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Federal Emergency Management Agency

Magnitude of Flood Flows for Selected Annual Exceedance Probabilities in Rhode Island Through 2010

Scientific Investigations Report 2012–5109

Version 1.2, March 2013

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

Front cover. March–April 2010 flooding along the Woonasquatucket River at Valley Street in Providence, Rhode Island, looking northward toward Atwells Avenue (traffic light) from Helme Street.

Back cover. Historical marker found along Simmons Brook at Simmonsville east of Providence, Rhode Island.

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors, Datum, and Abbreviations

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square mile (mi^2)	259.0	hectare (ha)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F-32)/1.8$$

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

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

Abbreviations

AEP	annual exceedance probability
AVP	average variance of prediction
BDF	basin development factor
B17B	Bulletin 17B
DA	drainage area
EMA	expected moments algorithm
FEMA	Federal Emergency Management Agency
GLS	generalized least square
IACWD	Interagency Committee on Water Data
IMPERV	impervious area
LPIII	log-Pearson type III
MGB	multiple Grubbs-Beck test
MOVE	maintenance of variance extension
NFF	National Flood Frequency

NHD	National Hydrography Dataset
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
OLS	ordinary least squares
PILP	potentially influential low peaks
RMSE	root mean square error
StorNHD	basin storage
STRDEN	stream density
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VIF	variance inflation factor
WIE	Weighted Independent Estimator
WLS	weighted least squares

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By Phillip J. Zarriello, Elizabeth A. Ahearn, and Sara B. Levin

Abstract

Heavy persistent rains from late February through March 2010 caused severe widespread flooding in Rhode Island that set or nearly set record flows and water levels at many long-term streamgages in the State. In response, the U.S. Geological Survey, in partnership with the Federal Emergency Management Agency, conducted a study to update estimates of flood magnitudes at streamgages and regional equations for estimating flood flows at ungaged locations. This report provides information needed for flood plain management, transportation infrastructure design, flood insurance studies, and other purposes that can help minimize future flood damages and risks.

The magnitudes of floods were determined from the annual peak flows at 43 streamgages in Rhode Island (20 sites), Connecticut (14 sites), and Massachusetts (9 sites) using the standard Bulletin 17B log-Pearson type III method and a modification of this method called the expected moments algorithm (EMA) for 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability (AEP) floods. Annual-peak flows were analyzed for the period of record through the 2010 water year; however, records were extended at 23 streamgages using the maintenance of variance extension (MOVE) procedure to best represent the longest period possible for determining the generalized skew and flood magnitudes. Generalized least square regression equations were developed from the flood quantiles computed at 41 streamgages (2 streamgages in Rhode Island with reported flood quantiles were not used in the regional regression because of regulation or redundancy) and their respective basin characteristics to estimate magnitude of floods at ungaged sites. Of 55 basin characteristics evaluated as potential explanatory variables, 3 were statistically significant—drainage area, stream density, and basin storage. The pseudo-coefficient of determination (pseudo-R^2) indicates these three explanatory variables explain 95 to 96 percent of the variance in the flood magnitudes from 20- to 0.2-percent AEPs. Estimates of uncertainty of the at-site and regression flood magnitudes are provided and were combined with their respective estimated flood quantiles to improve estimates of flood flows at streamgages.

This region has a long history of urban development, which is considered to have an important effect on flood flows. This study includes basins that have an impervious area ranging from 0.5 to 37 percent. Although imperviousness provided some explanatory power in the regression, it was not statistically significant at the 95-percent confidence level for any of the AEPs examined. Influence of urbanization on flood flows indicates a complex interaction with other characteristics that confounds a statistical explanation of its effects.

Standard methods for calculating magnitude of floods for given AEP are based on the assumption of stationarity, that is, the annual peak flows exhibit no significant trend over time. A subset of 16 streamgages with 70 or more years of unregulated systematic record indicates all but 4 streamgages have a statistically significant positive trend at the 95-percent confidence level; three of these are statistically significant at about the 90-percent confidence level or above. If the trend continues linearly in time, the estimated magnitude of floods for any AEP, on average, will increase by 6, 13, and 21 percent in 10, 20, and 30 years' time, respectively.

In 2010, new peaks of record were set at 18 of the 21 active streamgages in Rhode Island. The updated flood frequency analysis indicates the peaks at these streamgages ranged from 2- to 0.2-percent AEP. Many streamgages in the State peaked at a 0.5- and 0.2-percent AEP, except for streamgages in the Blackstone River Basin, which peaked from a 4- to 2-percent AEP.

Introduction

Following heavy persistent rains from late February through March 2010, severe flooding set or nearly set record streamflows and water levels, causing a state of emergency to be declared in many communities in Rhode Island, and a statewide presidential disaster declaration (EM–3311) on March 30, 2010. The President's action affected the emergency recovery operations in Bristol, Kent, Newport, Providence, and Washington Counties. The flood has been characterized as the worst in 200 years and is estimated to have caused damages in the hundreds of millions of dollars. As part of the recovery operations, the U.S. Department of Homeland Security's Federal Emergency Management Agency (FEMA) required analysis of the flood to assess damages and to prepare for and minimize future flood damages.

Flood flows in Rhode Island have not been comprehensively examined since the mid-1970s (Johnson and Laraway, 1977) and then only for a limited range of basin sizes and recurrence probabilities. Flood magnitudes for a range of annual exceedance probabilities (AEPs) are an important part of determining flood prone areas and risk assessment. Floods for a given AEP magnitude are routed through hydraulic models that convert the flow into a water level on the basis of the river's capacity or conveyance. The best possible estimates of flood magnitudes for given AEP at gaged and ungaged sites is crucial for delineating flood zones, flood plain management, and designing infrastructure such as bridges and culverts so the conveyance capacity of a river is not unduly impaired.

Evaluation of the March–April 2010 peak discharge relative to the magnitude of floods over a range of AEPs is an important part of the post flood analysis and future flood management needs. The U.S. Geological Survey (USGS) entered into an agreement with FEMA in August 2010 to document and characterize the March–April 2010 flood. This report addresses the magnitude of floods at gaged and ungaged sites as part of that effort.

Purpose and Scope

The purpose of this report is to document the magnitude of flood flows over a range of AEPs at streamgages in Rhode Island and to document statewide regional equations for estimating flood flows at ungaged locations. The data used in this report were compiled from annual peak flows from 43 streamgages in Rhode Island, Connecticut, and Massachusetts through the 2010 water year. The report presents estimates of flood flows at streamgages at 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs, which also have been referred to as 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return interval floods, respectively. Regression equations for calculating flood flows from selected basin characteristics for the same exceedance probabilities at ungaged streams and improving the estimated flood flows at gaged sites are presented. This report describes trends in the annual peak flow data and the implications for future floods. Also discussed are the influences of urbanization and the limitations of the study.

Study Area

The study area includes selected streamgages across Rhode Island and from eastern Connecticut and south-central and southeastern Massachusetts (fig. 1). Streamgages outside of the Rhode Island provide additional information that is representative of the hydrologic region, which can improve the analysis of flood magnitudes in Rhode Island.

Southern and eastern Rhode Island, southern Connecticut, and eastern Massachusetts are in the Coastal Lowland physiographic province of New England (Denny, 1982), which is characterized by low topography ranging in elevation from sea level to several hundred feet (fig. 1). Central and northwestern Rhode Island, northeastern Connecticut, and central Massachusetts are in the Central Uplands physiographic province of New England. This region is characterized by gently rolling hills with more incised valleys. The maximum elevation in the region is about 610 feet (ft).

Climate in the basin is classified as moist continental (National Oceanic and Atmospheric Administration, 2002) with a mean annual precipitation of about 46 inches that is normally evenly distributed throughout the year. Mean annual temperature is about 50°F in the region. Surficial geology consists of mainly glacial stratified deposits along the major river valleys and glacial till or exposed bedrock in the upland areas.

Land cover in the region ranges from highly developed in and near major metropolitan centers such as Providence, RI, to predominantly forested (fig. 2). Most developed areas are in eastern Rhode Island and Massachusetts, the Connecticut Valley (to the west), and coastal areas. Land cover and other characteristics vary by basin and are discussed in greater detail in the section describing basin characteristics used to develop region flood flow equations.

Hurricanes, remnants of hurricanes, and storms that never developed to hurricane strength are major causes of floods in southern New England. The National Oceanic and Atmospheric Administration (NOAA; undated) online tool for historical hurricane tracks indicates that 50 hurricanes, tropical storms, tropical depressions, and extratropical storms have passed within a 75 mile radius of central Rhode Island from 1851 through 2008 (fig. 3). These storms typically originate in the central Atlantic and follow a track along the eastern United States up through New England. The hurricane tracking program lists 24 storms that passed through the region since 1904 when streamflow data were first collected in the area; 20 of these occurred since 1944 when streamgages have been in more widespread operation.

Previous Studies

Major storms of New England from 1635 through the late 1800s have been summarized by Perley (1891); however, most accounts of these historical events focused on damages to sailing ships and harbors that were the main livelihood of communities at that time. From these accounts, the types of storms and frequency can be inferred but little information is given on the physical dimensions of storms, such as the magnitude of the peak flow or depth of flooding. More specific accounts of the magnitude of large floods in Rhode Island and other affected areas have been described by Kinnison (1930) for the 1927 flood and limited information on major floods prior to the 1927, Grover (1937) for the flood of 1936, Paulsen and others (1940) for the 1938 flood, Bogart (1960) for 1955 flood, Wood and others (1970) for the March 1968 flood, and Parker and others (1998) for the June 1998 flood. These accounts summarize streamflow information that was available at the time and indirect measurements of peak flows made following the floods. This usually entailed a hydraulic analysis made from high water marks surrounding a channel structure, such as a low-head dam, or a channel constriction, such as a bridge opening.

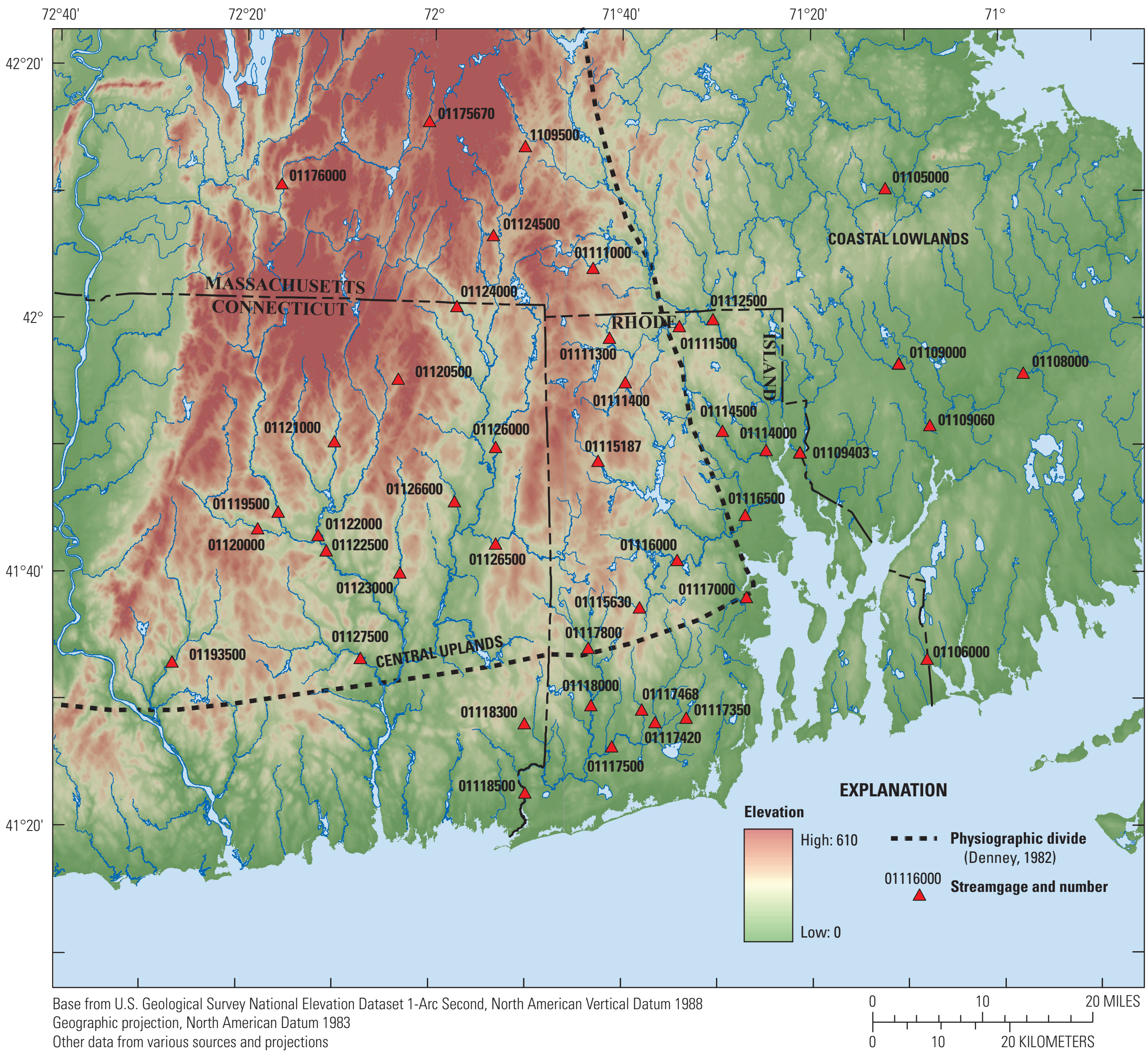

Figure 1. General area and selected streamgages used in the Rhode Island flood frequency study.

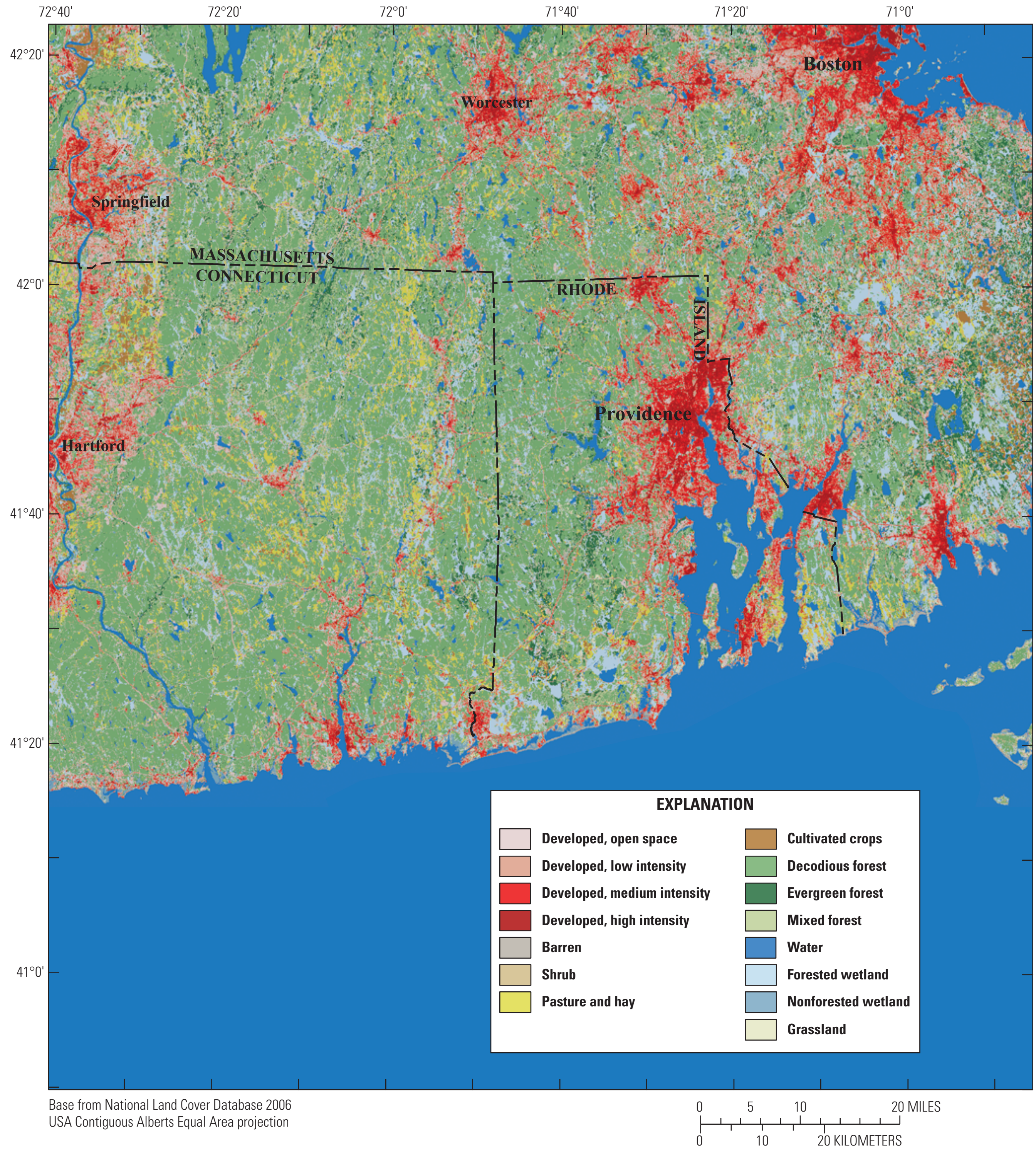

Figure 2. Land cover in the study area in Rhode Island, Connecticut, and Massachusetts from the 2006 National Land Cover Database.

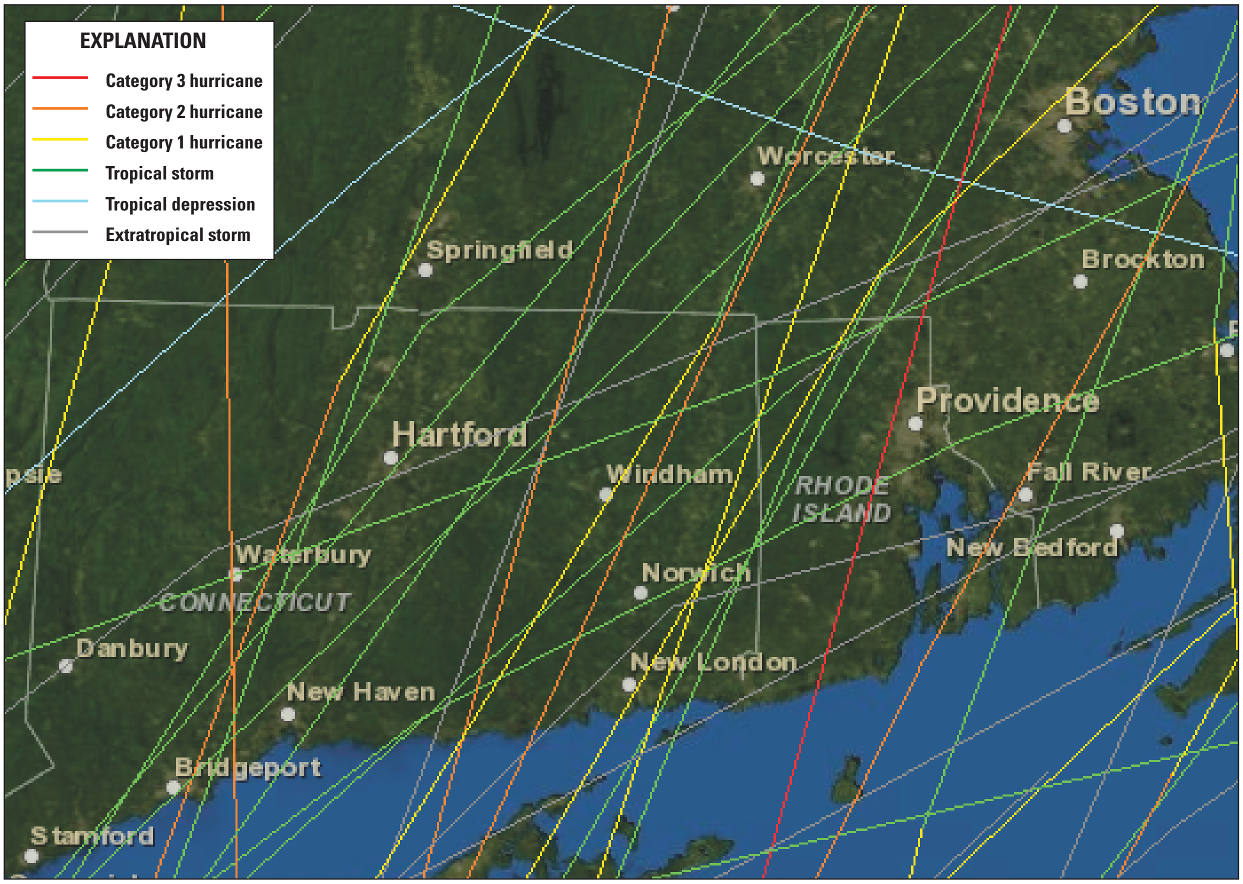

Image from National Oceanic and Atmospheric Administration Historical Hurricane Tracks at http://www.csc.noaa.gov/hurricanes

Figure 3. Hurricane and hurricane related storm tracks from 1851 through 2008 in and near Rhode Island.

Major floods of New England by Thomson and others (1964) summarized major events up to the early 1960s from actual records, including those previously mentioned, and from other sources, such as newspaper stories and accounts by local residents. The earliest flood reported in Rhode Island was from the Providence Gazette of January 13, 1770, for Pawtuxet River and other rivers— "* * * a great flood * * * many Mills, Bridges, etc. carried away. * * * Rivers higher than they have been known these 30 years, some say 50." (Thomson and others, 1964, p. M10). Similar to the description of storms of New England by Perley (1891), Thomson and others (1964) accounts of flooding often lack sufficient detail to provide information on the physical dimensions of the storm that could be used in flood frequency analysis.

The first regionalized flood flow estimates for New England were published by the U.S. Army Corps of Engineers (USACE) in 1958. The USACE study provided different frequency curves for hurricane and nonhurricane floods and emphasized the difficulty of estimating the true frequency of large floods. The study concluded that the floods of 1927, 1936, and 1955 in New England were rare events. Mixed population distributions for nonhurricane and hurricane related events at selected streamgages in Massachusetts were also found by Murphy (2001a,b). One limitation of a mixed population distribution analysis is the number of floods of hurricane origin. Moreover, the record 2010 flood, the largest flood in most parts of Rhode Island, was not of hurricane origin and, therefore, not associated with the largest flood events.

Benson (1962) evaluated floods and methods for computing the magnitude of floods in the United States for frequencies ranging from 1.2 to 300 years. Green (1964) developed regional flood frequency curves for the United States, of which Rhode Island would be included in the North Atlantic Slope basins that covered Maine to Connecticut. The report by Green contains a compilation of peak flow data through the 1960 water year and frequency curves for floods for a given exceedance probability to drainage area by subregions.

In 1977, Johnson and Laraway published flood flow equations for Rhode Island for small rural basins less than 10 square miles (mi^2) in area. The equations were developed for estimating the magnitude of 50- and 20-percent AEPs floods (2- and 5-year floods) from 38 streamgages using annual peak flow records for the 1966–71 water years. Regression equations for estimating flood flows at ungaged sites were developed that use basin area, mean basin elevation, and forest cover as explanatory variables. When the National Flood Frequency (NFF) software program was introduced in 1994 (Jennings and others, 1994) the Rhode Island flood flow equations developed by Johnson and Laraway (1977) were incorporated into the database along with 10-, 4-, and 2-percent AEP flood flows that were estimated from the 50-percent AEP using factors presented by Green (1964). Comparison of flood records for the long term (1941–67) and the short term (1966–71) suggest that the extrapolated values should include an additional adjustment coefficient of 0.79 to correct for the short-term record. Estimates for extreme floods (0.2-percent AEP) were also incorporated into NFF by linear interpolation as described by Thomas and Kirby (2002).

Data Compilation

Data from the USGS National Water Information System (NWIS) peak-flow database (U.S. Geological Survey, 2012) were initially compiled for 84 streamgages. This initially included all streamgages in Rhode Island with a record for 9 or more years (42 total) and selected streamgages in Connecticut (28 streamgages) and Massachusetts (14 streamgages) that were screened for their proximity to Rhode Island as well as for regulation, record length, and quality. Many of the streamgages were removed from further analysis because of short record length, regulation, or suspect data quality. Of the initial 84 streamgages, 40 were used in the regional skew analysis—17 in Rhode Island, 14 in Connecticut, and 9 in Massachusetts (fig. 1; table 1). The development of the regional regression equations included Adamsville Brook at Adamsville, RI (01106000), which was not used in the regional skew analysis because the record is from a relatively dry period, which caused an uncharacteristic large negative skew.

Magnitudes of floods for select AEPs were determined at the 41 streamgages used in the regional regression analysis and at long-term streamgages at Pawtuxet River at Cranston, RI (01116500), and Wood River near Arcadia, RI (01117800); these two streamgages were not used in the regional skew or regression analysis, however. Pawtuxet River at Cranston is regulated by the Scituate Reservoir and is not suitable for use in a regional analysis. Wood River near Arcadia is highly correlated with the downstream streamgage at Hope Valley (01118000) and is considered redundant. In statistical analyses, redundant sites incorrectly represent information in a regional context because they are not considered independent observations due to the fact that they share similar basin characteristics and hydrologic responses (Gruber and Stedinger, 2008).

Some streamgages are affected by flood control structures designed to decrease peak flows—Little River near Oxford, MA (01124500), Quinebaug River at Quinebaug, CT (01124000), Natchaug River at Willimantic, CT (01122000), and Shetucket River near Willimantic, CT (01122500). Flood control structures were built after these streamgages were in operation between 19 and 28 years; thus, these sites still have a sufficient period of unregulated flow that can be used in the flood frequency analysis. Unregulated annual peak flows at these streamgages were estimated after flood control structures were built using record extension methods. Annual peak flows also were estimated at relatively short-term streamgages and at long-term streamgages that were discontinued for short periods. The record extension provides the longest period possible for the flood frequency analysis.

Record Extension

Annual peak flow records were extended using a mathematical procedure developed by Hirsch (1982) known as maintenance of variance extension (MOVE). The method maintains the mean and variance of two streamgage records to extend the short-term record with the long-term streamgage (index station). MOVE is applied to the logarithms of the concurrent annual peaks of the two streamgage records.

Although the extended record analysis can potentially improve the regional skew estimate to better reflect long term conditions, it can also introduce increased inter-streamgage correlation by repeated use of an index station. Records were extended at 34 of the 84 streamgages initially selected. However, because the number of suitable index stations is limited, record extension was limited to 22 streamgages used in the skew and regression analyses (table 2) so that an index station was used no more than four times. Typically, an index station was used no more than twice to minimize inter-streamgage correlation in subsequent statistical analysis. Streamgages with extended record were selected on the basis of the length of record extended, the quality of the record extension, the number of times an index station was used, and the value of the streamgage in the analysis. Selection of extended record streamgages was generally made on the basis of the least amount of extended record and the greatest number of concurrent peaks as well as the best MOVE fit determined from the correlation coefficient and the root mean square error (RMSE). Several index streamgages were tested to determine the best streamgage to use for the record extension.

The index station record generally overlaps the short-term record and most concurrent peaks were related to the same event. Correspondingly, the number of concurrent peaks is generally equal to the length of the short-term record, but if the records do not overlap or if the annual peaks are not related to the same event, then the number of concurrent peaks was less. Concurrent records ranged from 11 to 65 years and averaged 34 years. Scatterplots indicate that the relation between the base 10 logarithms (log_{10}) transformed peak

Table 1. Streamgages compiled from the U.S. Geological Survey National Water Information System (NWIS) peak-flow database and pertinent characteristics used in regional flood flow analysis for Rhode Island.

[Years, number of years of systematic record or if regulated, number of years of unregulated record; DA, drainage area; mi^2, square miles; STRDEN, stream density; mi/mi^2, miles per square mile; StorNHD, storage; MBslp, mean basin slope; IMPERV, impervious area; SG, basin underlain by sand and gravel; R, River, nr, near; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

U.S. Geological Survey streamgage		Record			DA	STRDEN	Percent			
Number	Name	Begin	End	Years	(mi^2)	(mi/mi^2)	StorNHD	MBslp	IMPERV	SG
		Rhode Island streamgages								
01106000[a]	Adamsville Brook at Adamsville, RI	1941	1978	39	8.01	2.94	12.38	3.14	2.62	1.10
01109403	Ten Mile R at Pawtucket Ave at East Providence, RI	1986	2010	24	53.75	2.34	7.55	3.60	23.97	57.96
01111300	Nipmuc River nr Harrisville, RI	1964	2010	44	15.84	2.51	4.14	6.38	1.11	27.65
01111400	Chepachet River at Chepachet, RI	1965	1975	11	17.46	2.03	10.03	9.55	2.42	35.17
01111500	Branch River at Forestdale, RI	1940	2010	71	91.22	2.31	7.71	8.76	3.26	30.19
01112500	Blackstone River at Woonsocket, RI	1929	2010	82	403.97	2.46	6.82	7.84	10.52	27.97
01114000	Moshassuck River at Providence, RI	1963	2010	48	23.28	1.75	3.94	6.21	37.25	28.36
01114500	Woonasquatucket River at Centerdale, RI	1941	2010	69	38.19	2.46	10.73	10.25	11.63	22.29
01115187	Ponaganset River nr South Foster, RI	1994	2010	16	14.36	2.53	6.69	6.00	1.21	14.56
01115630	Nooseneck River at Nooseneck, RI	1964	1981	22	8.20	1.25	3.38	6.45	2.26	35.05
01116000	South Branch Pawtuxet River at Washington, RI	1940	2010	71	62.80	1.70	7.83	5.89	4.57	40.33
01116500[b]	Pawtuxet River at Cranston, RI	1939	2010	72	200	--	--	--	--	--
01117000	Hunt River nr East Greenwich, RI	1940	2010	71	22.89	1.99	7.92	5.73	14.72	50.89
01117350	Chipuxet River at West Kingston, RI	1973	2010	37	9.59	1.64	8.43	4.89	3.15	41.12
01117420	Usquepaug River nr Usquepaug, RI	1976	2010	35	36.12	1.65	6.68	5.01	1.92	34.04
01117468	Beaver River nr Usquepaug, RI	1977	2010	34	9.22	1.51	5.75	6.56	1.60	25.10
01117500	Pawcatuck River at Wood River Junction, RI	1940	2010	70	100.13	1.43	14.88	4.67	2.64	43.78
01117800[b]	Wood River nr Arcadia, RI	1964	2010	47	35.14	1.35	7.84	6.92	0.83	27.06
01118000	Wood River at Hope Valley, RI	1941	2010	69	74.53	1.45	7.85	6.52	1.95	25.27
01118500	Pawcatuck River at Westerly, RI	1940	2010	70	294.88	1.62	11.77	5.73	2.89	35.27

Table 1. Streamgages compiled from the U.S. Geological Survey National Water Information System (NWIS) peak-flow database and pertinent characteristics used in regional flood flow analysis for Rhode Island.—Continued

[Years, number of years of systematic record or if regulated, number of years of unregulated record; DA, drainage area; mi², square miles; STRDEN, stream density; mi/mi², miles per square mile; StorNHD, storage; MBslp, mean basin slope; IMPERV, impervious area; SG, basin underlain by sand and gravel; R, River, nr, near; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

U.S. Geological Survey streamgage		Record			DA	STRDEN	Percent			
Number	Name	Begin	End	Years	(mi²)	(mi/mi²)	StorNHD	MBslp	IMPERV	SG
		Massachusetts streamgages								
01105000	Neponset River at Norwood, MA	1939	2010	71	34.80	2.02	10.57	5.54	16.70	56.73
01108000	Taunton River nr Bridgewater, MA	1929	2010	65	261.36	2.37	18.96	3.11	10.94	51.76
01109000	Wading River nr Norton, MA	1925	2010	86	43.41	2.18	11.91	3.86	10.52	58.30
01109060	Threemile River at North Dighton, MA	1966	2010	44	84.34	2.43	12.18	3.31	12.38	64.38
01109500	Kettle Brook at Worcester, MA	1923	1978	56	31.29	3.16	8.93	7.99	9.80	17.16
01111000	Mumford River at East Douglas, MA	1939	1951	13	29.12	2.62	10.85	7.26	1.45	13.17
01124500	Little River nr Oxford, MA	1939	2010	19	27.41	3.26	11.37	8.03	1.73	9.21
01175670	Sevenmile River nr Spencer, MA	1960	2010	50	8.81	3.01	6.09	8.65	0.77	12.76
01176000	Quaboag River at West Brimfield, MA	1912	2010	98	149.47	3.01	8.55	8.78	1.83	21.31
		Connecticut streamgages								
01118300	Pendleton Hill Brook nr Clarks Falls, CT	1959	2010	52	4.00	1.57	5.86	7.76	0.50	9.99
01119500	Willimantic River nr Coventry, CT	1932	2010	79	122.27	2.83	4.69	9.12	1.90	12.22
01120000	Hop River nr Columbia, CT	1933	1984	52	74.54	2.31	5.28	7.71	1.70	9.97
01120500	Safford Brook nr Woodstock, CT	1951	1981	31	4.17	2.60	3.39	8.73	0.60	1.16
01121000	Mount Hope River nr Warrenville, CT	1941	2010	70	29.00	3.45	5.08	8.33	0.71	5.11
01122000	Natchaug River at Willimantic, CT	1931	2010	21	170.28	3.24	6.04	8.65	1.35	14.26
01122500	Shetucket River nr Willimantic, CT	1905	2010	28	401.43	2.86	5.36	8.52	1.88	13.79
01123000	Little River nr Hanover, CT	1952	2010	61	29.99	3.53	6.77	8.18	0.57	18.30
01124000	Quinebaug River at Quinebaug, CT	1932	2010	28	151.08	3.20	7.91	9.95	2.43	15.12
01126000	Fivemile River at Killingly, CT	1938	1984	48	57.99	2.70	10.94	7.06	1.72	22.40
01126500	Moosup River at Moosup, CT	1933	1984	52	83.35	2.07	5.81	6.62	1.72	23.95
01126600	Blackwell Brook nr Brooklyn, CT	1962	1976	15	16.96	2.69	7.64	8.17	0.78	8.72
01127500	Yantic River at Yantic, CT	1931	2010	80	89.20	2.84	7.07	7.29	1.44	15.70
01193500	Salmon River at East Hampton, CT	1929	2010	82	100.61	2.31	5.73	8.12	1.92	11.68

[a]Not used in regional skew analysis.

[b]Not used in regional skew or regression analysis.

Table 2. Streamgages used in the flood frequency analysis with extended record made with the maintenance of variance extension (MOVE).

[RI, Rhode Island; MA, Massachusetts; CT, Connecticut; R, River; Ave., Avenue; nr, near]

U.S. Geological Survey streamgage		Number of concurrent peaks	Index streamgage	Extended record	
Number	Name			Correlation coefficient	Total years
Rhode Island streamgages					
01111300	Nipmuc River near Harrisville, RI	44	01111500	0.95	71
01111400	Chepachet River at Chepachet, RI	11	01111500	0.86	71
01114000	Moshassuck River at Providence, RI	13	01114500	0.85	69
01115187	Ponaganset River near South Foster, RI	16	01111500	0.95	71
01115630	Nooseneck River at Nooseneck, RI	22	01111500	0.84	70
01117350	Chipuxet River at West Kingston, RI	37	01111500	0.92	71
01117420	Usquepaug River near Usquepaug, RI	35	01117500	0.96	70
01117468	Beaver River near Usquepaug, RI	35	01117500	0.94	69
1117800[a]	Wood River near Arcadia, RI	47	01118000	0.95	69
Massachusetts streamgages					
01108000	Taunton River near Bridgewater, MA	65	01109000	0.85	85
01109060	Threemile River at North Dighton, MA	44	01109000	0.98	85
01109403	Ten Mile R at Pawtucket Ave. at East Providence, RI	24	01109000	0.97	85
01111000	Mumford River at East Douglas, MA	13	01109000	0.92	71
01175670	Sevenmile River nr Spencer, MA	50	01176000	0.89	97
Connecticut streamgages					
01118300	Pendleton Hill Brook near Clarks Falls, CT	52	01118000	0.88	69
01120000	Hop River near Columbia, CT	52	01193500	0.91	78
01120500	Safford Brook near Woodstock, CT	30	01121000	0.87	70
01122000	Natchaug River at Willimantic, CT	20	01119500	0.94	80
01122500	Shetucket River near Willimantic, CT	20	01119500	0.95	87
01124000	Quinebaug River at Quinebaug, CT	28	01119500	0.92	92
01126000	Fivemile River at Killingly, CT	33	01123000	0.84	74
01126500	Moosup River at Moosup, CT	52	01127500	0.86	78
01126600	Blackwell Brook near Brooklyn, CT	15	01123000	0.97	59

[a]Streamgage not used in regional skew or regression analyses, but flood quantiles report for site.

discharges is linear. Correlation coefficients between the short- and long-term streamgage records ranged from 0.84 to 0.98 with an average of 0.91.

