

Prepared in cooperation with the U.S. Army Corps of Engineers

# **Analysis of Floods, Including the Tropical Storm Irene Inundation, of the Ottauquechee River in Woodstock, Bridgewater, and Killington and of Reservoir Brook in Bridgewater and Plymouth, Vermont**



Scientific Investigations Report 2014–5214

**Cover photo.** Photograph showing damage caused by tropical storm Irene (August 28–29, 2011) was taken looking west on U.S. Route 4 at a location just west of Bridgewater Corners in Bridgewater, Vermont. Photograph by Pete Fellows, Two Rivers-Ottawaquechee Regional Commission, used with permission.

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By Robert H. Flynn

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

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

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

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## Conversion Factors

Inch/Pound to International System of Units

<b>Multiply</b>	<b>By</b>	<b>To obtain</b>
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi <sup>2</sup> )	2.590	square kilometer (km <sup>2</sup> )
	Flow rate	
cubic foot per second (ft <sup>3</sup> /s)	0.02832	cubic meter per second (m <sup>3</sup> /s)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

## Datum

Vertical coordinate information is referenced to either stage (the height above an arbitrary datum established at a streamgage) or 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
DEM	digital elevation model
lidar	light detection and ranging
FIS	flood insurance study
GIS	geographic information system
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WY	water year



# Analysis of Floods, Including the Tropical Storm Irene Inundation, of the Ottauquechee River in Woodstock, Bridgewater, and Killington and of Reservoir Brook in Bridgewater and Plymouth, Vermont

By Robert H. Flynn

## Abstract

Digital flood-inundation maps were created by the U.S. Geological Survey (USGS) in cooperation with the U.S. Army Corps of Engineers, New York District for a 25-mile reach of the Ottauquechee River and a 2-mile reach of Reservoir Brook in Vermont. The reach of the Ottauquechee River that was studied extends from River Road Bridge in Killington, Vt., to the Taftsville Dam in the village of Taftsville, in the town of Woodstock, Vt., and the reach of Reservoir Brook extends from a location downstream from the Woodward Reservoir in Plymouth, Vt., to its confluence with the Ottauquechee River in Bridgewater, Vt. The inundation maps depict estimates of the areal extent of flooding corresponding to the 1-percent annual exceedance probability (AEP) flood (also referred to as the 100-year flood) and the peak of the tropical storm Irene flood of August 28, 2011, which was greater than the 0.2-percent AEP flood (also referred to as the 500-year flood), as referenced to the USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900).

In addition to the two digital flood inundation maps, flood profiles were created that depict the study reach flood elevation of tropical storm Irene of August 2011 and the 10-, 2-, 1-, and 0.2-percent AEP floods, also known as the 10-, 50-, 100-, and 500-year floods, respectively. The 10-, 2-, 1-, and 0.2-percent AEP flood discharges were determined using annual peak flow data from the USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900). Flood profiles were computed for the Ottauquechee River and Reservoir Brook by means of a one-dimensional step-backwater model. The model was calibrated using documented high-water marks of the peak of the tropical storm Irene flood of August 2011 as well as stage discharge data as determined for USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900). The simulated water-surface profiles were combined with a digital elevation model within a geographic information system to delineate the areas flooded during tropical storm Irene and for the 1-percent AEP

water-surface profile. The digital elevation model data were derived from light detection and ranging (lidar) data obtained for a 3,281-foot (1,000-meter) corridor along the Ottauquechee River study reach and were augmented with 33-foot (10-meter) contour interval data in the modeled flood-inundation areas outside the lidar corridor. The 33-foot (10-meter) contour interval USGS 15-minute quadrangle topographic digital raster graphics map used to augment lidar data was produced at a scale of 1:24,000. The digital flood inundation maps and flood profiles along with information regarding current stage from USGS streamgages on the Internet provide emergency management personnel and residents with information that is critical for flood response activities, such as evacuations and road closures, as well as for post-flood recovery efforts.

