Prepared in cooperation with the Massachusetts Department of Transportation

Magnitude of Flood Flows at Selected Annual Exceedance Probablities for Streams in Massachusetts

Scientific Investigations Report 2016–5156

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

Cover. **Front.** The Shawsheen River overtopping its banks downstream of U.S. Geological Survey streamgage 01100627, at Balmoral St. in Andover, Massachusetts, on March 17, 2010. Streamflow at the time of this photograph was 2,500 cubic feet per second. Photograph by Andrew Waite, U.S. Geological Survey.
Back. Flood damage to State Route 2 along the Cold River (looking downstream) in Savoy, Massachusetts, resulting from Tropical Storm Irene on August 28, 2011. Photograph by Stephen O’Brien, U.S. Geological Survey.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
inch (in.)	25.4	millimeter (mm)
mile (mi)	1.609	kilometer (km)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	2.590	square kilometer (km^2)
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:

$$°C = (°F - 32) / 1.8.$$

Datum

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
AVPnew	average variance of prediction for a new site
B17B	Bulletin 17B
CI	confidence interval
DRNAREA	drainage area, in square miles
ELEV	mean basin elevation in feet
EMA	expected moments algorithm
EPA	U.S. Environmental Protection Agency
GLS	generalized least square
IMPERV	impervious area
LC06STOR	basin storage defined by the percent area in open water and wetlands
LOWESS	locally weighted least squares

MassDOT	Massachusetts Department of Transportation
MGBT	multiple Grubbs-Beck test
MOVE	maintenance of variation extension
MSE	mean square error
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NSS	National Streamflow Statistics
NWIS	National Water Information System
OLS	ordinary least squares
PILFs	potentially influential low flows
SG	percent of basin area in sand and gravel
StrDEN	stream density
TAU	Kendall Tau test
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WgtE	weighted estimate
WLS	weighted least squares
WREG	Weighted Multiple Linear Regression program

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Abstract

The U.S. Geological Survey, in cooperation with the Massachusetts Department of Transportation, determined the magnitude of flood flows at selected annual exceedance probabilities (AEPs) at streamgages in Massachusetts and from these data developed equations for estimating flood flows at ungaged locations in the State. Flood magnitudes were determined for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs at 220 streamgages, 125 of which are in Massachusetts and 95 are in the adjacent States of Connecticut, New Hampshire, New York, Rhode Island, and Vermont. AEP flood flows were computed for streamgages using the expected moments algorithm weighted with a recently computed regional skewness coefficient for New England.

Regional regression equations were developed to estimate the magnitude of floods for selected AEP flows at ungaged sites from 199 selected streamgages and for 60 potential explanatory basin characteristics. AEP flows for 21 of the 125 streamgages in Massachusetts were not used in the final regional regression analysis, primarily because of regulation or redundancy. The final regression equations used generalized least squares methods to account for streamgage record length and correlation. Drainage area, mean basin elevation, and basin storage explained 86 to 93 percent of the variance in flood magnitude from the 50- to 0.2-percent AEPs, respectively. The estimates of AEP flows at streamgages can be improved by using a weighted estimate that is based on the magnitude of the flood and associated uncertainty from the at-site analysis and the regional regression equations. Weighting procedures for estimating AEP flows at an ungaged site on a gaged stream also are provided that improve estimates of flood flows at the ungaged site when hydrologic characteristics do not abruptly change.

Urbanization expressed as the percentage of imperviousness provided some explanatory power in the regional regression; however, it was not statistically significant at the 95-percent confidence level for any of the AEPs examined. The effect of urbanization on flood flows indicates a complex interaction with other basin characteristics. Another complicating factor is the assumption of stationarity, that is, the assumption that annual peak flows exhibit no significant trend over time. The results of the analysis show that stationarity does not prevail at all of the streamgages. About 27 percent of streamgages in Massachusetts and about 42 percent of streamgages in adjacent States with 20 or more years of systematic record used in the study show a significant positive trend at the 95-percent confidence level. The remaining streamgages had both positive and negative trends, but the trends were not statistically significant. Trends were shown to vary over time. In particular, during the past decade (2004–2013), peak flows were persistently above normal, which may give the impression of positive trends. Only continued monitoring will provide the information needed to determine whether recent increases in annual peak flows are a normal oscillation or a true trend.

The analysis used 37 years of additional data obtained since the last comprehensive study of flood flows in Massachusetts. In addition, new methods for computing flood flows at streamgages and regionalization improved estimates of flood magnitudes at gaged and ungaged locations and better defined the uncertainty of the estimates of AEP floods.

Introduction

Knowledge of the magnitude of floods at a given annual exceedance probability (AEP) is needed for the effective and safe design of bridges, culverts, roadbed elevations, and other structures. This information is also important for flood plain planning and management. The flood flow equations for Massachusetts currently incorporated into the U.S. Geological Survey (USGS) National Flood Frequency Program (Ries and Crouse, 2002) were developed from studies completed by Wandle in 1977 and revised in 1983 (the revision updated the regression methods used but did not include any new data from the 1977 report). Wandle (1983) reported the magnitude of floods at streamgages in Massachusetts up to the 1-percent annual AEP (referred to as the 100-year return interval) following the guidelines in Bulletin 17B (B17B; Interagency Advisory Committee on Water Data, 1981) and developed regionalized equations from the at-site analysis to estimate flood magnitudes at ungaged sites.

Equations for estimating flood magnitudes in Massachusetts using mixed-population distributions (that is, floods of different origins are fit to different theoretical distributions) were developed by Murphy (2001a, b). Although the guidelines in B17B have provisions for developing estimates of flood frequencies from theoretical distributions other than log-Pearson type III, the equations developed by Murphy have not been widely accepted, in part, because the analysis included only 30 streamgages in Massachusetts and because of the limited number of floods that were of tropical storm or hurricane origin. Prior work on flood magnitudes in Massachusetts was done by Knox and Johnson (1965) and Johnson and Tasker (1974). None of the previous studies provided prediction intervals around estimates of flood magnitude at ungaged sites for a given AEP, which can be an important consideration in structure design and flood risk assessment.

Since the work by Wandle (1983) and Murphy (2001a, b), about 37 and 20 years of additional streamflow records have accumulated, respectively, over which time many of the largest recorded peak flows have occurred. For example, annual peak flows in 2006 and 2010 at Ipswich River at Ipswich (01102000) exceeded the previous largest annual peak flow of record (1968) used by Wandle by about 72 and 47 percent, respectively. The 2006 and 2010 peak flows exceeded the largest annual peak flow of record (1987) used by Murphy by about 29 and 11 percent, respectively (fig. 1). Analyses of the April 2007 flood at 10 streamgages in central Massachusetts show large changes in the magnitude of a flood for a given AEP when updated with currently available data (Zarriello and Carlson, 2009). Large peak flows that often greatly exceed the peak flows of record in prior flood frequency analyses can have a profound effect on the statistical moments of the data from which the magnitude of a flood for a given AEP is determined.

Periodic examination of flood frequency characteristics at streamgages and the regional flood flow equations developed from those data is essential to ensure the best estimate of the flood magnitude for a given AEP. Reexamination also addresses a key recommendation of Massachusetts Executive Office of Energy and Environmental Affairs (2011) by establishing a benchmark for present flood conditions from which changes can be measured. To meet this need, the USGS entered into an agreement with the Massachusetts Department of Transportation (MassDOT) in 2013 to document and characterize the magnitude of flood flows at streamgages and to develop regional equations for estimating the magnitude of flood flows for most ungaged streams in the State.

Purpose and Scope

The report documents the magnitude of flood flows at 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs (in the past these have often been referred to as 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year return interval floods, respectively) at streamgages in Massachusetts. The report also documents the development of regional regression equations from the streamgage AEP analysis to estimate flood flows at ungaged locations and to improve estimates of flood flows at streamgages. The data used in this report were compiled from annual peak flows from 220 streamgages in Massachusetts, Connecticut, New Hampshire, New York, Rhode Island, and Vermont through water year[1] 2013 or the latest year of record

[1]A water year is the 12-month period beginning October 1 and ending September 30. It is designated by the year in which it ends.

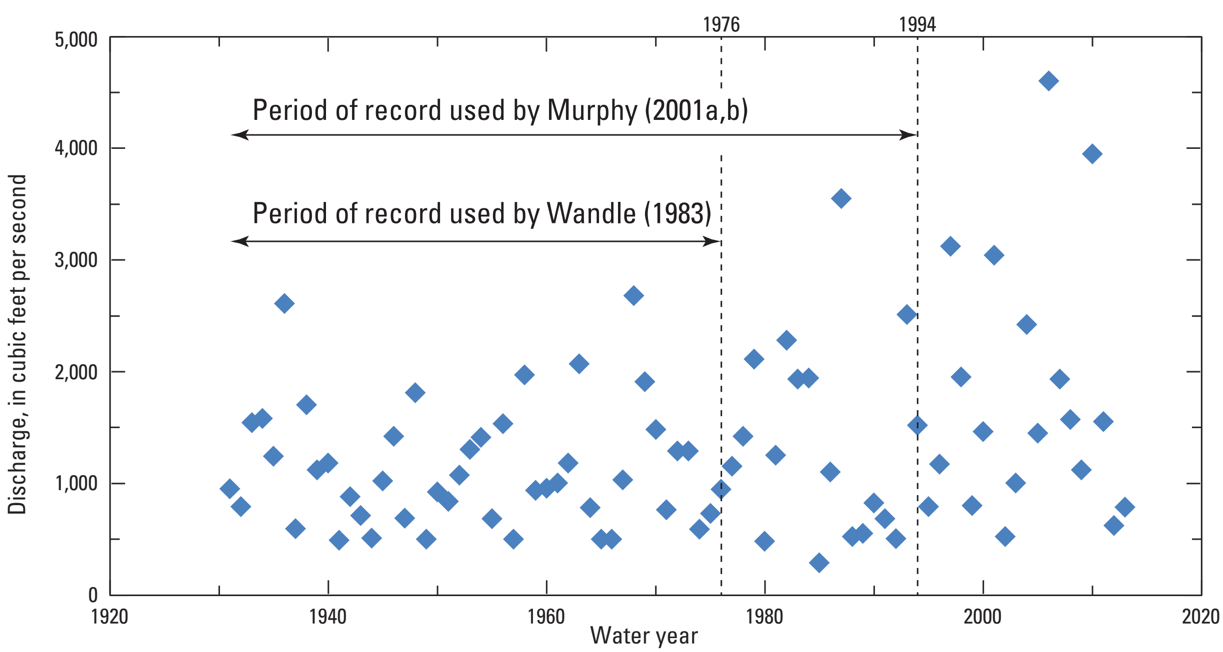


Figure 1. Annual peak flows recorded at Ipswich River at Ipswich, Massachusetts (01102000), and period of record used in studies of flood magnitude in Massachusetts. Water year is the 12-month period from October 1 of one year through September 30 of the following year and is designated by the calendar year in which it ends.

at discontinued streamgages. Trends in the annual peak flow at streamgages and the effects of urbanization, and their potential effects on future floods, are examined. Methods to better estimate flood flows at an ungaged site on a gaged stream near the streamgages are described. The limitations of the study and the uncertainties of the flood estimates are also discussed.

Study Area

The study area includes streamgages across Massachusetts and in the adjacent States (fig. 2) of Connecticut, New Hampshire, New York, Rhode Island, and Vermont that were considered suitable for use in the analysis (streamgage basin centroids are within about 40 miles of the Massachusetts border, have a relatively long period of record, and are unaffected or minimally affected by regulation). Streamgages outside of Massachusetts provide additional information representative of the hydrologic region. The regional regression equations developed for estimating flood magnitudes at ungaged sites do not include the U.S. Environmental Protection Agency (EPA) level III Atlantic Coastal Pine Barrens ecoregion (fig. 2; U.S. Environmental Protection Agency, 2010), which includes the southeastern most part of Massachusetts, Cape Cod, and the islands, because of its unique geohydrology and lack of streamflow information.

The EPA level III ecoregions, which denote generally similar types, quality, and quantity of environmental resources (Omernik, 1995), roughly coincide with physiographic provinces of New England by Denny (1982). The Northeastern Coastal Zone covers southeastern New Hampshire, eastern and south-central Massachusetts, Rhode Island, and most of Connecticut. The Northeastern Highlands cover most of New Hampshire, Vermont, north-central and western Massachusetts, northwestern Connecticut, and eastern New York. The drainage areas of selected streamgages used in the regional analysis are about evenly distributed between the Northeastern Coastal Zone and Northeastern Highlands ecoregions (108 and 91 streamgages, respectively). The Northeastern Highlands ecoregion is characterized by hills and mountains with high gradient streams, lakes formed from glacial processes, and a sparse population relative to the coastal region. The Northeastern Coastal Zone ecoregion is characterized by relatively low topography (plains to low and high hills) and greater development associated with the greatest concentration of people.

Climate in the study area 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 degrees Fahrenheit in the study area. Surficial geology consists of mainly glacial stratified deposits along the major river valleys and glacial till or exposed bedrock in the upland areas.

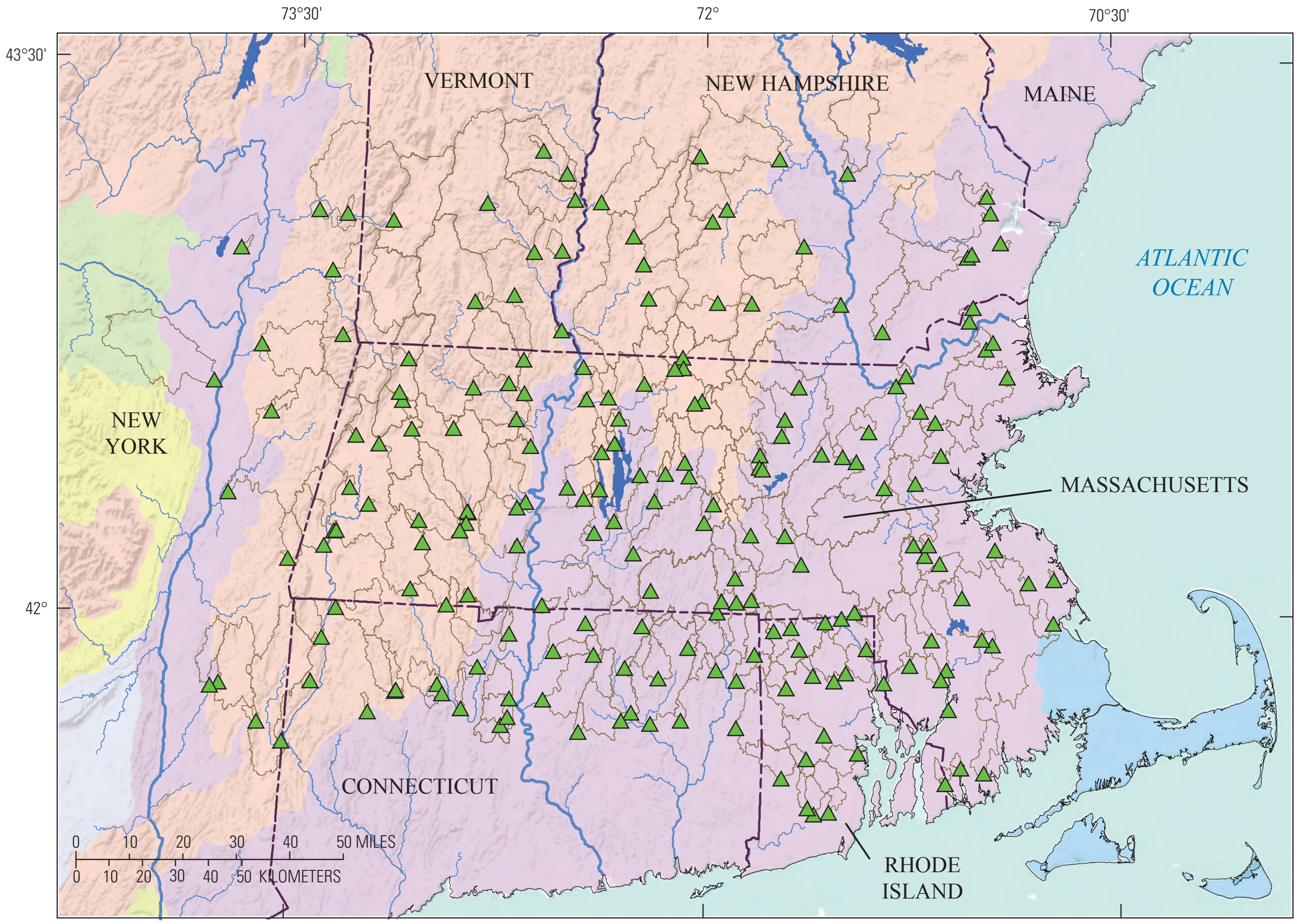
Land cover (Fry and others, 2011) for the study area ranges from highly developed in and near major metropolitan centers, such as Boston, to predominantly forested (fig. 3). Most developed areas are in eastern Massachusetts, the Connecticut River Valley, and coastal areas. Land cover and other characteristics vary by basin and are discussed in greater detail in the “Basin and Climate Characteristics” section, which describes basin characteristics used to develop regional 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 (undated) online tool for historical hurricane tracks indicates that 60 hurricanes, tropical storms, tropical depressions, and extratropical storms have passed within a 120 mile radius of central Massachusetts since 1851 (fig. 4). These storms typically originate in the central Atlantic and often follow a track along the eastern United States up through New England. The hurricane tracking program lists 36 storms that passed through the study area from 1851 through 2008. Streamflow data collection in the area began in 1904; 25 of the tracked storms occurred since 1944 when streamgages were more widespread in the State.

Previous Flood-Related Studies

Historical accounts of large floods provide some insight into the frequency of major events. Major storms in 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 a center of commerce at that time. Little information is available on the physical properties of these storms that can be used in flood frequency analysis, such as the magnitude of the peak flow or depth of flooding along a river reach.

Thomson and others (1964) summarized major flooding events in New England up to the early 1960s from streamflow records and other sources, such as the accounts by Perley (1891), newspaper stories, and accounts by local residents. A chronology of major storms dating back to 1620 is described, but the early accounts of the storms rarely have quantitative information that can be used other than to assess the frequency of large storms. An account of an 1807 storm on the Charles River in eastern Massachusetts reads, “There was a great freshet in the river following a thirty-six hour rain. Many mill dams and bridges were carried away, among them Boies dam at Waltham. . . . The Boies Dam was built in 1788” (Thomson and others, 1964). Similar to the description of storms of New England by Perley (1891), accounts of flooding by Thomson and others (1964) often lack sufficient detail to provide information that could be used in flood frequency analysis. The frequency of floods in New England was investigated by the U.S. Army Corps of Engineers in 1958 following major flooding in August and September 1955 from back-to-back remnants of Hurricanes Connie and Diane (U.S. Army Corps of Engineers, 1958). The report lists dates of 38 hurricane related floods dating back to 1916.



Base modified from U.S. Geological Survey digital data, 1:100,000, 2005
Hydrography from U.S. Geological Survey National Hydrography Dataset, 1:24,000, 2014

Ecoregions mapped by U.S. Environmental Protection Agency, 2010

EXPLANATION

U.S. Environmental Protection Agency level III ecoregion

Northeastern Coastal

Northeastern Highlands

Atlantic Coastal Pine Barrens

Northern Allegheny Plateau

Eastern Great Lakes Coastal Lowlands

Ridge and Valley

Basin boundary

Streamgage

Figure 2. U.S. Environmental Protection Agency level III ecoregions, distribution of streamgages used in the regional flood flow analysis for Massachusetts, and boundaries of basins upstream of the streamgages.

More recent accounts of large floods include analysis of the systematic peak flow record (that is, a period or periods of continuous annual peak-flow record) and other more quantitative information that can be used for flood analyses, such as indirect flow measurements made following a flood. A general overview of floods since the advent of streamgages is provided in Paulson and others (1991). Kinnison (1930) summarizes the November 1927 flood in New England caused by a tropical storm that followed a wet month. Few streamgages were in operation in 1927 to quantify the flood, but it is among the largest floods recorded in the western part of the State. Grover (1937) describes a rain and snowmelt flood in March 1936 that affected most parts of the State. The 1936 flood was the largest recorded flood of the Connecticut River at Hartford, CT (01190070) since 1801 and is still among the highest recorded peak flows among the few streamgages in operation

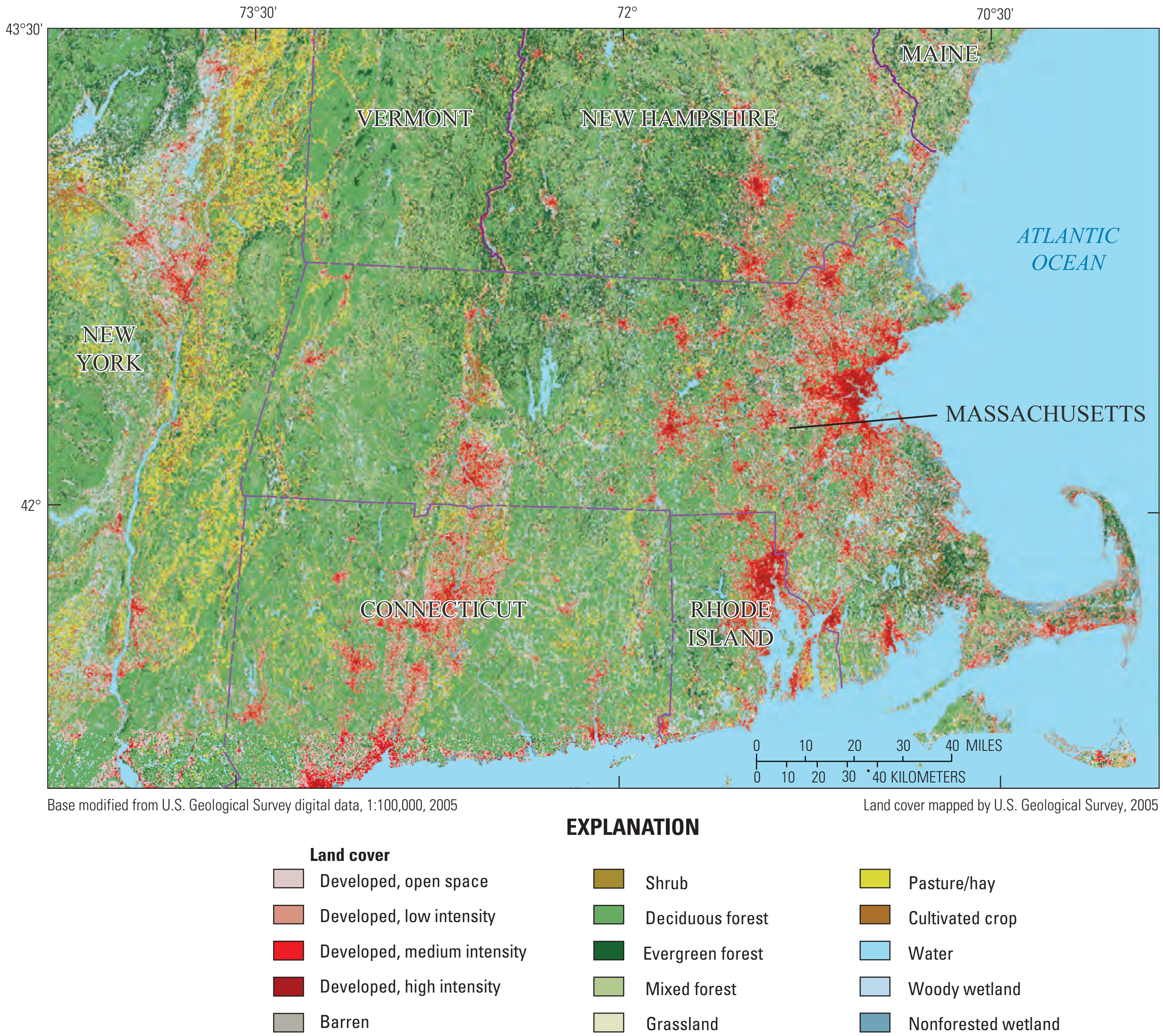


Figure 3. Land cover for the study area in Massachusetts and adjacent States.

at that time. Paulsen and others (1940) describe a hurricane related flood of September 1938, which is characterized as the worst disaster in New England with the most severe flooding in the western and central parts of the State. The 1938 flood was documented by indirect measurements at 11 streamgages in western and west-central Massachusetts, which still define the upper end of the stage-discharge rating for most of these streamgages.