The systematic peak flow records used in the statistical analysis ranged from 11 to 98 years with average length of 51 years prior to record extension. After records were extended at 22 of the 40 streamgages used in the regional skew analysis, record length ranged from 56 to 98 years with an average length of 76 years. In effect, this represents the annual peak flows and the corresponding conditions that produced those peaks from about 1934 to 2010 for developing a regional skew. Streamgages with extended records, on average, had about 44 years of systematic record and about 34 years of extended record.

Historic Data

Historic data are peak flows or stages, or both, that are outside the period of continuous record, also referred to as the systematic record. Historic peaks in the USGS peak-flow database are typically large infrequent events where an effort was made to quantify the flood prior to an established streamgage. Sometimes this information is also collected after a streamgage is discontinued for later use in flood frequency studies.

Seven of the selected streamgages used in this study have one or more historic peaks from the 1927, 1936, and 1938 water years (table 3). Historic data used in this study were at long-term streamgages that began operation following the

Table 3. Streamgages with historic records used in the study.

[--, no data in peak-flow file; stage, stage only; discharge, in cubic feet per second; years are water years; RI, Rhode Island; CT, Connecticut]

U.S. Geological Survey streamgage		Systematic record		Historic record peak discharge				Systematic record peak	
Number	Name	Begin	End	1927	1936	1938	Rank	Discharge	Year
01111500	Branch River at Forestdale, RI	1940	2010	--	5,800	--	2	6,290	2006
01118000	Wood River at Hope Valley, RI	1941	2010	--	1,540	--	8	5,470	2010
01118500	Pawcatuck River at Westerly, RI	1940	2010	6,300	3,150	Stage	3, 20	10,800	2010
01114500	Woonasquatucket River at Centerdale, RI	1941	2010	--	1,000	--	13	1,750	2010
01116000	South Branch Pawtuxet River at Washington, RI	1940	2010	--	1,810	--	4	5,480	2010
01117000	Hunt River near East Greenwich, RI	1940	2010	--	--	Stage	--	2,420	2010
01123000	Little River near Hanover, CT	1952	2010	--	1,450	2,100	18, 4	2,964	1978

major flood of 1938; most historic data were obtained after the 1936 flood. These data were determined by indirect measurements, such as flow over a dam, slope area, or contracted opening methods, using high water marks obtained following the flood. Indirect discharge measurements are subject to large uncertainties with a ±20 percent error generally considered a good measurement. Although the historic peaks are large in magnitude, they are generally well below the largest systematic record peak (table 3). The historic peak discharges ranked from second to the 20th highest peak of record and are generally appreciably smaller than the largest peak of record. Historic stage only records are believed to be caused by a tidal surge or are otherwise unrelated to the stage discharge relation at the streamgage and could not be used.

As previously described, larger historic peaks likely occurred but information on these events is qualitative and predates most efforts to quantify the magnitude of the event. One exception was found in the flood insurance study for the City of Warwick (Federal Emergency Management Agency, 1981), which states:

> "On February 11–14, 1886, a flood known as the greatest ever on the main stem Pawtuxet River resulted in 7 to 8 inches of rainfall over the basin augmented by snowmelt with an estimated water equivalent of 2 inches (Green, 1964). Experienced flood levels were 6 to 7 feet higher than any other known flood before or since this event. There was no record of flows on the main stem, but previous studies by the COE [U.S. Army Corps of Engineers] estimated the discharge of the river was about 14,000 ft^3/s in the vicinity of the present U.S. Geological Survey (USGS) gage site in Cranston."

No other information about how the 1886 flood peak was determined or reference to this event for design purposes in other areas in the region could be found.

The 1886 peak discharge is about equal to the measured 2010 flood peak at Pawtuxet River at Cranston, RI (01116500) streamgage, which is the largest recorded peak. Other supporting information on the magnitude of the 1886 flood was qualitative (Kinnison, 1930; Green, 1964; Thomson and others, 1964). Kinnison (1930) described the 1886 flood as being of such magnitude that "Records of this storm served as a basis for waterway design in this district since that time." The 1886 peak was treated as an historic peak in the flood analysis at Pawtuxet River at Cranston, RI (01116500) streamgage in this study, but it should also be noted this streamgage was not used in the regional analysis because of upstream regulation from a supply reservoir. Updated at-site flood statistics are reported for the streamgage because of flooding issues along this river. It should also be noted that the river was unregulated at the time of the 1886 flood, but the available storage in the supply reservoir was exhausted at the time of the 2010 peak (flow was going over the spillway), which indicates that the 2010 peak was minimally affected by regulation.

Magnitude of Flood Flows at Streamgages

The magnitude of floods at streamgages is typically determined from the statistical properties of the annual peak flows using guidelines developed by the Interagency Committee on Water Data (IACWD) last published in 1981 and revised in 1982, known and herein referred to as Bulletin 17B. Bulletin 17B generally recommends fitting annual peak flows at a streamgage to a log-Pearson type III (LPIII) distribution to describe the likelihood of occurrence, or the annual exceedance probability (AEP) of a flood, the procedure herein is referred to as B17B. The magnitude of the flood for a given AEP using B17B is computed from three properties of the logs of the annual peak data—the mean, the standard deviation, and the skew using the following equation:

$$\log Q_P = \overline{X} + K_P S \, , \qquad (1)$$

where

Q_P is the P-percent AEP flow, in cubic feet per second;

$\overline{X}$ is the mean of the logarithms of the annual peak flows;

K_P is a factor based on the skew coefficient and the given percent AEP and obtained from appendix 3 in Bulletin 17B; and

S is the standard deviation of the logarithms of the annual peak flows, which is a measure of the degree of variation of the annual values about the mean value.

A relatively new procedure for calculating the magnitude of flood flows from annual peak flow records, known as the expected moments algorithm (EMA), also was used in this study. The EMA also uses a LPIII distribution, but unlike the LPIII procedures outlined in B17B, which are constrained to the moments of point values, the EMA can accommodate interval data to better define the distribution characteristics of annual peak flows (Cohn and others, 1997). Interval data can represent conditions such as the potential range of annual peak flows outside of the systematic and historic record and the uncertainties around recorded peaks used in the analysis. The EMA then uses an iterative procedure to recompute the moments from the interval data starting from the systematic record moments; the algorithm converges when the newly computed moments no longer appreciably differ from the last iteration of the computed moments. If only a systematic record is used in the analysis (that is, no interval data is used) and low outliers are not present, B17B and EMA analyses produce the same result. However, the confidence intervals around the flood quantiles differ because of different methods used by each procedure (Cohn and others, 2001). The EMA is expected to replace the standard LPIII procedure in Bulletin 17B in the next update of the guidelines and was applied in this study by use of the FORTRAN program PeakfqSA (Tim Cohn, U.S. Geological Survey, written commun., March 9, 2011) and the USGS PeakFQ program version 6.0.14667.

Often peak flow records do not follow a normal distribution, which affects the shape of the frequency distribution curve and, thus, the magnitude of floods for a given exceedance probability. The asymmetry of the frequency distribution curve is measured by the station skew. A single station, especially one with a short record, typically does not provide an accurate estimate of the “true” skew. To compensate, Bulletin 17B recommends weighting the station skew with a generalized skew computed regionally from many streamgages to better utilize available information.

Skew Coefficient

Skews are highly influenced by the leverage of observations in the upper and lower tails of the annual peak flow record. Negative skews indicate that the left side of the probability distribution function is longer than the right side and that the bulk of the values lie to the right of the mean. In other words, smaller annual peaks outweigh the larger annual peaks, resulting in smaller computed flood flow for a given exceedance probability than records that are skewed to the right. The extent of this effect becomes more evident as the exceedance probability decreases. Bulletin 17B gives specific procedures for testing and handling high and low outliers because of their effect on the statistical properties of the data. It should be noted that skews are computed from the average cubed deviations from the mean of the logarithms of annual peak flows; thus, the shorter the record, the greater the likelihood that the skew will be leveraged by values at the tails of the distribution.

Low Outlier Adjustment

When streamgage records are skewed to the left by low outliers, the magnitude of flood flows are leveraged downward. Because the primary interest of a flood frequency analysis is the magnitude of floods that occur infrequently (AEP of 20 percent or less) Bulletin 17B outlines a conditional probability adjustment for low outliers before further analysis is made. Low outliers were initially detected and conditioned using the PeakFQ software (Flynn and others, 2006), which uses procedures described in Bulletin 17B; however, the test detects and conditions only the lowest outlier in the dataset. Single low outliers were detected in 5 of 40 streamgages used in the regional skew analysis (table 4).

Cohn and others developed a test to detect multiple low outliers (Tim Cohn, U.S. Geological Survey, written commun., March 3, 2011) using a modified version of the Grubbs-Beck test (Grubbs and Beck, 1972), referred to as the multiple Grubbs-Beck (MGB) test. The MGB test was used to check all streamgage records used in the analysis. Low outliers were detected at the same streamgages as previously detected by PeakFQ, but multiple low outliers were detected at Taunton River near Bridgewater, MA (01108000), at Moshassuck River in Providence, RI (01114000), and at Adamsville Brook in Adamsville, RI (01106000) at the 95-percent confidence level. Inspection of the Taunton River annual peak distribution indicates only a single low outlier was warranted, and only a single low outlier adjustment was used in subsequent analysis. Six low outliers were detected in the Adamsville Brook record that was conditioned in the at-site analysis using procedures in the EMA, which treats low outliers differently than the procedure outlined in Bulletin 17B. The EMA uses the MGB test to detect potentially influential low peaks (PILPs) and uses an iterative process to find the cutoff threshold along the LPIII distribution where PILPs no longer significantly affect the probability distribution. Annual peaks below that threshold are

Table 4. Outliers detected in peak-flow database for streamgages used in the flood-frequency analysis.

[Years of record applies to the systematic record; Thres-H, discharge threshold determined by Bulletin 17B test for high outliers; Thres-I, smallest retained observation determined by the modified Grubbs-Beck test; WY, water year in which outlier was detected; Q, magnitude of the outlier, in cubic feet per second (ft^3/s); --, no outliers detected; streamgages with no detected outliers are not listed; RI, Rhode Island; CT, Connecticut; MA, Massachusetts]

U.S. Geological Survey streamgage		Years of record	High outliers			Low outliers		
Number	Name		Thres-H	WY	Q	Thres-I	WY	Q
	Rhode Island streamgages							
01106000	Adamsville Brook at Adamsville, RI	39	436	--	--	117	[a]	--
01112500	Blackstone River at Woonsocket, RI	82	27,010	1955	32,900	1,970	--	--
01114000	Moshassuck River at Providence, RI	47	2,110	--	--	667	[b]	--
	(extended record)	69	2,290	--	--	469	1981	294
	(extended record)						1949	403
01116000	South Branch Pawtuxet River, RI	70	3,570	2010	5,480	245	--	--
01116500	Pawtuxet River at Cranston, RI	71	7,700	2010	14,200	695	--	--
01117000	Hunt River near East Greenwich, RI	70	1,750	2010	2,380	114	--	--
01117350	Chipuxet River at West Kingston, RI	37	595	2010	748	50	1981	20
	(extended record)	70	457	2010	748	38	1981	20
01117420	Usquepaug River near Usquepaug, RI	35	1,700	2010	2,070	140	--	--
	(extended record)	70	1,460	2010	2,070	140	--	--
01117468	Beaver River near Usquepaug, RI	34	655	2010	901	46	--	--
	(extended record)	69	554	2010	901	33	--	--
01117500	Pawcatuck River at Wood River Junction, RI	70	2,400	2010	3,490	350	--	--
01118000	Wood River at Hope Valley, RI	69	3,200	2010	5,470	460	--	--
01118500	Pawcatuck River at Westerly, RI	70	7,620	2010	10,800	1,270	--	--
	Connecticut streamgages							
01119500	Willimantic River near Coventry, CT	79	15,920	1955	24,200	728	--	--
01122000	Natchaug River at Willimantic, CT	21	17,410	1938	26,000	1,610	--	--
	(extended record)	80	24,520	1955	36,600	1,370	--	--
	(extended record)			1938	26,000			
01122500	Shetucket River near Willimantic, CT	28	30,960	1938	52,200	3,030	--	--
	(extended record)	87	45,530	1955	67,700	2,940	--	--
	(extended record)			1938	52,200			
01124000	Quinebaug River at Quinebaug, CT	28	22,840	1955	49,300	1,020	--	--
	(extended record)	92	21,550	1955	49,300	589	--	--
01193500	Salmon River at East Hampton, CT	82	18,290	1982	18,500	940	--	--
	Massachusetts streamgages							
01108000	Taunton River near Bridgewater, MA	65	6,080	--	--	1,250	1985	795
	(extended record)	85	6,577	--	--	1,736[c]	1985	795
01109500	Kettle Brook at Worcester, MA	56	3,330	1955	3,970	93	--	--
01124500	Little River near Oxford, MA	19	3,220	1955	8,340	66	--	--
	(extended record)	98	2,890	1955	8,340	138	--	--
01175670	Sevenmile River near Spencer, MA	50	767	–	–	64	1965	33
	(extended record)	98	1,180	1955	3,270	33	--	--
	(extended record)			1938	1,950			
01176000	Quaboag River at West Brimfield, MA	98	5,480	1955	12,800	540	--	--
	(extended record)			1938	8,470			

[a]Water years 1965, 1966, 1949, 1955, 1951, and 1950 with discharges of 66, 74, 85, 87, 90, and 103 ft^3/s, respectively.

[b]Water years 1981, 1970, and 1971 with discharges of 294, 503, and 507 ft^3/s, respectively.

[c]Fifteen low outliers detected, but only the 1985 peak plotted below the probability distribution curve.

treated as interval data that are less than the cutoff threshold value during the iterative process the EMA uses to converge on a new probability distribution. Despite the censoring of multiple PILPs at the Adamsville Brook streamgage, the EMA analysis still resulted in a large negative skew (-0.47) at this site that is atypical of the region. For this reason, the skew at the Adamsville Brook streamgage was not used to develop the regional skew.

High Outlier Adjustment

High outliers were detected in most of the streamgage annual peak records by PeakFQ (Flynn and others, 2006), which uses procedures described in Bulletin 17B. Historic peak flow data for the streamgages used in this study, as previously discussed, are often appreciably less than the highest peak in the systematic record. Other historical information is qualitative and does not provide the quantitative magnitude of the flood needed to treat high outliers.

High outliers detected in the streamgage records were retained as part of the systematic record without adjustment other than adjustments made for historic peaks in the peak-flow database. In some cases, when the historic peak is appreciably less than the highest peaks in the systematic record, a high outlier threshold was specified in the B17B analysis that was set equal to the computed high outlier threshold for the period of systematic record. This prevents the computed high outlier threshold with historic data being set lower than warranted by the distribution of the peak flow values when relatively small historic peaks are present in the data. However, because of the short time span between the historic data and the start of the systematic data, the high outlier threshold has little effect on the flood frequency analysis.

High outliers were detected in 20 of 40 streamgages used in the regional skew analysis (table 4). At most of these streamgages only a single high outlier was detected. Spatially plotted station skews indicate two areas with high skews (fig. 4) corresponding to high outliers that originate from the 1938, 1955, 1982, and 2010 floods (table 4). The recent 2010 flood accounted for all the high outliers in central Rhode Island. This flood resulted from a succession of low pressure systems from late February through late March that collectively produced as much as 25 inches of rain, which is more than half the total average annual rainfall. The resulting peak flows often exceeded the previously recorded peak by two to three times in the central Rhode Island area and appreciably affected 9 of the 14 streamgages used flood flow analysis in the state.

In early June 1982, a large low pressure system moved slowly into the northeast and stalled, resulting in up to 16 inches of rain during a 4-day period. The heaviest rain was in south-central Connecticut that resulted in a high outlier at Salmon River at East Hampton, CT (01193500). The event also produced high outliers at several other streamgages in this area that were not used in the final analysis in this study because of data concerns. In August 1955, back-to-back hurricanes, Connie and Diane, resulted about 20 inches of rain in a 2 week period in south-central Massachusetts, resulting in outliers at streamgages in south-central Massachusetts and north-central Connecticut. In September 1938, a large rainfall followed by a hurricane related rainfall event centered in northern Connecticut and central Massachusetts produced high outliers at three streamgages in that region. The 1938 flood was considered a major event; however, the 1938 peak has subsequently been exceeded by other peaks and is no longer detected as a high outlier at most streamgages that were in operation at the time or had an historic peak of the 1938 flood.

Generalized Regional Skew

The primary purpose of the generalized skew is to adjust the at-site skew to best reflect regional and long term conditions. Bulletin 17B recommends that generalized skews be developed from a minimum of 40 streamgages that are within a 100 mile radius of each other and have a record of at least 25 years. Skews were determined from the annual peak flow records at the 40 streamgages listed in table 1 and from subsets of these streamgages. Skews were examined to determine if geographic patterns exist, but none were found except for patterns related to high outliers previously described.

After conditioning for low outliers and historic adjustments, skews were determined from the at-site analysis of annual peak flows (table 5) following B17B methods as implemented in PeakFQ. The skew computed from records for all 40 streamgages averaged 0.567 with a standard error of estimate, also known as the root mean square error (RMSE), of 0.626. Skews and RMSEs were determined from subsets of streamgages with successively longer records greater than or equal to 25, 50, and 60 years. As the period of record increased, the number of streamgages available progressively decreased; the average skew generally increases and RMSE decreases with the increasing period of record (table 5).

The average skew and RMSE also was determined from the same 40 streamgages using the extended record at 23 streamgages as previously described after conditioning for low outliers and historic adjustments. Skews at some streamgages also were determined using the EMA to account for uncertainties in the annual peaks, better define the range of possible flows in the interval between historic and systematic data, and to censor multiple low outlier values. The accounting of data uncertainties used by the EMA is described in more detail in the section on “Quantifying Uncertainty of Annual Peaks.” At several streamgages with one or more low outliers or historic values, the standalone version of the EMA (PeakfqSA; Tim Cohn, U.S. Geological Survey, written commun., March 9, 2011) differed from the skew produced by the EMA implemented in PeakFQ version 6.0.14667. At these streamgages, the skew produced by B17B as implemented in PeakFQ was used to compute the regional skew; however, the differences were small and resulted in little change in the outcome of a regional skew.

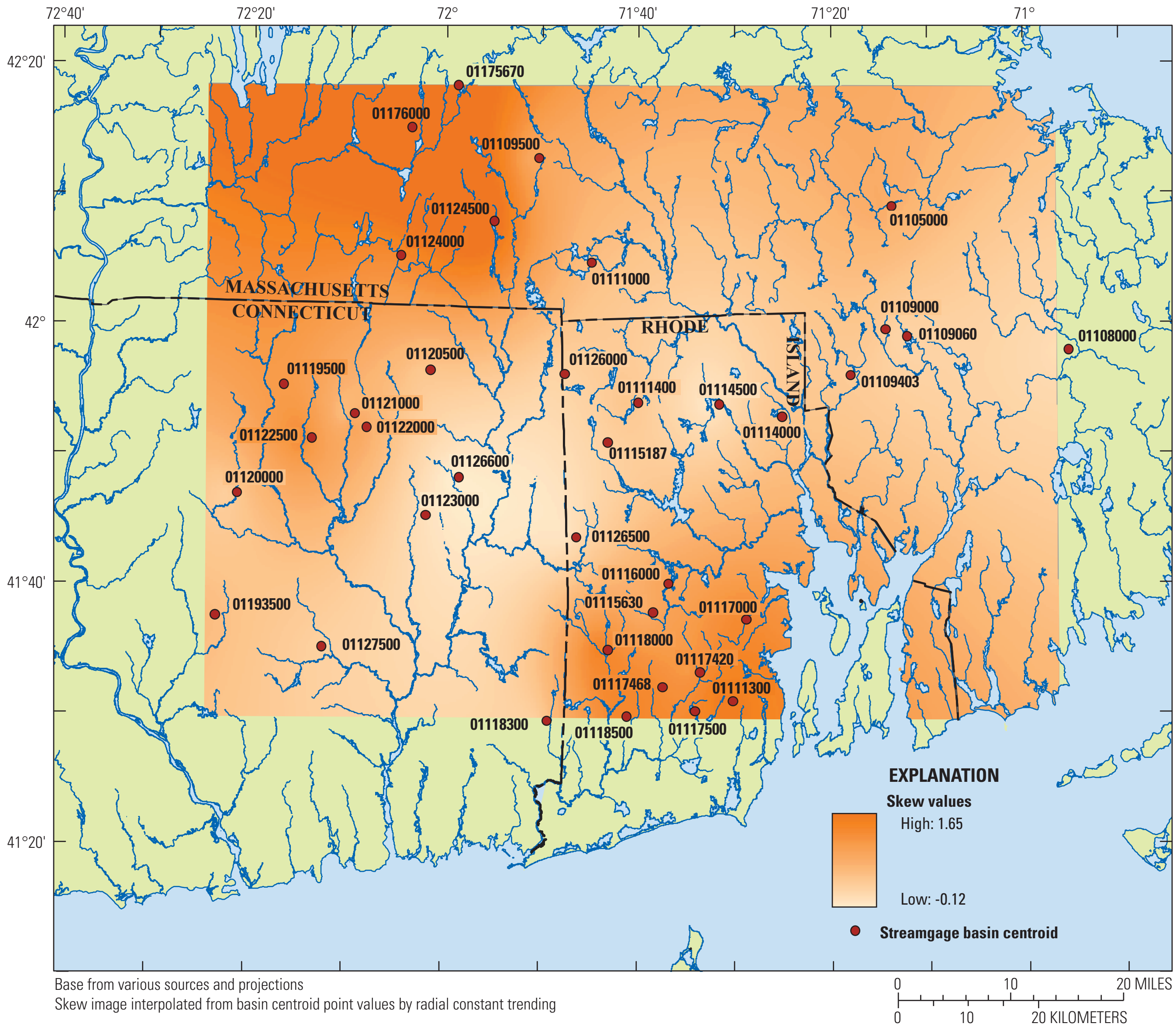

Figure 4. Streamgage skews used to develop the regional skew at selected streamgages in Rhode Island, eastern Connecticut, and south-central and eastern Massachusetts.

Table 5. Summary of generalized skew values determined for Rhode Island and nearby surrounding areas.

[RMSE, root mean square error; ≥, greater than or equal in reference to the length of the systematic record]

Selection criterion	Number of streamgages	Record length (years)		Skew	RMSE
		Average	Minimum		
All streamgages (no record extension)	40	51	11	0.567	0.624
≥ 25 years	29	60	28	0.576	0.555
≥ 50 years	21	69	50	0.512	0.438
≥ 60 years	16	75	61	0.603	0.427
All streamgages (23 with extended record)	40	77	56	0.522	0.463

The average skew of 0.52 and RMSE of 0.46 determined from 40 streamgages, 22 of which had extended record, were used to weigh the skews in the final at-site analysis of flood flows. These values are believed to best represent the generalized skew and error for the region by incorporating the largest number of streamgages and longest period possible. If the analysis were limited to streamgages with 25 or more years, as recommended in Bulletin 17B, about 24 percent of the streamgages would drop from the analysis.

The RMSE is a measure of the accuracy of the at-site skew, which is computed by the square root of the sum of the square differences between the at-site skew and the mean skew, divided by the number of sites minus one. The RMSE is used in the computation of the weighted skew and the confidence bounds of the flood magnitude in the at-site analyses. As currently implemented, the RMSE reflects sample and model error that has been separated in recent advances for computing generalized skews using Bayesian generalized least square (GLS) methods (Reis and others, 2005; Gruber and others, 2007). The Bayesian GLS methods could not be applied in this study because of time constraints; however, the robustness of the method should be considered in future flood frequency studies. It should be noted that the RMSE within the range of computed RMSE values (table 5) had only a minor effect on the flood magnitude and confidence intervals.

A larger regional skew could be warranted on the basis of the streamgages with high skews (fig. 4) associated with the four independent floods previously described. Areas minimally affected by these events and correspondingly areas of lower skews have an equal likelihood of an event of similar severity, which could justify a regional skew based on the average of the high skew values. The skew determined from the actual and extended records for the 18 streamgages with one or more high outliers averaged 0.93 (RMSE 0.37), or about 79 percent larger than the skew determined from the average skew (0.52) of the 40 streamgages. Sensitivity of the AEP flood magnitudes to the higher regional skew was evaluated for each of the 18 streamgages, which averaged 79 years in length and ranged from 56 to 98 years. Results indicate that, when the generalized skew increases from 0.52 to 0.93, the magnitudes of 1- and 0.2-percent AEP floods increase on average by about 7 and 13 percent, respectively. Conversely, floods with a 20-percent AEP decreased on average by 0.7 percent. Magnitudes increased by less than 5 percent for 10- to 2-percent AEP floods when the regional skew increased. However, a larger regional skew will have a greater effect on the flood magnitudes at a site as the streamgage record length at the site decreases.

Quantifying Uncertainty in Annual Peak Records

At a number of streamgages used in this study, the upper end of the stage-discharge rating is defined by one or more indirect measurements of streamflow. These measurements are based on hydraulic principles of contracted openings, flow over a dam, or slope area, and field information collected following a flood on high water levels and geometry of the channel and other structures. Even the best indirect measurements are subject to large uncertainties because of the accuracy of high water marks, debris confounding the hydraulic characteristics of structures, coefficients required by the hydraulic model, and other factors. Discharge determined by indirect methods sometimes far exceeds the highest direct streamflow measurements, which are generally made with greater accuracy. When this happens, the magnitude of annual peak flows above the direct streamflow measurement is affected by the accuracy of the indirect measurement. This in turn influences the magnitude of low probability floods, which are determined in large part by the largest peaks in the record that are defined by the upper part of the stage-discharge rating and its inaccuracies.

The uncertainty of annual peak flows associated with an indirect measurement or other causes can be incorporated into the at-site analysis by uncertainty estimates around the suspect peaks using the EMA. As an example, the high flow rating at Mount Hope River near Warrenville, CT (01121000) is defined by an indirect measurement following the 1955 flood using the contracted opening method. The indirect measurement of 5,590 cubic feet per second (ft^3/s) is the highest flow of record at this streamgage and is 2.6 times larger than the highest direct flow measurement of 2,150 ft^3/s. During the 70-year streamflow record (1941–2010), 11 systematic annual peaks were 5 to 260 percent greater than the highest measured streamflow, with a median of 27 percent larger. Examination of the high flow rating (fig. 5) indicates a bend to the right above the measured flows to draw the rating through the indirect measurement. Without the indirect measurement, the hydrologic characteristics of the site indicate that the rating would likely have been extended as a straight line on a log-log scale as indicated by the red line on figure 5. Assuming the gage height for the 1955 peak is correct, the discharge estimated from the straight line rating is about 36 percent less than the indirect measurement. It should also be noted that the rating changes over time below about 1,200 ft^3/s because of shifts in the channel control; the rating in effect at the time of the peak below 1,200 ft^3/s best represents the stage-discharge relation at that time.

Uncertainty estimates of annual peak flows above 2,000 ft^3/s were estimated on the basis of the difference between the current high flow rating (blue line) and the extrapolated straight line rating (red line) in figure 5 that were incorporated in the EMA analysis as a lower uncertainty interval (fig. 6A). The uncertainty of specified annual peak flows was only bounded by a lower threshold to reflect the difference between the ratings of the blue and red lines. Also included in the analysis was an estimated peak flow from the 1938 flood, which was listed only as a peak stage in the peak-flow database that does not appear to be relevant to the gage datum. It was assumed that stage was entered only in the peak-flow database because an indirect measurement for this flood was made far upstream of the current streamgage; the

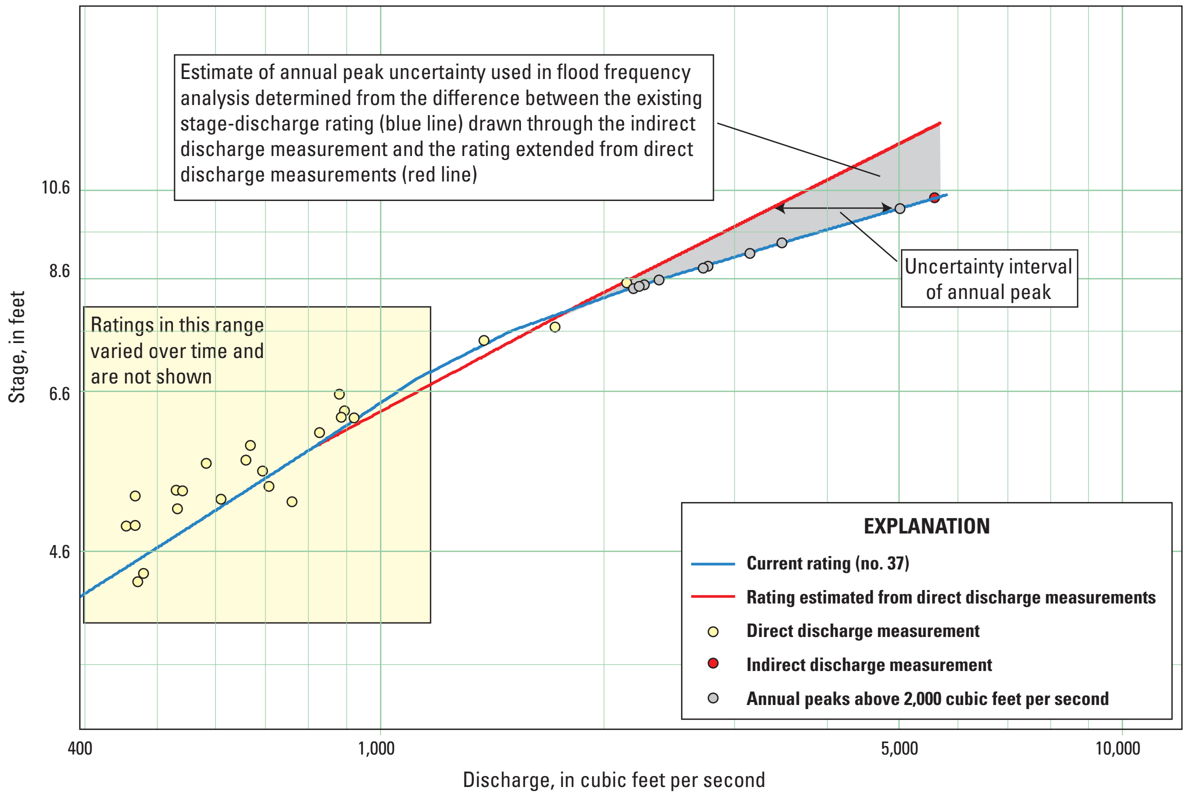

Figure 5. Upper stage-discharge rating and range of uncertainty of higher annual peak flows used in flood frequency analysis at Mount Hope River near Warrenville, CT (01121000).

drainage area at the streamgage is 28.6 mi^2, whereas the 1938 indirect measurement was made at a drainage area of 6.5 mi^2. The 1938 indirect measurement adjusted for drainage area was estimated to be 3,780 ft^3/s and was considered reasonable given the magnitudes of the 1938 and 1955 flood discharges at a nearby long-term streamgage (Hop River near Columbia, CT–0112000). Nevertheless, a ±25 percent lower and upper confidence interval was assigned to the 1938 peak discharge at Mount Hope River at Warrenville (2,840 and 4,720 ft^3/s, respectively) to reflect the normal error of an indirect measurement and the drainage area difference. In addition, the period between the historic peak (1938) and the start of the systematic record (1941) was assigned a perception threshold of 2,000 ft^3/s (blue vertical bar; fig. 6A), which informs the EMA analysis that peak flows during this period did not exceed that threshold.

The resulting probability distribution curves (fig. 6B) indicate that the EMA begins to deviate from the B17B curve at about the 20-percent exceedance probability, and the difference increases as the exceedance probability decreases. The EMA fitted curve is about equal to the lower 95-percent confidence B17B curve at the lower exceedance probabilities. Flood magnitudes calculated by the EMA that incorporate some of the data uncertainties at the Mount Hope River streamgage decreased relative to the flow computed by B17B from about 4 to 18 percent for the 10- to 0.2-percent exceedance probability, respectively (table 6). However, it should be noted that, despite the decrease in the fitted distribution curves from the B17B to the EMA, the magnitude of floods at the upper confidence level for lower probability floods was appreciably larger for the EMA than for the B17B distribution. The magnitudes of the upper confidence level EMA flows were about 6 to 60 percent larger for the 10- to 0.2-percent exceedance probability, respectively, relative to the B17B upper confidence level (fig. 6B; table 6).

Similar hydrologic judgment was used to determine uncertainties at other streamgages used in the analysis. Of the 43 streamgages used, uncertainty limits were specified at 20 streamgages for similar reasons described in the Mount Hope River example. The uncertainties of extended record peak flows were sometimes assigned on the basis of the quality of fit between the short-term streamgage and the index station, which in some cases were compounded by the uncertainties of both streamgage records. On average, the skew decreased by about 16 percent at streamgages where uncertainties were applied in the EMA analysis compared with the skew determined from B17B analysis.