## Introduction

On August 28 and 29, 2011, tropical storm Irene passed through Vermont with heavy rain and high winds. Rainfall totals of 3.2 to 8.15 inches were recorded across the State with Woodstock, Vt., receiving more than 7 inches of precipitation (Dupigny-Giroux and Hogan, 2011), particularly in the higher eastern slope areas of the Green Mountains. Flood levels along the Ottauquechee River eclipsed those of the historic flood of 1927, which for 83 years had been the benchmark of Vermont floods. The flood of 1927 had an estimated peak of 30,400 cubic feet per second (ft<sup>3</sup>/s) and the tropical storm Irene flood of August 2011 had an estimated (unregulated) peak flow of 38,200 at the USGS Ottauquechee River at North Hartland, Vt. streamgage (station 01151500). The USGS North Hartland streamgage was not active until October 1930 and is located downstream from the North Hartland dam. The peak flows of 1927 and 2011 were estimated. A discharge of 37,900 ft<sup>3</sup>/s is the estimated inflow for the reservoir at the North Hartland Dam (U.S. Army Corps of Engineers, 2013) for the August 2011 event.

## 2 Analysis of Floods at the Ottauquechee River and Reservoir Brook in Vermont

The towns of Woodstock, Bridgewater, Killington, and Plymouth, Vt., are rural communities with estimated populations of 3,047; 936; 806; and 619, respectively, in 2011 (Vermont Department of Health, 2013). The towns of Woodstock, Bridgewater, and Plymouth are in Windsor County (fig. 1). Woodstock is the county seat of Windsor County and includes the villages of Woodstock, South Woodstock, and Taftsville. Bridgewater contains the hamlets of Bridgewater Village, Bridgewater Corners, West Bridgewater, and Bridgewater Center. The town of Killington is in Rutland County and is the location of the headwaters of the Ottauquechee River.

Flood plains along the study reach of the Ottauquechee River are generally moderately developed with the exception of those within the Woodstock Village, which are moderately to highly developed, and contain a mix of residential and commercial structures. Periodic flooding occurs in low-lying areas along the Ottauquechee River with some of the most severe flooding occurring in early spring as a result of snowmelt and heavy rains in conjunction with ice jams (Federal Emergency Management Agency, (2002). Floods of large magnitude occurred along the Ottauquechee River in 1869, 1896, 1927, 1936, 1938, 1952, 1973, and 2011.

This study, done in cooperation with the U.S. Army Corps of Engineers, New York District includes two flood inundation maps and five flood profiles. In addition to these data, Vermont officials can rely on several information sources to make decisions on how to best alert the public and mitigate flood damages along the Ottauquechee River. One source is the Federal Emergency Management Agency flood insurance study (FIS) for Woodstock and Bridgewater (Federal Emergency Management Agency, 2007). A second source of information is the USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900), from which current or historical water levels (stage) can be obtained. A third source is the National Weather Service's graph of current stage at USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) available through the Advanced Hydrologic Prediction Service site (National Weather Service, 2013a).

