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Flooding in the Northeastern United States, 2011

Professional Paper 1821

U.S. Department of the Interior
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Outside cover. U.S. Geological Survey (USGS) streamgage 01388000 Ramapo River at Pompton Lakes, New Jersey, showing flood damages along Paterson-Hamburg Turnpike in Pompton Lakes on August 29, 2011, after major flooding associated with rainfall from the remnants of Hurricane Irene. Photograph by John Trainor, USGS.

Inside cover. Ice jam flooding on the Pemigewasset River at Plymouth, New Hampshire, March 2011. Photograph by Richard Kiah, USGS.

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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2015

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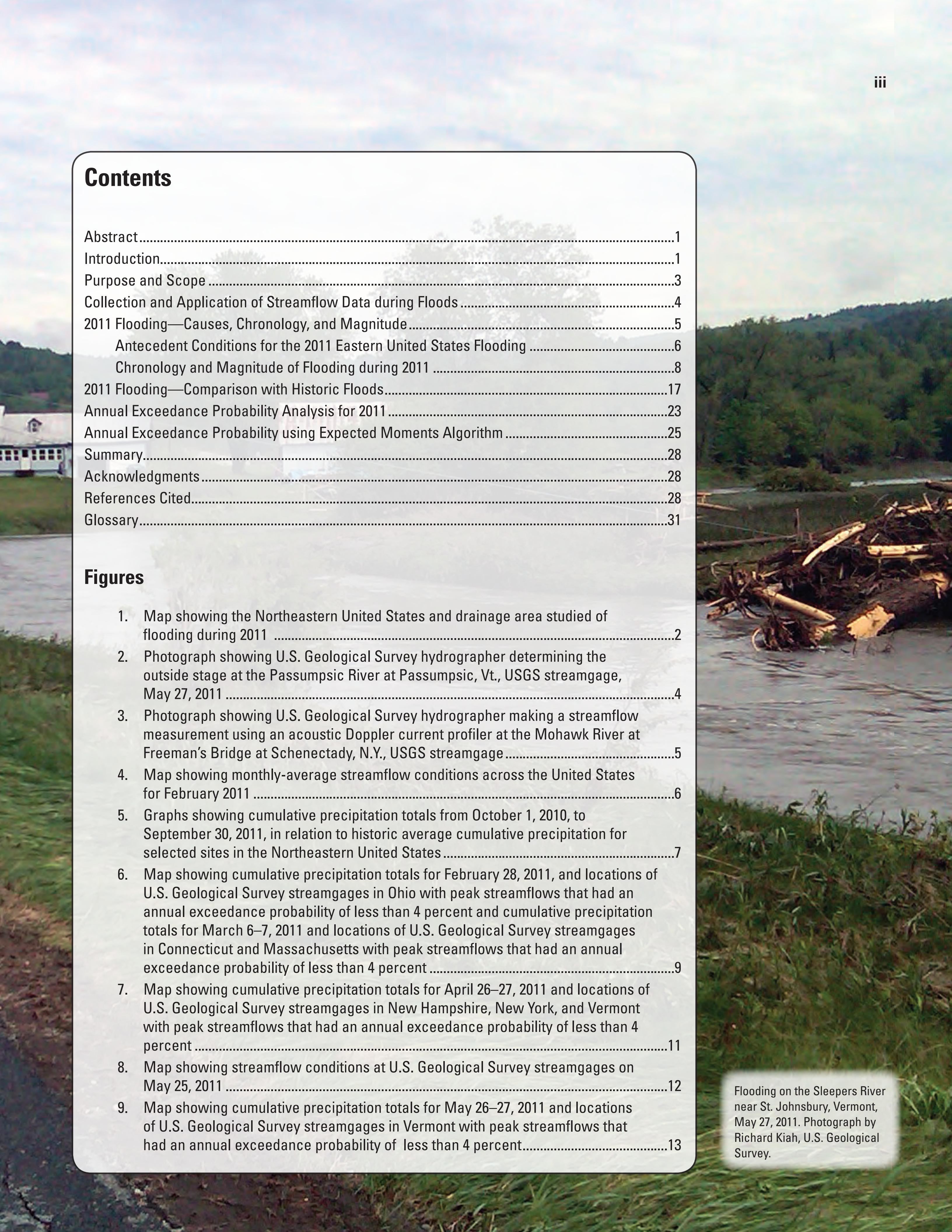


Flooding on the Sleepers River near St. Johnsbury, Vermont, May 27, 2011. Photograph by Richard Kiah, U.S. Geological Survey.

Tables

Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

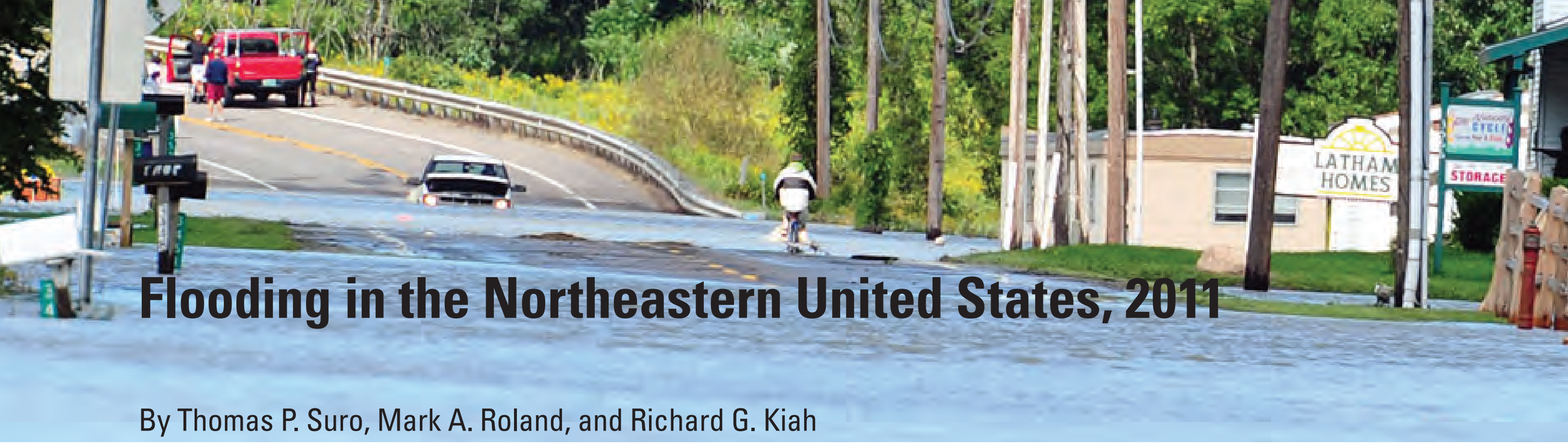
Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as
°C = (°F – 32) / 1.8.

Datums

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).

U.S. Geological Survey (USGS) hydrographer flagging a high-water mark in a tree after the flooding associated with Tropical Storm Lee in September 2011, near Bloomsburg, Pennsylvania. Photograph taken by Clinton D. Hittle, USGS.



Flooding in the Northeastern United States, 2011

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Abstract

Flooding in the Northeastern United States during 2011 was widespread and record setting. This report summarizes peak streamflows that were recorded by the U.S. Geological Survey (USGS) during separate flooding events in February, March, April, May, July, August, and September. The flooding of late April, which combined snowmelt and heavy rain and the floods associated with the tropical storms of late August and September, were the most severe and widespread. Precipitation totals from March to May for Pennsylvania, New York, and Vermont were documented as being the highest totals in 117 years of record. In late August, the heavy rains associated with Hurricane Irene produced widespread flooding in many parts of the Northeastern United States, which resulted in damage estimates in excess of $7 billion and approximately 45 deaths. In September, Tropical Storm Lee produced 6–12 inches of rain in parts of the Northeastern United States adding to the growing total of record peak streamflows set in 2011.

The annual exceedance probability (AEP) for 327 streamgages in the Northeastern United States were computed using annual peak streamflow data through 2011 and are included in this report. The 2011 peak streamflow for 129 of those streamgages was estimated to have an AEP of less than or equal to 1 percent. Almost 100 of these peak streamflows were a result of the flooding associated with Hurricane Irene in late August 2011. More extreme than the 1-percent AEP, is the 0.2-percent AEP. The USGS recorded peak streamflows at 31 streamgages that equaled or exceeded the estimated 0.2-percent AEP during 2011. Collectively, the USGS recorded peak streamflows having estimated AEPs of less than 1 percent in Connecticut, Delaware, Maine, Maryland, Massachusetts, Ohio, Pennsylvania, New Hampshire, New Jersey, New York, and Vermont and new period-of-record peak streamflows were recorded at more than 180 streamgages resulting from the floods of 2011.

Introduction

Flooding in the Northeastern United States (hereafter referred to as the Northeast) was documented on numerous rivers during the general time frame of February to September 2011 (fig. 1). The most severe flooding was associated with

Flooding associated with Tropical Storm Lee in September 2011. The Susquehanna River overflowing the right (west) bank looking north (upstream) near the intersection of Pine Street and Front Street in the Borough of Wormleysburg, Pennsylvania. Photograph taken by Scott A. Hoffman (U.S. Geological Survey).

Figure 1. The Northeastern United States and drainage area studied of flooding during 2011.

Hurricane Irene and the remnants of Tropical Storm Lee, which were back-to-back storms in late August and early September. Persistent spring precipitation combined with snowmelt produced earlier major flooding in parts of New Hampshire, New York, and Vermont (fig.1). Localized intense precipitation of short duration caused varying levels of flooding in parts of the Northeast in the early summer months, whereas excessive precipitation on saturated soils associated with two tropical cyclones produced record setting flooding during August and September in parts of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, and Vermont. Precipitation totals from March to May for much of Pennsylvania, New York, and Vermont ranged from about 16 inches to almost 20 inches, and the totals were documented as being the highest totals in 117 years of record (National Climate Data Center, 2012a). Record flood levels on Lake Champlain during April and May of 2011 exceeded the previous maximum known elevation since 1827 (Lumia and others, 2014).

In late August, Hurricane Irene tracked up the east coast of the United States and weakened from a category 1 hurricane (or cyclone) to a strong tropical storm as it made landfall in New Jersey. The heavy rains associated with this storm produced widespread flooding in many parts of the Northeast resulting in damage estimates in excess of $7 billion and approximately 45 deaths. In New Jersey, about 1 million people were evacuated (NBC News, 2014) and initial damage estimates were approximately $1 billion (Watson and others, 2014). In New York, 31 counties were declared disaster areas and damage estimates were more than $1.3 billion (Lumia and others, 2014) because of the flooding associated with rains from Hurricane Irene. As a result of this storm, nearly 100 U.S. Geological Survey (USGS) streamgages recorded a peak streamflow exceeding the 1-percent annual exceedance probability (AEP) and more than 70 USGS streamgages recorded a new period-of-record peak streamflow. The AEP is the probability, or chance, that a peak streamflow will be equaled or exceeded in any given year. In September 2011, another storm, the remnants of Tropical Storm Lee, tracked northward toward the still recovering Northeast delivering more heavy rains and widespread flooding. Rainfall totals were 6–12 inches throughout the Susquehanna River Basin and upwards of 12 inches in parts of southern New York.

The floods of 2011 in the Northeast stand out with respect to the cost of human life, property damage, and environmental effect but also stand out with respect to the persistence of the 2011 floods. The documentation of the severity and unusual repetitiveness of the flooding in the Northeast is important for the future protection of life and property. Other recently published USGS reports provide additional details and analyses of the 2011 flooding in New Jersey (Watson and others, 2014), New York (Lumia and others, 2014), Massachusetts (Olson and Bent, 2013; Bent and others, 2013), and Vermont (Medalie and Olson, 2013).

The flooding of 2011 was spread throughout the year and the region and resulted in about 300 USGS streamgages documenting peak streamflows that exceeded the 4-percent AEP streamflow, and of those, 129 streamgages documented peak streamflows that were less than or equal to the 1-percent AEP streamflow. The USGS recorded new period-of-record peak streamflows at more than 180 streamgages as a result of the floods of 2011. The National Weather Service (NWS) Flood Loss Report for the United States during 2011 indicated that direct freshwater damages from Hurricane Irene and Tropical Storm Lee totaled at least $3.9 billion from Virginia to Vermont (National Weather Service, 2014b).

The USGS is a national science agency and within its mission areas is charged with documenting the water resources and assessing natural hazards of the United States. Documenting flood peaks, along with the antecedent conditions, flood chronology, and AEP, will help to put the floods of 2011 into historic perspective and facilitate public and private awareness of the flooding potential and considerations of land use and flood-insurance regulations by local and regional citizens and elected officials. The data collected by the USGS to document these major floods will also assist other Federal, State, and local agencies with emergency management planning for future floods, hazard mitigation plans, and resiliency planning.

Purpose and Scope

The purpose of this report is to provide a broad overview of the flood magnitudes and frequencies in the Northeast during 2011. The USGS maintains a national database of water information and has flood documentation dating back to the 1800s. Documenting the magnitude, extent, and frequency of major floods preserves this important information that is necessary in protecting human life, property, and infrastructure. The streamgages included in this report were selected on the general basis of documenting a peak streamflow having an AEP of about 4 percent or less. The AEPs for all 327 streamgages presented in this report were computed using the log-Pearson type III (LPIII) method, and AEPs for 122 of these 327 streamgages also were computed by the Expected Moments Algorithm method. Other USGS flood reports providing more detailed analysis of the flooding in the Northeastern United States during 2011 are available at the USGS publications warehouse (http://pubs.er.usgs.gov/).

This report consolidates and summarizes the flooding information and documents the flood peaks (stage and streamflow) for many States in the Northeast that were affected by the floods of 2011. In this report, the 8-digit number listed in parentheses after a streamgage name is the USGS station number for that streamgage. Additionally, each USGS streamgage listed in table 1 (available at http://dx.doi.org/10.3133/pp1821) contains a map number that allows cross reference from the table to the respective map figure for that flood period.

Collection and Application of Streamflow Data during Floods

The organizational structure of the USGS is based on the following seven science mission areas: Climate and Land Use Change, Core Science Systems, Ecosystems, Energy and Minerals, Environmental Health, Natural Hazards, and Water. Specific to the Water Mission Area, one of the objectives is to provide tools that managers and policymakers can use for understanding, predicting, and mitigating water-related hazards such as floods (Evenson and others, 2013). To help accomplish this objective, the USGS collects and disseminates reliable, impartial, and timely information about the Nation's rivers and streams. The following are several examples from Holmes and others (2010) that include data collection and scientific interpretation of streamflow data as the data relate to flooding: the operation of a nationwide network of streamgages, the development of flood-inundation maps, the documentation of high-water mark elevations, and the determination of annual exceedance flood probabilities.

The USGS operates and maintains a network of more than 9,000 streamgages across the Nation that provides valuable streamflow information over the internet on a near real-time basis (http://waterdata.usgs.gov/usa/nwis/rt). This information may be related to water quality (such as pH, temperature, or turbidity); water level (commonly referred to as stage); or water quantity (typically reported as a rate of streamflow or discharge). Stage and streamflow data are of particular interest during times of flooding, or predicted flooding, to a variety of agencies, organizations, and municipalities, as well as the general public. The USGS streamgage network is continuously maintained and relations between river stage and streamflow are regularly checked to define constantly changing conditions to ensure quality data are available at all times. A photograph of a USGS hydrographer determining the outside stage at the Passumpsic River at Passumpsic, Vt. (01135500) streamgage on May 27, 2011, is shown in figure 2. The stage is determined by reading the staff gage on the outside of the streamgage shelter as an independent check on the hydrologic recording equipment inside of the streamgage shelter. The NWS uses information such as precipitation and historical streamflow data to forecast flood stages at select streamgages (also known as flood forecast sites) using mathematical models that simulate the movement of floodwater as it flows downstream. Flood forecast information typically is available 3–5 days in advance of events in many locations, with typical reporting intervals of 6 hours (National Weather Service, 2014a). The U.S. Army Corps of Engineers, the Federal Emergency Management Agency, and many other state and local agencies and organizations rely on streamflow data to assist in their respective operational duties such as water control, emergency management, and mitigation during times of flooding.

