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Flood-Inundation Maps for the North River in Colrain, Charlemont, and Shelburne, Massachusetts, From the Confluence of the East and West Branch North Rivers to the Deerfield River

Scientific Investigations Report 2015–5108

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

Cover. Map showing flood inundation for an upstream region of the North River study reach corresponding to a stage of 18.3 feet (equivalent to the 0.2-percent annual exceedance probability discharge and approximately depicts the August 28, 2011, tropical storm Irene peak flow) at the U.S. Geological Survey streamgage, North River at Shattuckville, Massachusetts (01169000) (not shown on map).

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SALLY JEWELL, Secretary

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

Vertical coordinate information is referenced to either stage (the height above an arbitrary datum established at a streamgage) or 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
AHPS	Advanced Hydrologic Prediction Service
DEM	digital elevation model
DGPS	differential global positioning system
FEMA	Federal Emergency Management Agency
GIS	geographic information system
HWM	high-water mark
lidar	light detection and ranging
NWS	National Weather Service
RTK	real-time kinematic
USGS	U.S. Geological Survey

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Abstract

A series of 10 digital flood-inundation maps were developed for a 3.3-mile reach of the North River in Colrain, Charlemont, and Shelburne, Massachusetts, by the U.S. Geological Survey in cooperation with the Federal Emergency Management Agency. The coverage of the maps extends from the confluence of the East and West Branch North Rivers to the Deerfield River. Peak-flow estimates at the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probabilities were computed for the reach from updated flood-frequency analyses. These peak flows were routed through a one-dimensional step-backwater hydraulic model to obtain the corresponding peak water-surface elevations and to place the tropical storm Irene flood of August 28, 2011, into historical context. The hydraulic model was calibrated by using the current [2015] stage-discharge relation at the U.S. Geological Survey streamgage North River at Shattuckville, MA (station number 01169000), and from documented high-water marks from the tropical storm Irene flood, which had a peak flow with approximately a 0.2-percent annual exceedance probability.

A hydraulic model was used to compute water-surface profiles for 10 flood stages referenced to the streamgage and ranging from 6.6 feet (ft; 464.5 ft North American Vertical Datum of 1988 [which is approximately bankfull]) to 18.3 ft (476.2 ft North American Vertical Datum of 1988 [which is the stage of the 0.2-percent annual exceedance probability peak flow and exceeds the maximum recorded water level at the streamgage and the National Weather Service major flood stage of 13.0 ft]. The mapped stages of 6.6 to 18.3 ft were selected to match the stages of flows for bankfull; the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probabilities; and an incremental stage of 17.0 ft. The simulated water-surface profiles were combined with a geographic information system digital elevation model derived from light detection and ranging (lidar) data with a 0.5-ft vertical accuracy to create a set of flood-inundation maps.

The availability of the flood-inundation maps, combined with information regarding near-real-time stage from the U.S. Geological Survey North River at Shattuckville, MA streamgage can provide emergency management personnel and residents with information that is critical for flood response activities, such as evacuations and road closures, and postflood recovery efforts. The flood-inundation maps are nonregulatory, but provide Federal, State, and local agencies and the public with estimates of the potential extent of flooding during selected peak-flow events.

Introduction

On August 22, 2011, Hurricane Irene travelled up the east coast of the United States affecting States from South Carolina to Maine. The large, category-1 hurricane buffeted the area with heavy rains, damaging winds, and storm surge, which resulted in damages estimated in the billions of dollars (Federal Emergency Management Agency, 2013). Although the hurricane was downgraded to a tropical storm before entering New England on August 28, 2011, it brought a period of intense rainfall with totals ranging from 3 to 10 inches over western Massachusetts. The rainfall and resulting runoff caused the streamflow of several rivers in western Massachusetts to peak at record levels on August 28–29, 2011. In many cases, the stage-discharge rating curves were exceeded for U.S. Geological Survey (USGS) streamgages that had been in operation for decades.

On September 3, 2011, a presidential disaster declaration (FEMA–4028–DR) was issued for Berkshire and Franklin Counties in northwestern Massachusetts (Federal Emergency Management Agency, 2013). On October 20, 2011, two other counties in western Massachusetts and five other counties in southeastern Massachusetts were added to this declaration. As of February 2013, Federal financial assistance to Massachusetts for recovery from tropical storm Irene exceeded $11 million for individual assistance and $53 million for public assistance (Federal Emergency Management Agency, 2013).

Tropical storm Irene resulted in peak flows on August 28, 2011, at USGS streamgages in the Deerfield River Basin that ranged from about the 1-percent to less than the 0.2-percent annual exceedance probability (AEP) floods. The peak flow of 30,300 cubic feet per second (ft^3/s) at the USGS North River at Shattuckville, MA streamgage (01169000; hereafter referred to as the North River streamgage; fig. 1) is roughly equivalent to the 0.2-percent AEP flood of 30,400 ft^3/s of the streamgage. This peak flow of 30,300 ft^3/s at the North River streamgage was determined from the current [2015] stage-discharge relation (rating curve), which was extended based on discharge determined from indirect flow estimation techniques (Matthai, 1967) and the stage of the peak. The USGS Green River near Colrain, MA streamgage (01170100; hereafter referred to the Green River streamgage) in the adjacent basin to the east of the North River (fig. 1) had a peak discharge of 13,200 ft^3/s, which is less than a 0.2-percent AEP flood (12,100 ft^3/s) at the Green River streamgage. This peak flow of 13,200 ft^3/s at the Green River streamgage was determined from the current [2015] stage-discharge relation (rating curve), which was extended based on discharge determined from indirect flow estimation techniques (Dalrymple and Benson, 1967; Matthai, 1967; Fulford, 1994; Bradley, 2012) and the stage of the peak.

The well field of the Village of Shelburne Falls within the Town of Shelburne along the North River in the mid-section of the study reach in Colrain was inundated during tropical storm Irene (Murphy, 2013). The Barnhardt Manufacturing Company building along the North River in the upper-section of the study reach (fig. 2) in Colrain was flooded. The Barnhardt dam about 0.5 mile (mi) upstream near the start of the study reach (fig. 1) was breached during tropical storm Irene. On the East Branch North River in Colrain, a streambank slope was eroded near the town's salt barn, and the town's highway garage and basement were flooded about 1.9 mi and 2.4 mi, respectively, upstream from the start of the study reach (fig. 1; Murphy, 2013). On the West Branch North River in Colrain, the Maxam Road bridge was partially washed out about 2.4 mi upstream from the start of the study reach (fig. 1).

