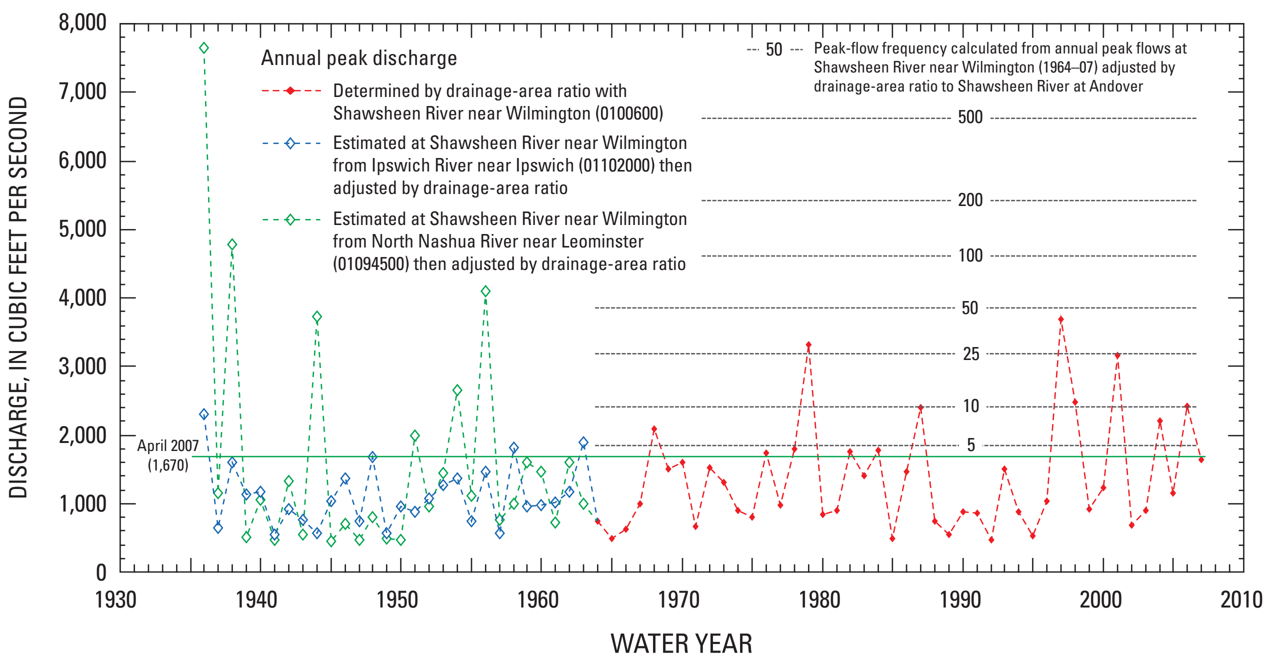


Figure 28. Observed and estimated annual peak discharge for water years 1936 through 2007 at Shawsheen River at Andover (0110627), Massachusetts.

the Ipswich River data. The 1936 estimated peak derived from the North Nashua River data was about three times greater than the peak derived from the Ipswich River data. These differences greatly influence the peak-flow analysis and particularly affect the magnitude of flood flows with a low exceedance probability (long return interval).

The estimated peak flows at Andover determined directly from the peak-flow record at Wilmington exceeded the April 2007 peak 12 times, most notably in 1979, 1997, and 2001 by about 98, 121, and 89 percent, respectively (fig. 28). The recorded April 2007 peak discharge (1,470 ft^3/s at Andover) was ranked 12th out of 44 annual peaks over the 1964–2007 period. Estimated annual peak flows derived from the Ipswich River record (1936–63) exceeded the April 2007 peak four times, but generally only by a small amount (1 to 38 percent). From these annual peak data the recorded April 2007 peak discharge was ranked 16th out of 72 over the 1936–2007 period. Estimated annual peak flows derived from the North Nashua River data (1936–63) exceeded the April 2007 peak six times with peaks in 1936, 1938, 1944, and 1956 greatly exceeding the April 2007 peak (123 to 358 percent). These four peaks also exceeded the peak discharge estimated directly from the Wilmington record (fig. 28) by as much as twice. From these annual peak data the recorded April 2007 peak discharge was ranked 18th out of 72 over the 1936–2007 period.

The Shawsheen River at Andover April 2007 peak discharge (1,470 ft^3/s) has about a 5-year return interval or less as determined by the different methods described above (table 16; fig. 29). The April 2007 peak discharge does not exceed the upper 95-percent confidence limit for a 5-year return interval as determined by the different methods (table 16). Although the relative magnitude of the April 2007 peak as determined by the various methods did not yield appreciably different results, the methods did diverge as the discharge increased. The peak discharge for a 100-year return interval determined from records extended with the North Nashua River data was about 65 percent greater than that determined from records extended with the Ipswich River data. Discharges for various return intervals determined from the period of record are between discharges determined from the extended record, but the magnitude of peak flows determined from the period of record were closer those determined from records extended with the Ipswich River data, reflecting the tighter relation of peak flows at Shawsheen River at Wilmington with those at Ipswich River near Ipswich than those at North Nashua River near Leominster (fig. 27).

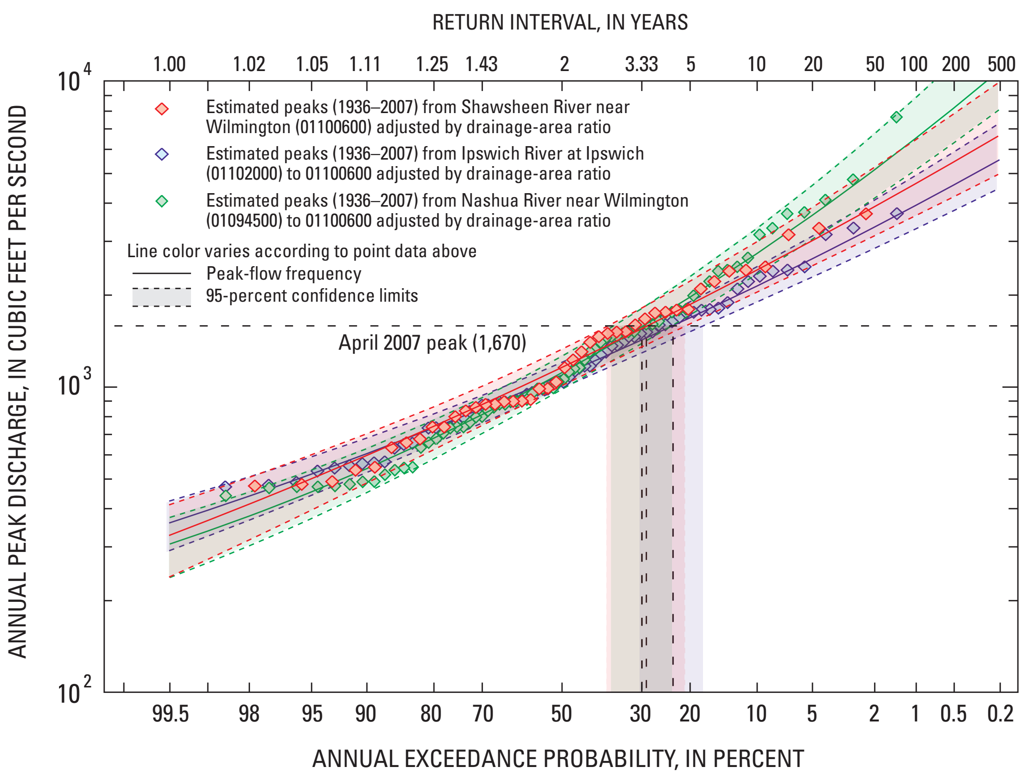


Figure 29. Peak-flow frequency computed from observed and estimated annual peak discharges for water years 1936 through 2007 for Shawsheen River at Andover (01100627), Massachusetts.

Table 16. Magnitude and confidence limits of flood flows at selected return intervals at Shawsheen River near Andover (01106270), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second								
		Period-of-record analysis (1950–2007)			Extended-record analysis (1936–2007)					
					Two-station comparison[1]			MOVE-1 extended record[2]		
		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit	
			Lower	Upper		Lower	Upper		Lower	Upper
					with Ipswich River near Ipswich (01102000)					
5	0.2	1,850	1,600	2,200	1,700	1,520	1,920	1,680	1,510	1,890
10	0.1	2,390	2,030	2,960	2,150	1,900	2,510	2,130	1,890	2,470
25	0.04	3,190	2,620	4,140	2,810	2,420	3,390	2,780	2,410	3,320
50	0.02	3,860	3,100	5,190	3,360	2,840	4,160	3,320	2,830	4,070
100	0.01	4,600	3,610	6,390	3,960	3,290	5,020	3,910	3,280	4,900
200	0.005	5,410	4,160	7,760	4,620	3,770	5,990	4,560	3,760	5,840
500	0.002	6,620	4,960	9,890	5,580	4,470	7,470	5,520	4,460	7,270
					with North Nashua River at Leominster (01094500)					
5	0.2				1,880	1,630	2,230	1,950	1,710	2,280
10	0.1				2,540	2,150	3,130	2,710	2,320	3,280
25	0.04				3,580	2,930	4,660	3,940	3,270	4,990
50	0.02				4,530	3,610	6,130	5,090	4,110	6,680
100	0.01				5,650	4,380	7,930	6,470	5,100	8,780
200	0.005				6,960	5,260	10,100	8,120	6,240	11,400
500	0.002				9,040	6,620	13,800	10,800	8,050	15,800

[1] Computed following Bulletin 17B, Appendix 7 guidelines (Interagency Advisory Committee on Water Data, 1982).

[2] Estimated annual-peak flows 1936–49 using MOVE-1 method (Hirsch, 1982).