Digital flood-inundation maps, which can be accessed through the USGS Flood Inundation Mapping Science Web site at http://water.usgs.gov/osw/flood_inundation/, depict the estimated areal extent and depth of flooding corresponding to stages at select USGS streamgages. These maps, in conjunction with the near real-time stage data from USGS streamgages and National Weather Service flood-stage forecasts, can help guide the general public in taking individual safety precautions and provide local officials with a tool to efficiently manage emergency flood operations. The documentation of high-water marks as a result of flooding is also an important piece of information that can be useful for validating the accuracy of data being recorded at streamgages and for developing water-surface profiles through a reach. Water-surface profiles may be used to assist in the calibration of mathematical models for flood simulation and many associated applications such as flood insurance studies, development of flood-mapping products, and (or) estimating flow quantities. Estimates of the frequency and magnitude of floods are essential for flood insurance studies, flood-plain management, and the design of bridges and flood-control structures (Roland and Stuckey, 2008). The estimation of flood frequencies and magnitudes is based on an analysis using annual peak streamflow data. The reliability of these data is contingent upon the accuracy of the data collected at a streamgage.

A primary function of a streamgage is to record the stage of the river, or stream, at the established location of the streamgage on a preset interval (for example, every 15 minutes) and transmit that data to a central USGS database

Figure 2. U.S. Geological Survey (USGS) hydrographer determining the outside stage at the Passumpsic River at Passumpsic, Vt. (01135500) USGS streamgage, May 27, 2011. Photograph by Richard Kiah, USGS.

on a near real-time basis where the data are processed and made available online to the public. Continuous real-time data are extremely valuable because the data allow for remote monitoring of stage at many rivers and streams across the United States. Stage data can be related to streamflow, or discharge (typically reported in units of cubic feet per second [ft^3/s]) by establishing a stage-discharge relation typically referred to as a rating curve. A rating curve is unique to each streamgage and is established by making a series of discrete streamflow measurements over a range of stages. These streamflow measurements and associated stages are plotted and used to define a relation (or curve) between stage and streamflow. Changes to channel geometry and drainage basin characteristics require continuous monitoring and adjustment of rating curves to accurately represent stage-discharge relationships. Defining a rating curve at extreme high stages can be challenging because of the relative infrequency of extreme flood events and, in some cases, not being able to physically access or measure a river or stream that is flooding. A photograph of a USGS hydrographer making a streamflow measurement at the Mohawk River at Freeman's Bridge at Schenectady, N.Y. (01354500) streamgage during the flooding associated with Hurricane Irene in August 2011 is shown in figure 3. The hydrographer is using an acoustic doppler current profiler (ADCP) mounted in a small boat and tethered by a rope to collect water depth and velocity data. The data are continuously transmitted by radio link to a nearby laptop, not shown in the photograph. During times of flooding, additional emphasis typically is placed on maintaining streamgage operations to ensure uninterrupted data delivery and on obtaining sufficient high-flow measurements for defining and adjusting rating curves.

Rating curves that have been well defined generally translate to increased confidence in the forecasted stages, resulting in improved reliability of stage and streamflow data during flood events. Reliable streamflow data provide emergency management agencies, first responders, and the general public with critical information about river conditions; thus, allowing better informed operational and response decisions for the protection of life and property. The ability of USGS field personnel to respond rapidly allows for the collection and dissemination of accurate and timely data to those who rely on the data. The USGS made more than 2,000 discrete measurements of streamflow to verify or define rating curves at many streamgages throughout the Northeast during the floods of August and September 2011.

2011 Flooding—Causes, Chronology, and Magnitude

Floods are caused when meteorological processes deliver more precipitation or runoff to a region than can be retained or stored in a watershed. Climate, geology, topography, and antecedent conditions all play a role in the delivery and retention of precipitation in a watershed. In a region as diverse as the Northeast, flood-causing processes can range from orographic lifting and thermal convection, to lake-effect precipitation along the Great Lakes, to extra tropical or tropical cyclones. Typically, localized flooding is caused by severe, convective storms; whereas, widespread flooding is caused by frontal systems that move into the region from the south and west or by tropical storms that can include cyclones (Paulson and others, 1991).

The 2011 flooding in the Northeast was on small streams and large rivers. Much of the flooding was widespread and included parts of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Ohio, Pennsylvania, and Vermont. During February to September of 2011, each month recorded at least one separate flood event somewhere in the Northeast.

Figure 3. U.S. Geological Survey (USGS) hydrographer making a streamflow measurement using an acoustic Doppler current profiler (ADCP) at the Mohawk River at Freeman's Bridge at Schenectady, N.Y. (01354500) USGS streamgage. Photograph by Alicia Gearwar, USGS.

Antecedent Conditions for the 2011 Eastern United States Flooding

As noted by Holmes and others (2010) the genesis of most major widespread flooding is not just one particular storm but the result of frequent and consistently abundant precipitation over the same geographic area for an extended period. As soils become saturated, infiltration capacities decrease and stream levels can rise to bankfull conditions or beyond. Additional precipitation and associated runoff will result in progressively severe flooding. In the Northeast, the presence of frozen soils or accumulated snow cover may be factors of great importance in determining the nature and extent of flooding. Flooding in 2011 began in late winter with February monthly streamflows ranging from 25 to 75 percent of normal for most of the Northeast (fig. 4). During the winter of 2010–11, above-average snowfall was reported in the northern States. The March 2011 snowpack was the seventh largest in the last 46 years (National Climatic Data Center, 2012b). In mountainous regions of New York and New England, the snowpack in some locations contained the equivalent of 18–20 inches of water (National Weather Service, 2012a), of which the melting contributed to flooding by saturating the soils and filling the streams to near bankfull conditions in numerous locations.

A dichotomy of conditions existed in the northeast during 2011 as evidenced when comparing October 2010 through September 2011 (The 12-month period from October 1, 2010 to September 30, 2011 is referred to as water year 2011) cumulative precipitation with historic average cumulative precipitation (1981–2010) for four selected precipitation gages (National Climatic Data Center, 2012a; fig. 5*A*–*D*). The October 2010 through September 2011 cumulative precipitation and the historic average cumulative precipitation at four selected sites in the northeast are shown in figure 5*A*–*D*. Water year 2011 was the wettest on record

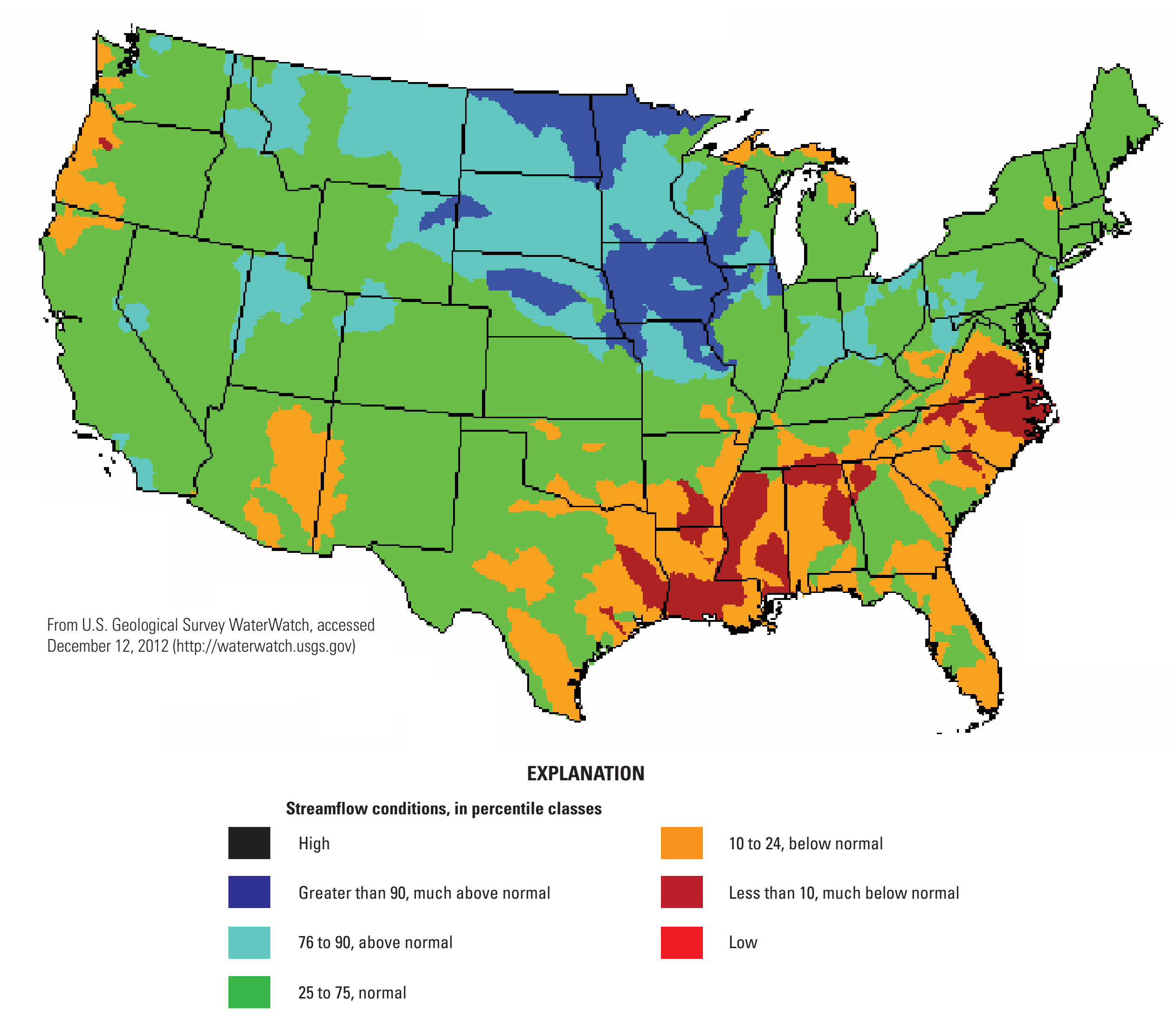


Figure 4. Monthly-average streamflow conditions across the United States for February 2011 (U.S. Geological Survey, 2012a).

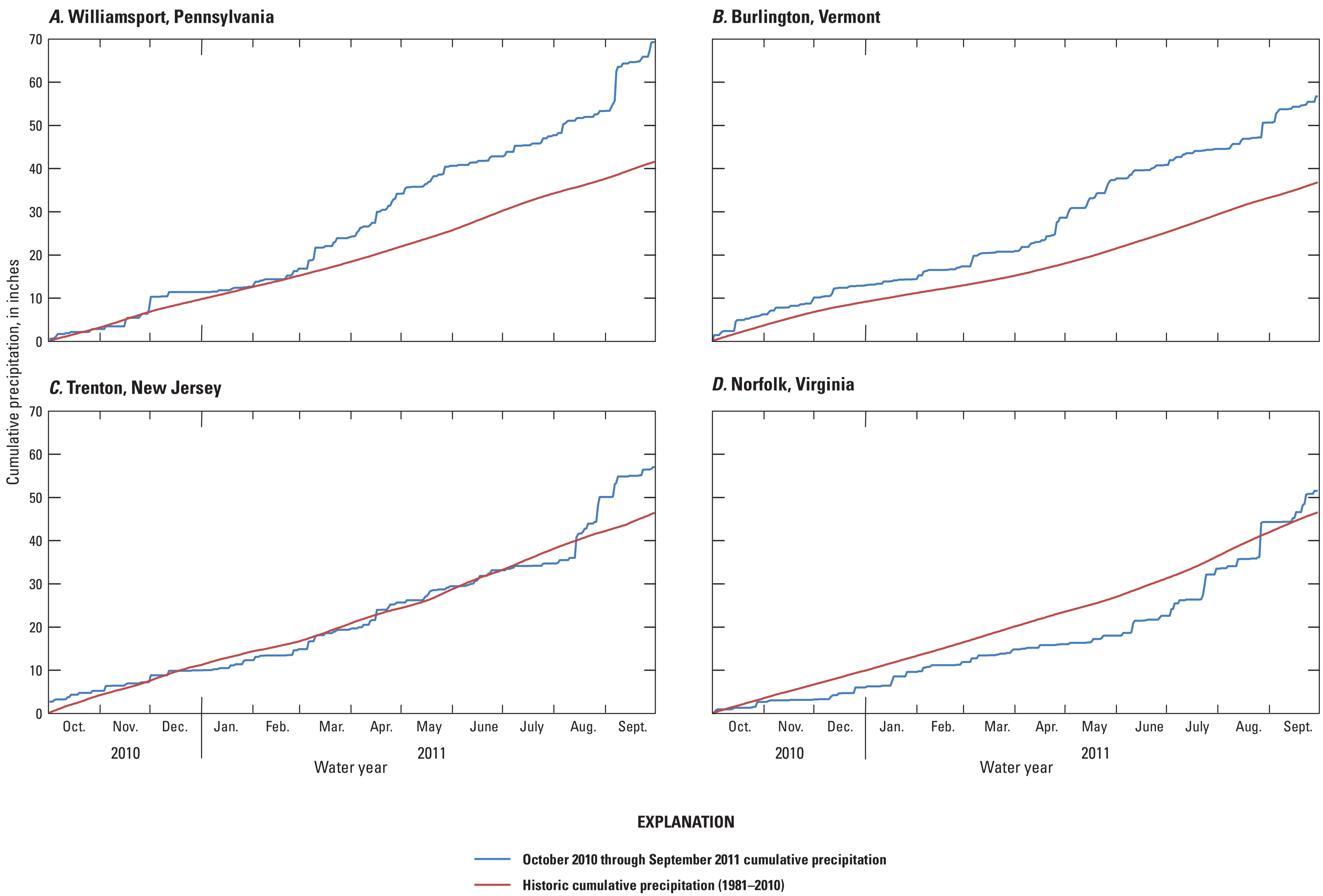


Figure 5. Cumulative precipitation totals from October 1, 2010, to September 30, 2011, in relation to historic average cumulative precipitation (1981–2010) for selected sites in the Northeastern United States (National Climatic Data Center, 2012b).

for hydrologic units in New England, New Jersey, New York, Ohio, and Pennsylvania (U.S. Geological Survey, 2012) as precipitation was consistently above normal. In contrast, some hydrologic units in Delaware, Maryland, and Virginia reported below normal to much-below normal runoff in water year 2011 as precipitation was normal to below normal during much of the year.

Chronology and Magnitude of Flooding during 2011

The 2011 Northeast floods recorded from February through September were caused by persistent spring precipitation combined with snowmelt, localized intense precipitation of short duration, and excessive precipitation amounts on saturated soils resulting from tropical cyclones. Well-above average precipitation amounts were observed in many areas of the Northeast. Parts of Pennsylvania, New England, New Jersey, and New York received precipitation from 4–20 inches above average (National Weather Service, 2012b). The 12-month total precipitation was composed of numerous discrete storm sequences that induced multiple flooding events in different geographic locations.

Peak streamflows for 327 streamgages in the northeast that had estimated AEPs of about 4 percent or less were included in table 1. Of these 327 streamgages, 183 recorded peak-of-record streamflows during the 2011 floods. A few selected streamgages that reported peak streamflows with estimated AEPs greater than 4 percent were also included in table 1 to indicate the extent of major flooding. Approaches used in computing AEPs are described in the “Annual Exceedance Probability Analysis, 2011” section of this report. To minimize figure clutter, only the major rivers (for example, Connecticut, Hudson, Susquehanna Rivers) and selected small rivers mentioned in the report text for that particular flood period are shown on the figures. The 2011 peak-stage and streamflow data, previous peak-of-record flood data, estimated AEP for the 2011 peak streamflow, and estimates of the magnitude of the streamflow corresponding to the 4-percent, 2-percent, 1-percent, and 0.2-percent AEP are listed in table 1. For each figure corresponding to a particular flood period, the size of the symbol for each streamgage represents the estimated AEP that corresponds to the magnitude of the computed peak streamflow—the less probable (less frequent) the peak streamflow, the larger the symbol. Daily NWS rainfall observations for the United States were used to represent cumulative precipitation totals for individual storm events (National Weather Service, 2012c).

The first flood-inducing precipitation events began on February 28, 2011 (fig. 6*A*) and March 6, 2011 (fig. 6*B*). These snowmelt-enhanced events caused major flooding in parts of Ohio, Connecticut, and Massachusetts. Flooding resulted from increased streamflow as well as localized ice jamming (U.S. Geological Survey, 2013).