### Purpose and Scope

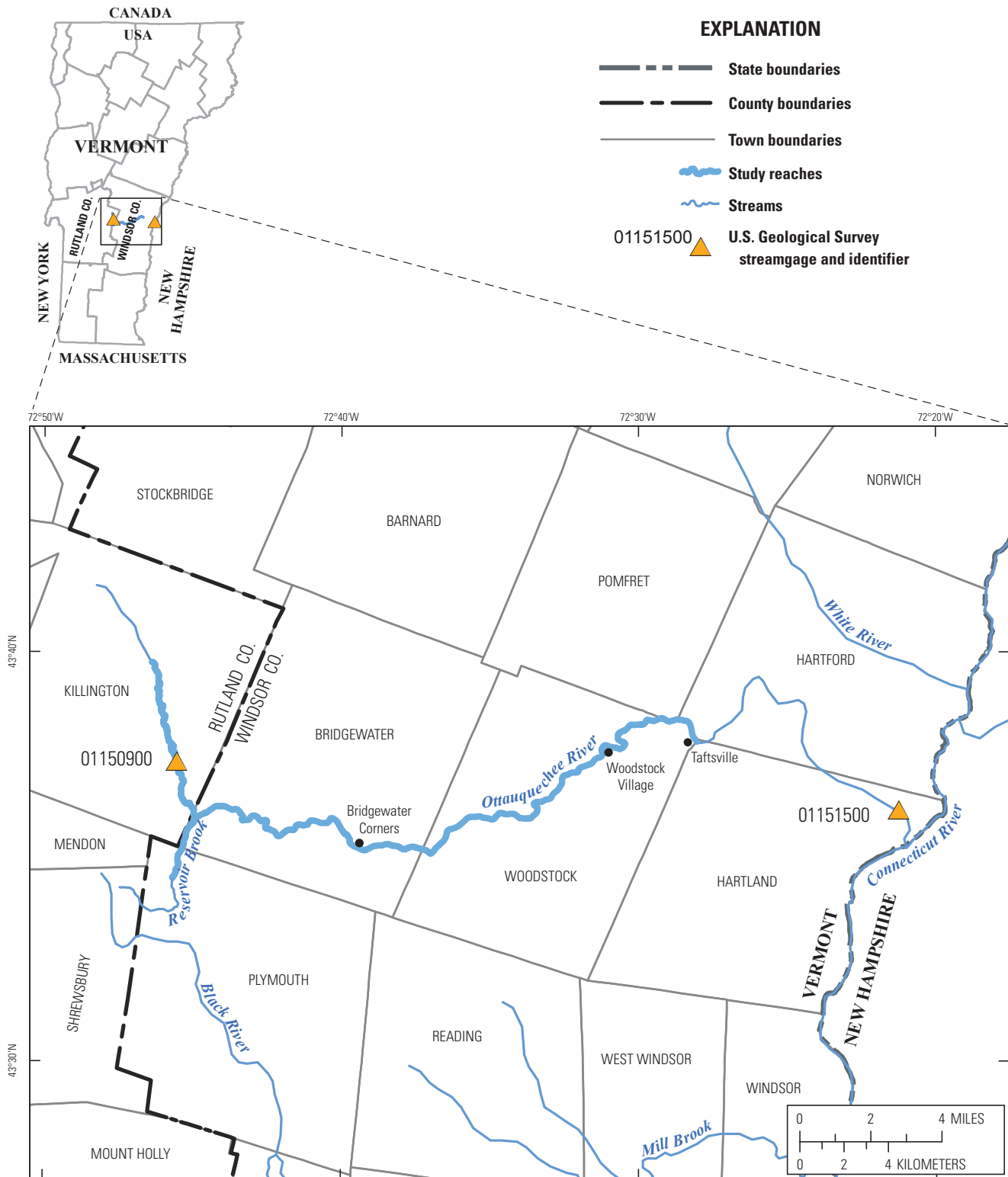
This report describes the development of (1) two digital maps of the estimated flood-inundation area of the 1-percent annual exceedance probability (AEP) flood (also referred to as the 100-year flood) and the peak of the tropical storm Irene flood that occurred August 28–29, 2011, and (2) five flood profiles of the estimated flood elevation for the 10-, 2-, 1-, and 0.2-percent AEP discharges and flood of tropical storm Irene for the Ottauquechee River in Woodstock, Bridgewater, and Killington, Vt., and Reservoir Brook in Bridgewater and Plymouth, Vt.