Back-to-back remnants of Hurricanes Connie (August 3) and Diane (August 7) in 1955 caused record flooding in the south-central part of the State (U.S. Army Corps of Engineers, 1956; U.S. Geological Survey, 1956; Bogart, 1960). These hurricanes tracked well west and south of central Massachusetts, but the cumulative rainfall during a 2-week period was still sufficient to cause widespread severe flooding in parts of Massachusetts and in Connecticut. Although not particularly noteworthy, the March 1968 flood is described by U.S. Army Corps of Engineers (1968), Wood and others (1970), Swallow and others (1971), Swallow and Fogarty (1973), and Swallow and Wood (1973). Parker and others (1998) describe the June 1998 flood. Comparable flooding occurred in 1979, but no specific reports were generated. Rain and snowmelt caused widespread flooding during March to April 1987 (Fontaine, 1987). Zarriello and Carlson (2009) describe flooding at 10 streamgages in north-central Massachusetts following a large nor’easter storm in

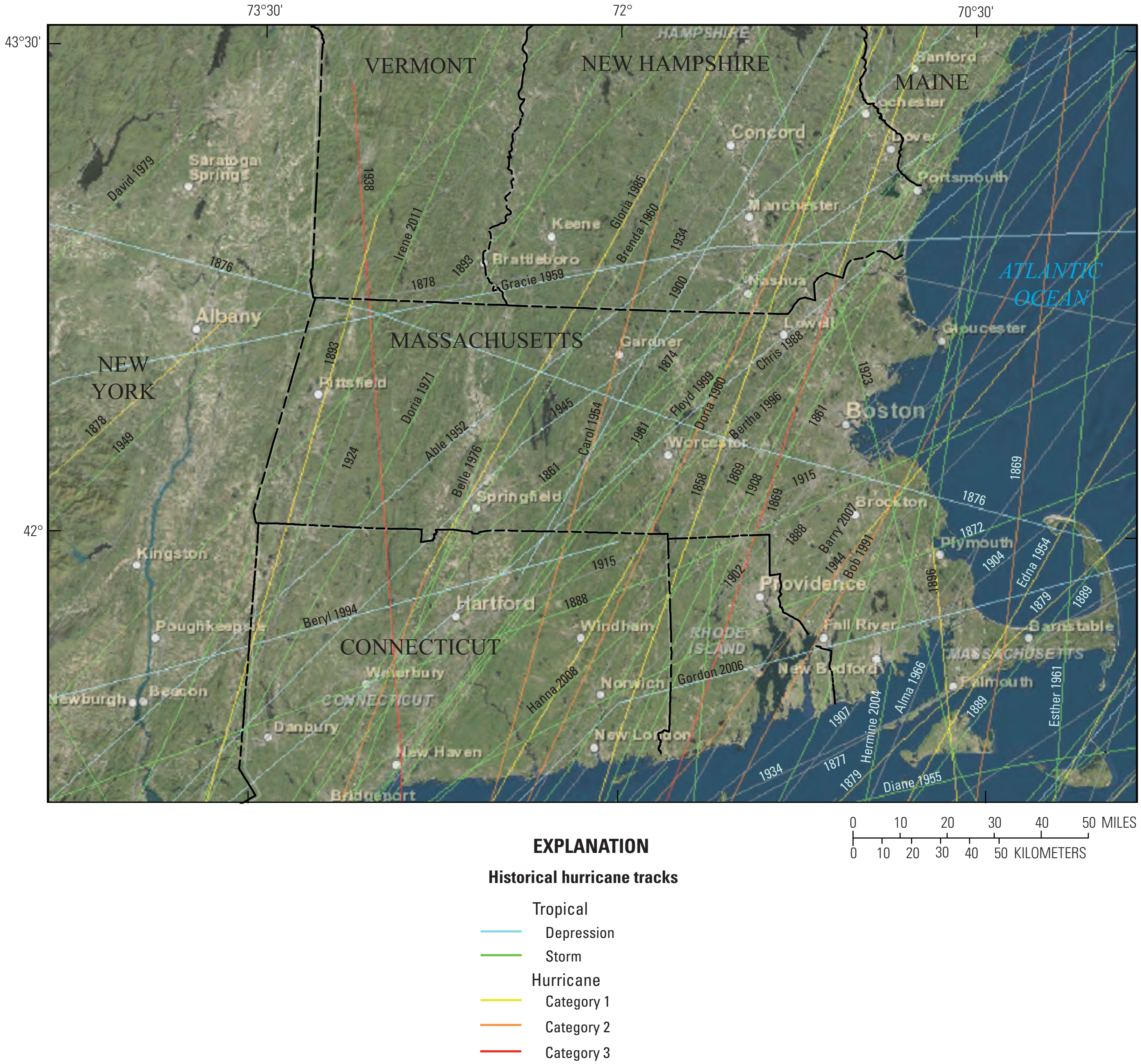


Figure 4. Hurricane and hurricane related storm tracks from 1851 through 2008 in and near Massachusetts; from National Oceanic and Atmospheric Administration (undated).

April 2007. Zarriello and Bent (2011) document high-water marks in eastern Massachusetts following heavy rains during March and April 2010 that set new peak flows of record at 13 streamgages in eastern and central-eastern Massachusetts. Remnants of Hurricane Irene in August 2011 set new peak flows of record at 10 streamgages in western Massachusetts with 25 or more years of record (Bent and others, 2013), but the 1938 peak flow was comparable or exceeded the 2011 peak flow at 5 streamgages (only 6 of the 25 long-term streamgages were in operation in 1938).

Regionalized flood flows for Massachusetts for selected annual exceedance probabilities were first published by Kinnison and Colby (1945) based on the correlation between mean annual floods and selected basin characteristics (drainage area, mean distance to outlet, mean altitude above streamgage, and storage area). Estimated flood flows for New England were published by the U.S. Army Corps of Engineers in 1958. The U.S. Army Corps of Engineers (1958) 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. Benson (1962) evaluated floods and methods for computing the magnitude of floods in New England for frequencies ranging from 1.2 to 300 years (83.3- to 0.33-percent AEPs, respectively). Benson evaluated a range of basin characteristics that affect the magnitude of floods and found six variables were significant in explaining the variation in peak flows at 254 sites throughout New England. Green (1964) developed regional flood frequency curves for estimating flood flows for any recurrence interval between 1.1 and 100 years (90.9- to 1-percent AEPs, respectively) for North Atlantic Slope Basins from Maine to Connecticut. Green (1964) compiled peak flow data through water year 1960 at 146 streamgages (the same streamgages used in Benson, 1962). From these data, composite curves were developed by subregion to relate the ratio of the mean annual flood to floods of varying frequencies (also referred to as the index flood method).

Johnson and Tasker (1974) published regional equations for estimating flood magnitudes in Massachusetts with return intervals of 2 to 100 years (50- to 1-percent AEPs, respectively). Johnson and Tasker (1974) was the first to use multiple regression techniques for the analysis; the significant explanatory variables were drainage area, main channel slope, and mean annual precipitation in the basin. Wandle (1977) published flood flow equations for Massachusetts for natural streams with drainage areas ranging from 0.25 to 497 square miles (mi^2). The equations were developed for estimating the magnitude of 50- to 0.2-percent AEPs floods from 113 streamgages using annual peak flows for the period of record up to 1976 water year. Wandle (1977) divided the State into two regions—eastern and western—to better define flood magnitudes. In 1983, Wandle published revised equations for estimating peak flows for 50- to 1-percent AEPs on small rural streams in Massachusetts. The revised equations used data from 95 streamgages that were divided in three regions of the State—eastern, central, and western. In the eastern region, drainage area was the only explanatory variable; in the central region, storage was added as an explanatory variable. In the western region, drainage area, mean basin slope, and mean basin elevation were used as explanatory variables. The revised equations improved the standard error of estimate by about 5 percent relative to the previous equations developed by Wandle in 1977. The 1983 equations by Wandle were incorporated into the National Flood Frequency Program for Massachusetts by Jennings and others (1994).

Murphy (2001a, b) examined mixed-population distributions for “normal” (average) and “tropical cyclone” annual peak flows at 30 selected streamgages in Massachusetts. Normal peak flows are spring high flows or nonextreme rainfall events, whereas tropical cyclone peak flows are related to hurricanes or hurricane-related events. Murphy (2001a, b) postulated that a single population distribution inadequately fit the true probability distribution and the true distribution could be better defined by a mixed-population distribution. The analysis used the period of record up to 1993, but the number of tropical cyclone-related peak flows ranged from zero at six streamgages to a maximum of six at two streamgages. Most streamgages used in the analysis had only one to three peak flows designated as tropical cyclone origin. Hence, a population distribution for these peak flows cannot be well defined. Although the method was not widely accepted, it may be of use in the future when a sufficient number of peak flows are available to define a mixed-population distribution.

As part of a regional flood flow analysis for Rhode Island, Zarriello and others (2012) used streamgages in south-central and southeastern Massachusetts as well as streamgages in Rhode Island and eastern Connecticut. The regional flood flow equations developed from the Rhode Island analysis have some applicability to streams in this region of Massachusetts.

Magnitude of Flood Flows at Streamgages

The magnitude of floods at streamgages were computed for 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs, which have often been referred to in the past as 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year floods, respectively. The AEP flows were generally determined in three parts. First, an initial analysis of annual peak flows at 153 streamgages throughout New England was made using the expected moments algorithm (EMA) to determine the at-site skew. The at-site skews for selected streamgages in Massachusetts and other New England States were then used in a regional skew analysis to determine the appropriate skew for weighting the at-site skew before computing the AEP flood flows at the streamgages (Veilleux and others, in press). The EMA analysis was repeated using the regional skew and its standard error for unregulated streamgages in Massachusetts and for nearby streamgages in adjacent States that could be used to develop regional flood flow equations.

Flood magnitudes were reported for some streamgages in Massachusetts but were not used in the regional skew because of regulation or redundancy. Streamgages on the same river or stream, or tributary thereof, were considered redundant if the drainage area between the streamgages was within an area about three times the drainage area of the smaller streamgage basin. Redundant streamgages with the longest period of record were generally used in the regional analysis. The only exception was Cadwell Creek near Pelham, Mass. (01174600), which was chosen over Cadwell Creek near Belchertown, Mass. (01174900) because the Pelham streamgage has nearly the same period of record but is within the smaller of the two small basins. All data used in the study are from the USGS National Water Information System (NWIS) peak-flow database (U.S. Geological Survey, 2012). Additional information for any USGS streamgage, including location and types of record, can be found at U.S. Geological Survey (2015).

The magnitude of floods at streamgages was determined from the statistical properties of the annual peak flows using guidelines developed by the Interagency Committee on Water Data (1981), which generally recommend fitting annual peak flows at a streamgage to a log-Pearson type III distribution to compute the magnitude of a flood for a given annual exceedance probability. The magnitude of the flood for a given AEP is computed from three properties of the logs of the annual peak flow data—mean, standard deviation, and skew—using the following equation:

$$\log Q_P = \overline{X} + K_P S \,, \tag{1}$$

where

- Q_P is the P-percent AEP flow, in cubic feet per second, where P equals the probability that an annual peak flow will be exceeded in a 1-year period;
- $\overline{X}$ is the mean of the logarithms of the annual peak flows;
- K_P is a factor that is based on the skew and the given percent AEP (obtained from B17B; Interagency Advisory Committee on Water Data, 1981, app. 3); 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.

An updated procedure similar to that of B17B, known as the EMA, was used in this study. The EMA uses a log-Pearson type III distribution, but unlike the log-Pearson type III procedures outlined in B17B, which are constrained to the moments of point values of the data, the EMA accommodates interval data, perception thresholds, and censoring of multiple low outliers to better define the distribution characteristics of annual peak flows (Cohn and others, 1997). Perception thresholds and interval data can represent conditions such as the potential range of annual peak flows outside the systematic and historic record as well as the uncertainties around recorded peak flows used in the analysis. The EMA then uses an iterative procedure to compute 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. When only a systematic record is used in the analysis (that is, no perception or interval data are 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 log-Pearson type III procedure in B17B in the next update of the guidelines. The EMA was applied in this study using USGS PeakFQ version 7.1 (Flynn and others, 2006).

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, B17B recommends weighting the station skew with a generalized skew computed regionally from many streamgages, described further in the "Magnitude of Flood Flows at Ungaged Streams" section.

Low Outlier Adjustment

When the distribution of peak flow records from a streamgage are skewed to the left by low outliers, the magnitude of flood flows, particularly for higher AEP floods, are leveraged downward. Because the primary interest of a flood frequency analysis is the magnitude of floods that occur with an AEP of 50 percent or less, B17B outlines a conditional probability adjustment for low outliers before further analysis is made. However, procedures in B17B identify and condition only the smallest low outlier and fail to detect and treat other potentially influential low flows (PILFs). A modified version of the Grubbs-Beck test (Grubbs and Beck, 1972) developed by Cohn and others (2013) and referred to as the multiple Grubbs-Beck test (MGBT) detects multiple PILFs that are censored by representing these outliers as "less-than" values in the EMA analysis. The resulting flood frequency distribution is more robust than the B17B method because the right-hand tail of the frequency distribution (large floods) is minimally affected by PILFs. The MGBT and conditioning of PILFs are incorporated into PeakFQ (version 7.1.23558) when using the EMA option. The EMA option was used for all streamgage analyses to develop a regional skew and again in the streamgage analyses weighted with the regional skew.

Although low outliers are generally uncommon in the humid northeast, the MGBT detected low outliers at 20 streamgages in Massachusetts and 12 streamgages in adjacent States used in the analysis (table 1). Streamgages with low outliers were conditioned by EMA by setting the outlier value to "less-than" the threshold determined by the MGBT. Most streamgages used in the analysis did not have PILFs. Streamgages with PILFs typically had only one or two PILFs, and these occurred mostly during the extended drought in the mid-1960s. At a few streamgages, multiple PILFs were detected and conditioned; these also occurred mostly during drought years.

Historic Data

Historic data are peak flows, stages, or both that are outside the period of continuous record referred to as the systematic record. Historic peak flows in the USGS peak-flow database (U.S. Geological Survey, 2012) are typically large infrequent events where an effort was made to quantify the

Table 1. Low outliers detected in peak-flow database for streamgages used in the flood flow analysis for Massachusetts.

[Threshold, discharge for low outliers determined by the multiple Grubbs-Beck test, in cubic feet per second (ft^3/s). Conditioned peaks indicate the discharge of low outliers modified to threshold value. MA, Massachusetts; Trib, Tributary; No, number; RI, Rhode Island; CT, Connecticut; NY, New York; NH, New Hampshire; Br., Branch]

Number	Name	Number of peak flows	Low outliers	Threshold (ft^3/s)	Conditioned peaks (ft^3/s)	Respective water year[1]
			Massachusetts			
01095200	Houghton Brook near Oakdale, MA	20	4	17	6, 10, 12	1966, 1971, 1967
01105730	Indian Head River at Hanover, MA	47	1	344	183	1985
01109060	Threemile River at North Dighton, MA	47	1	483	290	1985
01109070	Segreganset River near Dighton, MA	47	1	163	84	1985
01109100	Taunton River Trib near Fall River, MA	19	1	30	12, 17	1977, 1976
01123160	Wales Brook Trib near Wales, MA	20	1	14	13	1964
01163200	Otter River at Otter River, MA	49	1	76	29, 51	1965, 1971
01170900	Mill River near South Deerfield, MA	12	1	88	36	1965
01171500	Mill River at Northampton, MA	75	2	808	354, 660	1957, 1965
01174000	Hop Brook near New Salem, MA	35	2	76	29, 51	1971, 1965
01175670	Sevenmile River near Spencer, MA	53	1	64	33	1965
01176450	Roaring Brook near Belchertown, MA	12	2	83	32, 34	1965, 1966
01178230	Mill Brook at Plainfield, MA	19	3	130	35, 64, 81	1967, 1965, 1964
01183810	Longmeadow Brook near Longmeadow, MA	20	1	49	45	1967
01197050	Churchill Brook at Pittsfield, MA	11	1	12	4	1965
01197155	Housatonic River Trib No 2 at Lee, MA	10	4	45	15, 16, 18, 19	1966, 1971, 1967, 1965
01197300	Marsh Brook at Lenox, MA	12	1	51	20	1974
01197550	Housatonic River Trib at Risingdale, MA	21	2	12	5, 8	1966, 1965
01198000	Green River near Great Barrington, MA	29	1	648	220	1965
01333000	Green River at Williamstown, MA	64	2	550	325, 374	1965, 2012
			Rhode Island			
01117350	Chipuxet River at West Kingston, RI	40	1	50	20	1981
01111250	Dry Arm Brook near Wallum Lake, RI	13	3	45	15, 20, 36	1977, 1971, 1966
01113600	Blackstone River Trib no. 2 at Berkeley, RI	13	1	22	7	1966
			Connecticut			
01205700	East Branch Naugatuck River at Torrington, CT	41	1	299	132	1965
			New York			
01329154	Steele Brook at Shushan, NY	35	8	53	20, 35, 36, 38, 40, 40, 41, 43	1988, 1982, 1994, 2003, 1983, 1980, 1987, 1995
01333500	Little Hoosic River at Petersburg, NY	62	1	948	436	1965
01358500	Poesten Kill near Troy, NY	45	1	1,200	491	1965
01359528	Normans Kill at Albany, NY	39	1	2,300	1,400, 2,300	1992, 1995
01362100	Roeliff Jansen Kill near Hillsdale, NY	56	2	383	169, 180	1971, 1965
			New Hampshire			
01085800	West Branch Warner River near Bradford, NH	42	12	283	102, 104, 125, 130, 134, 160, 191, 194, 202, 206, 208, 210	1967, 1972, 1989, 2002, 1994, 1991, 1968, 1988, 1963, 1964, 1966, 1965
01086000	Warner River at Davisville, NH	54	1	981	604	1957
01091000	South Br. Piscataquog River near Goffstown, NH	43	19	1,940	615, 900, 968, 1,050, 1,060, 1,210, 1,280, 1,300, 1,350, 1,460, 1,560, 1,580, 1,600, 1,700, 1,730, 1,800, 1,800	1945, 1955, 1978, 1946, 2009, 1941, 1961, 1976, 1972, 1950, 1964, 1971, 2013, 1943, 1947, 1957, 1949, 1966, 1965

[1]Water year is the 12-month period from October 1 of one year through September 30 of the following year and is designated by the calendar year in which it ends.

flood prior to an established streamgage or after a streamgage was discontinued. Occasionally, historic data are not noteworthy, such as the 1980 peak flow at Kettle Brook (01109500) that was entered into the database soon after the streamgage was discontinued but has no effect on the probability distribution of the annual peak flows. In EMA analysis, the historic data extend the record between the systematic record and the historic data by a user defined threshold value. The threshold value typically is defined by the magnitude of the historic peak flow and generally, in addition to the historic data itself, influences the annual peak flow probability distribution.

Of the 34 streamgages with historic peak flows, 15 had those peak flows recorded during either 1936 or 1938 water years (table 2). Large peak flows likely occurred prior to the collection of quantitative records, which precludes the use of this information for most flood frequency analyses. Quantitative measurement of historic peak flows were typically determined by indirect methods, such as flow over a dam, slope area, or contracted opening computations, 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. Most historic peak flows occur prior to the period of systematic record, but a few historic peak flows were reported after the systematic operation of the streamgage was discontinued for streamgages in Massachusetts, New Hampshire, and New York.

The historic peak flows ranked from the 1st to the 53d highest peak flow of record. Most historic peak flows are among the highest recorded and can have a profound effect on the probability distribution of the annual peak flows. Some streamgages have historic stage only records, which were generally reported when the stage could not be used to estimate discharge. In some instances an interval was specified in the EMA analysis to reflect a large event but with a wide range of uncertainty as to the magnitude of the discharge.

Regional Skew

Skew is one of the three moments of the data used to determine the magnitude of a flood for a given probability and can be greatly affected by the leverage of observations in the upper and lower tails of the annual peak-flow record, particularly for short records. The purpose of the regionalized skew is to adjust the at-site skew to better reflect regional and long term conditions. Negative skews indicate that the left side of the probability distribution curve is longer than the right side and that most of the values lie to the right of the mean. In contrast, positive skews indicate the right side of the probability curve is longer than the left side. Current at-site probability methods condition low outlier values to minimize their effects on the estimated flood flow magnitudes. Still, the accuracy of the at-site skew cannot be determined, but the skew can be better defined by pooling information from surrounding streamgages to weight the at-site skew on the basis of the mean squared error of the at-site and regional skew values (Interagency Advisory Committee on Water Data, 1981). Generally, the shorter the record, the more weight is given to the value of the regional skew, so the accuracy of the regional skew becomes increasingly important as the at-site record length decreases. Note 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.

To obtain a regional value of skew, an independent regional analysis of skews in New England was made by Veilleux and others (in press), partly in conjunction with this study. Data were compiled from the NWIS peak-flow database (U.S. Geological Survey, 2012) through water year 2011 at 186 selected streamgages in New England—51 in Massachusetts, 36 in Connecticut, 26 in Maine, 43 in New Hampshire, 3 in New York, 13 in Rhode Island, and 14 in Vermont. An at-site skew was determined for each streamgage using the EMA (Cohn and others, 2001). Selected basin characteristics for streamgages were compiled from the national Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES II) database (Falcone, 2011) to provide consistency across the region for use as possible explanatory variables.

The regional skew analysis used Bayesian methods to examine the posterior distribution of regression parameters and the model error variance to minimize the effects of cross correlation (Veilleux, 2011; Veilleux and others, 2012). Of the 186 streamgages selected for the New England skew analysis, 169 were used in the Bayesian analysis because of possible redundancy at 17 sites. Numerous variables were tested to explain the variation of at-site skews across New England, but none were found to be statistically significant. A single, regional skew value of 0.37 was found most applicable for New England with an average variance of prediction for a new site (AVP_{new}) of 0.14. Documentation and results of the development of a regional skew for New England can be found in Veilleux and others (in press). The New England regional skew was then used to improve at-site estimates of the flood magnitude for a given probability at each streamgage. The final at-site analysis for determining the AEP flows requires the use of the standard error of the regional skew (0.37), which is equivalent to the square root of AVP_{new} (0.14) determined in the regional skew analysis for New England. The updated regional skew is estimated to have more than three times the explanatory power of the previous skews reported in the national map of B17B, as measured by the effective record length.