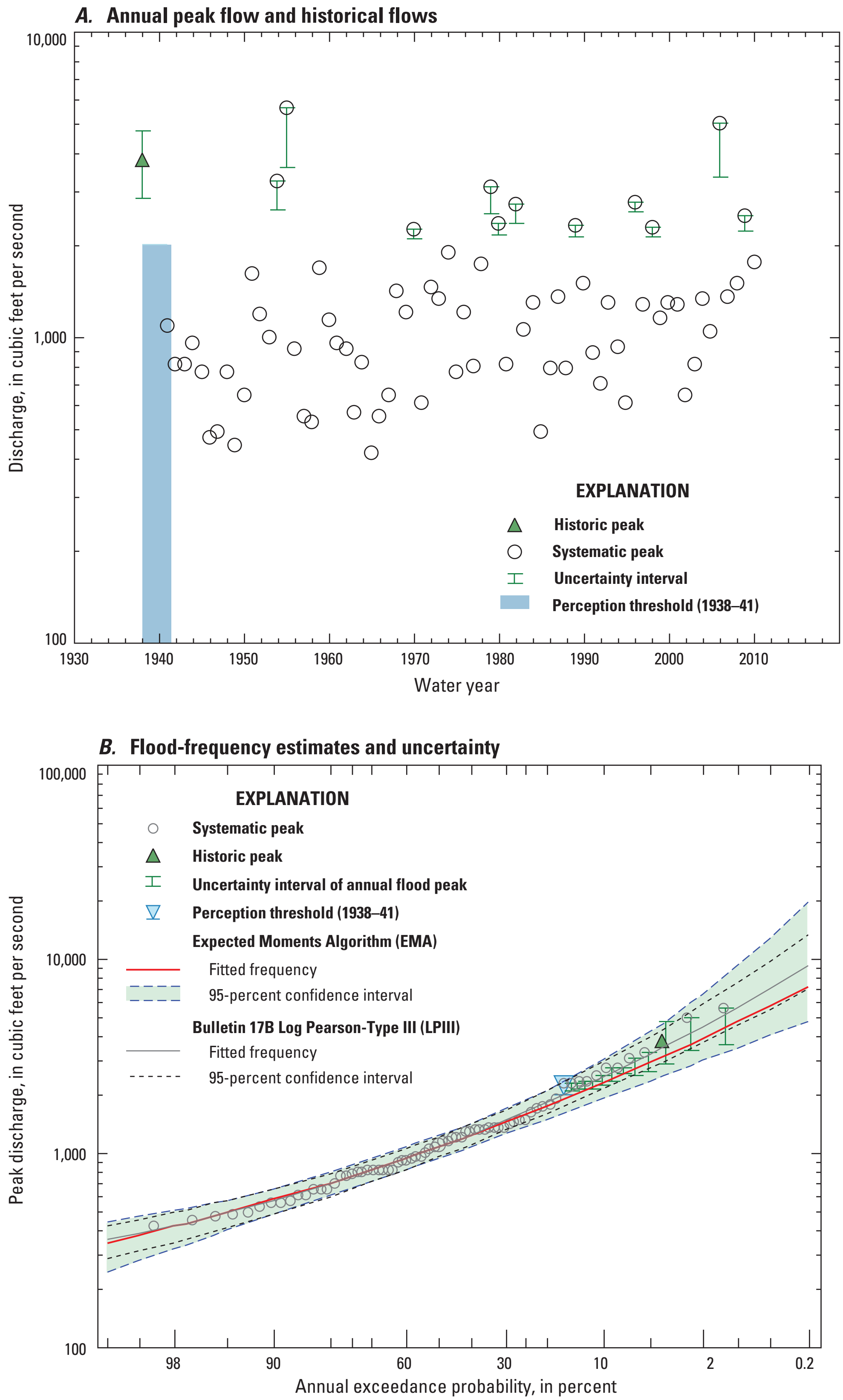

Figure 6. Uncertainty of *A,* annual peak and historic flows used to compute *B,* flood frequency curve at Mount Hope River near Warrenville, CT (01121000). The perception threshold, assigned to the period between the historic peak (1938) and the start of the systematic record (1941), informs the EMA analysis that peak flows during this period did not exceed that threshold. Bulletin 17B is Interagency Committee on Water Data (1981).

Table 6. Annual exceedance probability, flood quantiles, and confidence limits for Mount Hope River near Warrenville, CT (01121000).

[Values are in cubic feet per second except for percent difference. CT, Connecticut; AEP, annual exceedance probability; B17B, Bulletin 17B (Interagency Committee on Water Data, 1981); EMA, expected moments algorithm; %, percent]

AEP (percent)	B17B			EMA			Percent difference		
	Estimate	95% confidence		Estimate	95% confidence				
		Lower	Upper		Lower	Upper	Estimate	Lower	Upper
10	2,370	2,060	2,810	2,280	1,910	2,970	-3.8	-7.3	5.7
4	3,360	2,830	4,170	3,120	2,500	4,670	-7.1	-12	12
2	4,270	3,510	5,480	3,860	2,970	6,550	-9.6	-15	20
1	5,350	4,300	7,100	4,700	3,470	9,160	-12	-19	29
0.5	6,640	5,210	9,100	5,670	4,000	12,800	-15	-23	41
0.2	8,720	6,640	12,400	7,160	4,750	19,700	-18	-28	59

Annual Exceedance Probability Flood Estimates

The magnitudes of flood flows were computed at 43 streamgages in Rhode Island (20 sites), Connecticut (14 sites), and Massachusetts (9 sites) using B17B as implemented in PeakFQ (Flynn and others, 2006). At-site flood magnitudes also were computed by the EMA analysis (Cohn and others, 1997, 2001; Griffs and others, 2004) as implemented in PeakFQ version 6.0.14667 and in PeakfqSA (Tim Cohn, U.S. Geological Survey, written commun., March 9, 2011). All at-site analyses were determined using a weighted regional skew of 0.52 and RMSE of 0.46, except for Pawtuxet River at Cranston, RI (01116500), where only the at-site skew was used because of upstream regulation from a supply reservoir.

Results (table 7, in back of report) are presented for 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs, which are also referred to as 5-, 10-, 25-, 50-, 100-, 200-, and 500-year floods. The results include a B17B analysis for the streamgage period of record and for extended record were applicable, except for Chepachet River at Chepachet, RI (01111400), which only has 11 years of record and, therefore, only the extended record analysis is presented. For comparison purposes, the table also provides the flood flows computed from the systematic record, which are based on the station skew and do not account for low outlier or historic data adjustments.

Values listed in bold in table 7 (in back of report) are the values used to develop the regionalized flood flow regression equations. In general, values used in the regional regression were computed by B17B for the period of record if the record was not extended. If the record was extended, then the B17B extended record analysis values were used in the regional regression. If the uncertainties incorporated into the EMA were appreciable, then the EMA computed values were used; if the uncertainties are not appreciable or no uncertainties were incorporated into the analysis, then the EMA values are the same (or nearly so given rounding differences) to the B17B analysis for the same period of record. The EMA uncertainty estimates are summarized in the footnote for each streamgage where applicable.

Flood magnitude results are provided for Wood River near Arcadia, RI (01117800), but the streamgage was not used in the development of the regional flood flow equations. This long-term streamgage has 47 years of record, but the annual peak flows are highly correlated to the annual peaks at the downstream gage at Hope Valley (01118000) and therefore considered redundant. Pawtuxet River at Cranston, RI (01116500) also was not used in the regional regression because of upstream regulation.

Uncertainty of Estimates

Many factors affect the confidence interval surrounding estimates of the flood magnitude for a given AEP. Foremost is the extent to which the sample population (annual peak flows) represents the true population of flood magnitudes. Bulletin 17B incorporates this uncertainty by the length of the record, and the mean and variability of the peak flows used in the analysis; the confidence level decreases, particularly at the tails of the distribution, as the record length decreases and the variability increases.

In addition to the improvements the EMA makes for quantifying uncertainty for the period of nonsystematic record and for specific peaks used in the analysis, the EMA also provides a more robust estimate of the overall uncertainty of the flood magnitude by a derived approximation of the variance of the EMA moments and flood quantile estimators (Cohn and others, 2001). In practice, annual peaks, particularly high outliers, are generally within the 95-percent confidence level determined by the EMA but often are well outside the 95-percent confidence level determined by B17B. Hence, the confidence intervals for a given AEP are much broader for the EMA than for B17B, but are more realistic of the range of potential flows for a given AEP.

Magnitude of Flood Flows at Ungaged Streams

Equations to estimate magnitude of floods at selected AEPs at ungaged sites were developed from flood magnitudes at selected streamgages described above and their respective basin characteristics. Basin characteristics are used to explain the variability of flow for a given AEP through regional regression techniques. Similar to the at site analysis, regression equations were developed for 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods. The development of regional flood flow equations consist of three basic parts—(1) compilation of basin characteristics, (2) exploratory analysis of the characteristics and flood flows to evaluate the best explanatory variables and their transformations, and (3) use of robust regression methods to develop the final equations and uncertainty of the estimates.

Basin Characteristics

Basin characteristics are used to relate the magnitude of floods determined from the streamgage analyses to develop equations for estimating flood magnitudes at ungaged streams. A total of 55 basin and climate characteristics were compiled for the initial exploratory analysis of potential explanatory variables (appendix 1). These variables can be broadly characterized by land use type, terrain, infiltration, basin and stream morphology, and climate. The distribution of selected basin characteristics (fig. 7) for the 41 streamgages used in the analysis varied by state; generally, the characteristics overlap among states with differences reflecting the region characteristics shown in figures 1 and 2.

Exploratory Analysis

From the potential explanatory variables compiled, variables were evaluated for cross correlation and linearity. Variables that required transformation to achieve better linear relation are those that have a large range in values and are typically direct measures of a basin characteristic such as the drainage area (independent variable) and for flood flows (dependent variable). Most independent variables examined did not require transformation because they represent a characteristic that is normalized by the basin size or expressed in terms of a percentage, such as the percentage of basin that is impervious. Regardless of whether a transformation was needed, transformations were tested because of potential gains in the normality of the regression residuals. Exploratory statistics were made using TIBCO Spotfire S+ (version 8.1).

The ordinary least squares (OLS) method was used to identify explanatory variables that best describe the flood magnitudes for the selected AEPs using an automated subset selection from possible subsets of selected variables. Subsets of variables were made so that well correlated variables were not used simultaneously to avoid covariance that can adversely affect a regression. Variables within a subset are automatically tested individually and in various combinations to determine which variables or combinations of variables best explain the variability of the flood magnitudes for a given AEP among streamgages used in the analysis.

The explanatory variables that best describe the flood flows were selected on the basis of several factors, including the standard error (SE) of the estimate, Mallow's C_p statistic, (3) adjusted R^2, residual sum of squares (PRESS) statistic, and the statistical significance of the explanatory variables. The OLS models with a smaller SE, Mallow's C_p, and PRESS values and higher adjusted R^2 values were identified. In addition, the explanatory variables were selected based on normality of the distributed error or residuals and for multicolinearity by the variance inflation factor (VIF). From this analysis, six variables were chosen for further analysis—drainage area (DA), stream density (STRDEN), storage (StorNHD), mean basin slope (MBSLP), impervious area (IMPERV), and area underlain by sand and gravel (SG). The ranges of values used in the analysis are listed in table 8; the values by streamgage are listed in appendix 1.

The variables in table 8 were further tested using weighted least squares (WLS) regression, which indicated that transforming all variable values to base 10 logarithms produced slightly better models than only transforming flow and drainage area needed to satisfy requirements for linearity. WLS also was used to test different weighting schemes based on the period of record that was adjusted on the basis the overall quality of the record, and the amount of extended record and its quality. In all cases, the period of actual record produced a slightly better model fit than the other weights tested.

Regional Regression Equations

The final regression equations were developed by the generalized least squares (GLS) method as implemented in the Weighted Multiple Linear Regression program (WREG) version 1.03 (Eng and others, 2009). GLS in WREG incorporates the evolution of the technique as developed and described over time by Stedinger and Tasker (1985, 1986), Tasker and Stedinger (1989), Martins and Stedinger (2002), and Griffis and Stedinger (2007, 2009). The advantage of GLS compared with OLS and WLS is that GLS accounts for differences in available record length (as does WLS), but also accounts for the spatial correlation of concurrent annual peak flows among streamgages used in the regression. The GLS procedure separates the total variance of the residuals by model error and sample error by an estimator of the sampling error covariance matrix for each flood quantile and the error associated with the weighted skew. Collectively, the enhanced features of a GLS regression provide the most robust model for regionalization of flood flows (Griffis and Stedinger, 2007).

The best explanatory variables determined from the OLS and WLS analyses (table 8) were tested in GLS using the

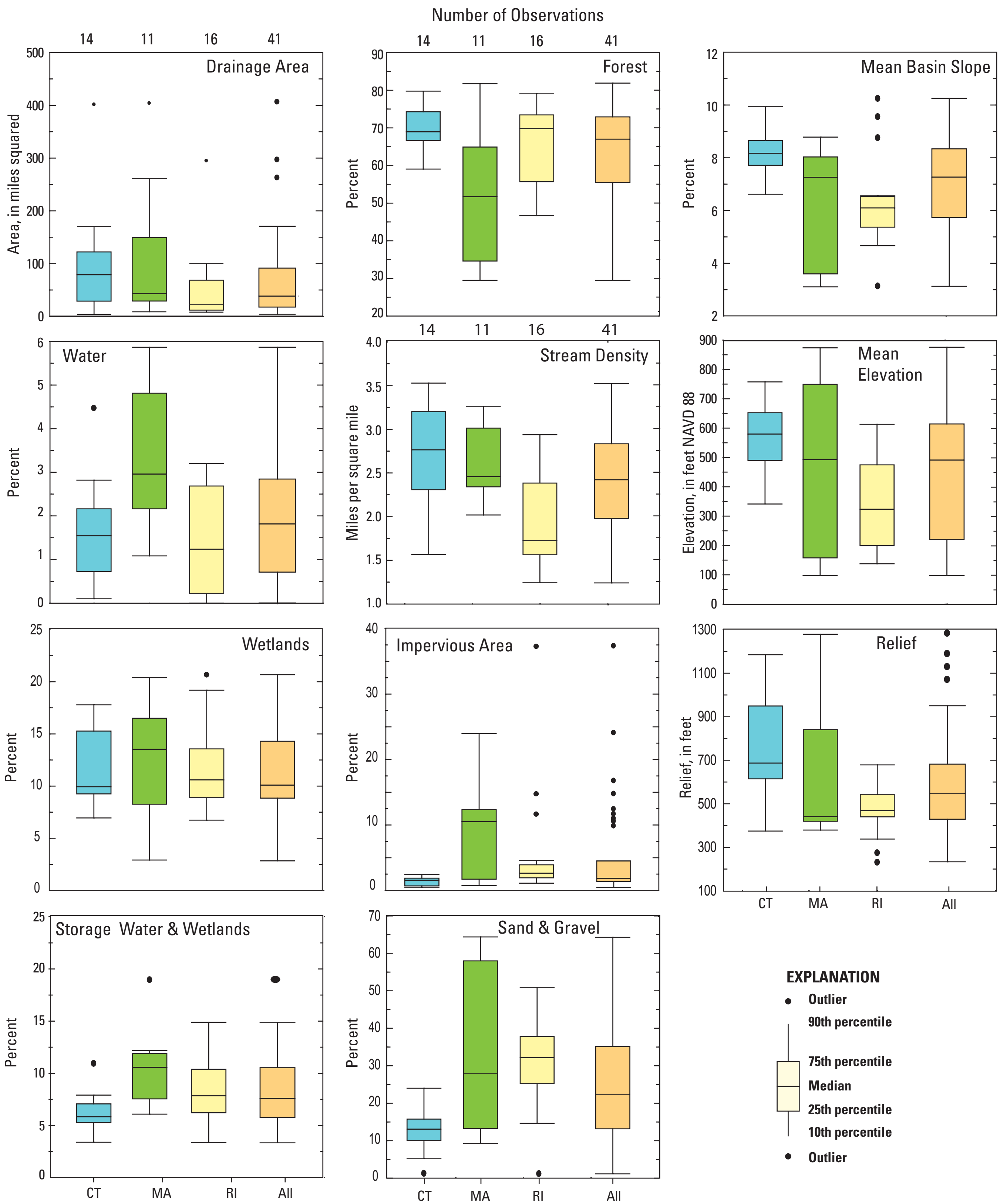

Figure 7. Selected streamgage basin characteristics in Rhode Island (RI), Connecticut (CT), and Massachusetts (MA) used in flood frequency analysis.

Table 8. Ranges of the basin characteristic values used to develop regional flood flow regression equations.

Basin characteristic	Name	Minimum	Mean	Maximum
Drainage area, in square miles	DA	4.00	80.2	404
Stream density, in miles per square mile	STRDEN	1.25	2.38	3.53
Storage, in percentage of basin in open water and wetlands[a]	StorNHD	3.37	8.08	19.0
Mean basin slope, in percent	MBSlp	3.11	6.92	10.2
Impervious area, in percentage of basin area	IMPERV	0.50	5.24	37.2
Sand and gravel, in percentage of basin underlain	SG	1.10	25.9	64.4

[a]As defined in the National Hydrography Dataset (NHD).

period of actual systematic record to develop the covariance matrix and weights. The final analysis used $\log_{10}$ transformations for all variables. For all the AEPs flood quantiles DA, STRDEN, and StorNHD were statistically significant at the 95-percent confidence level. The MBslp was not significant at the 95-percent confidence level for flood flows at and below the 4-percent AEP but was increasingly statistically significant for floods at and above the 2-percent AEP. However, including the MBslp in the regional equation was determined to be marginally beneficial at the lower exceedance probabilities and was dropped from the final equations. IMPERV, which is a surrogate measure of urbanization, was not statistically significant at the 95-percent confidence level at any AEP, but its influence on flood flows is discussed in more detail in the section on "Urban Influence."

The final regional regression equations for the 20- through 0.2-percent AEPs (5- to 500-year floods) are:

$$Q_{20\%} = 10^{(2.124+0.870\times log_{10}(DA)+0.770\times log_{10}(STRDEN)-0.856\times log_{10}(StorNHD))} \quad (2)$$

$$Q_{10\%} = 10^{(2.264+0.870\times log_{10}(DA)+0.790\times log_{10}(STRDEN)-0.893\times log_{10}(StorNHD))} \quad (3)$$

$$Q_{4\%} = 10^{(2.428+0.862\times log_{10}(DA)+0.802\times log_{10}(STRDEN)-0.919\times log_{10}(StorNHD))} \quad (4)$$

$$Q_{2\%} = 10^{(2.537+0.857\times log_{10}(DA)+0.801\times log_{10}(STRDEN)-0.940\times log_{10}(StorNHD))} \quad (5)$$

$$Q_{1\%} = 10^{(2.623+0.852\times log_{10}(DA)+0.792\times log_{10}(STRDEN)-0.941\times log_{10}(StorNHD))} \quad (6)$$

$$Q_{0.5\%} = 10^{(2.713+0.851\times log_{10}(DA)+0.816\times log_{10}(STRDEN)-0.975\times log_{10}(StorNHD))} \quad (7)$$

$$Q_{0.2\%} = 10^{(2.815+0.850\times log_{10}(DA)+0.829\times log_{10}(STRDEN)-1.002\times log_{10}(StorNHD))} \quad (8)$$

where

$Q_{20\%}$ .... $Q_{0.2\%}$ are flow magnitudes for 20- to 0.2-percent AEP floods, in cubic feet per second;

DA is the drainage area of the basin, in square miles;

STRDEN is the basin stream density, in miles per square mile; and

StorNHD is the basin storage, in percent.

Note that *DA* and *STRDEN* are positive coefficients, which means that, as *DA* and *STRDEN* increase, so does the magnitude of flow. *StorNHD* has a negative coefficient, which means that, as *StorNHD* increases, flow decreases. This is a reflection of the effects of storage in mitigating flood flows.

Equal distribution of residuals, the difference between the simulated and observed, is an important consideration in the validity of a linear regression model. Boxplots show residuals are nearly equally distributed around zero for each of the AEP flood quantiles (fig. 8), indicating the regression models are unbiased. Furthermore, the residuals show no spatial pattern (fig. 9), but appear to be inversely related to the station skew (fig. 4). Streamgages with high skews tend to have low residuals, and streamgages with low skews tend to have high residuals. One possible explanation is that streamgages with high at-site skews will have a lower weighted skew, causing the flow magnitudes to decrease and the residual to increase. Conversely, streamgages with low at-site skews will have a higher weighted skew, causing the flow magnitudes to increase and the residual to decrease.

No streamgage appears to have undue leverage or influence in the regression. However, Pendleton Hill Brook near Clark Falls, CT (01118300) is among the streamgages with the greatest leverage and influence because it has the smallest drainage area (4.0 mi^2) used in the analysis, and drainage area is the strongest explanatory variable. This underscores the importance of the inclusion of small basins in future regional regression equations if the equations are going to be applied to small drainage basins.

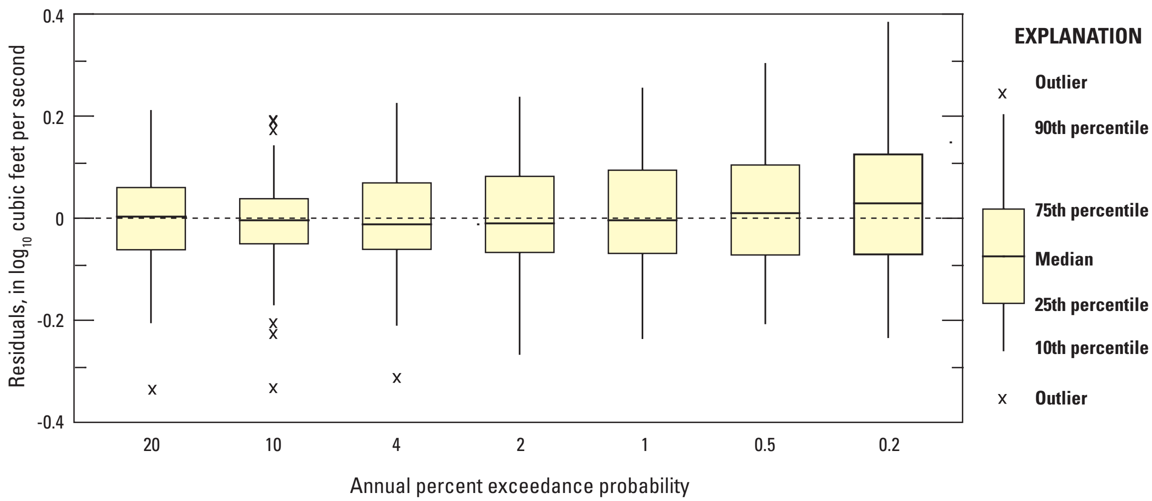

Figure 8. Residuals of generalized least squares (GLS) regional regression of floods for 20- to 0.2-percent annual exceedance probabilities at 41 selected streamgages in Rhode Island, Connecticut, and Massachusetts.

Accuracy and Limitations

Regression equations are statistical models developed from explanatory variables that best explain the variability of flood flows and are subject to the limitations of the data. These include the range of explanatory variables used in the analysis and the scatter or variance between the predicted and observed values. How well the predicted values represent the true values, or the accuracy of a regression, is an important consideration in the application of the model and the interpretation of the results.

The three parameter regionalized flood flow equations (2–8) best fit the computed at-site AEP flood flows (fig. 10A) without overfitting the data. At higher flows, the regionalized equations tend to undersimulate flood flows, but these values are from basins larger than 100 mi^2 outside of Rhode Island (fig. 10B). In addition, the Rhode Island regionalized flood flow equations are primarily needed for basins smaller than 100 mi^2 because the large basins in the state have long-term streamgages to can be used for flood analysis.

Several metrics of model fit are generated for the GLS analysis in WREG; these include the pseudo coefficient of determination (pseudo-R^2), the average standard error of prediction, and the standard model error. The pseudo-R^2 (Griffis and Stedinger, 2007) value is based on the variability in the dependent variable (flood flow) explained by the regression after removing the effect of time sampling error. The pseudo-R^2 is similar to the standard regression coefficient of determination (R^2) in that, the closer the value is to 1.0, the better the model fit and the greater the amount of variance explained by the regression. Pseudo-R^2 ranged from 94 to 96 percent and was slightly lower at the higher and lower AEPs flood quantiles (table 9). The percent average standard error of prediction (table 9) is the percentage form of the mean of the variances of prediction calculated at each of the streamgages used in constructing the regression model (Tasker and Stedinger, 1986). The square root of the variance of prediction is the standard error of prediction. Both are measures in the spread or dispersion of the predicted value from the observed value; hence, the lower the values, the less the expected spread of predictions around the true (unknown) value. Details of how the average variance of prediction and average standard error of prediction are determined are given in appendix 2.

The equations produce estimates of flood flows for the select exceedance probabilities where human influences have little or no effect on the magnitude of floods. Rivers with large regulated impoundments for water supply or flood control, for example, would not be an appropriate use of these equations. Applicability of flood flow estimates determined from basin characteristics outside the range characteristics from which the equations were derived (table 8) is unknown.

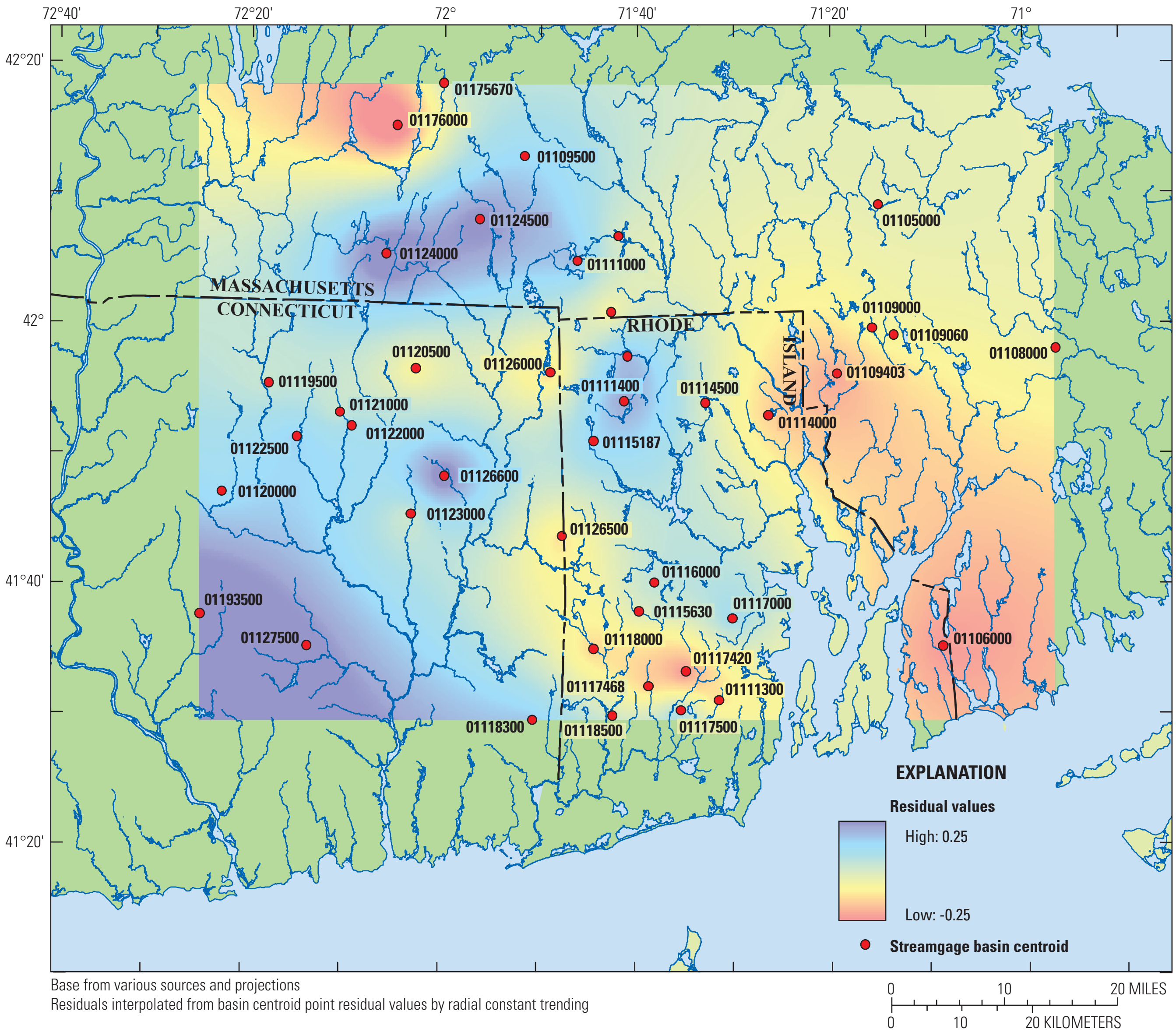

Figure 9. Residuals of generalized least squares (GLS) regional regression and at-site 1-percent annual exceedance probability flood flows at 41 selected streamgages in Rhode Island, Connecticut, and Massachusetts.

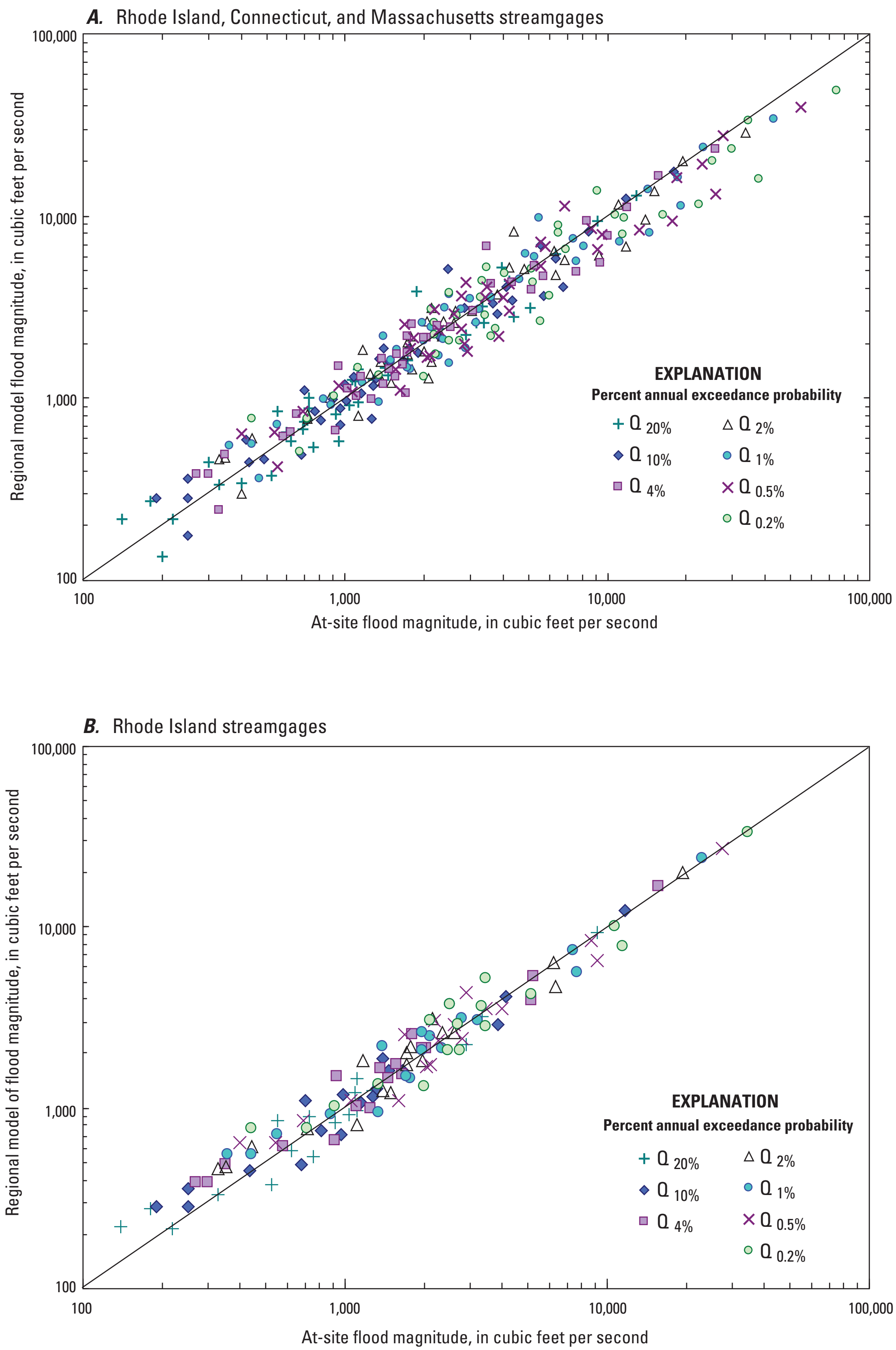

Figure 10. Flood magnitudes for selected annual exceedance probabilities determined from at-site analyses and from regional flood flow equations at *A,* 41 streamgages in Rhode Island, Connecticut, and Massachusetts, and *B,* 18 streamgages in Rhode Island.

Table 9. Pseudo-coefficient of determination (pseudo-R^2), average variance of prediction, and standard error of prediction for the regional flood flow regression equations.

Annual exceedance probability (percent)	Pseudo-R^2 (percent)	Average variance of prediction (percent)	Average standard error of prediction (percent)
20	96	27.2	25.1
10	95	25.9	23.4
4	96	24.0	20.9
2	96	24.5	21.1
1	96	24.2	20.6
0.5	96	26.6	22.3
0.2	95	29.6	24.8

Uncertainty Estimates of Regionalized Equations

The uncertainty of a regression equation is indicated by the confidence interval. A confidence interval is the spread between the minimum and maximum values within which there is a stated probability that the true value of the response variable can exist. As an example, the minimum and maximum values at the 95-percent confidence level for the 1-percent AEP flood for an ungaged site means there is 95-percent confidence that the true value of the 1-percent AEP flood is within the stated intervals.

Driver and Tasker (1990) have shown that a 100(1–α) confidence interval for the true value of a streamflow statistic obtained for an ungaged site from a regression equation can be computed by:

$$\frac{Q}{C} < Q < Q \times C \,, \qquad (9)$$

where

- Q is the flood magnitude for the ungaged site, in cubic feet per second; and
- C is the confidence interval computed as:

$$C = 10^{T * Sp,i} \,, \qquad (10)$$

where

- T Student *t* value from statistic table for a given confidence level and degrees of freedom (for a 95-percent level α = 0.05 and degrees of freedom is equal to number of observations minus the number of variables, 42 – 4 = 38; T = 2.024); and
- Sp,i is standard error of prediction for site *i*.

The value of Sp,i is computed using the equation:

$$Sp,i = [\gamma^2 + x_i U x_i']^{0.5} \qquad (11)$$

where

- γ^2 model error variance,
- x_i a row vector of the logarithms of the explanatory variables (*DA*, *STRDEN*, and *StorNHD*) for site *i*, augmented by a 1 as the first element;
- U covariance matrix for the regression coefficients; and
- x_i' transpose of x_i (Ludwig and Tasker, 1993).

An example calculation of the 95-percent confidence interval is given for a hypothetical ungaged stream site with the following characteristics—*DA* of 30 mi^2, *STRDEN* of 3.53 (mi/mi^2), and *StorNHD* of 6.77 percent. The x_i vector computed from the explanatory basin characteristics is

$$x_i = \{1, \log_{10}(30.0), \log_{10}(3.53), \log_{10}(6.77)\}.$$

The model error variance (γ^2) and the covariance matrix (*U*) were determined from the WREG GLS analysis and are reported in table 10. For a 1-percent AEP flood (100-year flood) the procedure for computing the 95-percent confidence interval is as follows:

- compute Sp,i using equation 11:

$$Sp,i = (0.00908+0.00361)^{0.5} = 0.11264;$$

  converted from $\log_{10}$ units
- compute C using equation 10:

$$C = 10^{(2.024 \times 0.11264)} = 1.69037$$

- compute the 1-percent AEP flood from equation 6:

$$Q_{1\%} = 3{,}590 \text{ ft}^3/\text{s}$$

- compute the 95-percent confidence interval from equation 9:

$$\frac{3{,}590}{1.69037} < Q_{1\%} < 3{,}950 \times 1.69037 \,,$$

- or

$$2{,}110 \text{ ft}^3/\text{s} < 3{,}590 \text{ ft}^3/\text{s} < 6{,}070 \text{ ft}^3/\text{s}.$$

A spreadsheet for solving the regional regression equations at ungaged sites from user specified explanatory values for flood magnitudes with a 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs and the 95-percent confidence interval can be accessed through a hyperlink in appendix 3. The graphical results from the hypothetical test basin computed from the spreadsheet are shown in figure 11.

Table 10. Model error variance and covariance values needed to determine the uncertainty of the regional regression equations.