In response to the presidential disaster declaration for Massachusetts, Federal Emergency Management Agency (FEMA) authorized the USGS to locate and survey the elevations of high-water marks (HWMs) resulting from the August 28, 2011, flood due to tropical storm Irene on selected river reaches in the Deerfield and Hoosic River Basins of northwestern Massachusetts, including the North River from the confluence of the East and West Branch North Rivers to the Deerfield River in Colrain, Charlemont, and Shelburne. An April 2012 interagency agreement between FEMA (Region I, New England) and the USGS authorized the development of a set of flood-inundation maps that would cover a range of stages from about bankfull to the highest recorded stage at the streamgage. The mapped flood stages of 6.6 to 18.3 feet (ft) were selected to match flows from bankfull to 0.2-percent AEP to meet FEMA's criteria for being flood recovery maps, but for this reason, mapped flood stages do not generally fall at exact 1-ft increments. The flood of August 2011 corresponds to a flood with an approximate AEP of 0.2 percent; therefore, the map with an AEP of 0.2 percent is used to depict this flood.

Before this study, emergency responders in Colrain, Charlemont, and Shelburne relied on several information sources to make decisions on how to best alert the public and mitigate flood damages. One source is the FEMA flood insurance studies for these municipalities (Federal Emergency Management Agency, 1980a-c). A second source of information is the North River streamgage, from which current [2015] and historical (since 1939) river stage and discharges, including annual peak flows, can be obtained (U.S. Geological Survey, 2014a).

Although knowing the real-time stage at a USGS streamgage is useful for residents in the immediate vicinity of a streamgage, it is of limited use to residents upstream or downstream from the streamgage because the water-surface elevation of the stage is not constant along the entire stream reach. Knowledge of a stage at a streamgage is difficult to translate into depth and areal extent of flooding at points distant from the streamgage. One way to address these informational gaps is to produce a flood-inundation map library that is referenced to the stages recorded at the USGS streamgage. By referring to the appropriate map, emergency responders can discern the severity of flooding (depth of water and areal extent), identify roads that could be or may soon be flooded, and make plans for notification or evacuation of residents in danger for some distance upstream and downstream from the streamgage. In addition, the capability to visualize the potential extent of flooding has been shown to motivate residents to take precautions and heed warnings that they previously might have disregarded.

Purpose and Scope

This report describes the development of a hydraulic model for a 3.3-mi reach of the North River in Colrain, Charlemont, and Shelburne from the confluence of the East Branch North River and the West Branch North River to the confluence with the Deerfield River. This report also describes the application of flow frequency analyses to the hydraulic model and the creation of a series of flood-inundation maps for the modeled section of the river. The maps cover a range in stage from 6.6 to 18.3 ft and correspond to stages associated with the bankfull flow (Bent and Waite, 2013) and with the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP flows that were computed based on the peak-flow record of the North River streamgage. A 17.0-ft stage was also mapped to fill the 2.8-ft gap between the 0.5- and 0.2-percent AEPs. The flood inundation maps are developed for display on the USGS Flood Inundation Mapper Web site (http://wimcloud.usgs.gov/apps/FIM/FloodInundationMapper.html).

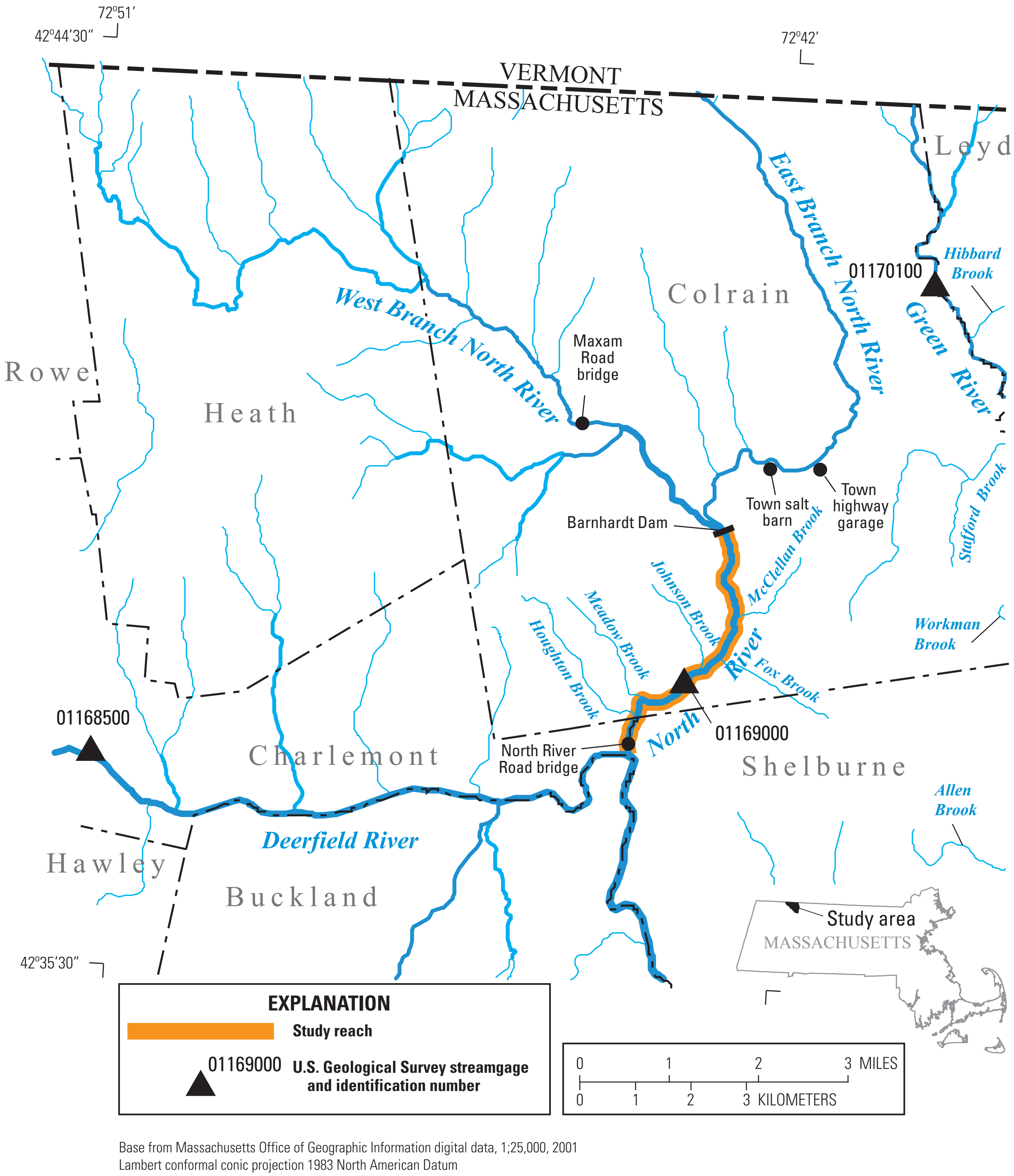
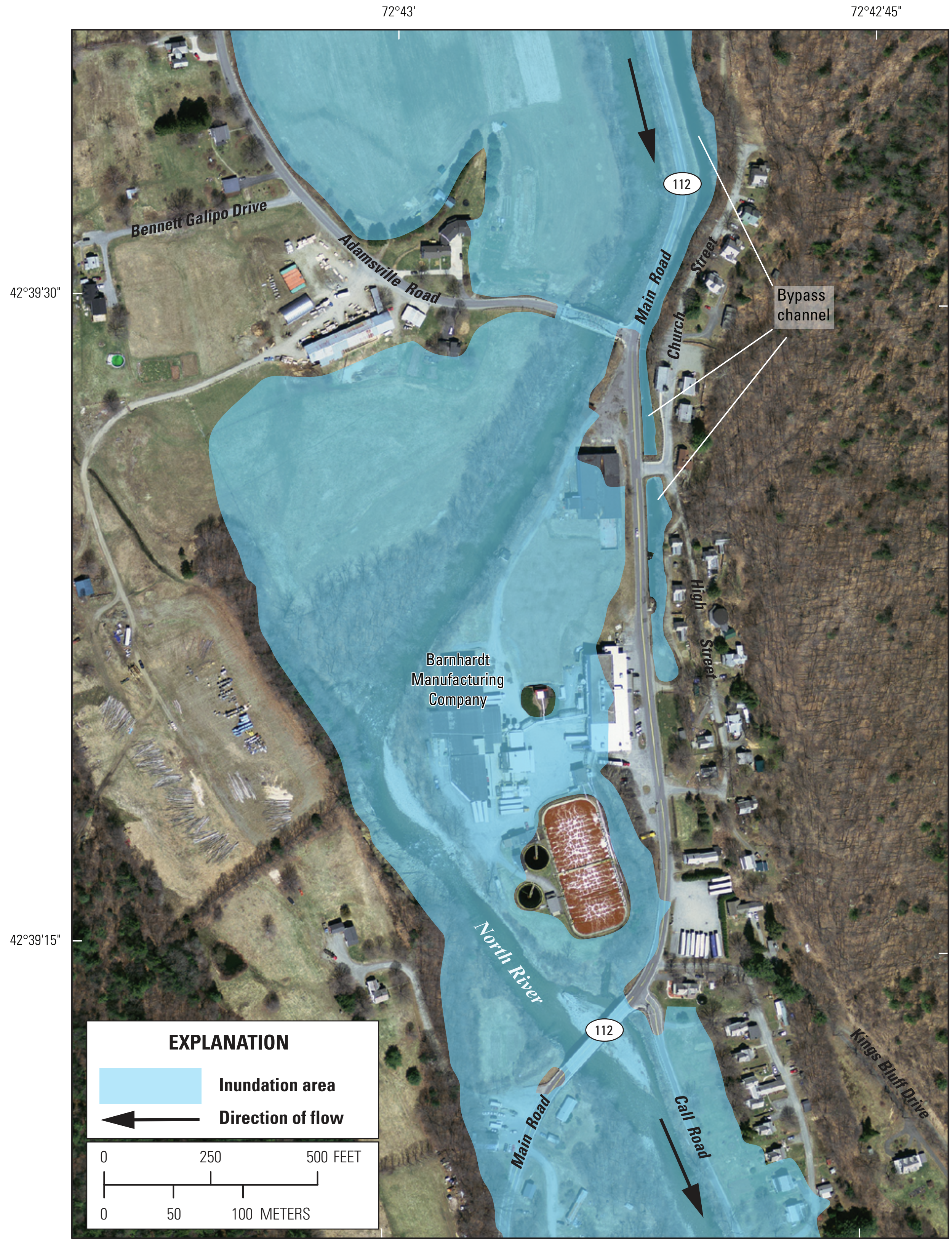