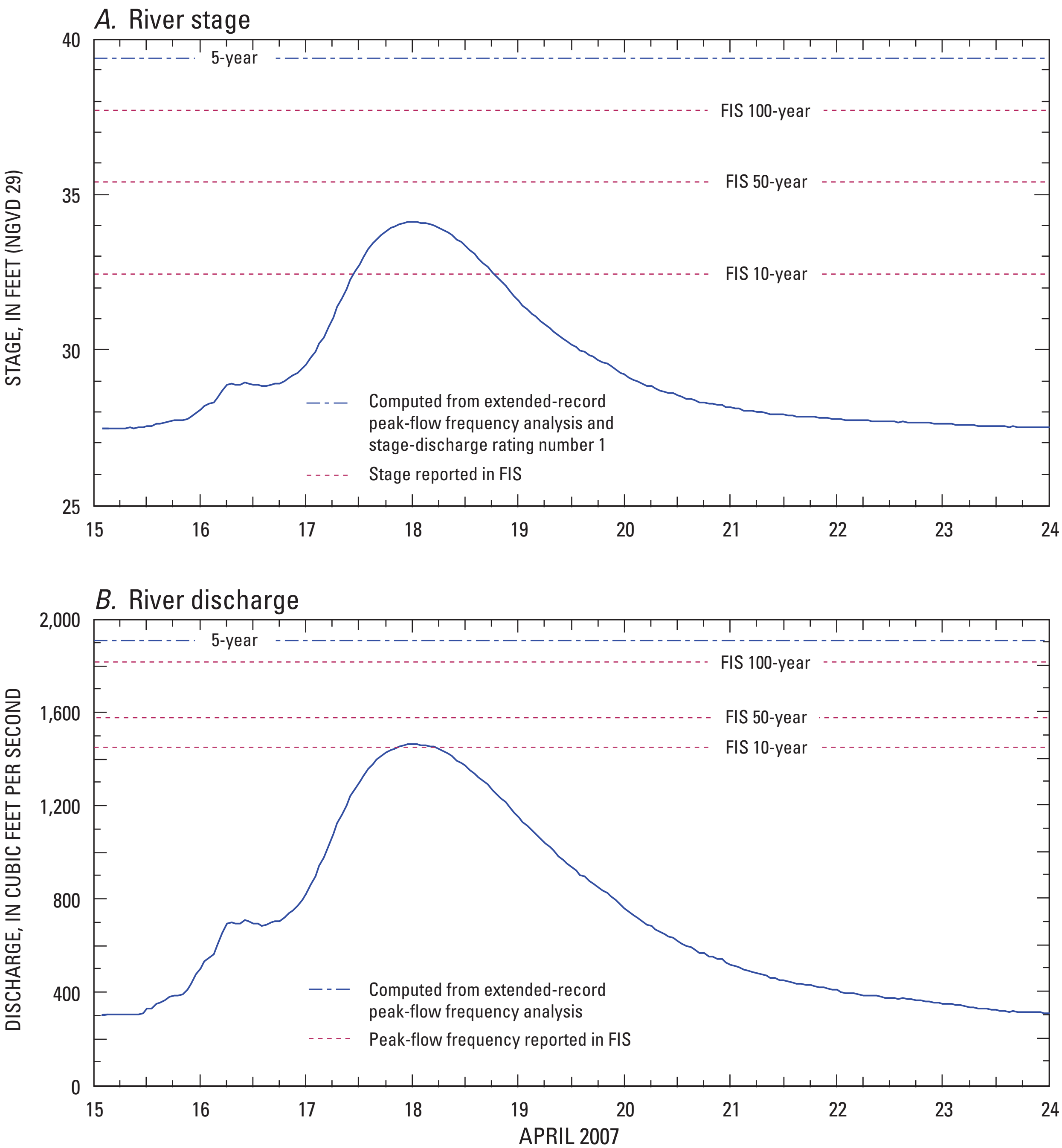


Figure 30. April 15–23, 2007, *(A)* stage and *(B)* discharge at Shawsheen River at Andover (01100627), Massachusetts. [FIS, flood-insurance study by FEMA (1989)]

The FEMA flood-insurance study revised in 1989 for the Town of Andover (FEMA, 1989) indicates the April 2007 peak stage (34.15 ft) was between a 10- and 50-year stage (fig. 30A). Shawsheen River at Andover is not part of the NWS Advanced Hydrologic Prediction network; therefore, a flood-warning stage is not available. The upstream streamflow-gaging station at Wilmington, is part of the NWS Advanced Hydrologic Prediction network; stage at this location was above the NWS flood stage (87.44 ft) for about 1.5 days and peaked on April 17 about 0.8 ft above flood stage. The return interval of the April 2007 peak discharge determined from the peak-flow frequency analysis varied depending on the data used, but was less than a 5-year return interval (fig. 30B). The flood-insurance study indicates the April 2007 peak discharge has about a 10-year return interval.

The Town of Andover flood insurance study (FEMA, 1989) reports the discharge for 10-, 50-, 100-, and 500-year return intervals for the Shawsheen River near the streamgage (about 3,800,000 ft upstream of the corporate limit) of 1,450; 2,170; 2,525; and 3,550 ft^3/s, respectively (table 17). These discharges were about two to three times lower than the estimated flood magnitudes determined by the various methods (table 16).

Peak flows calculated from extended records using the North Nashua River differed most from the flood flows for the Shawsheen River reported in the flood-insurance study (table 17). The magnitude of flood flows estimated from records extended with the North Nashua River were about two to three times greater than those in flood-insurance study; the differences increased as the return interval increased. The rating differs substantially from the stage-discharge relation defined by the flows and flood profile determined in the flood-insurance study. The estimated stage (rating 1) for a 10-year flood flow calculated from the extended record using the North Nashua River data at the 10-year return interval (2,710 ft^3/s) is about 22 ft greater than the 10-year flood stage shown on the flood insurance study profile (FEMA, 1989; plate 03). The estimated stage for a 10-year flood flow calculated from the extended record using the Ipswich River data (2,130 ft^3/s) is about 41 ft, or about 9 ft greater than that reported in the flood-insurance study. The stage-discharge relation at this site is defined by only a few measurements and the rating is estimated above 113 ft (gage datum of about 11.3 ft).

Table 17. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Shawsheen River at Andover (01100627), Massachusetts.

[ft, feet in NVGD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
						Stage (ft)	Discharge	
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	[4]Discharge rating 1 (ft^3/s)	[5]Discharge (ft^3/s)	[4]Stage rating 1 (ft)		Table 1 (ft^3/s)	Rating (ft^3/s)
5	--	--	--	1,950	39.2	--	--	--
10	32.4	1,450	1,240	2,710	53.0	21.6	1,470	1,260
25	--	--	--	3,940	--	--	--	--
50	35.4	2,170	1,590	5,090	--	--	3,500	2,920
100	36.7	2,525	1,710	6,470	--	--	4,760	3,945
200	--	--	--	8,120	--	--	--	--
500	44.0	3,550	2,310	10,800	--	--	8,490	7,250

[1] Town of Andover flood-insurance study (FEMA, 1989).

[2] Flood stages at streamflow-gaging station; 3,800 ft above corporate limit on flood profile (FEMA, 1989; pl. 03P).

[3] Flood-insurance study summary of discharges used in determining flood elevations (FEMA, 1989; table 1, at Andover-Lawrence corporate limits).

[4] Stage determined from stage-discharge rating number 1; above 34 ft rating is estimated; stage for discharges greater than 3,600 ft^3/s not determined because they extend far beyond the rating.

[5] Determined from flood-frequency analysis of MOVE-1 extended record with North Nashua River at Leominster (01094500).

Mill River at Northampton–01171500

Annual peak-flow records for the Mill River at Northampton span a 70-year period from water years 1938 through 2007. The 1938 water year peak predates the start of continuous-streamgaging operation in October 1938 (beginning of the 1939 water year), but was determined following a hurricane in September of that year by indirect measurements conducted near the streamflow-gaging station (6,680 ft^3/s) and 6 mi upstream of the station (7,330 ft^3/s). The average of these two measurements (7,000 ft^3/s) was entered in the peak-flow file and used in the peak-flow frequency analysis. For consistency with the other stations examined in this study, the peak flows for 1936 and 1937 were estimated using MOVE-1 and concurrent peak-flow records at the Quaboag River at West Brimfield (01176000) and the West Branch Westfield River at Huntington (01181000). The centroids of the Quaboag and West Branch Westfield River Basins are about 34 and 17 mi to the southeast and southwest of the centroid of the Mill River Basin, respectively. Estimated peak discharges varied from the observed (fig. 31) and, in general, the peaks calculated from the West Branch Westfield River data were in better agreement with the observed peaks (RMSE 1,008 ft^3/s) than the peaks calculated from the Quaboag River data (RMSE 2,524 ft^3/s). Regardless of which index station was used, the estimated 1936 peak discharge was near or below the three largest peaks of record and, therefore, did not exert a large influence in the peak-flow analysis. The estimated peaks shown in figure 32 were determined from the two stations weighted on the basis of the RMSE. The peak in April 2007 was the third highest discharge recorded, exceeded only by the peak discharge in the 1938 and 1955 water years. The 1938 and 1955 peak discharges are relatively close in magnitude (within 14 percent) to the April 2007 peak discharge (fig. 32).

Peak-flow-frequency analysis determined from the period of record indicates the April 2007 peak flow (6,150 ft^3/s) has a return interval of about 50 years and is within the 95-percent confidence limits of a 25- to 100-year return interval (table 18, fig. 33). The extended-record analysis, unlike many of the other stations examined, yielded little change in the magnitudes of peaks for various return intervals mainly because the records were extended for only 2 years and the magnitudes of the estimated peaks were near other peaks in the period of record. A peak-flow analysis of the weighted estimates of the 1936 and 1937 peaks and the recorded peaks indicate the April 2007 peak discharge had about the same return interval, but the 95-percent confidence limit was between a 25- and 50-year return interval (table 18). Records extended on the basis of the relation with the Quaboag River data produced discharges that were only about 2 to 6 percent higher than the discharges determined from the period-of-record analysis for return intervals of 5 to 500 years, respectively. Records extended on the basis of the relation with the West Branch Westfield River produced discharges that were about 1 percent less than the discharges determined from the period-of-record analysis for return intervals of 5- to 500-years.

The FEMA flood-insurance study completed in 1976 for the City of Northampton indicates the April 2007 peak stage (188.26 ft) was between a 10- and 50-year flood (fig. 34A) at Clement Street (present location of streamflow-gaging station) on the flood profile (FEMA, 1976; plate-O5P). Mill River at Northampton exceeded the NWS flood stage (182.68 ft) for about 1 day and peaked on April 16 at about 5.6 ft above flood stage. The return interval of the April 2007 peak discharge determined from the peak-flow frequency analysis made in this study approached that of a 50-year flood (fig. 34B).

The City of Northampton flood-insurance study discharge for 10-, 50-, 100- and 500-year return intervals for the Mill River near the streamgage (about 4.66 mi upstream from the mouth) was estimated to be 4,700; 8,200; 10,500; and 16,000 ft^3/s, respectively (FEMA, 1976; interpolated from fig. 6). These discharges were obtained from a log-Pearson Type III distribution of 36 years of annual peak-flow record (1938–73) at the Mill River streamflow-gaging station. The flood-insurance study flood flows are about 7, 27, 42, and 64 percent greater than discharges calculated in this study for 10-, 50-, 100-, and 500-year return intervals as determined from the extended record analysis. This result demonstrates the leveraging of the large peaks in 1938 and 1955 over the relatively short record used in the flood-insurance study (1938–73) compared to the length of the record used in this analysis (1936–2007).

Correspondingly, the flood stages determined from the current stage-discharge relation (rating 46) for flood flows calculated in this study are somewhat less than the flood stages shown at Clement Street (FEMA, 1976). Differences in stage ranged from about 0.8 to 1.6 ft for flood flows with return intervals of 10 to 500 years (table 19).