The scope of the study was limited to a 25-mile (mi) reach of the Ottauquechee River from River Road bridge in Killington, Vt., to the Taftsville Dam in the village of Taftsville, located in Woodstock, Vt., and a 2-mi reach of Reservoir Brook from a point downstream from Woodward Reservoir in Plymouth to its confluence with the Ottauquechee River in Bridgewater (fig. 1). Tasks specific to the development of the flood maps and profiles were (1) analysis of annual peak flow data from the two USGS streamgages on the Ottauquechee River—Ottauquechee River near West Bridgewater, Vt., (station 01150900) and Ottauquechee River at North Hartland, Vt. (station 01151500; table 1), (2) collection of topographic data and geometric data (for structures and bridges) throughout the study reaches, (3) determination of energy-loss factors in the stream channel and flood plain and compilation of steady-flow data, (4) calibration of flood model to the August 2011 flood of tropical storm Irene using high-water-mark data (Medalie and Olson, 2013) (5) computation of water-surface profiles for the 10-, 2-, 1-, and 0.2-percent AEP discharges and the 2011 flood of tropical storm Irene by use of the U.S. Army Corps of Engineers (USACE) HEC–RAS computer program (U.S. Army Corps of Engineers, 2010), (6) production of estimated flood-inundation maps for the 1-percent AEP flood and the peak of the flood resulting from tropical storm Irene using the USACE HEC–GeoRas computer program (U.S. Army Corps of Engineers, 2009) and a geographic information system (GIS), and (7) creation of a USGS report and digital map with inundation layers (this report).

Methods used are generally cited from previously published reports. If techniques varied significantly from previously documented methods because of local hydrologic conditions or availability of data, they are described in detail in this report. Digital flood inundation maps were produced for the 1-percent AEP flood and the August 2011 flood caused by tropical storm Irene.

### Description of Study Area

The Ottauquechee River and Reservoir Brook are in east-central Vermont in the Vermont Piedmont physiographic province and the Vermont Piedmont and the Green Mountains/Berkshire Highlands ecoregions (U.S. Environmental Protection Agency, 2010). The drainage area for the Ottauquechee River study reach ranges from 192 square miles (mi<sup>2</sup>) at the corporate limit between Woodstock and Hartland, Vt., to 20.1 mi<sup>2</sup> at the upstream extent of the Ottauquechee River study reach at the River Road bridge in Killington. The drainage area for the 2-mi Reservoir Brook study reach is 7.6 mi<sup>2</sup> at the confluence with the Ottauquechee River. The Ottauquechee River study reach has 23 major road crossings or other structures that lie within the channel or the adjacent flood plain. The Reservoir Brook study reach has 4 major road crossings that lie within the channel or the adjacent flood plain.



**Figure 1.** Location of study reaches of the Ottauquechee River and Reservoir Brook, Vermont, and location of U.S. Geological Survey streamgages 01150900 and 01151500 on the Ottauquechee River.

## 4 Analysis of Floods at the Ottauquechee River and Reservoir Brook in Vermont

**Table 1.** Site information for U.S. Geological Survey streamgages at the Ottauquechee River and Reservoir Brook, Vermont.

[mi<sup>2</sup>, square miles; ft, feet; USGS, U.S. Geological Survey; WY, water year]

USGS streamgage name	Stream-gage number	Drainage area, in mi <sup>2</sup>	Latitude	Longitude	Period of record	Maximum recorded stage at streamgage, in ft, and date
Ottauquechee River near West Bridgewater, Vt.	01150900	23.4	43°37'20"	72°45'34"	October 1984 to July 2010, October 2011 to current year, and estimated peak of WYs 1928 and 2011	14.95, August 28, 2011
Ottauquechee River at North Hartland, Vt.	01151500	221	43°36'09"	72°21'17"	October 1930 to March 1961 and estimated peak of WYs 1928, 1973, 1987, 2011 (flow regulated since March 1961)	21.50, November 1927

The headwaters of the Ottauquechee River originate in the Green Mountains in the Town of Killington, approximately 11 mi northwest of the Bridgewater-Woodstock corporate limit, and the river flows generally eastward to its confluence with the Connecticut River at North Hartland. Reservoir Brook is one of the major tributaries to the Ottauquechee River and joins the main stem as it flows through Bridgewater, Vt. The basin terrain for both study reaches is generally steep. The Ottauquechee River study reach is approximately 25 mi long and has an average channel slope of 23.3 feet per mile (ft/mi). The Reservoir Brook study reach is approximately 2 mi long and has an average channel slope of 151 ft/mi. Although the basin is still under development, during 2000–11, the population of Woodstock, Bridgewater, and Killington decreased by 5.7 percent from 3,216 to 3,047, by 4.5 percent from 971 to 936, and by 26.4 percent from 988 to 806, respectively (Vermont Department of Health, 2013). Although the three towns along the Ottauquechee River study reach had a decrease in population, along the upstream half of the study reach of Reservoir Brook, the population of Plymouth, Vt., increased by 11.5 percent from 583 to 619 during 2000–11. The downstream half of the study reach of Reservoir Brook is in Killington and Bridgewater.