Figure 1. Location of North River study reach in Colrain, Charlemont, and Shelburne, Massachusetts, and U.S. Geological Survey streamgages.



Base from Office of Geographic Information (MassGIS) orthophotographs, 2009
Lambert conformal conic projection, North American Datum 1983

Figure 2. Flood inundation for an upstream region of the North River study reach corresponding to a stage of 18.3 feet (equivalent to the 0.2-percent annual exceedance probability discharge and approximately depicts the August 28, 2011, tropical storm Irene peak flow) at the U.S. Geological Survey North River at Shattuckville, MA (01169000) streamgage (not shown on map).

Study Area Description

The study reach of the North River is in Franklin County in northwestern Massachusetts. The land use in the study reach is mainly forested with a few farm fields and residential homes along the river. The study reach flows south from the confluence of the East Branch North River and the West Branch North River through Colrain and continues south at the town border of Charlemont and Shelburne until it reaches the confluence with the Deerfield River (fig. 1). There are several tributaries to the North River within the study reach: Fox Brook (1.27-square-mile [mi^2] drainage area), Houghton Brook (1.01-mi^2 drainage area), Johnson Brook (0.54-mi^2 drainage area), McClellan Brook (1.20-mi^2 drainage area), Meadow Brook (1.47-mi^2 drainage area), and a few unnamed tributaries. The North River streamgage (01169000) is in the village of Shattuckville in the town of Colrain and is approximately 2.1 mi from the upstream end of the reach at the confluence of the East Branch North River with the West Branch North River and 1.2 mi from the downstream end of the reach at the confluence of the North River with the Deerfield River (fig. 1). The streamgage has a drainage area of 89.0 mi^2. The study reach is traversed by four bridges and includes one low-head dam (fig. 1) and a bypass channel (fig. 2) with two bridges crossing to a mill.

Creation of Flood-Inundation Map Library

The USGS has standardized the procedures for creating flood-inundation maps for flood-prone communities so that the process followed and the resulting products are similar regardless of which USGS office is responsible for the work. Tasks specific to development of the flood maps for this study of the North River are (1) collection of topographic and bathymetric data for selected cross sections and geometric data for structures and bridges along the study reach, (2) estimation of energy-loss factors (roughness coefficients) in the stream channel and flood plain and determination of steady-flow data, (3) computation of water-surface profiles using the U.S. Army Corps of Engineers HEC–RAS computer program (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2010), (4) production of estimated flood-inundation maps at various flood stages using the U.S. Army Corps of Engineers HEC–GeoRAS computer program (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2009) and a geographic information system (GIS), and (5) preparation of the maps, both as shapefile polygons that depict the areal extent of flood inundation and as depth grids that provide the depth of floodwaters, for display on a USGS flood-inundation mapping application.

Computation of Water-Surface Profiles

The water-surface profiles used to produce the ten flood-inundation maps in this study were computed using HEC–RAS version 4.1.0 (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2010). HEC–RAS is a one-dimensional step-backwater model for simulation of water-surface profiles with steady-state (gradually varied) or unsteady-state flow computation options.

Hydrology

The study reach includes the North River streamgage which has been in operation since October 1939 (01169000; fig. 1; table 1). The North River streamgage is about 20 ft upstream from a large bedrock outcrop in the stream channel with a small concrete weir on the right side of the channel and 0.45 mi upstream of State Route 112 (Main Street) in Shattuckville a village of Colrain. The river stage is measured every 15 minutes, transmitted hourly via satellite, and is available the USGS National Water Information System (NWIS) Web site (U.S. Geological Survey, 2014a). River stage data from this streamgage are referenced to a local datum, but can be converted to water-surface elevations referenced to the North American Vertical Datum of 1988 (NAVD 88) by

Table 1. Information about the U.S. Geological Survey North River at Shattuckville, MA streamgage (01169000).