In Ohio, more than 4 inches of snow-water equivalent was present on February 27, 2011, and was reduced to trace amounts by March 1, 2011 (National Weather Service, 2012d). Peak-of-record streamflow was recorded at the USGS streamgages Ottawa River at Lima, Ohio (04187100); Honey Creek at Melmore, Ohio (04197100); and Old Woman Creek at Berlin Road near Huron, Ohio (04199155). In this report, the 8-digit number listed in parentheses after a streamgage name is the USGS station number for that streamgage. In Southern New England upwards of 10 inches of snow-water equivalent was present on March 5, 2011, and was reduced to trace amounts by March 8, 2011 (National Weather Service, 2012d). Peak-of-record streamflow was recorded at the USGS streamgage Saugatuck River near Redding, Conn. (01208990; table 1). Rain and rapidly melting snow combined to mobilize the ice cover on some northern rivers causing ice jams and localized flooding in some locations. The late February and early March events did not result in severe flooding outside of Ohio and southern New England; however, the widespread rainfall and snowmelt contributed to increased soil-moisture levels and streamflows in other areas.

Precipitation and snowmelt contributed to flooding in late April and early May of 2011. During April 26–29, 2011, above normal temperatures, snowmelt in the mountains, and bands of rainfall and thunderstorms (fig. 7) caused flooding in northern areas of New Hampshire, New York, and Vermont. The snow-water equivalent in the mountains of New York and Vermont held upwards of 10 inches of water on April 26, 2011(National Weather Service, 2012e). Substantial flooding occurred along the Hudson River in New York as peak-of-record streamflows were recorded at the USGS streamgages in North Creek (01315500), Hadley (01318500), Fort Edward (01327750), and Stillwater (01331095). The peak streamflow recorded at the USGS streamgage Hudson River at Newcomb, NY (01312000), was the second highest peak on record and was only exceeded by the peak of January 1998 (table 1). Other peak-of-record streamflows were recorded at USGS streamgages in New Hampshire and Vermont (table 1).

In the winter and spring of 2011, record rainfall and snowmelt for much of the Northeast contributed to streamflows that were above normal at numerous USGS streamgages in New England, New York, New Jersey, Delaware, and Maryland (fig. 8). Precipitation totals for March through May in New York (16.68 inches), Pennsylvania (19.13 inches), and Vermont (17.14 inches) were the highest in 117 years of record (National Climate Data Center, 2012a). Record rainfall contributed to record flooding on Lake Champlain during the spring of 2011. Lake Champlain was above the National Weather Service flood stage of 100 feet (ft) for 68 days from April 13 to June 19, 2011. The peak water-surface elevation of Lake Champlain, 103.27 ft, was recorded on May 6, 2011, at the Lake Champlain at Burlington (04294500) lake gage (Kiah and others, 2013). This elevation surpassed the maximum known elevation since at least 1827 of 102.1 ft on May 4, 1869.

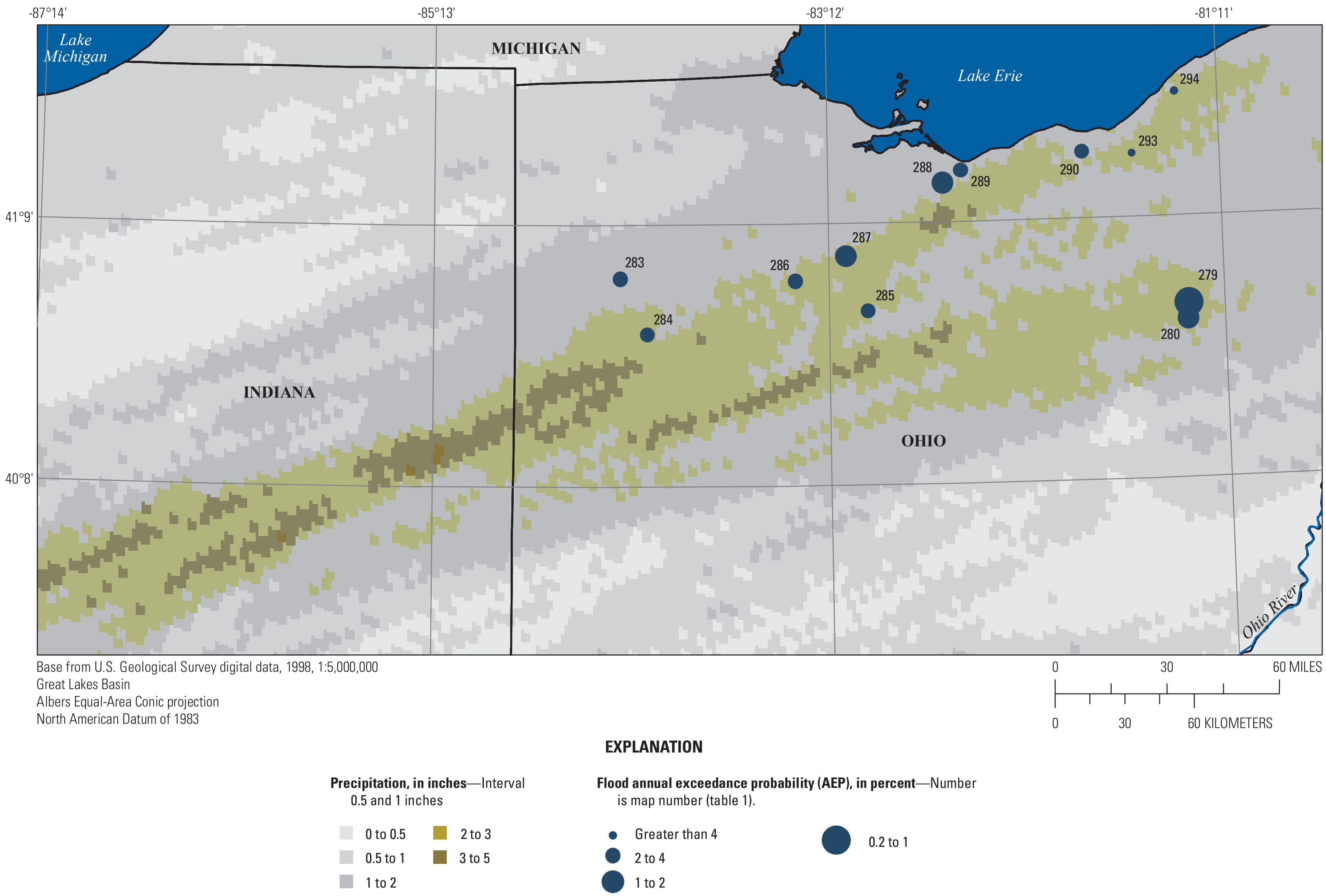


Figure 6. Cumulative precipitation totals for *A*, February 28, 2011, and locations of U.S. Geological Survey streamgages in Ohio with peak streamflows that had an annual exceedance probability of less than 4 percent and *B*, cumulative precipitation totals for March 6–7, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in Connecticut and Massachusetts with peak streamflows that had an annual exceedance probability of less than 4 percent.

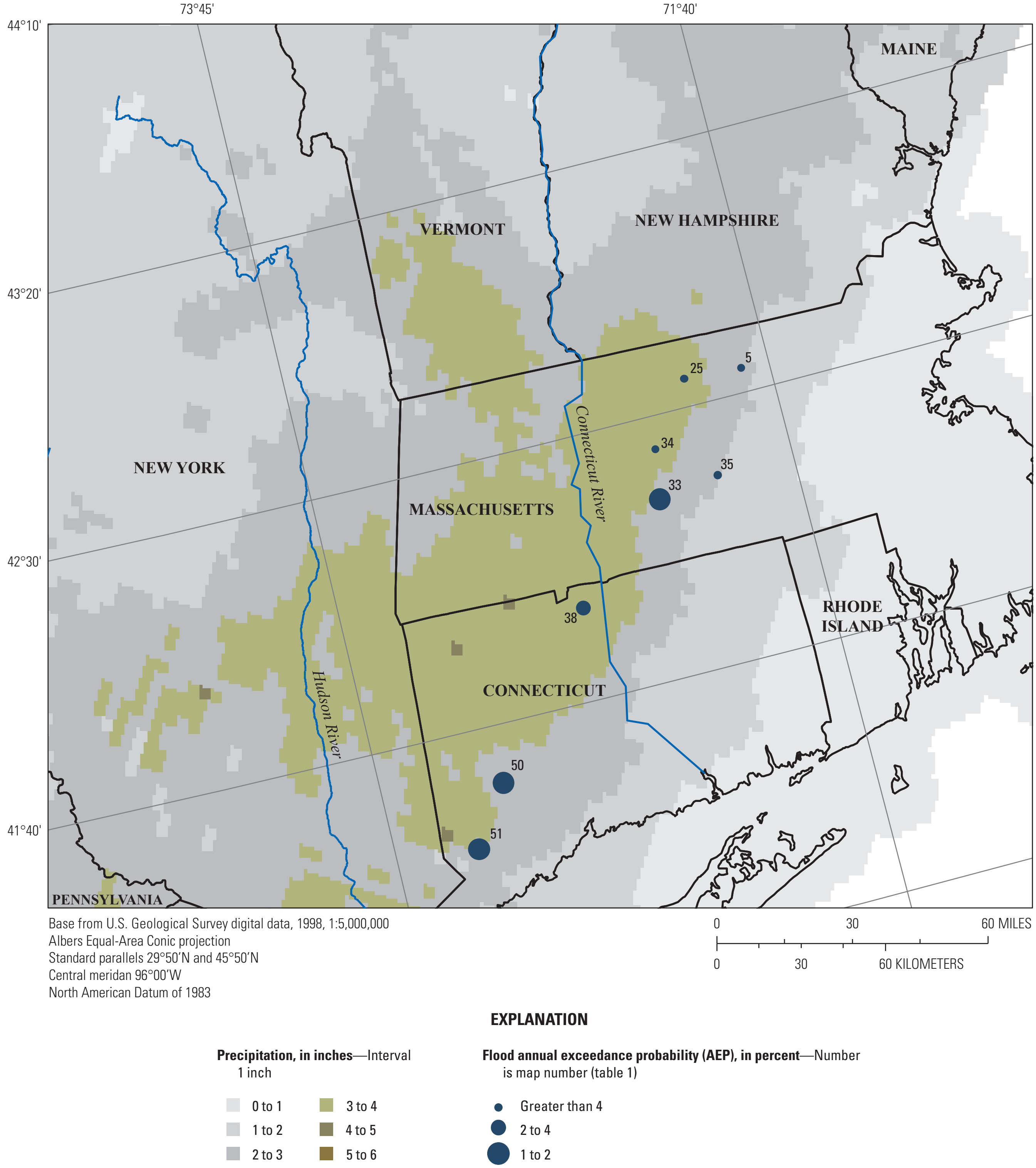


Figure 6. Cumulative precipitation totals for *A*, February 28, 2011, and locations of U.S. Geological Survey streamgages in Ohio with peak streamflows that had an annual exceedance probability of less than 4 percent and *B*, cumulative precipitation totals for March 6–7, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in Connecticut and Massachusetts with peak streamflows that had an annual exceedance probability of less than 4 percent.—Continued

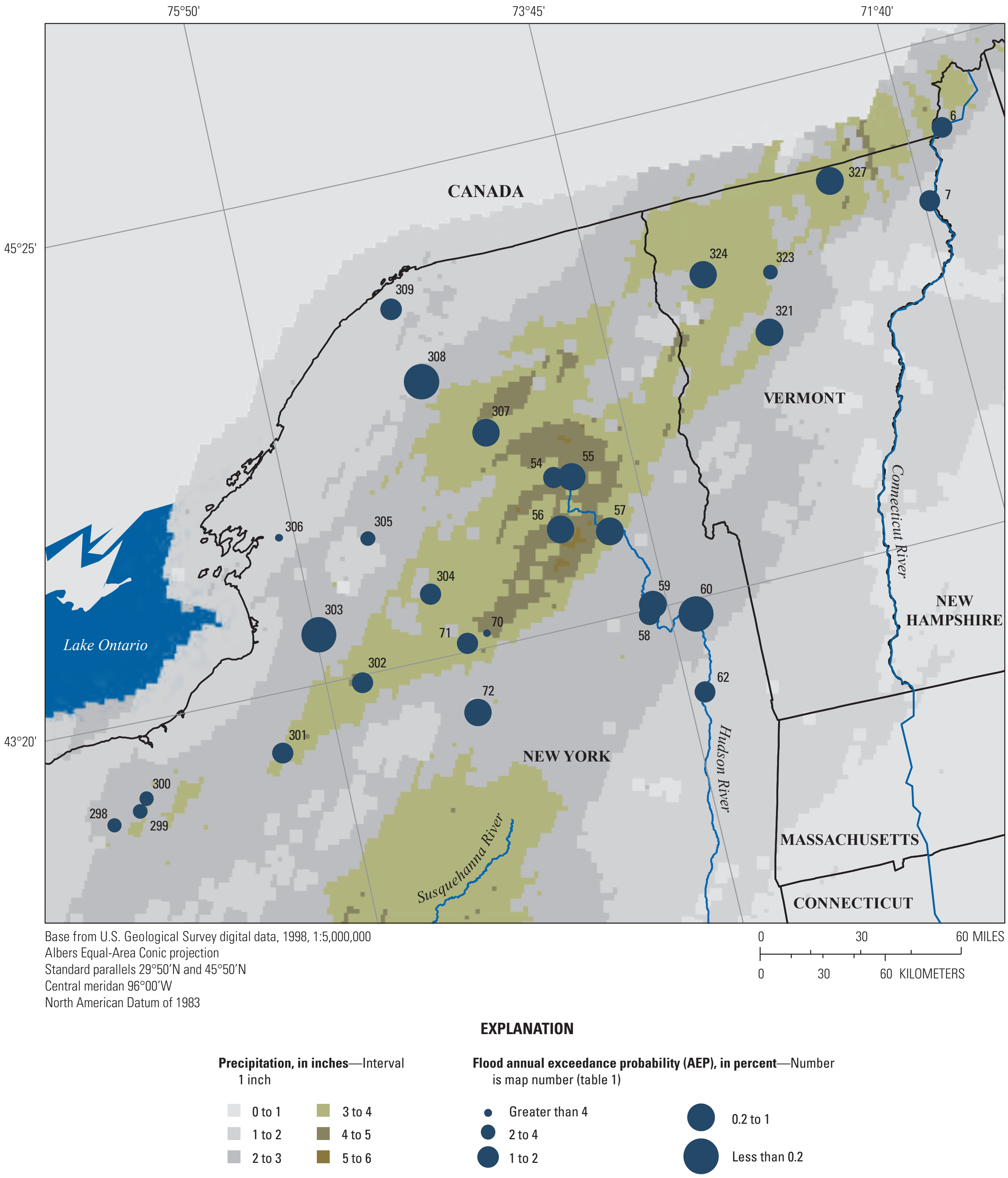


Figure 7. Cumulative precipitation totals for April 26–27, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in New Hampshire, New York, and Vermont with peak streamflows that had an annual exceedance probability of less than 4 percent.