At-Site Flood Flow Estimates

Peak-flow data from the NWIS database (U.S. Geological Survey, 2012) were compiled for 220 streamgages in Massachusetts and adjacent States (table 3). Of these, 125 streamgages are in Massachusetts, of which 104 were used in the regional flood flow analysis for computing peak

Table 2. Streamgages with historic data used in the Massachusetts flood flow analysis.

[Systematic record indicates the period(s) of continuous streamflow record at a streamgage. Historic record indicates an individual flow measurement made outside the period(s) of systematic record. Systematic record peak flow indicates the highest flow made during the period(s) of systematic record. Q, discharge in cubic feet per second; MA, Massachusetts; —, no data in peak-flow file; RI, Rhode Island; Stage, stage only with discharge estimated in some cases by use of interval data as specified in the footnotes; CT, Connecticut; NY, New York; VT, Vermont; NH, New Hampshire; Br., Branch]

U.S. Geological Survey streamgage		Systematic record[1]		Historic record		Systematic record peak flow	
Number	Name	Begin	End	Year	Q	Year	Q
Massachusetts							
01103500	Charles River at Dover, MA	1938	2013	1936	3,170	1955, 1968	3,220
01109500	Kettle Brook at Worcester, MA	1924	1978	1980	258	1955	3,970
01110500	Blackstone River at Northbridge, MA[2]	1940	2003	1936, 1979	7,510, 6,190	1955	16,900
01171300	Fort River near Amherst, MA	1967	1996	1936, 1938	2,360, 1,640	1979	2,100
01332000	North Br. Hoosic River at North Adams, MA	1932	1990	1928, 2011	9,980, 9,700	1938	8,950
Rhode Island							
01106000	Adamsville Brook at Adamsville, RI	1941	1978	1987	163	1970	317
01111500	Branch River at Forestdale, RI	1940	2013	1936	5,800	2006	6,290
01114500	Woonasquatucket River at Centerdale, RI	1941	2013	1936	1,000	2010	1,810
01116000	South Br. Pawtuxet River at Washington, RI	1940	2013	1936	1,810	2010	5,490
01117000	Hunt River near East Greenwich, RI	1940	2010	1938	Stage	2010	2,420
01118000	Wood River at Hope Valley, RI	1941	2010	1936	1,540	2010	5,470
Connecticut							
01121000	Mount Hope River near Warrenville, CT	1941	2013	1938	Stage	1955	5,590
01126000	Fivemile River at Killingly, CT	1939	1984	1936	1,600	1968	1,840
01184490	Broad Brook at Broad Brook, CT	1962	2013	1938	960	2006	1,990
01190100	Piper Brook at Newington Junction, CT	1958	1983	1955	2,200	1980	2,400
New York							
01329500	Batten Kill at Battenville, NY[3]	1923	2003	1904, 1913	11,700, 8,400	1928	21,300
01358500	Poesten Kill near Troy, NY	1924	1968	1977, 1984	5,500, 4,220	1938	11,900
01359528	Normans Kill at Albany, NY	1968	2013	1956, 1960	13,600, 13,000	2011	13,200
01361000	Kinderhook Creek at Rossman, NY	1909	2013	1913, 1984	8,780, 12,700	1949	29,800
01372200	Wappinger Creek near Clinton Corners, NY	1956	1982	1984	4,700	1983	8,510
01372300	Little Wappinger Creek at Salt Point, NY	1956	1975	1984	1,120	1975	1,590
Vermont							
01153500	Williams River at Brockways Mills, VT[4]	1941	2012	1938	Stage	2011	19,588
01154000	Saxtons River at Saxtons River, VT	1941	2013	1936, 1938	9,620, stage	2011	21,600
01329000	Batten Kill at Arlington, VT	1929	1984	2011	7,640	1936	11,100
New Hampshire							
01073600	Dudley Brook near Exeter, NH	1962	1985	2006, 2007	660, 470	1973	358
01082000	Contoocook River at Peterborough, NH[5]	1946	2013	1938, 1980	Stage[6], 1,650	2007	4,110
01084000	North Br. River near Antrim, NH	1925	1971	2006, 2010	5,190, 1,750	1936	5,190
01084500	Beard Brook near Hillsboro, NH	1946	1976	2006, 2007	4,800, 3,550	1960	2,190
01085800	West Br. Warner River near Bradford, NH	1963	2004	2006	1,010	2003	883
01086000	Warner River at Davisville, NH	1938	2013	1938	Stage[7]	2006	8,640
01089500	Suncook River at North Chichester, NH[8]	1919	2013	2006, 2007	7,600, 10,600	1936	12,900
01091000	South Br. Piscataquog River near Goffstown, NH[9]	1941	2013	2006, 2007	7,180, stage	2010	4,940
01094000	Souhegan River at Merrimack, NH[10]	1910	2013	1980	3,020	1936	16,900
01157000	Ashuelot River near Gilsum, NH[11]	1923	2013	2006	10,200	1938	5,220

[1]Indicates water year, which is the 12-month period from October 1 of one year through September 30 of the following year and is designated by the calendar year in which it ends.

[2]No record from 1978 to 1995.

[3]No record from 1968 to 1986; historic peak flows for 1904, 1913, 1977, and 1984 were 11,700, 8,400, 15,000, and 11,600 cubic feet per second, respectively.

[4]No record from 1985 to 1986.

[5]No record from 1978 to 1981; historic record stage for 1938 only with specified interval of 2,000 to 4,000 cubic feet per second.

[6]Not listed as historic peak.

[7]Peak interval used for 1938 is 3,000 to 5,000 cubic feet per second; no record from 1979 to 1999.

[8]No record for 1921, 1928, and from 1978 to 2007.

[9]No record from 1979 to 2008.

[10]No record from 1977 to 1981.

[11]No record from 1981 to 2005 and from 2007 to 2009.

flows at ungaged sites (table 3*A*). The other 21 streamgages in Massachusetts were unsuited for use in the regional analysis primarily because of redundancy or regulation, but they were reported in order to provide a comprehensive compilation of AEP peak flows in the State. For 10 of the Massachusetts streamgages, an analysis of the peak flows recorded prior to and after regulation was conducted; data acquired prior to regulation were used for seven of these streamgages in the regional analysis. Sixty-four of the Massssachusetts streamgages used in the regional analysis have 20 or more years of systematic record (median record length 50 years), and 40 of the Massachusetts streamgages have less than 20 years systematic record. Streamgages with less than 20 years of systematic record were used in the regional regressions primarily because these streamgages represent small drainage areas (less than a few square miles).

Table 3. Estimated magnitude of flood flows, confidence limits for selected annual exceedance probabilities, and trends in annual peak flows at streamgages in *A*, Massachusetts, by drainage basin, and *B*, adjacent States, by State, for the period of record through water year 2013.

[Table available for download at https://doi.org/10.3133/sir20165156]

Ninety-five streamgages in adjacent States (table 3*B*) with basin centroids within about 40 miles of Massachusetts were selected for use in the regional analysis. Streamgages outside of Massachusetts were selected on the basis of their suitability for use in the regional analysis (little or no regulation, nonredundant sites, and relatively long systematic records). The median systematic record length for streamgages outside of Massachusetts was 38 years.

For all streamgages, AEP flood magnitudes were computed using the weighted skew determined from the regional skew (0.37), the standard error of the regional skew (0.37), the AVP_{new} (0.14), and the at-site skew, except for streamgages that are regulated or for periods of record when regulation occurred. AEP flows computed on the basis of the at-site skew are provided to show the effect of the weighted skew in the analysis or to provide estimated AEP flows at regulated streamgages. Table 3 presents flows for a range of AEP floods and the 95-percent confidence interval of the AEP flow estimates for the weighted skew or the at-site AEP flow estimate for streamgages affected by regulation. Also listed in table 3 are trends in annual peak-flow data computed using the nonparametric Kendall Tau test (Kendall and Gibbons, 1990), which are discussed in the "Trends in Annual Peak Flows" section.

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 floods that may occur. The guidelines in B17B (Interagency Advisory Committee on Water Data, 1981) incorporate this uncertainty using the length of the record and the mean and variability of the peak flows in the analysis; as the record length decreases and the variability increases, the confidence level decreases, particularly at the upper tail of the distribution.

In addition to the improvements the EMA makes toward quantifying record gaps or the period between historic and systematic records, the EMA 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 peak flows, 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 typically much broader for the EMA than they were for B17B, but the EMA analysis provides a more realistic range of potential flows for a given AEP. The flow at the upper and lower 95-percent confidence intervals for various AEPs is listed in table 3.

Magnitude of Flood Flows at Ungaged Streams

Regional equations to estimate the magnitude of floods at selected AEPs at ungaged sites and to improve estimates of flood flows at gaged sites were developed from AEP flood magnitudes at selected streamgages and their respective basin characteristics. Basin and climate characteristics were examined to explain the variability of flow for a given AEP using regional regression techniques. Similar to the streamgage analysis, regression equations were developed for 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP flood flows. The development of regional flood flow equations consists of three basic parts—(1) compilation of basin characteristics, (2) exploratory analysis 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.

AEP flood flows determined at 220 streamgages were compiled prior to the regional regression analysis. Of these 220 streamgages, 199 were used in the regional regression analysis—104 in Massachusetts, 34 in Connecticut, 19 in New Hampshire, 13 in New York, 19 in Rhode Island, and 10 in Vermont. Twenty-one streamgages in Massachusetts were not used in the regional regression analysis primarily because of redundancy or regulation that could affect the magnitude of flood flows.

Basin and Climate Characteristics

Basin and climate characteristics are used to relate the magnitude of flood flows determined from the streamgage analyses in order to develop equations for estimating flood magnitudes. Sixty basin and climate characteristics were compiled for potential use as explanatory variables (appendix 1). These variables can be broadly characterized by land use type, terrain, infiltration, basin and stream morphology, and climate (table 4 lists a compilation of the 19 most significant variables used in the regional analysis). The distribution of 11 selected basin characteristics (fig. 5) for the 199 streamgages used in the analysis varied by State; generally, the characteristics overlap among States with differences reflecting the regional characteristics shown in figures 2 and 3.

Table 4. Selected streamgages and basin characteristics used in the flood flow analysis for Massachusetts.

[Table available for download at https://doi.org/10.3133/sir20165156]

Of the 60 basin and climate characteristics evaluated as potential explanatory variables in the regression, only the 3 most statistically significant characteristics discussed in the "Regional Regression Equations" section were used in the final regional flood flow equations—drainage area (*DRNAREA*), mean basin elevation (*ELEV*), and percent basin storage (*LC06STOR*). Basin boundaries were obtained from existing basin boundary datasets or delineated from the 10-meter resolution National Elevation Dataset (NED). Drainage area was transformed to base-10 logarithms, as were the AEP flows (dependent variable), for linearity. The mean elevation (in feet) was determined from the NED, which are provided in units of feet referenced to the North American Vertical Datum of 1988 (NAVD 88). Storage was determined as the percentage of the basin area classified as open water, forested wetlands, and nonforested wetlands in the National Land Cover Database 2006 (Fry and others, 2011).

Exploratory Analysis

The potential independent explanatory variables were evaluated for cross correlation and linearity with the dependent AEP flows and correlation with each other. Variables that required transformation to achieve better linear relation are those that have a large range of values and are typically a direct measure of a basin characteristic, such as the drainage area and the AEP flood flows. 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 with impervious cover. Exploratory statistics were determined using *R* version 3.1.0 (R Core Team, 2014). Exploratory statistics examine correlations between variables and identify variables that best describe the flood magnitudes using ordinary least squares (OLS) regression with an automated variable subset selection analysis. Subsets of variables were selected so that well correlated variables were not used simultaneously in order to avoid covariance that can adversely affect a regression. The subset selection process used a step backwards exhaustive function that reports the best three models for each of the explanatory variable combinations. Models are filtered on the basis of Mallows *Cp* value, but other regression statistics are reported including residual sum of squares (PRESS) statistic, adjusted-R^2 and R^2, and the standard error of the estimate.

Any of the subset models can be selected for further analysis that includes details of the OLS regression coefficients and model fit statistics not reported in the subset selection output. Additional statistics include the normality of the distributed error or residuals, multicolinearity measured by the variance inflation factor, goodness of model fit without over fitting the model as measured by Akaike's information criterion and Bayesian information criterion, influence of points measured by Cook's distance (D) and the F-statistic, significance of a variable in the regression (*p*-value), and various plots of linearity and fit.

On the basis of the exploratory OLS regression analysis, it was concluded that four variables would be further analyzed using the more robust generalized least squares (GLS) regression analysis—drainage area (*DRNAREA*), in square miles, storage (*LC06STOR*), in percent of basin classified as open water or wetlands, mean basin elevation (*ELEV*), in feet, and stream density (*StrDEN*). Other transformations and variables were tested in *R* version 3.1.0, including separating models into subregions, but no significant gain in the model fit was realized. Use of percent of basin area with impervious cover (*IMPERV*) and percent area underlain by sand and gravel (*SG*) did not result in significant gains in the OLS model fit but were further evaluated using GLS regressions. The ranges of these six explanatory variables in the analysis are listed in table 5.

Subsets of data based on regional position of the streamgage and record length were also evaluated using OLS analysis. The regional position was determined using EPA Northeastern Coastal Zone and Northeastern Highland ecoregion level III regions on the basis of where the greatest amount of the basin drainage area lies; only a few basins were divided between ecoregions. Subsets of data by ecoregion (fig. 2) were about equally divided between the coastal (91 streamgages) and highlands (108 streamgages). OLS regressions indicate that a subregional model for the Northeastern Highlands fits slightly better than a single model for the entire study area, and a single subregional model for the Northeastern Coastal Zone area is slightly worse than a single model for the entire study area. The differences between a single model and subregional models as measured by the *Cp*, *PRESS*, adjusted-R^2 and R^2, and the standard error of the estimate were not sufficient to merit separate models.

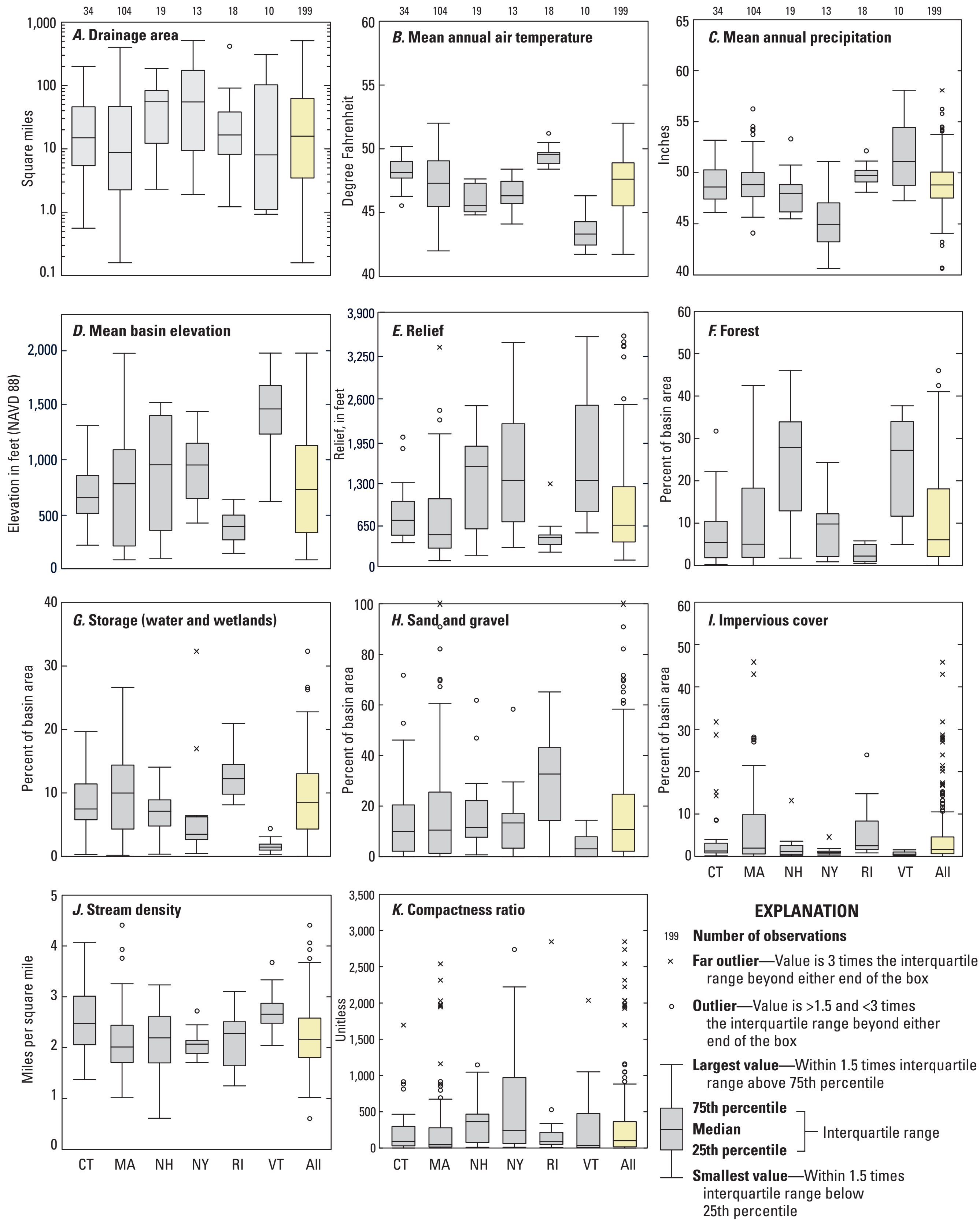


Figure 5. Basin characteristics of selected streamgages in Massachusetts (MA), Connecticut (CT), New Hampshire (NH), New York (NY), Rhode Island (RI), and Vermont (VT). *A*, drainage area; *B*, mean annual air temperature; *C*, mean annual precipitation; *D*, mean basin elevation; *E*, relief; *F*, forest land cover; *G*, storage (water and wetlands) land cover; *H*, sand and gravel land cover; *I*, impervious cover; *J*, stream density; and *K*, compactness ratio. NAVD 88, North American Vertical Datum of 1988; >, greater than; <, less than.

Table 5. Ranges of selected basin characteristic values considered in the development of regional flood flow regression equations for Massachusetts.

Basin characteristic	Name	Minimum	Mean	Maximum
Drainage area, in square miles (untransformed)	*DRNAREA*	0.16	52.8	512
Storage, in percentage of basin area in open water and wetlands[1]	*LC06STOR*	0.00	9.14	32.3
Mean basin elevation, in feet	*ELEV*	81.0	758	1,949
Stream density, in miles per square mile	*StrDEN*	0.61	2.25	4.41
Impervious area, in percentage of basin area[1]	*IMPERV*	0.00	4.77	45.9
Sand and gravel, in percentage of basin area[1]	*SG*	0.00	17.8	100

[1]As defined in Fry and others (2011).

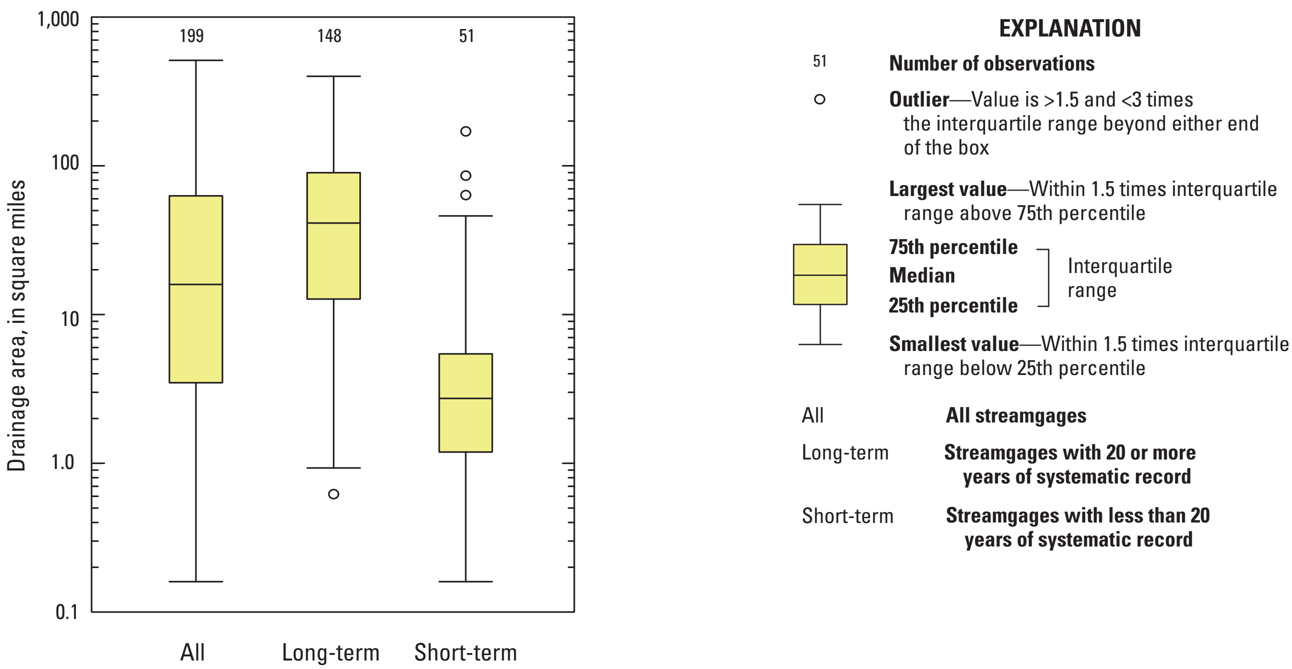


Figure 6. Drainage area distribution for all streamgages and streamgages with long-term (equal to or greater than 20 years) and short-term (less than 20 years) systematic records used in the flood flow analysis for Massachusetts. >, greater than; <, less than.

Subset models that are based on streamgages with less than (<) 20 years of systematic record and streamgages with 20 or more years (≥) of record were tested to evaluate the effect of short-term record streamgages. Streamgages with <20 years of record (51 streamgages) compose the majority of streamgages with small drainage basins (fig. 6); the interquartile range of basin area for the 51 short-term streamgages is well below the interquartile range of basin area for the 148 long-term streamgages. Separate OLS models developed from long-term streamgages (≥20 years of systematic record) produced a slightly better model fit than a single model developed from all streamgages and a slightly worse fit than a model developed from only short-term streamgages relative to a single model. The best subset model for long-term streamgages included drainage area, mean basin elevation, and total storage, whereas the best subset model for short-term streamgages included only drainage area and mean elevation. Most of the difference between the short- and long-term models was in the standard error of estimate, which differed by about 16 percent between short- and long-term subset models. Hence, the advantage of a single model developed from all streamgages outweighs the advantage of a slightly better model developed from only long-term streamgages.