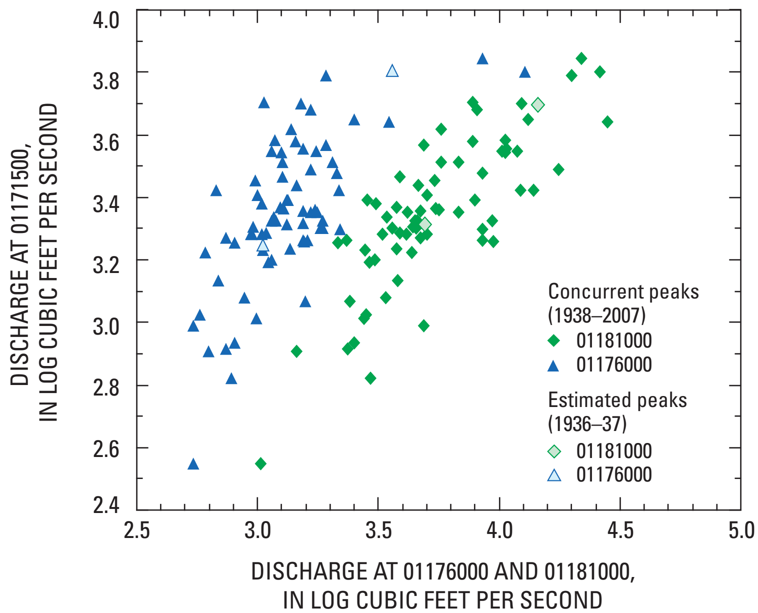


Figure 31. Relation between observed annual peak discharges for water years 1938 through 2007 at Mill River at Northampton (01171500) and Quaboag River at West Brimfield (01176000) and to West Branch Westfield River at Huntington (01181000), Massachusetts.

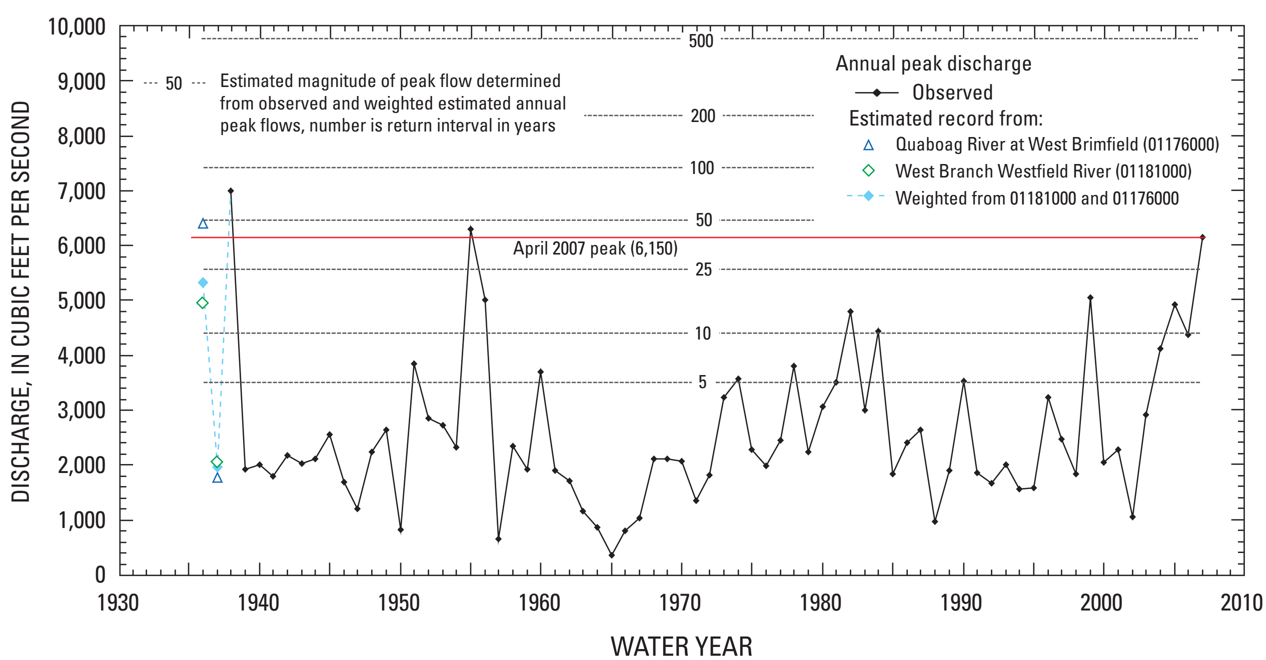


Figure 32. Observed and estimated peak annual discharge for water years 1936 through 2007, Mill River at Northampton (01171500), Massachusetts.

Table 18. Magnitude and confidence limits of flood flows at selected return intervals at Mill River at Northampton (01171500), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second: Period-of-record analysis (1938–2007): Expected peak	Period-of-record analysis (1938–2007): 95-percent confidence limit: Lower	Period-of-record analysis (1938–2007): 95-percent confidence limit: Upper	Extended-record analysis (1936–2007)[1]: Expected peak	Extended-record analysis (1936–2007)[1]: 95-percent confidence limit: Lower	Extended-record analysis (1936–2007)[1]: 95-percent confidence limit: Upper
5	0.2	3,470	3,110	3,940	3,520	3,160	3,980
10	0.1	4,320	3,820	5,020	4,390	3,880	5,090
25	0.04	5,460	4,730	6,530	5,560	4,820	6,630
50	0.02	6,350	5,420	7,740	6,470	5,530	7,880
100	0.01	7,260	6,120	9,030	7,410	6,250	9,200
200	0.005	8,210	6,830	10,400	8,400	6,990	10,600
500	0.002	9,520	7,800	12,300	9,760	8,000	12,600

[1] Estimated annual-peak flows 1936–37 using MOVE-1 method (Hirsch, 1982); weighted average of flows determined from Quaboag River at West Brimfield (01176000) and West Branch Westfield River at Huntington (01181000).

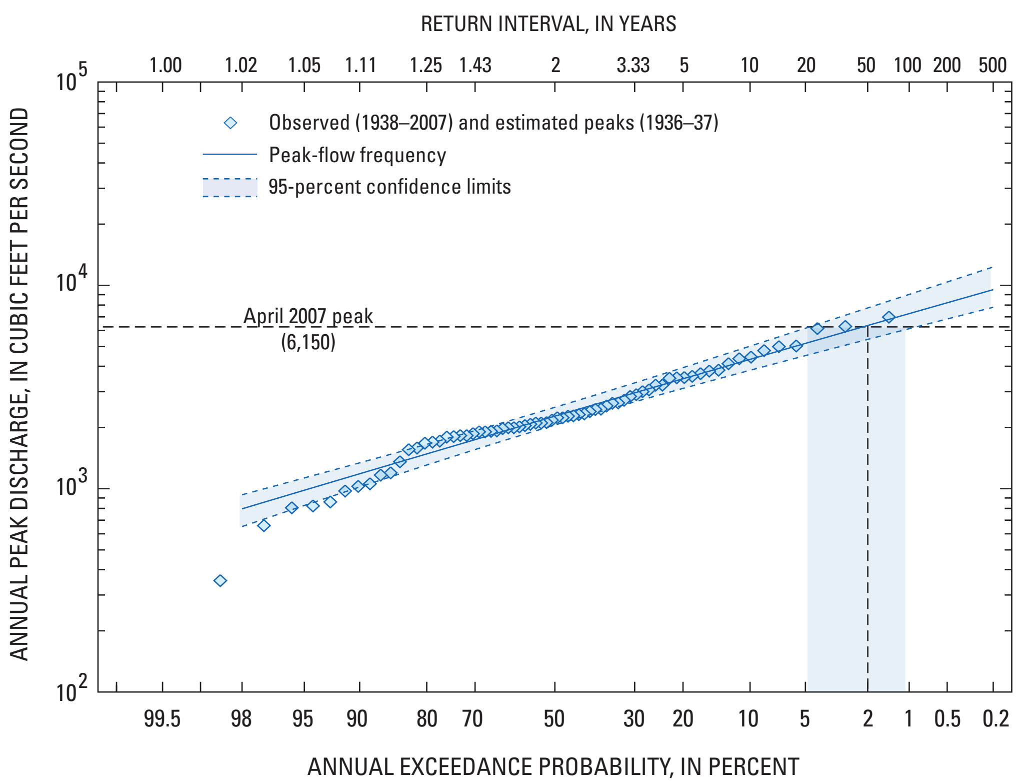


Figure 33. Peak-flow frequency computed from observed and estimated annual peaks for water years 1936 through 2007 at Mill River at Northampton (01171500), Massachusetts.

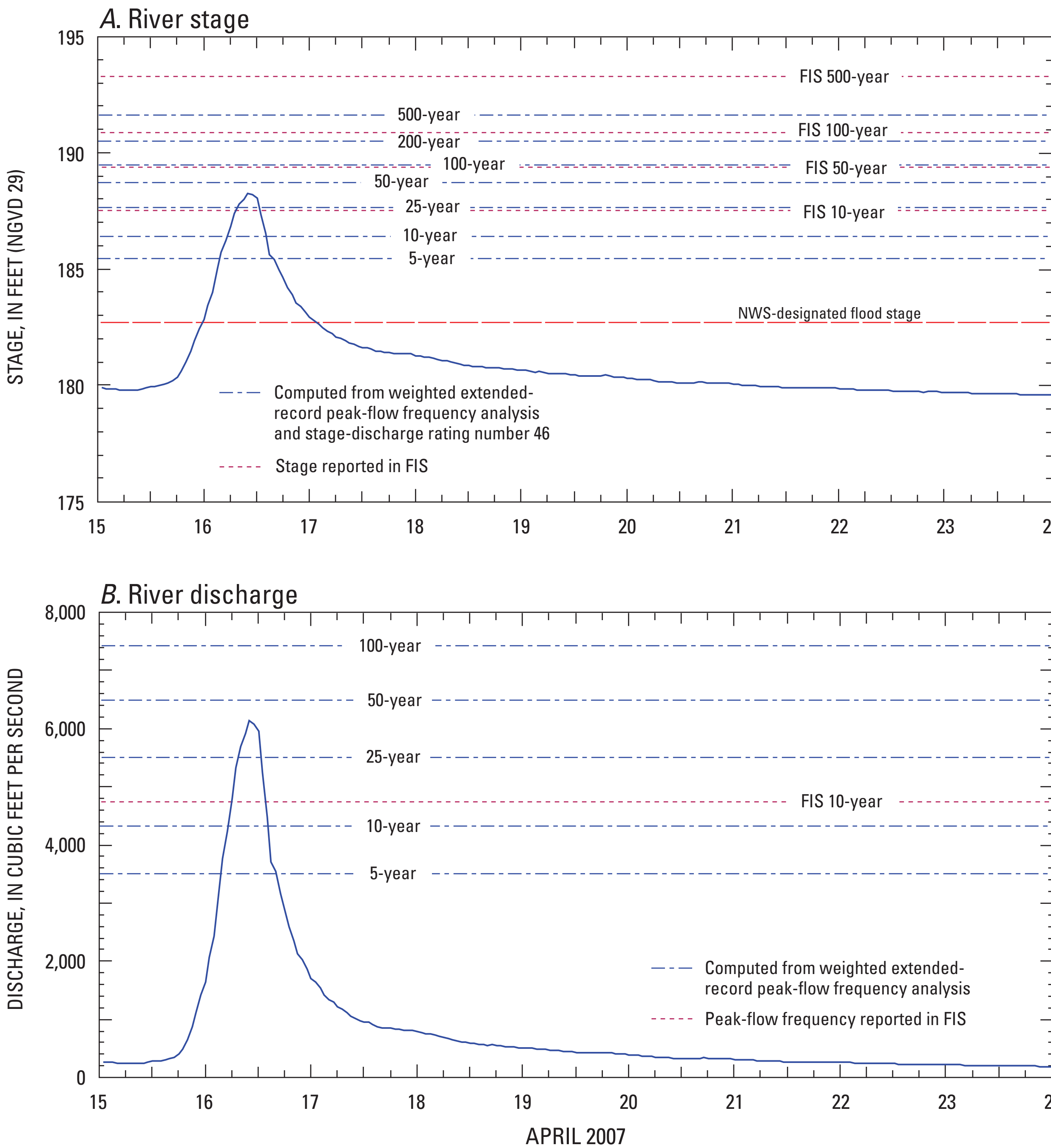


Figure 34. April 15–23, 2007, *(A)* stage and *(B)* discharge at Mill River at Northampton (01171500), Massachusetts. [NWS, National Weather Service; FIS, flood-insurance study by FEMA (1976)]

Table 19. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Mill River at Northampton (01171500), Massachusetts.