[γ^2, the regression model error variance in equation 11; *U*, the covariance matrix in equation 11; The matrix horizontal and vertical variables are defined by the constant and the independent variables in equations 2–8 in the order they are given]

Annual exceedance probability (percent)	Model error (γ^2)	Covariance matrix (*U*)			
20	0.0115	0.01494	-0.00113	-0.00998	-0.00962
		-0.00113	0.00153	-0.00046	-0.00143
		-0.00998	-0.00046	0.03065	-0.00023
		-0.00962	-0.00143	-0.00023	0.01350
10	0.0101	0.01508	-0.00117	-0.01026	-0.00911
		-0.00117	0.00146	-0.00021	-0.00139
		-0.01026	-0.00021	0.03025	-0.00024
		-0.00911	-0.00139	-0.00024	0.01273
4	0.0081	0.01522	-0.00113	-0.01083	-0.00857
		-0.00113	0.00136	0.00009	-0.00139
		-0.01083	0.00009	0.03150	-0.00075
		-0.00857	-0.00139	-0.00075	0.01215
2	0.0082	0.01710	-0.00123	-0.01244	-0.00938
		-0.00123	0.00147	0.00022	-0.00156
		-0.01244	0.00022	0.03611	-0.00113
		-0.00938	-0.00156	-0.00113	0.01338
1	0.0078	0.01847	-0.00122	-0.01446	-0.00998
		-0.00122	0.00154	0.00042	-0.00177
		-0.01446	0.00042	0.04305	-0.00227
		-0.00998	-0.00177	-0.00227	0.01479
0.5	0.0092	0.02183	-0.00150	-0.01640	-0.01158
		-0.00150	0.00180	0.00046	-0.00199
		-0.01640	0.00046	0.04755	-0.00195
		-0.01158	-0.00199	-0.00195	0.01672
0.2	0.0113	0.02696	-0.00184	-0.02055	-0.01427
		-0.00184	0.00223	0.00059	-0.00247
		-0.02055	0.00059	0.05946	-0.00252
		-0.01427	-0.00247	-0.00252	0.02067

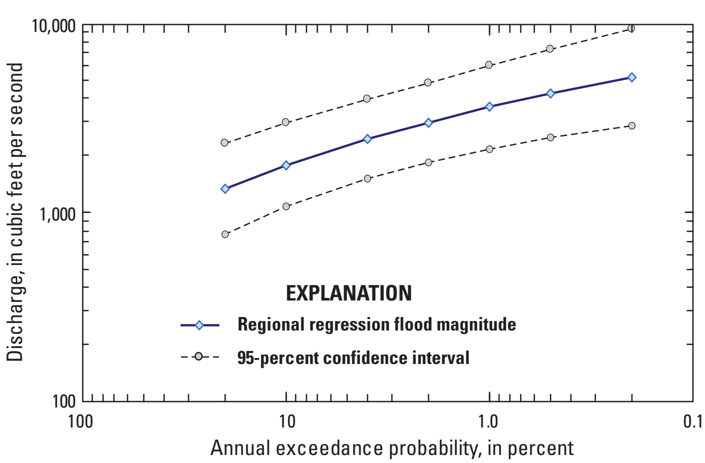

Figure 11. Regional regression estimates of the flood flows and confidence intervals for a hypothetical basin. The hypothetical basin has a drainage area *(DA)* of 30 square miles, a stream density *(STRDEN)* of 3.53 miles per square mile, and storage *(StorHDN)* of 6.77 percent.

Factors Affecting Flood Flow Estimates

Many factors affect the magnitude of flood flows, some of which are incorporated into the regional regression equations by the most significant explanatory variables. Two important factors not included in the regional regression that can affect estimates of the magnitude of floods are the extent of urbanization and trends in the annual peak flows. Urbanization can restrict infiltration of precipitation and alter drainage patterns to move water away from developed areas. To the extent that the streamgages used in the analysis reflect different degrees of urbanization, and if the effects of urbanization are reasonably stable over the streamgage record, the at-site analysis includes these effects in the computed flood magnitudes. Hence, regional regression equations developed reflect the effects of urbanization over the range of urban gradients of the streamgages used. The basic question is how representative the streamgages used in the analysis are to other urbanized basins where flood flow regression equations are applied. Trends in annual peak flows affect the fundamental statistical basis for flood frequency analysis as currently performed, which is based on the assumption of stationarity. Trends can affect both the at-site analyses of flood flows and the regression equations on which they are based.

Urban Influence

Urban drainage basins contain appreciable amounts of impervious surface, such as roads and rooftops, which restrict infiltration of precipitation into the soil and alter drainage systems to move water away from developed areas through storm water drainage systems and channelized streams. These changes can result in increased storm runoff and can alter the timing of runoff in a way that increases the magnitude of the peak streamflow for a given amount of precipitation. The effects of imperviousness have been found to be more pronounced for small, more frequent storms than large infrequent storms (Hollis, 1975; Konrad, 2003). The reason for this is that, during large storms, soils become saturated, preventing further infiltration; this causes surface runoff to increase similar to the effect an impervious surface has for any size storm. Nevertheless, urban adjustments to regionalized flood flow equations for rural basins have been made to include some measure of urbanization, such as impervious surface (Southard, 2010), population density (Watson and Schopp, 2009), or composite urban indices, such as the basin development factor, which accounts for impervious surface as well as storm sewers, culverts, and stream channel alterations (Sauer and others, 1983; Sherwood, 1994).

The suite of basin characteristics tested in the development of regional flood flow equations for Rhode Island includes the percentage of the basin that is covered by impervious area (IMPERV). IMPERV was considered an important factor because of the long history of development in this region and the recognition that most basins of interest with respect to flooding are urbanized to some extent. IMPERV in the basins used in the regionalization analysis ranged from 0.5 to 37 percent with a mean of 5.2 percent (table 8), but the inter-quartile range among all basins was between 1.4 and 4.6 percent, which limits the extent that to which urbanization can be addressed from the available data.

As previously mentioned, IMPERV was not a statistically significant explanatory variable at the 95-percent confidence level for any of the exceedance probabilities examined. Despite this lack of significance in this analysis, other studies (Robbins and Pope, 1996; Southard, 2010; Gotvald and Knaak, 2011) found that imperviousness is an important predictor of the magnitude of flood flows. The exploratory statistical analysis done in this study indicated that IMPERV provided some explanatory power, generally ranking fifth or sixth among the variables examined.

The relation of IMPERV to the magnitude of the AEP flood quantile was further examined and was found to be complicated by other basin characteristics that can offset the effects of urbanization. Most notable was no relation was found between the magnitude of the 20-percent AEP flow and imperviousness for all basins (fig. 12A) but when the basins are stratified by surficial geology type, basins underlain by more than 40 percent sand and gravel show an increasing relation between the magnitude of the 20-percent AEP flow and imperviousness (fig. 12B). Areas with higher percentages of sand and gravel generally allow for greater storm water infiltration; thus, when the infiltration capacity is reduced by imperviousness, the effects on peak flows become more apparent than in areas with naturally lower infiltration. Sand and gravel deposits also tend to be in valley fill areas in the lower parts of the basin where urban areas tend to be more concentrated. Where urban areas are concentrated in the lower basin the effects on peak runoff are less pronounced because the enhanced drainage from the urban areas accelerates the peak relative to the peak from the upper parts of the basin that can reduce overall peak flow from the basin. This interplay between variables complicates the effects of urbanization and its significance in regional analyses.

The relative increase in the annual maximum discharge in urbanized basins has been shown to be more substantial for small frequent floods than for large infrequent floods (Hollis, 1975; Konrad and Booth, 2002; Konrad, 2003). A similar relation can be seen at three long-term streamgages in Moshassuck River at Providence, RI (01114000), Woonasquatucket River at Centerdale, RI (01114500), and Wood River near Arcadia, RI (01117800). All three sites generally have similar dominant explanatory basin characteristics (table 11) except for the percentage of impervious area (about 37, 12, and 0.8 percent, respectively). The dominant explanatory basin characteristics at these sites ranged between 23.1 to 38.3 mi^2 for DA, 1.35 to 2.46 mi/mi^2 for STRDEN, and 4 to 11 percent for StorNHD. The mean basin slope (6 to 10 percent) and percentage of area underlain by sand and gravel (22 to 28 percent) are also similar among basins. The basins are also in close proximity to each other;

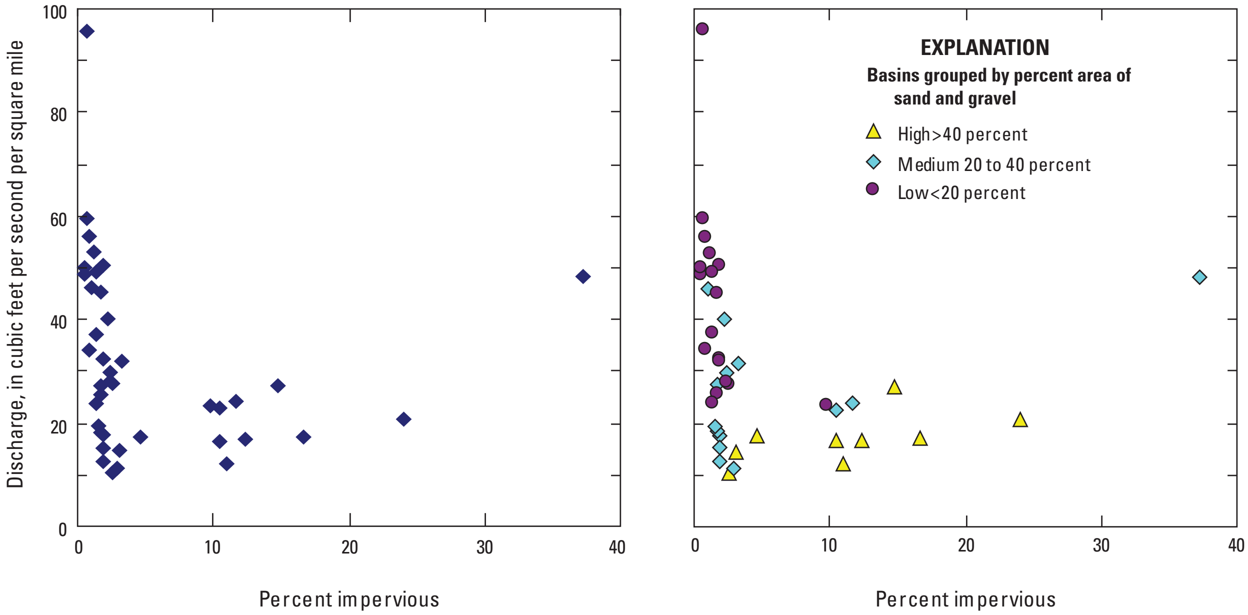

Figure 12. Relation of the magnitude of the 20-percent annual exceedance probability flood determined by regionalized equation to impervious area for *A,* all basins and *B,* basins grouped by ranges of the basin underlain by sand and gravel.

the Moshassuck River and the Woonasquatucket River Basins share a common divide, and the Wood River Basin is about 24 miles to the southwest of the other basins. Recent urban development in these basins has been mostly redevelopment of old development that dates back to the early industrial revolution (1800s) in the United States. Thus, the period of common streamflow record from these basins that starts in 1964 is largely unaffected by new urban growth.

The 47-year common streamflow record and similar basin characteristics among these basins, other than the extent of imperviousness, provides an opportunity to compare the effects of urbanization. The at-site analysis as described previously was performed for each of these streamgages using a common period of record (1964–2010). The AEP flood quantiles were normalized for drainage area for comparison. Flood magnitudes increased as the percent impervious area increased for high AEP flows (smaller more frequent floods). However, when expressed as a ratio of the flood magnitude of the more urbanized basin to the less urbanized basin, the differences between basins becomes less clear (fig. 13). In all cases, the ratio decreases as the AEP decreases; that is, the effects of urbanization decrease for larger less frequent floods. The ratio of the Woonasquatucket River to the Wood River is near one at the 1-percent AEP flood flow and becomes less than one for less frequent floods. Further, the relative difference in the normalized flood magnitude between the two most urbanized basins (Moshassuck and the Woonasquatucket River) and the least urbanized basin (Wood River) decrease more as the AEP decreases relative to the differences between the two more urbanized basins. The most prominent decrease in the ratio

Table 11. Characteristics of three basins used to compare effects of urbanization.

[DA, drainage area; mi², square mile; Elev, elevation in North American Vertical Datum of 1988; STRDEN, stream density; mi², square miles; mi/mi², miles per square mile; IMPERV, imperviousness; StorNHD, storage; S&G, sand and gravel]

Number	River	DA (mi²)	Elev (feet)	STRDEN (mi/mi²)	Percent				
					Slope	Forest	IMPERV	StorNHD	S&G
01114000	Moshassuck	23.1	202	1.75	6.2	53	37.2	3.9	28.4
01114500	Woonasquatucket	38.3	360	2.46	10.2	73	11.6	10.7	22.3
01117800	Wood	35.2	390	1.35	6.9	71	0.83	7.8	27.1

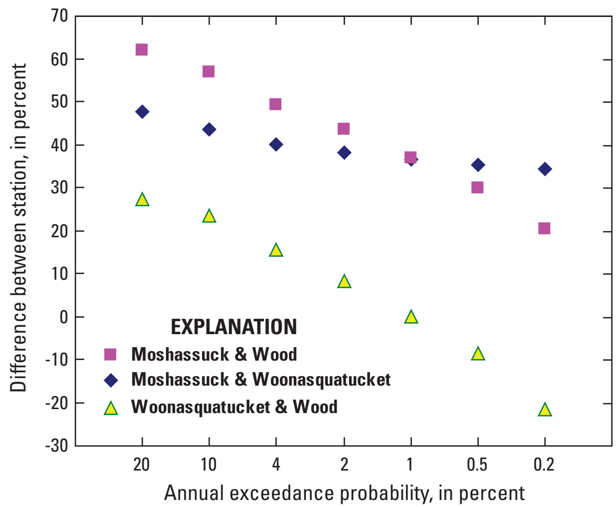

Figure 13. Ratio of flood magnitudes for select annual exceedance probabilities normalized by drainage area between streamgages with different extents of basin urbanization. The at-site analysis was computed from annual peak records from 1964–2010 for the Moshassuck River at Providence, RI (01114000), Woonasquatucket River at Centerdale, RI, (01114500), and Wood River near Arcadia, RI (01117800).

as the AEP decreases was between the most urbanized basin (Moshassuck) and the least urbanized basin (Wood River)—from about 2.6 to 1.3 for 20- to 0.2-percent AEP flood flows, respectively. The least amount of change was between the two most urbanized basins—from about 1.5 to 1.9 for 20- to 0.2-percent AEP flood flows, respectively. The reason for these relative differences is not clear, but underscores some of the differences discussed previously and below.

Adjustments to regional rural flood flow equations to account for the influence of urbanization on flood magnitudes have been developed by Sauer and others (1983) for the United States. The rural equations were modified by Sauer and others to adjust for urbanization by including channel slope, basin storage, rainfall, impervious surface, and the basin development factor (BDF). The BDF is an index that accounts for alterations to the stream channel, sewering, and the extent of curbed streets, which often requires extensive field investigation to determine. Sauer and others showed that the urban to rural peak discharge ratio increases as impervious surface and BDF increase and decreases as the return period of the storm increases. For the 2-year storm, the ratio ranged from 1.3 in areas with low percent impervious and low BDF to 3.6 in basins with high impervious surface and a high BDF. For the 100-year storm, the ratio of urban to rural flood flow ranged from 1.1 in areas of low impervious and low BDF to 2.4 in basins with high impervious and high BDF.

A more recent urban adjustment to rural flood flow equations was developed by Moglen and Shivers (2006) using either imperviousness or population density. The principal advantage of this method compared with the method developed by Sauer and others (1983) is that the explanatory variables can be readily obtained from available geographic information. However, the Moglen and Shivers method requires a different, time consuming process that involves adjusting annual peak flows over time to solve for coefficients that minimize an objective function in a nonlinear regression model. This analysis was not performed, but the calibrated coefficients for simple impervious models determined by Moglen and Shivers (2006) from 78 streamgages with 30 years record from several areas of the country are based on the following equations:

$$UQ_{20\%} = 2.866 \times RQ_{20\%}^{0.862} \left(IA+1\right)^{0.147} \tag{12}$$

$$UQ_{10\%} = 2.827 \times RQ_{10\%}^{0.866} \left(IA+1\right)^{0.128} \tag{13}$$

$$UQ_{4\%} = 2.965 \times RQ_{4\%}^{0.870} \left(IA+1\right)^{0.102} \tag{14}$$

$$UQ_{2\%} = 3.080 \times RQ_{2\%}^{0.873} \left(IA+1\right)^{0.0825} \tag{15}$$

$$UQ_{1\%} = 3.206 \times RQ_{1\%}^{0.876} \left(IA+1\right)^{0.0628} \tag{16}$$

$$UQ_{0.2\%} = 3.541 \times RQ_{0.2\%}^{0.883} \left(IA+1\right)^{0.0166} \tag{17}$$

where

$UQ_{p\%}$ discharge adjusted for urbanization, in cubic feet per second, for p-percent AEP;

$RQ_{p\%}$ rural discharge estimate, in cubic feet per second, for p-percent AEP; and

IA impervious area, in percent.

The calibrated equations (12–17) indicate that imperviousness becomes less influential as the AEP decreases. That is, imperviousness is more important for floods that occur more frequently than for floods that occur less frequently. Equations 12–17 could be used to adjust the equations (2–8) developed in this study for urbanization, but further work is needed to determine the applicability of the coefficients.

Separate equations or adjustments to rural equations have been developed for urban and rural areas in other geographic regions. Adjustments to rural regression equations were made using methods similar to Sauer for North Carolina from the percent impervious cover (Robbins and Pope, 1996) and Jefferson County, Kentucky, by the BDF (Martin and others, 1997). Urban flood flow equations have been developed explicitly for Alabama (Hedgecock and Lee, 2010), Georgia (Gotvald and Knaak, 2011), and Missouri (Southard,

2010) from either the BDF (Alabama) or the percentage of impervious surface (Georgia and Missouri), in addition to other basin characteristics. The ratios of urban to rural flood flows for 20- and 1-percent AEP were computed from the Alabama, Georgia, Kentucky, Missouri, and North Carolina studies. The median ratios of urban to rural flood flows were 1.4 for the 20-percent AEP and 1.2 for the 1-percent AEP, but in some cases (Missouri in particular), the ratio drops below 1.0 (fig. 14). This further underscores the complex effects of urbanization and the interaction other basin characteristics can have on peak runoff.

Although the effects of urbanization were shown to have a relative decrease with the decreasing flood AEP in this and other studies, the analysis in this study also indicates that the flood magnitude linearly increases in relation to increasing imperviousness in some basins with otherwise similar properties. However, there were insufficient data to develop a statistically significant relation, and further research is needed in this area, particularly for small, highly developed basins, to better assess the effects of urbanization on flood flows. The regionalized equations developed in this study appear to apply reasonably well to basins with less than 37 percent impervious area with drainage areas greater than 10 mi^2, but the applicability of the regional flood flow equations (2–8) in small urbanized basins is unknown.

Trends in Annual Peak Flows

Standard methods for calculating the magnitude of floods for a given exceedance probability are based on the assumption of stationarity, that is, the annual peak flows exhibit no significant trend over time. Milly and others (2008) called this assumption into question and advocated for new methods to replace models based on stationarity. Several studies have documented increases in low and median flows across the United States (McCabe and Wolock, 2002; Lins and Slack, 2005; Small and others, 2006), but trends in peak flows are less evident in the literature. In New England, Walter and Vogel (2010) found increasing high flows in urbanizing basins, but increasing high flows have also been shown by Hodgkins and Dudley (2005), Collins (2009), and Huntington and others (2009) in basins minimally affected by urbanization. Failing to take increasing trends in annual peak flows into account in a flood frequency analysis could potentially lead to the

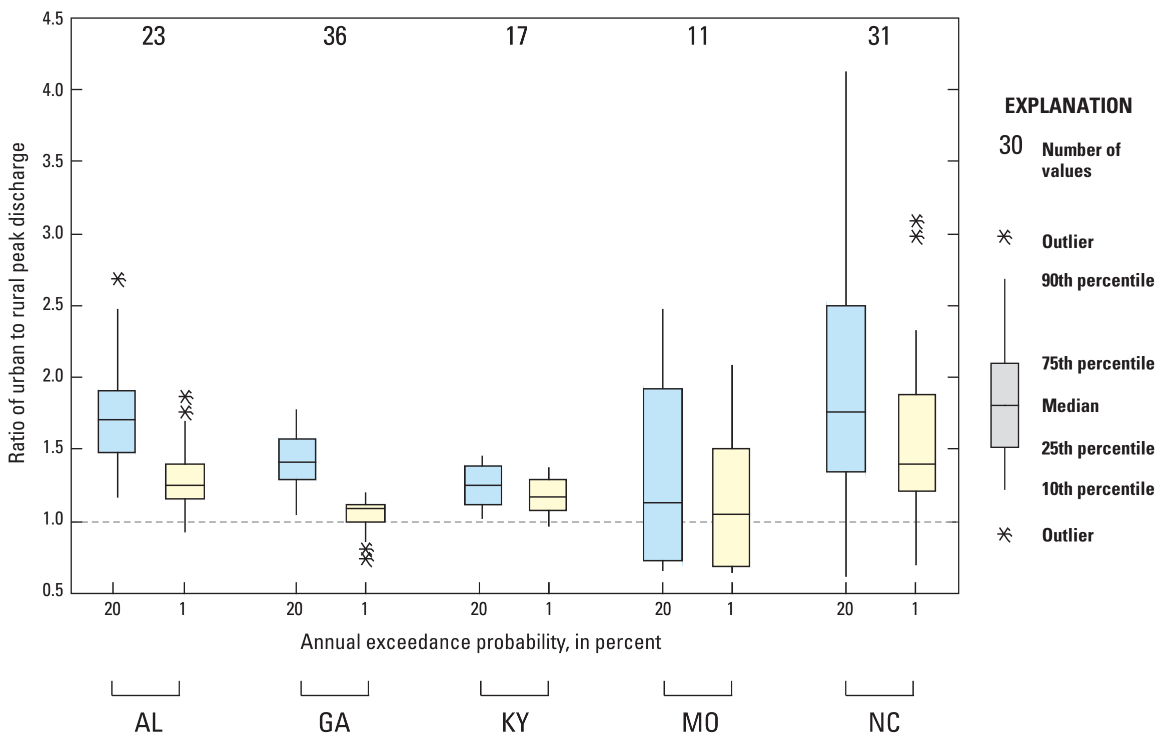

Figure 14. Ratio of urban to rural peak discharges for 20- and 1-percent annual exceedance probability flood in five states with separate flood flow equations. The variation of urban to rural flood flow ratios calculated in previous studies for Alabama (AL), Georgia (GA), Kentucky (KY), Missouri (MO), and North Carolina (NC) underscores the complex interaction of urbanization and other basin characteristics on peak runoff.

underestimation of flood magnitudes or incorrect frequency of floods of a given magnitude, or both, at some point in the future.

Trends in annual peak flows were tested using Kendall's trend test (Helsel and Hirsch, 2002) for the 41 streamgages used in the regional flood flow analysis. The test indicated 76 percent of these streamgages had a statistically significant positive trend at the 95-percent confidence level (this includes the extended record at 23 streamgages). The Kendall-Theil robust line or Theil slope for sites with statistically significant trends ranged from 0.6 to 43 percent with a median slope of 4.0 percent. A subset of streamgages (16 sites) with 70 or more years of unregulated systematic record (table 12) indicate all but four sites have a statistically significant positive trend at the 95-percent confidence level with a Theil slope ranging from 3.2 to 28 percent with a median slope of 11 percent. Three of the other four streamgages have a statistically significant positive trend at about the 90-percent confidence level or above; only one streamgage, Little River near Hanover, CT (01123000), has a positive trend appreciably less than the 90-percent confidence level.

Plots of annual peak flows over time often mask trends because of normal variation in the magnitude of flows. An example plot (fig. 15A) of annual peak flows for Branch River at Forestdale, RI (01111500) shows little evidence of a trend; however, when a linear trend line was added (dashed blue line) to approximate the Kendall-Theil slope, the positive trend becomes apparent. When the annual peaks are identified by quartile range (fig. 15B), the plot indicates peaks within the interquartile and below the lower quartile have little or no trend, but peaks above the upper quartile have an appreciable upward trend. Plots of annual peaks at the other 15 long-term streamgages with statistically significant trends generally show similar patterns.

Table 12. Trends in annual peak flows at streamgages with 70 or more years of unregulated systematic recorded identified by the Kendall trend test.

[No., number; TAU, is a function of the number of positive (concordant) pairs minus the number of negative (discordant) pairs; P, is the statistical test for significance; light shaded cells indicate trend was not significant above the 95-percent confidence level; dark shading indicates trend was not significant; RI, Rhode Island; CT, Connecticut; MA, Massachusetts]

U.S. Geological Survey streamgage		Record			TAU	P-value	Theil slope
Number	Name	Begin	End	No. of years			
Rhode Island streamgages							
01111500	Branch River at Forestdale, RI	1940	2010	71	0.207	0.011	13.7
01112500	Blackstone River at Woonsocket, RI	1929	2010	82	0.174	0.021	28.5
01117500	Pawcatuck River at Wood River Junction, RI	1940	2010	70	0.233	0.004	14.3
01118000	Wood River at Hope Valley, RI	1941	2010	69	0.247	0.003	6.3
01118500	Pawcatuck River at Westerly, RI	1940	2010	70	0.233	0.004	14.3
01114500	Woonasquatucket River at Centerdale, RI	1941	2010	69	0.268	0.001	6.3
01116000	South Branch Pawtuxet River at Washington, RI	1940	2010	71	0.166	0.042	4.1
01117000	Hunt River near East Greenwich, RI	1940	2010	71	0.334	0.000	3.2
Connecticut streamgages							
01119500	Willimantic River near Coventry, CT	1932	2010	79	0.124	0.107	11.2
01123000	Little River near Hanover, CT	1952	2010	61	0.086	0.336	4.5
01121000	Mount Hope River near Warrenville, CT	1941	2010	70	0.233	0.004	8.5
01127500	Yantic River at Yantic, CT	1931	2010	81	0.164	0.031	16. 1
01193500	Salmon River at East Hampton, CT	1929	2010	83	0.233	0.002	22.9
Massachusetts streamgages							
01109000	Wading River near Norton, MA	1925	2010	86	0.121	0.103	1.6
01105000	Neponset River at Norwood, MA	1939	2010	71	0.333	0.000	3.7
01176000	Quaboag River at West Brimfield, MA	1912	2010	97	0.126	0.067	3.0

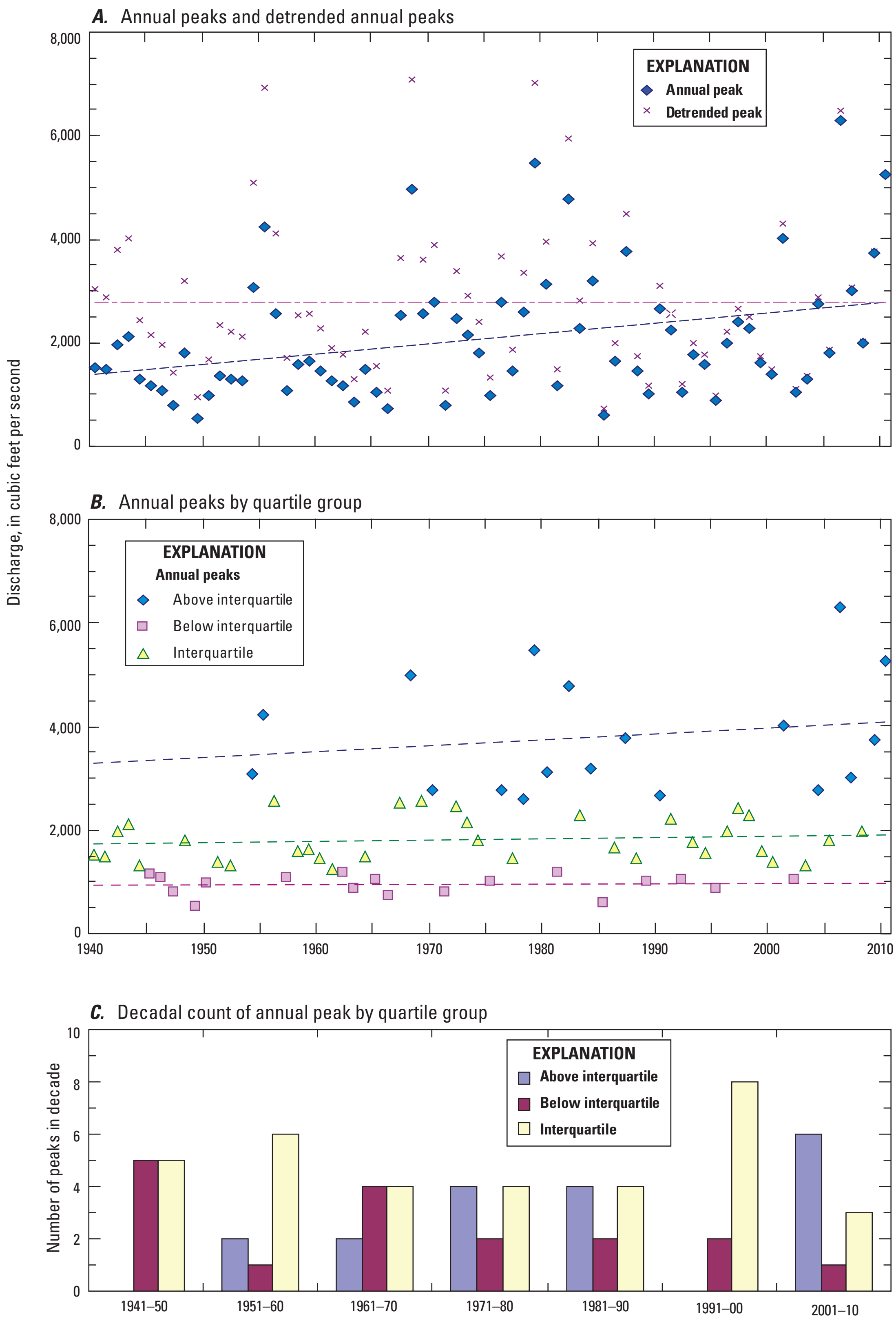

Figure 15. Trends in *A,* annual peak flows and detrended annual peaks, *B,* annual peak flows by quartile group, and *C,* decadal count of annual peak flows by quartile group for Branch River at Forestdale, RI (01111500).

Histograms of the number of annual peak flows within each quartile group by decade (fig. 15C) generally indicate an increasing number of peaks in the upper quartile range over time and a decreasing number of peaks in the lower quartile over time. Decades of relatively high annual peaks (2001–10), low annual peaks (1941–50), and average annual peaks (1951–60 and 1991–2000) are also revealed. Similar patterns are seen in histograms (fig. 16) of the average number of annual peak flows within each quartile by decade at the 15 streamgages with statistically significant trends above about the 90-percent confidence level (table 12).

Several approaches for incorporating temporal trends into a flood frequency analysis have been discussed in the literature. One approach is to assume a parametric distribution for annual peak flows to model the parameters of the distribution as a function of time using linear regression (Katz and others, 2002) or nonlinear methods (Villarini and others, 2009; Ouarda and El-Adlouni, 2011). Another approach fits a locally weighted least squares (LOESS) smoothed curve to the annual peaks (Ries and Dillow, 2006). Data are adjusted by subtracting the difference between the LOESS line and each of the annual peaks from the final value of the LOESS curve to "detrend" the data, the hypothesis being that the trend is removed but the variance in the data is preserved. This effectively rotates the data upward (when the trend is positive) around a pivot point at the end of the data record as shown in figure 15A. This method appears to unduly affect normal cycles of relatively wet and dry periods and was not used to adjust peaks in this study.

Walter and Vogel (2010) developed magnification and recurrence reduction factors to examine how a linear trend would affect flood magnitudes and recurrence intervals at a future time. Peak flows at a streamgage were first modeled as a function of time using a log-linear regression. The quantile function calculates the flood magnitude at a given exceedance probability. In the presence of a linear trend, the log-normal quantile function may be expressed as a function of time by substituting the regression equation into the cumulative distribution function. The magnification factor is the ratio of the quantile function at a future time to the quantile function at present. After simplification of terms, the magnification factor can be expressed as a function of the slope of the regression and the time period, as follows:

$$M = e^{\beta \times \Delta t}, \tag{18}$$

where

M is the flood modification factor, that is, the change in flood magnitude over a specified time;

β is the slope of the lognormal regression of annual peak flow and time; and

Δt is the projected time period.

The method assumes that the linear trend persists at the same rate over the projected time period and can be used to calculate the amount by which a given flood flow must be multiplied to represent a flood of the same exceedance probability over that time interval.

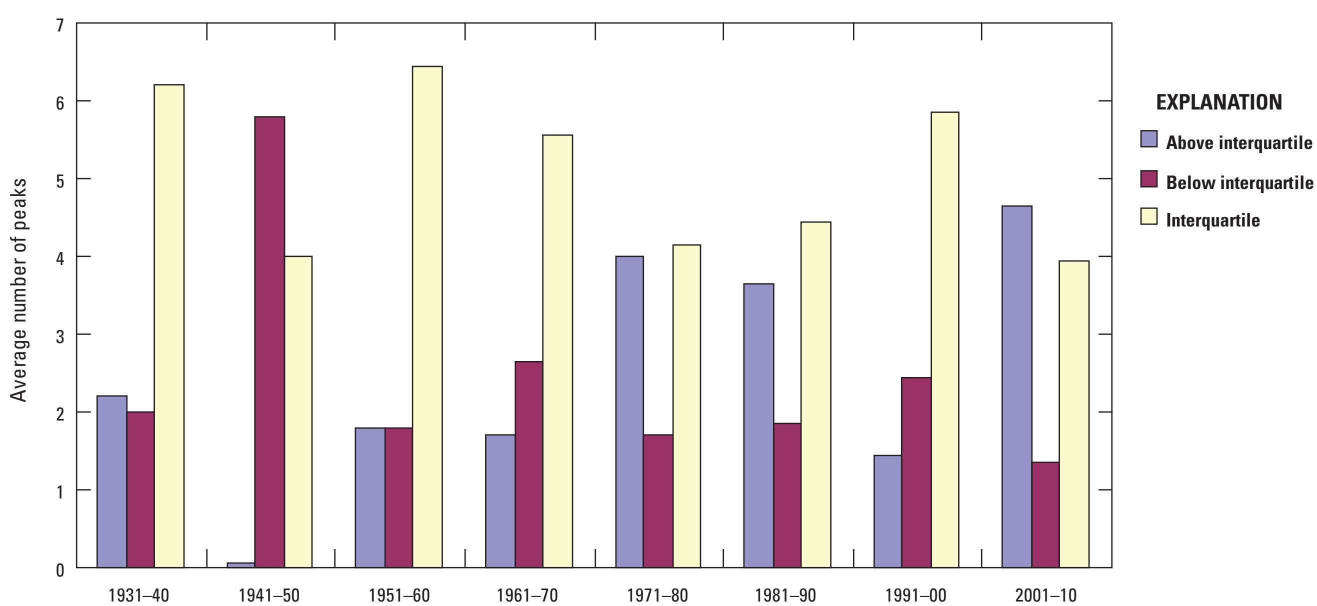

Figure 16. Average number of annual peak flows by decade by quartile range among 15 streamgages with statistically significant trends above about the 90-percent confidence level.

The flood magnification factors (equation 18) were calculated at 15 unregulated streamgages with long-term records (table 12) with statistically significant trends. Flood magnification factors determined for 10-, 20-, and 30-year projections had computed means of 1.06, 1.13, and 1.21 respectively. In other words, if the linear trend in annual peak flows persists, the flood with a given exceedance probability will, on average, be 6, 13, and 21 percent greater in magnitude in 10, 20, and 30 years, respectively. The distribution of the flood magnification factors at the 15 streamgages projected for 10, 20, and 30 years out in the future are shown in figure 17A with values ranging from 0.14 to 12 percent, 2.8 to 25 percent, and 4.3 to 39 percent for 10, 20, and 30 years out from 2010, respectively. The range in flood magnification factors can be applied to floods of any exceedance probability.