Regional Regression Equations

The final regional regression equations were developed using the GLS method as implemented in the Weighted Multiple Linear Regression (WREG) program version 1.05 (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 weighted least squares (WLS) regression is that GLS accounts for differences in available record length (as does WLS), but GLS 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 analyses (table 5) were tested in GLS using the period of systematic record to develop the covariance matrix and weights. The final analysis used $\log_{10}$ transformations for the response variable (discharge) and for the independent variable drainage area (*DRNAREA*) to maintain linearity. *ELEV* and *LC06STOR* were multiplied by 0.001 and 0.01, respectively, to improve the precision of the model coefficients; *ELEV* was divided by 3.28084 to convert the input units from feet to meters. The final regional regression equations for the 50- through 0.2-percent AEPs (2- to 500-year floods, respectively) are as follows:

$$Q_{50} = 10^{\left[1.631+0.801\times\log_{10}(DRNAREA)+0.589\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.137\times0.01\times(LC06STOR)\right]}, \quad (2)$$

$$Q_{20} = 10^{\left[1.851+0.789\times\log_{10}(DRNAREA)+0.641\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.132\times0.01\times(LC06STOR)\right]}, \quad (3)$$

$$Q_{10} = 10^{\left[1.969+0.782\times\log_{10}(DRNAREA)+0.682\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.126\times0.01\times(LC06STOR)\right]}, \quad (4)$$

$$Q_{4} = 10^{\left[2.098+0.775\times\log_{10}(DRNAREA)+0.729\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.129\times0.01\times(LC06STOR)\right]}, \quad (5)$$

$$Q_{2} = 10^{\left[2.182+0.771\times\log_{10}(DRNAREA)+0.760\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.134\times0.01\times(LC06STOR)\right]}, \quad (6)$$

$$Q_{1} = 10^{\left[2.256+0.767\times\log_{10}(DRNAREA)+0.790\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.137\times0.01\times(LC06STOR)\right]}, \quad (7)$$

$$Q_{0.5} = 10^{\left[2.325+0.764\times\log_{10}(DRNAREA)+0.816\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.148\times0.01\times(LC06STOR)\right]}, \text{ and} \quad (8)$$

$$Q_{0.2} = 10^{\left[2.408+0.760\times\log_{10}(DRNAREA)+0.849\times0.001\times\left(\frac{ELEV}{3.28084}\right)-1.158\times0.01\times(LC06STOR)\right]}, \quad (9)$$

where

$Q_{50}, \ldots, Q_{0.2}$ are flow magnitudes for 50- to 0.2-percent AEP floods, in cubic feet per second;

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

ELEV is the mean elevation of the basin, in feet; and

LC06STOR is the total storage defined by the percent basin area classified as wetlands and open water.

Basins of streamgages used in the regional regression analysis ranged in drainage area from 0.16 to 512 square miles (mi^2; mean 52.8 mi^2), with a mean elevation ranging from 81 to 1,949 feet (ft; mean 758 ft) and total storage (percent of basin area in open water and wetlands) ranging from 0 to 32.3 percent (mean 9.14 percent). Drainage area (*DRNAREA*) alone generally provided about 94 percent of the explanatory power in the regional regression. *ELEV* and *LC06STOR* provided modest improvements in the model fit. Note that *DRNAREA* and *ELEV* are positive coefficients, which means that, as *DRNAREA* and *ELEV* increase, so does the magnitude of flow. *LC06STOR* has a negative coefficient, which means that, as *LC06STOR* increases, flow decreases reflecting the effects of storage in mitigating flood flows. *ELEV* also provides a degree of a surrogate measure for ecoregion, basin slope, and other explanatory characteristics that had some explanatory power in the exploratory OLS analysis but were not significant themselves. *StrDEN* and *SG* provided marginal gains in the model fit but did not justify including a fourth variable in the regional model. *IMPERV* was not statistically significant at the 95-percent confidence level at any AEP. The influence of impervious surface on flood flows is discussed in more detail in the “Urban Influence” section.

Equal distribution of residuals, the difference between the simulated and observed values, 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. 7). Furthermore, the residuals show no spatial pattern (fig. 8), indicating no need for subregional models or additional explanatory variables. The GLS regressions were not affected by undue leverage or influence from any single or set of streamgages used in the analysis.

Diagnostic plots for the GLS regression model for the 1-percent AEP flow indicate a sound model fit. The distribution of residuals shown in figure 9*A* indicates the error term is normally distributed and is minimally skewed over the range of theoretical quantiles. Residuals, standardized residuals, and the fitted model do not show excess influence or leverage (fig. 9*B*–*D*). About 96 percent of the standardized residuals are within ±2.0 percent and all are within about ±2.5 percent. The model fit is linear (fig. 9*D*) but shows some skew to the 1:1 line because of the unequal weighting used in GLS regression model. This also accounts for why residuals are not evenly distributed around the zero lines (fig. 9*A*–*C*). Other AEP flows show similar graphical model fit characteristics.

Accuracy and Limitations

Regression equations are statistical models developed from basin characteristics that best explain the variability of flood flows but 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, which is a measure of the accuracy of a regression, is an important consideration in the application of the model and the interpretation of the results.

The variable regionalized flood flow equations (equations 2 through 9) best fit the computed at-site AEP flood flows (fig. 10) without over fitting the data. The model error variance progressively increases as the AEP decreases (fig. 10; table 6). The largest outlier was at the Segreganset River near Dighton, Mass. (01109070), which was appreciably undersimulated at

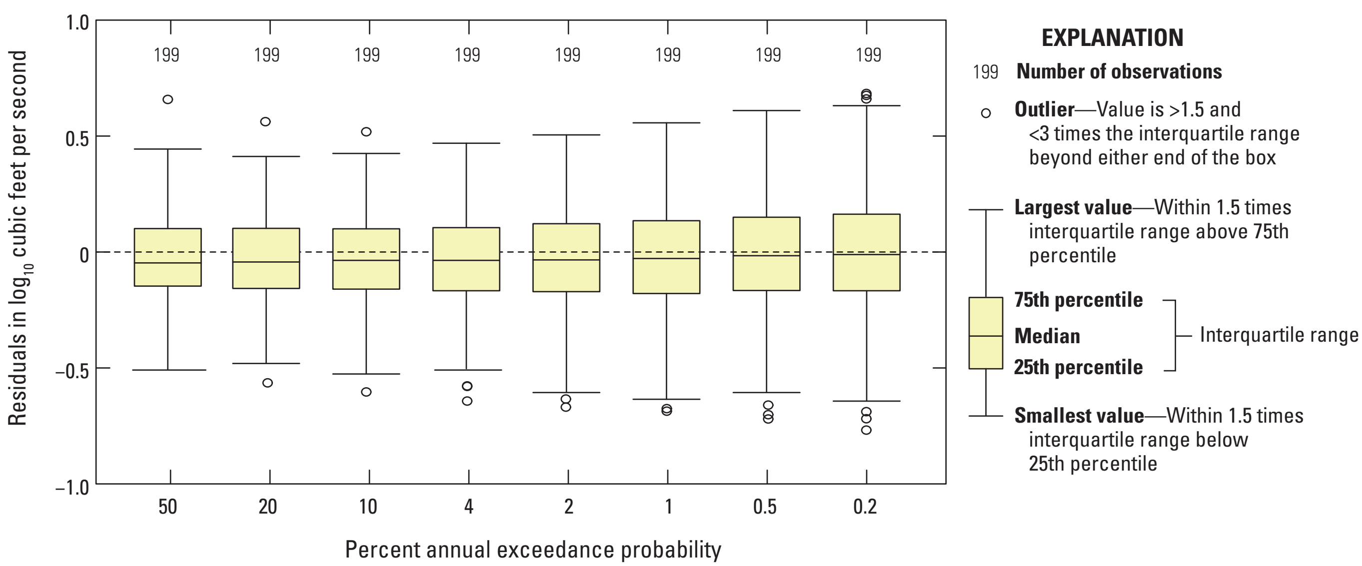


Figure 7. Residuals from generalized least squares (GLS) regression equations for 50- to 0.2-percent annual exceedance probability floods at 199 selected streamgages used in the flood flow analysis for Massachusetts. >, greater than; <, less than.

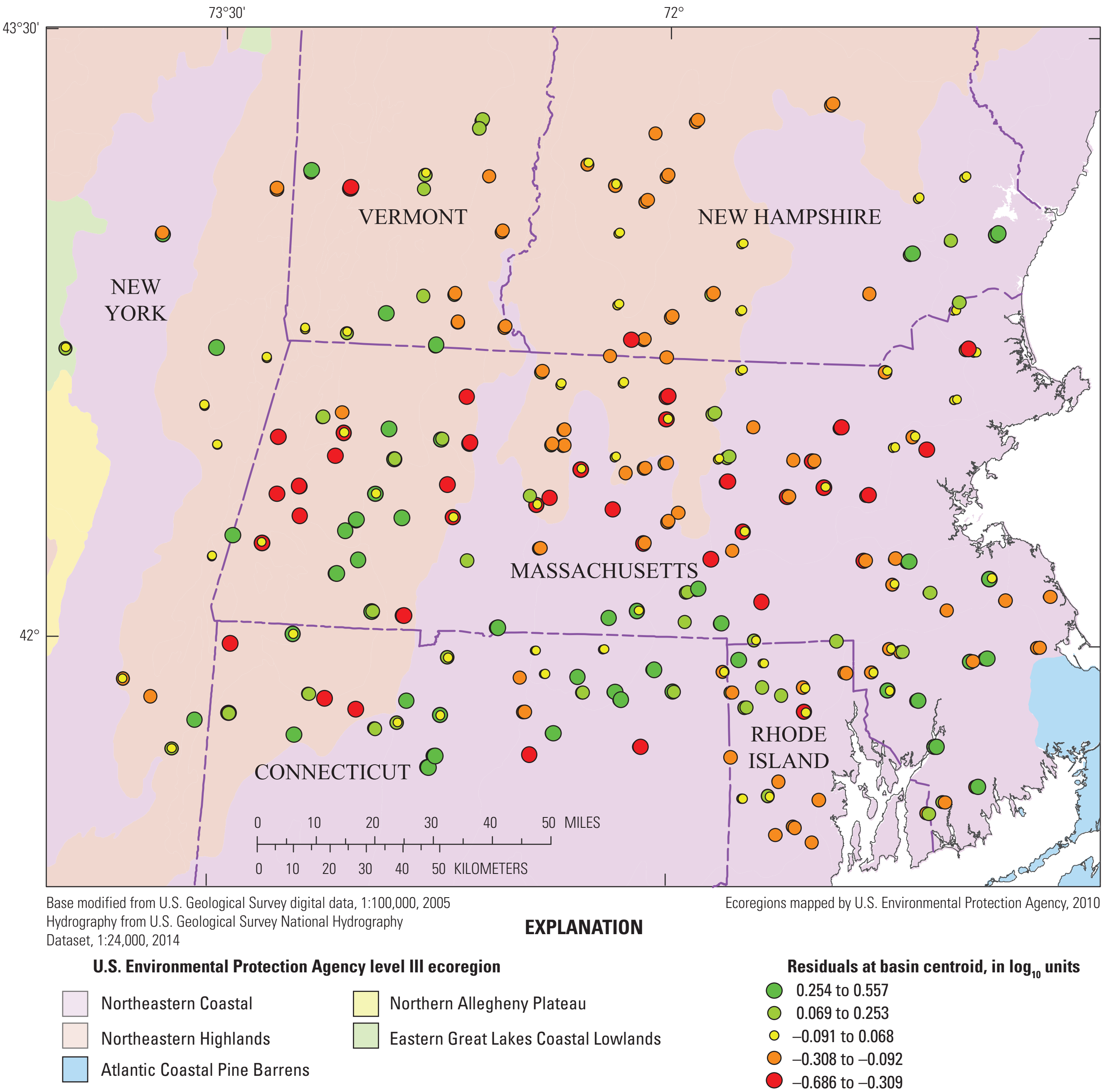


Figure 8. Generalized least squares (GLS) regression residuals for the 1-percent annual exceedance probability flood flow at 199 selected streamgage basin centroids used in the flood flow analysis for Massachusetts.

the 50-percent AEP flow, but became less of an outlier as the AEP decreased. One possible explanation is that this basin was among the lowest in elevation (115 feet) and above the upper quartile in total storage (17 percent) relative to the other basins used in the analysis (fig. 5). This may reflect the potential model error when the secondary explanatory variables *ELEV* and *LC06STOR* are at or near opposite extremes of the dataset used in the analysis.

Several metrics of model fit are generated for the GLS analysis in WREG, including the pseudocoefficient of determination (pseudo-R^2; Griffis and Stedinger, 2007), the average standard error of prediction, and the standard model error. The pseudo-R^2 value is based on the variability of 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

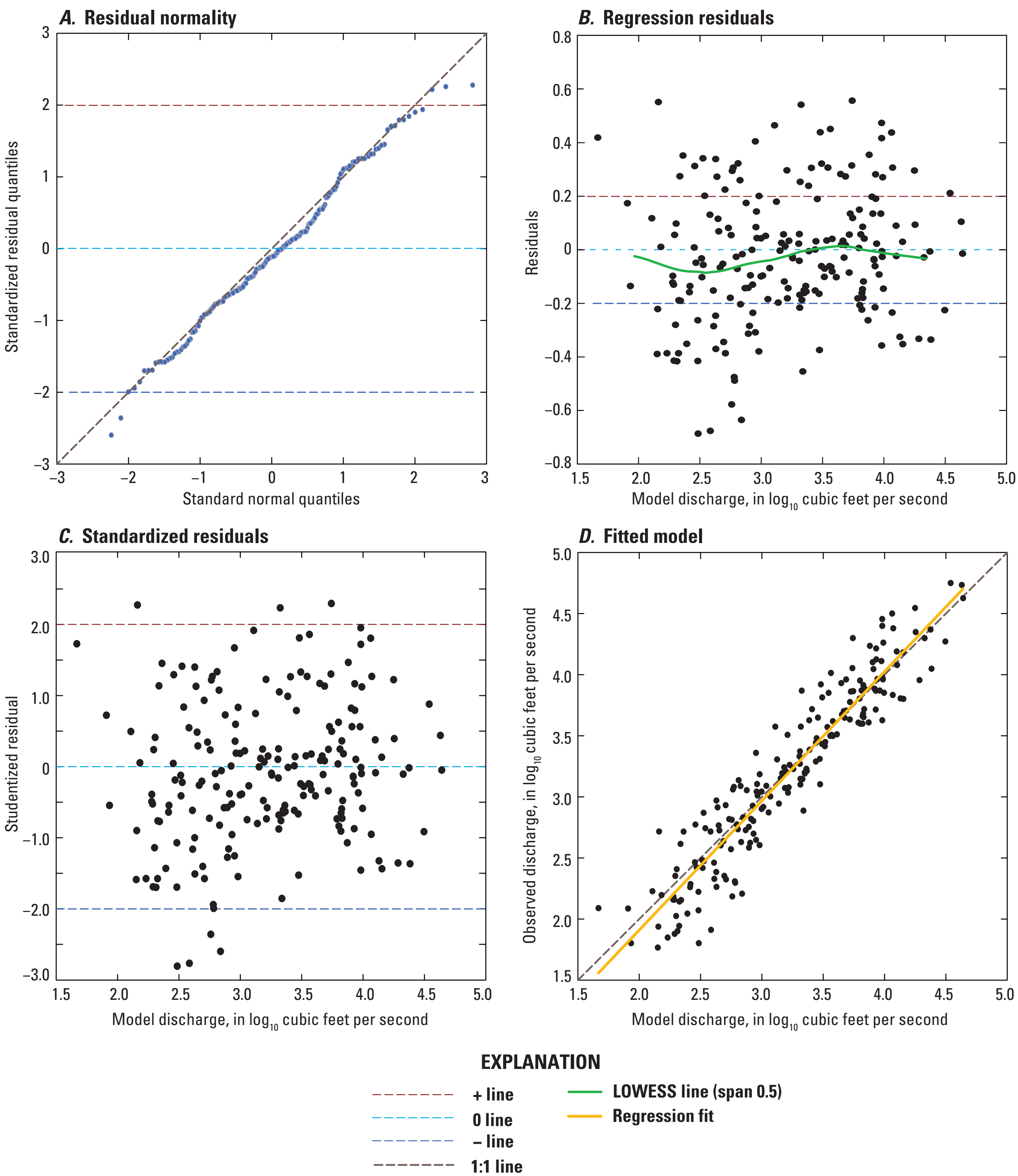


Figure 9. Diagnostic plots for generalized least squares (GLS) regression for the 1-percent annual exceedance probability flood flow for *A*, residual normality, *B*, regression residuals, *C*, standardized residuals, and *D*, fitted model for regionalized flood flows in Massachusetts.

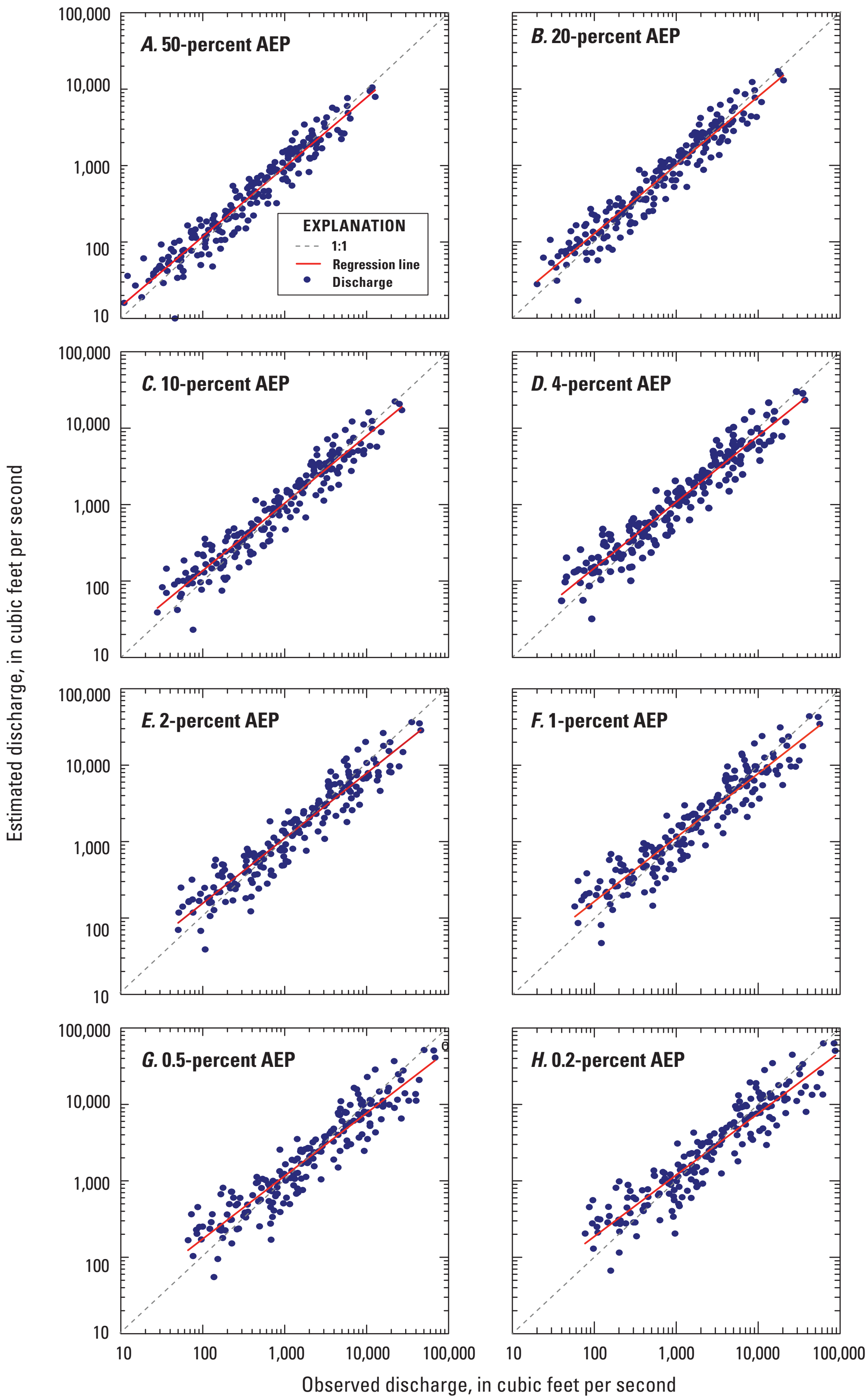


Figure 10. Observed (at-site analyses) and estimated (regional flood flow equations) flood magnitudes for selected percent annual exceedance probabilities (AEP) at 199 streamgages used in the flood flow analysis for Massachusetts.

Table 6. Generalized least squares model fit characteristics for selected annual exceedance probability flood flows determined from selected streamgages used for the flood flow analysis for Massachusetts.

[MSE, mean squared error; pseudo-R^2, pseudocoefficient of determination]

Annual exceedance probability (percent)	MSE of unweighted residuals (log units)	Average variance of prediction (log units)	Average standard error of prediction (percent)	Pseudo R^2 (percent)	Model error variance (log units)	Standard model error (percent)
50	0.035	0.031	42.3	93.3	0.030	41.4
20	0.039	0.033	43.4	92.7	0.031	42.3
10	0.043	0.034	44.7	92.1	0.033	43.4
4	0.050	0.038	47.1	91.1	0.036	45.6
2	0.055	0.041	49.4	90.1	0.039	47.6
1	0.061	0.045	51.8	89.0	0.042	49.8
0.5	0.068	0.048	54.1	87.9	0.045	51.9
0.2	0.077	0.054	57.6	86.2	0.050	55.1

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. The pseudo-R^2 ranged from about 86 to 93 percent and decreased slightly as the AEP flood decreased (table 6). The percent average standard error of prediction is the percentage form of the mean of the variances of prediction calculated for each of the streamgages used in constructing the regression model (Tasker and Stedinger, 1989). The square root of the variance of prediction is the standard error of prediction. Both are measures of 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 listed in appendix 2.

The regional regression equations produce estimates of flood flows for a wide range of streams in Massachusetts, except those in the southeasternmost part of the State, Cape Cod, and the islands (Atlantic Coastal Pine Barrens level III ecoregion; fig. 2), or where human influences affect the magnitude of floods. Rivers with large regulated impoundments for water supply or flood control, for example, would not be appropriate for use of these equations. Applicability of flood flow estimates determined from basin characteristics outside the range of characteristics from which the equations were derived (table 5) is unknown.

The regional regression equations were developed from streamgages with drainage areas ranging from 0.16 to 512 mi^2, but most of the small basins (less than 5 mi^2) have <20 years of systematic record (fig. 6). Most of the streamgages with small basins used in the analysis were installed in the mid-1960s and operated until the mid-1970s for the purpose of the initial flood frequency study in Wandle (1977). The severest drought of record in the northeast occurred from 1961 to 1969 (Paulson and others, 1991). As such, these basins share a short common period of record that characterizes the hydroclimate of that period, which can bias the statistical moments used to calculate the AEP flows.

The potential effects of using a common short-term record relative to a long-term record were examined by comparing the EMA-computed AEP flows from a long-term record to a clipped period of record for the same streamgages. Six long-term streamgages representing different regions of the State were used for the analysis. Flows computed from the clipped record (1963–74) reflect the period of record at many small basins used to develop regional equations. The short-term record AEP flows are underestimated relative to the long-term record flows in most areas except in the southeastern part of the State. In the central and western parts of the State, the AEP flows computed from short-term records were about 15 to 62 percent less than flows computed from the long-term record; the differences increase as the AEP decreases. In southeastern Massachusetts, the AEP flows computed from the short-term record were larger those that computed from the long-term record. Differences in the at-site skews computed from short-term and long-term records are apparent as are the mitigating effects of the weighted skew (table 7).