[ft, feet in NVGD 29; ft³/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study			Present study		Difference between present and flood-insurance studies		
	[2]Stage (ft)	[3]Discharge figure 6 (ft³/s)	[4]Discharge rating 46 (ft³/s)	[5]Discharge (ft³/s)	[4]Stage rating 46 (ft)	Stage (ft)	Discharge Table 1 (ft³/s)	Discharge Rating (ft³/s)
5	--	--	--	3,520	185.4	--	--	--
10	187.5	4,700	5,400	4,390	186.4	-1.1	-310	-1,010
25	--	--	--	5,560	187.7	--	--	--
50	189.4	8,200	7,400	6,470	188.6	-0.8	-1,730	-930
100	190.9	10,500	9,050	7,410	189.5	-1.4	-3,090	-1,640
200	--	--	--	8,400	190.4	--	--	--
500	193.3	16,000	12,000	9,760	191.7	-1.6	-6,240	-2,240

[1] City of Northampton flood-insurance study (FEMA, 1976).

[2] Flood stages at streamflow-gaging station; 4.66 mi above mouth (Clements Streeet) on flood profile (FEMA, 1976; pl. 05P).

[3] Flood-insurance study interpolated discharges (FEMA, 1976; fig. 6).

[4] Stage determined from stage-discharge rating number 46; above 188 ft rating is estimated.

[5] Determined from flood-frequency analysis of MOVE-1 extended record.

Sevenmile River near Spencer–01175670

Annual peak-flow records for Sevenmile River near Spencer span a 47 year period, water years 1961 through 2007. Peak flows for 1936 through 1960 were estimated using MOVE-1 and concurrent peak-flow records from North Nashua River near Leominster (01094500) and Quaboag River at West Brimfield (01176000). The centroids of the North Nashua River and Quaboag River Basins are about 20 and 6 mi north and southwest of the centroid of the Sevenmile River Basin, respectively; the Sevenmile River is tributary to the Quaboag River. Estimated peak discharges varied from the observed, particularly with estimated peaks derived from the North Nashua River data (fig. 35); the RMSE of the estimated discharge determined from North Nashua River and Quaboag River data was 122 and 64 ft³/s, respectively.

The April 2007 peak discharge (453 ft³/s) was the second highest recorded, exceeded only in the 2006 water year by about twice (905 ft³/s), but was nearly equaled in the 1968 water year (fig. 36). Although some of the estimated peaks derived from either index station were higher than the observed peaks of record (fig. 36), the 1938 and 1955 peaks derived from the Quaboag River data were substantially greater than those derived from the Nashua River data. The estimated peaks derived from the North Nashua River data exceeded the April 2007 peak in 1936, 1938, 1944, and 1956 by about 206, 84, 40, and 56 percent, respectively; the 1936 peak exceeded the 2006 peak by about 53 percent. The estimated peaks derived from the Quaboag River data exceeded the April 2007 peak in 1936, 1938, and 1955 by about 66, 442, and 861 percent, respectively; the 1936 and 1955 peaks exceeded the 2006 peak by about 171 and 381 percent, respectively.

As in the MOVE-1 relation described for the Shawsheen River, the most appropriate index station is not necessarily determined by the lowest RMSE between estimated and observed flows. The RMSE resulting from the Quaboag River data was about half that resulting from North Nashua River data, but some of the estimated peaks during 1936–60 reflect much different meterologic conditions at the two index stations, particularly in 1938 and 1955. If meterologic conditions that contributed to the peak discharge in one basin better reflect those in the Sevenmile River Basin in a particular year, then that index basin would provide a better estimate of the magnitude of flood flows. Determining which index station, or weighting of index stations, best matches the meteorologic and hydrologic conditions leading to the peak for a particular event requires a detailed analysis of the storms that leverage the distribution of peaks. Although such an analysis was not possible as part of this investigation, this type of analysis could improve estimates of the magnitude of peak flows for various return intervals. For example,

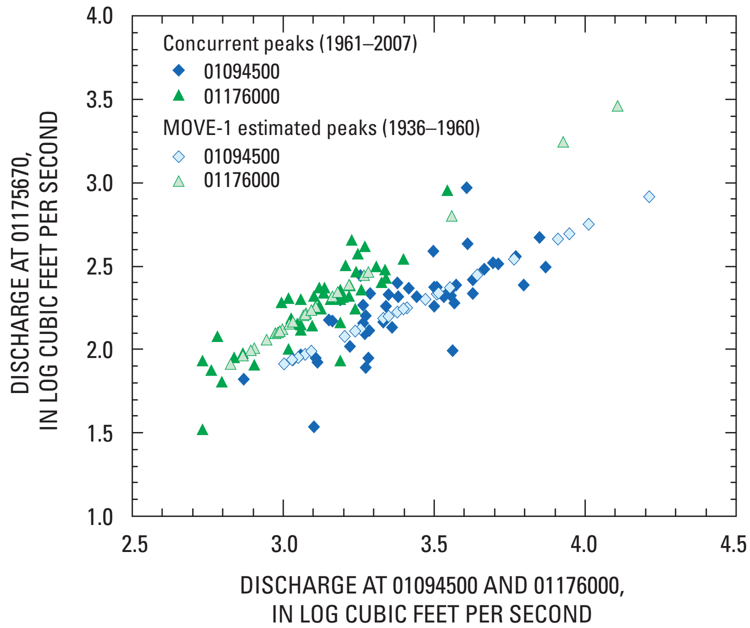


Figure 35. Relation between observed annual peak discharges for water years 1961 through 2007 at Sevenmile River near Spencer (01175670) and North Nashua River at Leominster (01094500) and to Quaboag River at West Brimfield (01176000), Massachusetts.

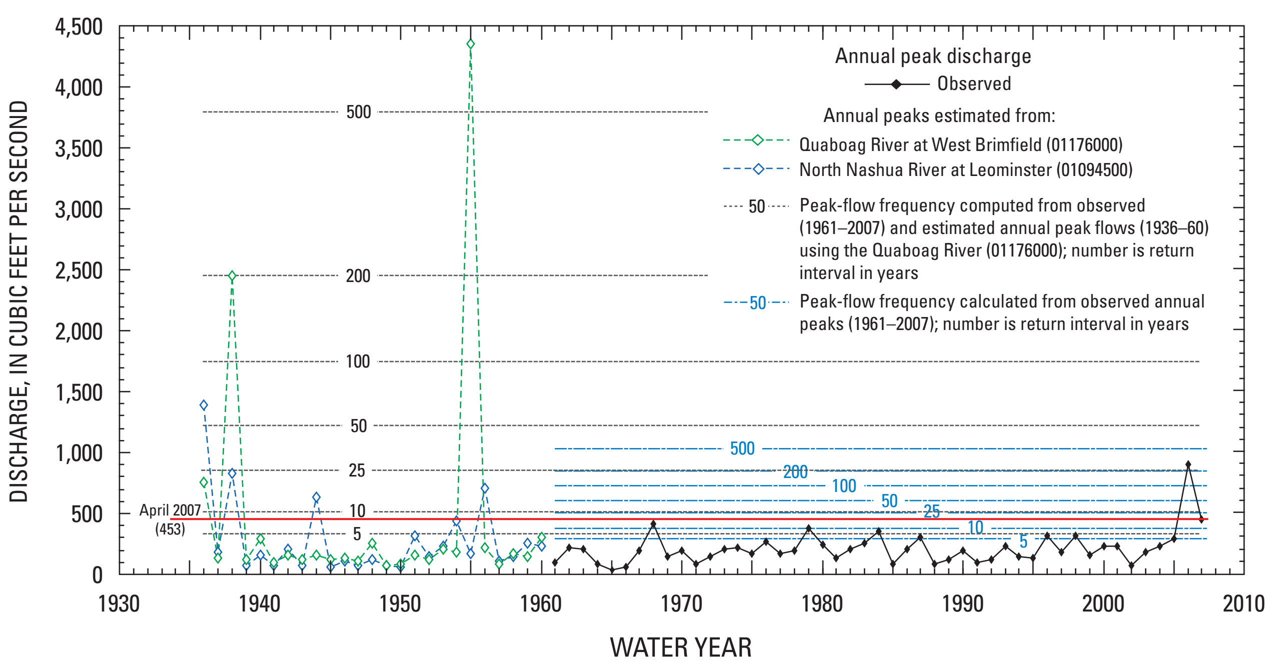


Figure 36. Observed and estimated annual peak discharge for water years 1936 through 2007 at Sevenmile River near Spencer (01175670), Massachusetts.

back-to-back hurricanes Connie and Diane produced about 20 in. of precipitation in a 2-week period in August 1955 in south-central Massachusetts that resulted in the peak of record at Quaboag River, but did not even result in the 1955 water-year peak discharge in the North Nashua River. Without further investigation, the question remains as to whether the precipitation in the Sevenmile River Basin in August 1955 was closer to that in the Quaboag River Basin, which produced the highest peak flow in a 94-year record by a wide margin, or closer to that of the North Nashua River Basin, which did not even result in the peak discharge for the water year. Estimation of other major peaks should consider similar questions about the meterologic and hydrologic conditions in the choice of an index station because of the influence these storms exert on the magnitude of flows for small exceedance probabilities (long return intervals).

Peak-flow frequency analysis for the period of record indicates the April 2007 peak flow (453 ft^3/s) has a return interval of 10 to 25 years (table 20; fig. 37). The April peak flow was close to a 10-year discharge computed from the extended-record analysis and the two-station analysis with the North Nashua River and Quaboag River data (table 20; fig. 37) and was within the 95-percent confidence limits of a 10-year return interval determined by each of these methods.

Discharges for various return intervals determined from the period-of-record analysis were less for all return intervals greater than 5 years than that those determined by the various extended-record methods. Discharges for various return intervals determined from the two-station analysis with the North Nashua River and the Quaboag River data and the extended-record analysis determined from the North Nashua River data were similar for a given return interval. Discharges determined from records extended with the Quaboag River data were always greater than those produced by the other methods for various return intervals; these differences increased as the exceedance probability decreased (return interval increased). Discharges for various return intervals determined from records extended with the Quaboag River data underscore the leveraging of the estimated 1938 and 1955 peak discharges, which are not expressed to the same extent in the two-station comparison method that uses the ratios of the log mean discharges and standard deviations of the long- and short-term stations.