[Streamgage location is shown in figure 1. NAD 83, North American Datum of 1983; NAVD 88, North American Vertical Datum of 1988; mi^2, square mile; ft, foot; ft^3/s, cubic foot per second]

Site information	
Station name	North River at Shattuckville, MA
Station number	01169000
Drainage area	89.0 mi^2
Latitude (decimal degrees, NAD 83)	42.638418
Longitude (decimal degrees, NAD 83)	-72.725092
Period of peak-flow record, in water years[1]	1940 to present
Maximum stage (gage datum [elevation, above NAVD 88]); date	18.17 ft (476.08 ft); August 28, 2011[2]
Maximum discharge; date	30,300 ft^3/s; August 28, 2011

[1]Water year is the 12-month period starting October 1 through September 30 of the next year, designated by the calendar year in which it ends.

[2]The maximum stage of 18.17 ft was based on high-water marks collected at the streamgage.

adding 457.91 ft. Continuous records of streamflow at the streamgage are computed from a stage-discharge relation (rating curve) developed through concurrent stage and streamflow measurements since October 1939. The current [2015] rating curve is number 39.1 (U.S. Geological Survey, 2014a).

Discharges that were input into the hydraulic model corresponded to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods at the North River streamgage (table 2) and were estimated using the following methods. The estimated discharges are weighted values calculated with the USGS Weighted Independent Estimator (WIE) program (Cohn and others, 2012) that combines the at-site and regional regression estimates with the variance of these estimates. The at-site estimates for the North River streamgage, which were based on 74 years of record (water years[1] 1940–2013), were determined by the standard log-Pearson type III method described in Interagency Advisory Committee on Water Data (1982) and a modification of this method called the Expected Moments Algorithm (EMA; Cohn and others, 1997, 2001; Griffis and others, 2004). The regional regression estimates (Olson, 2014) use the drainage area (in square miles), the area of a basin covered by wetlands and open water (as a percentage), and the basin-wide mean annual precipitation (in inches) to estimate flow statistics. Peak flows at the streamgage were transferred 1.2 mi downstream from the streamgage (the study reach downstream limit) using a drainage-area ratio method that combines regression equation estimates at the new location with the weighted estimates computed at the streamgage site (table 2; Olson, 2014, equations 19 and 20).

The AEP flows and the tropical storm Irene (August 28, 2011) peak flow (30,300 ft³/s) were transferred downstream from the North River streamgage to the North River's confluence with the Deerfield River with a drainage-area ratio method (Johnstone and Cross, 1949) using the following equation:

$$Q_u = Q_g \left(\frac{DA_u}{DA_g} \right)^e \quad (1)$$

where

- Q_u is the streamflow at an ungaged location, in cubic feet per second;
- Q_g is the streamflow at a gaged location, in cubic feet per second;
- DA_u is the drainage area at an ungaged location, in square miles;
- DA_g is the drainage area at a gaged location, in square miles; and
- e is the exponent of the drainage-area-only regional regression equations (Olson, 2014) for the appropriate AEP (table 3).

The peak flow of 30,300 ft³/s is close to the 0.2-percent AEP at the North River streamgage, so an *e* value of 0.816 (table 3) from Olson's (2014, equation 27) drainage-area-only equation was used in this drainage-area ratio method. The estimated peak flows at the North River streamgage for tropical storm Irene are presented in table 4. The estimated peak flows at the North River streamgage were used for the upper study reach from the confluence of the East Branch North River and West Branch North River downstream to the streamgage. This accounted for inflows from the tributaries

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

Table 2. Peak-discharge estimates for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probabilities for the U.S. Geological Survey North River at Shattuckville, MA streamgage (01169000).

[Streamgage is shown in figure 1 and described in table 1. Calculated using the Expected Moments Algorithm (EMA), regional regression equations, and Weighted Independent Estimator (WIE) software. %, percent; ft, foot; s, second; $\log_{10}$, logarithm base 10]

Annual exceedance probability, in percent	EMA using annual peak flows for water years 1941–2013				Vermont regional regression equation[a]		WIE[b]	
	Peak flow, in ft³/s	Variance, in $\log_{10}$ units	95-percent lower confidence interval, in ft³/s	95-pecent upper confidence interval, in ft³/s	Peak flow, in ft³/s	Variance, in $\log_{10}$ units	Peak flow, in ft³/s	Variance, in $\log_{10}$ units
50	4,890	0.0009	4,280	5,640	3,160	0.0213	4,800	0.0009
20	8,120	0.0014	6,940	9,890	4,850	0.0225	7,880	0.0013
10	10,900	0.0022	9,030	14,000	6,130	0.0257	10,400	0.0020
4	15,100	0.0037	12,000	21,600	8,010	0.0304	14,100	0.0033
2	18,800	0.0052	14,500	29,300	9,610	0.0338	17,200	0.0045
1	23,200	0.0071	17,100	39,500	11,300	0.0370	20,800	0.0060
0.5	28,200	0.0095	20,000	52,700	13,200	0.0420	24,700	0.0077
0.2	36,100	0.0132	24,200	76,500	16,100	0.0487	30,700	0.0104

[a]The Vermont regional regression equation is from Olson (2014).

[b]WIE is from Cohn and others (2012).

Fox Brook, Johnson Brook, and McClellan Brook (fig. 1). Drainage-area ratio adjustments were made to the estimated peak flows for the lower study reach from the North River streamgage downstream to its confluence with the Deerfield River (table 4). These adjustments were done to account for inflows from the tributaries Houghton Brook and Meadow Brook (fig. 1). Inflows from other smaller tributaries were considered inconsequential to the computation of water-surface elevations along the study reach because of the magnitudes of the flows in the North River.

Topographic and Bathymetric Data

All topographic data used in the model are referenced vertically to the NAVD 88 and horizontally to the North American Datum of 1983 (NAD 83). Cross-section elevation data were obtained from a digital elevation model (DEM) that was derived from light detection and ranging (lidar) data that were collected during March and April 2012 by Northrop Grumman Information Systems, Advanced GEOINT Solutions Operating Unit (National Oceanic and Atmospheric Administration, 2013). The original lidar data have a vertical accuracy of 0.5 ft at a 95-percent confidence level for the bare-earth terrain land-cover category. By these criteria, the lidar data support production of 2-ft contours (Snyder and others, 2014). The final DEM was resampled to a 6.5-ft grid-cell size to decrease the GIS processing time. By using HEC–GeoRAS, a set of procedures, tools, and utilities for processing geospatial data in Esri ArcGIS, elevation data were extracted from the DEM for 57 cross sections and subsequently input into the HEC–RAS model. Because lidar data cannot provide ground elevations below the water surface of a stream, channel cross sections were surveyed by USGS field crews. A differential global positioning system (DGPS) with real-time kinematic (RTK) technology was used to derive horizontal locations and the elevation of the water surface at each surveyed cross section and hydraulic structure (bridges and dams) during August 2012 and July 2013. Fifteen measurements of the elevations at three National Geodetic Survey benchmark (permanent identification numbers MZ0232, MZ0286, and MZ1181) locations in Franklin County, Massachusetts during August 2012 and July 2013 differed from their known elevations by 0.019 to 0.200 ft. The median difference of these 15 RTK DGPS measurements from the known elevations of these 3 benchmarks was 0.085 ft.