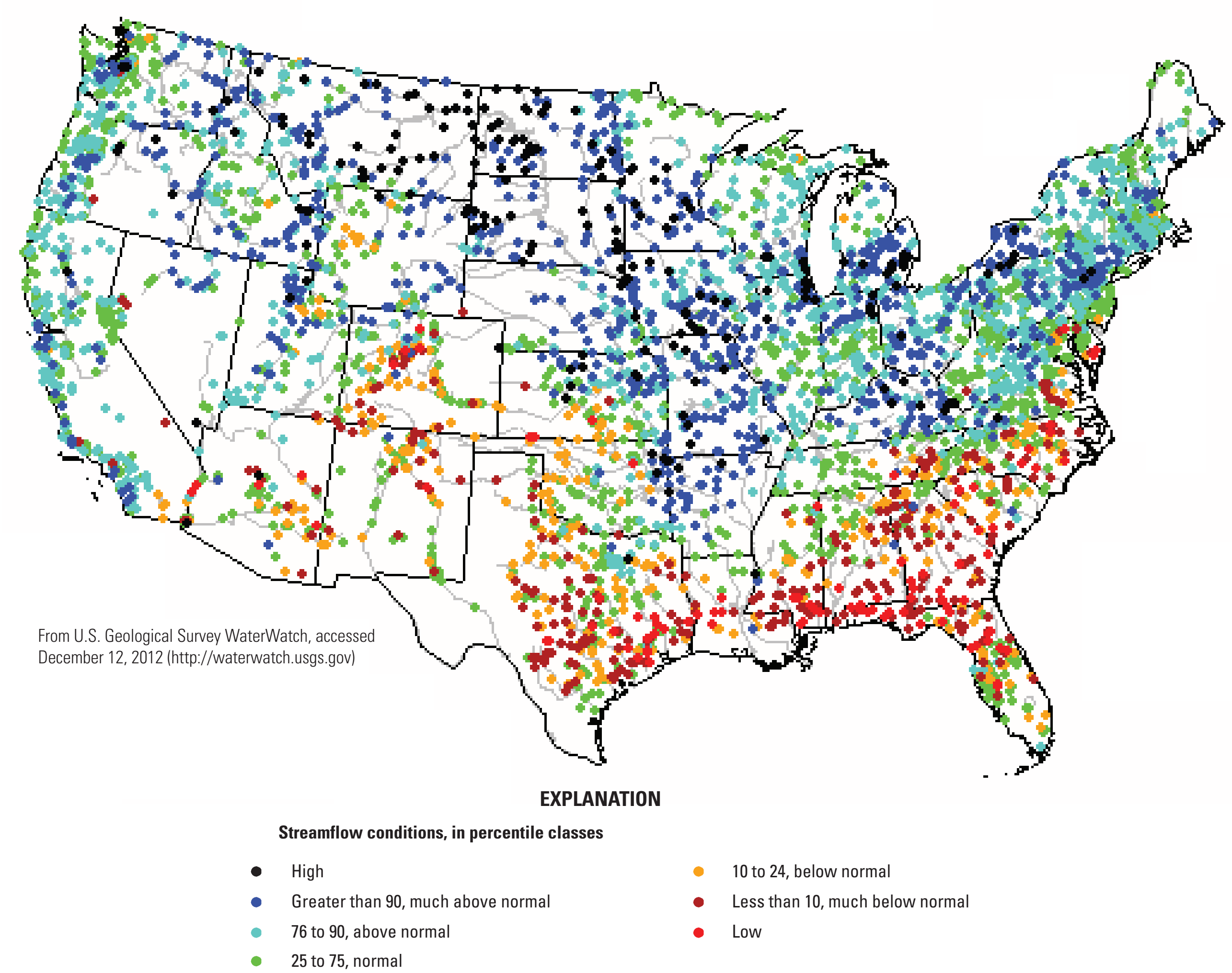


Figure 8. Streamflow conditions at U.S. Geological Survey streamgages on May 25, 2011 (U.S. Geological Survey, 2012).

An isolated weather system in late May contributed precipitation amounts as much as 7 inches as a band of storms tracked across northern Vermont on May 26–27, 2011 (fig. 9). Localized thunderstorms, hail, and heavy rainfall were associated with several miniature supercells (National Weather Service, 2012f). Substantial flooding was limited mostly to streams with drainage areas less than 100 square miles (mi^2), such as Sleepers River near St. Johnsbury, Vt. (01135300), where a peak-of-record streamflow was recorded on May 27, 2011 (table 1).

Hurricane Irene made landfall in New Jersey on August 28, 2011, as a category 1 hurricane, according to initial reports, weakened to a tropical storm as it moved towards New York and to an extra tropical cyclone over Vermont. Winds and widespread flooding resulted in damage estimates in excess of $7 billion and approximately 45 deaths (National Oceanic and Atmospheric Administration, 2012). Additional information about the origins and life cycle of Hurricane Irene can be found in the NWS Hurricane Irene Tropical Cyclone Report (Avila and Cangialosi, 2011). The NWS rainfall observations for the Northeast from August 27–29, 2011, document cumulative precipitation of more than 6 inches over an area of about 20,000 mi^2, with some areas receiving two to three times as much precipitation (fig. 11). The intense rainfall associated with Hurricane Irene contributed to new August total precipitation records for New Hampshire, New Jersey, New York, and Vermont (National Climatic Data Center, 2012b). The record precipitation produced streamflows with estimated AEPs less than 4 percent at 186 USGS streamgages, of which 119 were period-of-record peaks. Particularly hard hit were New York (46 peak-of-record streamflows), New Jersey (32 peak-of-record streamflows), and Vermont (12 peak-of-record streamflows). Peak-of-record streamflows were recorded at 31 additional USGS streamgages in Delaware, Maine, Maryland, Massachusetts, New Hampshire, and Pennsylvania. In the Green Mountains of Vermont, 13 communities were isolated for days as floodwaters damaged or destroyed more than 480 bridges, 960 culverts, and 500 miles of State

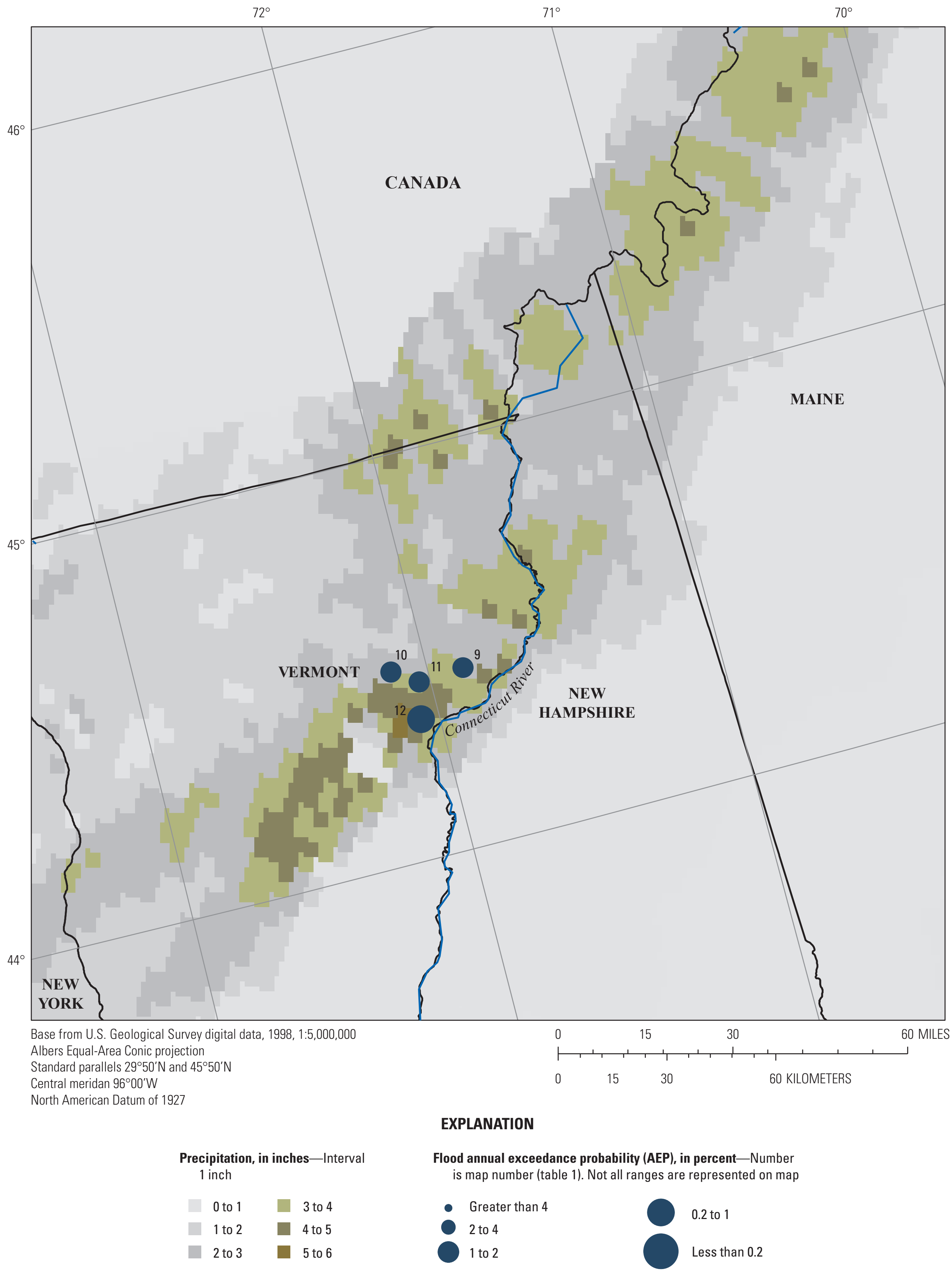


Figure 9. Cumulative precipitation totals for May 26–27, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in Vermont with peak streamflows that had an annual exceedance probability of less than 4 percent.

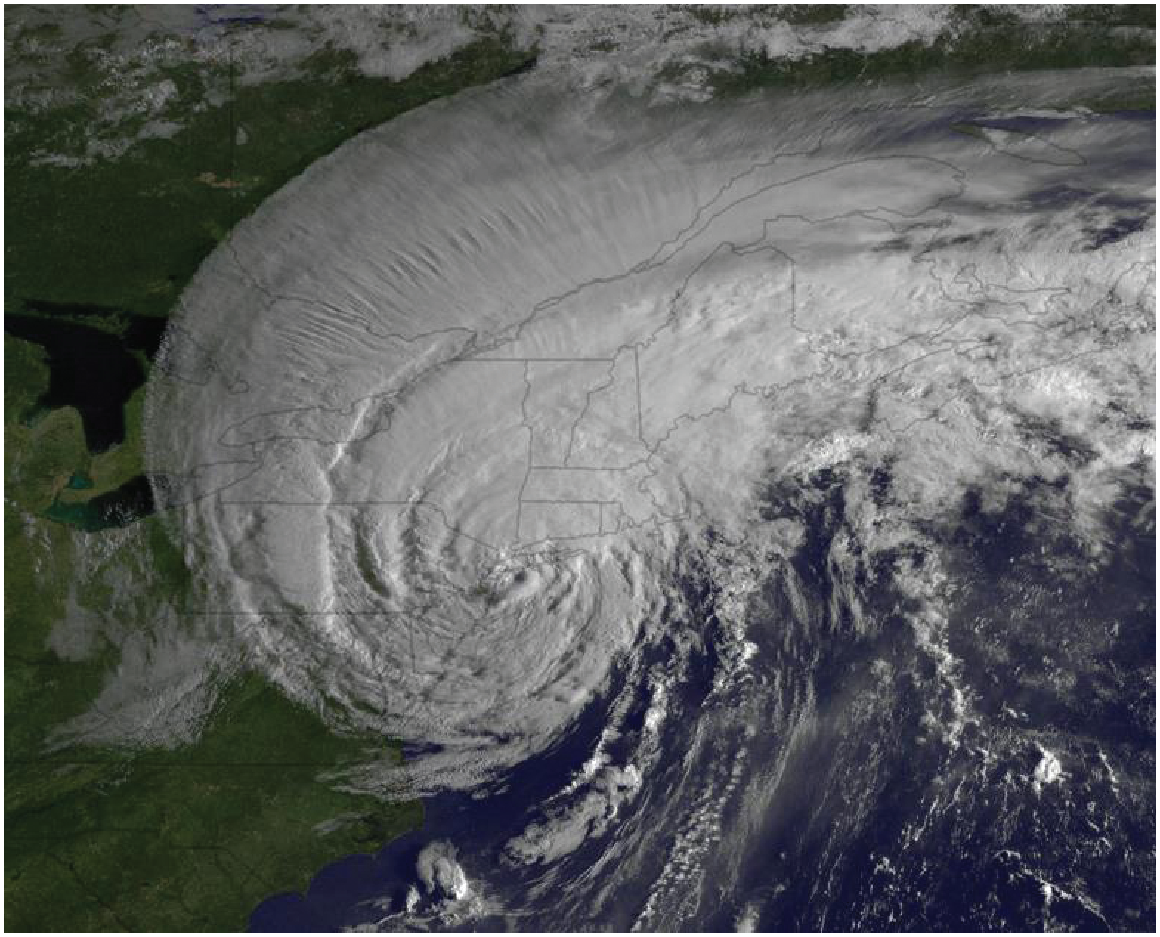


Figure 10. Geostationary Operational Environmental Satellite (GOES) east image of Hurricane Irene making landfall near New York City on August 28, 2011. Image is courtesy of the National Oceanic and Atmospheric Administration, 2011.

highways (Vermont Emergency Management, 2014). Runoff greater than 700 cubic feet per second per square mile was computed in high-elevation, small drainage tributaries in the Green Mountains (USGS streamgages Whetstone Brook Tributary near Marlboro, Vt. [01156300] and Kent Brook near Killington, Vt. [01150800]). The USGS streamgage at Saxtons River at Saxtons River, Vt. (01154000), recorded a peak streamflow of 21,600 ft^3/s on August 28 that was 155 percent greater than the previous peak-of-record streamflow (8,460 ft^3/s) set in 1976 (table 1), and the peak stage of 19.58 ft was the maximum stage since at least 1869.

Recovery efforts for Hurricane Irene were still underway when remnants of Tropical Storm Lee tracked across the Northeast drenching already saturated areas of Maryland, New Jersey, New York, and Pennsylvania. During September 8–9, substantial precipitation and subsequent flooding took place as 6–12 inches were reported throughout the Susquehanna River Basin and upwards of 12 inches of rain was reported in parts of southern New York, and greater than 20 inches was reported in parts of Virginia (fig. 12). Peak streamflows having an estimated AEP of less than 4 percent were recorded at 59 USGS streamgages, of which 31 were period-of-record peaks (table 1). In the upper reaches of the Susquehanna River, near peak-of-record streamflows were recorded at the streamgages Susquehanna River at Unadilla, N.Y. (01500500) and Susquehanna River at Conklin, N.Y. (01503000). Farther downstream along the Susquehanna River in New York, peak-of-record streamflows were recorded at the USGS streamgages in the communities of Vestal (01513500), Owego (01513831), and Waverly (01515000). In Binghamton, N.Y., about 20,000 residents were evacuated (Associated Press, 2011) as the streamgage Susquehanna River at Vestal, N.Y. (01513500) reached a peak-of-record stage of 35.26 ft with an associated peak streamflow of 129,000 ft^3/s on September 8. The peak stage of 35.26 ft was 1.6 ft higher than the previous peak-of-record stage of 33.66 ft set in 2006. Farther downstream at the streamgage Susquehanna River at Waverly, N.Y. (01515000), located 1 mi. downstream from the New York-Pennsylvania State line, a peak-of-record stage of 26.67 ft and discharge of 167,000 ft^3/s were recorded. The 2011 peak stage exceeded the previous peak-of-record stage set during the flood of June 2006 by more than 4 ft and exceeded the historic peak stage set back in March of 1936 by more than 5 ft (Suro and others, 2009).

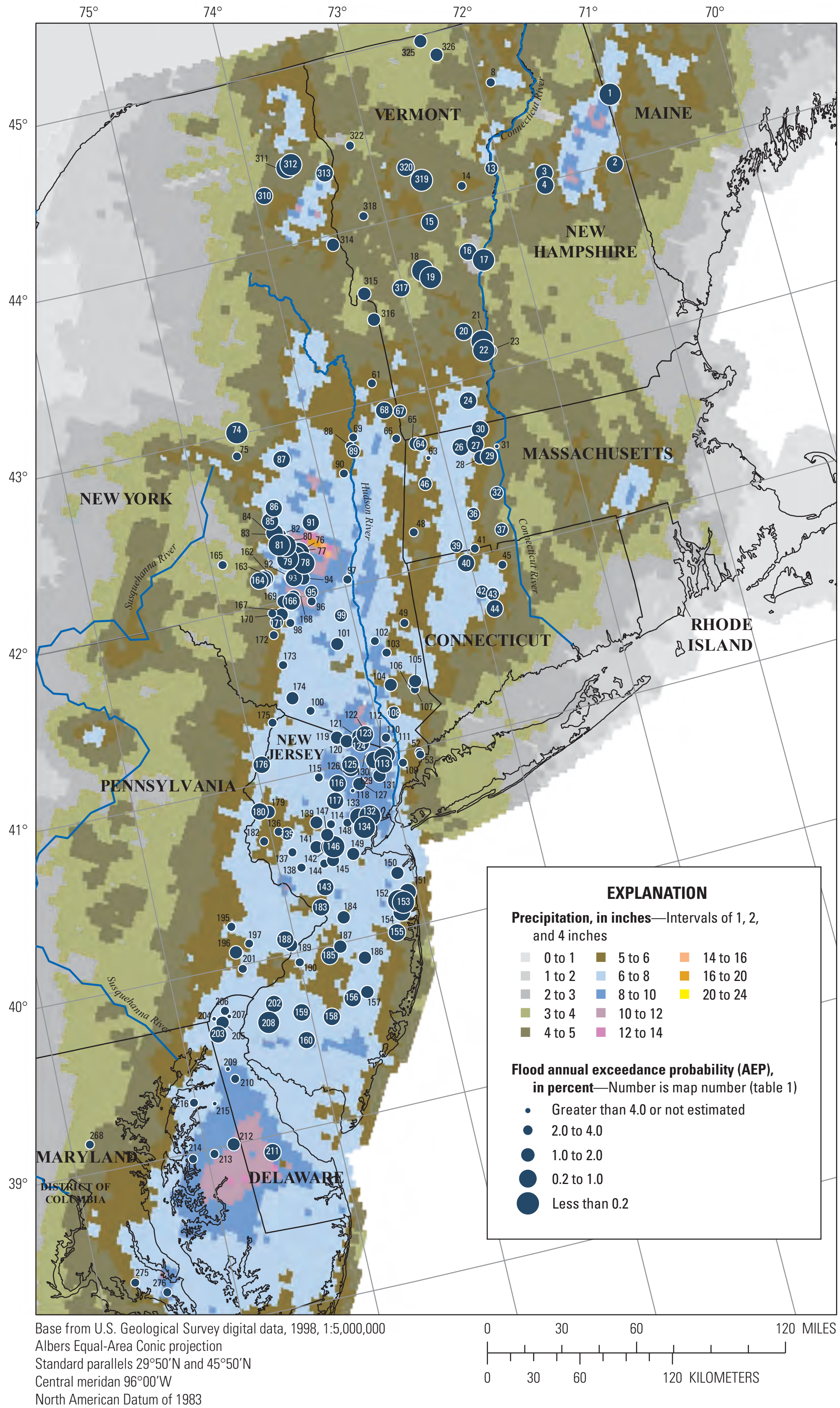


Figure 11. Cumulative precipitation totals for August 27–29, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in Delaware, Maine, Massachusetts, Maryland, New Hampshire, New Jersey, New York, and Vermont with peak streamflows that had an annual exceedance probability of less than 4 percent.