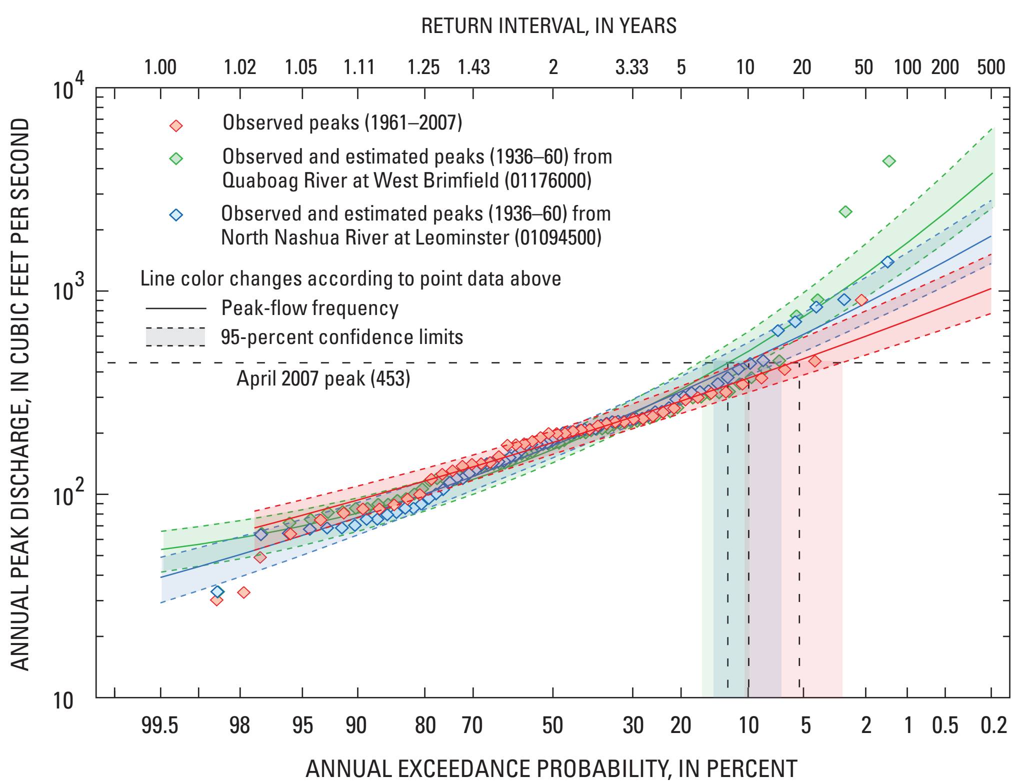


Figure 37. Peak-flow frequency computed from observed and estimated annual peaks for water years 1936 through 2007 at Sevenmile River near Spencer (01175670), Massachusetts.

Table 20. Magnitude and confidence limits of flood flows at select return intervals at Sevenmile River near Spencer (01175670), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second								
		Period-of-record analysis (1961–2007)			Extended-record analysis (1936–2007)					
					Two-station comparison[1]			MOVE-1 extended record[2]		
		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit		Expected peak	95-percent confidence limit	
			Lower	Upper		Lower	Upper		Lower	Upper
					with North Nashua River at Leominster (01094500)					
5	0.2	290	250	340	300	260	360	320	270	380
10	0.1	370	320	460	420	350	520	450	380	550
25	0.04	500	410	640	600	490	790	660	540	860
50	0.02	600	480	800	770	610	1,050	860	690	1,160
100	0.01	710	560	980	967	750	1,360	1,100	860	1,530
200	0.005	840	650	1,190	1,200	900	1,740	1,390	1,050	2,000
500	0.002	1,030	780	1,520	1,560	1,140	2,380	1,850	1,360	2,780
					with Quaboag River at West Brimfield (01176000)					
5	0.2				270	240	310	330	280	390
10	0.1				380	330	460	510	420	630
25	0.04				580	480	740	850	670	1,130
50	0.02				780	630	1,030	1,220	940	1,720
100	0.01				1,040	810	1,420	1,740	1,280	2,580
200	0.005				1,370	1,040	1,950	2,450	1,740	3,820
500	0.002				1,950	1,420	2,940	3,800	2,560	6,330

[1] Computed following Bulletin 17B, Appendix 7 guidelines (Interagency Advisory Committee on Water Data, 1982).

[2] Estimated annual-peak flows 1936–60 using MOVE-1 method (Hirsch, 1982).

Although the expected return period of the April 2007 peak determined by the various methods was not large, the magnitude of flood flows determined by the various methods can differ substantially as the discharge increases. This is particularly true of the analysis made with records extended with the Quaboag River data, which diverged most substantially from the other methods with increasing discharge (fig. 37). The peak discharge for a 100-year return interval determined from records extended with the Quaboag River data was about 140 percent greater than that determined from the period of record and about 60 percent greater than that determined from records extended with the North Nashua River data. The discharges determined from the records extended with the North Nashua River data were about midway between the discharges computed from the records extended with the Quaboag River data and those determined from the period of record for exceedance probabilities less than about 20 percent (fig. 37).

The FEMA flood-insurance study revised in 1990 for the Town of Spencer (FEMA, 1990) did not extend to the streamflow-gaging station location (gage is about 3,500 ft upstream from the study limits). Therefore, comparisons to the flood-insurance study were limited to discharges used in flow routing for the flood-insurance study. The streamflow-gaging station on Sevenmile River near Spencer is not part of the NWS Advanced Hydrologic Prediction network; therefore, a flood-warning stage is not available. The river peaked at the streamflow-gaging station on April 16 at a stage of 646.5 ft (fig. 38A).

Peak-flow analysis varied by the method and data used; for reference, peak flows determined from records extended with the North Nashua River data and the Quaboag River data are shown in figure 38B. The April 2007 peak flow approached or equalled the 10-year discharge on the basis of the record extended using the Quaboag River and North Nashua River data, respectively, and exceeded the flood-insurance study 10-year discharge (fig. 38B).

The Town of Spencer flood insurance study reports discharge for 10-, 50-, 100- and 500-year return intervals for Sevenmile River near the confluence of Cranberry River (FEMA, 1990; table 1). These flows were determined by a precipitation-runoff model run with 48-hour design-storm hyetograph. The reported drainage area near the confluence with the Cranberry River is 31.6 mi^2 and is about 3.6 times larger than the drainage area at the streamflow-gaging station (8.81 mi^2). Using a simple drainage-area ratio, discharges reported near the confluence with the Cranberry River were adjusted to those at the streamflow-gaging station and are estimated at about 350, 620, 800, and 1,260 ft^3/s for return intervals of 10, 50, 100, and 500 years, respectively (table 21). The flood flows calculated in this study from extended-record analysis methods are about 10 to 200 percent greater than the interpolated flood flows; differences increase as the return interval increases. Discharges computed by the two-station comparison method with the North Nashua River generally yielded the smallest differences with the flood-insurance-study discharges, ranging from about 20 to 25 percent. Discharge computed from records extended with the Quaboag River data yielded the greatest differences with the flood-insurance-study discharges, ranging from about 45 to 200 percent for return intervals of 10 and 500 years, respectively. The period-of-record peak-flow analysis yielded the smallest overall differences with the flood-insurance-study discharges, ranging from about 7 to -18 percent for return intervals of 10 and 500 years, respectively.

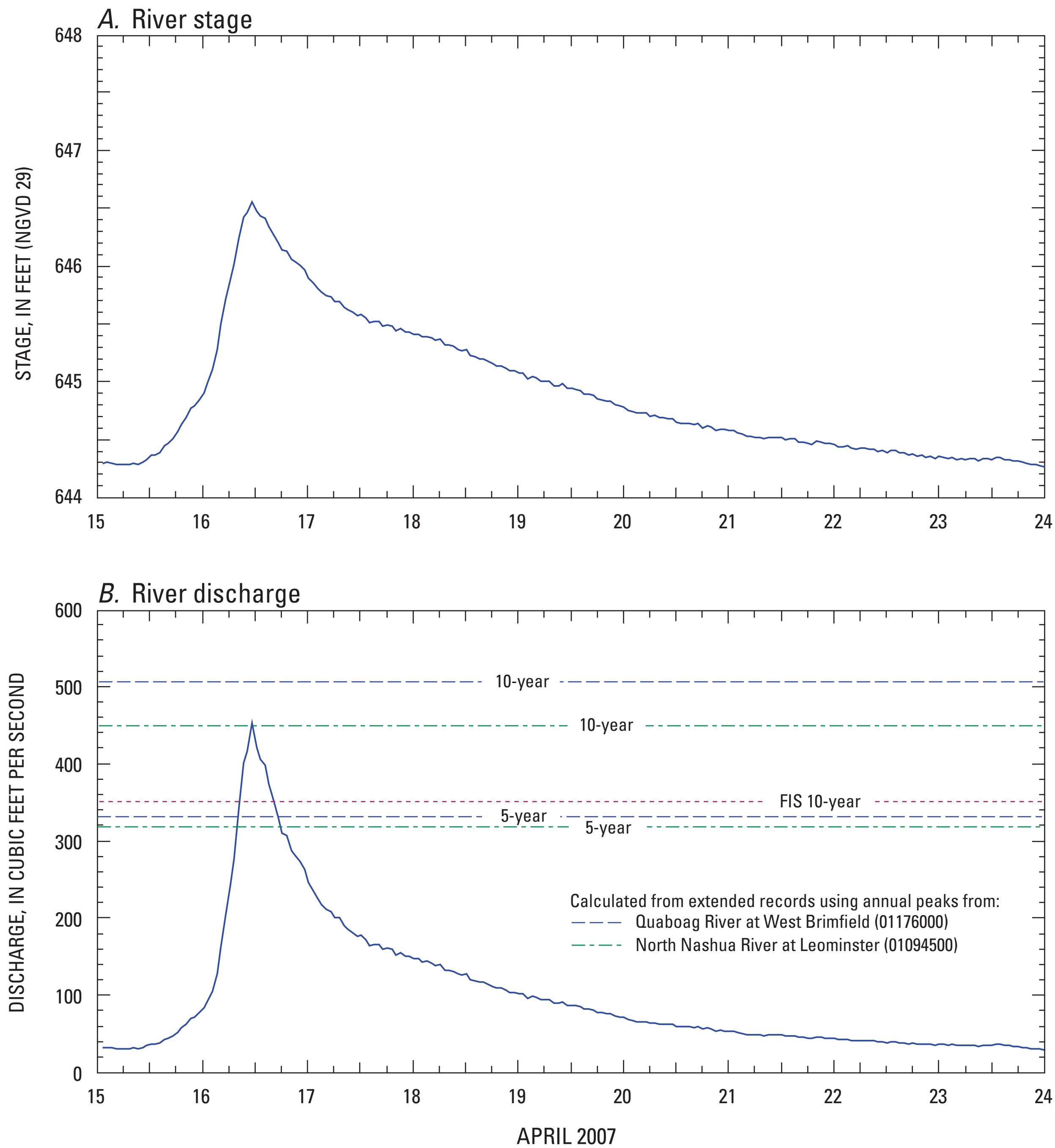


Figure 38. April 15–23, 2007, *(A)* stage and *(B)* discharge at Sevenmile River near Spencer (01175670), Massachusetts. [FIS, flood insurance study by FEMA (1990)]

Table 21. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for Sevenmile River near Spencer (01175670), Massachusetts.