Where possible, DEM-generated cross sections were made to coincide with the locations of the within-channel, field-surveyed cross sections. In these cases, within-channel data were directly merged with the DEM data. For all other cross sections, the within-channel data were estimated by interpolation from the closest field-surveyed cross section.

Table 3. Exponent of drainage area used to calculate flood flows for the given annual exceedance probabilities for the North River in Colrain, Charlemont, and Shelburne, Massachusetts.

Annual exceedance probability, in percent	Exponent of drainage area[a, b]
20	0.855
10	0.847
4	0.838
2	0.833
1	0.827
0.5	0.822
0.2	0.816
Flood peak flow on August 28, 2011 (tropical storm Irene)	0.816

[a]Exponent of drainage area is variable *e* used in equation 1 of this report.

[b]The exponents of drainage area are from Olson (2014).

Hydraulic Model

The hydraulic model for this study was developed using HEC–RAS version 4.1.0 (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2010). Nine structures—four bridges (Adamsville Road, State Route 112 in two locations, and North River Road), a partially breached low-head dam (Barnhardt Dam, just downstream of the confluence of the East Branch North River and West Branch North River; fig. 1), and a bypass channel (fig. 2), which begins 0.3 mi upstream of Adamsville Road for a mill 0.2 mi downstream of Adamsville

Table 4. Peak-discharge estimates at selected locations on the North River in Colrain, Charlemont, and Shelburne, Massachusetts.

[Locations shown in figure 1. mi^2, square miles; ft^3/s, cubic feet per second; %, percent; USGS, U.S. Geological Survey]

Location on North River	Drainage area, in mi^2	Estimated peak discharge, in ft^3/s, for annual exceedance probabilities								Peak flow August 28, 2011 (tropical storm Irene), flood, in ft^3/s
		50%	20%	10%	4%	2%	1%	0.5%	0.2%	
Confluence with the Deerfield River	93.0	4,980	8,170	10,800	14,600	17,800	21,500	25,600	31,800	31,400
USGS North River at Shattuckville, MA (01169000) streamgage	89.0	4,800	7,880	10,400	14,100	17,200	20,800	24,700	30,700	30,300

Road, with three bridges (State Route 112 in two locations and High Street)—have the potential to affect water-surface elevations during floods along the stream reach. Bridge-geometry and cross-section data were obtained from field surveys by the USGS in August 2012 and July 2013.

Hydraulic analyses require the estimation of energy losses that result from frictional resistance exerted by a channel on flow. These energy losses are quantified by the Manning's roughness coefficient (*n*-value). Initial (precalibration) *n*-values were selected on the basis of field observations and high-resolution aerial photographs. The upper section of the reach is primarily farm fields on the right edge of water (looking downstream) and a mill and bypass channel and residential development on the left edge of water (looking downstream). The middle section of the reach is primarily farm fields with a few residential homes and some wooded areas along the riparian corridor. The lower section is steeper than the other sections of the reach and is primarily wooded with fairly dense vegetation, as is the riparian corridor throughout the entire reach. The channel *n*-values range from 0.045 to 0.065 because the channel is sand and gravel channel with cobbles to large boulders interspersed. The overbanks of the reaches are mostly in the forested riparian corridor and farm fields and the *n*-values vary from 0.07 to 0.11 depending on the openness of the section. Bankfull top widths typically are between 100 and 200 ft wide. As part of the calibration process, the initial *n*-values were adjusted until the differences between simulated and observed water-surface elevations at the streamgage were minimized.

The HEC–RAS analysis was done using the steady-state flow computation option. Subcritical (tranquil) flow regime was assumed for the simulations. Normal depth was based on an estimated average bed slope of 0.0066 ft/ft. The HEC–RAS model was calibrated to the current [2015] stage-discharge relation (rating curve 39.1) at the North River streamgage and to documented HWMs from the tropical storm Irene in August 2011 (Bent and others, 2013). Model calibration to tropical storm Irene HMWs was accomplished by adjusting Manning's roughness coefficients (*n*-values) until the results of the hydraulic computations closely agreed with the observed water-surface elevations from the HWMs for given flows during tropical storm Irene.

Differences between surveyed and simulated water-surface elevations of HWMs in the study reach for the August 28, 2011, flood were less than 1 ft for 12 of the 19 HWMs, between 1 and 2 ft for 5 of the 19 HWMs, and greater than 2 ft for 2 of the 19 HWMs (table 5). It can be somewhat common for field crews to collect an HWM that is lower than the peak water-surface elevation of a flood because marks can be left by debris, seeds, and mud on the falling limb of the hydrograph. This is likely the case with HWM–MA–NORTH–149 or HWM–MA–NORTH–147, as both have differences greater than 2 ft between the surveyed and simulated water-surface elevations and the surveyed elevations are lower than the simulated elevations. Overall, the results demonstrate that the model is capable of simulating accurate water levels over a wide range of flows in the North River reach.

Development of Water-Surface Profiles

The calibrated hydraulic model was used to generate water-surface profiles for a total of 10 flood stages between 6.6 ft and 18.3 ft as referenced to the local datum of the North River streamgage (01169000; table 6). The 6.6-ft and 18.3-ft stages correspond to NAVD 88 elevations of 464.5 ft and 476.2 ft, respectively. The mapped stages from 6.6 to 18.3 ft were selected to match the flood stages from bankfull as identified by Bent and Waite (2013) and from the 50- to 0.2-percent AEPs floods (floods with recurrence interval from 2 to 500 years; table 6). The mapped stages do not fall at exact 1-ft increments because the flood stages match the stages associated with bankfull and the AEPs. Additionally, a map was produced for a stage of 17.0 ft to avoid a stage gap of 2.8 ft between the profiles for the 0.5- and 0.2-percent AEPs.

The National Weather Service (NWS) Advance Hydrologic Prediction Service (AHPS) defined action stage of 6.0 ft (National Weather Service, 2014) at the North River streamgage is below the bankfull stage of 6.6 ft (lowest stage mapped) and thus is not shown as a mapped flood stage. The 9.1-ft stage is approximately the NWS AHPS defined minor flood stage of 9.0 ft (National Weather Service, 2014). The NWS AHPS defined moderate and major flood stages of 11.0 ft and 13.0 ft, respectively (National Weather Service, 2014). These moderate and major flood stages are approximated by the 11.4- and 12.6-ft-stage water-surface profiles. The 18.3-ft stage is 5.3 ft higher than the NWS AHPS defined major flood stage of 13.0 ft for the streamgage (National Weather Service, 2014) and exceeds the highest recorded stage at the streamgage—the August 28, 2011, peak of 18.17 ft.