The effects of using a short-term portion (1963–74) of a long-term record can be seen in the discharge-to-probability distribution plots (fig. 11). At Wading River near Norton (0110900) most short-term peak flows fall on the same discharge-to-probability curve as the long-term record, except at the highest flow. The highest annual peak flow in the short-term record is the second highest peak flow in the long-term record, which causes the short-term record fitted discharge probability curve to shift to the left relative to the long-term record AEP curve. As a result, the short-term record AEP flows are larger than the long-term record AEP flows. In contrast, the short-term record at East Branch Swift River (01174500) does not include peak flows within about the highest 10 peak flows of the long-term record. As a result, the fitted discharge probability curve is shifted to the right

Table 7. Annual exceedance probability flood flows computed from six streamgages in Massachusetts from long-term records and from records for water years 1963 to 1974.

[XX, not applicable]

Station number	Region	Period of record	Skew		Flow, in cubic feet per second, by percent annual exceedance probability flow							
			At-site	Weighted	50	20	10	4	2	1	0.5	0.2
01102000	Northeast	1931–2013	0.167	0.237	1,107	1,814	2,379	3,208	3,913	4,697	5,568	6,870
		1963–1974	0.052	0.289	1,043	1,712	2,254	3,058	3,750	4,526	5,396	6,711
		Percent difference	XX	XX	-5.8%	-5.6%	-5.3%	-4.7%	-4.2%	-3.6%	-3.1%	-2.3%
01109000	Southeast	1926–2013	0.246	0.289	484	716	890	1,133	1,331	1,545	1,775	2,110
		1963–1974	0.764	0.459	488	751	962	1,273	1,540	1,840	2,178	2,689
		Percent difference	XX	XX	0.8%	4.9%	8.0%	12.4%	15.7%	19.1%	22.7%	27.4%
01171500	North-central	1939–2013	-0.348	-0.026	2,278	3,474	4,326	5,462	6,346	7,260	8,210	9,525
		1963–1974	0.029	0.299	1,472	2,378	3,105	4,176	5,092	6,115	7,258	8,977
		Percent difference	XX	XX	-35.4%	-31.5%	-28.2%	-23.5%	-19.8%	-15.8%	-11.6%	-5.8%
01174500	Central	1937–2013	0.820	0.607	716	1,150	1,521	2,101	2,624	3,236	3,951	5,085
		1963–1974	-0.321	0.243	605	828	984	1,190	1,351	1,518	1,692	1,934
		Percent difference	XX	XX	-15.5%	-28.0%	-35.3%	-43.4%	-48.5%	-53.1%	-57.2%	-62.0%
01197500	Southwest	1914–2013	0.704	0.354	3,815	5,457	6,671	8,355	9,720	11,180	12,760	15,030
		1963–1974	0.266	0.344	3,057	4,109	4,850	5,838	6,614	7,423	8,273	9,467
		Percent difference	XX	XX	-19.9%	-24.7%	-27.3%	-30.1%	-32.0%	-33.6%	-35.2%	-37.0%
01331500	Northwest	1932–2013	0.700	0.554	1,121	1,687	2,142	2,816	3,397	4,051	4,790	5,916
		1963–1974	0.527	0.407	890	1,303	1,617	2,064	2,435	2,838	3,280	3,930
		Percent difference	XX	XX	-20.7%	-22.8%	-24.5%	-26.7%	-28.3%	-29.9%	-31.5%	-33.6%
Average percent difference, excluding southeast streamgage					-19.4%	-22.5%	-24.1%	-25.7%	-26.5%	-27.2%	-27.7%	-28.1%

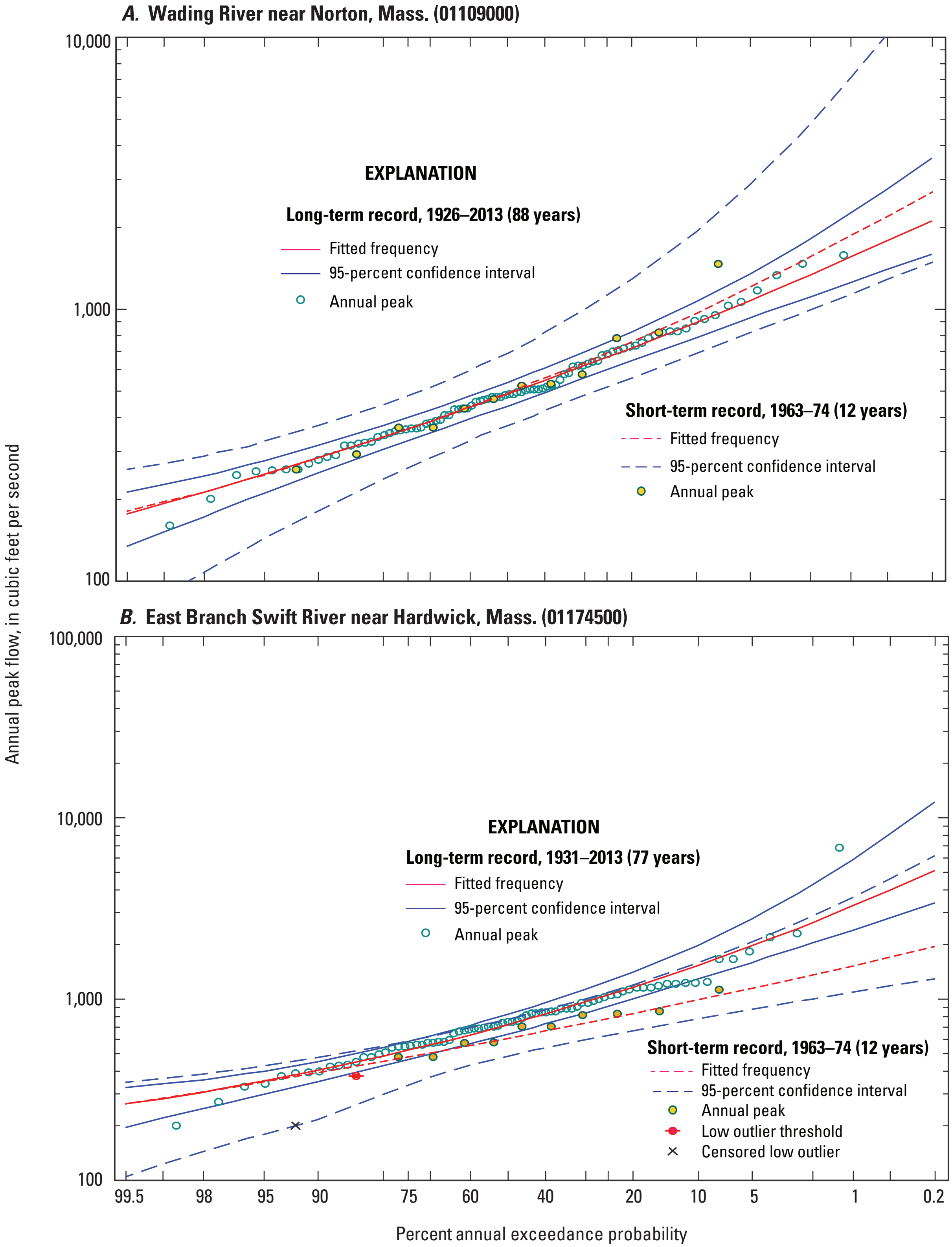


Figure 11. Flood flow probability plots computed using the expected moments algorithm for the entire period of record and a short-term record sample (water years 1963–74) at the *A*, Wading River near Norton, Mass. (01109000) and *B*, East Branch Swift River near Hardwick, Mass. (01174500) streamgages.

relative to the long-term discharge probability curve, causing the short-term AEP flows to be less than the long-term AEP flows. Most of the streamgages with short-term records appear to have a condition similar to that shown for the East Branch Swift River (01174500), as indicated by the bias of short-term records in most regions of the State (table 7). In all cases, the 95-percent confidence interval increases as the number of annual peak flows decrease.

Uncertainty Estimates of Regionalized Equations

The uncertainty of a regression equation is indicated by the range of values within a specific confidence interval or 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 90-percent prediction intervals for the 1-percent AEP flood means there is 90-percent confidence that the true value of the 1-percent AEP flood is within that stated interval.

Tasker and Driver (1988) have shown that a 100 $(1-\alpha)$ prediction interval (α of 0.10 equals a 90-percent prediction interval) for the true value of a streamflow statistic obtained for an ungaged site from a regression equation can be computed using the following equation:

$$\frac{Q}{C} < Q < Q \times C, \tag{10}$$

where

Q is the flood magnitude for the ungaged site, in cubic feet per second; and

C is the confidence interval computed using the following equation:

$$C = 10^{T,\, S_{p,i}}, \tag{11}$$

where

T is the Student's t-distribution value (1.65) from a standard statistics table for a given confidence level and degree of freedom (for a 90-percent level $\alpha = 0.10$ and >100 degrees of freedom), and

$S_{p,i}$ is the standard error of prediction for site i; the value of $S_{p,i}$ is computed using the following equation:

$$S_{p,i} = [\sigma^2 + x_i U x_i']^{0.5}, \tag{12}$$

where

σ^2 is the model error variance, in log units;

x_i is a row vector of the explanatory variables [$\log_{10}$(*DRNAREA*), *ELEV*×0.001, and *LC06STOR*×0.01] for site i, augmented by a 1 as the first element;

U is the covariance matrix for the regression coefficients; and

x_i' is the transpose of x_i from Ludwig and Tasker (1993).

An example calculation of the 90-percent prediction interval is given for a hypothetical ungaged stream site with the following characteristics: *DRNAREA* of 18 mi^2, *ELEV* of 689 ft, and *LC06STOR* of 8.0 percent (values determined from the median of all streamgages used in the analysis). The x_i vector computed from the explanatory basin characteristics is as follows:

$$x_i = \{1, \log_{10}(18.0), (689/3.28084 \times 0.001), (8.0 \times 0.01)\}. \tag{13}$$

The model error variance (σ^2) and the covariance matrix (U) were determined from the WREG GLS analysis and are reported in table 8. For a 1-percent AEP flow, the procedure for computing the 90-percent prediction interval is as follows:

- Compute $S_{p,i,}$ using equation 12, as follows: $S_{p,i} = (0.0420+0.00298)^{0.5} = 0.21210$; converted from $\log_{10}$ units, this equals a range of -38.6 to 63.0 percent.
- Compute C, using equation 11, as follows: $C = 10^{(1.65 \times 0.21210)} = 2.23854$.
- Compute the 1-percent AEP flood, using equation 7, as follows: Q_1 = 1,967 cubic feet per second (ft^3/s).
- Compute the 90-percent prediction interval, using equation 10, where
  $$\frac{1{,}967}{2.23854} < Q_{1\%} < 1{,}967 \times 2.23850$$
  or 879 ft^3/s < 1,967 ft^3/s < 4,400 ft^3/s.

A worksheet for solving the regional regression equations at ungaged sites from user specified explanatory values for flood magnitudes with 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs and the 90-percent prediction interval is available in appendix 3. The graphical results from the hypothetical test basin computed from the worksheet are shown in figure 12.

Table 8. Model error variance and covariance values associated with selected annual exceedance probabilities used to determine the uncertainty of the regional regression equation flood flows for Massachusetts.

[Variance and covariance are in log units. σ^2, regression model error variance (as used in equation 12); *U*, covariance matrix (as used in equation 12; the matrix horizontal and vertical variables are defined by the constant and the independent variables in equations 2 through 9 in the order they are given); E-[XX], $\times 10^{-[XX]}$]

Percent annual exceedance probability	Model error variance (σ^2)	Covariance matrix *(U)*			
50	0.030	2.787E-03	-5.295E-04	-6.791E-03	-3.360E-03
		-5.295E-04	4.171E-04	-5.352E-04	-2.314E-04
		-6.791E-03	-5.352E-04	5.598E-02	1.033E-02
		-3.360E-03	-2.314E-04	1.033E-02	1.175E-02
20	0.031	3.248E-03	-6.231E-04	-7.249E-03	-3.716E-03
		-6.231E-04	4.708E-04	-5.444E-04	-2.310E-04
		-7.249E-03	-5.444E-04	5.994E-02	1.068E-02
		-3.716E-03	-2.310E-04	1.068E-02	1.336E-02
10	0.033	3.733E-03	-7.099E-04	-7.770E-03	-4.148E-03
		-7.099E-04	5.236E-04	-5.729E-04	-2.328E-04
		-7.770E-03	-5.729E-04	6.479E-02	1.110E-02
		-4.148E-03	-2.328E-04	1.110E-02	1.525E-02
4	0.036	4.473E-03	-8.384E-04	-8.717E-03	-4.858E-03
		-8.384E-04	6.057E-04	-6.338E-04	-2.375E-04
		-8.717E-03	-6.338E-04	7.325E-02	1.206E-02
		-4.858E-03	-2.375E-04	1.206E-02	1.829E-02
2	0.039	5.106E-03	-9.467E-04	-9.622E-03	-5.494E-03
		-9.467E-04	6.779E-04	-6.962E-04	-2.448E-04
		-9.622E-03	-6.962E-04	8.118E-02	1.306E-02
		-5.494E-03	-2.448E-04	1.306E-02	2.097E-02
1	0.042	5.759E-03	-1.057E-03	-1.057E-02	-6.160E-03
		-1.057E-03	7.523E-04	-7.634E-04	-2.516E-04
		-1.057E-02	-7.634E-04	8.947E-02	1.412E-02
		-6.160E-03	-2.516E-04	1.412E-02	2.377E-02
0.5	0.045	6.433E-03	-1.171E-03	-1.156E-02	-6.855E-03
		-1.171E-03	8.293E-04	-8.350E-04	-2.582E-04
		-1.156E-02	-8.350E-04	9.813E-02	1.524E-02
		-6.855E-03	-2.582E-04	1.524E-02	2.669E-02
0.2	0.050	7.394E-03	-1.334E-03	-1.305E-02	-7.869E-03
		-1.334E-03	9.419E-04	-9.434E-04	-2.703E-04
		-1.305E-02	-9.434E-04	1.110E-01	1.698E-02
		-7.869E-03	-2.703E-04	1.698E-02	3.091E-02

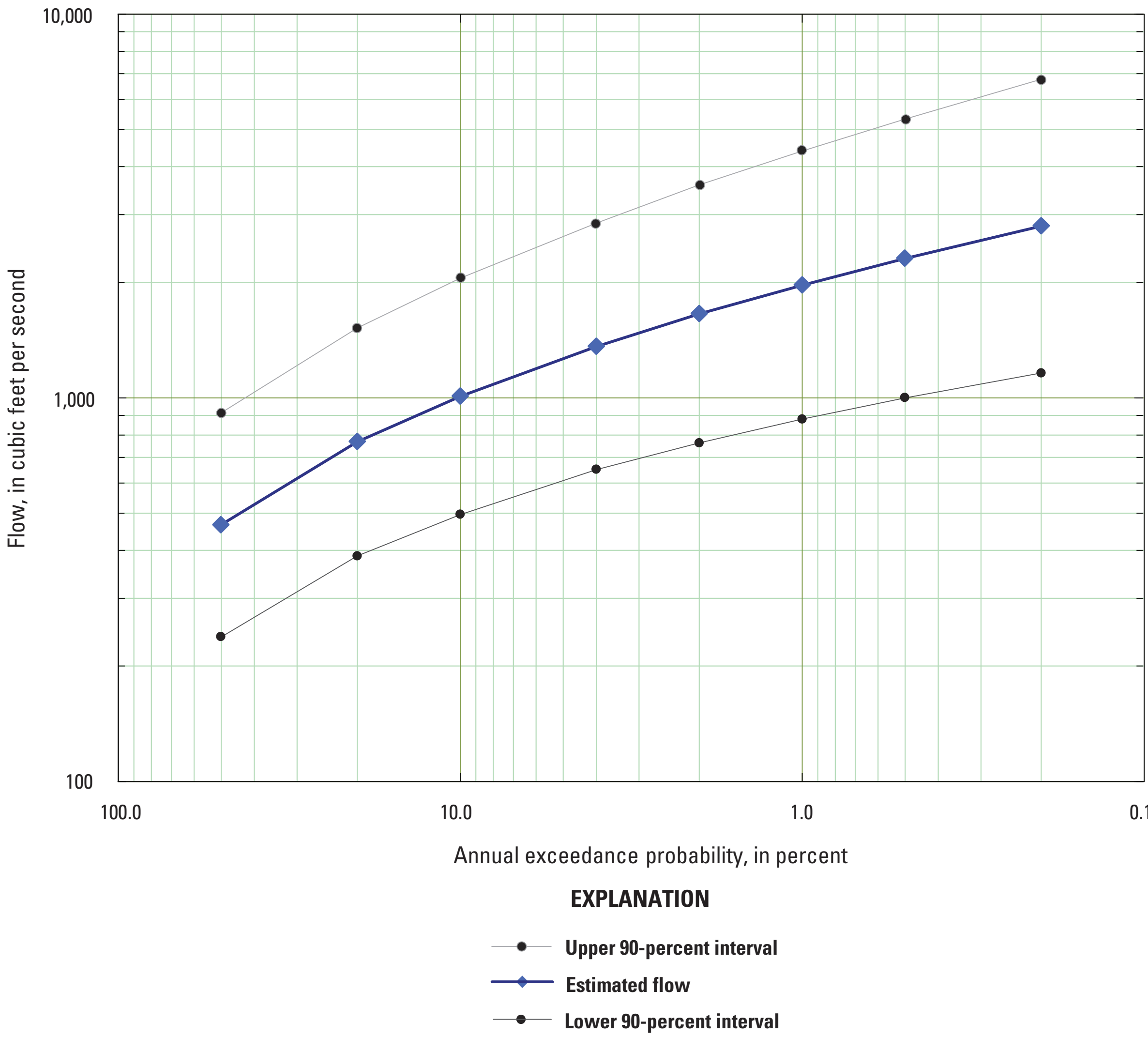


Figure 12. Regional regression estimates of the flood flows and prediction intervals for a hypothetical basin with a drainage area of 18 square miles, a mean basin elevation of 689 feet, and total storage of 8 percent.

Factors Affecting Flood Flow Estimates

Many factors affect the magnitude of flood flows, some of which are incorporated into the regional regression equation 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 rapidly move water away from developed areas. To the extent that the streamgages used in the analysis reflect different degrees of urbanization and where the effects of urbanization are reasonably stable over the streamgage record, the at-site analysis includes these effects in the computed flood magnitudes. Hence, the regional regression equations developed reflect the effects of urbanization over the range of urban gradients of the streamgages used. However, the question remains as to how representative the streamgages used in the analysis are of other urbanized basins where flood flow equations are applied. Trends in annual peak flows affect the fundamental statistical basis for flood analysis as currently performed, which assumes stationarity, that is, the assumption that annual peak flows exhibit no significant trend over time. The results of the analysis show that stationarity does not prevail at all of the streamgages. 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. Often these changes result in increased storm runoff by altering the amount of precipitation that infiltrates into the ground and the timing of runoff. The effects of imperviousness have been found to be more pronounced for small, more frequent storms than for large infrequent storms (Hollis, 1975; Konrad, 2003). The reason for this is that, during large storms, soils become saturated, preventing further infiltration into the soil. As a result, surface runoff increases, and the effects are similar to the effects of an impervious surface for any size storm or antecedent condition. Nevertheless, many flood studies have made adjustments to regionalized flood flow equations for rural basins 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) and 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 Massachusetts includes *IMPERV*, which was considered a potentially important factor because of the long history of development in this region and the recognition that many basins of interest with respect to flooding are urbanized to some extent. *IMPERV* for the streamgage basins used in the regionalization analysis based on 2006 land cover ranged from 0 to about 46 percent with a median of 1.6 percent and an interquartile range between 0.6 and 4.6 percent (fig. 5), which limits the extent to which urbanization can be addressed from the available data. In both the OLS and GLS regression analyses, *IMPERV* was not a significant explanatory variable in determining the magnitude of AEP flows for any of the exceedance probabilities examined. It should also be noted that land use in many streamgage basins likely changed over the course of the peak-flow record.

Regional flood flow studies (Robbins and Pope, 1996; Southard, 2010; Gotvald and Knaak, 2011; Feaster and others, 2014) have found that *IMPERV* is an important predictor of the magnitude of flood flows. In general, 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). Results of the exploratory statistical analysis in this study indicate that *IMPERV* provided some explanatory power; however, as previously noted, it was not enough to be significant.

Further analysis indicates the relation of *IMPERV* to the magnitude of the AEP flood to be complicated by other basin characteristics that can offset the effects of urbanization. Basins used in the regional flood analysis were stratified by the quartile range of the percent of sand and gravel and were plotted by the flood magnitude normalized for drainage area (fig. 13). Basins with more than 25 percent sand and gravel (greater than the upper quartile; fig. 13, symbol ×) show little or no increase in flood magnitude with increasing

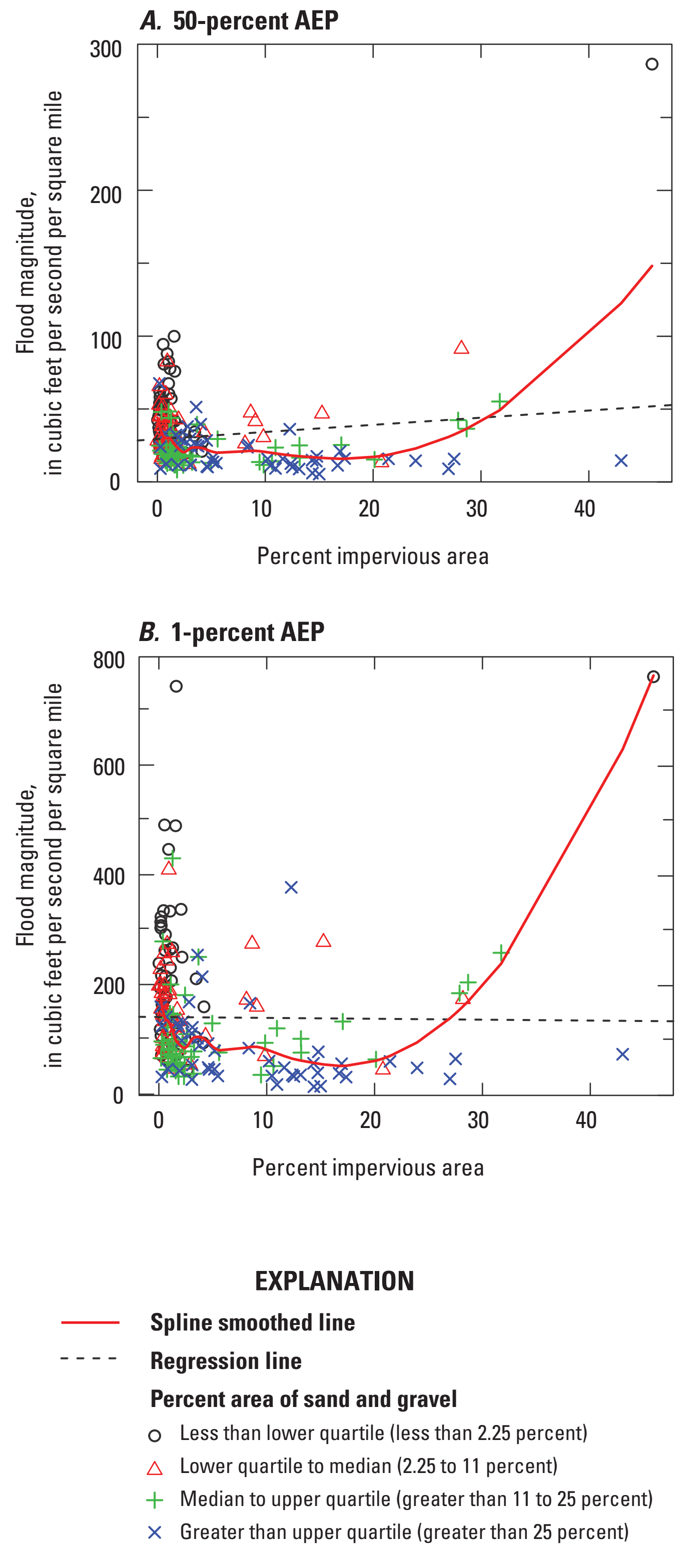


Figure 13. Relation of impervious area to flood magnitude at the *A*, 50-percent and *B*, 1-percent annual exceedance probability (AEP) flood normalized for drainage area and grouped by ranges of the percent area of sand and gravel for 199 selected streamgages used in the flood flow analysis for Massachusetts. >, greater than; <, less than.

imperviousness. In contrast, basins with little or no sand and gravel (less than the lower quartile; fig. 13, symbol ◦) have a wide range of flood magnitudes over a small range of imperviousness, except for one outlier. The outlier, Taunton River tributary near Fall River, Mass. (01109100) has the highest flood magnitude normalized for drainage area and has the greatest percent imperviousness of all streamgage basins used in the study (46 percent) with no underlying sand and gravel. Note that this streamgage represents the smallest basin in the study (area of 0.16 mi^2). In contrast, Aberjona River at Winchester (01102500) is a moderate size basin (23.1 mi^2) with about 43 percent imperviousness and about 37 percent sand and gravel, but it has one of the smallest per unit area discharges for the 50- and 1-percent AEPs. This underscores the inconclusiveness of any relation between flood magnitude and imperviousness but indicates how imperviousness can affect flood magnitudes in small basins.