[ft^3/s, cubic feet per second; Delta, difference between peak flows from flood-insurance study and extended-record peak-flow analysis; --, not determined]

Return interval (years)	Flood-insurance study discharge (ft^3/s)[1]	Discharge determined by flood-frequency analysis made with MOVE-1 extended record from			
		North Nashua River at Leominster (01094500)		Quaboag River at West Brimfield (01176000)	
		(ft^3/s)	Delta (ft^3/s)	(ft^3/s)	Delta (ft^3/s)
5	--	320	--	330	--
10	350	450	100	510	160
25	--	660	--	850	--
50	620	860	240	1,220	600
100	800	1,100	300	1,740	940
200	--	1,390	--	2,450	--
500	1,260	1,850	590	3,800	2,540

[1] Town of Spencer flood-insurance study adjusted by drainage-area ratio 0.28 (FEMA, 1990; table 1, upstream from Cranberry River).

West Branch Westfield River near Huntington–01181000

Annual peak-flow records for the West Branch Westfield River near Huntington span a 72 year period, water years 1936 through 2007. Because the observed record spans the desired period of time used in the analysis and because there is no appreciable regulation that affects flows, no extension of record was necessary at this site. The peak in April 2007 (19,700 ft^3/s) was the third highest discharge recorded, exceeded only by the 1938, 1955, and 2006 water year peaks. The 1938, 1955, and 2006 peak discharges exceeded the April 2007 peak by about 11, 32, and 43 percent, respectively (fig. 39). The April 2007 peak discharge was about 310 percent greater than the period-of-record median discharge.

The FEMA flood-insurance study completed in 1988 for the Town of Huntington (FEMA, 1988) indicates the April 2007 peak stage (396.42 ft) was still about 2 ft below the 10-year flood stage (fig. 41A). The river stage was above the NWS-designated flood stage (392.60 ft) for less than a day and peaked about 3.8 ft above the NWS flood stage on April 16. Peak-flow frequency analysis indicates the April 2007 peak flow had a return interval of about 25 years and was within the 95-percent confidence limits of the 25-year return interval (table 22, fig. 40B). The flood-insurance study indicates the April 2007 peak discharge was between the 10- and 50-year discharges. The peak discharge in October 2006 (28,100 ft^3/s) was near a 100-year discharge.

The Town of Huntington flood-insurance study reports peak discharges determined from 43 years record at the West Branch Westfield River streamflow-gaging station of 12,780; 23,360; 29,200; and 46,600 ft^3/s for 10-, 50-, 100- and 500-year return intervals, respectively (table 23). These discharges are about 3 to 7 percent less than those estimated for the same return intervals in this study; the difference increases as discharge increases. This difference is expected because the flood-insurance study was completed in April 1988, prior to two of the highest annual peaks recorded in 2006 and the April 2007.

Correspondingly, the flood stages determined from the current stage-discharge relation (rating 12) in this study are lower than the flood-insurance-study flood stages, but the differences are too large to be attributed to differences in discharge alone. Differences ranged from about 3.3 to 5.8 ft for flood flows with return intervals of 10 to 500 years, respectively (table 23). Some of these differences are attributed to a change in the gage pool in October 1989 (moved 200 ft downstream), which resulted in a different stage-discharge relation than that in place at the time of the flood-insurance study and a flood profile that changes rapidly near the gage location. Because of the major change in the rating, stage or converted stage to discharge between the flood-insurance study and this study were not compared.

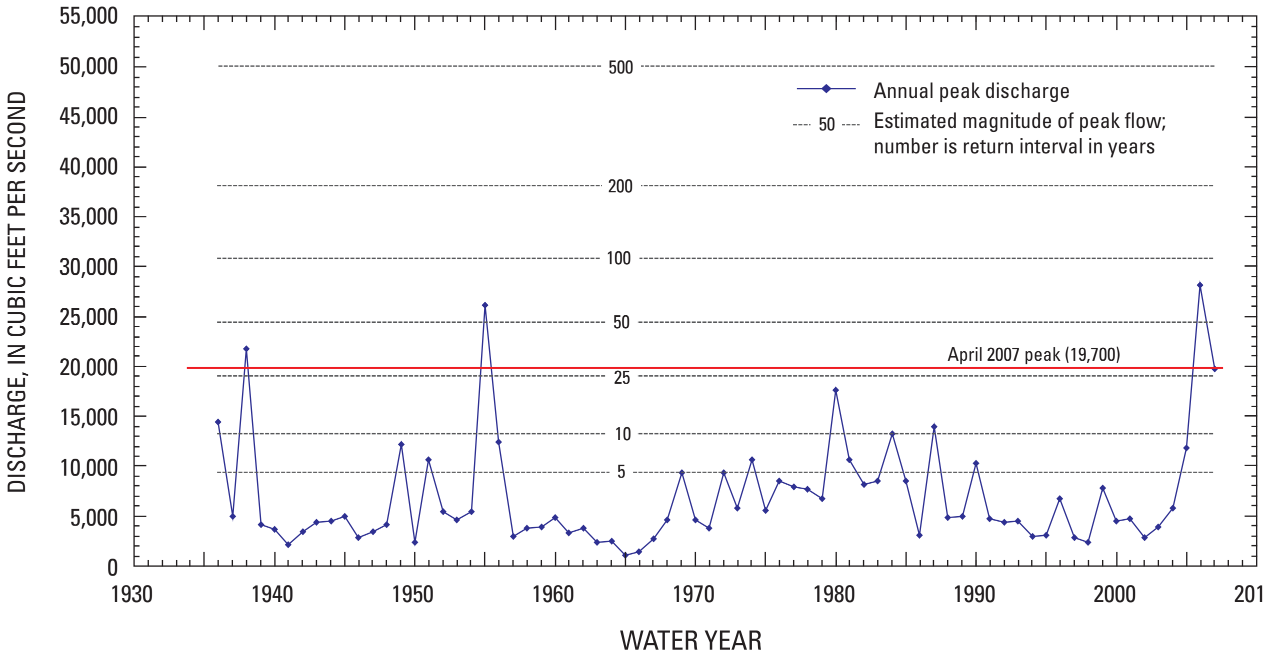


Figure 39. Observed annual peak discharge for water years 1936 through 2007 at West Branch Westfield River near Huntington (01181000), Massachusetts.

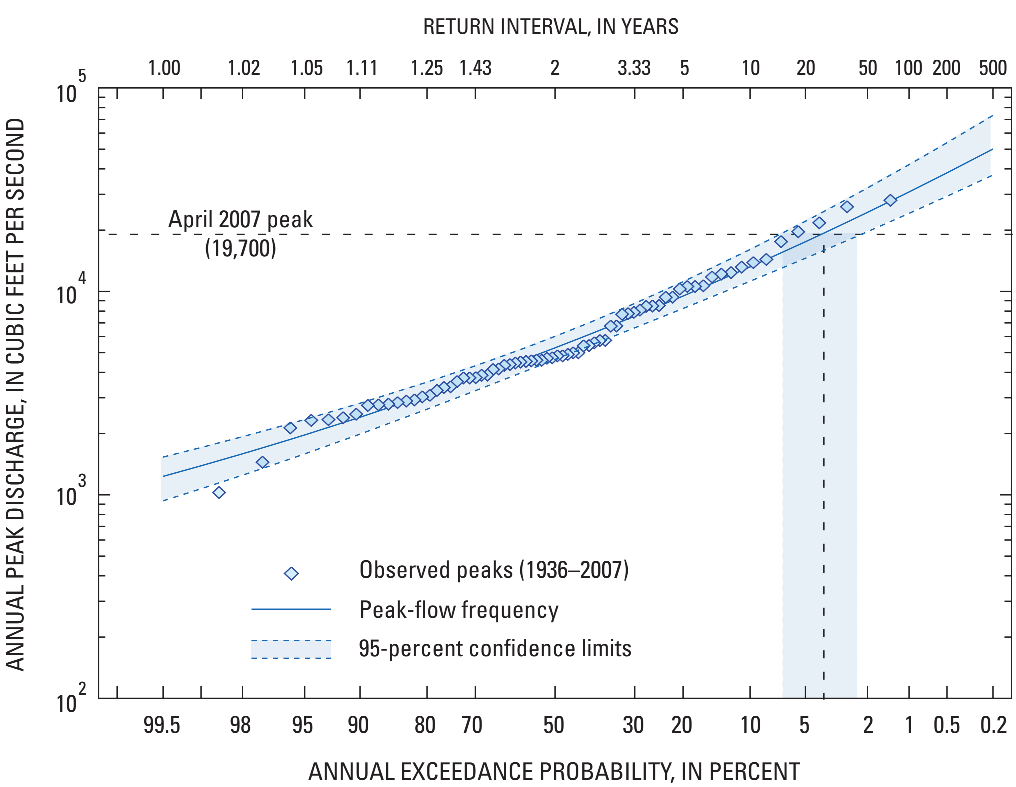


Figure 40. Peak-flow frequency computed from observed annual peaks for water years 1936 through 2007 at West Branch Westfield River near Huntington (01181000), Massachusetts.