The stages corresponding to the 50- to 0.2-percent AEP discharges (table 6), which were computed by flood-frequency analyses, were obtained from the current [2015] stage-discharge relation (rating curve 39.1) for the North River streamgage. Rating curve 39.1 includes stages from 0.10 to 18.40 ft and corresponding discharges from 3.20 to 30,800 ft^3/s, respectively. Discharges were transferred upstream and downstream from the streamgage using the drainage area methods discussed in the "Hydrology" section. The model-simulated water-surface elevations for 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods are tabulated in appendix 1.

Flood-Inundation Maps

Flood-inundation maps were created in a GIS for the 10 water-surface profiles by combining the profiles and DEM data. The maps depict the flood-inundation extent (flood-plain boundaries) of the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEP floods for the North River streamgage (table 6). Two additional maps were included —one for the stage of bankfull discharge at the streamgage and another for a stage between the stages modeled from the 0.5- and 0.2-percent AEP flood discharges (17.0 ft, gage datum) to

Table 5. Calibration of hydraulic model to water-surface elevations at selected locations along the North River in Colrain, Charlemont, and Shelburne, Massachusetts, for the tropical storm Irene (August 28, 2011) flood.

[Negative values in difference in elevation column indicate that the surveyed elevation was lower than the modeled elevation. HWM, high-water mark; ID, identification number; NAVD 88, North American Vertical Datum of 1988]

River station, in feet[a]	HWM ID[b]	HWM rating[b]	Water-surface elevation, in feet above NAVD 88		Difference in elevation, in feet
			Surveyed HWM[b]	Model simulated	
17,503	HWM–MA–NORTH–151	Fair	523.30	521.42	1.88
16,886	HWM–MA–NORTH–152	Good	518.40	520.07	-1.67
16,337	HWM–MA–NORTH–149	Fair	516.05	519.07	-3.03
15,607	HWM–MA–NORTH–150	Good	513.06	511.52	1.54
14,111	HWM–MA–NORTH–147	Good	503.42	505.97	-2.55
13,472	HWM–MA–NORTH–148	Good	503.19	502.57	0.62
6,524	HWM–MA–NORTH–143	Good	477.06	476.46	0.60
6,524	HWM–MA–NORTH–145	Fair	476.34	476.24	0.10
6,524	HWM–MA–NORTH–144	Fair	475.81	476.16	-0.35
6,524	HWM–MA–NORTH–146	Good	477.09	476.05	1.04
4,853	HWM–MA–NORTH–141B	Fair	459.09	458.79	0.30
4,179	HWM–MA–NORTH–141	Fair	458.69	458.75	-0.06
4,179	HWM–MA–NORTH–141C	Fair	458.77	457.98	0.79
4,179	HWM–MA–NORTH–141A	Fair	457.49	457.95	-0.46
3,991	HWM–MA–NORTH–142	Fair	456.17	456.12	0.05
3,914	HWM–MA–NORTH–142B	Fair	455.45	454.55	0.90
3,914	HWM–MA–NORTH–142A	Fair	455.99	454.38	1.61
917	HWM–MA–NORTH–139	Good	437.81	438.40	-0.59
165	HWM–MA–NORTH–140	Good	436.69	436.55	0.14

[a]Cross-section identification numbers are referenced to the longitudinal baseline used in the hydraulic model starting at the most downstream point in the model.

[b]From Bent and others (2013).

Table 6. Stage, elevation, discharge, and annual exceedance probabilities at the U.S. Geological Survey streamgage North River at Shattuckville, MA (01169000) for profiles mapped on the North River in Colrain, Charlemont, and Shelburne, Massachusetts.

[Steamgage is shown in figure 1 and described in table 1. ft, foot; NAVD 88, North American Vertical Datum of 1988; ft^3/s, cubic feet per second; NA, not applicable]

Grid identification	Stage, in ft	Elevation, in ft above NAVD 88	Discharge, in ft^3/s	Annual exceedance probability, in percent
NorthMA_01[a]	6.6	464.5	3,070	NA
NorthMA_02	7.7	465.6	4,800	50
NorthMA_03	9.1	467.0	7,880	20
NorthMA_04	10.0	467.9	10,400	10
NorthMA_05	11.4	469.3	14,100	4
NorthMA_06	12.6	470.5	17,200	2
NorthMA_07	13.9	471.8	20,800	1
NorthMA_08	15.5	473.4	24,700	0.5
NorthMA_09	17.0	474.9	28,000	NA
NorthMA_10[b]	18.3	476.2	30,700	0.2

[a]NorthMA_01 map depicts the bankfull discharge estimate by Bent and Waite (2013).

[b]NorthMA_10 map has an annual exceedance probability of 0.2 percent and thus approximately depicts the flood of August 28, 2011 (tropical storm Irene).

eliminate a 2.8 ft gap in the map series. The water-surface elevations of the lower part of the North River study reach from about North River Road bridge (fig. 1) to the confluence with the Deerfield River (downstreammost few hundred feet of the reach) could be affected by backwater from high flood stages (water-surface elevations) on the Deerfield River. The tropical storm Irene flood of August 28, 2011, equated to an AEP of approximately 0.2 percent and thus is depicted by the map with a stage of 18.3 ft and a 0.2-percent AEP.

The DEM data were derived from the lidar data described in the “Topographic and Bathymetric Data” section and have an estimated vertical accuracy of 1 ft plus or minus (±) 1 ft. Estimated flood-inundation boundaries for each simulated profile were developed with the HEC–GeoRAS software (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2009), which allows the preparation of geometric data for import into HEC–RAS and processes simulation results exported from HEC–RAS (U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2010). Shapefile polygons and depth grids of the inundated areas for each profile were modified, as required, in the ArcMap application of ArcGIS (Esri, 2014) to ensure a hydraulically reasonable transition of the flood boundaries between modeled cross sections.

The flood-inundation areas are overlaid on high-resolution, geospatially referenced aerial photographs of the study area (fig. 2). Any inundated areas that were detached from the main channel were examined to identify subsurface connections with the main river, such as through culverts under roadways. Where such connections existed, the mapped inundated areas were retained in their respective flood maps; otherwise, the erroneously delineated parts of the flood extent were deleted. Bridge surfaces are shown as noninundated up to the lowest flood stage that either intersects the lowest structural chord of the bridge or completely inundates one or both approaches to the bridge. Where the lowest flood stage either intersects the lowest structural chord of the bridge or completely inundates one or both approaches to the bridge, the bridge surface is depicted as being inundated. A shaded building should not be interpreted to mean that the structure is completely submerged, but rather that bare-earth surfaces in the vicinity of the building are inundated and the water depth (as indicated in the mapping application by hovering the cursor over the inundated area) near the building would be an estimate of the water level inside the structure, unless flood-proofing measures had been implemented. Estimates of water depth can be obtained from the depth-grid data that are included with the presentation of the flood maps on an interactive USGS mapping application described in the “Flood-Inundation Map Delivery” section.