At successively lower percentages of sand and gravel (fig. 13), the flood magnitude normalized for drainage area increases as the percent imperviousness increases. Although not significant, the regression line fit through all points shows a slight increase in the 50-percent AEP flow and a slight decrease in the 1-percent AEP flow as the percent imperviousness increases.

Although the overall relation between flood magnitude and imperviousness is not significant, the interplay with other variables may affect how urbanization changes the flood magnitude, the significance of which is diminished in a regional analysis. For example, deposits of sand and gravel tend to be in valley fill in the lower parts of the basin where urban areas tend to be more concentrated. This juxtaposition of urban and nonurban areas could reduce downstream peak flows because the enhanced drainage from the urban areas accelerates the peak flow relative to the peak flow from the upper parts of the basin offsetting the timing of peak flow runoff. Other factors such as basin slope, stream channel slope, storage in wetlands, and open water also alter the timing of peak flow, which could affect the influence of urban areas on peak flows. The analysis also underscores that not all impervious surfaces are equal in terms of their runoff response to precipitation. Impervious surfaces that are directly connected to streams responds differently than those that drain to a pervious surface. However, information was not available to determine the types of impervious surfaces in the study area or how imperviousness may have changed over time.

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. 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 positive trends in annual peak flows into account in a flood frequency analysis could potentially lead to the underestimation of flood magnitudes or incorrect frequency of floods of a given magnitude at some point in the future.

Trends in annual peak flow values at each streamgage (table 3) were tested using the nonparametric Kendall Tau test (Kendall and Gibbons, 1990) that compares the rank of each peak flow value against the rank of the chronologically previous peak flow value in the series. Trends were evaluated at 148 long-term streamgages in Massachusetts and adjacent States with ≥20 years of systematic record; the systematic record averaged 50 years. Of these streamgages, 52 (35 percent) had a significant positive trend (p-value less than or equal to [≤] 0.05: probability that the null hypothesis of no trend is true or, in other terms, a 95-percent confidence that the trend is true). An additional 12 streamgages (8 percent) had a positive trend with p-values between the 0.05 and 0.10 significance level, and one streamgage had a significant negative trend (table 9).

In Massachusetts, about 27 percent of the streamgages (17 out of 64) had a significant positive trend at a p-value ≤ 0.05, and 5 additional streamgages had a positive trend at a p-value > 0.05 and ≤ 0.1 (table 9). Only the streamgage at Kettle Brook at Worcester, Mass. (01109500) had a significant negative trend, which likely is an artifact of the streamgage being discontinued in 1978. About 42 percent of nearby streamgages in adjacent States (35 out of 84) had a significant positive trend ($p \leq 0.05$), and 7 additional streamgages had a positive trend at a p-value > 0.05 and ≤ 0.10. Although about 35 percent of all long-term streamgages in the study area (52 of 148) had a clear positive trend ($p \leq 0.05$), most streamgages did not (fig. 14). Connecticut has the highest percentage of the streamgages used in the study with a significant positive trend, but overall trends do not appear to have a spatial pattern over the study area (fig. 14). The average trend slope for streamgages with significant positive trends ($p \leq 0.05$) in Massachusetts was 9.2 cubic feet per second per year ($ft^3/s/yr$), and slopes ranged from 1.3 to 41 $ft^3/s/yr$ (table 3*A*). The slope of streamgages with significant positive trends ($p \leq 0.05$) in adjacent States averaged 12.7 $ft^3/s/yr$, and slopes ranged from 1.4 $ft^3/s/yr$ in Vermont to 48 $ft^3/s/yr$ in Connecticut (table 3*B*).

A subset of 63 streamgages with long periods of record was created to further evaluate trends in annual peak flows during the past 30, 50, and 70 years (table 10) through 2013. The dataset included 36 streamgages from Massachusetts and 27 streamgages in adjacent States and had a systematic period of record ranging from 38 to 101 years with an average length of about 67 years. Most streamgages have records through water year 2013. The number of streamgages used

Table 9. Streamgages with 20 or more years of unregulated systematic record with significant trends in annual peak flows identified by the Kendall Tau test used in the flood flow analysis for Massachusetts.

[Systematic record is the period with a continuous record and is for water years from October 1 to September 30, designated by the year in which the period ends. *P* values in black font indicate trends with *P* values (statistical test for significance) less than 0.05; *P* values in blue font indicate trends with *P* values between 0.05 and 0.10. Slope values in red font indicate a negative trend; slope values in black font indicate a positive trend. TAU is a function of the number of positive (concordant) pairs minus the number of negative (discordant) pairs. Slope is the Theil slope of the trend, in cubic feet per second per year. *DRNAREA*, drainage area; mi², square mile; MA, Massachusetts; CT, Connecticut; Bk, Brook; nr, near; Rd, Road; NY, New York; NH, New Hampshire; RI, Rhode Island; E., East; VT, Vermont; Trib, Tributary; @, at; Rt., Route]

U.S. Geological Survey streamgage		*DRNAREA* (mi²)[1]	Systematic record			Trend		
Number	Name		Begin	End	Years	TAU	*P* value	Slope
Massachusetts								
01094500	North Nashua River at Leominster, MA	109	1936	2013	78	0.203	0.008	17.62
01097000	Assabet River at Maynard, MA	114	1942	2013	72	0.160	0.048	6.39
01099500	Concord R Below R Meadow Bk, at Lowell, MA	400	1938	2013	76	0.156	0.046	10.44
01100800	Cobbler Brook near Merrimac, MA	0.74	1963	1983	21	0.343	0.032	1.75
01101500	Ipswich River at South Middleton, MA	44.5	1938	2013	76	0.171	0.029	2.23
01102000	Ipswich River near Ipswich, MA	125	1931	2013	83	0.125	0.095	5.00
01102500	Aberjona River at Winchester, MA	24.8	1940	2013	75	0.299	0.000	3.73
01103500	Charles River at Dover, MA	183	1936	2013	76	0.181	0.021	5.84
01105000	Neponset River at Norwood, MA	34.8	1938	2013	74	0.326	0.000	3.31
01108000	Taunton River near Bridgewater, MA	261	1930	2013	67	0.181	0.030	10.39
01109000	Wading River near Norton, MA	43.4	1926	2013	88	0.122	0.093	1.53
01109500	Kettle Brook at Worcester, MA	31.4	1924	1978	55	-0.255	0.006	-5.43
01110000	Quinsigamond River at North Grafton, MA	25.5	1940	2013	74	0.211	0.008	1.55
01110500	Blackstone River at Northbridge, MA	140	1940	2003	46	0.313	0.002	29.57
01123160	Wales Brook Tributary near Wales, MA	0.72	1964	1983	20	0.405	0.014	1.32
01163200	Otter River at Otter River, MA	33.8	1965	2013	49	0.176	0.076	3.83
01169000	North River at Shattuckville, MA	89.9	1940	2013	74	0.264	0.001	40.64
01169900	South River near Conway, MA	24.1	1967	2013	47	0.181	0.074	20.83
01171500	Mill River at Northampton, MA	54.0	1939	2013	75	0.189	0.017	12.78
01174500	East Branch Swift River near Hardwick, MA	43.6	1937	2013	77	0.136	0.080	3.21
01175670	Sevenmile River near Spencer, MA	8.81	1961	2013	53	0.253	0.008	2.32
01176000	Quaboag River at West Brimfield, MA	150	1913	2013	101	0.153	0.023	3.67
01183810	Longmeadow Brook near Longmeadow, MA	4.56	1963	1983	20	0.379	0.021	2.03
Connecticut								
01119300	Roaring Brook near Staffordville, CT	5.61	1960	1984	25	0.48	0.001	12.50
01119360	Conat Brook at West Willington, CT	2.12	1964	1983	20	0.463	0.005	3.64
01119500	Willimantic River near Coventry, CT	122	1932	2013	82	0.144	0.057	12.29
01121000	Mount Hope River near Warrenville, CT	29.0	1938	2013	72	0.243	0.002	8.41
01122680	Merrick Bk nr Scotland, CT	5.29	1960	1984	25	0.34	0.018	12.50
01125900	Cady Bk at East Putnam, CT	8.36	1964	1984	21	0.367	0.021	16.83
01126000	Fivemile River at Killingly, CT	57.8	1938	1984	47	0.264	0.009	10.63
01184100	Stony Brook near West Suffield, CT	10.5	1960	2013	54	0.301	0.001	7.50
01184300	Gillette Brook at Somers, CT	3.64	1960	1984	25	0.377	0.009	6.31
01184490	Broad Brook at Broad Brook, CT	15.5	1938	2013	47	0.021	0.840	0.48
01187300	Hubbard River near West Hartland, CT	20.6	1938	2012	74	0.344	0.000	14.89
01187800	Nepaug River near Nepaug, CT	23.4	1922	2001	62	0.327	0.000	11.00

Table 9. Streamgages with 20 or more years of unregulated systematic record with significant trends in annual peak flows identified by the Kendall Tau test used in the flood flow analysis for Massachusetts.—Continued

[Systematic record is the period with a continuous record and is for water years from October 1 to September 30, designated by the year in which the period ends. *P* values in black font indicate trends with *P* values (statistical test for significance) less than 0.05; *P* values in blue font indicate trends with *P* values between 0.05 and 0.10. Slope values in red font indicate a negative trend; slope values in black font indicate a positive trend. TAU is a function of the number of positive (concordant) pairs minus the number of negative (discordant) pairs. Slope is the Theil slope of the trend, in cubic feet per second per year. *DRNAREA*, drainage area; mi^2, square mile; MA, Massachusetts; CT, Connecticut; Bk, Brook; nr, near; Rd, Road; NY, New York; NH, New Hampshire; RI, Rhode Island; E., East; VT, Vermont; Trib, Tributary; @, at; Rt., Route]

U.S. Geological Survey streamgage		*DRNAREA* (mi^2)[1]	Systematic record			Trend		
Number	Name		Begin	End	Years	TAU	*P* value	Slope
Connecticut—Continued								
01188100	Roaring Brook at Unionville, CT	7.55	1962	1984	23	0.53	0.000	10.94
01189200	Stratton Brook nr Simsbury, CT	5.44	1964	1984	21	0.638	0.000	13.28
01190100	Piper Brook at Newington Junction, CT	14.4	1955	1980	23	0.447	0.003	48.00
01190500	South Branch Park River at Hartford, CT	40.4	1936	1981	46	0.184	0.074	26.96
01191900	Charter Brook near Crystal Lake, CT	8.48	1965	1984	20	0.316	0.055	12.56
01192500	Hockanum River near East Hartford, CT	73.3	1920	2013	87	0.23	0.002	8.00
01193300	Blackledge River near Gilead, CT	6.77	1960	1984	25	0.49	0.001	9.01
01199050	Salmon Creek at Lime Rock, CT	29.4	1949	2013	52	0.199	0.038	6.70
01199200	Guinea Brook at West Woods Rd at Ellsworth, CT	3.51	1960	1981	22	0.346	0.026	3.92
01202700	Butternut Brook nr Litchfield, CT	2.43	1960	1984	25	0.37	0.010	11.28
New York								
01334500	Hoosic River near Eagle Bridge, NY	512	1911	2013	103	0.213	0.001	44.44
01360640	Valatie Kill near Nassau, NY	9.45	1991	2013	23	0.281	0.064	13.67
01372200	Wappinger Creek near Clinton Corners, NY	92.5	1956	1984	27	0.245	0.076	30.36
01372300	Little Wappinger Creek at Salt Point, NY	32.9	1956	1984	20	0.332	0.044	32.30
New Hampshire								
01082000	Contoocook River at Peterborough, NH	67.4	1938	2013	64	0.194	0.024	7.80
01085800	West Br. Warner River nr Bradford, NH	5.89	1963	2006	42	0.275	0.011	7.18
01093800	Stony Brook Tributary near Temple, NH	3.60	1964	2004	41	0.295	0.007	3.87
Rhode Island								
01106000	Adamsville Brook at Adamsville, RI	8.05	1941	1987	28	0.223	0.050	1.93
01109403	Ten Mile River at E. Providence , RI	53.7	1987	2013	27	0.274	0.048	15.27
01111300	Nipmuc River near Harrisville, RI	15.8	1965	2013	49	0.202	0.042	6.85
01111500	Branch River at Forestdale, RI	91.2	1936	2013	74	0.188	0.018	11.50
01112500	Blackstone River at Woonsocket, RI	417	1929	2013	85	0.18	0.015	27.26
01114500	Woonasquatucket River at Centerdale, RI	38.2	1936	2013	72	0.267	0.001	5.67
01115630	Nooseneck River at Nooseneck, RI	8.20	1964	2013	25	0.3	0.038	8.12
01117000	Hunt River near East Greenwich, RI	22.9	1938	2013	73	0.325	0.000	2.89
Vermont								
01153500	Williams River at Brockways Mills, VT	102	1938	2012	70	0.234	0.004	30.45
01154000	Saxtons River at Saxtons River, VT	72.1	1936	2013	54	0.19	0.043	20.00
01155350	Trib to West River Trib @ Rt 30 nr Jamaica, VT	0.93	1964	2013	30	0.23	0.077	1.06
01156300	Whetstone Brook Trib nr Marlboro, VT	1.08	1963	2013	26	0.295	0.036	3.27
01156450	Connecticut River Trib nr Vernon, VT	1.10	1964	2013	26	0.391	0.005	1.42

[1]Drainage areas (in mi^2) were determined with a GIS and do not supersede areas listed in the USGS NWIS database.

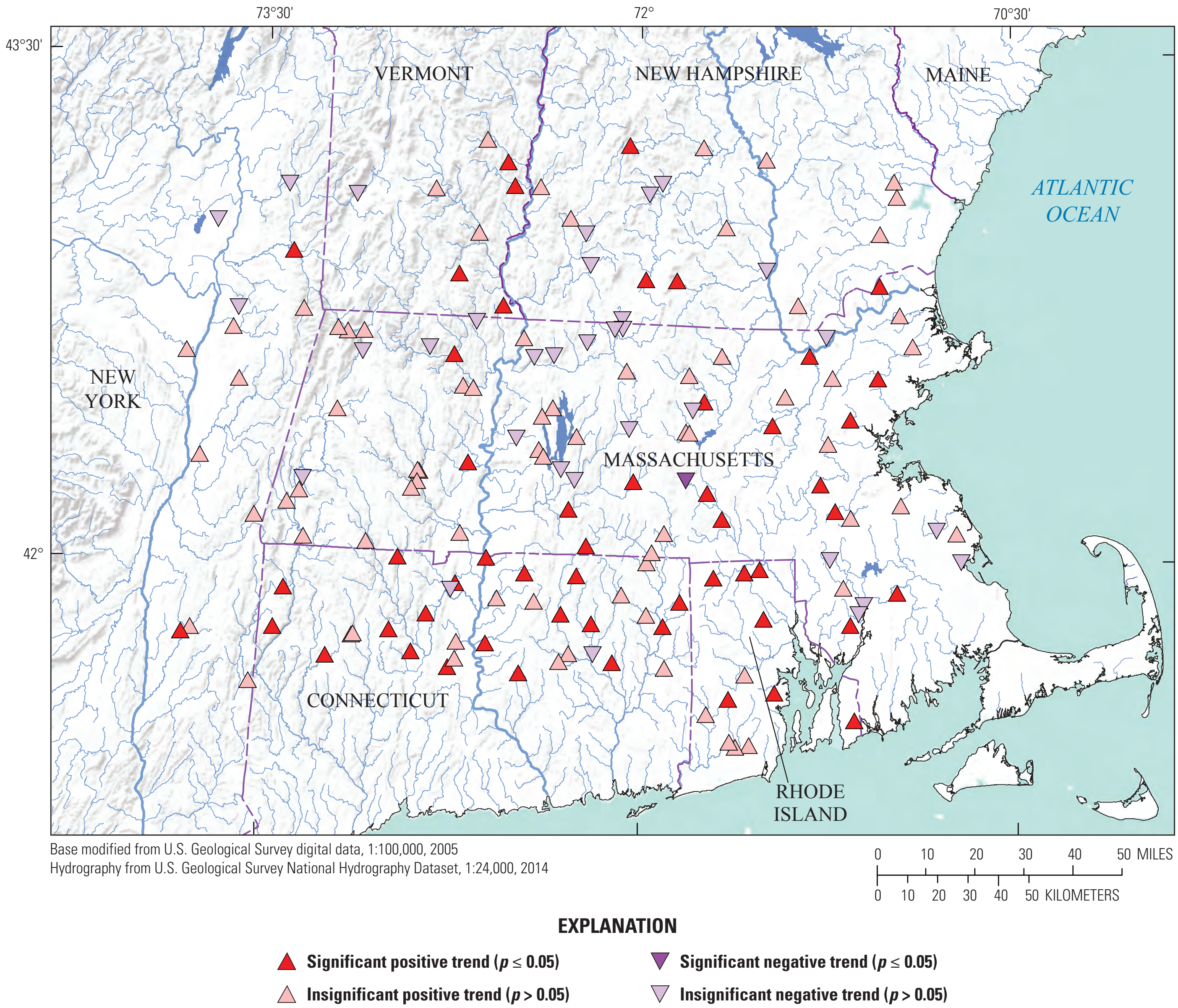


Figure 14. Trends in annual peak flows at 148 selected long-term streamgages with 20 or more years of record used in the flood flow analysis for Massachusetts. >, greater than; ≤, less than or equal to.

in the analysis decreased as the years of analysis increased because of the length of available record. In addition, some streamgages were not used if more than 2 years of data were missing for the 30-year analysis and more than 5 years for the 50- and 70-year analyses.

Over the period of record, 27 of 63 streamgages (about 43 percent) had a significant positive trend at $p \leq 0.05$ with an average slope of 10.4 $ft^3/s/yr$, and 33 streamgages (about 52 percent) had a significant positive trend at $p \leq 0.10$ with an average slope of 10.0 $ft^3/s/yr$. Interestingly, only 3 of the 57 streamgages (5.3 percent of the total) with nearly complete records since 1983 (30 years) had a significant positive trend (at $p \leq 0.05$), but the slope was nearly double (21.9 $ft^3/s/yr$) the slope for the period of record (at $p \leq 0.05$). During the past 50 years (since 1963), 17 of 54 streamgages (31.5 percent) had a significant positive trend (at $p < 0.05$) and markedly increased slope in the trend (28.9 $ft^3/s/yr$). Records since 1943 indicate a step increase in the percentage of streamgages (55.9 percent of the total) with a significant positive trend (at $p \leq 0.05$), but the slope of the trend was not as large (14.1 $ft^3/s/yr$). The reasons the trend pattern changes is not entirely clear, but in some cases, the normal variability in the annual peak flow appears to affect the significance and slope, depending on the period used in the analysis. No relation was found between the level of confidence (p-value) or the slope of the trend and the percent impervious cover.

Table 10. Summary of Kendall trend analysis using progressively longer periods of record ending in water year 2013 for selected streamgages used in the flood flow analysis for Massachusetts.

[p, significance level; ≤, less than or equal to]

	Water years			Entire period of record
	1983–2013 (30 years)	1963–2013 (50 years)	1943–2013 (70 years)	
Number of streamgages used in the analysis for the stated period	57	54	34	63
Streamgages with significant positive trend at $p \leq 0.05$				
Count	3	17	19	27
Percentage of total	5.3	31.5	55.9	42.9
Slope of trend line, in cubic feet per second per year	21.9	28.9	14.1	10.4
Streamgages with significant positive trend at $p \leq 0.10$				
Count	8	24	22	33
Percentage of total	14.0	44.4	64.7	52.4
Slope of trend line, in cubic feet per second per year	19.9	23.0	13.5	10.0
Years of record for streamgages with significant positive trend at $p \leq 0.05$				
Minimum	28	45	65	38
Maximum	30	50	70	101
Average	29.9	49.0	69.7	67.2

Annual peak flows for decadal periods between 1914 and 2013 were also examined for 34 long-term streamgages with continuous record starting in 1943 or earlier. Histograms (fig. 15) show the median percentage of streamgages within each decade that had peak flows outside of their long-term, period-of-record interquartile ranges. The histograms indicate that the 1914–23, 1974–83, and 2004–13 periods had a high percentage of peak flows greater than their long-term upper quartiles, whereas the 1944–53 and 1964–73 periods had a high percentage of peak flows less than their long-term lower quartiles. Individual streamgages with an increasing number of peaks above the long-term upper quartile and a deceasing number of peaks below the long-term lower quartile generally had a significant positive trend as measured by the Kendall Tau test. A similar pattern of higher or lower than normal annual peak flows is indicated by the percentage of annual peaks within each decadal period that are above the long-term median peak flow. The average percentage above the long-term median for all streamgages is shown in figure 15 by a bold red line; individual streamgages are shown by the thin gray lines, which indicate the range of variability among streamgages and time periods.

The percentage of peak flows above or below the long-term interquartile range, and the percentage of peak flows above the long-term median during the past 100 years have an oscillatory pattern. This pattern shows the decadal-scale variability in peak flows in the study area and underscores the fact that trend identification depends upon the period of record chosen for analysis. For example, in the past decade (2004–13), peak flows were persistently greater than the long-term (1914–2013) normal (fig. 15). However, only continued monitoring will provide the information needed to determine whether the positive trend observed at about 43 percent of the long-term streamgages is real or a normal oscillation of peak flows. Although several methods for incorporating temporal trends into a flood frequency analysis have been presented in the literature, no further analysis was made in the study in this report to adjust AEP flows for trends, given the inconsistent trends at long-term streamgages (fig. 14) and the variability in the trends over time (fig. 15). Furthermore, none of the methods in the literature have been widely adopted, and adjusting for trends remains controversial in the research community.