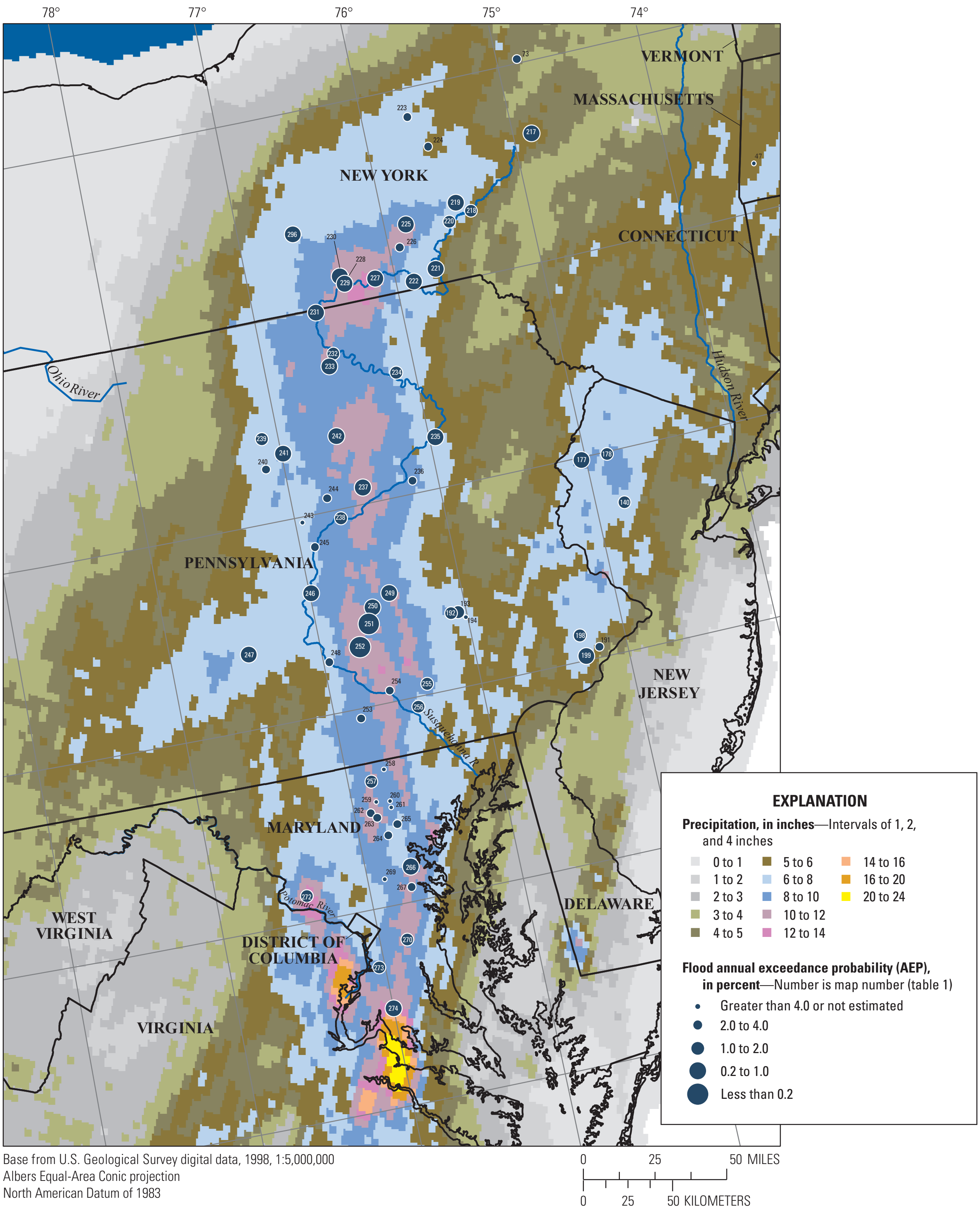


Figure 12. Cumulative precipitation totals for September 6–9, 2011 (National Weather Service, 2012c) and locations of U.S. Geological Survey streamgages in Maryland, New Jersey, New York, and Pennsylvania with peak streamflows that had an annual exceedance probability of less than 4 percent.

2011 Flooding—Comparison with Historic Floods

In 2011, record-breaking rainfall events produced widespread flooding across the Northeast resulting in peak streamflows being recorded at 327 streamgages that generally equaled or exceeded the estimated 4-percent AEP streamflow (table 1), of which 263 were recorded during the months of August and September. As previously discussed, some of the storm events in 2011 tended to be more isolated in nature leading to more localized flooding; however, the storms that had the most effect on a regional basis were two tropical systems, Tropical Storm Irene and the remnants of Tropical Storm Lee. Arriving only a week apart from each other in late August and early September, tropical storms Irene and Lee caused catastrophic flooding. The NWS reported 37 fatalities directly related to freshwater flooding and direct freshwater flood damages of $3.9 billion from Virginia to Vermont (National Weather Service, 2014a). Other reports summarize 45 fatalities and more than $7 billion in total damages (National Oceanic and Atmospheric Administration, 2012). Tropical Storm Irene made landfall at Little Egg Inlet, N.J., (fig. 1) on August 28, 2011, depositing 6–7 inches of precipitation across most of the State causing record-breaking floods at many streams. In New Jersey alone, about 1 million people across the State were evacuated, and every county was declared a Federal disaster area (Watson and others, 2014).

As stated by Holmes and others (2010, 2013) in discussing 2008 flooding in the Midwest United States and 2011 floods in the central United States, when significant rainfall events produce flooding, it is important to document the magnitude of a flood so it can be put into context for comparison with previous floods (table 1). Eight USGS streamgages in the Northeast were selected to illustrate the comparison of historic flood peaks to the flood peaks recorded during the 2011 floods. A timeline of annual peak streamflows for each of these eight streamgages was plotted to show a comparison of the magnitude of 2011 flood peaks with previous annual peak streamflows (fig. 13). The estimated values of the 4-, 2-, 1-, and 0.2-percent AEP flood quantiles are also included for each streamgage to provide perspective among recorded annual peaks. Additionally, hydrographs for a subset of these selected USGS streamgages in the Northeast are presented in figure 14*A*–*D* that depict daily mean streamflow over time (represented by a solid line) as well as the annual peak streamflows for select years (represented by an independent marker), thus allowing comparison of the 2011 flood events to previous major floods. The annual peak streamflows are associated with a peak stage at a specific time (or instant) when a river crested; therefore, the values will be equal to, or higher than the daily mean streamflows. Comparatively, the hydrographs presented in figure 14*A*–*D* show that streamgages monitoring streamflow on a larger river, such as the streamgages Susquehanna River at Waverly, N.Y. (01515000; fig. 14*A*) and Susquehanna River at Danville, Pa. (01540500; fig. 14*B*), which have drainage areas of approximately 4,770 and 11,200 mi^2 respectively, can have a daily mean streamflow that is of relatively similar magnitude as the instantaneous peak; whereas, streamgages monitoring streamflow on relatively smaller rivers, such as the streamgages Saco River at Conway, N.H. (01064500; fig. 14*C*) or North River at Shattuckville, Mass. (01169000; fig. 14*D*), which have drainage areas of approximately 385 and 90 mi^2, respectively, may have daily mean streamflows significantly less than the instantaneous peak. Several factors and basin characteristics may contribute to the ratio of peak streamflow to daily mean streamflow, such as rainfall duration and intensity, percentage of impervious surfaces within a basin, and channel slope; however, for larger drainage basins the time required for precipitation to drain through the basin is probably a large part of the reason why the ratio is lower.

At many USGS streamgages, the 2011 peak streamflows were the largest peaks in many decades. Major flooding because of a combination of rain with significant snowmelt during April 26–May 4, 2011, resulted in new peak-of-record streamflows being recorded at Hudson River at Hadley, N.Y. (01318500, fig. 1); at Raquette River at Raymondville, N.Y. (04268000, fig. 1) and at 10 additional streamgages in the Hudson and St. Lawrence River Basins in northeastern New York. In western New York, streamgages on Flint Creek and North Branch Salmon River, tributaries to Lake Ontario, also recorded new period-of-record streamflows during April 26– May 4, 2011. A new period-of-record peak streamflow of 34,900 ft^3/s was recorded on April 28, 2011, at the streamgage Hudson River at North Creek, N.Y. (01315500; table 1), which has been in operation since 1907 (fig. 13), exceeding the previous peak streamflow of 28,900 ft^3/s on December 31, 1948. Other select streamgages within the Hudson River Basin experiencing new peaks-of-record were the streamgages Indian River near Indian Lake, N.Y. (01315000; table 1); West Canada Creek at Kast Bridge, N.Y. (01346000; table 1); and Hudson River at Hadley, N.Y. (01318500; table 1), which have periods of record dating back to 1913, 1921, and 1922, respectively. In the St. Lawrence River Basin, the streamgage Raquette River at Piercefield, N.Y. (04266500; table 1) has peak streamflow records dating back to 1909, and a new period-of-record peak streamflow of 10,400 ft^3/s was set on May 1, 2011. New period-of-record peak streamflows also were recorded farther downstream at the Raquette River at South Colton, N.Y. (04267500; table 1) and Raquette River at Raymondville, N.Y. (04268000; table 1; Suro, 2011) streamgages.

In 1955, the mid-Atlantic and Northeast United States experienced massive amounts of rainfall from hurricanes Connie and Diane, which were within about a week of each other. The hurricanes caused severe flooding across the region resulting in an estimated 180 deaths and $680 million dollars in property damage (National Weather Service, 2014d). The USGS streamgages recorded record flood peaks across the Northeast as a result of precipitation associated with hurricanes Connie and Diane. Flood peaks from the 1955

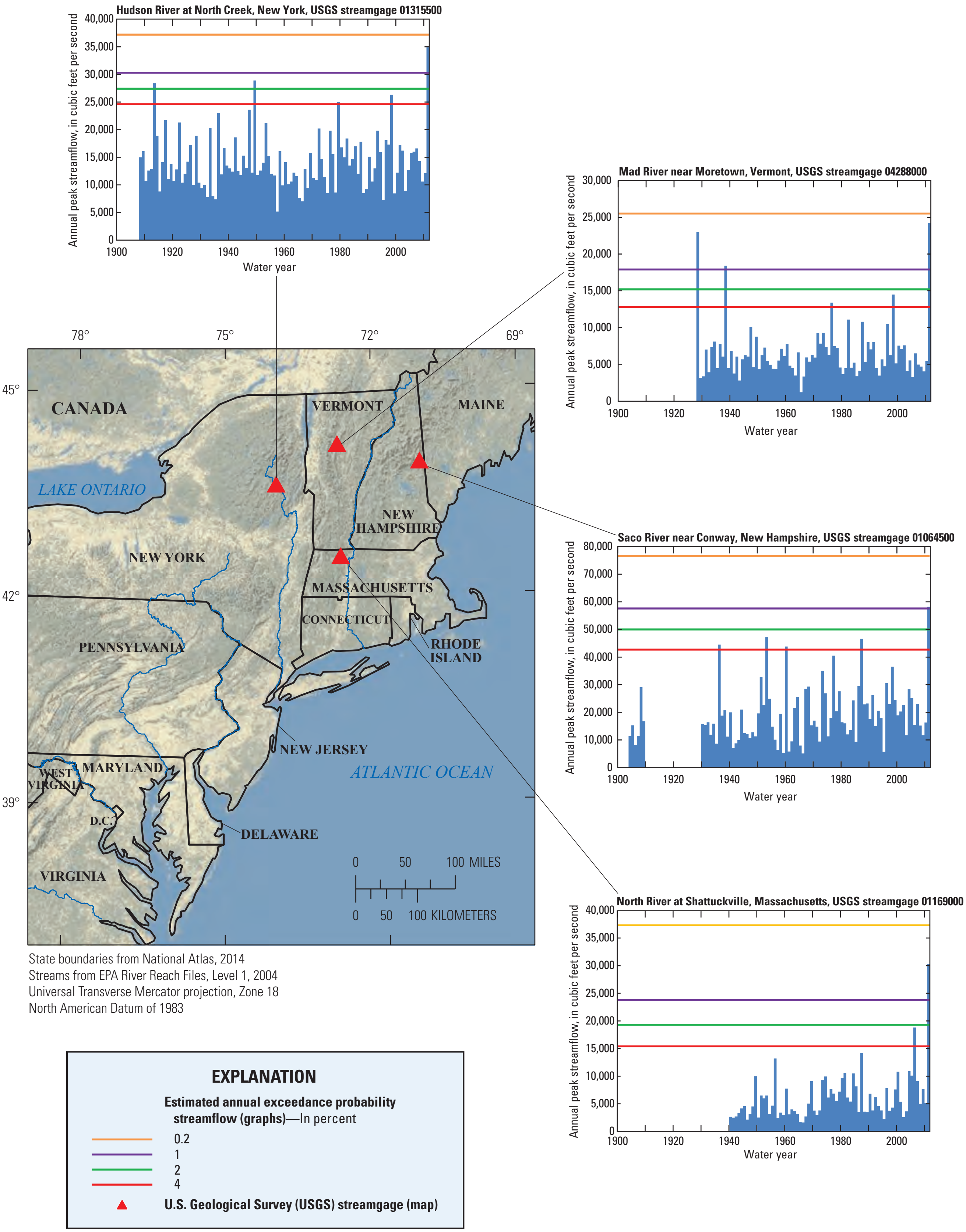


Figure 13. Annual peak streamflows through 2011 and the 4-, 2-, 1-, and 0.2-percent annual exceedance probability streamflows for selected U.S. Geological Survey streamgages in the Northeast.