Flood-Inundation Map Delivery

The flood-inundation mapping science Web site (http://water.usgs.gov/osw/flood_inundation) makes USGS flood-inundation study information available to the public through a mapping application that presents map libraries and provides detailed information on flood extents and depths for modeled sites in the United States. The mapping application enables the production of customized flood-inundation maps from the map library through a print-on-demand feature that allows the user to zoom to the area of interest, choose the desired stage, and print only that part of the map (fig. 2). The flood-inundation maps are displayed in sufficient detail so that preparations for flooding and decisions for emergency response can be done efficiently. In addition to the capability of viewing and printing maps through the USGS mapping application, shapefiles depicting flood plain boundaries, cross sections, and base flood elevations for the 1-percent AEP flood are available through links presented in appendix 2. The mapping application provides a link to the USGS NWIS Web page (U.S. Geological Survey, 2014a), which presents the current (real-time) stage and streamflow data at the North River streamgage (01169000) to which the inundation maps are referenced.

Disclaimer for Flood-Inundation Maps

The flood-inundation maps should not be used for navigation, regulatory, permitting, or other legal purposes. The USGS provides these maps as-is for a quick reference, emergency planning tool, but assumes no legal liability or responsibility resulting from the use of this information.

Uncertainties and Limitations Regarding Use of Flood-Inundation Maps

Although the flood-inundation maps represent the boundaries of inundated areas with a distinct line, some uncertainty is associated with these maps. There are uncertainties associated with the hydrology, the model, the observed water surfaces, and the mapping. The flood boundaries shown were estimated on the basis of flood stages and streamflows at the North River streamgage. There are errors associated with the stage-discharge rating curves used to estimate flow at the streamgages as the rating curve is smoothed through the streamflow measurements and the concurrent stage. Uncertainty values associated with the estimated flood flows for the AEPs are listed in table 2; the uncertainty values are in the estimated variances and the 95-percent lower and upper confidence intervals for the AEPs. Estimates of flow are computed upstream and downstream from the streamgages using the estimates of flows at the streamgage and then adjusting them for the change in drainage area from the streamgage to the new location. Meteorological factors such as the timing and distribution of precipitation may cause actual streamflows along the modeled reach to vary from those assumed during a flood, which may lead to variations in the water-surface elevations and inundation boundaries shown.

Water-surface elevations along the stream reaches were estimated using steady-state hydraulic modeling, assuming unobstructed flow, and using streamflows and hydrologic conditions anticipated at the streamgage. The hydraulic model reflects the land-cover characteristics and any bridge, dam, or other hydraulic structures existing as of the surveying done in August 2012 and July 2013. The HEC–RAS model is a one-dimensional hydraulic model and, as such, cannot always capture everything that is going on during a flood. Additional areas may be flooded as a result of unanticipated conditions, such as changes in the streambed elevation or roughness, backwater into major tributaries along a main stem river, or backwater from localized debris. HEC–RAS models are more accurate when they are calibrated to flows from streamgages and to HWMs collected after flooding events. The HWMs collected in the field are from actual events and are given a rating from poor (±0.2 ft) to excellent (±0.05 ft) at the time they are collected (table 5). Ratings of the HWMs often reflect the quality of the mark itself and do not always take into account when the mark occurred during a storm, as some very clear marks can happen on the recession of a flood when the stage holds steady for a time. Thus, the models are as good as the data to which they are calibrated.

The accuracy of the floodwater extent and depth portrayed on the flood-inundation maps will vary with the accuracy of the DEM used to simulate the land surface. Thus, the mapping of the flood boundaries and the depths of the inundated areas on the maps have some uncertainty.

Summary

A series of 10 digital flood-inundation maps were developed in cooperation with the Federal Emergency Management Agency (FEMA) for the 3.3-mile reach of the North River from the confluence with of the East and West Branch North Rivers to the Deerfield River in Colrain, Charlemont, and Shelburne, Massachusetts. The maps were developed by using the U.S. Army Corps of Engineers HEC–RAS and HEC–GeoRAS programs to compute water-surface profiles and to delineate estimated flood-inundation areas and depths of flooding for selected stages. The HEC–RAS hydraulic model was calibrated to the current [2015] stage-discharge relation (rating curve 39.1) at the U.S Geological Survey (USGS) North River at Shattuckville, MA streamgage (01169000) and to the peak water-surface elevations (high-water marks) along the 3.3-mile reach from the August 28, 2011, flood (tropical storm Irene). The tropical storm Irene peak flow at the North River streamgage had approximately a 0.2-percent annual exceedance probability (AEP).

The hydraulic model was used to simulate 10 water-surface profiles for flood stages referenced to the streamgage datum and ranging from 6.6 feet (ft; 464.5 ft North American Vertical Datum of 1988), which is bankfull and is 2.4 ft lower than the National Weather Service (NWS)-defined minor flood stage (9.0 ft), to 18.3 ft (476.2 ft North American Vertical Datum of 1988), which exceeds the maximum recorded stage (18.17 ft, August 28, 2011, tropical storm Irene) and the NWS major flood stage (13.0 ft). Modeled water-surface profiles correspond to floods with 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs and to the August 28, 2011, flood, making them consistent with FEMA flood recovery maps as well. Two additional modeled water-surface profiles are included that correspond to the stage at bankfull discharge and a stage of 17.0 ft to avoid a stage gap of 2.8 ft between the 0.5- and 0.2-percent AEP profiles.

Water-surface profiles were combined with a geographic information system (GIS) digital elevation model derived from light detection and ranging (lidar) data to delineate estimated flood-inundation areas as shapefile polygons and depth grids for each profile. These flood-inundation polygons were overlaid on high-resolution, geospatially referenced aerial photographs of the study area. The flood maps are available through a mapping application that can be accessed on the USGS flood-inundation mapping science Web site (http://water.usgs.gov/osw/flood_inundation) and as a part of this report. Interactive use of the maps on the USGS mapping application can give users a general indication of water depth at any point by using the mouse cursor to click within the shaded areas. These maps, in conjunction with the real-time stage data for the North River at Shattuckville, MA streamgage (01169000) from the National Water Information System (U.S. Geological Survey, 2014a), will help guide the general public in taking individual safety precautions and will provide emergency management personnel with a tool to efficiently manage emergency flood operations and postflood recovery efforts. The flood-inundation maps are nonregulatory, but provide Federal, State, and local agencies and the public with estimates of the potential extent of flooding during selected peak-flow events.

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Appendixes

Appendix 1. Simulated Water-Surface Elevations at Modeled Cross Sections Along the North River, Colrain, Charlemont, and Shelburne, Massachusetts

Appendix 2. Shapefiles of Flood Inundation Areas for the 1- and 0.2-Percent Annual Exceedance Probability Flows Along the North River Study Reach in Colrain, Charlemont, and Shelburne, Massachusetts

[The files are available at http://dx.doi.org/10.3133/sir20155108].