When a trend is observed and quantified, adjustments can be made by correcting earlier peak flows to current conditions (removing trend) or projecting the trend to future conditions. One method to remove a trend assumes a parametric distribution for annual peak flows in order 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 (LOWESS) smoothed curve to the annual peak flows (Ries and Dillow, 2006). Data are adjusted by subtracting the difference between the LOWESS line and each of the annual peak flows from the final value of the LOWESS 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. However, this method appears to unduly affect normal cycles of wet and dry periods.

Vogel and others (2011) recommend use of 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 are first modeled as

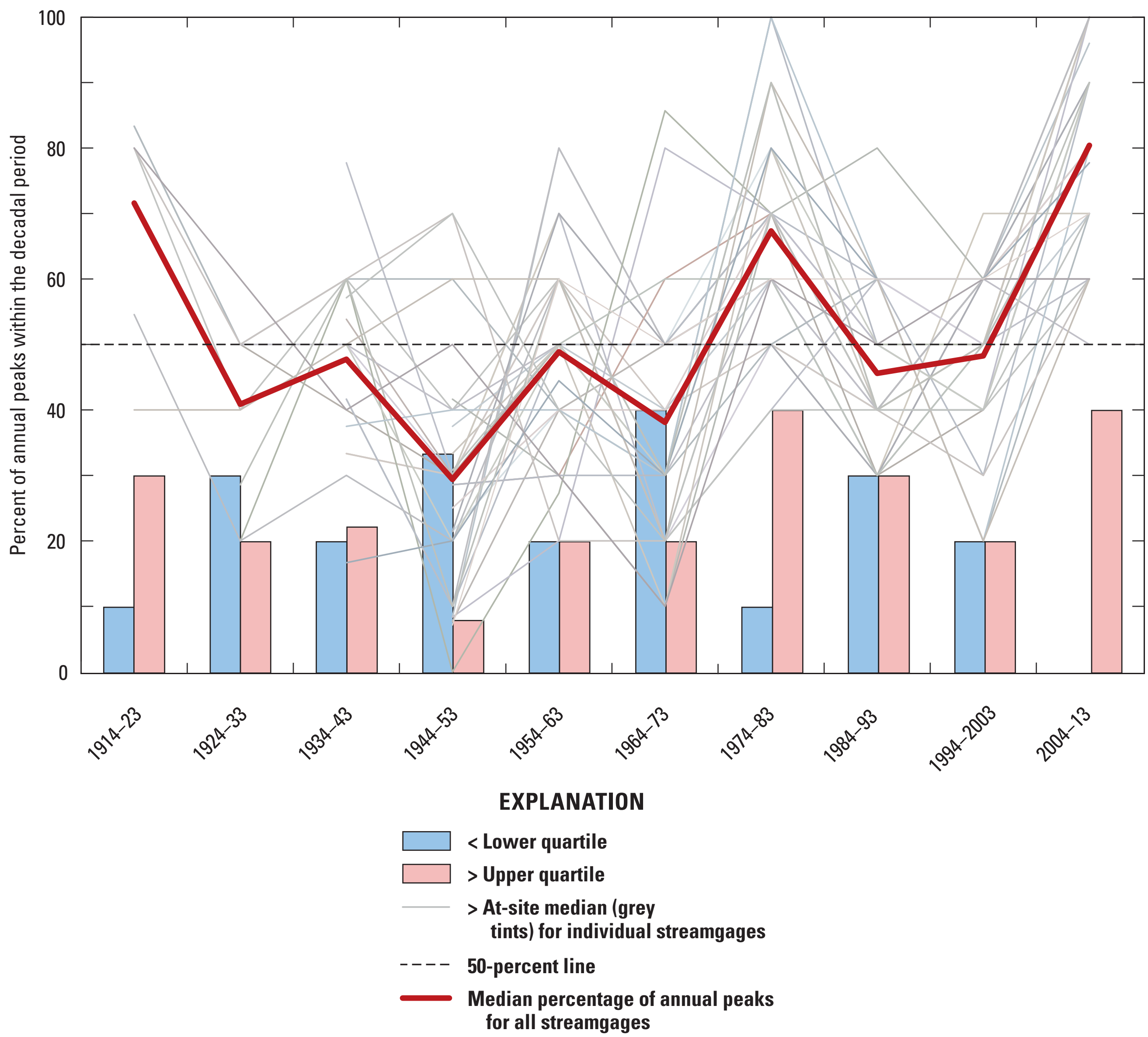


Figure 15. Percentage of annual peak flows, by decade (bars), that are greater than the upper quartile or lower than the lower quartile of a long-term (1914–2013) series of annual peak flows for 34 streamgages used in the flood flow study for Massachusetts with continuous record starting in 1943 or earlier. The bold red line shows the average percentage of annual peak flows, by decade, that is greater than the long-term median peak flow for all streamgages. The thin lines show the percentages of annual peak flows, by decade, that are greater than the respective long-term median peak flows for each individual streamgage.

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 for a projected time, as follows:

$$M = e^{\beta \times \Delta t}, \tag{14}$$

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 application of 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 period. The flood magnification factors (equation 14) were calculated for two streamgages with long-term records and statistically significant trends—Ipswich River at Ipswich, Mass. (01102000) and Mill River at Northhampton, Mass. (01171500), which have log-normal regression slopes of 0.00196 and 0.00243, respectively. Flood magnification factors determined for 10-, 20-, and 30-year projections had computed means of 1.02, 1.04, and 1.06 for Ipswich River at Ipswich and 1.02, 1.05, and 1.08 for Mill River at Northampton, respectively. In other words, if the linear trend in annual peak flows persists, the flood with a given AEP will, on average, be 2, 4, and 7 percent greater in magnitude in 10, 20, and 30 years, respectively.

It should be emphasized that the magnification and recurrence reduction factors computed using the methods of Vogel and others (2011) assume the same linear trend, which may not continue over the projected time periods. Statistical procedures for nonstationarity are in their infancy, and the trends observed in the data used in this study and the effects on flood frequency will require further work as this science evolves and new data are obtained.

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. Application of regional regression equations at ungaged sites, including the limits of basin characteristics used to develop the equations and uncertainties of the AEP floods estimates, were described previously. This section provides additional information on how flood estimates for an ungaged site can improve at-site estimates of flood flows at a streamgage and how a flood estimate for an ungaged site on a gaged stream can be improved. Additional information is provided on the application of methods at streamgages with limited record, incorporation of results into a national database, and comparison of the updated AEP flood estimates with past regional flood studies in Massachusetts.

Weighted Estimates of Flood Flows at Streamgages

Flood flow estimates for a given AEP at streamgages, particularly those with short records, can be improved using a weighted average of estimates made with the streamgage analysis and the regional regression equations. The procedure assumes that these estimates are independent, which is considered true in most practical instances in B17B. Exceptions may include regional regression equations that are based on clusters of streamgages in close proximity or with uniformly short periods of record. Clusters of streamgages do not appear to be a factor in this analysis, but many streamgages (27 streamgages) with small drainage areas (<20 mi^2) have a short period of systematic record that generally spans from the mid-1960s to the mid-1970s; this can bias the magnitude of AEP flows with small drainage areas. If the at-site and regression flood flow statistics are not independent, the variance of a weighted estimate will be larger than the variance of each estimate. Also noteworthy is that, when basin characteristics are outside the range of characteristics used in the regional regression or if peak flows at a streamgage are appreciably affected by regulation, a weighted estimate is not appropriate.

In the past, the weights for flood flow estimates were often made on the basis of 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 streamgage 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 independent flood flow estimates 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 (Interagency Advisory Committee on Water Data, 1981, app. 8). When the variance corresponding to one of the estimates is high, the uncertainty is high, and the weight applied to that estimate is relatively small. In contrast, when the variance is low, the uncertainty is low, and the weight applied to that estimate is relatively large. Thus, a weighted estimate of the AEP flow is inversely proportional to the variance of each flood flow estimate, and the associated variances are determined using (all variables are in log$_{10}$ units)

$$Q_{wgt,i} = \frac{\left(Q_{site,i} \times V_{reg,i}\right) + \left(Q_{reg,i} \times V_{site,i}\right)}{V_{site,i} + V_{reg,i}}, \qquad (15)$$

where

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

Similarly, a weighted variance can be calculated from the inverse variances of each flood flow estimate using (all variables are in $\log_{10}$ units), as follows:

$$V_{wgt,i} = \frac{V_{site,i} \times V_{reg,i}}{V_{site,i} + V_{reg,i}}, \qquad (16)$$

The 95-percent confidence interval (95%_CI) can be calculated from the weighted estimates determined by equations 15 and 16 using the following equations:

$$95\%\_CI_{upper,i} = 10^{Q_{wgt,i}+1.96\sqrt{V_{wgt,i}}}, \text{ and} \qquad (17)$$

$$95\%\_CI_{lower,i} = 10^{Q_{wgt,i}-1.96\sqrt{V_{wgt,i}}}. \qquad (18)$$

The variables needed to calculate equations 15 and 16 are obtained directly from output from PeakFQ (v. 7.1) and WREG (v.1.05) for sites used in the regional regression model. WREG computes a variance of prediction for each streamgage used in the regional regression analysis that is used for V_{reg}. For streamgages that are not used in the regional regression but have sufficient data for computation of at-site AEP flows, the average variance of prediction (*AVP*) for the regression (table 6) can be substituted for V_{reg} to compute a weighted estimate of AEP flows for the site. For example, the *AVP* would be used to compute a weighted flow estimate for a site not used in the regional regression because of redundancy.

Weighted estimates of AEP flows are reported in table 11 for most Massachusetts streamgages. Streamgages not included in table 11 generally include those operated for less than 10 years, located on Cape Cod, or that are heavily regulated (although some presently regulated streamgages that were operated prior to regulation are included). For comparison, the at-site EMA and regional GLS regression flood flows along with the percent difference between the EMA and weighted values are reported. A positive difference indicates the weighted estimate is greater than the EMA estimate, and a negative value indicates the weighted estimate is smaller than the EMA estimate.

Table 11. Magnitude and variance of 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability flood flows for selected streamgages in Massachusetts.

[Table available for download at https://doi.org/10.3133/sir20165156]

In general, the variance of the at-site EMA estimated AEP flow decreases as the streamgage record length increases, and therefore, more weight is given to the at-site analysis relative to the regional regression analysis as the record length increases. The magnitude of weighted flood estimates, on average, ranged from about 3 to 6 percent greater than the at-site flood estimate and the difference between the EMA and weighted AEP flows progressively increased as the AEP decreased (fig. 16). Differences in the 50-percent AEP flow ranged from –17 to 29 percent with an interquartile range of –0.6 to 2.7 percent. Differences for the 0.2-percent AEP flows were largest and ranged from –66 to 56 percent with an interquartile range of –6.6 to 12 percent. The increasing difference with decreasing flood probability is due to the greater uncertainty of flood flows as the AEP decreases for at-site analysis and the regional regression equations.

Flood Flows at Streamgages with Limited Record

Flood magnitudes determined at streamgages with short records are subject to greater inaccuracies relative to streamgages with long records 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 use of a weighted skew in the at-site analysis as previously described. The weighted skew is inversely proportional to the variance of the at-site skew and the regional skew and the estimated flows from each method, as described in B17B; however, this procedure is not without flaws because the true variance may not be accurately represented particularly for streamgages with short-term records.

Many streamgages with short-term records were used in the regional regression analysis to provide information on small drainage basins. Most of these streamgages were operated from the mid-1960s to the mid-1970s or mid-1980s for the purpose of the flood flow study by Wandle (1983) and are evenly distributed throughout the study area. Estimates of flood flows for selected AEPs were determined at these sites and weighted with estimates determined from the regional regression equations to provide a better at-site estimate as previously discussed. However, AEP flows for small basins may be biased by the short common period of record as previously discussed.

The peak flow record of short-term streamgages not used in the analysis can be extended using maintenance of variation extension (MOVE; Hirsch, 1982) to better reflect long term conditions before conducting an EMA analysis. The EMA results could be combined with regional regression estimated flows to produce a better estimate of the at-site AEP flood flows; however, the variance of the at-site analysis would be biased by the record extension and may not reflect the true confidence of the at-site estimate.

Flood Flows at an Ungaged Site on a Gaged Stream

Estimates of flood flows upstream or downstream from a streamgage, within limits, can be improved by combining the streamgage information with the regional regression

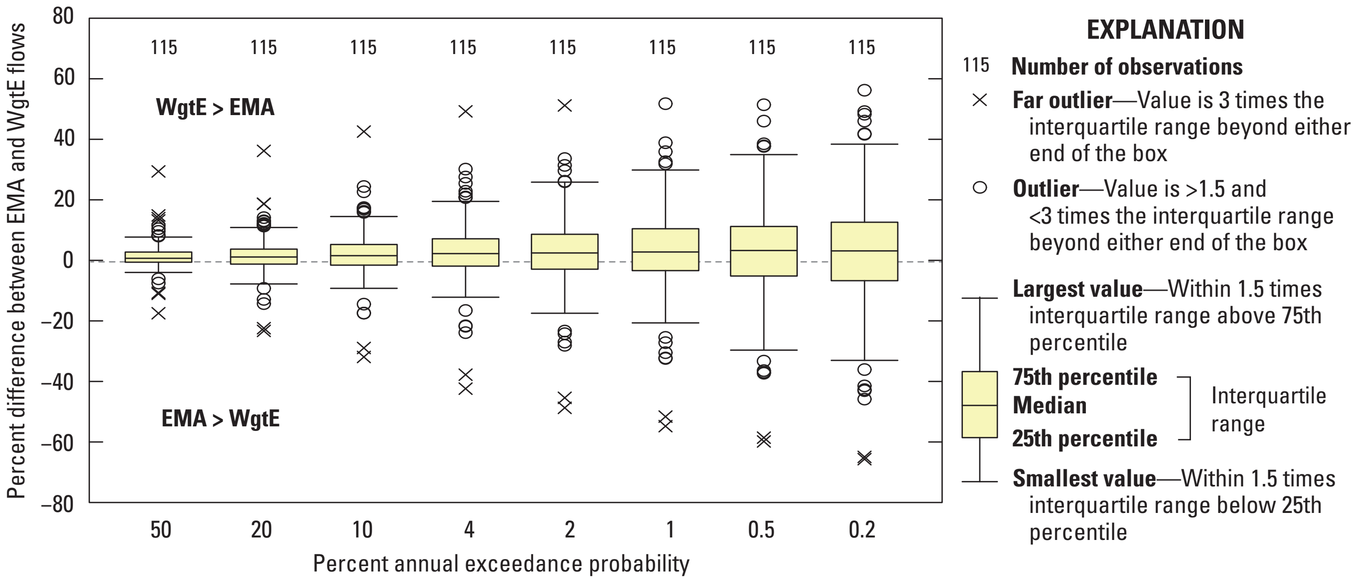


Figure 16. Differences between flood flows calculated from at-site expected moments algorithm (EMA) analyses and weighted estimates (WgtE) for selected annual exceedance probabilities for streamgages in Massachusetts. >, greater than.

information. Sauer (1974) first presented a method for better estimating flows at an ungaged site that is based on the difference in drainage area between the gaged and ungaged sites, the weighted estimates of flow at the gaged site, and the regional regression estimates of flow at the gaged and ungaged sites. A similar weighting procedure was presented by Guimaraes and Bohman (1992) and Stamey and Hess (1993) and used by Ries (2007) to improve flood frequency estimates for a rural ungaged site with a drainage area that is from 0.5 to 1.5 times the drainage area of a streamgage on the same stream. This approach is used in the USGS StreamStats interactive online tool for solving regionalized equations (http://water.usgs.gov/osw/streamstats/; Ries and others, 2008) to adjust flood flows on the basis of the drainage area ratio of the ungaged and gaged sites to adjust the streamgage weighted AEP flow, which is then weighted with the regional regression AEP flow at the ungaged site. In the first step, the basic adjusted flow for a site above or below a streamgage is determined using the following equation:

$$Q_{P(u)g} = \left(\frac{DA_u}{DA_g}\right)^b Q_{P(g)w}, \tag{19}$$

where

$Q_{P(u)g}$ is the scaled 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;

b is the exponent of drainage area from the appropriate regression equations (table 12); and

$Q_{P(g)w}$ is the weighted flow estimate for the selected P-percent AEP at the gaged site, in cubic feet per second.

The use of the basic adjusted flow for a site above or below a streamgage dates from at least as far back as the “Elements of Applied Hydrology” (Johnstone and Cross, 1949). Note that the weighted estimate of flow at a gaged site was not used in this first step.

Exponents from regional flood flow equations derived from WREG using a GLS analysis of drainage area ranged from 0.80 to 0.76 for the 50- to 0.2-percent AEP flows (table 12). The average or median exponent b over the range of exceedance probabilities is commonly used in equation 19 because the exponent does not vary greatly.

The second step is to weight the scaled ungaged site weighted AEP flow ($Q_{P(u)g}$) with the regional regression estimated flow at the ungaged site ($Q_{P(u)r}$) to determine a weighted AEP estimate at the ungaged site ($Q_{P(u)w}$) using the following equation:

$$Q_{P(u)w} = \left(\frac{2\Delta DA}{DA_g}\right) Q_{P(u)r} + \left(1 - \frac{2\Delta DA}{DA_g}\right) Q_{P(u)g}, \tag{20}$$

where

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

$Q_{P(u)r}$ is the regional regression flow estimate for the selected *P*-percent AEP at the ungaged site, in cubic feet per second.

By combining equations 19 and 20, the weighted discharge at the ungaged site can be computed using the following equation:

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

An example application of this procedure is shown for the 1-percent AEP flow at a hypothetical site on Priest Brook in north-central Massachusetts. Priest Brook was chosen as an example because the regional regression estimated flow at the Priest Brook near Winchendon (01162500) streamgage had one of the highest residual errors. As such, the example demonstrates the added value of using streamgage flow data to estimate flows at an ungaged site where possible. The streamgage has 96 years of systematic record from 1917 to 2013 (missing record in 1918), so the at-site AEP flows can be estimated with a relatively high degree of certainty. The 1-percent AEP at-site flow estimate at the streamgage is 1,580 ft^3/s, whereas the regional regression flow at the streamgage is 2,240 ft^3/s and the weighted estimate of flow at the streamgage is 1,640 ft^3/s (table 11). For the hypothetical example, the presence of a site upstream from the streamgage with a drainage area of 17 mi^2 (the streamgage has a drainage area of 19.2 mi^2) was assumed; other explanatory basin characteristics remain the same (*ELEV* = 1,096 feet; *LC06STOR* = 13.6 percent). Equation 21 produces a flow estimate of 1,620 ft^3/s for the 1-percent AEP flow at this site, which, as expected, is slightly lower than the weighted estimate (1,640 ft^3/s) for the downstream streamgage.

A worksheet for solving the flood flows for a given AEP on a stream upstream or downstream from a gaged location using equation 21 is available in appendix 3. Equation 21 requires user-specified drainage areas at the gaged and ungaged sites, regional regression-estimated AEP flows for the ungaged site (can be determined from the “US–DS Flow” worksheet in the workbook in appendix 3), and the at-site AEP flood flow determined from the streamgage analyses for the same exceedance probability (table 11). The weighting procedure should not be used when hydrologic characteristics abruptly change, such as a large in-stream impoundment between ungaged and gaged sites. In addition, for the gaged site, 10 or more years of peak-flow record are needed to yield meaningful at-site analytical results.

For an ungaged site that is between two gaged sites on the same stream, two flow estimates can be made using the method and criteria outlined above, but additional hydrologic judgment may be necessary to determine which estimate (or some interpolation thereof) is most appropriate. Only a few rivers in Massachusetts have multiple streamgages that could be used to compute multiple adjusted estimates at an ungaged site. Other factors that need to be considered when evaluating the two estimates include differences in the length of record at the streamgages and the quality of the peak-flow record.

Table 12. Regional exponent for drainage area adjustment of flood flows at an ungaged site on a gaged stream in Massachusetts.

Percent annual exceedance probability	Exponent *b*
50	0.80
20	0.79
10	0.78
4	0.78
2	0.77
1	0.77
0.5	0.76
0.2	0.76

National Database

The results of this study are entered into the online USGS National Streamflow Statistics (NSS) database (http://water.usgs.gov/osw/programs/nss/), which provides regional flood flow statistics and other streamflow statistics developed and published by the USGS for every State through cooperative programs, such as this study. The NSS also provides information on the accuracy of the estimated streamflow statistics, such as 95-percent confidence intervals for estimated flood flows at a streamgage.

The NSS is used by USGS StreamStats (http://water.usgs.gov/osw/streamstats/; Ries and others, 2008), which allows a user to select either a gaged or an ungaged site on a river, and obtain statistical information such as flood flow estimates and the uncertainty of those estimates at the selected site. StreamStats provides fast, reproducible results usable by anyone with internet access that provides a substantial cost savings to MassDOT and other users of this information.

Comparison With Previous Studies

The updated at-site flood AEP flows and regional regression equations developed from these data raise the question of how the results compare with previous flood analyses because the estimated flows directly affect infrastructure design, flood inundation, and other work that utilizes information on the magnitude of floods. Comparisons were made for flood magnitudes from the 50- to 0.2-percent AEP at Massachusetts streamgages in this study with flood magnitudes from previous studies by Wandle (1983) and Murphy (2001b). Wandle (1983) was the last and only comprehensive flood flow analysis for Massachusetts streams and was limited to peak flow data through water year 1976. Although Wandle (1983) was targeted for "small rural streams," 33 of the 95 streamgages used in that study had drainage areas greater than 20 mi^2 and as large as 260 mi^2. Wandle (1983) developed equations for computing flood flows at ungaged streams in Massachusetts that have been in wide use since that time and provide the basis for comparison with this study. The mixed-population distribution AEP-computed flows from Murphy (2001b) are also used for comparison, but the analysis in Murphy (2001b) was limited to data from 30 streamgages for the period of record through water year 1993. Murphy (2001b) did not develop regional equations to compute AEP flows at ungaged sites. The comparisons reflect differences in the period of record and differences in methods and are limited to streamgages in Massachusetts.

The at-site analysis comparison includes the difference between 50- to 1-percent AEP flows computed using B17B methods and the EMA analysis for 83 streamgages, B17B and mixed-population 1-percent AEP flow for 27 streamgages, and mixed-population and EMA for the 1- and 0.2-percent AEP flows for 27 streamgages (table 13). The differences between the at-site analyses are shown in boxplots in figure 17. Positive differences indicate that flows from the more recent at-site analyses are greater than those from the previous at-site analyses; in contrast, negative percent differences indicate that the updated AEP flows are smaller than the previous AEP flows.

Table 13. Annual exceedance probability flood flows reported by Wandle (1983) and Murphy (2001b) and computed in this study at selected streamgages in Massachusetts.

[Table available for download at https://doi.org/10.3133/sir20165156]

The 50- to 1-percent AEP flows from the EMA at-site analysis, on average, were about 6 to 10 percent greater than the B17B at-site flows computed by Wandle (1983); differences ranged from about 1 to –7 percent at the lower quartile to about 13 to 23 percent at the upper quartile (fig. 17). In general, the differences increased as the AEP decreased. Differences between EMA- and B17B-computed AEP flows are mainly attributed to the additional 37 years of record (at most sites) used in the EMA analysis because few streamgages are appreciably affected by EMA enhancements (censoring low outliers, threshold values, and interval data). The additional years of record used in the EMA analyses include a disproportional number of the highest peak flows of record, underlying the need to periodically update flood flow statistics and regional regression equations.