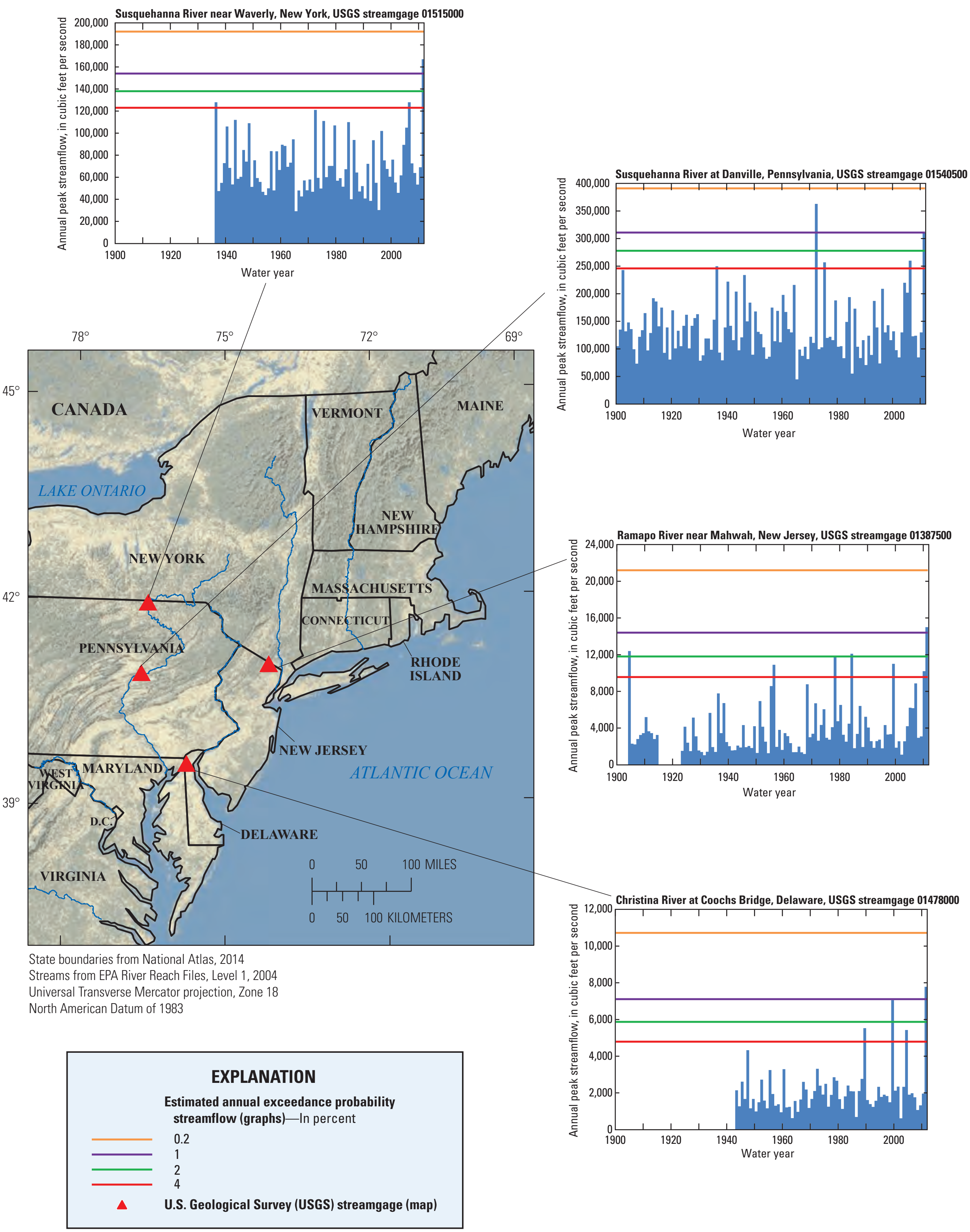
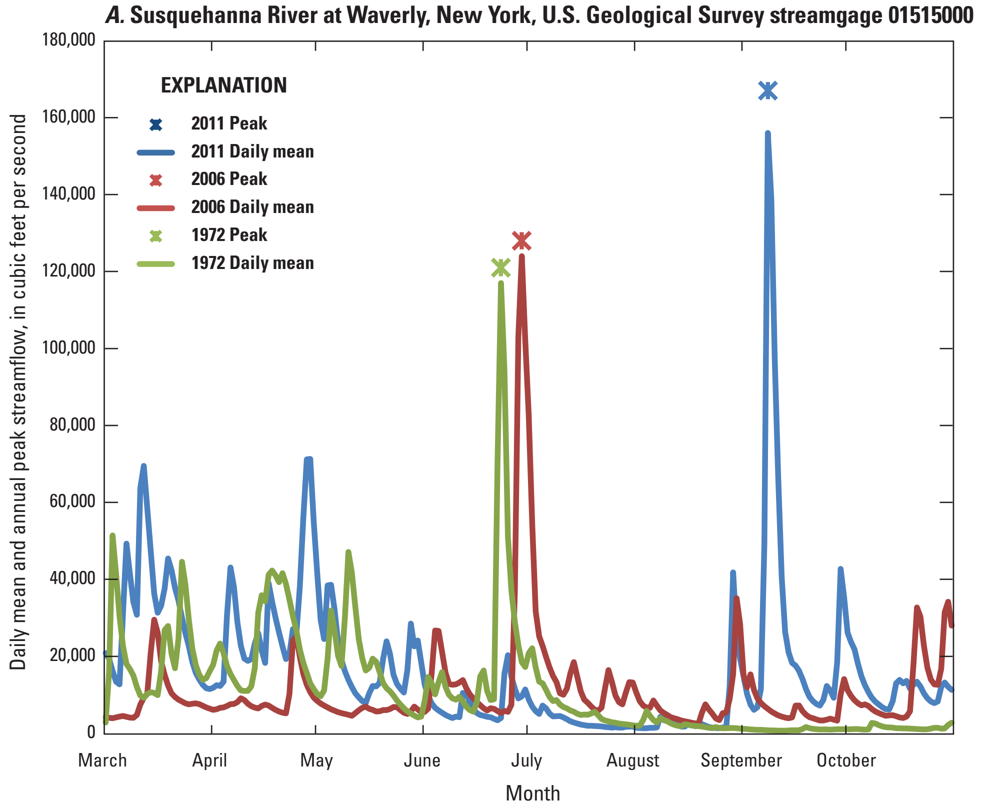


Figure 13. Annual peak streamflows through 2011 and the 4-, 2-, 1-, and 0.2-percent annual exceedance probability streamflows for selected U.S. Geological Survey streamgages in the Northeast.—Continued



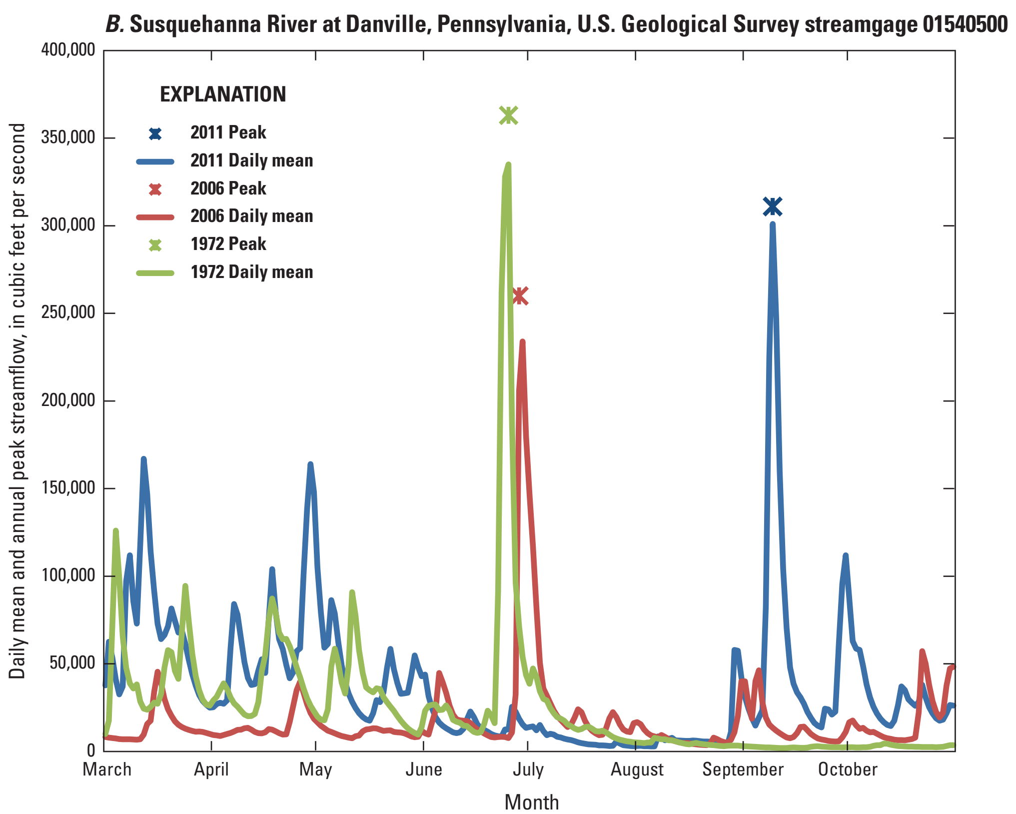
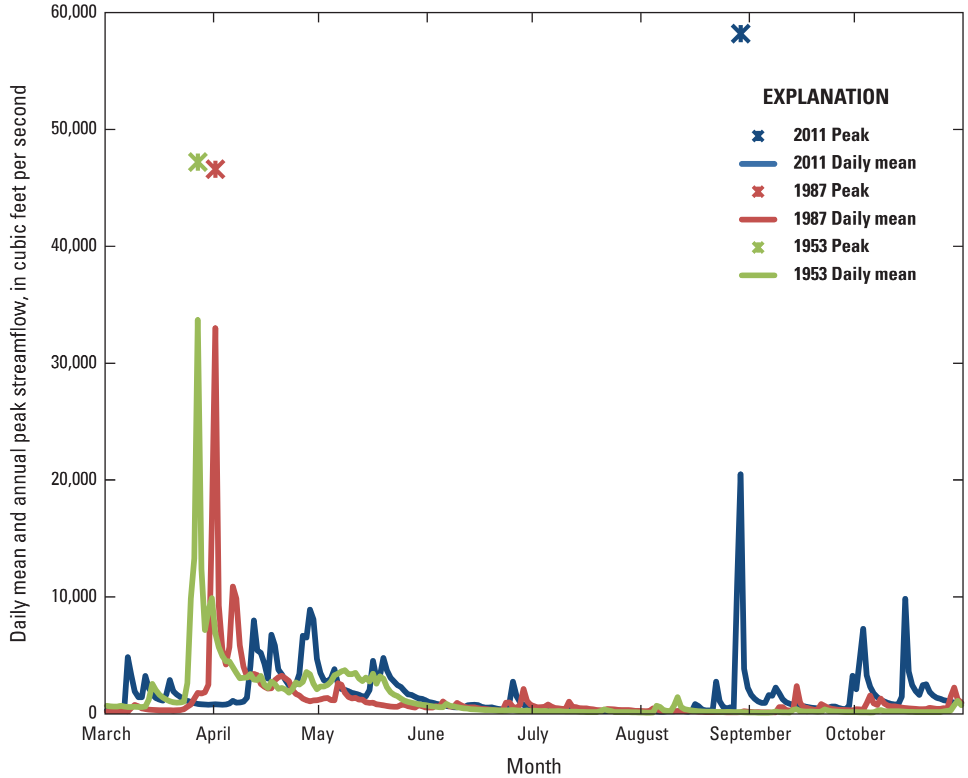


Figure 14. Streamflow for selected U.S. Geological Survey streamgages in the northeast for the 2011 flood period and selected previous major floods.

C. **Saco River near Conway, New Hampshire, U.S. Geological Survey streamgage 01064500**



D. **North River at Shattuckville, Massachussetts, U.S. Geological Survey streamgage 01169000**

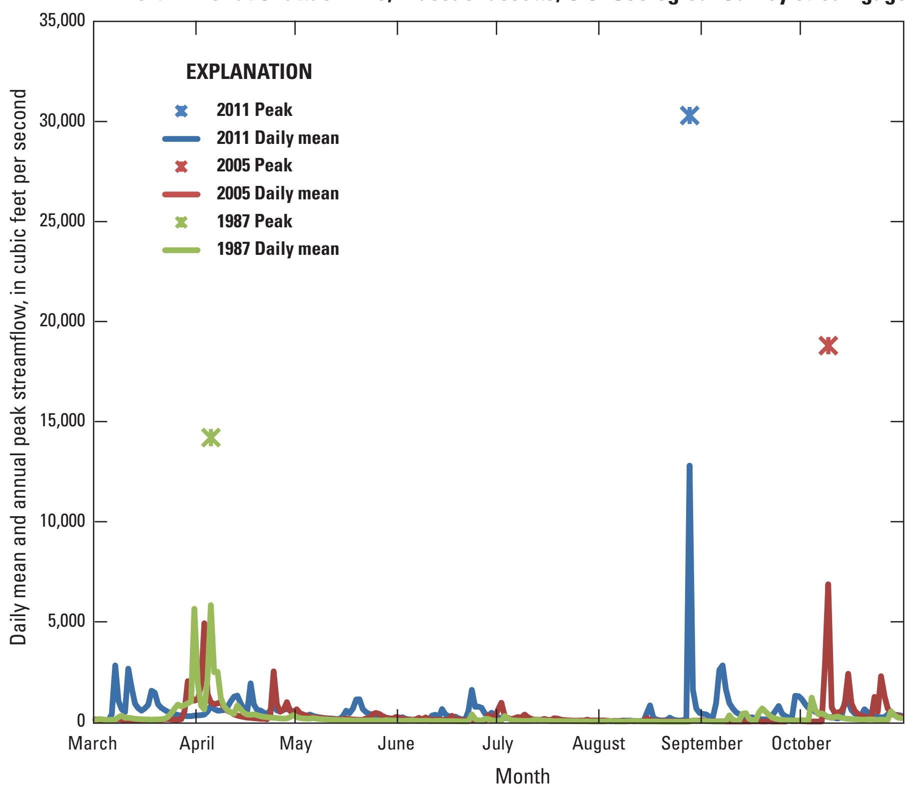


Figure 14. Streamflow for selected U.S. Geological Survey streamgages in the northeast for the 2011 flood period and selected previous major floods.—Continued

storms are still the highest recorded peaks for streamgages such as West Branch Farmington River near New Boston, Mass. (01185500); Rutgers Creek at Gardnerville, N.Y. (01368500); and Delaware River at Trenton, N.J. (01463500). For other streamgages that were in operation during 1955 and 2011, such as Mill River at Northampton, Mass. (01171500); Roundout Creek at Rosendale, N.Y. (01367500); and Flat Brook near Flatbrookville, N.J. (01440000); flooding from Tropical Storm Irene produced comparatively higher peaks (table 1). In the Passaic and Hackensack River Basins in New Jersey (fig. 1), the streamgages Whippany River at Morristown, N.J. (01381500); Wanaque River at Awosting, N.J. (01383500); Ramapo River near Mahwah, N.J. (01387500; fig. 13); and Ramapo River at Pompton Lakes, N.J. (01388000) recorded the highest flood peaks in more than 90 years of record (table 1; Watson and others, 2014). A photograph of rescuers using a boat to navigate the flooded streets of Pompton Lakes, N.J., after the Ramapo River overflowed its banks because of the heavy rain associated with Tropical Storm Irene on August 29, 2011, is shown in figure 15.

Heavy rainfall from Hurricane Floyd in September 1999 resulted in record flooding in parts of Maryland, Delaware, New Jersey, Pennsylvania and New York. The flood peaks from September 1999 at several streamgages in the northeast such as Wissahickon Creek at Mouth, Philadelphia, Pa. (01474000), White Clay Creek near Newark, Del. (01479000), and the Raritan River at Manville, N.J. (01400500), which has 100 years of streamflow record, were not surpassed by the flood peaks of 2011. However, for other streamgages such as Sawmill Creek at Glen Burnie, Md. (01589500); Hackensack River at West Nyack, N.Y. (01376800); and Christina River at Coochs Bridge, Del. (01478000; fig. 13), all of which were in operation in 1999, flooding from Tropical Storm Irene in 2011 did surpass the 1999 flood peaks, establishing new period-of-record flood peaks (table 1).

Figure 15. Rescuers use a boat to navigate the flooded streets of Pompton Lakes, N.J., as the Ramapo River overflows its banks because of the heavy rain on August 29, 2011. Photograph by Robert Atkinson, U.S. Geological Survey.

In the New England region, flooding associated with Tropical Storm Irene in late August 2011 resulted in new period-of-record peak streamflows being recorded at 37 streamgages across Vermont, western Massachusetts, northern New Hampshire, and parts of eastern New York (Olson and Bent, 2013). The 2011 peak-of-record streamflow at the streamgage North River at Shattuckville, Mass. (01169000) was 30,300 ft^3/s, which exceeded the previously known maximum streamflow of 18,800 ft^3/s, which was recorded in 2005 (figs. 13, 14*D*, table 1). Peak-of-record streamflows were also recorded at the streamgages Saco River near Conway, N.H. (01064500; figs. 13, 14*C,* table 1) and Mad River near Moretown, Vt. (04288000; fig. 13, table 1), which have periods of record dating back to 1904 and 1928, respectively.