### Previous Studies

The current FIS for the town and village of Woodstock (Federal Emergency Management Agency, 2007) was completed by the USGS in 2000. The current FIS for Bridgewater (Federal Emergency Management Agency, 2007) was completed by Dufresne-Henry Engineering Corporation for the Federal Insurance Administration in 1980 (Federal Emergency Management Agency, 2007). These studies provide information on the 1.0- and 0.2-percent AEP water-surface profiles and associated flood-plain maps for the Ottauquechee River. There were no previous studies for Ottauquechee River in Killington or for Reservoir Brook in Bridgewater and Plymouth, Vt.

## Constructing Water-Surface Profiles

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

### Hydrologic and Steady-Flow Data

Estimates of the peak discharges for the 1.0-percent AEP flood profile along Ottauquechee River and Reservoir Brook, as listed in table 2 for the study reach, are described in this report. For tropical storm Irene, USACE estimated a discharge of 37,900 ft<sup>3</sup>/s at the North Hartland Dam (U.S. Army Corps of Engineers, 2013) downstream from the study area. The discharge estimate of 38,200 ft<sup>3</sup>/s at the USGS Ottauquechee River at North Hartland, Vt. streamgage (station 01151500) was based on a drainage-area relation with the North Hartland Dam and represents the unregulated discharge that would have occurred as a result of tropical storm Irene without the regulation of North Hartland Dam upstream from the USGS Ottauquechee River at North Hartland, Vt. streamgage (station 01151500).

### Flood-Flow Frequency

The study-area hydrologic network consists of two streamgages on the Ottauquechee River (fig. 1; table 1), USGS Ottauquechee River at North Hartland, Vt. (station 01151500) downstream from the study reach and USGS Ottauquechee River near West Bridgewater, Vt. (station 01150900). The USGS Ottauquechee River at North Hartland, Vt. streamgage (station 01151500) is downstream from the North Hartland



**Table 2.** Discharge estimates for selected locations on the Ottauquechee River and Reservoir Brook, Vermont, in 2013.

[AEP, annual exceedance probability; mi<sup>2</sup>, square miles; %, percent; ft<sup>3</sup>/s, cubic feet per second; USGS, U.S. Geological Survey; VT, Vermont; \*, unregulated flow estimate]

Location on Ottauquechee River	Drainage area, in mi <sup>2</sup>	1% AEP discharge estimate, in ft <sup>3</sup> /s	Tropical storm Irene discharge estimate, in ft <sup>3</sup> /s	Percentage of total 1% AEP discharge
Streamgage 01151500, Ottauquechee River at North Hartland, Vt.				
Downstream of dam	223	*43,400	*38,200 <sup>a</sup>	100
Town line (Woodstock/Hartland)	192	37,600	34,800	87
Below confluence with Barnard Brook	183	35,900	33,700	83
Town line (downstream corporate limit Woodstock Village)	145	28,700	29,100	66
Downstream of confluence with Kedron Brook	143	28,300	28,800	65
Town line (corporate limit of Woodstock Village)	127	25,300	26,700	58
Downstream of confluence with Cox Reservoir Brook	126	25,100	26,600	58
Upstream of confluence with Cox Reservoir Brook	123	24,500	26,200	56
Downstream of confluence with Beaver Brook	119	23,800	25,600	55
Downstream of confluence with Curtis Hollow Brook	108	21,600	24,100	50
At Bridgewater/Woodstock corporate limit	103	20,700	23,400	48
Downstream of confluence with Broad Brook	100	20,000	22,900	46
Downstream of confluence with North Branch	72	14,700	18,600	34
Downstream of confluence with Reservoir Brook	36	7,530	12,000	17
Upstream of confluence with Reservoir Brook	29	6,020	10,300	14
Downstream of confluence with Falls Brook	28	5,860	10,100	13
Downstream of confluence of Brook to north of Spruce Knoll	24	5,160	9,320	12
Streamgage 01150900, Ottauquechee River near West Bridgewater, Vt.				
At streamgage	23	4,960	9,070	11
Downstream of confluence with Brimstone Brook	20	4,300	8,260	10
Confluence with Ottauquechee River	7.6	1,510	1,650	100
Downstream of confluence with Madden Brook	6.3	625	1,480	41
Upstream of confluence with Madden Brook	4.1	390	1,130	26