Alternatively, a recurrence reduction factor computes the change in the expected average return time of a flood based on a persistent linear trend. An increasing trend causes the average return time of a given magnitude flood to decrease in the future. Walter and Vogel (2010) define the recurrence reduction factor as the ratio of the return period of a given magnitude flood at some point in the future to the return period of the same magnitude flood at present. The return period of a flood is often misinterpreted, and therefore, its use

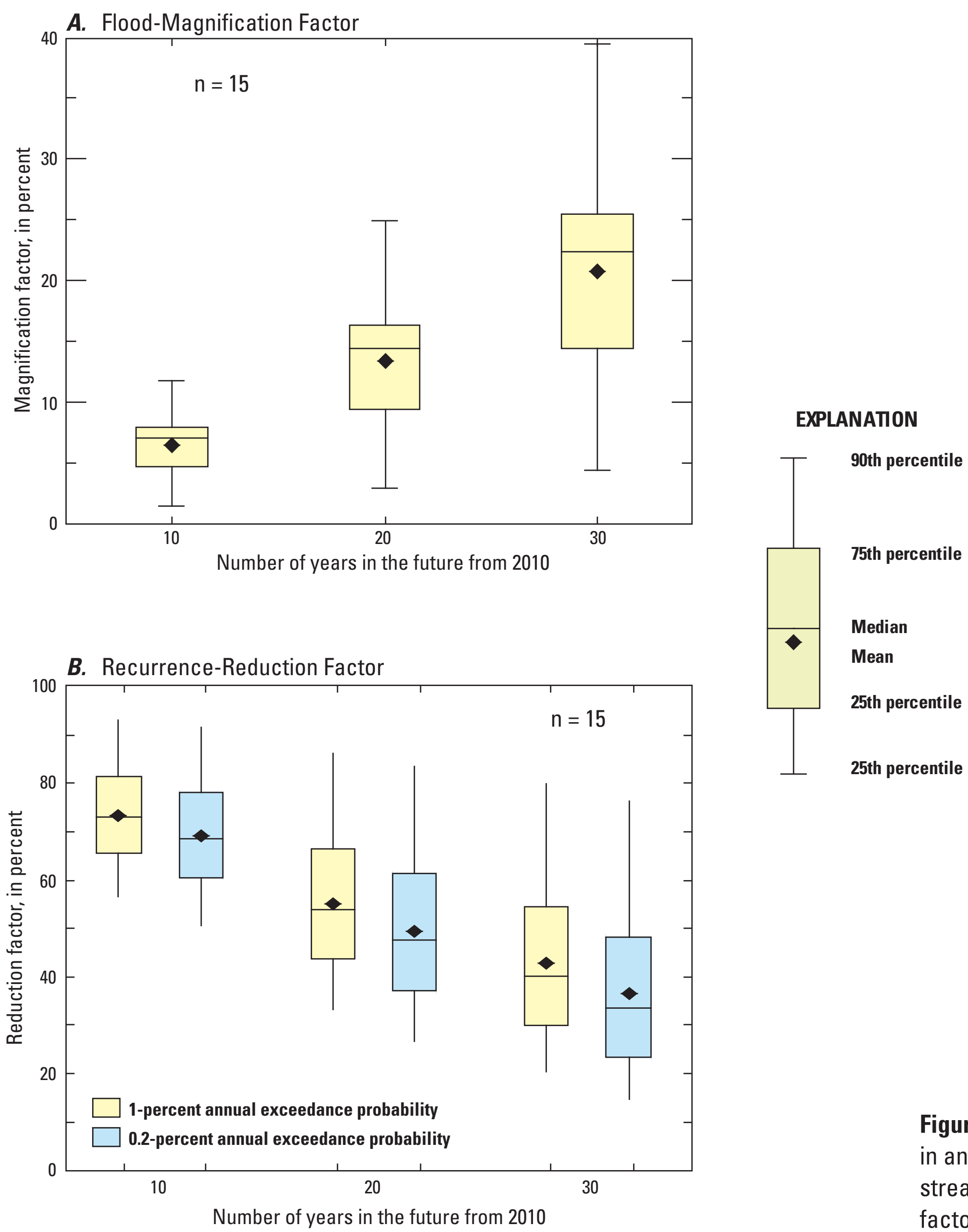

Figure 17. Projected influence of trends in annual peak flows at 15 long-term streamgages by the *A*, flood magnification factor and *B*, recurrence reduction factor.

has diminished in recent flood frequency analyses but is used here for illustrative purposes. The recurrence reduction factor is the increase in frequency for a given magnitude flood in the presence of a trend derived by equating the quantile function for the present condition at a given exceedance probability to the quantile at a future period. For example, a 0.5 recurrence reduction factor during a 10-year period would mean that a 100-year flood (1-percent AEP) would become a 50-year flood (2-percent AEP) in 10 years time. That is, a flood magnitude for a given AEP will likely occur twice as frequently if the trend persists at the 0.5 reduction factor rate.

Recurrence reduction factors calculated for 100- and 500-year floods were projected out for the 10-, 20-, and 30-year periods (fig. 17B). The trend at the 15 unregulated streamgages with long-term records (table 12) with statistically significant trends, on average, indicate that a 100-year flood at present (2010) would have an average return period of 73, 55, and 43 years when projected 10, 20, and 30 years in the future. A 500-year flood at present would have an average return period of 344, 245, and 182 years when projected 10, 20, and 30 years in the future. While these results can be unsettling, it should be emphasized that the change factors computed by the methods of Walter and Vogel (2010) assume the same linear trend, which may not continue over the projected time periods. True trends can only be determined by continued monitoring of streamflow. Statistical procedures for nonstationarity are in their infancy, and the trends observed in the data used in this study and its effects on flood frequency will require further work as this science evolves.

Application of Methods and Significance of Results

Floods are considered random events that have inherent uncertainties associated with the data, or lack thereof, and various errors and limitations of the statistical methods used to estimate the magnitude of floods for a given AEP. Our understanding of flood flows and the associated risks can be improved by applying the information gained from the streamgage flood frequency and the regional regression analyses. The analyses can also improve our understanding of flood flows at short-term streamgages not used in the analyses and exceedance probability of the 2010 flood in Rhode Island.

Weighted Estimates of Flood Flows at Streamgages

Flood flow estimates for a given AEP at streamgages, particularly those with short records, can be improved by a weighted average of two independent estimates from the streamgage analyses and the regional regression equations. The procedure assumes that the estimates are independent, which is considered true in most practical instances by Bulletin 17B. Exceptions may include regional regression equations based on clusters of streamgages in close proximity or with uniformly short periods of record; this does not appear to be a factor in this analysis. If the at-site and regression flood flow statistics are not independent, then the variance of a weighted estimate will be larger than the variance of each estimate. Also note that if basin characteristics are outside the range of characteristics used in the regional regression or if the high flows at a streamgage are appreciably affected by regulation, then a weighted estimate should not be made.

In the past, the weights for flood flow estimates were often made based on the number of years of record used to determine the at-site estimate and the equivalent years of record for the regression equation. The equivalent years of record is an approximation of the gage record needed to achieve accuracy comparable with that of the regression model (Tasker and Stedinger, 1989). This approach often fails to account for the true variance of the respective flood flow estimate and the information content provided by the regional skew. For example, the variance of the annual peak flow record will determine the reliability of the probability distribution even for streamgage records of equal length.

A weighted estimate can be calculated from the variance of independent estimates, which can be viewed as a measure of the uncertainty. When the variance corresponding to one of the estimates is high, the uncertainty is high and the weight applied to that estimate should be relatively small. Conversely, when the variance is low, the uncertainty is low and the weight applied to that estimate should be relatively large. Thus, the optimum weight is inversely proportional to the variance of each flood flow estimate, which is described in Bulletin 17B and can be calculated from the $\log_{10}$ of flood flows and variances as follows:

$$Q_{wgt} = \frac{(Q_{site} \times V_{reg}) + (Q_{reg} \times V_{site})}{V_{site} + V_{reg}}\ , \qquad (19)$$

where

Q_{wgt} is the weighted flow estimate for a given AEP,
Q_{site} is the at-site flow estimate for a given AEP,
Q_{reg} is the regional regression flood flow estimate for a given AEP,
V_{site} is the variance of the at-site estimate for a given AEP, and
V_{reg} is the variance of the regional regression estimate for a given AEP.

Similarly, a weighted variance can be calculated from the inverse variances of each flood flow estimate by:

$$V_{wgt} = \frac{V_{site} \times V_{reg}}{V_{site} + V_{reg}}\ . \qquad (20)$$

There are a number of variables needed to calculate the variance of the at-site and regional regression flood flow estimates. The at-site variance is based on the number of peak flow observations and the $\log_{10}$ values of the mean, standard deviation, and skew determined by the B17B or the EMA analysis and the RMSE of the regional skew used. In this analysis, the regional regression variance is determined from the standard error of the model, the number of explanatory variables, and the covariance matrix (*U*) of the explanatory variables used in equation. To facilitate the computation of the weighted estimate (equation 19), the USGS developed the Weighted Independent Estimator (WIE) program (Cohn and others, 2012).

Weighted estimates of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP flood flows were calculated using the WIE and are reported in table 13 (in back of report) for the Rhode Island streamgages reported in table 7 (in back of report); the WIE values in table 13 (in back of report) are the arithmetic transformation of the $\log_{10}$ values of flow computed in equation 19. For comparison, the at-site and regression flood flows along with the percent difference between the at-site value and WIE values also are reported. A positive difference indicates the weighted estimate is greater than the at-site estimate, and conversely, a negative value indicates the weighted estimate is smaller than the at-site estimate. Differences between the magnitude of floods determined from the at-site and weighted estimates progressively increase as the exceedance probability decreases (fig. 18); differences at the 0.2-percent AEP flows were largest and ranged from -45 to 23 percent. A flood with a 20-percent AEP has an interquartile range of -1.0 to 1.4 percent, whereas a flood with a 0.2-percent AEP has an interquartile range of -16 to 5.8 percent. The increasing difference with decreasing flood probability is attributed to the greater uncertainty of flood flows as the AEP decreases.

Flood Flows at Streamgages with Limited Record

Flood magnitudes determined at streamgages with short records are subject to greater inaccuracies because the statistical properties of the record are less likely to reflect long term conditions. This is referred to as the sampling error of the true population, and the effects of the sampling error are mitigated to some extent by a skew weighted to the generalized skew representative of the region. The weighted skew is inversely proportional to the variance of each estimate as described in Bulletin 17B; however, this procedure is not without flaws because the true variance may not be accurately represented, particularly for streamgages with short records. Streamgages with short records can be extended using MOVE to better reflect long-term conditions, as was done for 23 of streamgages used in the study; however, the extrapolated record is made with less confidence as the concurrent short- and long-term streamgage record decreases. The regional flood frequency analysis did not include all the available short-term streamgages initially complied for the study because of the greater uncertainties associated with these streamgages and because of the limited number of index stations available for record extension. Still, flood flow estimates at short-term

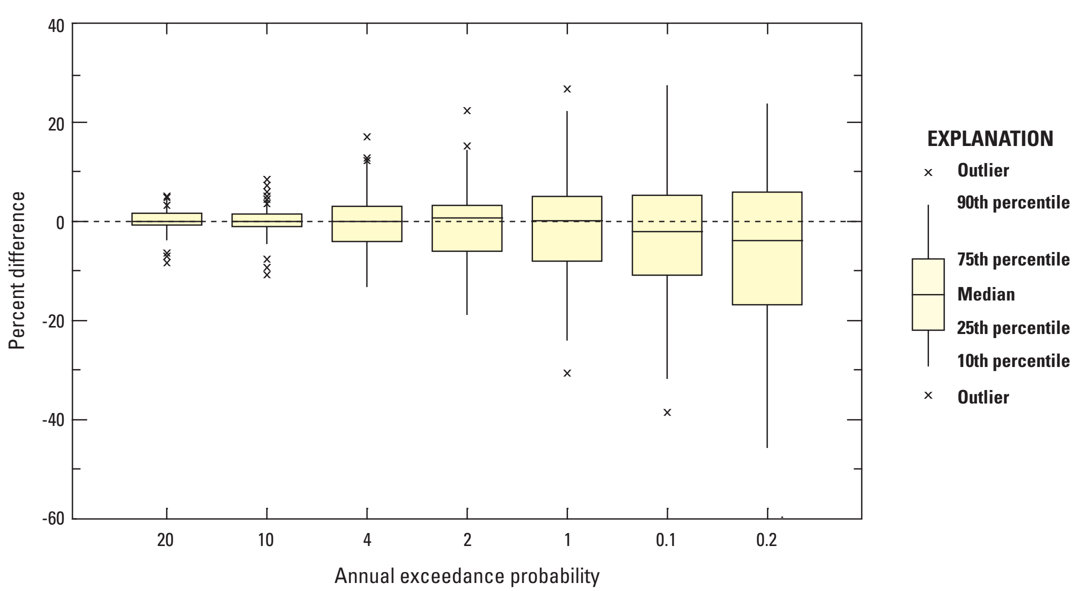

Figure 18. Range of differences between flood flows calculated from at-site analysis of annual peak flows and weighted independent estimate for selected annual exceedance probabilities.

streamgages provide additional information for flood insurance studies, infrastructure design, and other purposes in basins with short-term streamgages not used in the regional analysis.

In preparation of the Johnson and Laraway (1977) flood frequency study, 20 streamgages were established in Rhode Island that generally ran between the mid-1960s and mid-1970s. The drainage area for these streams ranged from 0.5 to 7.33 mi^2 with a median of 3.1 mi^2 (table 14). While data for small basins are generally lacking, the record at these streamgages has a median length of 9 years. Three streamgages established later for other purposes have been in operation 10, 12, and 16 years with drainage areas of 3.6, 20, and 5.0 mi^2, respectively (table 14). In 2010, 17 other streamgages were in operation in Rhode Island that were not compiled because they have a record of less than 6 years, but could be of value in future flood frequency studies.

The distribution of flood flows was estimated at 19 of the short-term streamgages using B17B analysis of the systematic record, B17B and EMA analysis of the extended record, and the regional regression equation regardless of its applicability to the site (table 15, in back of report). That is, many of these short-term streamgages had basin characteristics outside the range applicable to the regional flood flow equations, particularly drainage area size. Four of the short-term streamgages (Metacomt Brook at East Providence, RI–01109300; Mowry Painc Brook near Chepachet, RI–01111450; Shippee Brook tributary at North Foster, RI–01115200; Furnace Hill Brook at Cranston, RI–01116870) were not included in the analysis because of suspect data quality (for example, the annual peak flows are excessively large for drainage basins of that size and showed little variation over the period data was collected). Thirteen of the 19 streamgages have basin characteristics outside of the range of characteristics used to develop the

Table 14. Streamgages with short-term records in Rhode Island that were not used in the regional flood frequency analysis.

[DA, drainage area; mi^2, square miles; STRDEN, stream density; mi/mi^2, miles per square mile; StorNHD, storage; trib, tributary; --, not determined; 17 other streamgages are in the U.S. Geological Survey peak-flow database but with no greater than 6 years record]

U.S. Geological Survey streamgage		Record			DA (mi^2)	STRDEN (mi/mi^2)	StorNHD (percent)
Number	Name	Begin	End	Years			
01106100	Cold Brook near Adamsville, RI	1966	1973	9	1.15	2.86	5.64
01109300	Metacomt Brook at E. Providence, RI[a]	1966	1973	9	0.82	--	--
01111250	Dry Arm Brook near Wallum Lake, RI	1966	1978	13	1.74	2.20	14.69
01111450	Mowry Painc Brook near Chepachet, RI[a]	1966	1973	9	1.87	--	--
01112700	Blackstone River trib 1 at Woonsocket, RI	1965	1974	10	2.31	1.97	2.88
01113600	Blackstone River trib 2 at Berkeley, RI	1966	1978	13	1.04	1.56	5.25
01113695	Catamint Brook at Cumberland, RI	2000	2010	10	3.55	2.29	5.99
01115098	Peeptoad Brook near North Scituate, RI	1994	2010	16	4.96	1.68	17.15
01115100	Mosquitohawk Brook near North Scituate, RI	1965	1974	9	3.06	2.41	17.18
01115200	Shippee Brook trib at North Foster, RI[a]	1966	1974	9	2.42	--	--
01115300	Wilbur Hollow Brook near Clayville, RI	1966	1978	13	4.61	2.26	8.27
01115770	Carr River near Nooseneck, RI	1964	1980	20	7.33	1.88	8.78
01115830	Bear Brook near Coventry, RI	1966	1978	13	3.98	1.68	1.76
01116300	Furnace Hill Brook at Cranston, RI[a]	1965	1974	9	4.19	2.39	5.29
01116600	Pocasset River near North Scituate, RI	1966	1978	13	1.34	3.10	10.66
01116650	Hardig Brook near W. Warwick, RI	1966	1973	9	3.19	2.00	1.48
01116870	Frenchtown Brook near Davisville, RI	1966	1973	9	3.12	2.15	6.75
01117250	Browns Brook at Wakefield, RI	1966	1973	9	0.5	0.53	13.30
01117370	Queen River at Liberty, RI	1998	2010	12	19.6	1.73	4.42
01117600	Meadow Brook near Carolina, RI	1965	1974	11	5.53	1.67	9.15
01117820	Wood River trib near Arcadia, RI	1966	1973	9	0.77	1.46	1.87
01118020	Perry Healy Brook near Bradford, RI	1966	1973	9	1.82	1.48	12.84
01126200	Bucks Horn Brook at Greene, RI	1965	1974	9	5.52	2.32	9.78

[a]Suspect peak flow record.

regional regression equations, mostly because drainage areas were about 20 to 90 percent smaller than the minimum drainage area (4.0 mi^2) used in the regional regression. At these streamgages, regional regression estimates were reported, but no uncertainty limits or weighted estimates are given because the equations were applied to basins outside the appropriate limits of the equations.

Results indicate a wide variation between the flood estimates by method and by site with similar drainage areas. Generally, flood flows differed less between the period of record and extended record estimates than between extended record and regression estimates. Differences between the period of record and extended record estimates ranged from -46 to 37 percent and from -64 to 251 percent for 20- and 0.2-percent AEPs, respectively. Differences between the extended record and regression estimates ranged from -83 to 345 percent and from -89 to 541 percent for 20- and 0.2-percent AEPs, respectively. Differences between methods at a site tended to be consistent across the range of AEP flows. Generally, the flood flow information from the short-term streamgage can be used with greater confidence when the differences between methods are small. The results also indicate the need for additional data in small basins.

The streamgage at Carr River near Nooseneck, RI (01116600) was established in 1964, discontinued in 1980, and reactivated in 2006. Collectively, the Carr River streamgage has 20 years of annual peak flows that provide a reasonable length of record to independently verify the regional regression equations for a small basin; the drainage area at the streamgage is 6.74 mi^2. The same regional skew (0.52) and RMSE (0.46) applied elsewhere this study was used in this at-site analysis. The magnitude of flood flows determined by a B17B analysis for the period of record on average was 37 greater than that determined from the extended record analysis; flows ranged from 27 to 45 percent greater for 20- and 0.2-percent AEP, respectively. Carr River records were extended back to 1941 using MOVE and the Hunt River near East Greenwich, RI (01117000) as the index streamgage; the MOVE fit reasonably well with a correlation coefficient of 0.89 and an RMSE of 60 ft^3/s. Flood magnitudes derived from the regional regression equation were consistently less than those computed from the period of record B17B analysis; flows ranged from 18 to 71 percent less for 20- and 0.2-percent AEP, respectively. On the other hand, the regression equation flood magnitudes compared with the extended record B17B analysis were 13 percent greater at the 20-percent AEP, matched the 10-percent AEP, and were progressively smaller (14 to 48 percent) from the 4- to 0.2-percent AEP, respectively. All but the 0.5- and 0.2-percent AEP regional regression flows for this streamgage were within the percent average standard error of prediction.

Flood Flows at an Ungaged Site on a Gaged Stream

Estimates of flood flows on a stream above or below a gaged location, within limits, can be improved by combining the streamgage information with the regional regression equation. Verdi and Dixon (2011) present a method for better estimating flows at an ungaged site on a gaged stream from Sauer (1974) for streamgages with a record of 10 or more years (equation 21). To obtain a weighted peak-flow estimate ($Q_{P(u)w}$) for an AEP at the ungaged site, the flood flow estimate for an upstream or downstream gaged ($Q_{P(g)w}$) must first be determined by the at-site analysis (table 7, in back of report) adjusted by the WIE analysis reported in table 13 (in back of report). Streamgages in Rhode Island with short records not included in the regional analysis are listed in table 14, but most should not be used because they have drainage areas outside the applicable limits of the regional regression equations. The weighted estimate for the ungaged site ($Q_{P(u)w}$) on a gaged stream is then computed as follows:

$$Q_{P(u)w} = \left[\left(\frac{2\Delta DA}{DA_g}\right) + \left(1 - \frac{2\Delta DA}{DA_g}\right)\left(\frac{Q_{P(g)w}}{Q_{P(g)r}}\right)\right] Q_{P(u)r}\,, \quad (21)$$

where

$Q_{P(u)w}$ is the flow estimate for the selected P-percent AEP at the ungaged site, in cubic feet per second;

ΔDA is the absolute difference between the drainage areas at the gaged and ungaged sites, in square miles;

DA_g is the drainage area for the gaged site, in square miles;

$Q_{P(g)w}$ is the weighted flow at the streamgage derived from at-site analysis and regional regression equations for the selected P-percent AEP (table 13, in back of report), in cubic feet per second;

$Q_{P(g)r}$ is the flow estimate derived from the applicable regional equations 2–8 for the selected P-percent AEP at the gaged site, in cubic feet per second; and

$Q_{P(u)r}$ is the flow estimate derived from the applicable regional equations 2–8 for the selected P-percent AEP at the ungaged site, in cubic feet per second.

Use of equation 21 gives no weight to the at-site estimate when the drainage area ratio between the gaged and ungaged sites are less than 0.5 or greater than 1.5 and gives increased weight to the at-site estimate as the drainage area ratio approaches 1. The weighting procedure should not be used when hydrologic characteristics abruptly change, such as a large instream impoundment between the sites.

An example application of this procedure is the computation of the weighted 1-percent AEP flow, for a hypothetical site on the Wood River above Hope Valley, RI (01117500) streamgage. For simplicity and comparative purposes, the example assumes the ungaged site is the streamgage at Wood River at Arcadia, RI (01117800). It also should be noted that the Wood River at Arcadia streamgage was not used in the development of the regionalized flood flow equations because of its high correlation with the downstream streamgage at Hope Valley.

1. Obtain the value of $Q_{1\%(g)w}$ for the streamgage in table 13 (in back of report) (= 3,160 ft^3/s)

2. Obtain the ΔDA between the gaged and ungaged sites (=74.53 – 35.14 = 39.39 mi^2)

3. Compute the regional regression ($Q_{1\%(u)r}$) for the ungaged site using equation 6

$$(= 10^{(2.623+(0.852\times\log_{10}(35.14))+(0.792\times\log_{10}(1.35))-(0.941\times\log_{10}(7.84)))}$$

$$= 1{,}590 \text{ ft}^3/\text{s})$$

4. Compute the regional regression ($Q_{1\%(g)r}$) for the gaged site using equation 5 (= 3,200 ft^3/s) and

5. Compute the weighted estimate for the ungaged site ($Q_{1\%(u)w}$) using equation 21

$$\left(\frac{2\times\text{-}39.39}{74.53}+\left(\left(1-\frac{2\times\text{-}39.39}{74.53}\right)\times\frac{3{,}160}{3{,}200}\right)\times 1{,}590\right.$$

$$= 1{,}590 \text{ ft}^3/\text{s}.$$

The adjusted discharge (1,590 ft^3/s) at the “ungaged” site determined by equation 21 is no different than the computed value from the regional regression (1,590 ft^3/s) because the drainage area at the “ungaged” site is under the lower limit of the drainage area ratio (0.47); thus, all the weight is put on regional regression flow value.

A similar, but simpler approach used in StreamStats (an interactive online tool for solving regionalized equations; Ries and others, 2008) is used to adjust flood flows on the basis of the drainage area ratio at the gaged and ungaged sites on the same stream. The weighting procedure should not be applied when the drainage area ratio is less than 0.5 or greater than 1.5 or when hydrologic characteristics abruptly change between the sites. The adjustment method for a site above or below a gaged location in StreamStats goes at least a far back as the Elements of Applied Hydrology (Johnstone and Cross, 1949):

$$Q_{P(u)w} = \left(\frac{DA_u}{DA_g}\right)^b Q_{P(g)w}\,, \qquad (22)$$

where

- $Q_{P(u)w}$ is the flow estimate for the selected P-percent AEP at the ungaged site, in cubic feet per second;
- DA_u is the drainage area at the ungaged site, in square miles;
- DA_g is the drainage area at the streamgage, in square miles;
- $Q_{P(g)w}$ is the weighted flow estimate for the selected P-percent AEP at the ungaged site, in cubic feet per second; and
- b is the exponent of drainage area from the appropriate regression equations.

Exponents from regional flood flow equations derived from WREG using a GLS analysis of drainage area range from 0.76 to 0.80 (table 16). The average exponent *b* over the range of exceedance probabilities (0.78 in this study) is used by some in equation 22 to obtain a weighted estimate of a flood flow at an ungaged site on a gaged stream for any exceedance probability flood. Solving equation 22 for Wood River at Arcadia (the “ungaged” site) yields a discharge of 1,770 ft^3/s (= [35.14/74.53]$^{0.77}$ × 3,160) for the 1-percent AEP flow. The adjusted 1-percent AEP flow is about 11 percent larger than the computed magnitude from the regional regression equation (1,590 ft^3/s) and about 8 percent larger than the weighted at-site flood magnitude (1,640 ft^3/s).

Table 16. Regional exponent for drainage area adjustment of a flood flows at an ungaged site on gaged stream determined from the regional regression of drainage area.

[Note, the constant is not used in the drainage area ratio adjustment but could be used to estimate flood flows at ungaged site from drainage area only]

Percent annual exceedance probability	Exponent *b*	Constant
20	0.81	1.76
10	0.80	1.88
4	0.79	2.04
2	0.78	2.14
1	0.77	2.23
0.5	0.77	2.32
0.2	0.76	2.42

In some instances, equation 21 can produce flows that do not increase in the downstream direction when the change in drainage area is small and the change in basin storage is large. This is because, in the underlying regional regression used in equation 21 (equations 2–8), basin storage (StorNHD) is a negative term, which causes the flood quantile to decrease as StorNHD increases. Although, this can be true, some applications require flows increase in the downstream direction and care should be taken to ensure the desired result. A hybrid of equations 21 and 22 presented by Guimaraes and Bohman (1992) and Stamey and Hess (1993) can be used to ensure increasing flow in the downstream direction:

$$Q_{P(u)w} = \left[\left(\frac{2\Delta DA}{DA_g} \right) Q_{P(u)r} + \left(1 - \frac{2\Delta DA}{DA_g} \right) \left(\frac{DA_u}{DA_g} \right)^b Q_{P(g)w} \right]. \quad (23)$$

Similar to the other methods, this method only applies when the ungaged site is within 0.5 and 1.5 times the drainage area of the streamgage and there is no major change in basin characteristics between sites. Using the same example as before, equation 23 yields an adjusted discharge of 1,580 ft^3/s, which is about 4 percent less than the WIE flow (1,640 ft^3/s) at Wood River at Arcadia, RI (01117800) determined from the at-site analysis weighted by the regional regression equation (table 13, in back of report).

A spreadsheet for solving the flood flows for a given exceedance probability on a stream above or below a gaged location by these methods can be accessed through a hyperlink in appendix 3. The equation 21 requires user specified drainage area at the gaged and ungaged sites, regional regression estimated flood magnitudes for the ungaged and gaged sites for a given exceedance probability, and flood magnitude determined from the streamgage analysis for the same exceedance probability. Equation 23 is solved simultaneously with equation 21, but does not require the regional regression estimated flood magnitude at the streamgage. The drainage area ratio method (equation 22) only requires user specified drainage areas at the gaged site and flood magnitude determined from the streamgage analysis for a given exceedance probability at the gaged site. In this test example, the “ungaged” site, which is actually a long-term streamgage, the more complex method (equation 23) was marginally closer to the at-site flood flow estimate than the simpler method (equation 22).

For an ungaged site that is between two gaged sites on the same stream, two flow estimates can be made using the methods and criteria outlined above, but additional hydrologic judgment may be necessary to determine which method and estimates (or some interpolation thereof) are most appropriate. Only a few rivers in Rhode Island have multiple gages to apply multiple adjusted estimates of flood flows at an ungaged site on a gaged stream, such as Pawcatuck River between Westerly and Wood River Junction and Wood River between Hope Valley and Arcadia. Other factors that should be considered when evaluating the two estimates include differences in the length of record for the two streamgages and the quality of the peak flow record.

Comparison with a Previous Rhode Island Flood Study

With the development of updated at-site flood statistics and regional regression relations, a question that arises is how have results changed between previous and updated analyses. Comparisons were made for flood magnitudes at the 10-, 1-, and 0.2-percent exceedance probabilities using the 18 Rhode Island streamgages in this study (table 7, in back of report), 10 of which had been used in the previous study by Johnson and Laraway (1977), which was intended for use in small drainage basins (less than about 10 mi^2) and for frequent floods (the data used in that study only spanned 6 years of record from 1966–71). Regression equations had been developed for 50- and 20-percent AEP floods and were then extrapolated to 10-, 4-, and 2-percent AEP floods using factors presented by Green (1964). Further extrapolations were made to a 1-percent AEP flood when the equations were incorporated into the NFF program (Jennings and others, 1994) and to a 0.2-percent AEP flood when NFF was replaced by the National Streamflow Statistics (NSS) program (Ries and Crouse, 2002).

Comparisons were made between the flood magnitudes obtained from the at-site analyses determined from the weighted skew coefficient and the regional regression equations in this report. A second comparison was made between the at-site flows and those calculated from the previous Rhode Island flood flow equations, and a third comparison was made between the updated and previous flood flow equations. The distribution of the differences between the at-site analyses, the updated equations, and the previous regional equations are shown by boxplots in figure 19.

Positive differences indicate that the updated regression equation results are greater than the at-site results or previous regression equation results; negative percentage differences indicate that the updated regression equation results are smaller than the at-site results or previous regression equation results. Most notable is that the median difference in values between the updated regional equation and the at-site analyses

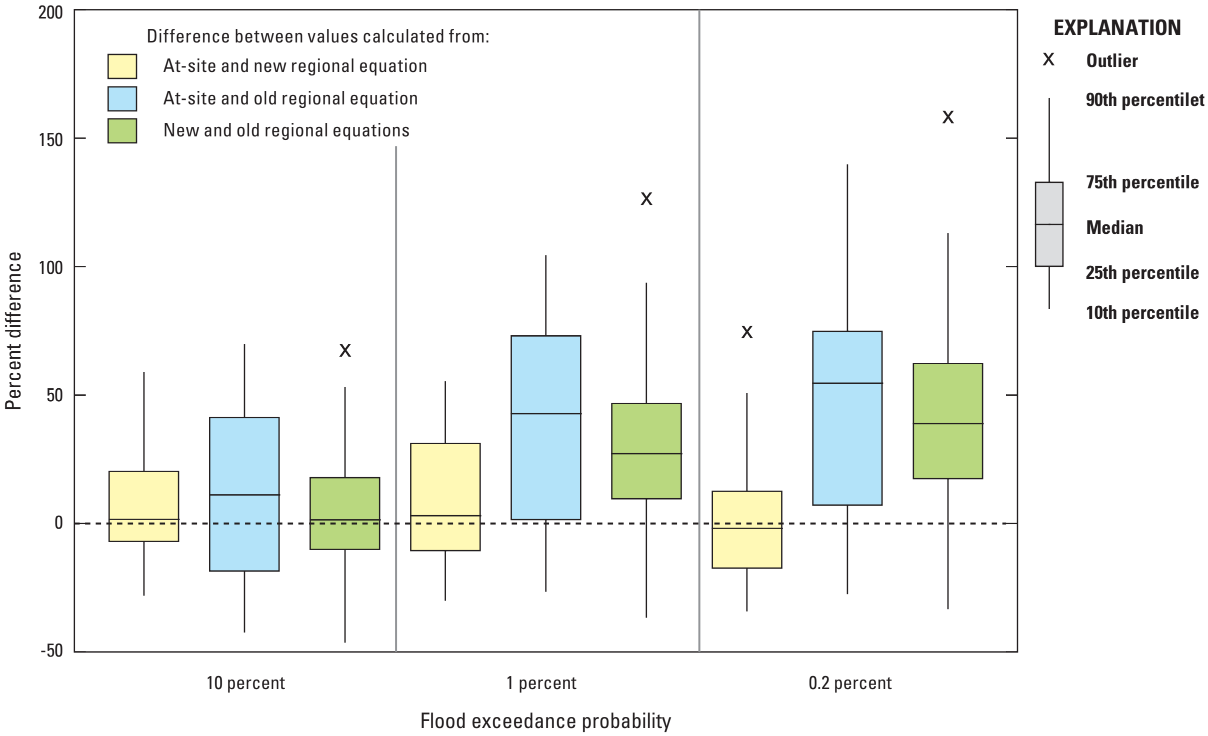

Figure 19. Differences from at-site analyses and regional regression equations in this study and regression equations from previous study by Johnson and Laraway (1977) for 18 streamgages in Rhode Island (table 7) for 10-, 1-, and 0.2-percent annual exceedance probability floods.

are near zero, whereas the median difference between the previous regional equation and the at-site analyses are appreciably higher than zero. Hence, the previous equations generally produce larger flows than the updated equations, particularly as the exceedance probability decreases, underscoring the limitation of how the previous regression equations were developed. At the 1- and 0.2-percent AEP, the median differences between the at-site analyses and previous flood equations are about 43 and 55 percent, respectively, and the lower quartile is above the zero line. Generally, the large differences between the updated and previous flood flow equations can be explained by the additional record used in the analyses and the disproportional number of the highest peaks in the years following the end of the record used in the previous study. These differences highlight the need to periodically update flood flow statistics and regional regression equations.

Annual Exceedance Probability of the 2010 Flood in Rhode Island

One of the purposes of this study was to determine the annual exceedance probability of the 2010 flood in Rhode Island. Of the 21 active streamgages in Rhode Island in 2010, 18 set new record peak flows (table 17) with AEPs ranging from 2 to 0.2 percent (50- to 500-year return interval, respectively). Most 2010 peak flows were between a 0.5- and 0.2-percent AEP except for streamgages in the Blackstone River Basin, which lie in the northern part of Rhode Island and in Massachusetts and did not set new record peak flows during the 2010 flood; the AEP of the peak flows at these streamgages ranged from 4 and 2 percent (25- to 50-year return interval, respectively).

Table 17. March–April 2010 flood peak and annual exceedance probability at active streamgages in Rhode Island.