In September 2011, the Susquehanna River main stem experienced record-setting (or near record-setting) streamflows at USGS streamgages in New York and Pennsylvania where water levels topped levees along the river, which inundated several cities in New York including Waverly, Owego, Vestal, Endicott, Johnson City, and downtown Binghamton (National Weather Service, 2014a). The streamgage Susquehanna River at Waverly, N.Y. (01515000; figs. 13, 14*A*, table 1), situated near the New York-Pennsylvania border, has been in operation since 1936, and the September 2011 flood peak is the largest streamflow recorded at this site and exceeds the previous peak-of-record stage set in 2006 by more than 4 ft. The peak streamflows associated with the September 2011 event at the streamgages along the Susquehanna River at Towanda (01531500; table 1); at Wilkes-Barre (01536500; table 1); and at Danville, Pa. (01540500; figs. 13, 14*B*, table 1); were second only to the peak-of-record streamflows associated with Hurricane Agnes in 1972. In Harrisburg, Pennsylvania, where the forecast of flooding led to the evacuation of about 100,000 people, including 10,000 people and the Governor's residence in the downtown area (National Weather Service, 2014a), the September 2011 recorded peak streamflow at the streamgage Susquehanna River at Harrisburg, Pa. (01570500; table 1) was 590,000 ft^3/s, well below the 1972 peak-of-record streamflow of 1,020,000 ft^3/s. Conversely, on Swatara Creek (a tributary joining the Susquehanna River approximately 10 miles downstream from the Susquehanna River at Harrisburg streamgage), the September 2011 peak streamflow recorded at the streamgage Swatara Creek at Harper Tavern, Pa. (01573000; table 1) exceeded the 1972 peak by approximately 12 percent. The difference in annual peak streamflow relations between the Susquehanna River at Harrisburg streamgage and the Swatara Creek at Harper Tavern streamgage for the 1972 and 2011 storm events may be attributed to relative size of basins at the gaged locations (24,100 and 337 mi^2, respectively) and the geographic and temporal distribution of the rainfall associated with each storm event.

The 1972 flooding was a result of heavy and persistent rainfall associated with the remnants of Hurricane Agnes and resulted in major flooding on many of the tributaries and much of the main stem of the Susquehanna River in Pennsylvania and the southern tier of New York. Nationwide, 122 deaths were attributed to Agnes, of which 50 were in the State of Pennsylvania, and total damages from the storm reached more than $3 billion dollars nationwide, with more than $2 billion dollars in losses in the Susquehanna River Basin (National Weather Service, 2014c).

Annual Exceedance Probability Analysis for 2011

This report provides the results of exceedance probability analyses of annual peak streamflow for 327 selected streamgages in the Northeast that experienced moderate to major flooding during 2011. The probability analyses were computed using annual peak streamflow data through 2011. Current methods outlined in Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) were used for the analysis, but the results of newer experimental methods of flood frequency analysis are presented in table 2 (available at http://dx.doi.org/10.3133/pp1821) for comparison. An explanation of these newer experimental methods is provided in the section titled Annual Exceedance Probability using Expected Moments Algorithm.

The evaluation of future flood risk is an integral part of why the probability of annual maximum streamflow is analyzed. Knowing the flood ranking at a streamgage or the maximum elevation at selected locations helps in understanding local flooding conditions, but an analysis of the exceedance probability of an annual peak streamflow allows for a better evaluation of the flood risk and provides data for better infrastructure design and flood damage mitigation planning. Annual peak streamflows are used to estimate a probability distribution. The probability distribution relates the probability to the magnitude of a specific peak streamflow being equaled or exceeded in any given year.

The selection of the probability distribution and the process of fitting the parameters of the distribution can vary depending on the underlying characteristics of the data. The Interagency Advisory Committee on Water Data produced standard guidelines adopted by many Federal agencies for consistent computations of these probabilities known as Bulletin 17B (Interagency Advisory Committee on Water Data, 1982). These guidelines recommend the use of the LPIII distribution and the "method of moments" for estimating the distribution parameters (mean, standard deviation, and skewness of the data). The analysis is based on annual peak streamflow data at USGS streamgages, which are available online from the USGS National Water Information System (NWIS) at http://waterdata.usgs.gov/nwis (U.S. Geological Survey, 2013). In many previously published USGS reports flood probabilities have been expressed as flood frequencies using a T-year recurrence interval for a particular flood quantile (for example, the "100-year flood"). Use of the T-year recurrence interval to describe flood probability is now discouraged by many agencies (including USGS) because it tends to confuse the general public. A T-year recurrence interval is sometimes interpreted to imply that there is a set time interval between floods of a specific magnitude when, in fact, floods are random processes that are best understood using probabilistic terms. The use of an AEP percentage to describe the estimated probability of selected flood magnitudes is recommended as a way to better communicate the annual chance of occurrence. The reader can convert from the AEP to the previously used T-year recurrence interval by simply taking the reciprocal of the AEP. For example, the 1-percent AEP flood corresponds to a streamflow magnitude that has a 1-percent chance of being equaled or exceeded in any given year. A 1-percent chance relates to a probability of 0.01 when expressed as a decimal. The reciprocal of 0.01 is 100; thus, the T-year recurrence interval for the 1-percent AEP flood is referred to as the 100-year flood.

Aerial views of damage in West Bridgewater, Vermont, as a result of floodwaters during Tropical Storm Irene in August 2011. Photograph courtesy of Lars Gange, Mansfield Heliflight.

AEP flood quantiles can be computed in many different ways, including the above referenced Bulletin 17B methods that were used for this report. The reliability of the flood quantiles computed using Bulletin 17B methods may be expressed as a "variance of prediction" that is computed by using the asymptotic formula given by Cohn and others (2001), with the addition of the mean-squared error of generalized skew (Griffis and others, 2004). The variance of prediction varies as a function of record length, the fitted flood-probability distribution parameters (mean, standard deviation, and weighted skew), and the accuracy of the method used to determine the regional skew component of the weighted skew.

An additional method is the use of regional regression techniques to develop regional regression equations (RRE) to estimate the AEP flood quantiles. These techniques are used to develop a relation between flood-probability data at many streamgages throughout a region and basin characteristics of those streams (Jennings and others, 1994). Once developed, the RRE can be used to estimate various streamflow characteristics, such as the 1-percent AEP flood quantile, for almost any location along a stream (gaged or ungagged) within the reliable boundaries of the RREs. The variance of prediction from the regional regression is a function of the RRE and values of independent variables used to develop the streamflow estimate from the RRE. The variance generally increases with departure of actual values from mean values of the independent variables.

The USGS National Streamflow Statistics (NSS) Program has software (http://water.usgs.gov/ software/nss.html) that can be used to apply the RRE by allowing the user to enter basin and land-use characteristics (drainage area, basin slope, area of wetlands, surficial geology, and so on) that are used in the equations as independent (explanatory) variables into RRE and compute various streamflow characteristics. The USGS StreamStats Program has developed a more comprehensive online tool called "StreamStats", which allows the user to work in an interactive map environment to select a site of interest and have basin and streamflow characteristics computed and displayed in a report format (http://water.usgs.gov/osw/streamstats).

Debris catches on snowmobile bridge near Waterbury, Vermont, as a result of floodwaters from the Winooski River during Tropical Storm Irene, in August 2011. Photograph courtesy of Lars Gange, Mansfield Heliflight.

Holmes and others (2010) provided detailed discussions about how to express the accuracy of RREs in terms of equivalent years of record and suggested that weighting by variance provides a more natural characterization of the underlying uncertainty of the various peak streamflow estimates. At a gaged location, the optimal estimate of the AEP flood quantile is determined by weighting the AEP flood-quantile estimate determined from the Bulletin 17B methods with the AEP flood quantile estimate determined from the RRE. The weights are inversely proportional to the variances of prediction (equation 1), yielding the weighted estimator:

$$\mathrm{Log}Q_{P,OPT} = \frac{\left(Var[RRE]\times \mathrm{Log}Q_{P,LPIII} + Var[LPIII]\times \mathrm{Log}Q_{P,RRE}\right)}{\left(Var[RRE]+Var[LPIII]\right)} \qquad (1)$$

where

$Q_{P,OPT}$ is the optimal estimate of AEP flood quantile for a particular probability of flooding (*p*; Interagency Advisory Committee on Water Data, 1982, appendix 8),

$Var[RRE]$ is the variance of the RRE estimate of the AEP flood quantile for a particular probability of flooding (*p*),

$Q_{P,LPIII}$ is the Bulletin 17B method estimate of the AEP flood quantile for a particular probability of flooding (*p*),

$Var[LPIII]$ is the variance of the Bulletin 17B estimate of the AEP flood quantile for a particular probability of flooding (*p*), and

$Q_{P,RRE}$ is the RRE estimate of the AEP flood quantile for a particular probability of flooding (*p*).

Previous USGS reports have expressed the accuracy of RREs in terms of equivalent years of record and used these estimates with the length of record at the streamgage to combine RRE and LPIII AEP flood quantile estimates (for example, Hodge and Tasker, 1995; Ries and Dillow, 2006). Although this method was presented in the Bulletin 17B guideline, the length of record can fail to account for the true variance of LPIII flood-probability estimates. For all records of the same length, the accuracy is assumed to be of the same reliability, which may not be accurate. The flood-probability distributions computed from two different streamgage records of the same length may not be of equal reliability because of differences in underlying variances of the streamflow records for each site. For example, one streamgage may have less stable control conditions and more highly varied records making it more difficult to accurately measure the streamflow than another. The LPIII distributions at the first streamgage, therefore, could have larger variances than the second streamgage in the example. More importantly, the equivalent years-of-record concept, although relatively easy to understand, misrepresents the relation between the AEP flood quantile estimates and the variances. Using estimated variances provides a more natural characterization of the underlying uncertainty of the various streamflow estimates. The weighted estimates of the AEP flood quantiles corresponding to the

4-, 2-, 1-, and 0.2-percent AEP, along with their respective 95-percent confidence limits, for selected streamgages in the Northeast, are listed in table 1. Streamgages that generally recorded an annual peak streamflow that exceeded the 4-percent AEP during 2011 were included in table 1, with a few exceptions to help define the extent of major flooding.

Another statistic included in table 1 that was typically not included in previous USGS reports is the “typical range” for the 66.7-percent confidence level for the computed AEPs for the 2011 flood peaks. In table 1, the values under the column heading of “AEP for observed 2011 flood” are the estimated AEPs for each 2011 flood peak and the corresponding typical range of the AEP. The AEPs of the 2011 floods were calculated using the methods outline in USGS Office of Surface Water Technical Memorandum 2013.01 (U.S. Geological Survey, 2012b). As previously stated, the AEP is estimated from a LPIII statistical model fit to the at-site peak streamflow data. The typical range is presented to report the lower and upper bounds on 66.7-percent confidence level for the true AEP. These bounds, unlike the AEP estimate, are based on order statistics and do not assume a model. The distinction is important because the model-based AEP estimates may occasionally lie outside the nonparametric confidence bounds, which intuitively may not make sense to the reader. The confidence bounds, or typical range of the true AEP, are intended to communicate the magnitude of the uncertainty in estimates of the AEP by providing the likely range of the AEP corresponding to the k-th largest event in a sample of size *N*. For example, if the exceedance probability corresponding to a particular flood at 2 percent is estimated, the understanding is that the uncertainty in this statistic is large, and, in general, a 66.7-percent confidence level for the true exceedance probability of the 2-percent flood extends from 0.4 to 4 percent.

The Streamflow of 2011—Water Year Summary shows that statewide streamflow in the northeast was above average to wet using a statistical period from 1930 to 2011(Jian and others, 2012). During 2011, the USGS recorded peak streamflows that were generally equal to or less than a 4-percent AEP at 327 streamgages in the northeast. These 327 streamgages that generally recorded moderate to major flooding during 2011 in the northeast are listed in table 1 and shown in figure 16. More than 180 of the 327 streamgages listed recorded a new period-of-record peak streamflow in 2011. Peak streamflows greater than or equal to the 1-percent AEP discharge were recorded at 129 streamgages across Connecticut, Delaware, Maine, Maryland, Massachusetts, Ohio, Pennsylvania, New Hampshire, New Jersey, New York, and Vermont. Additionally, nearly 100 of the 129 peaks with an AEP of 1 percent or less were a result of the flooding associated with Hurricane Irene in late August 2011, and at 24 of these streamgages the recorded peak was extreme enough to exceed the 0.2-percent AEP during the August storm. A total of 31 of the streamgages listed in table 1 recorded peak streamflows that equaled or exceeded the 0.2-percent AEP during 2011.

Annual Exceedance Probability using Expected Moments Algorithm

The Hydrology Subcommittee of the Interagency Advisory Committee on Water Data (1982) developed the Bulletin 17B guidelines for determining flood frequency studies in the United States. These guidelines include methods for improving skew estimates and testing for outliers, but the authors of Bulletin 17B also identified the need for methodological improvements and recommended further study. The Hydrologic Frequency Analysis Work Group is considering modest changes to Bulletin 17B guidelines to address those recommendations for improved methods. The work group is proposing the adoption of the expected moments algorithm (EMA; Cohn and others, 1997) with Multiple Grubbs-Beck low outlier screening (Cohn and others, 2013).

AEPs using the EMA method for 122 of the 327 streamgages included in table 1 are listed in table 2 (available at http://dx.doi.org/10.3133/pp1821). The peak streamflows that are reported in table 1 are also included in table 2 as a reference. The 122 streamgages included in table 2 that have AEP estimates using the EMA method are also shown in figure 17 as an additional geographic reference.

Aerial view of damage along U.S. Route 4 near Killington, Vermont, as a result of floodwaters during Tropical Storm Irene in August 2011. Photograph courtesy of Lars Gange, Mansfield Heliflight.

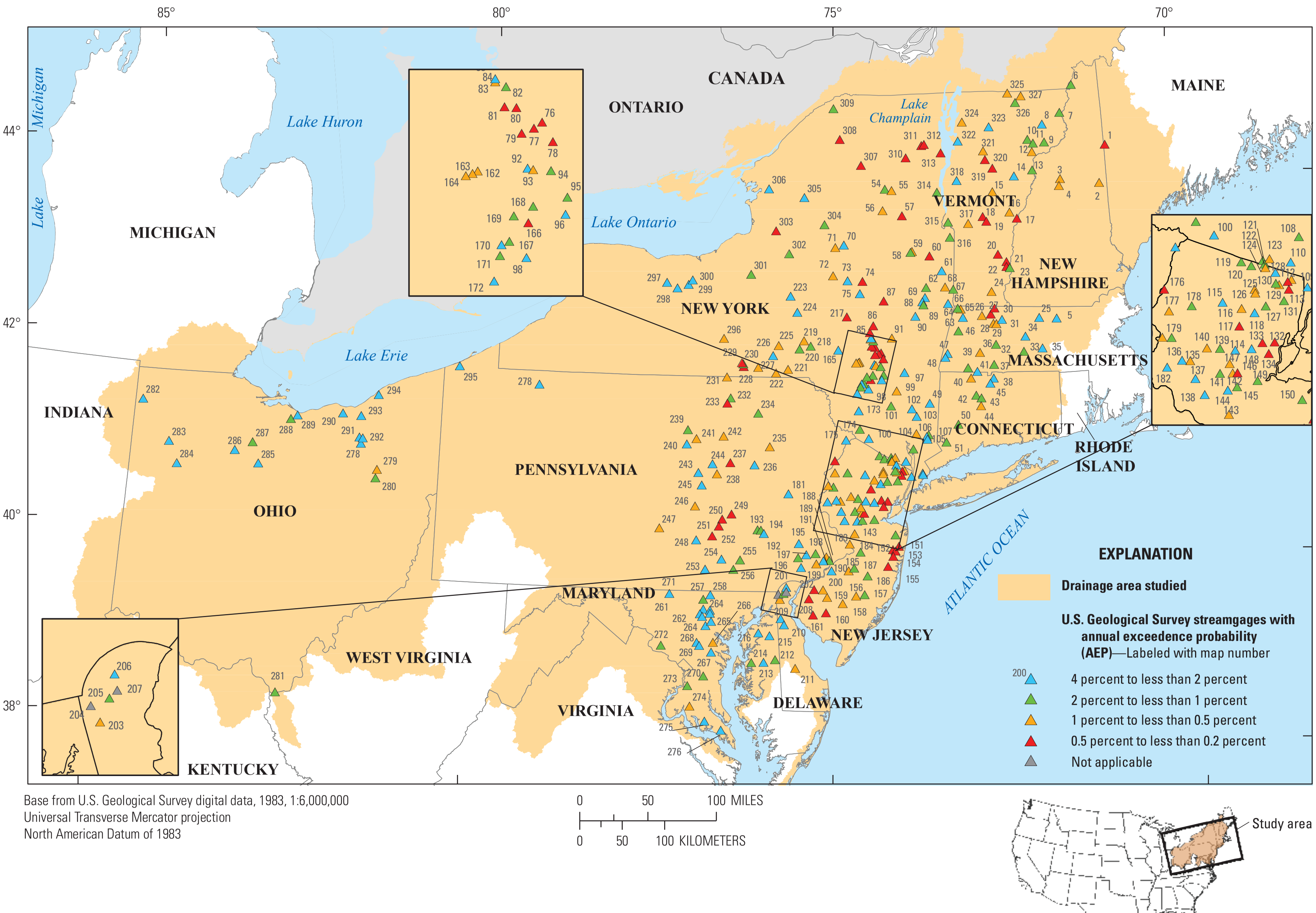


Figure 16. Annual exceedance probabilities computed for peak streamflows during 2011 at selected USGS streamgages in the Northeastern United States and major drainage basins studied during 2011 flooding. (Data are listed in table 1).