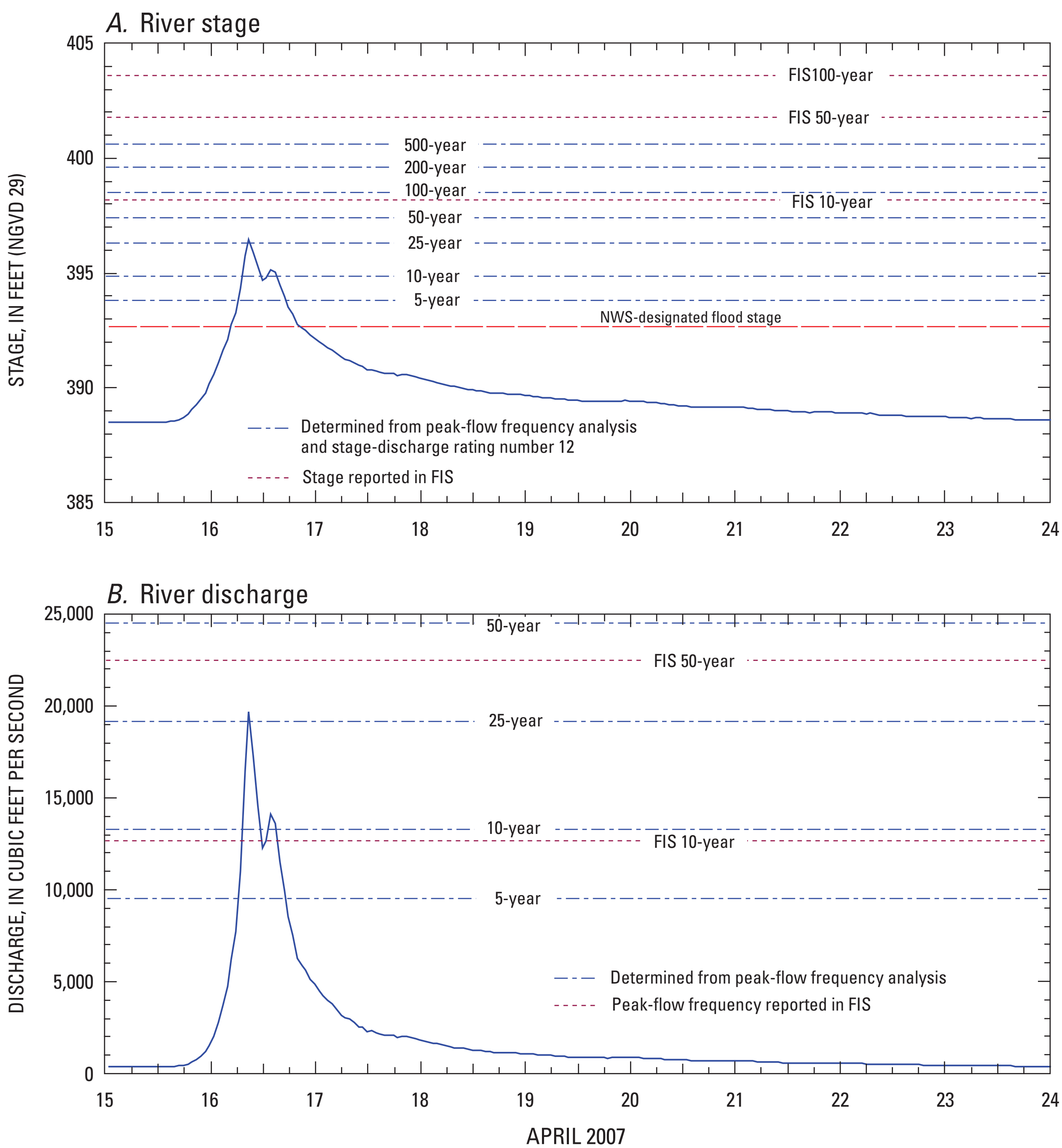


Figure 41. April 15–23, 2007, *(A)* stage and *(B)* discharge at West Branch Westfield River near Huntington (01181000), Massachusetts. [NWS, National Weather Service; FIS, flood-insurance study by FEMA (1988)]

Table 22. Magnitude and confidence limits of flood flows at select return intervals at West Branch Westfield River near Huntington (01181000), Massachusetts.

Return interval (years)	Exceedance probability	Estimated magnitude of flood flow, in cubic feet per second		
		Period-of-record analysis (1936–2007)		
		Expected peak	95-percent confidence limit	
			Lower	Upper
5	0.2	9,490	8,240	11,200
10	0.1	13,200	11,200	16,100
25	0.04	19,100	15,700	24,300
50	0.02	24,500	19,700	32,300
100	0.01	30,800	24,200	42,000
200	0.005	38,200	29,300	53,800
500	0.002	50,100	37,300	73,300

Table 23. Comparison of flood stage and discharge at selected return intervals reported in community flood-insurance study to values determined in this study for West Branch Westfield River near Huntington (01181000), Massachusetts.

[ft, feet in NVGD 29; ft^3/s, cubic feet per second; --, not determined]

Return interval (years)	[1]Flood-insurance study		Present study		Difference between present and flood-insurance studies	
	[2]Stage (ft)	[3]Discharge table 1 (ft^3/s)	Discharge (ft^3/s)	[4]Stage rating 12 (ft)	Stage (ft)	Discharge (ft^3/s)
5	--	--	9,490	393.9	--	--
10	398.2	12,780	13,200	394.9	-3.3	420
25	--	--	19,100	396.3	--	--
50	401.8	23,360	24,500	397.4	-4.4	1,140
100	403.6	29,200	30,800	398.4	-5.2	1,600
200	--	--	38,200	399.7	--	--
500	407.4	46,600	50,100	401.6	-5.8	3,500

[1] Town of Huntington flood-insurance study (FEMA, 1988).

[2] Flood stages at streamflow-gaging station; 7,831,000 ft above mouth on flood profile (FEMA, 1988; pl. 07P).

[3] Flood-insurance study (FEMA, 1988; table 1, at streamflow-gaging station).

[4] Stage determined from stage-discharge rating number 12; above 398 ft rating is estimated.

Magnitude of Peak-Flow in Relation to Drainage Area

A general relation exists between the size of the drainage basin and the magnitude of flood flows at selected return intervals. Basin area typically dominates multivariate regression equations for estimating the magnitude of flood flows. In Connecticut (Ahearn, 2003) and New York (Lumia and others, 2006), single-variable explanatory equations using drainage area were developed along with multivariate equations because drainage area explained the majority of the variance. The six streamflow-gaging stations in this study with the longest unaltered peak-flow records (North Nashua River at Fitchburg, Stillwater River near Sterling, Squannacook River near West Groton, Mill River at Northampton, Sevenmile River near Spencer, and West Branch Westfield River near Huntington) also indicate a strong relation between drainage area and the magnitude of flows at selected return intervals (fig. 42).

Lines shown in figure 42 are drawn from simple exponential equations developed from the point data at the six streamflow-gaging stations. Equations for estimating the flow magnitudes for 5-, 10-, 25-, 50-, 100-, 200-, and 500-year floods and coefficients of determination (r^2) are provided in table 24. The coefficients of determination from these equations range from 0.89 to 0.95; the coefficients are smallest at the 5- and 200-year return intervals (0.93) and at the 500-year return interval (0.89). These equations were developed from peak-flow frequency analysis made from extended records (except at West Branch Westfield River); the points used to develop the equations in table 24 are from the extended records that produced the highest magnitude flows.

Generally, these equations produced a better estimate of flood flows at ungaged rivers for drainage areas between 8 and 100 mi^2 for central Massachusetts than the existing state-wide equations developed by Wandle (1983). Compared to the flood-flow magnitudes determined for various return intervals from this study, Wandle's equations consistently underestimate flood flows for return periods of 10 years or more. Wandle's equations underestimated flood flows by a median of -50 percent for a 5-year return flood to -61 percent for a 100-year return flood (table 24) at 9 of the 10 sites examined in this study; the Merrimack River at Lowell is not included in this analysis because of its drainage-area size. Wandle did not develop equations for 200- and 500-year flood flows.

The drainage-area equation results (table 24) generally overestimated the magnitude of flood flows determined from the peak-flow analysis at the nine streamflow-gaging stations in this study. The median difference between the station peak-flow analysis and the drainage-area equation flood flows ranged from 4.7 to 22 percent for 200- and 5-year return intervals, respectively (table 24). However, the drainage-area equations overestimated flood flows in some basins and underestimated flood flows in others (fig. 42; table 24). Generally, the differences increased as the return interval decreased. This analysis indicates that, until robust regional equations can be developed from all appropriate streamflow-gaging stations in Massachusetts and nearby states, the drainage-area equations in table 24 provide a more conservative estimate (higher discharges) of flood flows at ungaged basins in central Massachusetts than those presently available from Wandle's equations. In basins in or near surrounding states, flood-flow equations developed for that state provide the most reasonable estimate of flood flows at an ungaged site.

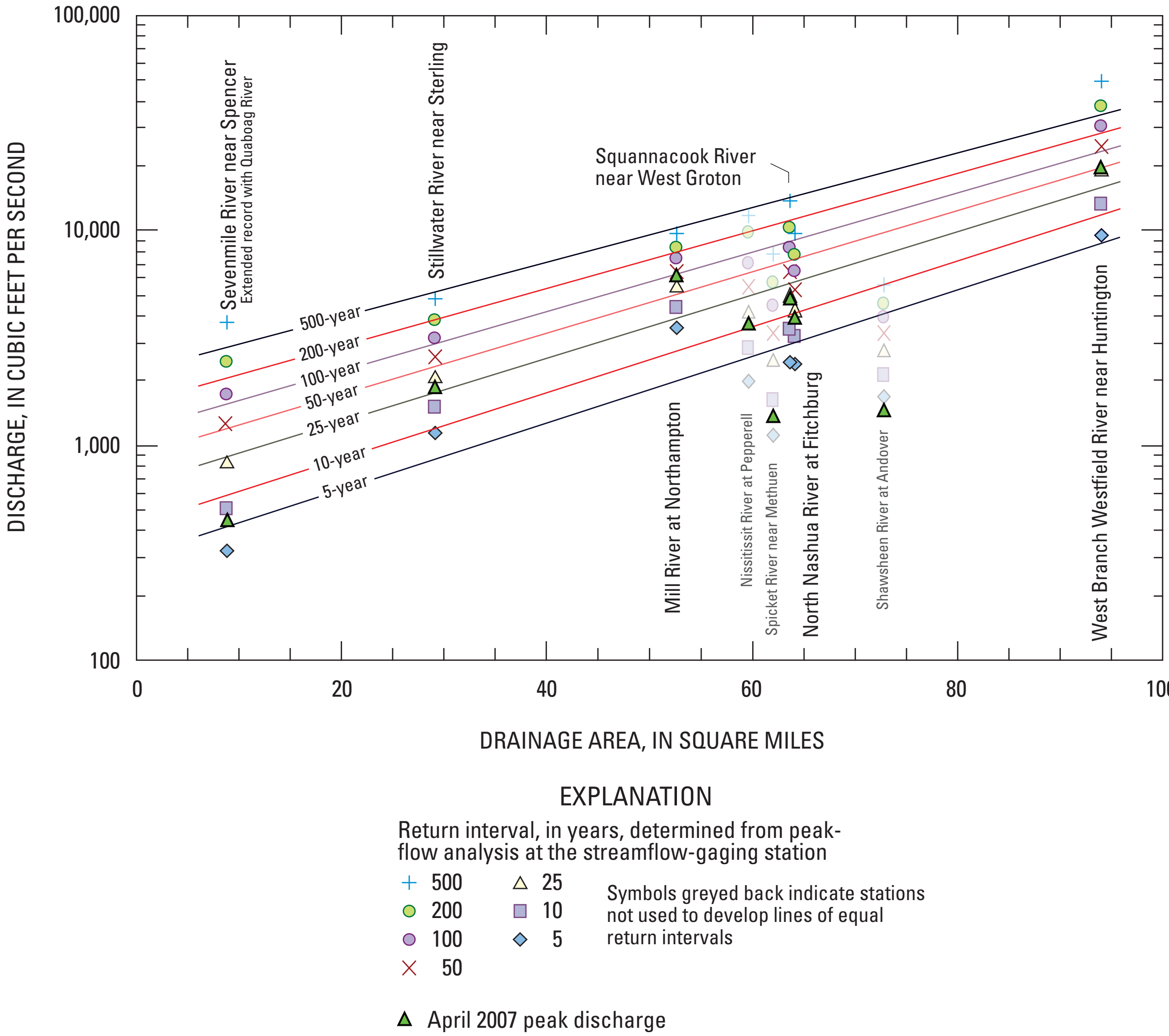


Figure 42. Magnitude of flood flows in relation to drainage area at selected streamflow-gaging stations in central Massachusetts.