<sup>a</sup>USGS flow estimate was 4,430 ft<sup>3</sup>/s at streamgage 01150900 due to regulation of flow at the dam in Hartland, Vermont. Estimates downstream of the dam and shown in the table are for unregulated flow.

dam and flood control reservoir (an impoundment). Flow at this site has been regulated since 1960. Unregulated peak flow estimates at the North Hartland dam were determined by the USACE and were incorporated into the analysis for this streamgage. The analysis of the peak streamflow data for USGS Ottauquechee River at North Hartland, Vt. streamgage (station 01151500) included water years<sup>1</sup> (WYs) 1928, 1931–60, 1973, 1987, and 2011 and for USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900), WYs 1928, and 1985–2011. Water levels (stage) were measured continuously, and continuous records of streamflow were computed, at both of the sites. All water-surface elevations are referenced to the North American Vertical Datum of

1988 (NAVD 88). The streamgages are equipped with satellite radio transmitters that allow data to be transmitted routinely on the Internet within 1 hour of collection. In addition, some discrete discharge measurements were made at the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) for which streamflow records were unavailable from August 2010 to October 2011. These measurements were made during periods of moderate to high flow and were used for model calibration. Indirect flow measurements (Matthai, 1967) were made at the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) to aid in determining peak flow for the August 2011 tropical storm Irene flood. Longitudinal water-surface profiles from high-water marks along the main channel were documented following the tropical storm Irene flood in August of 2011 and were used for model calibration (Medalie and Olson, 2013).

<sup>1</sup>A water year starts on October 1 and end on September 30 and is designated by the year in which it ends.

## 6 Analysis of Floods at the Ottauquechee River and Reservoir Brook in Vermont

The USACE owns and operates the flood control dam that reduces flood discharges in and downstream from the town of Hartland. The drainage area upstream from the North Hartland Dam is 220 mi<sup>2</sup>. The upstream reservoir at the North Hartland Dam can store 6 inches of runoff (Federal Emergency Management Agency, 2002) and substantially reduces flood discharges downstream from the dam on the Ottauquechee River and downstream on the Connecticut River. For example, the August 2011 tropical storm Irene flood-peak discharge for the dam was limited to 4,430 ft<sup>3</sup>/s (U.S. Geological Survey, 2014), whereas the USACE estimated that without regulation due to the dam and impoundment a discharge of 37,900 ft<sup>3</sup>/s would have occurred at the location of the dam (U.S. Army Corps of Engineers, 2013).

Steady-flow data consisted of flow regime, boundary conditions (known stage associated with a discharge measurement, critical depth, or normal depth), and peak-discharge information from the two Ottauquechee streamgages. At the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900), model calibration was based on discharge values with known stages along with high-water-mark data collected after tropical storm Irene (Medalie and Olson, 2013). Normal depth boundary condition was used for determination of the Ottauquechee River model starting water surfaces, based on the average stream slope downstream from the Taftsville dam. For Reservoir Brook study reach, normal depth boundary conditions were assumed by using a friction slope estimated from the average streambed slope through the reach.