The mixed-population 1-percent AEP flow, on average, was about 14-percent greater than the B17B-computed flows. Some of this difference is attributed to the additional 18 years of record used by Murphy (2001b), but the greater part of the difference is attributed to the fundamental differences in the methods. On average, the EMA flow was about 14 percent greater than the mixed-population-computed flow at the 1-percent AEP and about 8 percent less at the 0.2-percent AEP (fig. 17). The differences are inconsistent at the 1- and 0.2-percent AEP and, thus, are attributed mainly to differences in the methods.

Differences in AEP flows computed using the regional regression equations by Wandle (1983) and the regional equations developed as part of this study reflect the differences in the at-site analyses used to develop the regression equations and the improved regression methods. Wandle used OLS regression, and this study used GLS regression. Differences between 50- to 1-percent AEP flows reported for 82 streamgages in Massachusetts by Wandle and those computed in this study are shown in figure 18. Note that Jackstraw Brook at Westborough, Mass. (01097450) was not included in this plot or the previous at-site analysis comparison (fig. 17) because annual peak flows at this site are coded as being either estimated or greater than the reported value. Positive differences indicate that the GLS regression flows are greater than the OLS regression flows; negative differences indicate that the GLS regression flows are smaller than the OLS regression flows.

Overall, the GLS regression equations yielded higher flows than the OLS regression equations over the range of AEP flows where both equations could be applied (fig. 18). This is consistent with the differences between the B17B and EMA at-site flows that are mainly attributed to the additional years of record used in the EMA analysis. Note, the OLS equations were not developed for the 0.5- and 0.2-percent AEP floods. On average, the GLS equation flows were about 31 to 45 percent greater than the OLS equation flows; differences were generally consistent across the AEP flows. The largest difference was at Housatonic River tributary at Risingdale, Mass. (01197550) where the GLS regression equation resulted in flows that ranged from about 250 to 370 percent larger than the flows computed using the OLS equations. The Housatonic River tributary has a small basin (0.86 mi^2) in western Massachusetts with no storage. This error is mostly attributed to the values for the explanatory variables being at or near the outer limits of the values used in the analysis (particularly storage and elevation being at opposite limits of the data) but also, in part, to the short common period of record used at many of the small basins.

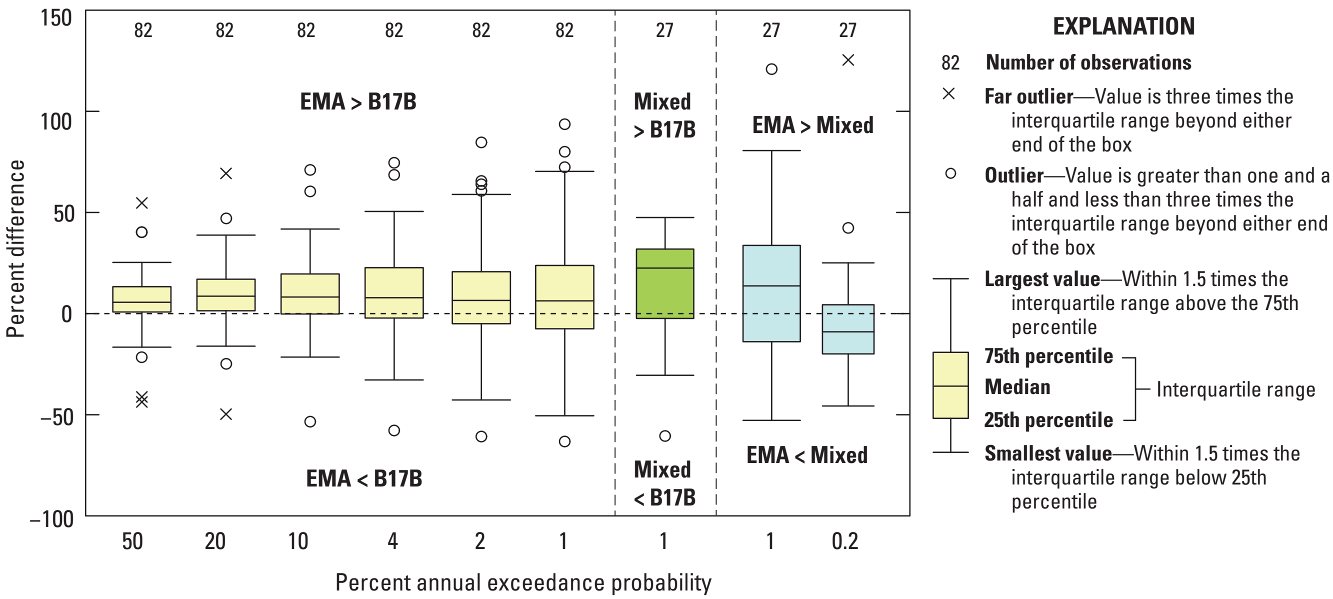


Figure 17. Percent differences between at-site analyses computed by Wandle (1983) using Bulletin 17B (B17B; Interagency Advisory Committee on Water Data, 1981) methods for the period of record up to water year 1976, by Murphy (2001b) using mixed population distribution (mixed) for the period of record up to water year 1993, and expected moments analysis (EMA) in this study for the period of record up to water year 2013 for 82 streamgages in Massachusetts. >, greater than; <, less than.

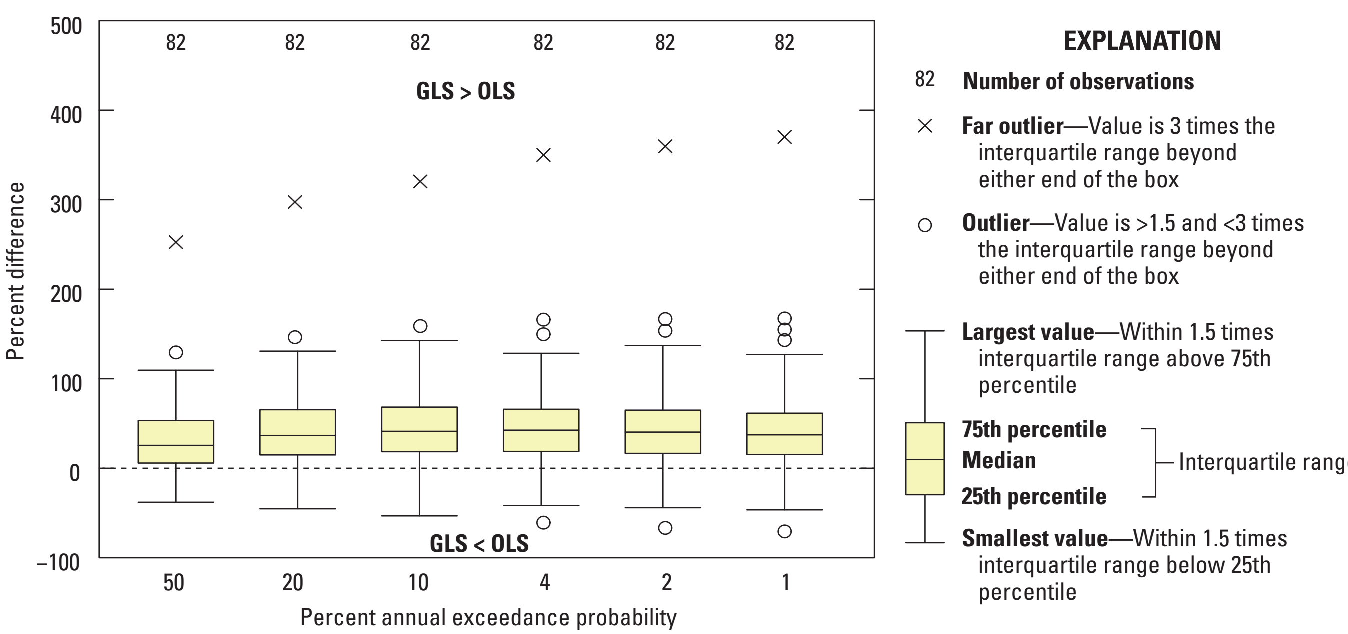


Figure 18. Differences between regional ordinary least squares (OLS) regression equations developed by Wandle (1983) and generalized-least squares (GLS) regional regression equations developed as part of this study for 50- to 1-percent annual exceedance probability flood flows at 82 streamgages in Massachusetts. >, greater than; <, less than.

Summary and Conclusions

The magnitudes of flood flows at gaged sites on Massachusetts streams were estimated and regional equations for estimating flood flows at ungaged sites were developed in a study conducted by the U.S. Geological Survey (USGS) in cooperation with the Massachusetts Department of Transportation. Periodic evaluations are necessary because new data and techniques improve the accuracy of flood flow estimates that are important for flood plain management, transportation infrastructure design, hazard preparedness, flood insurance studies, and other purposes to help minimize future flood damages and risks. The magnitudes of flood flows at selected streamgages in Massachusetts were estimated at selected annual exceedance probabilities (AEPs).

Skew, an important statistical measure used to define the probability distribution of annual peak flows at a streamgage, is improved by pooling regional information. In a related study, developed in part from this study, a regional skew was computed for New England on the basis of the at-site skews computed using the expected moments algorithm (EMA) at 153 streamgages throughout New England and Bayesian weighted least squares and generalized least squares methods. Although various basin characteristics were tested, none was significant, and a single skew of 0.37 was found to be the best model of skew for New England. The average variance of prediction of the regional skew was 0.14. The updated regional skew is estimated to have more than three times the explanatory power of the previous skew values reported on the national map in Bulletin 17B.

The EMA weighted with the regional skew and error was used to determine flood magnitudes at selected AEPs at 220 streamgages, of which 125 are in Massachusetts and 95 are in the adjacent States of Connecticut, New Hampshire, New York, Rhode Island, and Vermont. Annual peak flow data through water year 2013 were used for the streamgages' periods of record or unregulated periods. Unregulated streamgages in adjacent States that have basin centroids within about 40 miles of Massachusetts and suitable record length were used in the regional flood flow analysis for Massachusetts. Of the 125 streamgages in Massachusetts, 104 were used in the regional regression analysis; the other 21 were not used primarily because they were considered redundant or sufficiently regulated to affect the magnitude of annual peak flows. At-site analyses were reported for 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods. The EMA provides an improvement compared with the previous methods used to compute a log-Pearson type III probability distribution by addressing data uncertainty, gaps in systematic record or gaps between the systematic record and historic peak flows, and censoring of low outliers. In addition, the EMA provides improved estimates of the 95-percent confidence intervals of the AEP flows.

Regional regression equations were developed to estimate the magnitudes of floods at ungaged sites at the selected AEPs using AEP flows from 199 streamgages and basin characteristics. A total of 60 basin characteristics were evaluated as potential explanatory variables in the regression; however, only the three most statistically significant characteristics were used in the final regional flood flow equations—drainage area, mean basin elevation, and percent basin storage. Basins of streamgages used in the regional analysis range in size from 0.16 to 512 square miles (mi^2; mean 52.8 mi^2), with a mean basin elevation ranging from 81 to 1,949 feet (ft; mean 758 ft), and storage (percent of basin area in open water and wetlands) ranging from 0 to 32.3 percent (mean 9.14 percent). These ranges should be considered the applicable limits of basin characteristics for applying the regional equations. The regional equations can still be computed beyond this range of characteristics, but the confidence of the results cannot be determined.

The final regression equations were developed using the USGS Weighted Multiple Linear Regression program using the generalized least squares regression method, which is considered to be the most robust regression method for regional analysis because it accounts for record lengths and correlation between streamgages. The pseudocoefficient of determination (pseudo-R^2) indicates that the explanatory variables explain 86 to 93 percent of the variance in the flood magnitude for 50- to 0.2-percent AEPs. The 90-percent prediction interval for each AEP flood flow computed from the regional regression equation model error variance and the covariance are also reported.

Flood flow estimates for a given AEP at a gaged site, particularly at sites with short records, can be improved by using a weighted average of two independent estimates from 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 of the two estimates. The magnitude of weighted floods, on average, ranged from about 3 to 6 percent greater than the at-site flood estimate. Estimates of flood flows on a stream upstream or downstream from 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 hydrologic characteristics of the ungaged and gaged basin do not abruptly change and their drainage area ratios are generally within 0.5 to 1.5 of each other.

Effects of urbanization were examined because impervious cover is generally considered an important factor in determining the magnitude of a flood and many parts of the State that have a long history of urban development. The imperviousness in the streamgage basins used in the regression analysis ranged from 0 to 46 percent; however, the median imperviousness was only 1.6 percent. Although imperviousness provided some explanatory power in the regression analysis, it was not statistically significant. Further analyses of imperviousness indicate a complex interplay with other basin characteristics, particularly the percent area of sand and gravel.

The AEP flood flows are based on the assumption of stationarity, that is, the assumption that annual peak flows exhibit no significant trend over time. The results of the analysis show that stationarity does not prevail at all of the streamgages. Streamgages used in the study with 20 or more years of systematic record show a significant positive trend at the 95-percent confidence level in about 27 percent (17 out of 64) of streamgages in Massachusetts and about 42 percent (35 out of 84) of streamgages in adjacent States; one streamgage in Massachusetts had a significant negative trend, which was attributed to the period of record. The average trend slope of streamgages with significant positive trends was 9.2 cubic feet per second per year, and slopes ranged from 1.3 to 41 cubic feet per second per year in Massachusetts. The remaining 96 streamgages used in the analysis had both positive and negative trends that were not significant. A subset of 63 streamgages with significant positive trends was used to assess trends during 30-, 50-, and 70-year intervals ending in 2013. Trends and the level of significance vary for different lengths of record and oscillations in the annual peak flows. A decadal analysis of trends shows that, in the past decade (2004–13), peak flows were persistently greater than normal. Only continued streamflow monitoring will provide the information needed to determine whether recent increases in annual peak flows are a normal oscillation or a true trend in annual peak flows.

The analysis used 37 years of additional data since the last comprehensive study of flood flows in Massachusetts. In addition, new methods for computing flood flows at streamgages and regionalization improve estimates of flood magnitudes at both gaged and ungaged locations and better define the uncertainty of the estimates of AEP floods.

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Glossary

adjusted r-squared The adjusted coefficient of determination, 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 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-flow 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 flow 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 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, which equates to $\alpha = 5$ 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 Method for fitting a probability distribution to annual peak flow data using a generalized method of moments, similar to the standard log-Pearson type III method described in Interagency Advisory Committee on Water Data (1981), except the expected moments algorithm can also use interval data, whereas log-Pearson type III 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 peak flows used in the analysis.

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

historic flood Magnitude of a flood measured, or estimated, outside the systematic period of record. Typically, these are floods whose peak is determined by indirect measurement methods.

leverage In statistics, leverage is used to identify those observations that are far away from corresponding average predictor values and may or may not have a large effect on the outcome of an analysis.

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

maintenance of variation extension 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 squared error 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 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 relation.

predicted residual sum of squares A validation type estimator of error. Predicted residual sum of squares 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.

pseudocoefficient of determination A statistic generated by the generalized least squares regression, the pseudocoefficient of determination (or pseudo-R squared) is similar to the adjusted coefficient of determination in that it is a measure of the predictive strength of the regression model except that it removes the time sampling error.

root mean squared error 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 squared error of the regional skew estimate.

skew 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 flows at the streamgage. Because the skew is sensitive to outliers, it may be an unreliable estimate of the true skew, especially for small samples; the guidelines in Interagency Committee on Water Data (1982) recommend 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 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.

systematic record A period or periods of continuous annual peak-flow record.

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

weighted least squares 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.

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

Appendixes 1–3

Appendix 1. Basin and Climate Characteristics Considered for Use as Explanatory Variables in the Regional Regression Analysis for Estimating Flood Flows in Massachusetts

Table 1–1. Basin and climate characteristics considered for use as explanatory variables in the regional regression analysis for estimating flood flows in Massachusetts.

[dd, decimal degree; ft, foot; ft/mi, foot per mile; mi, mile; mi/mi^2, mile per square mile; mi^2, square mile; °F, degree Fahrenheit; π, pi (3.14159); XX, not applicable]

Characteristic	Name	Unit	Notes
		Shape[1]	
Drainage area	DRNAREA	mi^2	
X-coordinate at center of basin	CentX	dd	Massachusetts State plane coordinates
Y-coordinate at center of basin	CentY	dd	Massachusetts State plane coordinates
X-coordinate at outlet of basin	GageX	dd	Massachusetts State plane coordinates
Y-coordinate at outlet of basin	GageY	dd	Massachusetts State plane coordinates
Basin perimeter	BP	mi	
Compactness ratio	CR	None	Calculated as $BP/2\ (\pi \times DA)$^0.5
Basin length	BL	mi	Distance from outlet to headwater along main axis
Effective width	BW	mi	Calculated as DA/BL
Elongation ratio	ER	None	Calculated as [4×DA / π × BL^2]^0.5 = 1.13 × (1 / SF)^0.5
Shape factor	SF	None	Calculated as BL/BW
Rotundity	RB	None	Calculated as $[\pi \times BL^2] / 4\ DA = 0.785 \times SF$
		Land cover[2]	
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 as ModDen + HiDen
Total urban area	Urban	Percent	Calculated as 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 as DecFor + ConFor + MixFor
Total forest and low density development area	Forest2	Percent	Calculated as Forest + ForWet + LowDen
Area of barren land	Barren	Percent	
Area of shrub land	Shrub	Percent	
Total open area	Open	Percent	Calculated as Barren + Shrub
Area of grassland	Grass	Percent	
Area of pasture	Pasture	Percent	
Area of cropland	Crop	Percent	
Total agriculture area	Agr	Percent	
Area of forested wetlands	ForWet	Percent	
Area of nonforest wetlands	Wetland	Percent	
Total wetland area	AllWet	Percent	
Storage area of lakes, ponds, and wetlands	LC06STOR	Percent	
Area of impervious land[3]	IMPERV	Percent	NLCD 2006 impervious surface
Storage area of lakes, ponds, and wetlands[4]	StorNHD	Percent	Wetlands delineation not consistent across States

Table 1–1. Explanatory variables in regionalized regression equations for estimating flood flows in Massachusetts.—Continued

[dd, decimal degree; ft, foot; ft/mi, foot per mile; mi, mile; mi/mi^2, mile per square mile; mi^2, square mile; °F, degree Fahrenheit; π, pi (3.14159); XX, not applicable]

Characteristic	Name	Unit	Notes
		Topography[5]	
Mean basin slope	Slope	Percent	
Mean basin elevation	ELEV	m	
Maximum basin elevation	ELEVmax	m	
Minimum basin elevation	ELEVmin	m	
Basin relief	RELIEF	m	
Basin outlet elevation	OutletELEV	m	
		Infiltration	
Area of sand and gravel deposits[6]	SG	Percent	
Area of till deposits[6]	Till	Percent	
Area of fine grain deposits[6]	Fines	Percent	
Area of organic rich deposits[6]	Muck	Percent	
Area of hydrologic soils[7]			
Group A	SoilA	Percent	
Group B	SoilB	Percent	
Group C	SoilC	Percent	
Group D	SoilD	Percent	
		Climate[8]	
Annual precipitation	PRECIP	Inches	
Annual air temperature	TempF	°F	
Precipitation, 24-hour: [9]			
10-year	10yr_24hr	in.	Maximum 24 hour precipitation for a 10-year recurrence interval
100-year	100yr_24hr	in.	Maximum 24 hour precipitation for a 100-year recurrence interval
500-year	500yr_24hr	in.	Maximum 24 hour precipitation for a 500-year recurrence interval
		Stream network[10]	
Total length of streams	StrTOT	mi^2	
Stream density	StrDEN	mi/mi^2	Calculated as StrTOT/DA
		Ecoregions[11]	
Ecoregion	EcoReg4	XX	Level IV ecoregions
Ecoregion	EcoReg3	XX	Level III ecoregions

[1]Source: Basin boundaries coverage (internal).

[2]Source: Multi-Resolution Land Characteristics (MRLC) Consortium, National Land Cover Database (NLCD) 2006 (http://viewer.nationalmap.gov/viewer/).

[3]Source: U.S. Geological Survey, The National Map, National Land Cover Database (NLCD) 2006 impervious surface layer (http://viewer.nationalmap.gov/viewer/).

[4]Source: U.S. Geological Survey, The National Map, National Hydrography Dataset (NHD), scale 1:24,000 (http://viewer.nationalmap.gov/viewer/).

[5]Source: U.S. Geological Survey, The National Map, National Elevation Dataset (NED) 10-meter resolution, North American Vertical Datum of 1988 (http://viewer.nationalmap.gov/viewer/).

[6]Source: U.S. Geological Survey, Quaternary sediments in the glaciated United States, Map I–1970 (http://pubs.usgs.gov/ds/656/).

[7]Source: Natural Resource Conservation Service (NRCS), STATGO2 data (http://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx).

[8]Source: PRISM Climate Group, 30-year (1981–2010) normal data (http://www.prism.oregonstate.edu/normals/).

[9]Source: Northeast Regional Climate Center, extreme precipitation in New York and New England data (http://precip.eas.cornell.edu/).

[10]Source: U.S. Geological Survey, The National Map, National Hydrography Dataset (NHD) 1:24,000 (http://viewer.nationalmap.gov/viewer/).

[11]Source: U.S. Environmental Protection Agency, level III and IV ecoregions map server (http://geodata.epa.gov/ArcGIS/rest/services/ORD/USEPA_Ecoregions_Level_III_and_IV/MapServer).

Appendix 2. Measurement of Regression Error for Massachusetts

The accuracy of a regression analysis 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 (Eng and others, 2009) and is computed using the following equation:

$$V_{p,i} = \gamma^2 + MSE_{s,i}, \tag{2–1}$$

where

γ^2 is the model error variance, and

$MSE_{s,i}$ is the 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 using the following equation:

$$AVP = \gamma^2 + \frac{MSE_{s,i}}{n}. \tag{2–2}$$

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:

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

where

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

Reference Cited

Eng, Ken, Chen, Yin-Yu, and Kiang, J.E., 2009, User’s guide to the weighted-multiple-linear-regression program (WREG version 1.0): U.S. Geological Survey Techniques and Methods, book 4, chap. A8, 21 p. [Also available at https://pubs.usgs.gov/tm/tm4a8.]

Appendix 3. Applications for Estimating Selected Annual Exceedance Probability Flood Flows and 90-Percent Prediction Intervals at Ungaged Sites, and Estimating Flood Flows Upstream and Downstream of Gaged Sites in Massachusetts

[The workbook is available for download at https://doi.org/10.3133/sir20165156]

Description of Worksheets

Table 3–1A. Ungaged Site

Computes annual exceedance probability (AEP) flood flows and 90-percent prediction interval from regional regression equations developed for ungaged sites in Massachusetts.

Table 3–1B. CoVariance

Used to compute 90-percent prediction interval flows reported in Ungaged Site worksheet of this workbook.

Table 3–1C. US–DS Flow

Equations for improving estimates of flood flows, within certain limits, at an ungaged site on a stream upstream (US) or downstream (DS) from a gaged site in Massachusetts.

Table 3–1D. Station Lookup

Streamgages and pertinent basin characteristics used in regional regression analysis, for reference purposes.

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