Table 24. Simple regression equations for estimating the magnitude of peak flow at 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return intervals from drainage area in unregulated streams in central Massachusetts.

[EXP(n) represents e (approximately equal to 2.718) raised to the nth power; n is the drainage area multiplied by a coefficient that depends on the return interval. Q_x, flood flows for selected return intervals in cubic feet per second; DA, drainage area in square miles; r^2, coefficient of determination; --, equation not available]

Exponential equation	r^2	Percent difference[1]					
		Drainage area equation			Wandle equations		
		Median	Range		Median	Range	
			Low	High		Low	High
Q_5 = 266.3*EXP(0.038*DA)	0.93	22	-44	152	-50	10	-64
Q_{10} = 393.1*EXP(0.037*DA)	0.94	20	-37	140	-55	-3.4	-68
Q_{25} = 625.1*EXP(0.035*DA)	0.95	15	-29	119	-58	-16	-71
Q_{50} = 865.5*EXP(0.034*DA)	0.95	16	-20	113	-60	-10	-74
Q_{100} = 1189*EXP(0.032*DA)	0.94	10	-22	97	-61	-3.6	-76
Q_{200} = 1614*EXP(0.031*DA)	0.93	4.7	-22	94	--	--	--
Q_{500} = 2382*EXP(0.028*DA)	0.89	8.0	-34	73	--	--	--

[1] Calculated from flow magnitudes determined from peak-flow frequency analysis in this study at nine streamflow-gaging stations (excludes Merrimack River at Lowell, Mass.) compared to drainage area equations developed in this study and to Wandle's regional equations (Wandle, 1983). Stations used to develop the equations are indicated in figure 42.

Summary

In 2008 the USGS, in cooperation with FEMA, conducted a study to characterize flooding at 10 selected streamflow-gaging stations in Massachusetts from the large nor'easter storm of April 15–18, 2007. The nor'easter brought heavy rains to the region with the highest quantities (about 7 in.) falling along a north-south line over the Berkshire Mountains in western Massachusetts and in an arc north from Worcester through Fitchburg, Massachusetts, into New Hampshire. Coupled with normal high seasonal flows, this storm caused extensive flooding in parts of the state that prompted a disaster declaration by the President and a response by FEMA.

To assist FEMA in its mission of natural-hazard preparedness and mitigation, the USGS undertook an analysis of peak-flow magnitudes for 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return intervals from currently available data (peak-flow records up to 2007) from 10 streamflow-gaging stations that experienced the heaviest flooding from the April 2007 storm. The analysis helped characterize the magnitude of the April 2007 flood relative to historical data and to results of previous flood-insurance studies conducted in various communities. The streamflow-gaging stations examined include (in order of USGS identification number)—North Nashua River at Fitchburg (01094400), Stillwater River near Sterling (01095220), Squannacook River near West Groton (01096000), Nissitissit River at Pepperell (01096503), Merrimack River at Lowell (01100000), Spicket River near Methuen (01100561), Shawsheen River at Andover (01100627), Mill River at Northampton (01171500), Sevenmile River near Spencer (01175670), and West Branch Westfield River near Huntington (01181000).

Systematic annual peak-flow data from the USGS NWIS Peak-Flow File were analyzed using the program PeakFQ, which fits the logarithms of the annual peaks to a Pearson Type III probability distribution following the guidelines of flood-flow frequency analysis in Bulletin 17B. For most stations, the analysis included augmenting the station record with longer-term records from one or more nearby stations using the two-station comparison method in Bulletin 17B and record extension using the Maintenance of Variance Extension (MOVE-1) technique. The latter method was used to provide a common period of comparison to the 1936 water year because it dates back to the year with the highest known peak flow in some parts of the state or includes the highest flows in the other parts of the state, notably the floods of 1936, 1938, and 1955. In addition, recently developed regional flood-flow equations for New Hampshire were used to calculate

the magnitude of floods at Nissitissit River at Pepperell and Spicket River near Methuen because these stations have been in operation a short time, the contributing area lies mostly in New Hampshire, and no surrogate station could be used as an alternative way of estimating floods. At Shawsheen River at Andover, which also has a short record, the upstream station at Wilmington was used to estimate the magnitude of flood flows. The return interval of the April 2007 flood was determined at each of the 10 stations by the various peak-flow frequency analyses. In addition, flood magnitudes for various return intervals determined in this study were compared to flood discharge and stage information available in various flood-insurance-study reports.

The April 2007 peak discharge was among the highest discharges recorded or estimated since 1936, often ranking between the 3d- and 5th-highest discharges for that period. The return interval of the April 2007 peak discharge differed among sites and the methods used to compute flood flows. The peak discharge and stage from the April 2007 storm, along with the return interval of the storm on the basis of discharge and stage, are summarized in table 25. If the April 2007 peak discharge was within 10 percent of the computed discharge from the peak-flow frequency analysis for a given return interval, then that return interval was assigned to the storm. If the April 2007 peak discharge differed by more than 10 percent from the computed discharge for any given return interval, then the storm return interval was assigned to the return interval for the discharge closest to the storm peak with a "less than" symbol (<) to indicate that the storm peak was between the return interval and the next lowest return interval, but closest to the return interval indicated. The April 2007 peak discharge was never closer to a return interval with a discharge greater than the storm peak; therefore, a "greater than" symbol (>) was never used. The return intervals for the 95-percent confidence limits of the April 2007 peak discharge are also included in table 25.

In general, the April 2007 storm peak discharge has a return interval between 25 and 50 years, although at the northeasternmost stations the storm has an expected return interval of about 5 years. At Sevenmile River near Spencer, the April 2007 peak discharge return interval computed from the extended records was less than at most other stations (about a 10-year return interval). The return interval computed from the extended-record analysis generally was the same at the 95-percent confidence limits, except at stations where the April 2007 peak discharge differed from the computed return interval by more than 10 percent. The return period of the April 2007 peak discharge computed from the period of record, although long in many cases, had a much larger band of uncertainty–often encompassing the next-lowest and next-highest return interval bands. In general, the April 2007 peak-discharge return interval computed from the extended-record analysis was less than the return interval computed from the period-of-record analysis, indicating that for a given return interval, the period-of-record discharge was less than the discharge computed from the extended-record analysis. This finding underscores the leveraging effect of the large pre-record storms in the computation of flood-flow magnitude.

The magnitude of flood flows for the Merrimack River at Lowell is complicated by a historical record with a period of no flood control, a transition period as flood-control reservoirs were built, and the period of current flood-control operation. Various methods for analyzing the peak-flows record for the Merrimack River at Lowell produced appreciably different results. Flood flows computed from post-flood-control peak-flow records with the adjusted 1936 and 1938 peak flow treated as historical events indicate the April 2007 storm approached a 100-year return flow. Flood flows computed from an estimated continuous post-flood-control peak record back to 1936 indicate the April 2007 peak discharge is near a 50-year return flow. The uncertainty of the return interval of the post-flood-control floods is large, spanning from the next-lowest to the next-highest return interval regardless of the analysis method used.

The return intervals of the April 2007 nor'easter peak stage in relation to various flood-insurance-study flood profiles differed considerably from the results of peak-flow frequency analysis at some sites, but were comparable at other sites. The magnitude of flood flows used in the flood-insurance studies used to compute flood stage often differed considerably (typically much lower) from the magnitude of flood flows determined by peak-flow frequency analysis in this study. The flood stage determined from the current (2008) stage-discharge rating at a given streamflow-gaging station and the computed magnitude of flood flows for various return intervals also resulted in a much different stage at the station than that shown in the flood-insurance-study flood profiles.

Equations for estimating the flow magnitudes for 5-, 10-, 25-, 50-, 100-, 200-, and 500- year floods were developed from the relation of drainage area to the magnitude of flood flows calculated at six streamflow-gaging stations with the longest unaltered peak-flow record (North Nashua River at Fitchburg, Stillwater River near Sterling, Squannacook River near West Groton, Mill River at Northampton, Sevenmile River near Spencer, and West Branch Westfield River near Huntington). These equations produced a more conservative estimate of flood flows (higher discharges) than the existing regional equations for estimating flood flows at ungaged rivers in Massachusetts. Large differences in the magnitude of flood flows for various return intervals between the current peak-flow frequency analysis results and those of existing regional equations and discharges used in flood-insurance studies indicate a need to develop up-to-date, robust regional equations from all appropriate streamflow-gaging station data in Massachusetts and nearby states.

Table 25. Summary of April 2007 peak flows and stages, and the estimated return interval of the storm peak discharge and stage at ten selected streamflow-gaging stations in Massachusetts.

[USACE, U.S. Army Corps of Engineers; mi^2, square miles; ft^3/s, cubic feet per second; ft, feet in NVGD 29; FEMA, Federal Emergency Management Agency; --, not determined; <, less than]

U.S. Geological Survey streamflow-gaging station		Drain-age area (mi^2)	Start of record	Years of record	April 2007 peak			Expected return interval of April 2007 peak discharge or stage						
								Period-of-record discharge analysis			Extended-record discharge analysis			[5]FEMA stage
									95-percent confidence limit			95-percent confidence limit		
Name	Number				Dis-charge (ft^3/s)	Stage (gage datum)	Stage (ft)	Return interval	Lower	Upper	Return interval	Lower	Upper	Return interval
North Nashua River at Fitchburg	01094400	64.2	Oct. 1972	35	3,930	8.59	403.48	50	25	100	25	25	25	10–25
Stillwater River near Sterling	01095220	31.6	Apr. 1994	13	1,850	9.10	406.15	--	--	--	< 25	10	25	50–100
Squannacook River near West Groton	01096000	63.7	Oct. 1949	58	4,820	8.50	252.77	50	25	100	25	25	25	10
Nissitissit River at Pepperell	01096503	59.6	Mar. 2006	1	3,700	8.29	183.26	[3]25	--	--	< 50	25	50	50
Merrimack River at Lowell	01100000	4,635	Jun. 1923	84	89,800	58.09	63.27	25	25	25	--	--	--	50
with USACE flood-control dams			1964	[1]44–[2]72				[1]<100	50	200	[2]50	25	100	--
Spicket River near Methuen	01100561	62.1	Mar. 2001	6	1,360	9.01	109.91	[3]5	--	--	5	5	10	10–50
Shawsheen River at Andover	01100627	72.8	Oct. 2006	1	1,470	34.15	34.15	--	--	--	[4]5	5	5	10–50
Mill River at Northampton	01171500	52.6	Oct. 1938	70	6,150	15.58	188.26	50	25	100	50	25	50	10–50
Sevenmile River near Spencer	01175670	8.81	Feb. 1961	47	453	12.12	646.55	25	10	25	10	10	10	--
West Branch Westfield River near Huntington	01181000	94.0	Sep. 1935	72	19,700	12.82	396.42	25	25	50	--	--	--	10

[1] Record included USACE estimates of 1936 and 1938 peaks as if flood-control reservoirs were in place.

[2] Record estimated for 1936–64 period using MOVE-1 as if USACE flood-control reservoirs were in place.

[3] Estimated using New Hampshire regional equations (Olson, 2009).

[4] Estimated from Shawsheen River near Wilmington record adjusted by drainage-area ratio.

[5] FEMA community flood-insurance studies.

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