[Values in **bold** typeface indicate new peak of record. AEP, annual exceedance probability determined from weighted estimates in table 7. ft^3/s, cubic feet per second; %, percent; R, river; Ave., Avenue; Rd., Road; RI, Rhode Island; nr, near; --, not determined]

U.S. Geological Survey streamgage		Start of record	2010 Flood peak				Previous record peak	
Number	Name		Date	Gage height, (feet)	Discharge (ft^3/s)	AEP (%)	Discharge (ft^3/s)	Date
Ten Mile River Basin								
01109403	Ten Mile R, Pawtucket Ave. at East Providence, RI	1986	03/31/2010	**10.79**	**2,600**	1	2,190	10/16/2005
Blackstone River Basin								
01111300	Nipmuc River near Harrisville, RI	1964	03/30/2010	8.29	1,800	2	1,870	10/15/2005
01111500	Branch River at Forestdale, RI	1940	03/31/2010	12.05	5,260	4	6,290	10/15/2005
01112500	Blackstone River at Woonsocket, RI	1929	03/31/2010	14.50	14,900	4	32,900[a]	08/19/1955
Pawtuxet, Woonasquatucket, Moshassuck, and Hunt River Basins								
01114000	Moshassuck River at Providence, RI	1963	03/30/2010	**6.26**	**2,040**	1	1,990	10/15/2005
01114500	Woonasquatucket River at Centerdale, RI	1941	03/30/2010	**9.00**	**1,750**	2	1,530	10/15/2005
01115098	Peeptoad Brook at Elmdale Rd. nr North Scituate, RI	1994	03/30/2010	**2.55**	**249**	4	180	10/20/1996
01115187	Ponaganset River at South Foster, RI	1994	03/14/2010	**6.57**	**1,330**	2	1,110	06/17/2001
01115630	Nooseneck River at Nooseneck, RI	1964[b]	03/30/2010	**5.32**	**1,020**	0.2	762	08/11/2008
01116000	South Branch Pawtuxet River at Washington, RI	1940	03/31/2010	**9.22**	**5,480**	0.2	1,980	06/06/1982
01116500	Pawtuxet River at Cranston, RI	1939	03/31/2010	**20.79**	**14,900**	0.2[c]	5,440	06/07/1982
01117000	Hunt River near East Greenwich, RI	1940	03/30/2010	**5.61**	**2,380**	0.2	1,680	10/15/2005
Pawcatuck River Basin								
01117350	Chipuxet River at West Kingston, RI	1973	03/31/2010	**9.78**	**748**	0.2	306	10/16/2005
01117370	Queen River at Liberty Rd. at Liberty, RI	1998	03/30/2010	**8.44**	**1,830**	0.2[c]	713	10/15/2005
01117420	Usquepaug River near Usquepaug, RI	1976	03/31/2010	**11.16**	**2,070**	0.5	1,060	06/06/1982
01117430	Pawcatuck River at Kenyon, RI	2002	04/01/2010	**7.21**	**2,510**	--	885	04/17/2007
01117468	Beaver River near Usquepaug, RI	1974	03/30/2010	**6.41**	**901**	0.2	329	06/06/1982
01117500	Pawcatuck River at Wood River Junction, RI	1940	04/01/2010	**11.16**	**3,490**	0.2	1,860	06/07/1982
01117800	Wood River near Arcadia, RI	1964	03/31/2010	**10.56**	**2,650**	0.2	1480	06/06/1982
01118000	Wood River at Hope Valley, RI	1941	03/30/2010	**13.72**	**5,470**	0.2	2,390	06/06/1982
01118500	Pawcatuck River at Westerly, RI	1940	03/30/2010	**15.38**	**10,800**	0.2	7,070	06/06/1982

[a]Previously coded as a dam break, but recent inspection of the record indicates this had little effect on the peak.

[b]Ended in 1981 and restarted in 2007.

[c]Determined from at-site flood analysis.

Summary and Conclusions

A statewide disaster was declared for Rhode Island by the President on March 30, 2010, following heavy persistent rains from late February through March 2010 that caused severe flooding and set, or nearly set, record streamflows and water levels at many long-term streamgages in the state. Following floods of this severity, updating and documenting the magnitude of annual exceedance probability (AEP) floods is important for flood plain management, transportation infrastructure design, and flood insurance studies to help minimize future flood damages and risks. In August 2010, the U.S. Geological Survey (USGS) entered into an agreement with the Federal Emergency Management Agency to document and characterize the March–April 2010 flood. As part of that agreement, a study was conducted to estimate the magnitude of flood flows at selected AEPs at streamgages in Rhode Island and to develop statewide regional equations for estimating flood flows at ungaged locations.

To better represent the Rhode Island region, the magnitude of floods were determined at 43 streamgages including 20 in Rhode Island, 14 in eastern Connecticut, and 9 in southeastern and south central Massachusetts. At-site analyses were made using the standard Bulletin 17B (Interagency Committee on Water Data, 1981) log-Pearson type III (B17B) methods as implemented in PeakFQ (Flynn and others, 2006) and by the expected moments algorithm (EMA) for 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods. The B17B and EMA methods use the same statistical moments (mean, standard deviation, and skew) of the logs of the annual peak flows to fit the data to a log-Pearson type III probability distribution. The difference is that the B17B method fits the data point values, whereas the EMA method uses point and interval data to better utilize available information. The inverse of the AEP is an approximation of the recurrence interval of a flood, which for the AEPs listed are 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return intervals, respectively.

The at-site AEP flood magnitudes were computed using a weighted skew determined from the average skews at 40 streamgages. Annual peak flow records were extended at 22 of the 40 streamgages using the maintenance of variance extension (MOVE) procedure to best represent the generalized skew for the region by incorporating the largest number of streamgages and longest period possible. After adjustments for low outliers, historic data, and uncertainties in the annual peak flows, an average skew of 0.52 was determined for the region with a root mean square error of 0.46. At 18 long-term streamgages used in the skew analysis, high outliers were detected (annual peaks that far exceed other annual peaks) that were caused by four large independent events. Skews at these 18 streamgages averaged 0.93 and were 79 percent larger than the average skew determined from the 40 streamgages. It could be argued that because the high outliers are caused by independent events, the higher average skew values are more representative of the regional long-term population distribution. A change in the regional skew from 0.52 to 0.93 resulted in an average increase in the magnitude of 1- and 0.2-percent AEP floods by about 7 and 13 percent, respectively, but had progressively less effect on successively higher probability floods (more frequent floods).

Flood magnitudes were reported at selected AEPs at 43 streamgages, which included three additional streamgages in Rhode Island that were not used in the regional skew analysis because of regulation, an atypical large negative skew, and redundancy with a longer term downstream gage. In addition to flood flow estimates for selected AEPs, the magnitude of the 95-percent confidence interval was determined at each streamgage. The confidence interval determined by the EMA is considered more robust and a more accurate measure of the possible flood magnitudes for a given AEP than those determined by the standard B17B method. Regression equations to estimate magnitude of floods at selected AEPs at ungaged sites were developed from 41 of these streamgages; two of the three additional streamgages in Rhode Island were not used in the regional regression equation development because of regulation or redundancy.

Regional regression equations were developed to estimate magnitude of floods at selected AEPs at ungaged sites from at-site flood quantiles and their respective basin characteristics. A total of 55 basin characteristics were evaluated as potential explanatory variables in the regression; however, only three characteristics were statistically significant—drainage area (DA) in square miles, stream density (STRDEN) in miles per square mile, and basin storage (StorNHD) in percent. Stream density and storage were derived from the 1:24:000 National Hydrography Dataset (NHD). Storage is the total area of wetlands and water over the basin. All values used in the regression were transformed to base 10 logarithms. The final regression equations were developed using the USGS Weighted Multiple Linear Regression (WREG) program determined by the Generalized Least Squares (GLS) method, which is considered the most applicable for regional analysis because it accounts for streamgage record lengths and correlation between streamgages. The pseudo coefficient of determination (pseudo R^2) indicates that the explanatory variables explain 95 to 96 percent of the variance in the flood magnitude from 20- to 0.2-percent AEPs at the 41 streamgages used to develop the regression equations. Flood flows at the 95-percent confidence level for each exceedance probability derived from the regional regression equation model error variance and the covariance matrix are also reported.

Flood flow estimates for a given AEP at gaged sites, particularly at sites with short records, can be improved by a weighted average of two independent estimates of the at-site analysis and the regional regression equations. The weighted estimate is based on the magnitude of the flood and uncertainty associated with each estimate. Differences between the magnitude of floods determined from the at-site estimate and the weighted estimate ranged from -44 to 28 percent; a positive value indicates the weighted estimate is greater than the at-site estimate, and conversely, a negative value indicates the weighted estimate is smaller than the at-site estimate.

The progressive increase in difference with decreasing flood probability is attributed to the greater uncertainty of the flood magnitude as the exceedance probability decreases. Estimates of flood flows on a stream above or below a gaged location, within limits, also can be improved by combining the streamgage information with the regional regression equation. A weighting procedure is applicable when the ungaged to gaged drainage area ratio is between 0.5 and 1.5 and hydrologic characteristics of the basin do not abruptly change.

Effects of urbanization on flood flows also were examined because impervious cover is generally considered an important factor, and this region has a long history of urban development. The imperviousness of the streamgage basins used in the regression analysis ranged from 0.5 to 37 percent with a mean of 5.2 percent, and although imperviousness provided some explanatory power in the regression, it was not statistically significant at the 95-percent confidence level for any of the exceedance probabilities examined. Stratified datasets indicated a linear relation for 20-percent AEP floods that increase with increasing imperviousness, but only for basins underlain by 40 percent or more sand and gravel. The magnitude of the 20-percent AEP flood flow appears to be unrelated to imperviousness for basins underlain by less than 20 percent sand and gravel. For flood flows with lower AEPs, the relation between surficial deposits and imperviousness progressively weakened. This result is confirmed by analysis of three long-term streamgages in close proximity to each other with similar characteristics except for the percentage of imperviousness. Although regional flood studies in other areas of the country have found urbanization to be an important factor, results from this study indicate a complex interaction with other characteristics that confounds a statistical portrayal of urban effects on flood flows. Further research is needed in this area, particularly for small, highly developed basins where little data exist.

Standard methods for calculating the magnitude of floods for given exceedance probabilities are based on the assumption of stationarity, that is, annual peak flows exhibit no significant trend over time. A subset of 16 streamgages with 70 or more years of unregulated systematic record indicates all but 4 have a statistically significant positive trend at the 95-percent confidence level; three streamgages had a significant positive trend between the about 90- and 95-percent confidence level. The Theil slope of the 15 streamgages with statistical significance ranged from 3.2 to 28 percent with a median slope of 11 percent. If this trend continued linearly in time, then the magnitude of a flood with a given exceedance probability, on average, would be 6, 13, and 21 percent greater in 10, 20, and 30 years, respectively. Trends and their effects can only be ascertained by continued monitoring of streamflow and the continued development of the science of nonstationarity in flood frequency analysis.

One of the purposes of updating the flood frequency information for Rhode Island was to assess the AEP of the 2010 flood. Of the 21 active streamgages in Rhode Island in 2010, 18 set new record peaks with AEPs ranging from 2 and 0.2 percent (50- to 500-year return interval, respectively). Most 2010 peak flows were between a 0.5- and 0.2-percent AEP except for streamgages in the Blackstone River Basin, which ranged between a 4- and 2-percent AEP.

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Glossary

adjusted r-squared (adj-R^2) The adjusted coefficient of determination (adj-R^2), a measure of the percentage of the variation explained by the explanatory variables of the equation adjusted for the number of parameters in the equation.

annual exceedance probability (AEP) The expected annual probability of a flood, previously referred to in terms of return period of a flood. The probability, often expressed as a decimal fraction less than 1.0, that an annual peak discharge will be exceeded in a 1-year period. The reciprocal of the exceedance probability is referred to as the recurrence interval or return period in years.

annual peak The maximum instantaneous discharge occurring during a water year.

average standard error of prediction The square root of the average spread or dispersion of the predicted value from the observed mean.

average variance of prediction (AVP) The average spread or dispersion of the predicted value from the observed mean.

confidence interval The range of an estimated parameter value in which the true value lies for a specified probability (95-percent confidence level, α = 5 percent, is generally used throughout this report).

covariance A measure of how much two random variables change together. Positive values indicate variables tend to show similar behavior, whereas negative values indicate the greater value of one variable correspond to the smaller value of the other variable. In multiple variable regression, covariance is expressed in matrix form sized according to the number of variables in the regression.

expected moments algorithm (EMA) Method for fitting a probability distribution to annual peak discharge data using a generalized method of moments, similar to the standard log-Pearson type III (LPIII) method described in Bulletin 17B (Interagency Advisory Committee on Water Data, 1981), except the expected moments algorithm (EMA) can also use interval data, whereas LPIII is restricted to point data. Interval data provide additional information that cannot be represented by point data, such as the potential range of annual peak flows outside of the systematic and historic record and the uncertainties around recorded peaks used in the analysis.

generalized least squares (GLS) A regression method that accounts for differences in the variances and cross correlations of the errors associated with different recorded discharges; known as GLS. Differences in variances can result from differences in the length of record for each site, whereas cross correlations among concurrent annual peak discharges results in cross correlation between estimated flood statistics, such as quantiles and skew coefficients.

historic flood Magnitude of a flood recorded, or estimated, outside the systematic period of record.

log-Pearson type III (LPIII) A frequency distribution determined from the statistical moments of the annual peak flow mean, standard deviation, and skew.

maintenance of variation extension (MOVE) A linear regression technique used for filling in missing streamflow data measurements or producing a unique extended streamflow sequence that maintains the mean and variance for the sample.

Mallow's C_p An estimate of the standardized mean square error of prediction; this is a compromise between maximizing the explained variance by including all relevant variables and minimizing the standard error by keeping the number of variables as small as possible.

mean square error (MSE) The average of the squares of the differences between the estimated values and the measured values. This metric represents how closely, on average, an estimated value matches a measured value.

multicolinearity A statistical phenomenon in which two or more predictor variables in a multiple regression model are highly correlated, in which case the regression coefficients may change erratically in response to small changes in the model or the data.

ordinary least squares (OLS) Linear regression method is standard approach to the "least squares" solution of fitting and independent variable to one or more dependent variables.

outlier A data point that departs from the trend of the rest of a dataset as described by a distribution or other mathematical relationship.

100-year flood An annual peak discharge having an average recurrence interval of 100 years, corresponding to an annual exceedance probability of 1 percent.

predicted residual sum of squares (PRESS) A validation type estimator of error. Predicted residual sum of squares (PRESS) uses *n*-1 observations to develop the equation and then estimates the value of the observation that was left out. The process is repeated for each observation, and the prediction errors are squared and summed.

pseudo-R-squared (pseudo-R^2) A statistic generated by GLS regression, the pseudo coefficient of determination (pseudo-R^2) is similar to the adj-R^2 in that it is a measure of the predictive strength of the regression model except that it removes the time sampling error.

root mean square error (RMSE) The square root of the sum of the squares of the differences between estimated and the measured values divided by the number of observations minus one. This metric represents the magnitude of the differences between the estimated and measured values. Of particular concern in this report is the root mean square error (RMSE) of the regional skew estimate.

skew (γ) A statistical measure of the data symmetry or lack thereof used to compute the flood frequency distribution. The skew generally is computed from the logarithms of annual peak discharges at the streamgage. Because the skew is sensitive to outliers, it may be an unreliable estimate of the true skew, especially for small samples; Bulletin 17B (Interagency Committee on Water Data, 1981) recommends that the skew is weighted with a regional, or generalized, skew that is based on data from many long-term streamgages to produce at-site flood frequency estimates.

standard error of estimate (SE) Also referred to as the root mean squared error of the residuals, it is the standard deviation of observed values about the regression line. It is computed by dividing the unexplained variation or the error sum of squares by its degrees of freedom. In this study, the standard error is based on one standard deviation.

variance A measure of the spread or dispersion of a set of values around their mean calculated by the mean of the squares of the deviation of the value from the mean, which is equal to the square of the standard deviation.

variance inflation factor (VIF) Expresses the ratio of the actual variance of the coefficient of the explanatory variable to its variance if it were independent of the explanatory variables. A variance inflation factor greater than 5 to 10 generally indicates multicolinearity, a serious problem in the regression models.

variance of prediction (VP) A measure of the likely difference between the prediction provided by a regression model and the actual value of the variable.

weighted independent estimator (WIE) A software program that weights two independent estimates inversely proportional to the uncertainty of the individual estimates.

weighted least squares (WLS) A regression method that accounts for the variation in the errors caused by unequal record lengths at streamgages used to estimate the flood characteristics of interest. Weighted least squares regression incorporates weights associated with each data point into the fitting criterion. The size of the weights corresponds to the precision of the information contained in the record.

Tables 7, 13, and 15

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.

[AEP, annual exceedance probability, in percent. Period of record analysis, the systematic record and historic peaks if present. Extended record analysis, includes the period of record plus records estimated by maintenance of variance extension (MOVE). Length of record used in the analysis is shown below each streamgage. B17B, flood frequency analysis made using Bulletin 17B (Interagency Committee on Water Data, 1981) guidelines. EMA, expected moments algorithm; the EMA analysis is for the period of record for stations were the record is not extended. Values in **bold** typeface are values used in the regional analysis. All values are in cubic feet per second (ft³/s). All values except for the systematic peak were computed from a weighted skew of 0.52 and root mean square error of 0.46. %, percent; --, station record was not extended; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence Lower	95% confidence Upper		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Rhode Island streamgages											
Adamville Brook at Adamville, RI (01106000)											
		1941–1978, 1987[a]									
20	5	220	200	250	220	--	--	--	**220**	190	250
10	10	260	230	300	250	--	--	--	**250**	220	300
4	25	310	270	370	290	--	--	--	**300**	250	390
2	50	340	290	420	310	--	--	--	**330**	280	480
1	100	380	320	470	330	--	--	--	**360**	300	580
0.5	200	410	340	520	340	--	--	--	**400**	320	700
0.2	500	450	380	590	360	--	--	--	**440**	340	900
[a]EMA analysis detected and conditioned six low ouliers.											
Beaver River near Usquepaug, RI (01117468)											
		1976–2010			1942–2010[a,b]						
20	5	230	190	290	230	**190**	170	210	190	160	230
10	10	320	260	410	320	**250**	220	300	250	210	340
4	25	460	360	650	470	**350**	300	430	350	280	580
2	50	590	450	880	610	**450**	370	570	450	330	880
1	100	750	550	1,200	790	**560**	460	740	560	400	1,320
0.5	200	950	670	1,600	1,000	**700**	560	950	700	470	2,010
0.2	500	1,300	850	2,240	1,370	**930**	710	1,310	920	570	3,500
[a]Actual records 1942–1975 extended using Wood River at Hope Valley, RI (01118000).											
[b]Error of ±6% assigned to 1968 peak for EMA analysis.											
Blackstone River at Woonsocket, RI (01112500)											
		1929–2010									
20	5	**9,160**	8,290	10,300	9,180	--	--	--	9,160	8,030	10,800
10	10	**11,800**	10,500	13,600	11,800	--	--	--	11,800	10,100	14,900
4	25	**15,800**	13,800	18,800	15,700	--	--	--	15,800	13,000	22,300
2	50	**19,300**	16,400	23,500	19,100	--	--	--	19,300	15,300	30,200
1	100	**23,100**	19,400	28,900	22,800	--	--	--	23,100	17,700	40,600
0.5	200	**27,500**	22,700	35,100	27,100	--	--	--	27,500	20,200	54,400
0.2	500	**34,200**	27,500	44,900	33,400	--	--	--	34,200	23,700	79,600
Branch River at Forestdale, RI (01111500)											
		1940–2010 (1936 Historic peak)									
20	5	**2,890**	2,560	3,320	2,830	--	--	--	2,820	2,430	3,400
10	10	**3,800**	3,310	4,490	3,670	--	--	--	3,680	3,100	4,730
4	25	**5,160**	4,380	6,330	4,880	--	--	--	4,960	4,010	7,180
2	50	**6,320**	5,260	7,980	5,880	--	--	--	6,040	4,720	9,740
1	100	**7,630**	6,230	9,900	6,990	--	--	--	7,250	5,450	13,100
0.5	200	**9,100**	7,290	12,100	8,200	--	--	--	8,600	6,200	17,500
0.2	500	**11,300**	8,860	15,600	9,990	--	--	--	10,600	7,240	25,500

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence			Peak flow estimate	95% confidence		Peak flow estimate	95% confidence	
			Lower	Upper			Lower	Upper		Lower	Upper
Rhode Island streamgages—Continued											
Chepachet River at Chepachet, RI (01111400)											
		1965–1975			1940–2010[a]						
20	5	--	--	--	520	**520**	470	600	520	450	630
10	10	--	--	--	680	**680**	600	800	680	570	880
4	25	--	--	--	910	**920**	780	1,120	920	740	1,340
2	50	--	--	--	1,100	**1,120**	940	1,400	1,120	870	1,820
1	100	--	--	--	1,310	**1,350**	1,110	1,730	1,350	1,010	2,470
0.5	200	--	--	--	1,540	**1,600**	1,290	2,110	1,600	1,150	3,340
0.2	500	--	--	--	1,900	**1,990**	1,570	2,710	1,990	1,350	4,920
[a]Actual records 1965–75 extended using Branch River at Forestdale, RI (01111500).											
Chipuxet River at West Kingston, RI (01117350)											
		1974–2010			1941–2010[a,b]						
20	5	180	160	220	150	**140**	130	160	140	120	180
10	10	250	210	320	200	**190**	170	230	190	160	270
4	25	360	290	490	280	**270**	230	330	270	210	460
2	50	460	360	670	360	**350**	290	440	350	260	700
1	100	580	440	890	450	**440**	360	570	440	310	1,080
0.5	200	730	530	1,170	560	**550**	430	740	550	360	1,660
0.2	500	980	680	1,670	750	**730**	560	1,030	730	450	2,980
[a]Actual records 1974–2010 extended using Hunt River at East Greenwich, RI (01117000).											
[b]Error of ±8% assigned to 1968 and 1970 peaks for EMA analysis.											
Hunt River near East Greenwich, RI (01117000)											
		1941–2010									
20	5	**610**	550	690	610	--	--	--	610	530	750
10	10	**810**	710	940	810	--	--	--	810	680	1,080
4	25	**1,110**	957	1,350	1,140	--	--	--	1,110	880	1,780
2	50	**1,390**	1,170	1,740	1,450	--	--	--	1,390	1,060	2,610
1	100	**1,720**	1,420	2,220	1,820	--	--	--	1,720	1,240	3,850
0.5	200	**2,120**	1,700	2,810	2,280	--	--	--	2,120	1,450	5,710
0.2	500	**2,750**	2,140	3,800	3,040	--	--	--	2,750	1,750	9,620
[a]Set high threshold (1,748 ft^3/s) to reflect that 1938 peak was large but less than 2010 peak (2,380 ft^3/s), 1938 stage only and reflects storm surge.											
Moshassuck River at Providence, RI (01114000)											
		1964–2010			1942–2010[a]						
20	5	1,210	1,120	1,320	1,140	**1,120**	1,050	1,220	1,130	1,030	1,260
10	10	1,400	1,290	1,560	1,320	**1,320**	1,220	1,450	1,320	1,190	1,540
4	25	1,660	1,500	1,910	1,540	**1,570**	1,430	1,770	1,580	1,390	1,970
2	50	1,870	1,660	2,190	1,690	**1,770**	1,590	2,030	1,770	1,530	2,360
1	100	2,090	1,830	2,500	1,840	**1,980**	1,750	2,300	1,970	1,660	2,800
0.5	200	2,320	2,000	2,820	1,990	**2,190**	1,920	2,590	2,180	1,790	3,320
0.2	500	2,640	2,240	3,300	2,180	**2,490**	2,150	3,000	2,460	1,960	4,130
[a]Actual records 1964–2010 extended using Woonasquatucket River at Centerdale, RI (01114500).											
Nipmuc River near Harrisville, RI (01111300)											
		1965–2010			1940–2010[a,b]						
20	5	880	740	1,100	730	**730**	640	850	730	620	900
10	10	1,200	980	1,520	980	**990**	850	1,180	990	810	1,310
4	25	1,640	1,300	2,210	1,360	**1,380**	1,150	1,720	1,380	1,080	2,100
2	50	2,020	1,570	2,840	1,680	**1,720**	1,410	2,220	1,720	1,300	2,980
1	100	2,450	1,860	3,580	2,050	**2,120**	1,700	2,820	2,120	1,530	4,190
0.5	200	2,930	2,170	4,430	2,470	**2,580**	2,020	3,530	2,580	1,780	5,850
0.2	500	3,650	2,630	5,760	3,100	**3,290**	2,510	4,660	3,280	2,120	9,020
[a]Actual records 1965–2010 extended using Branch River at Forestdale, RI (01111500).											
[b]Error of ±5% assigned to 1954 and 1955 peaks for EMA analysis.											

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence			Peak flow estimate	95% confidence		Peak flow estimate	95% confidence	
			Lower	Upper			Lower	Upper		Lower	Upper
Rhode Island streamgages—Continued											
Nooseneck River at Nooseneck, RI (01115630)											
		1965–1975				1942–2010[a,b]					
20	5	430	340	590	330	**330**	290	370	330	280	400
10	10	600	450	880	430	**430**	380	500	430	360	560
4	25	860	620	1,400	580	**580**	500	710	580	470	890
2	50	1,100	760	1,930	720	**720**	600	910	720	550	1,260
1	100	1,380	920	2,600	880	**880**	720	1,140	880	650	1,780
0.5	200	1,710	1,100	3,450	1,070	**1,060**	850	1,420	1,060	750	2,500
0.2	500	2,240	1,380	4,920	1,350	**1,350**	1,050	1,860	1,350	890	3,930
[a]Actual record 1965–75 extended using Wood River at Hope Valley, RI (01118000).											
[b]Error of ±16% assigned to 1982 peak.											
Pawtuxet River at Cranston, RI (01116500)											
		1940–2010[a]									
20	5	2,830	2,570	3,170	2,830	--	--	--	2,900	2,400	3,420
10	10	3,740	3,330	4,300	3,740	--	--	--	3,840	3,220	4,840
4	25	5,230	4,520	6,290	5,230	--	--	--	5,420	4,330	8,340
2	50	6,640	5,600	8,260	6,640	--	--	--	6,940	5,290	14,100
1	100	8,370	6,880	10,800	8,370	--	--	--	8,820	6,370	24,000
0.5	200	10,500	8,400	13,900	10,500	--	--	--	11,100	7,590	38,200
0.2	500	14,000	10,800	19,400	14,000	--	--	--	15,000	9,450	70,700
[a]Station skew is used because of upstream regulation; historical peaks of 1886 and 1938 are included in analysis. Streamgage not used in regionalization analysis because of upstream regulation by Scituate Reservoir.											
Pawcatuck River at Westerly, RI (01118500)											
		1941–2010 (Historical peaks 1927 and 1936[b])									
20	5	**3,300**	3,040	3,620	3,310	--	--	--	3,400	3,030	3,940
10	10	**4,080**	3,710	4,570	4,160	--	--	--	4,230	3,680	5,200
4	25	**5,230**	4,650	6,060	5,480	--	--	--	5,460	4,560	7,550
2	50	**6,220**	5,440	7,390	6,680	--	--	--	6,530	5,260	10,100
1	100	**7,340**	6,310	8,930	8,070	--	--	--	7,730	6,000	13,500
0.5	200	**8,610**	7,270	10,700	9,700	--	--	--	9,100	6,790	18,100
0.2	500	**10,600**	8,700	13,600	12,300	--	--	--	11,200	7,910	26,700
[a]Set high threshold (7,625 ft^3/s) above 1936 historical peak (3,150 ft^3/s) to reflect that 1938 peak was likely larger.											
Pawcatuck River at Wood River Junction, RI (01117500)											
		1941–2010									
20	5	**1,030**	950	1,140	1,020	--	--	--	1,030	910	1,210
10	10	**1,280**	1,160	1,450	1,290	--	--	--	1,280	1,110	1,620
4	25	**1,660**	1,470	1,940	1,690	--	--	--	1,660	1,380	2,420
2	50	**1,990**	1,730	2,380	2,050	--	--	--	1,990	1,590	3,300
1	100	**2,370**	2,020	2,900	2,470	--	--	--	2,370	1,820	4,510
0.5	200	**2,790**	2,340	3,510	2,950	--	--	--	2,790	2,060	6,190
0.2	500	**3,440**	2,810	4,470	3,720	--	--	--	3,440	2,400	9,410
Ponaganset River at South Foster, RI (01115187)[a]											
		1995–2010				1940–2010[a,b]					
20	5	940	750	1,280	760	**760**	680	860	760	660	890
10	10	1,200	940	1,770	960	**960**	850	1,120	960	820	1,200
4	25	1,580	1,180	2,550	1,230	**1,260**	1,080	1,510	1,260	1,040	1,740
2	50	1,890	1,370	3,260	1,460	**1,500**	1,270	1,850	1,500	1,200	2,280
1	100	2,220	1,560	4,100	1,690	**1,760**	1,470	2,220	1,770	1,370	2,960
0.5	200	2,590	1,770	5,080	1,940	**2,050**	1,680	2,640	2,050	1,530	3,820
0.2	500	3,130	2,050	6,620	2,300	**2,470**	1,990	3,280	2,480	1,760	5,290
[a]Actual records 1995-2010 extended using Branch River at Forestdale, RI (01111500).											
[b]Error of ±5% assigned to 1955, 1968, 1979, and 1982 peak for EMA analysis.											

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence Lower	95% confidence Upper		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Rhode Island streamgages—Continued											
South Branch Pawtuxet River at Washington, RI (01116000)											
		1941–2010 (Historical peak 1936)									
20	5	**1,090**	970	1,260	1,100	--	--	--	1,120	940	1,380
10	10	**1,470**	1,280	1,740	1,480	--	--	--	1,500	1,240	2,030
4	25	**2,060**	1,740	2,540	2,100	--	--	--	2,130	1,660	3,360
2	50	**2,600**	2,140	3,320	2,660	--	--	--	2,700	2,000	4,930
1	100	**3,230**	2,610	4,260	3,340	--	--	--	3,370	2,380	7,230
0.5	200	**3,980**	3,140	5,410	4,150	--	--	--	4,170	2,800	10,600
0.2	500	**5,170**	3,960	7,310	5,450	--	--	--	5,450	3,410	17,500
[a]Set high threshold (3,568 ft³/s) above 1936 historical peak (1,000 ft³/s) to reflect that 1938 peak was larger but less than 2010 peak (5,480 ft³/s).											
Ten Mile River at Pawtucket Avenue at East Providence, RI (01109403)											
		1987–2010			1926–2010[a,b]						
20	5	1,270	1,060	1,610	1,120	**1,120**	1,020	1,240	1,120	1,000	1,290
10	10	1,640	1,340	2,190	1,400	**1,400**	1,260	1,590	1,400	1,230	1,700
4	25	2,180	1,710	3,140	1,780	**1,800**	1,590	2,100	1,800	1,530	2,390
2	50	2,640	2,010	4,010	2,100	**2,130**	1,860	2,540	2,130	1,750	3,070
1	100	3,160	2,340	5,050	2,430	**2,490**	2,140	3,020	2,490	1,980	3,910
0.5	200	3,740	2,690	6,280	2,790	**2,880**	2,440	3,560	2,880	2,220	4,960
0.2	500	4,620	3,200	8,250	3,320	**3,450**	2,870	4,370	3,460	2,540	6,740
[a]Actual records 1987–2010 extended using Wading River near Norton, MA (01109000). [b]Error of ±3% assigned to 1931, 1936, 1938, 1946, 1954–55, 1968–70, 1978–79, and 1983–84 peaks for EMA analysis.											
Usquepaug River near Usquepaug, RI (01117420)											
		1976–2010			1941–2010[a,b]						
20	5	660	570	800	550	**550**	500	610	550	480	660
10	10	860	720	1,090	710	**710**	630	810	710	600	920
4	25	1,170	950	1,570	960	**950**	820	1,130	950	770	1,450
2	50	1,440	1,140	2,030	1,180	**1,160**	980	1,420	1,170	904	2,040
1	100	1,750	1,340	2,570	1,440	**1,400**	1,170	1,770	1,410	1,050	2,890
0.5	200	2,110	1,570	3,220	1,750	**1,680**	1,380	2,190	1,700	1,200	4,100
0.2	500	2,660	1,910	4,290	2,240	**2,130**	1,690	2,860	2,150	1,430	6,500
[a]Records extended using Pawcatuck River at Wood River Junction, RI (01117500). [b]Error of ±4% assigned to 1968 peak for EMA analysis.											
Wood River near Arcadia, RI (01117800)											
		1964–2010			1942–2010[a]						
20	5	700	610	820	620	620	560	700	620	540	760
10	10	920	790	1,120	820	810	720	940	820	680	1,100
4	25	1,280	1,060	1,640	1,140	1,100	950	1,330	1,120	890	1,800
2	50	1,610	1,300	2,150	1,450	1,370	1,160	1,700	1,400	1,060	2,650
1	100	2,000	1,570	2,780	1,820	1,680	1,390	2,160	1,740	1,250	3,910
0.5	200	2,460	1,880	3,560	2,260	2,050	1,650	2,700	2,120	1,460	5,800
0.2	500	3,200	2,360	4,880	2,990	2,630	2,060	3,600	2,750	1,760	9,780
[a]Actual records for 1964–2010 extended using Wood River at Hope Valley, RI (01118000); includes use of 1936 historical peak. Streamgage not used in regional analysis because of high correlation of annual peaks to downstream streamgage at Hope Valley.											
Wood River at Hope Valley, RI (01118000)											
		1942–2010 (Historical peak 1936[a])									
20	5	**1,310**	1,200	1,450	1,300	--	--	--	1,310	1,160	1,540
10	10	**1,650**	1,490	1,870	1,670	--	--	--	1,650	1,420	2,100
4	25	**2,170**	1,910	2,550	2,250	--	--	--	2,170	1,780	3,170
2	50	**2,630**	2,270	3,180	2,790	--	--	--	2,630	2,080	4,380
1	100	**3,160**	2,670	3,920	3,440	--	--	--	3,160	2,390	6,080
0.5	200	**3,760**	3,120	4,800	4,200	--	--	--	3,760	2,730	8,460
0.2	500	**4,710**	3,810	6,220	5,450	--	--	--	4,700	3,210	13,100
[a]Set high threshold (2,500 ft³/s) above 1936 historical peak (1,540 ft³/s) to reflect that the 1938 peak was likely larger.											