Appendix 1. Simulated Water-Surface Elevations at Modeled Cross Sections Along the North River, Colrain, Charlemont, and Shelburne, Massachusetts

Table 1–1. Simulated water-surface elevations for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability (AEP) floods; the August 28, 2011, flood; and the 1-percent AEP floodway at each modeled cross section along the North River, Colrain, Charlemont, and Shelburne, Massachusetts.

[Cross-section identification numbers (IDs) are referenced to the longitudinal baseline used in the hydraulic model starting at the most downstream point in the model. Floodway is the channel of a river and the adjacent flood plain that must be kept free of encroachment so that the base flood (1-percent AEP flood) can be conveyed without increasing the water-surface elevation more than 1 foot (ft). %, percent]

Cross-section ID, in ft	AEP, in ft								1% AEP floodway, in ft
	50%	20%	10%	4%	2%	1%	0.5%	0.2%	
17,503.46	514.26	515.93	516.98	518.13	518.91	519.79	520.50	521.80	520.68
17,281.63	513.01	514.70	515.60	516.54	517.00	517.73	518.84	521.04	519.37
17,212.37	508.89	511.26	512.94	515.03	516.46	517.73	518.84	521.04	519.33
17,053.77	507.69	510.27	511.99	514.05	515.41	516.69	517.93	520.54	518.41
16,886.21	506.89	509.69	511.42	513.36	514.63	515.96	517.30	520.26	517.45
16,589.55	506.25	509.00	510.60	512.28	513.32	514.36	515.47	519.91	515.74
16,337.08	505.39	508.09	509.66	511.26	512.33	513.66	515.20	519.84	514.64
15,760.13	503.60	506.08	507.55	508.96	510.21	512.01	513.79	519.04	513.17
15,675.33	503.46	505.96	507.46	508.84	509.95	511.17	512.34	518.86	512.62
15,607.69	503.17	505.65	507.07	508.21	509.10	509.99	510.54	511.54	511.47
15,544.51	502.94	505.40	506.81	507.90	508.81	509.76	510.34	511.54	510.91
15,252.88	500.96	503.03	504.30	505.95	507.21	508.52	509.23	510.98	509.12
14,623.82	498.18	500.32	501.80	503.54	504.71	505.90	507.13	508.90	506.76
14,110.51	495.28	497.53	499.08	500.86	501.90	502.99	504.13	506.07	504.30
13,687.58	494.87	497.27	498.89	500.72	501.76	502.84	503.99	505.94	503.93
13,627.51	494.62	496.95	498.52	500.23	501.14	501.84	502.77	504.67	503.26
13,559.86	494.24	496.56	498.10	499.73	500.50	501.36	502.16	503.39	502.48
13,472.47	493.77	496.14	497.68	499.35	500.13	501.00	501.87	503.12	502.00
12,975.73	492.34	494.60	496.07	497.87	498.21	499.14	500.07	501.37	500.00
12,373.40	489.41	491.27	492.27	493.37	494.58	495.57	496.46	497.68	496.43
11,993.03	488.56	490.39	491.38	492.64	493.54	494.46	495.37	496.63	495.35
11,569.11	487.70	489.56	490.69	491.97	492.86	493.78	494.66	495.88	494.74
10,970.42	485.62	487.72	488.89	489.90	490.62	491.35	492.04	493.00	492.75
10,362.70	483.59	485.74	486.68	488.00	488.78	489.50	490.17	491.19	490.20
9,876.16	481.75	483.40	484.62	485.50	486.12	486.80	487.64	489.19	488.14
9,356.34	480.51	482.31	483.54	484.49	484.96	485.77	486.87	488.73	486.95
8,819.52	478.29	479.70	480.62	481.30	482.67	484.18	485.72	487.91	485.44
8,303.16	475.32	477.41	478.62	480.51	481.99	483.60	485.23	487.50	484.99
7,564.80	473.06	475.41	477.01	479.08	480.65	482.32	483.98	486.25	483.81
7,146.85	471.45	473.66	475.14	477.01	478.44	479.94	481.40	483.32	481.05
6,524.03	466.31	468.69	470.13	471.79	472.71	473.46	474.53	476.34	475.01
6,161.91	459.81	461.47	462.81	464.75	466.46	468.40	470.39	473.35	469.62
5,768.36	454.96	457.76	459.76	462.29	464.25	466.42	468.69	472.00	467.86
5,647.21	453.96	456.25	457.83	459.68	461.03	462.43	463.85	466.00	464.05

Table 1–1. Simulated water-surface elevations for the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probability (AEP) floods; the August 28, 2011, flood; and the 1-percent AEP floodway at each modeled cross section along the North River, Colrain, Charlemont, and Shelburne, Massachusetts.—Continued

[Cross-section identification numbers (IDs) are referenced to the longitudinal baseline used in the hydraulic model starting at the most downstream point in the model. Floodway is the channel of a river and the adjacent flood plain that must be kept free of encroachment so that the base flood (1-percent AEP flood) can be conveyed without increasing the water-surface elevation more than 1 foot (ft). %, percent]

Cross-section ID, in ft	AEP, in ft								1% AEP floodway, in ft
	50%	20%	10%	4%	4%	1%	0.5%	0.2%	
5,593.58	453.69	455.89	457.39	459.14	460.40	461.69	462.97	464.67	463.37
5,533.53	453.33	455.55	457.11	458.99	460.41	461.93	463.51	465.72	463.54
5,162.16	451.50	453.79	455.40	457.40	458.94	460.61	462.36	464.78	461.85
4,853.22	448.44	450.63	452.07	453.75	455.01	456.37	457.80	459.81	458.19
4,179.92	444.90	447.13	448.71	450.77	452.36	454.07	455.86	458.33	455.36
4,080.40	444.26	446.53	448.11	450.09	451.61	453.23	454.90	457.19	454.85
3,991.24	443.86	446.14	447.70	449.66	451.17	452.80	454.48	456.80	454.45
3,913.91	442.71	444.92	446.39	448.16	449.49	450.91	452.40	454.42	452.72
3,420.57	440.04	442.34	443.86	445.75	447.21	448.80	450.49	452.73	450.02
2,712.46	434.65	436.44	437.69	439.12	440.13	441.18	442.22	444.05	441.73
2,109.54	429.99	431.84	433.11	434.79	436.11	437.58	439.09	441.21	438.34
1,646.05	427.16	429.00	430.33	432.10	433.51	435.12	436.73	438.99	436.13
916.80	422.40	424.61	426.22	428.32	429.94	431.69	433.53	436.16	432.82
354.45	420.03	422.53	424.30	426.57	428.29	430.16	432.09	434.81	431.39
266.97	418.96	421.32	422.98	425.07	426.67	428.42	430.23	432.88	429.67
210.33	418.54	420.95	422.66	424.84	426.53	428.38	430.26	432.91	429.67
165.54	417.36	419.44	420.89	422.73	424.11	425.57	427.05	429.09	427.17
0.00	416.25	418.32	419.77	421.60	422.97	424.43	425.92	427.97	425.97

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