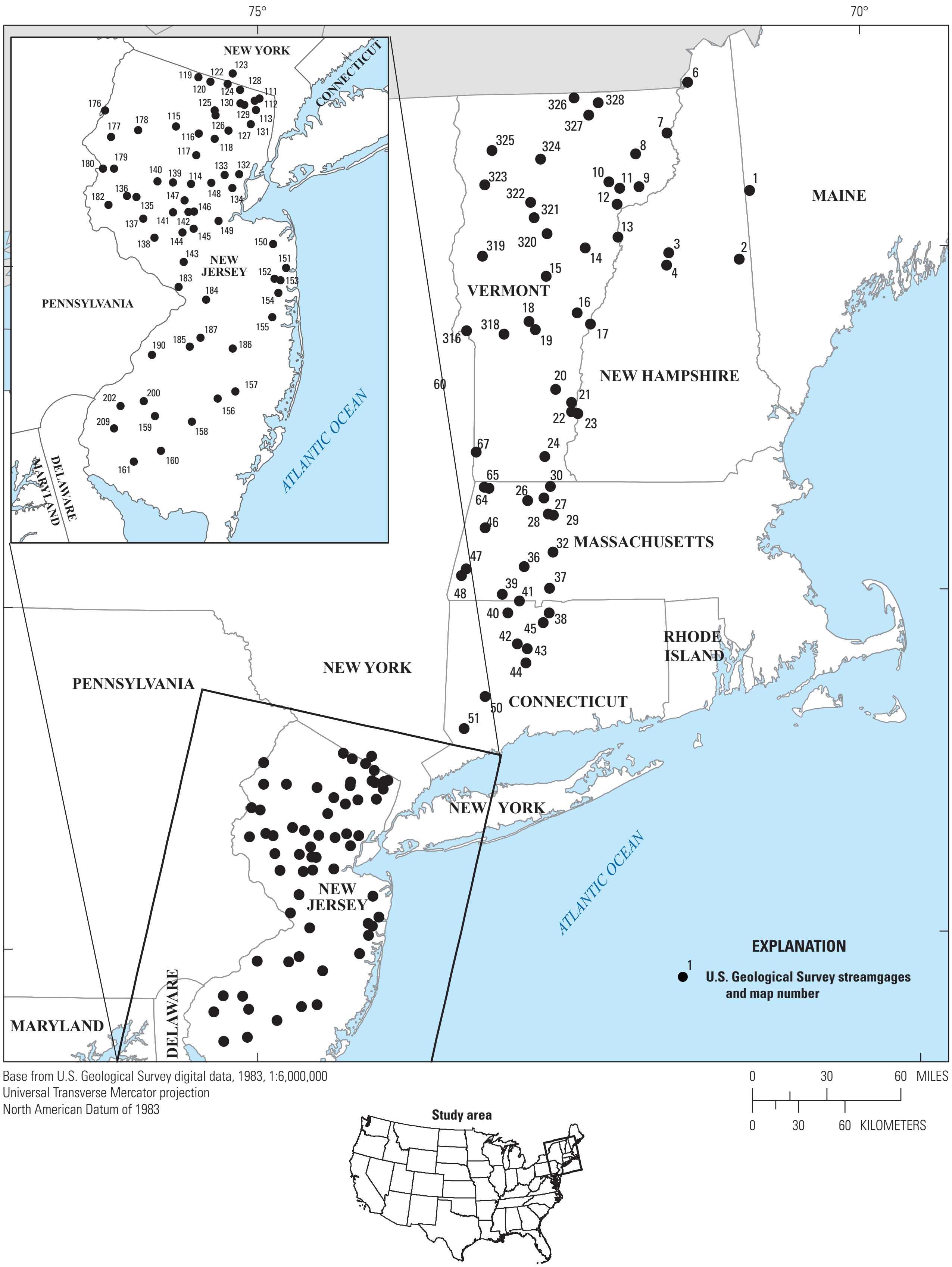


Figure 17. Selected U.S. Geological Survey streamgages in the Northeastern United States with annual exceedance probabilities computed using the expected moments algorithm method. (Data are listed in table 2).

Summary

The combination of several major flooding events in 2011 caused damages that were estimated to exceed $7 billion in the Northeastern United States. The flooding in the Northeastern United States also resulted in approximately 45 deaths and more than 180 U.S. Geological Survey (USGS) streamgages recorded new period-of-record maximum. The flooding events began in late February and early March with snowmelt-enhanced peak streamflows in northern Ohio, western Connecticut, and central Massachusetts. In late April, parts of northern New Hampshire, New York, and Vermont were flooded as a result of rainfall on heavy snowpack. Relatively wet conditions persisted throughout the year as a result of numerous small scale rain events (summer thunderstorms) from late May through mid-August, until record-setting precipitation associated with Hurricane Irene and the remnants of Tropical Storm Lee caused major flooding disasters throughout the Northeastern United States.

In the winter and spring of 2011, record rainfall and snowmelt throughout many areas of the Northeastern United States contributed to streamflows that were above normal at numerous USGS streamgages in New England, New York, New Jersey, Delaware, and Maryland. During the spring of 2011, the streamgage Lake Champlain at Burlington,Vt. (04294500) recorded record flooding as a result of the combined runoff from record rainfall and snowmelt. Lake Champlain was above the National Weather Service flood stage of 100 feet (ft) for 68 days from April 13 to June 19, 2011, and peaked at 103.27 ft on May 6, 2011, surpassing the maximum known elevation since at least 1827 of 102.1 ft on May 4, 1869. The intense rainfall associated with Hurricane Irene contributed to new August total precipitation records for New Hampshire, New Jersey, New York, and Vermont and resulted in new period-of-record peak streamflows being recorded at 119 USGS streamgages. In the Green Mountains of Vermont, 13 communities were isolated for days as floodwaters damaged or destroyed bridges, culverts, and 500 miles of State highways. New York reported similar damages to roads and bridges, and every county in New Jersey was declared a Federal disaster area. Several streamgages in New York and New Jersey, with more than 90 years of data, recorded new peak-of-record maximums during the 2011 flood. In early September 2011, rainfall associated with the remnants of Tropical Storm Lee caused the main stem of the Susquehanna River and many tributaries to rise to record setting levels in southern New York and Pennsylvania. The peak streamflows associated with the early September 2011 event at the streamgages Susquehanna River at Towanda, Pa., Susquehanna River at Wilkes-Barre, Pa., and Susquehanna River at Danville, Pa., were second only to the peak-of-record streamflows associated with Hurricane Agnes in 1972.

Annual Exceedance Probabilities (AEPs) were estimated for 327 sites in the Northeastern United States using annual peak streamflows through 2011. The peak streamflows analyzed were estimated to have an AEP of 1 percent or less at 129 streamgages in Connecticut, Delaware, Maine, Maryland, Massachusetts, Ohio, Pennsylvania, New Hampshire, New Jersey, New York, and Vermont. Flooding associated with Hurricane Irene contributed to 100 of the 129 streamflow peaks with an AEP of 1 percent or less and 24 of the peak streamflows with an AEP of 0.2 percent or less. In 2011, 31 streamgages recorded peak streamflows that equaled or exceeded the more extreme 0.2-percent AEP.

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Glossary

Note: Glossary definitions are taken from Langbein and Iseri (1960) whenever possible.

A

annual exceedance probability (AEP) The probability, or chance, of a flood of a given streamflow magnitude being equaled or exceeded in any given year. The probability can be expressed as a fraction, decimal, or percentage.

annual exceedance probability flood quantile (AEP flood quantile) The value of the peak streamflow that corresponds to a particular annual exceedance probability (for example, 1-percent AEP flood quantile).

B

Bulletin 17B Report by the Interagency Advisory Committee on Water Data, published in 1982, that identifies guidelines delineates the recommended method for flood-probability analysis.

C

confidence limits To gage the accuracy of an approximation based on a probability distribution, upper and lower confidence limits can be estimated based on the properties of the probability distribution. This report includes the 95-percent confidence limits of the estimate of the flood quantiles as computed by the methods outlined in Bulletin 17B.

confidence interval is based on order statistics and is intended to communicate the general magnitude of the uncertainty in estimates of the AEP by providing the likely range of the AEP corresponding to the k-th largest event in a sample of size *N*. AEP estimates may occasionally lie outside the nonparametric confidence intervals.

D

discharge In its simplest concept discharge means outflow; therefore, the use of this term is not restricted as to course or location, and it can be applied to describe the flow of water from a pipe or from a drainage basin.

E

expected moments algorithm is an alternative to maximum likelihood estimation (MLE) or the Bulletin 17 (Interagency Advisory Committee on Water Data, 1982) methods for incorporating historical information in flood frequency analysis or studies.

F

flood An overflow or inundation that comes from a river or other body of water, and causes or threatens damage.

flood peak The highest value of the stage or streamflow attained by a flood; generally designated as peak stage or peak streamflow, respectively. The annual flood peak is the largest flood peak for a given year or water year.

flood quantile *See* annual exceedance probability flood quantile.

flood stage The stage at which overflow of the natural banks of a stream begins to cause damage in the reach in which the water surface elevation is measured.

H

hydrograph A graph showing stage, streamflow, velocity, or other property of water with respect to time.

L

log-Pearson type III probability distribution (LPIII) One of the family of probability distributions developed by Karl Pearson that is commonly used in the United States as a best-fit for the distribution of annual peak flood streamflows and is suggested in Bulletin 17B as “the base method” for analysis procedures developed by the Interagency Advisory Committee on Water Data (1982).

O

orographic lifting The change in air flow when the topography of the land forces the air up the side of a mountain.

P

peak-of-record streamflow The largest instantaneous streamflow value for the period that data have been collected.

peak stage *See* flood peak.

peak streamflow *See* flood peak.

precipitation As used in hydrology, precipitation is the discharge of water, in liquid or solid state, out of the atmosphere, generally upon a land or water surface. It is the common process by which atmospheric water becomes surface or subsurface water. The term "precipitation" is also commonly used to designate the quantity of water that is precipitated.

probability A means to express the likelihood of something occurring, also known as chance. The probability can be expressed as a fraction, decimal, or percentage.

probability distribution Describes the range of possible values that a random variable can attain and the probability that the value of the random variable is within any subset of that range.

R

rating curve A graph showing the relation between the stage (gage height), usually plotted as the ordinate, and amount of water flowing in the channel (streamflow) expressed as volume per unit time, plotted as abscissa.

recurrence interval The average interval of time within which the given flood is expected to be equaled or exceeded once.

regional regression equation Equation developed through use of regression techniques that relate the flood-probability data at many streamgages in a region to the basin characteristics of the streams monitored by the streamgages. For any location along a stream, a user can enter the basin characteristics (for example, drainage area, basin slope) as independent variables into the equations and compute various flow characteristics (for example, 1-percent AEP flood quantile, 2-percent AEP flood quantile, and annual mean streamflow).

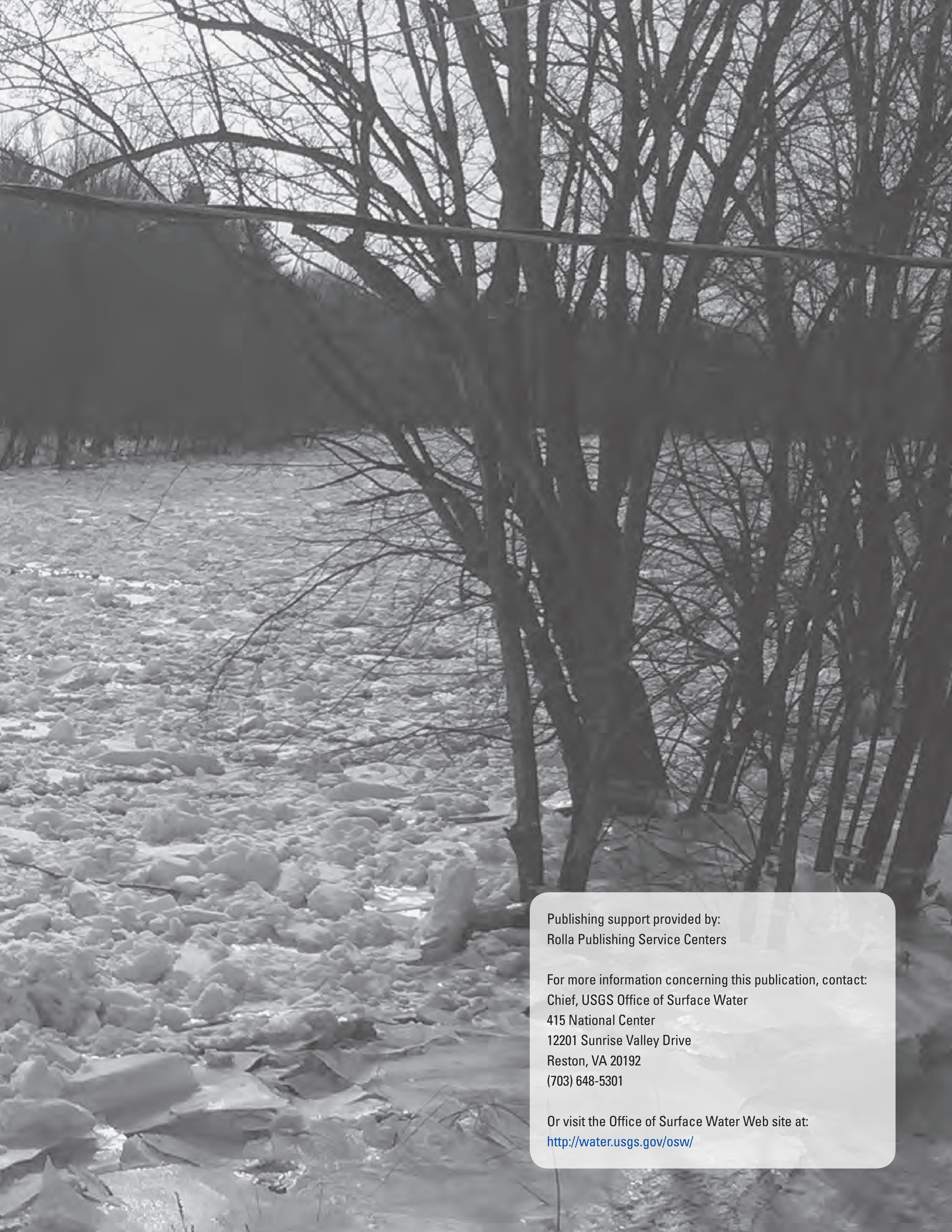
S

stage Height of a water surface above an established datum, also known as gage height.

streamflow The discharge that occurs in a natural channel. Although the term discharge can be applied to flow in a canal, the word streamflow uniquely describes the discharge in a surface stream course. The units of measurement generally are reported in cubic feet per second (ft^3/s).

streamgage A particular site on a stream where a record of streamflow is obtained.

Debris catches on snowmobile bridge near Waterbury, Vermont, as a result of floodwaters from the Winooski River during Tropical Storm Irene, in August 2011. Photograph courtesy of Lars Gange, Mansfield Heliflight.



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