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence			Peak flow estimate	95% confidence		Peak flow estimate	95% confidence	
			Lower	Upper			Lower	Upper		Lower	Upper
Rhode Island streamgages—Continued											
Woonasquatucket River at Centerdale, RI (01114500)											
		1942–2010 (Historical peak 1936[a])									
20	5	**920**	820	1,040	920	--	--	--	910	800	1,060
10	10	**1,150**	1,020	1,340	1,150	--	--	--	1,150	990	1,400
4	25	**1,470**	1,270	1,760	1,440	--	--	--	1,460	1,230	1,940
2	50	**1,720**	1,460	2,110	1,670	--	--	--	1,720	1,400	2,450
1	100	**1,990**	1,670	2,490	1,900	--	--	--	1,980	1,570	3,070
0.5	200	**2,270**	1,880	2,900	2,130	--	--	--	2,270	1,740	3,810
0.2	500	**2,670**	2,170	3,500	2,460	--	--	--	2,670	1,960	5,020
[a]Set high threshold (1,500 ft^3/s) above 1936 historical peak (1,000 ft^3/s) to reflect that the 1938 peak was likely larger.											
Massachusetts streamgages											
Kettle Brook at Worcester, MA (01109500)											
		1924–1980									
20	5	**730**	610	900	720	--	--	--	730	570	1,000
10	10	**1,080**	880	1,400	1,080	--	--	--	1,080	810	1,740
4	25	**1,720**	1,330	2,380	1,730	--	--	--	1,720	1,190	3,580
2	50	**2,350**	1,760	3,430	2,390	--	--	--	2,350	1,540	6,230
1	100	**3,170**	2,300	4,850	3,230	--	--	--	3,170	1,930	10,900
0.5	200	**4,200**	2,940	6,760	4,320	--	--	--	4,200	2,380	19,000
0.2	500	**6,000**	4,020	10,300	6,230	--	--	--	6,000	3,070	39,800
Little River near Oxford, MA (01124500)											
		1940–1958			1913–2010[a]						
20	5	830	600	1,300	670	**700**	630	800	700	600	870
10	10	1,340	920	2,370	1,010	**1,010**	890	1,180	1,010	820	1,400
4	25	2,360	1,480	4,980	1,680	**1,570**	1,330	1,920	1,570	1,190	2,670
2	50	3,510	2,050	8,450	2,460	**2,140**	1,760	2,720	2,140	1,520	4,400
1	100	5,120	2,790	14,000	3,560	**2,890**	2,310	3,810	2,890	1,920	7,280
0.5	200	7,360	3,740	23,000	5,140	**3,860**	3,010	5,280	3,860	2,380	12,100
0.2	500	11,700	5,440	43,200	8,310	**5,610**	4,210	8,040	5,610	3,140	23,900
[a]Records extended 1913–39 and after 1959 using Quaboag River at West Brimfield, MA (01176000). Records after 1959 were extended because of flood control regulation.											
Mumford River at East Douglas, MA (01111000)											
		1939–1951, 1955, 2004–2010			1940–2010						
20	5	680	510	1,000	700	**690**	600	810	690	580	870
10	10	1,000	720	1,640	960	**960**	820	1,170	960	780	1,320
4	25	1,570	1,060	2,980	1,380	**1,390**	1,150	1,770	1,390	1,070	2,250
2	50	2,140	1,360	4,530	1,760	**1,790**	1,440	2,360	1,790	1,310	3,350
1	100	2,880	1,730	6,760	2,210	**2,260**	1,780	3,080	2,260	1,570	4,950
0.5	200	3,810	2,170	9,930	2,740	**2,820**	2,160	3,960	2,820	1,860	7,270
0.2	500	5,440	2,890	16,200	3,580	**3,710**	2,760	5,430	3,710	2,280	12,000
[a]Actual record 1939–51, 2004–10 extended using Branch River at Forestdale, RI (01111500).											
Neponset River at Norwood, MA (01105000)											
		1939–2010									
20	5	**600**	540	670	600	--	--	--	600	520	710
10	10	**770**	680	890	770	--	--	--	770	650	990
4	25	**1,020**	890	1,220	1,020	--	--	--	1,020	830	1,510
2	50	**1,240**	1,060	1,520	1,240	--	--	--	1,240	970	2,080
1	100	**1,490**	1,240	1,870	1,490	--	--	--	1,490	1,120	2,860
0.5	200	**1,770**	1,450	2,280	1,770	--	--	--	1,780	1,280	3,940
0.2	500	**2,200**	1,760	2,930	2,200	--	--	--	2,220	1,510	5,990

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence Lower	95% confidence Upper		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
					Massachusetts streamgages—Continued						
Quaboag River at West Brimfield, MA (01176000)											
						1913–2010					
20	5	**1,870**	1,710	2,060	1,790	--	--	--	1,870	1,640	2,210
10	10	**2,470**	2,230	2,780	2,450	--	--	--	2,470	2,110	3,170
4	25	**3,460**	3,040	4,040	3,660	--	--	--	3,460	2,790	5,210
2	50	**4,390**	3,780	5,270	4,920	--	--	--	4,390	3,370	7,640
1	100	**5,530**	4,660	6,830	6,600	--	--	--	5,530	4,030	11,300
0.5	200	**6,910**	5,710	8,780	8,820	--	--	--	6,910	4,770	16,700
0.2	500	**9,220**	7,400	12,100	12,900	--	--	--	9,220	5,890	28,200
Sevenmile River near Spencer, MA (01175760)											
		1961–2010				1913–2010[a,b]					
20	5	290	250	340	280	**300**	260	330	300	250	370
10	10	360	310	440	420	**420**	370	490	420	340	580
4	25	470	390	580	690	**650**	550	790	650	490	1,100
2	50	550	450	710	990	**880**	730	1,110	880	630	1,790
1	100	640	520	840	1,400	**1,180**	940	1,540	1,180	790	2,930
0.5	200	730	580	990	1,980	**1,560**	1,220	2,120	1,570	980	4,810
0.2	500	860	680	1,200	3,110	**2,240**	1,690	3,180	2,260	1,280	9,340
[a]Actual records 1961–2010 extended using Quaboag River at West Brimfield, MA (01176000).											
[b]Error of ±11% assigned to 1936, 1938, and 1955 peaks for EMA analysis.											
Taunton River near Bridgewater, MA (01108000)											
		1931–76, 85–89, 96, 98–2010				1926–2010[a,b]					
20	5	3,200	2,980	3,470	3,210	**3,160**	2,970	3,400	3,150	2,910	3,460
10	10	3,710	3,420	4,090	3,670	**3,670**	3,420	4,000	3,660	3,350	4,130
4	25	4,350	3,960	4,900	4,210	**4,320**	3,960	4,790	4,300	3,860	5,120
2	50	4,840	4,350	5,530	4,580	**4,800**	4,370	5,400	4,780	4,220	5,960
1	100	5,320	4,740	6,180	4,930	**5,290**	4,770	6,020	5,260	4,550	6,880
0.5	200	5,820	5,140	6,850	5,260	**5,780**	5,170	6,660	5,750	4,870	7,900
0.2	500	6,500	5,660	7,770	5,680	**6,450**	5,700	7,540	6,410	5,270	9,430
[a]Actual record 1931–76, 1985–89, 1996, 1998–2010 extended using Wading River near Norton, MA (01109000).											
[b]Error of ±15% assigned to 1979, 1983, and 1984 peaks.											
Threemile River near North Dighton, MA (01109060)											
		1967–2010				1926–2010[a,b]					
20	5	1,640	1,440	1,930	1,430	**1,420**	1,300	1,580	1,420	1,270	1,630
10	10	2,050	1,760	2,490	1,760	**1,760**	1,590	1,990	1,760	1,550	2,110
4	25	2,600	2,180	3,280	2,200	**2,230**	1,980	2,590	2,240	1,910	2,890
2	50	3,030	2,500	3,940	2,550	**2,610**	2,280	3,090	2,620	2,180	3,630
1	100	3,490	2,820	4,640	2,920	**3,010**	2,600	3,630	3,020	2,440	4,530
0.5	200	3,960	3,160	5,400	3,300	**3,440**	2,930	4,220	3,460	2,710	5,600
0.2	500	4,620	3,610	6,500	3,840	**4,060**	3,400	5,080	4,080	3,060	7,360
[a]Actual records 1967–2010 extended using Wading River near Norton, MA (01109000).											
[b]Error of ±2% assigned to 1931, 1936, and 1955 peaks for EMA analysis.											
Wading River near Norton, MA (01109000)											
						1926–2010					
20	5	**720**	660	790	720	--	--	--	720	640	820
10	10	**900**	810	1,010	890	--	--	--	900	780	1,080
4	25	**1,150**	1,020	1,330	1,140	--	--	--	1,150	970	1,520
2	50	**1,360**	1,180	1,610	1,330	--	--	--	1,360	1,120	1,940
1	100	**1,580**	1,360	1,910	1,540	--	--	--	1,580	1,260	2,470
0.5	200	**1,830**	1,550	2,250	1,770	--	--	--	1,830	1,410	3,130
0.2	500	**2,180**	1,820	2,760	2,100	--	--	--	2,180	1,610	4,250

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence			Peak flow estimate	95% confidence		Peak flow estimate	95% confidence	
			Lower	Upper			Lower	Upper		Lower	Upper
Connecticut streamgages											
Blackwell Brook near Brooklyn, CT (01126600)											
		1962-1976				1952–2010[a]					
20	5	920	680	1,400	950	**950**	820	1,120	950	790	1,180
10	10	1,270	900	2,160	1,240	**1,260**	1,060	1,540	1,260	1,030	1,660
4	25	1,810	1,220	3,520	1,630	**1,700**	1,400	2,170	1,700	1,340	2,550
2	50	2,300	1,480	4,890	1,940	**2,070**	1,670	2,720	2,070	1,580	3,460
1	100	2,850	1,760	6,640	2,260	**2,470**	1,960	3,350	2,480	1,820	4,630
0.5	200	3,490	2,070	8,830	2,600	**2,920**	2,270	4,050	2,920	2,060	6,140
0.2	500	4,470	2,520	12,600	3,070	**3,560**	2,710	5,120	3,580	2,370	8,800
[a]Actual records 1962–76 extended using Little River near Hanover, CT (01123000) to 1952–1961 and 1977–2010.											
Fivemile River at Killingly, CT (01126000)											
		1938–1984				1938–2010[a]					
20	5	1,060	930	1,250	1,060	**1,060**	960	1,190	1,060	930	1,240
10	10	1,370	1,180	1,660	1,330	**1,340**	1,190	1,540	1,330	1,150	1,640
4	25	1,830	1,530	2,320	1,700	**1,720**	1,500	2,050	1,720	1,440	2,330
2	50	2,220	1,810	2,900	1,990	**2,040**	1,750	2,480	2,040	1,650	3,000
1	100	2,650	2,120	3,580	2,300	**2,390**	2,010	2,970	2,380	1,870	3,840
0.5	200	3,130	2,450	4,370	2,630	**2,760**	2,290	3,500	2,750	2,090	4,880
0.2	500	3,850	2,940	5,600	3,090	**3,300**	2,690	4,290	3,290	2,380	6,640
[a]Actual records 1938–1984 extended using Little River near Hanover, CT (01123000).											
Hop River near Columbia, CT (01120000)											
		1933–1984				1933–2010[a]					
20	5	3,360	2,920	3,960	3,380	**3,370**	3,040	3,810	3,370	2,950	3,970
10	10	4,460	3,800	5,460	4,310	**4,330**	3,830	5,010	4,330	3,710	5,390
4	25	6,140	5,060	7,900	5,620	**5,710**	4,940	6,820	5,710	4,720	7,880
2	50	7,620	6,130	10,200	6,690	**6,860**	5,830	8,400	6,860	5,490	10,400
1	100	9,300	7,310	12,800	7,840	**8,120**	6,800	10,200	8,120	6,280	13,600
0.5	200	11,200	8,620	16,000	9,090	**9,510**	7,830	12,200	9,520	7,090	17,600
0.2	500	14,200	10,600	21,100	10,900	**11,600**	9,330	15,200	11,600	8,190	24,700
[a]Actual records 1933–1984 extended using Salmon River near East Hampton, CT (01193500).											
Little River near Hanover, CT (01123000)											
						1952–2010[a]					
20	5	**1,410**	1,240	1,630	1,410	--	--	--	1,370	1,180	1,620
10	10	**1,810**	1,570	2,170	1,800	--	--	--	1,760	1,500	2,200
4	25	**2,390**	2,020	2,980	2,340	--	--	--	2,320	1,910	3,200
2	50	**2,870**	2,370	3,680	2,770	--	--	--	2,780	2,220	4,200
1	100	**3,390**	2,750	4,460	3,220	--	--	--	3,280	2,530	5,470
0.5	200	**3,960**	3,160	5,330	3,710	--	--	--	3,820	2,840	7,060
0.2	500	**4,780**	3,730	6,640	4,400	--	--	--	4,620	3,260	9,790
[a]61 years of actual record, but "historical" record spanned 75 years; Lower perception threshold of 1,450 ft^3/s used in EMA from 1937–51.											
Moosup River at Moosup, CT (01126500)											
		1933–1984				1933–2010[a]					
20	5	2,230	1,990	2,560	2,280	**2,280**	2,060	2,560	2,290	2,020	2,650
10	10	2,820	2,460	3,330	2,810	**2,840**	2,540	3,250	2,860	2,490	3,450
4	25	3,640	3,110	4,490	3,510	**3,600**	3,160	4,240	3,630	3,070	4,750
2	50	4,330	3,620	5,490	4,040	**4,210**	3,630	5,060	4,240	3,500	5,960
1	100	5,080	4,170	6,620	4,580	**4,850**	4,130	5,930	4,880	3,910	7,400
0.5	200	5,910	4,760	7,900	5,140	**5,520**	4,640	6,870	5,560	4,320	9,110
0.2	500	7,120	5,600	9,840	5,910	**6,460**	5,350	8,230	6,520	4,840	11,900
[a]Actual records 1933–1984 extended using Yantic River at Yantic, CT (01127500).											

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis B17B Peak flow estimate	Period of record analysis B17B 95% confidence Lower	Period of record analysis B17B 95% confidence Upper	Systematic peak flow estimate	Extended record analysis B17B Peak flow estimate	Extended record analysis B17B 95% confidence Lower	Extended record analysis B17B 95% confidence Upper	Extended record analysis EMA Peak flow estimate	Extended record analysis EMA 95% confidence Lower	Extended record analysis EMA 95% confidence Upper
Connecticut streamgages—Continued											
Mount Hope River near Warrenville, CT (01121000)											
		1941–2010									
20	5	1,760	1,560	2,020	1,760	--	--	--	**1,730**	1,490	2,090
10	10	2,370	2,060	2,810	2,370	--	--	--	**2,270**	1,910	2,940
4	25	3,340	2,810	4,140	3,350	--	--	--	**3,090**	2,480	4,560
2	50	4,220	3,480	5,410	4,260	--	--	--	**3,800**	2,940	6,320
1	100	5,270	4,240	6,970	5,330	--	--	--	**4,610**	3,420	8,720
0.5	200	6,500	5,110	8,870	6,600	--	--	--	**5,530**	3,930	12,000
0.2	500	8,480	6,470	12,000	8,650	--	--	--	**6,950**	4,650	18,100
[b]Lower confidence limits set 12 peaks above 2,250 ft³/s (average -18.4%) for EMA analysis.											
Natchaug River at Willimantic, CT (01122000)											
		1931–1951 (pre-flood control)			1931–2010[a,b]						
20	5	6,030	4,730	8,290	6,620	6,690	5,930	7,660	**6,350**	5,460	7,700
10	10	8,660	6,550	13,000	9,350	9,320	8,100	11,000	**8,510**	7,100	11,200
4	25	13,300	9,440	22,500	14,100	13,800	11,600	17,100	**11,900**	9,470	18,300
2	50	17,900	12,100	33,300	18,900	18,100	14,800	23,300	**15,000**	11,400	26,400
1	100	23,800	15,300	48,500	25,000	23,500	18,800	31,300	**18,700**	13,600	38,200
0.5	200	31,200	19,100	69,800	32,800	30,200	23,400	41,600	**23,000**	15,900	55,100
0.2	500	44,300	25,400	111,000	46,400	41,400	31,200	59,800	**30,000**	19,300	89,200
[a]Actual pre-flood control records 1931–1951 extended using Willimantic River near Coventry, CT (01119500).											
[b]Lower confidence limits set 18 peaks above 5,370 ft³/s by an average -18% for EMA analysis.											
Pendleton Brook Hill near Clark Falls, CT (01118300)											
		1959–2010			1942–2010[a,b]						
20	5	220	190	260	200	200	180	230	**200**	170	230
10	10	280	240	340	260	260	220	300	**250**	210	320
4	25	370	310	470	340	340	290	420	**330**	270	470
2	50	450	370	580	410	420	350	520	**400**	320	620
1	100	530	430	710	480	500	410	640	**470**	360	820
0.5	200	620	490	860	570	590	480	780	**550**	410	1070
0.2	500	760	580	1080	690	730	570	990	**670**	470	1520
[a]Actual records 1959–2010 extended using Wood River at Hope Valley, RI (01118000).											
[b]Error of -31% assigned to 2010 peak for EMA analysis.											
Quinebaug River at Quinebaug, CT (01124000)											
		1932–1959 (pre-flood control)			1919–2010[a]						
20	5	4,820	3,620	6,920	4,190	4,270	3,720	4,980	**4,250**	3,520	5,420
10	10	7,950	5,700	12,600	6,460	6,440	5,490	7,790	**6,320**	5,020	8,970
4	25	14,400	9,560	26,200	10,900	10,500	8,600	13,400	**10,100**	7,440	17,400
2	50	21,900	13,600	44,300	15,800	14,800	11,700	19,600	**13,900**	9,670	28,700
1	100	32,700	19,100	73,500	22,700	20,500	15,800	28,400	**18,900**	12,300	47,400
0.5	200	48,200	26,400	120,000	32,300	28,100	21,000	40,500	**25,500**	15,400	78,200
0.2	500	79,000	39,900	226,000	50,700	42,000	30,100	63,800	**37,100**	20,400	151,000
[a]Pre-flood control records (1932–59) extended using Quinebaug River at Jewett City, CT (01127000) from 1919–31 and post-flood control records extended using Willimantic River at Coventry, CT (01119500) from 1960–2010.											
[b]Lower confidence limits set 1955 and 2006 peaks of -30 and -7.1%, respectively, for EMA analysis.											

Table 7. Estimated magnitude of flood flows and confidence limits for selected annual exceedance probabilities at selected streamgages in Rhode Island, Connecticut, and Massachusetts for the period of record through 2010.—Continued

AEP (%)	Return interval (years)	Period of record analysis			Systematic peak flow estimate	Extended record analysis					
		B17B				B17B			EMA		
		Peak flow estimate	95% confidence			Peak flow estimate	95% confidence		Peak flow estimate	95% confidence	
			Lower	Upper			Lower	Upper		Lower	Upper
Connecticut streamgages—Continued											
Safford Brook near Woodstock Valley, CT (01120500)											
		1951–1981			1941–2010[a,b]						
20	5	520	440	630	430	430	400	480	**400**	360	470
10	10	660	550	840	540	550	490	620	**490**	430	600
4	25	870	710	1,170	700	710	620	830	**620**	530	830
2	50	1,000	830	1,480	840	840	720	1,020	**720**	600	1,050
1	100	1,200	960	1,830	983	990	840	1,230	**830**	670	1,330
0.5	200	1,500	1,100	2,240	1,140	1,160	960	1,470	**950**	740	1,670
0.2	500	1,800	1,310	2,900	1,390	1,400	1,140	1,840	**1,120**	830	2,240
[a]Actual records 1951–1981 extended using Mount Hope River near Warrenville, CT (01121000).											
[b]Lower confidence limits set for 1951–81 peaks from 0 to -45% (-19.4% average) for EMA analysis.											
Salmon River near East Hampton, CT (01193500)											
		1929–2010									
20	5	5,140	4,570	5,870	5,140	--	--	--	**5,060**	4,350	6,100
10	10	6,970	6,080	8,200	6,970	--	--	--	**6,770**	5,670	8,750
4	25	9,870	8,370	12,100	9,850	--	--	--	**9,400**	7,530	13,800
2	50	12,500	10,400	15,800	12,500	--	--	--	**11,700**	9,030	19,400
1	100	15,600	12,700	20,300	15,600	--	--	--	**14,400**	10,600	26,900
0.5	200	19,300	15,300	25,800	19,200	--	--	--	**17,500**	12,400	37,300
0.2	500	25,100	19,400	34,800	24,900	--	--	--	**22,400**	14,800	57,000
[b]Lower confidence limits set 1956, 1973, 1974, 1979, and 1982 peaks of -12, -21, -12, -26, and -20%, respectively, for EMA analysis.											
Shetucket River near Willimantic, CT (01122500)											
		1904–51 (pre-flood control)			1904–2010[a]						
20	5	11,000	9,040	14,000	12,800	**12,700**	11,400	14,300	11,600	9,910	14,100
10	10	15,300	12,200	20,800	17,800	**17,200**	15,200	20,000	16,500	13,700	21,500
4	25	22,600	17,200	33,700	26,500	**24,800**	21,200	30,000	24,600	19,300	36,600
2	50	29,800	21,800	47,700	35,200	**32,000**	26,800	40,000	32,200	24,200	54,000
1	100	38,800	27,200	66,500	46,100	**40,700**	33,300	52,500	41,400	29,600	79,200
0.5	200	50,000	33,600	91,700	60,000	**51,300**	41,000	68,200	52,400	35,600	115,000
0.2	500	69,200	44,000	139,000	84,100	**69,000**	53,400	95,400	70,500	44,600	188,000
[a]Actual pre-flood control records 1904–1906, 1920–1921, 1929–1951, after 1951 record extended using Willimantic River near Coventry, CT (01119500).											
[b]87 years of actual record, but "historical" record spanned 107 years; Lower confidence limits for 1955 and 2006 peaks of -5.3 and -5.4%, respectively, for EMA analysis; Lower perception threshold of 3,500 ft^3/s used in EMA during record gaps from 1907–19 and 1922–28.											
Willimantic River near Coventry, CT (01119500)											
		1932–2010									
20	5	3,990	3,510	4,620	3,960	--	--	--	**3,970**	3,330	4,990
10	10	5,670	4,880	6,800	5,680	--	--	--	**5,590**	4,520	7,760
4	25	8,560	7,110	10,800	8,730	--	--	--	**8,320**	6,330	13,800
2	50	11,400	9,210	14,900	11,800	--	--	--	**11,000**	7,900	21,300
1	100	15,000	11,800	20,300	15,700	--	--	--	**14,200**	9,670	32,900
0.5	200	19,400	14,800	27,300	20,800	--	--	--	**18,200**	11,700	50,700
0.2	500	27,000	20,000	39,900	29,600	--	--	--	**25,000**	14,700	89,700
[b]Errors of -11, -12, -5 and -8% assigned to 1936, 1955, 1982, and 2006 peaks, respectively, for EMA analysis.											
Yantic River at Yantic, CT (01127500)											
		1931–2010									
20	5	4,410	3,940	5,010	4,420	--	--	--	**4,380**	3,800	5,200
10	10	5,800	5,090	6,770	5,780	--	--	--	**5,710**	4,850	7,180
4	25	7,870	6,740	9,520	7,770	--	--	--	**7,660**	6,270	10,700
2	50	9,660	8,120	12,000	9,460	--	--	--	**9,310**	7,370	14,300
1	100	11,700	9,630	14,900	11,300	--	--	--	**11,100**	8,500	19,000
0.5	200	13,900	11,300	18,200	13,400	--	--	--	**13,200**	9,670	25,000
0.2	500	17,400	13,800	23,400	16,600	--	--	--	**16,200**	11,300	35,700
[b]Lower confidence limit set 1938 peak for EMA analysis.											

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft³/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	
Rhode Island streamgages							
Adamville Brook at Adamville, RI (01106000)							
20	220	0.001	220	0.015	220	0.001	0.0
10	250	0.001	280	0.013	250	0.001	0.0
4	300	0.002	380	0.011	300	0.002	0.0
2	330	0.002	460	0.012	350	0.002	6.1
1	360	0.003	540	0.012	400	0.003	11.1
0.5	400	0.004	630	0.014	440	0.003	10.0
0.2	440	0.006	750	0.017	510	0.005	15.9
Beaver River near Usquepaug, RI (01117468)							
20	190	0.001	280	0.014	200	0.001	5.3
10	250	0.003	370	0.013	270	0.002	8.0
4	350	0.005	510	0.011	400	0.003	14.3
2	450	0.008	620	0.012	510	0.005	13.3
1	560	0.012	740	0.012	650	0.006	16.1
0.5	700	0.016	870	0.014	790	0.008	12.9
0.2	930	0.024	1,050	0.017	1,000	0.010	7.5
Blackstone River at Woonsocket, RI (01112500)							
20	9,160	0.001	9,530	0.014	9,180	0.001	0.2
10	11,800	0.002	12,500	0.013	11,900	0.001	0.8
4	15,800	0.003	16,700	0.011	16,000	0.002	1.3
2	19,300	0.004	20,000	0.011	19,500	0.003	1.0
1	23,100	0.006	23,400	0.011	23,200	0.004	0.4
0.5	27,500	0.009	27,400	0.013	27,500	0.005	0.0
0.2	34,200	0.012	33,100	0.016	33,700	0.007	-1.5
Branch River at Forestdale, RI (01111500)							
20	2,890	0.001	2,240	0.012	2,820	0.001	-2.4
10	3,800	0.002	2,910	0.011	3,660	0.002	-3.7
4	5,160	0.004	3,930	0.010	4,800	0.003	-7.0
2	6,320	0.005	4,730	0.010	5,720	0.003	-9.5
1	7,630	0.007	5,580	0.010	6,660	0.004	-12.7
0.5	9,100	0.010	6,500	0.011	7,780	0.005	-14.5
0.2	11,300	0.015	7,830	0.014	9,400	0.007	-16.8
Chepachet River at Chepachet, RI (01111400)							
20	520	0.001	380	0.013	510	0.001	-1.9
10	680	0.002	490	0.012	650	0.002	-4.4
4	920	0.003	670	0.010	850	0.003	-7.6
2	1,120	0.005	810	0.011	1,010	0.003	-9.8
1	1,350	0.007	960	0.010	1,170	0.004	-13.3
0.5	1,600	0.010	1,110	0.012	1,360	0.005	-15.0
0.2	1,990	0.014	1,320	0.015	1,630	0.007	-18.1

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft³/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	
Rhode Island streamgages—Continued							
Chipuxet River at West Kingston, RI (01117350)							
20	140	0.001	220	0.014	150	0.001	7.1
10	190	0.003	290	0.013	210	0.002	10.5
4	270	0.005	390	0.011	310	0.004	14.8
2	350	0.008	480	0.012	400	0.005	14.3
1	440	0.012	570	0.011	500	0.006	13.6
0.5	550	0.017	660	0.014	610	0.008	10.9
0.2	730	0.026	790	0.017	770	0.010	5.5
Hunt River near East Greenwich, RI (01117000)							
20	610	0.001	590	0.013	610	0.001	0.0
10	810	0.002	760	0.011	800	0.002	-1.2
4	1,110	0.004	1,030	0.010	1,090	0.003	-1.8
2	1,390	0.007	1,250	0.010	1,330	0.004	-4.3
1	1,720	0.010	1,490	0.010	1,600	0.005	-7.0
0.5	2,120	0.014	1,730	0.012	1,890	0.006	-10.8
0.2	2,750	0.021	2,080	0.014	2,330	0.009	-15.3
Moshassuck River at Providence, RI (01114000)							
20	1,120	0.000	980	0.014	1,120	0.000	0.0
10	1,320	0.001	1,300	0.013	1,320	0.001	0.0
4	1,570	0.001	1,790	0.011	1,590	0.001	1.3
2	1,770	0.002	2,200	0.012	1,820	0.002	2.8
1	1,980	0.003	2,620	0.011	2,080	0.002	5.1
0.5	2,190	0.004	3,110	0.014	2,350	0.003	7.3
0.2	2,490	0.005	3,810	0.017	2,740	0.004	10.0
Nipmuc River near Harrisville, RI (01111300)							
20	730	0.002	890	0.013	750	0.001	2.7
10	990	0.002	1,180	0.012	1,020	0.002	3.0
4	1,380	0.004	1,640	0.011	1,450	0.003	5.1
2	1,720	0.006	2,020	0.011	1,830	0.004	6.4
1	2,120	0.009	2,410	0.011	2,250	0.005	6.1
0.5	2,580	0.012	2,880	0.013	2,720	0.006	5.4
0.2	3,290	0.018	3,530	0.016	3,410	0.008	3.6
Nooseneck River at Nooseneck, RI (01115630)							
20	330	0.001	350	0.016	330	0.001	0.0
10	430	0.002	460	0.015	430	0.002	0.0
4	580	0.004	640	0.014	600	0.003	3.4
2	720	0.006	800	0.014	740	0.004	2.8
1	880	0.009	960	0.015	910	0.005	3.4
0.5	1,060	0.012	1,130	0.017	1,090	0.007	2.8
0.2	1,350	0.017	1,390	0.021	1,370	0.010	1.5

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft^3/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	
Rhode Island streamgages—Continued							
Pawcatuck River at Westerly, RI (01118500)							
20	3,300	0.001	3,300	0.014	3,300	0.001	0.0
10	4,080	0.001	4,190	0.013	4,090	0.001	0.2
4	5,230	0.003	5,510	0.011	5,290	0.002	1.1
2	6,220	0.004	6,540	0.011	6,320	0.003	1.6
1	7,340	0.006	7,690	0.011	7,480	0.004	1.9
0.5	8,610	0.008	8,760	0.013	8,690	0.005	0.9
0.2	10,600	0.012	10,400	0.016	10,500	0.007	-0.9
Pawcatuck River at Wood River Junction, RI (01117500)							
20	1,030	0.001	960	0.015	1,020	0.001	-1.0
10	1,280	0.001	1,200	0.013	1,280	0.001	0.0
4	1,660	0.003	1,580	0.011	1,650	0.002	-0.6
2	1,990	0.004	1,880	0.012	1,960	0.003	-1.5
1	2,370	0.007	2,220	0.012	2,310	0.004	-2.5
0.5	2,790	0.009	2,500	0.014	2,670	0.006	-4.3
0.2	3,440	0.013	2,940	0.018	3,220	0.008	-6.4
Ponaganset River at South Foster, RI (01115187)							
20	760	0.001	540	0.013	740	0.001	-2.6
10	960	0.002	710	0.012	930	0.001	-3.1
4	1,260	0.003	980	0.010	1,190	0.002	-5.6
2	1,500	0.004	1,190	0.010	1,410	0.003	-6.0
1	1,760	0.006	1,420	0.010	1,630	0.004	-7.4
0.5	2,050	0.007	1,670	0.012	1,890	0.005	-7.8
0.2	2,470	0.011	2,020	0.015	2,270	0.006	-8.1
South Branch Pawtuxet River at Washington, RI (01116000)							
20	1,090	0.002	1,260	0.013	1,110	0.001	1.8
10	1,470	0.002	1,630	0.012	1,500	0.002	2.0
4	2,060	0.005	2,200	0.010	2,100	0.003	1.9
2	2,600	0.007	2,650	0.010	2,620	0.004	0.8
1	3,230	0.010	3,140	0.010	3,180	0.005	-1.5
0.5	3,980	0.014	3,630	0.012	3,790	0.007	-4.8
0.2	5,170	0.021	4,360	0.015	4,680	0.009	-9.5
Ten Mile River at Pawtucket Avenue at East Providence, RI, (01109403)							
20	1,120	0.001	1,450	0.012	1,140	0.001	1.8
10	1,400	0.001	1,890	0.011	1,440	0.001	2.9
4	1,800	0.002	2,560	0.009	1,920	0.002	6.7
2	2,130	0.003	3,090	0.010	2,330	0.002	9.4
1	2,490	0.004	3,660	0.009	2,820	0.003	13.3
0.5	2,880	0.006	4,280	0.011	3,300	0.004	14.6
0.2	3,450	0.009	5,160	0.014	4,030	0.005	16.8

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft^3/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	
Rhode Island streamgages—Continued							
Usquepaug River near Usquepaug, RI (01117420)							
20	550	0.001	870	0.013	570	0.001	3.6
10	710	0.002	1,130	0.012	750	0.002	5.6
4	950	0.004	1,540	0.010	1,070	0.003	12.6
2	1,160	0.006	1,870	0.011	1,360	0.004	17.2
1	1,400	0.008	2,220	0.011	1,710	0.005	22.1
0.5	1,680	0.011	2,580	0.013	2,060	0.006	22.6
0.2	2,130	0.016	3,110	0.015	2,580	0.008	21.1
Wood River near Arcadia, RI (01117800)							
20	620	0.001	640	0.061	620	0.001	0.0
10	810	0.002	820	0.059	810	0.002	0.0
4	1,100	0.004	1,110	0.058	1,100	0.004	0.0
2	1,370	0.007	1,340	0.064	1,360	0.006	-0.7
1	1,680	0.010	1,590	0.072	1,640	0.009	-2.4
0.5	2,050	0.014	1,830	0.081	1,940	0.012	-5.4
0.2	2,630	0.020	2,200	0.101	2,390	0.017	-9.1
Wood River at Hope Valley, RI (01118000)							
20	1,310	0.001	1,290	0.014	1,310	0.001	0.0
10	1,650	0.002	1,670	0.012	1,650	0.001	0.0
4	2,170	0.003	2,240	0.011	2,190	0.002	0.9
2	2,630	0.005	2,700	0.011	2,650	0.004	0.8
1	3,160	0.007	3,200	0.011	3,180	0.004	0.6
0.5	3,760	0.011	3,690	0.013	3,730	0.006	-0.8
0.2	4,710	0.016	4,410	0.016	4,570	0.008	-3.0
Woonasquatucket River at Centerdale, RI (01114500)							
20	920	0.001	830	0.013	910	0.001	-1.1
10	1,150	0.001	1,070	0.011	1,140	0.001	-0.9
4	1,470	0.002	1,440	0.010	1,460	0.002	-0.7
2	1,720	0.003	1,720	0.010	1,720	0.002	0.0
1	1,990	0.005	2,040	0.010	2,000	0.003	0.5
0.5	2,270	0.006	2,360	0.012	2,300	0.004	1.3
0.2	2,670	0.009	2,820	0.014	2,720	0.005	1.9
Massachusetts streamgages							
Kettle Brook at Worcester, MA (01109500)							
20	730	0.004	990	0.013	780	0.003	6.8
10	1,080	0.006	1,290	0.012	1,150	0.004	6.5
4	1,720	0.011	1,750	0.010	1,740	0.005	1.2
2	2,350	0.016	2,110	0.011	2,200	0.006	-6.4
1	3,170	0.023	2,500	0.010	2,690	0.007	-15.1
0.5	4,200	0.032	2,930	0.012	3,230	0.009	-23.1
0.2	6,000	0.046	3,530	0.015	4,020	0.011	-33.0

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft^3/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	
Massachusetts streamgages—Continued							
Little River near Oxford, MA (01124500)							
20	700	0.002	740	0.014	710	0.001	1.4
10	1,010	0.003	950	0.012	1,000	0.002	-1.0
4	1,570	0.006	1,280	0.011	1,460	0.004	-7.0
2	2,140	0.010	1,540	0.011	1,830	0.005	-14.5
1	2,890	0.015	1,820	0.011	2,200	0.006	-23.9
0.5	3,860	0.022	2,120	0.013	2,640	0.008	-31.6
0.2	5,610	0.033	2,540	0.016	3,280	0.011	-41.5
Mumford River at East Douglas, MA (01111000)							
20	690	0.002	680	0.013	690	0.002	0.0
10	960	0.003	880	0.012	950	0.002	-1.0
4	1,390	0.005	1,190	0.010	1,320	0.003	-5.0
2	1,790	0.008	1,420	0.010	1,620	0.005	-9.5
1	2,260	0.012	1,690	0.010	1,930	0.005	-14.6
0.5	2,820	0.016	1,950	0.012	2,290	0.007	-18.8
0.2	3,710	0.023	2,340	0.014	2,800	0.009	-24.5
Neponset River at Norwood, MA (01105000)							
20	600	0.001	670	0.013	610	0.001	1.7
10	770	0.002	850	0.012	780	0.002	1.3
4	1,020	0.003	1,150	0.010	1,050	0.002	2.9
2	1,240	0.005	1,380	0.010	1,280	0.003	3.2
1	1,490	0.007	1,640	0.010	1,550	0.004	4.0
0.5	1,770	0.010	1,890	0.012	1,820	0.005	2.8
0.2	2,200	0.014	2,250	0.014	2,220	0.007	0.9
Quaboag River at West Brimfield, MA (01176000)							
20	1,870	0.001	3,860	0.013	1,960	0.001	4.8
10	2,470	0.002	5,030	0.012	2,700	0.002	9.3
4	3,460	0.004	6,750	0.010	4,120	0.003	19.1
2	4,390	0.006	8,080	0.011	5,460	0.004	24.4
1	5,530	0.009	9,490	0.010	7,120	0.005	28.8
0.5	6,910	0.013	11,100	0.012	8,800	0.006	27.4
0.2	9,220	0.020	13,400	0.015	11,400	0.009	23.6
Sevenmile River near Spencer, MA (01175760)							
20	300	0.002	440	0.014	310	0.001	3.3
10	420	0.003	580	0.012	450	0.002	7.1
4	650	0.006	800	0.011	700	0.004	7.7
2	880	0.010	980	0.011	930	0.005	5.7
1	1,180	0.015	1,170	0.011	1,180	0.006	0.0
0.5	1,560	0.021	1,390	0.013	1,450	0.008	-7.1
0.2	2,240	0.031	1,700	0.016	1,860	0.011	-17.0

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft^3/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	
Massachusetts streamgages—Continued							
Taunton River near Bridgewater, MA (01108000)							
20	3,160	0.000	2,640	0.014	3,160	0.000	0.0
10	3,670	0.000	3,330	0.013	3,660	0.000	-0.3
4	4,320	0.001	4,340	0.011	4,320	0.001	0.0
2	4,800	0.001	5,100	0.011	4,830	0.001	0.6
1	5,290	0.002	5,980	0.011	5,380	0.001	1.7
0.5	5,780	0.002	6,760	0.013	5,920	0.002	2.4
0.2	6,450	0.003	7,940	0.016	6,690	0.003	3.7
Threemile River near North Dighton, MA (01109060)							
20	1,420	0.001	1,470	0.013	1,430	0.001	0.7
10	1,760	0.001	1,880	0.012	1,770	0.001	0.6
4	2,230	0.002	2,510	0.010	2,270	0.001	1.8
2	2,610	0.003	2,990	0.010	2,680	0.002	2.7
1	3,010	0.004	3,530	0.010	3,150	0.003	4.7
0.5	3,440	0.005	4,060	0.012	3,620	0.003	5.2
0.2	4,060	0.007	4,830	0.014	4,300	0.005	5.9
Wading River near Norton, MA (01109000)							
20	720	0.001	770	0.013	720	0.001	0.0
10	900	0.001	990	0.012	900	0.001	0.0
4	1,150	0.002	1,320	0.010	1,170	0.002	1.7
2	1,360	0.003	1,580	0.010	1,400	0.002	2.9
1	1,580	0.004	1,880	0.010	1,660	0.003	5.1
0.5	1,830	0.006	2,150	0.012	1,920	0.004	4.9
0.2	2,180	0.008	2,560	0.014	2,310	0.005	6.0
Connecticut streamgages							
Blackwell Brook near Brooklyn, CT (01126600)							
20	950	0.002	590	0.013	890	0.002	-6.3
10	1,260	0.002	770	0.012	1,150	0.002	-8.7
4	1,700	0.004	1,050	0.010	1,480	0.003	-12.9
2	2,070	0.006	1,270	0.010	1,740	0.004	-15.9
1	2,470	0.008	1,510	0.010	1,980	0.004	-19.8
0.5	2,920	0.011	1,770	0.012	2,300	0.006	-21.2
0.2	3,560	0.015	2,140	0.015	2,750	0.007	-22.8
Fivemile River at Killingly, CT (01126000)							
20	1,060	0.001	1,260	0.013	1,070	0.001	0.9
10	1,340	0.001	1,630	0.012	1,360	0.001	1.5
4	1,720	0.002	2,190	0.010	1,810	0.002	5.2
2	2,040	0.003	2,620	0.010	2,180	0.003	6.9
1	2,390	0.005	3,090	0.010	2,600	0.003	8.8
0.5	2,760	0.007	3,570	0.012	3,030	0.004	9.8
0.2	3,300	0.010	4,270	0.014	3,660	0.006	10.9

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft³/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	
Connecticut streamgages—Continued							
Hop River near Columbia, CT (01120000)							
20	3,370	0.001	2,600	0.013	3,310	0.001	-1.8
10	4,330	0.002	3,430	0.012	4,220	0.001	-2.5
4	5,710	0.003	4,670	0.010	5,480	0.002	-4.0
2	6,860	0.004	5,670	0.011	6,520	0.003	-5.0
1	8,120	0.006	6,700	0.010	7,600	0.004	-6.4
0.5	9,510	0.008	7,910	0.012	8,880	0.005	-6.6
0.2	11,600	0.011	9,630	0.015	10,700	0.006	-7.8
Little River near Hanover, CT (01123000)							
20	1,410	0.001	1,320	0.014	1,400	0.001	-0.7
10	1,810	0.002	1,740	0.012	1,800	0.002	-0.6
4	2,390	0.003	2,380	0.011	2,390	0.003	0.0
2	2,870	0.005	2,890	0.011	2,880	0.003	0.3
1	3,390	0.007	3,410	0.011	3,400	0.004	0.3
0.5	3,960	0.009	4,040	0.013	4,000	0.005	1.0
0.2	4,780	0.013	4,920	0.016	4,840	0.007	1.3
Moosup River at Moosup, CT (01126500)							
20	2,280	0.001	2,430	0.013	2,290	0.001	0.4
10	2,840	0.001	3,180	0.012	2,870	0.001	1.1
4	3,600	0.002	4,320	0.010	3,710	0.002	3.1
2	4,210	0.003	5,230	0.010	4,400	0.002	4.5
1	4,850	0.004	6,180	0.010	5,180	0.003	6.8
0.5	5,520	0.005	7,260	0.012	5,990	0.004	8.5
0.2	6,460	0.007	8,800	0.015	7,160	0.005	10.8
Mount Hope River near Warrenville, CT (01121000)							
20	1,730	0.001	1,610	0.014	1,720	0.001	-0.6
10	2,270	0.002	2,140	0.013	2,260	0.002	-0.4
4	3,090	0.004	2,960	0.011	3,060	0.003	-1.0
2	3,800	0.006	3,610	0.012	3,740	0.004	-1.6
1	4,610	0.008	4,270	0.011	4,480	0.005	-2.8
0.5	5,530	0.011	5,100	0.014	5,350	0.006	-3.3
0.2	6,950	0.016	6,250	0.017	6,620	0.008	-4.7
Natchaug River at Willimantic, CT (01122000)							
20	6,350	0.001	6,160	0.014	6,320	0.001	-0.5
10	8,510	0.002	8,150	0.013	8,440	0.002	-0.8
4	11,900	0.004	11,000	0.011	11,700	0.003	-1.7
2	15,000	0.006	13,300	0.012	14,400	0.004	-4.0
1	18,700	0.009	15,600	0.011	17,200	0.005	-8.0
0.5	23,000	0.013	18,500	0.014	20,700	0.007	-10.0
0.2	30,000	0.019	22,500	0.017	25,700	0.009	-14.3

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft^3/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	Flow (ft^3/s)	Variance	
Connecticut streamgages—Continued							
Pendleton Brook Hill near Clark Falls, CT (01118300)							
20	200	0.001	140	0.015	190	0.001	-5.0
10	250	0.002	180	0.014	240	0.002	-4.0
4	330	0.003	250	0.012	310	0.002	-6.1
2	400	0.004	310	0.013	370	0.003	-7.5
1	470	0.006	370	0.013	440	0.004	-6.4
0.5	550	0.008	430	0.015	510	0.005	-7.3
0.2	670	0.012	520	0.018	610	0.007	-9.0
Quinebaug River at Quinebaug, CT (01124000)							
20	4,250	0.002	4,370	0.013	4,260	0.002	0.2
10	6,320	0.004	5,720	0.012	6,170	0.003	-2.4
4	10,100	0.007	7,700	0.010	9,010	0.004	-10.8
2	13,900	0.011	9,230	0.011	11,300	0.006	-18.7
1	18,900	0.017	10,800	0.011	13,500	0.006	-28.6
0.5	25,500	0.023	12,700	0.013	16,200	0.008	-36.5
0.2	37,100	0.035	15,400	0.016	20,200	0.011	-45.6
Safford Brook near Woodstock Valley, CT (01120500)							
20	400	0.001	340	0.015	400	0.001	0.0
10	490	0.001	460	0.014	490	0.001	0.0
4	620	0.002	640	0.012	620	0.002	0.0
2	720	0.003	800	0.013	740	0.002	2.8
1	830	0.004	960	0.012	860	0.003	3.6
0.5	950	0.006	1,160	0.015	1,000	0.004	5.3
0.2	1,120	0.008	1,430	0.018	1,210	0.006	8.0
Salmon River near East Hampton, CT (01193500)							
20	5,060	0.001	3,140	0.013	4,840	0.001	-4.3
10	6,770	0.002	4,130	0.012	6,280	0.002	-7.2
4	9,400	0.004	5,610	0.010	8,170	0.003	-13.1
2	11,700	0.006	6,790	0.010	9,690	0.004	-17.2
1	14,400	0.008	8,010	0.010	11,100	0.004	-22.9
0.5	17,500	0.011	9,430	0.012	13,100	0.006	-25.1
0.2	22,400	0.016	11,400	0.015	15,800	0.008	-29.5
Shetucket River near Willimantic, CT (01122500)							
20	12,700	0.001	13,000	0.015	12,700	0.001	0.0
10	17,200	0.002	17,300	0.013	17,300	0.002	0.6
4	24,800	0.005	23,300	0.012	24,400	0.003	-1.6
2	32,000	0.007	28,000	0.012	30,500	0.005	-4.7
1	40,700	0.011	32,800	0.012	36,800	0.006	-9.6
0.5	51,300	0.015	38,800	0.015	44,500	0.007	-13.3
0.2	69,000	0.022	47,300	0.018	55,900	0.010	-19.0

Table 13. Magnitude and variance of 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability floods determined from at-site analyses, regional regression equations, and weighted independent estimates.—Continued

[At-site, Bulletin 17B or expected moments algorithm results highlighted in table 7; Values may not exactly match because of rounding; ft³/s, cubic feet per second; RI, Rhode Island; MA, Massachusetts; CT, Connecticut]

Annual exceedance probability (percent)	At-site		Regional regression		Weighted		Percent difference at site and weighted flow
	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	Flow (ft³/s)	Variance	
Connecticut streamgages—Continued							
Willimantic River near Coventry, CT (01119500)							
20	3,970	0.002	5,170	0.014	4,100	0.002	3.3
10	5,590	0.003	6,880	0.013	5,820	0.002	4.1
4	8,320	0.006	9,390	0.011	8,690	0.004	4.4
2	11,000	0.009	11,400	0.012	11,200	0.005	1.8
1	14,200	0.013	13,400	0.011	13,800	0.006	-2.8
0.5	18,200	0.019	16,000	0.014	16,900	0.008	-7.1
0.2	25,000	0.027	19,500	0.017	21,500	0.010	-14.0
Yantic River at Yantic, CT (01127500)							
20	4,380	0.001	2,770	0.013	4,220	0.001	-3.7
10	5,710	0.002	3,640	0.012	5,390	0.001	-5.6
4	7,660	0.003	4,930	0.010	6,920	0.002	-9.7
2	9,310	0.004	5,940	0.010	8,140	0.003	-12.6
1	11,100	0.006	7,000	0.010	9,330	0.004	-15.9
0.5	13,200	0.008	8,220	0.012	10,800	0.005	-18.2
0.2	16,200	0.012	9,950	0.015	13,000	0.007	-19.8

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.

[AEP, annual exceedance probability, in percent; Period of record analysis, is the systematic record; Extended record analysis, includes the period of record plus records estimated by MOVE; record length indicated below each station; B17B, flood frequency analysis made using Bulletin 17B guidelines; EMA, expected moments algorithm; All values in cubic feet per second (ft^3/s); All at-site analysis made using a weighted regional skew of 0.52 and root mean square error of 0.46; --, indicates analysis not made because basin characteristics were out of range of the characteristics used to develop regional regression equation; csg, crest stage gage; Values in red color indicate one or more of the streamgage basin characteristics outside the range of values used to develop regional regression equation, most commonly the basin drainage area, which is provided following the station name; %, percent; RI, Rhode Island]

AEP	Return interval (years)	Period of record analysis			Extended record analysis						Regional regression			Weighted average		
		B17B			B17B			EMA								
		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Bear Brook near Coventry, RI (csg) (01115830)												(3.98 mi²)[b]				
		1966–78			1942–2010[a]											
20	5	150	130	190	160	150	170	160	140	180	410	--	--	--	--	--
10	10	170	150	220	190	180	220	190	170	240	560	--	--	--	--	--
4	25	200	170	270	250	220	280	250	210	350	790	--	--	--	--	--
2	50	220	180	310	290	250	340	290	240	460	1,000	--	--	--	--	--
1	100	240	190	360	340	290	410	340	270	620	1,210	--	--	--	--	--
0.5	200	260	210	400	390	340	480	390	300	830	1,470	--	--	--	--	--
0.2	500	280	220	460	480	400	610	480	340	1,200	1,840	--	--	--	--	--
[a]Record extended with Wood River at Hope Valley, RI (01118000).																
[b]Basin storage (StorNHD) is 50% less than the range of values used to develop regional regression equation.																
Blackstone River Tributary at Woonsocket, RI (01112700)												(2.07 mi²)				
		1966–74			1926–2010[a]											
20	5	190	150	310	160	150	180	160	150	190	170	--	--	--	--	--
10	10	250	180	450	200	180	230	200	180	240	230	--	--	--	--	--
4	25	330	230	690	260	230	300	260	220	340	330	--	--	--	--	--
2	50	400	260	940	300	270	360	300	250	430	410	--	--	--	--	--
1	100	470	300	1,200	350	300	430	350	280	540	490	--	--	--	--	--
0.5	200	550	340	1,600	410	340	500	410	320	680	590	--	--	--	--	--
0.2	500	670	390	2,300	480	400	610	480	360	910	740	--	--	--	--	–
[a]Record extended with Wading River near Norton, MA (01109000).																
Blackstone River Tributary No. 2 at Berkeley, RI (csg) (01113600)												(1.11 mi²)				
		1966–78			1926–2010[a]											
20	5	43	37	52	41	37	46	41	36	47	49	--	--	--	--	--
10	10	50	42	64	52	46	59	52	45	62	65	--	--	--	--	--
4	25	60	49	83	66	58	77	66	56	85	91	--	--	--	--	--
2	50	67	54	100	77	67	92	77	64	110	110	--	--	--	--	--
1	100	76	60	120	89	76	110	89	72	130	140	--	--	--	--	--
0.5	200	84	65	140	100	86	130	100	79	160	160	--	--	--	--	--
0.2	500	97	72	170	120	99	150	120	89	210	200	--	--	--	--	--
[a]Record extended with Wading River near Norton, MA (01109000).																

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis B17B Peak flow estimate	Period of record B17B 95% confidence Lower	Period of record B17B 95% confidence Upper	Extended record B17B Peak flow estimate	Extended record B17B 95% confidence Lower	Extended record B17B 95% confidence Upper	Extended record EMA Peak flow estimate	Extended record EMA 95% confidence Lower	Extended record EMA 95% confidence Upper	Regional regression Peak flow estimate	Regional regression 95% confidence Lower	Regional regression 95% confidence Upper	Weighted average Peak flow estimate	Weighted average 95% confidence Lower	Weighted average 95% confidence Upper
Browns Brook at Wakefield, RI (csg) (01117250)											(0.44 mi²)					
		1966–74			1959–2010[a]											
20	5	19	16	24	26	23	30	26	22	34	4	--	--	--	--	--
10	10	22	18	30	35	30	42	35	28	52	5	--	--	--	--	--
4	25	25	21	38	49	41	62	49	37	94	7	--	--	--	--	--
2	50	28	22	45	63	51	82	63	45	150	9	--	--	--	--	--
1	100	31	24	52	79	62	110	79	53	240	11	--	--	--	--	--
0.5	200	33	26	60	98	76	140	98	63	390	12	--	--	--	--	--
0.2	500	37	28	71	130	97	200	130	77	680	14	--	--	--	--	--
[a]Record extended with Pendleton Hill Brook near Clark Falls, CT (01118300).																
Bucks Horn Brook at Greene, RI (01126200)											(5.49 mi²)					
		1966–74			1940–2010[a]									1940–2010[a]		
20	5	270	200	460	230	210	270	230	200	280	160	93	270	200	180	230
10	10	360	250	690	300	260	350	300	260	380	210	120	340	250	210	290
4	25	480	320	1,100	400	340	480	400	330	560	280	180	450	320	260	390
2	50	580	370	1,500	480	400	590	480	380	750	340	210	550	370	290	470
1	100	700	430	2,100	570	470	720	570	430	1,000	410	250	660	250	220	300
0.5	200	830	480	2,700	670	550	870	670	490	1,300	470	280	800	490	350	680
0.2	500	1,000	570	3,800	820	650	1,100	820	570	1,900	570	320	1,010	580	390	860
[a]Record extended with Branch River at Forestdale, RI (01111500).																
Carr River near Nooseneck, RI (01115770)											(6.74 mi²)					
		1964–79; 2007–10			1941–2010[a]									1941–2010[a]		
20	5	220	170	330	160	140	190	160	130	210	180	100	300	160	130	200
10	10	340	240	550	230	200	280	230	180	350	230	140	380	230	180	310
4	25	550	370	1,000	360	290	460	360	260	690	310	200	500	350	240	510
2	50	770	490	1,600	480	380	650	480	330	1,200	380	230	620	460	390	740
1	100	1,100	640	2,500	640	500	900	640	410	2,000	460	280	730	590	340	1,020
0.5	200	1,500	820	3,800	850	640	1,200	850	500	3,500	530	310	890	744	390	1,410
0.2	500	2,200	1,100	6,400	1,200	870	1,900	1,200	650	7,300	630	350	1,130	980	460	2,100
[a]Record extended with Hunt River near East Greenwich, RI (01117000).																

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis			Extended record analysis						Regional regression			Weighted average		
		B17B			B17B			EMA								
		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Catamint Brook at Cumberland, RI (01113695)												(3.55 mi²)				
		2000–10			1940–2010[a]											
20	5	120	100	170	100	93	110	99	90	110	160	--	--	--	--	--
10	10	150	120	220	120	110	130	120	100	140	210	--	--	--	--	--
4	25	180	140	290	140	130	160	140	120	180	300	--	--	--	--	--
2	50	200	150	350	160	140	190	160	140	220	370	--	--	--	--	--
1	100	230	170	430	180	160	210	180	150	260	440	--	--	--	--	--
0.5	200	250	180	510	200	180	240	200	160	310	520	--	--	--	--	--
0.2	500	290	200	630	230	200	280	230	180	390	630	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01111500).																
Cold Brook near Adamsville, RI (csg) (01106100)												(1.17 mi²)				
		1966–1974			1940–2010[a]											
20	5	0	0	0	78	69	90	78	66	97	78	--	--	--	--	--
10	10	0	0	0	110	92	130	110	87	140	100	--	--	--	--	--
4	25	0	0	0	150	130	190	150	120	250	150	--	--	--	--	--
2	50	0	0	0	190	160	250	190	140	370	180	--	--	--	--	--
1	100	0	0	0	240	190	320	240	170	550	220	--	--	--	--	--
0.5	200	0	0	0	300	240	410	300	200	830	260	--	--	--	--	--
0.2	500	0	0	0	400	300	570	400	250	1,400	320	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01111500) to 1940–65 and Nipmuc River near Harrisville, RI (01111300) to 1975–2010.																
Dry Arm Brook near Wallum Lake, RI (csg) (01111250)												(1.45 mi²)				
		1966–1978			1940–2010[a]											
20	5	84	66	120	78	69	90	78	67	94	34	--	--	--	--	--
10	10	110	81	160	100	88	120	100	86	130	43	--	--	--	--	--
4	25	130	99	230	140	120	170	140	110	200	59	--	--	--	--	--
2	50	160	110	290	170	140	210	170	130	260	71	--	--	--	--	--
1	100	180	130	360	200	160	260	200	150	350	86	--	--	--	--	--
0.5	200	210	140	430	230	190	310	230	170	460	98	--	--	--	--	--
0.2	500	240	160	550	290	230	390	290	200	660	120	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01111500).																

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis			Extended record analysis						Regional regression			Weighted average		
		B17B			B17B			EMA								
		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Frenchtown Brook near Davisville, RI (csg) (01116870)												(2.96 mi²)				
		1966–1974			1941–2010[a]											
20	5	88	64	150	99	86	110	99	82	130	120	--	--	--	--	--
10	10	120	82	230	140	120	170	140	110	200	160	--	--	--	--	--
4	25	160	110	390	210	170	260	210	160	370	220	--	--	--	--	--
2	50	200	130	560	270	220	360	270	190	590	270	--	--	--	--	--
1	100	250	150	780	360	280	490	360	240	960	320	--	--	--	--	--
0.5	200	300	170	1,100	460	350	650	460	290	1,600	380	--	--	--	--	--
0.2	500	380	200	1,600	630	460	950	630	360	3,000	460	--	--	--	--	--
[a]Record extended with Hunt River near East Greenwich, RI (01117000).																
Hardig Brook near West Warwick, RI (csg) (01116650)												(3.25 mi²)				
		1966–1974			1942–2010[a]											
20	5	250	210	330	260	240	290	260	240	310	450	--	--	--	--	--
10	10	290	240	410	330	300	370	330	280	410	620	--	--	--	--	--
4	25	340	280	540	420	370	490	420	350	600	900	--	--	--	--	--
2	50	390	300	650	500	440	590	500	400	810	1,130	--	--	--	--	--
1	100	430	330	770	590	500	720	590	460	1,100	1,370	--	--	--	--	--
0.5	200	480	360	920	690	580	860	690	510	1,490	1,680	--	--	--	--	--
0.2	500	540	390	1,140	840	700	1,080	840	600	2,230	2,120	--	--	--	--	--
[a]Record extended with Wood River at Hope Valley, RI (01118000).																
Meadow Brook near Carolina, RI (01117600)												(4.76 mi²)				
		1966–1974			1942–2010[a]									1942–2010[a]		
20	5	92	73	130	97	87	110	97	83	120	120	67	200	97	82	120
10	10	120	90	180	130	110	150	130	110	180	150	88	250	130	100	160
4	25	150	110	280	180	150	220	180	140	300	200	120	330	180	130	240
2	50	190	130	370	230	190	290	230	170	450	250	150	410	230	160	330
1	100	220	150	490	280	230	370	280	200	690	300	180	490	290	180	440
0.5	200	270	170	640	350	280	470	350	230	1,060	340	200	590	350	210	590
0.2	500	330	200	900	460	360	650	460	290	1,870	410	220	750	450	240	840

[a]Record extended with Wood River at Hope Valley, RI (01118000).

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis B17B Peak flow estimate	Period of record analysis B17B 95% confidence Lower	Period of record analysis B17B 95% confidence Upper	Extended record analysis B17B Peak flow estimate	Extended record analysis B17B 95% confidence Lower	Extended record analysis B17B 95% confidence Upper	Extended record analysis EMA Peak flow estimate	Extended record analysis EMA 95% confidence Lower	Extended record analysis EMA 95% confidence Upper	Regional regression Peak flow estimate	Regional regression 95% confidence Lower	Regional regression 95% confidence Upper	Weighted average Peak flow estimate	Weighted average 95% confidence Lower	Weighted average 95% confidence Upper
Mosquitohawk Brook near North Scituate, RI (01115100)											(3.09 mi²)					
		1966–1974			1940–2010[a]											
20	5	370	240	730	300	260	360	300	250	380	61	--	--	--	--	--
10	10	530	330	1,270	420	360	520	420	340	580	77	--	--	--	--	--
4	25	790	460	2,400	610	500	788	610	470	977	110	--	--	--	--	--
2	50	1,040	570	3,690	790	630	1,040	790	580	1,430	130	--	--	--	--	--
1	100	1,320	680	5,500	990	770	1,360	990	690	2,080	150	--	--	--	--	--
0.5	200	1,650	810	8,000	1,220	930	1,730	1,220	810	2,990	170	--	--	--	--	--
0.2	500	2,190	1,000	12,700	1,600	1,180	2,350	1,600	990	4,800	200	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01115000).																
Peeptoad Brook at Elmdale Road near North Scituate, RI (01115098)											(4.83 mi²)					
		1995–2010			1940–2010[a]									1940–2010[a]		
20	5	180	150	220	150	140	170	150	140	170	68	38	120	150	130	170
10	10	210	180	280	180	170	210	180	160	220	86	49	150	180	160	210
4	25	250	210	360	230	200	270	230	200	300	120	69	200	230	190	270
2	50	290	230	430	270	230	320	270	220	380	140	81	240	260	210	330
1	100	320	250	500	310	260	370	310	250	470	170	96	290	300	220	390
0.5	200	360	270	570	350	300	430	350	270	590	190	100	340	330	240	460
0.2	500	410	300	690	400	340	510	410	300	770	220	120	430	390	270	560
[a]Record extended with Branch River at Forestdale, RI (01115000).																
Perry Healy Brook near Bradford, RI (csg) (01118020)											(1.78 mi²)					
		1966–74			1940–2010[a]											
20	5	60	42	110	56	49	64	56	48	67	33	--	--	--	--	--
10	10	84	56	180	73	64	86	73	61	96	42	--	--	--	--	--
4	25	120	77	330	100	85	120	100	80	150	58	--	--	--	--	--
2	50	160	94	510	120	100	160	120	95	210	70	--	--	--	--	--
1	100	210	110	760	150	120	200	150	110	290	85	--	--	--	--	--
0.5	200	260	130	1,120	180	140	240	180	130	400	97	--	--	--	--	--
0.2	500	350	170	1,820	230	180	310	230	150	610	110	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01115000).																

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis			Extended record analysis						Regional regression			Weighted average		
		B17B			B17B			EMA								
		Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper	Peak flow estimate	95% confidence Lower	95% confidence Upper
Pocasset River near North Scituate, RI (csg) (01116600)											(1.22 mi²)					
		1966–74			1940–2010[a]											
20	5	45	36	65	44	40	49	44	38	51	50	--	--	--	--	--
10	10	58	44	90	55	49	63	55	47	68	64	--	--	--	--	--
4	25	76	55	130	71	62	84	71	59	97	89	--	--	--	--	--
2	50	90	64	170	84	72	100	84	68	130	110	--	--	--	--	--
1	100	110	72	220	98	83	120	98	77	160	130	--	--	--	--	--
0.5	200	120	81	270	110	94	140	110	86	210	150	--	--	--	--	--
0.2	500	150	94	350	140	110	180	140	98	290	180	--	--	--	--	--
[a]Record extended with Branch River at Forestdale, RI (01115000).																
Queen River at Liberty, RI (01117370)											(19.8 mi²)					
		1999–2010			1940–2010[a]									1940–2010[a]		
20	5	710	500	1,190	380	340	440	380	330	480	760	450	1,290	390	330	460
10	10	1,040	700	2,030	520	450	600	520	430	710	1,010	610	1,660	530	420	660
4	25	1,620	1,010	3,850	730	620	890	730	570	1,230	1,390	880	2,200	770	563	1,050
2	50	2,190	1,280	6,030	930	770	1,180	940	690	1,880	1,710	1,050	2,760	1,000	680	1,460
1	100	2,900	1,600	9,230	1,170	946	1,540	1,180	820	2,880	2,040	1,260	3,270	1,280	820	2,010
0.5	200	3,810	1,970	13,900	1,460	1,150	1,980	1,480	970	4,440	2,410	1,430	4,050	1,600	950	2,710
0.2	500	5,350	2,560	23,200	1,940	1,480	2,750	1,960	1,200	7,900	2,940	1,640	5,220	2,120	1,140	3,960
[a]Record extended with Hunt River at East Greenwich, RI (01117000) 1941–75 and Usquepaug River near Usquepaug (01117420) 1976–1998.																
Wilbur Hollow Brook near Clayville, RI (csg) (01115300)											(4.57 mi²)					
		1966–1978												1940–2010[a]		
20	5	220	180	290	200	180	230	200	180	230	150	90	260	200	180	230
10	10	270	210	390	250	220	280	250	220	280	200	120	330	249	210	290
4	25	330	250	530	320	280	370	320	280	370	270	170	440	310	260	380
2	50	390	290	660	370	320	440	370	320	440	330	200	540	370	290	470
1	100	440	320	810	430	360	520	430	360	520	400	250	650	420	320	570
0.5	200	500	350	970	490	410	610	490	410	610	470	280	790	490	350	680
0.2	500	590	400	1,220	580	480	740	580	480	740	560	320	1,010	580	390	860
[a]Record extended with Branch River at Forestdale, RI (01115000).																

Table 15. Estimated magnitude of flood flows and confidence limits for annual exceedance probabilities at short-term streamgages in Rhode Island.—Continued

AEP	Return interval (years)	Period of record analysis B17B Peak flow estimate	Period of record B17B 95% confidence Lower	Period of record B17B 95% confidence Upper	Extended record analysis B17B Peak flow estimate	Extended B17B 95% confidence Lower	Extended B17B 95% confidence Upper	Extended record analysis EMA Peak flow estimate	Extended EMA 95% confidence Lower	Extended EMA 95% confidence Upper	Regional regression Peak flow estimate	Regional regression 95% confidence Lower	Regional regression 95% confidence Upper	Weighted average Peak flow estimate	Weighted average 95% confidence Lower	Weighted average 95% confidence Upper
Wood River Tributary near Arcadia, RI (csg) (01117820)												(0.84 mi²)				
		1966–1974			1940–2010[a]											
20	5	20	16	27	20	19	22	20	18	24	89	--	--	--	--	--
10	10	23	18	35	25	23	28	25	22	31	120	--	--	--	--	--
4	25	28	22	48	32	28	37	32	27	46	180	--	--	--	--	--
2	50	32	24	59	38	33	45	38	30	63	220	--	--	--	--	--
1	100	36	26	71	45	38	55	45	35	85	270	--	--	--	--	--
0.5	200	40	28	85	52	44	66	52	39	120	330	--	--	--	--	--
0.2	500	46	31	110	64	53	83	64	45	180	410	--	--	--	--	--

[a]Record extended with Wood River at Hope Valley, RI (01118000).

Appendixes 1–3

Appendix 1. Basin Characteristics Considered for Use in the Regional Regression Analysis

Table 1–1. Basin characteristics tested for use as explanatory variables in regionalized regression equations for estimated flood flows at ungaged sites.

[ft, foot; ft/mi, feet per mile; mi, mile; mi/mi, miles per mile; mi/mi^2, miles per square mile; mi^2, square mile; °F, degrees Fahrenheit]

Basin characteristic	Name	Unit	Notes
		Shape	
Source: Basin boundaries covers (internal)			
Drainage area	DA	mi^2	
X-coordinate at center of basin	centroid_x	ft	Rhode Island State plane coordinates
Y-coordinate at center of basin	centroid_y	ft	Rhode Island State plane coordinates
X-coordinate at outlet of basin	outlet_x	ft	Rhode Island State plane coordinates
Y-coordinate at outlet of basin	outlet_y	ft	Rhode Island State plane coordinates
Basin perimeter	BP	mi^2	
Compactness ratio	CR	None	Calculated: $BP/2\ (pi \times DA)^{0.5}$
Basin length	BL	mi	Distance from outlet to headwater along main axis
Effective width	BW	mi	Calculated: DA/BL
Elongation ratio	ER	None	Calculated: $[4 \times DA/pi \times BL^2]^{0.5} = 1.13(1/SF)^{0.5}$
Shape factor	SF	None	Calculated: BL/BW
Rotundity	RB	None	Calculated: $[\pi \times BL^2] / 4\ DA = 0.785 \times SF$
		Land cover	
Source: National Land Cover Dataset (NLCD) 2006 http://www.epa.gov/mrlc/nlcd-2006.html			
Area of open water	Water	Percent	
Area of open urban	OpenUrb	Percent	
Area of low density development	LowDen	Percent	
Area of moderate density development	ModDen	Percent	
Area of high density development	HiDen	Percent	
Area of moderate to high density development	ModHiUrb	Percent	Calculated: ModDen + HiDen
Total urban area	AllUrban	Percent	Calculated: LowDen + MpdDen + HiDen
Area of deciduous forests	DecFor	Percent	
Area of coniferous forests	ConFor	Percent	
Area of mixed forests	MixFor	Percent	
Total forest area	Forest	Percent	Calculated: DecFor + ConFor + MixFor
Total forest and low density development area	Forest2	Percent	Calculated: Forest + ForWet + LowDen
Area of barren land	Barren	Percent	
Area of shrub land	Shrub	Percent	
Total open area	Open	Percent	Calculated: Barren + Srub
Area of grassland	Grass	Percent	
Area of pasture	Pature	Percent	
Area of cropland	Crop	Percent	
Total agriculture area	Agr	Percent	Calculated: Grass + Pasture + Crop
Area of forested wetlands	ForWet	Percent	
Area of nonforest wetlands	Wetland	Percent	
Total wetland area	AllWet	Percent	Calculated: ForWet + Wetland
Storage area of lakes, ponds, and wetlands	StorNLCD	Percent	Calculated: Water + AllWet

Table 1–1. Basin characteristics tested for use as explanatory variables in regionalized regression equations for estimated flood flows at ungaged sites.—Continued

[ft, foot; ft/mi, feet per mile; mi, mile; mi/mi, miles per mile; mi/mi², miles per square mile; mi², square mile; °F, degrees Fahrenheit]

Basin characteristic	Name	Unit	Notes
Land cover—Continued			
Source: National Land Cover Dataset (NLCD) 2001 impervous surface layer http://www.csc.noaa.gov/digitalcoast/data/nlcd-impervious/index.html			
Area of impervious land	IMPERV	Percent	NLCD 2001 Impervious Surface
Source: National Hydrography Dataset (NHD) 1:24,000 http://nhd.usgs.gov/			
Storage area of lakes, ponds, and wetlands	StorNHD	Percent	Calculated from 1:24,000 NHD
Terrain			
Source: National Elevation Dataset (NED) 10-meter resolution http://seamless.usgs.gov/ned13.php			
Mean basin slope	MBslp	Percent	
Mean basin elevation	ELEV	ft	
Maximum basin elevation	ELEVmax	ft	
Minimum basin elevation	ELEVmin	ft	
Basin relief	RELIEF	ft	
Basin outlet elevation	OUTLETELEV	ft	
Infiltration			
Source: State GIS portals http://www.mass.gov/mgis/sg24k.htm http://www.edc.uri.edu/rigis/data/data.aspx?ISO=geoscientificInformation http://www.ct.gov/dep/cwp/view.asp?a=2698&q=322898			
Area of sand and gravel deposits	SG	Percent	
Area of till deposits	Till	Percent	
Source: Natural Resource Conservation Service (NRCS) SSURGO data http://soildatamart.nrcs.usda.gov/Default.aspx			
Area of hydrologic soils group A	SoilA	Percent	
Area of hydrologic soils group B	SoilB	Percent	
Area of hydrologic soils group C	SoilC	Percent	
Area of hydrologic soils group D	SoilD	Percent	
Climate			
Source: DAYMET - daily surface weather data and climatological summaries http://www.daymet.org/default.jsp			
Mean annual total precipitation	PRECIP	Inches	
Mean maximum daily temperature	MTempF	°F	
Stream network			
Source: National Hydrography Dataset (NHD) 1:24,000 http://nhd.usgs.gov/			
Total length of streams	STRMTOT	mi²	
Main channel slope	MCslp	ft/mi	Calculated: 10 and 85 percent of main channel distance.
Main channel sinuosity	SINOUS	mi/mi	Calculated: MCL/BL
Stream density	STRDEN	mi/mi²	Calculated: STRMTOT/DA

Appendix 2. Measurement of Regression Error

The accuracy of a regression depends on the model error and the sampling error. Model error measures the ability of the explanatory variables to estimate the flood flows calculated from the streamgage records. The model error depends on the number and predictive power of the explanatory variables in a regression equation. Sampling error measures the ability of a finite number of streamgages with a finite record to describe the true characteristics of flood flows. The sampling error depends on the number and record length of streamgages used in the analysis, which decreases as the number of streamgages and record lengths increase.

A measure of the uncertainty in a regression equation estimate for a site, i, is the variance of prediction, $V_{p,i}$. The $V_{p,i}$ is the sum of the model error variance and sampling error variance and is computed using the following equation (Eng and others, 2009):

$$V_{p,i} = \gamma^2 + MSE_{s,i} \,, \qquad (2\text{–}1)$$

where

γ^2 model error variance, and

$MSE_{s,i}$ sampling mean square error for site i.

Assuming that the explanatory variables for the streamgages in a regression analysis are representative of all streamgages in the region, the average accuracy of prediction for a regression equation is determined by computing the average variance of prediction, AVP, for n number of streamgages:

$$AVP = \gamma^2 + \frac{1}{n} MSE_{s,i} \qquad (2\text{–}2)$$

A more traditional measure of the accuracy is the standard error of prediction, S_p, which is simply the square root of the variance of prediction. The average standard error of prediction for a regression equation can be computed in percent error using AVP, in log units, and the following transformation:

$$S_{p,ave} = 100\,[10^{2.3026(AVP)} - 1]^{0.5} \qquad (2\text{–}3)$$

where

$S_{p,ave}$ is the average standard error of prediction, in percent.

Appendix 3. Link to Spreadsheet RI_Flood-Flow-Equations.xls

[Click on worksheet title below to link to spreadsheet]

Regional-FFQ Computes annual-exceedance probability (AEP) flood flows and 95-percent confidence interval from regional regression equations developed for ungaged sites in Rhode Island.

US-DS Flow Equations for improving estimates of flood flows, within certain limits, at an ungaged site on a stream above or below a gaged location in Rhode Island.

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