The 10-, 2-, 1-, and 0.2-percent AEP discharges upstream from North Hartland Dam were determined on the basis of a log-Pearson type III analysis, as described in U.S. Interagency Advisory Committee on Water Data (1982), with the moments based approach of the expected moments algorithm (Cohn and others, 2001) to determine peak discharges at the Ottauquechee River at North Hartland, Vt. streamgage (station 01151500) downstream from the North Hartland Dam. Bulletin 17B provides procedures for weighting station skews, for determining historical peaks, and for detecting and treating outliers and trends. The Grubbs-Beck test was used to identify data outliers (Cohn and others, 2013). Peak discharge data, as recorded at the streamgage prior to dam construction and regulation, were used in the analyses (WYs 1928 and 1931–60), along with estimates of unregulated peak discharge as determined by USACE for 1973, 1987, and 2011. The peak discharge for the Ottauquechee River flood at the North Hartland Dam as a result of tropical storm Irene of August 2011 was determined by the USACE.

The 10-, 2-, 1- and 0.2-percent AEP discharges at the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) were determined on the basis of an expected moments algorithm analysis of peak discharges at that streamgage (WYs 1928 and 1985–2011). The 10-, 2-, 1- and 0.2-percent AEP discharges and tropical storm Irene Flood peak were determined at locations on the Ottauquechee River between the two USGS streamgages by use of a drainage-area

relation applied to the log-Pearson type III peak-flow frequency curve at the streamgages

$$\frac{Q}{Q_g} = \left( \frac{A}{A_g} \right)^n, \quad (1)$$

where

- $Q$  is the flow at the ungaged site,
- $Q_g$  is the flow at the USGS streamgage,
- $A$  is the drainage area at the ungaged site,
- $A_g$  is the drainage area at the USGS streamgage,
- and
- $n$  is the drainage-area adjustment value.

The values of the exponent  $n$  ranges from 0.95 to 0.96 for the AEP discharges and is 0.64 for the tropical storm Irene flood peak estimates, determined using the AEP discharge values, drainage areas, and indirectly determined peak flows of tropical storm Irene at the Ottauquechee River streamgages.

The 10-, 2-, 1- and 0.2-percent AEP discharges were determined for Reservoir Brook using the Vermont Peak flow equations (Olson, 2002) within StreamStats (U.S. Geological Survey, 2012a). The Reservoir Brook peak discharge value for tropical storm Irene at the confluence with Ottauquechee River was determined on the basis of the values determined from the drainage-area relation along the Ottauquechee River upstream and downstream from the confluence with Reservoir Brook. The Reservoir Brook August 2011 tropical storm Irene peak discharge values at locations upstream from its confluence with the Ottauquechee River were determined using a drainage-area relation.

### Topographic and Bathymetric Data

Where applicable, data from the current Ottauquechee River FIS study (2007) were used to augment the flow model. Cross sections were spot checked with surveyed field data. All roadway crossings were verified by field survey, and structures that were added or modified since the last FIS were surveyed or resurveyed, respectively, as needed for inclusion in the model. Overbank and channel cross sections were developed from lidar (Fugro Earthdata, Inc., 2012), 10-meter (m) digital raster graphics (U.S. Geological Survey, 1998), and USGS field surveys that were conducted in the summer and fall of 2013. These cross sections provide detailed ground-elevation data and channel-elevation data below the water surface. Elevation data were collected by using standard surveying techniques to measure depth relative to an established benchmark or reference mark and Differential Global Positioning System instrumentation to determine horizontal and vertical position. Lidar data that have a vertical accuracy that meets or exceeds a verified American Society of Photogrammetry and Remote Sensing class 1 vertical accuracy of  $\pm 9.25$  centimeters (cm) and horizontal accuracy of 1:600 (Fugro Earthdata, Inc., 2012)



were used to provide digital elevation data for the parts of the cross sections that were above the water surface at the time of the surveys. The lidar data were collected during April 7–18, 2012, by Fugro Earthdata, Inc. (2012). Postprocessing of these data was completed by Fugro Earthdata, Inc., in November 2012. Although lidar typically is not able to accurately determine underwater channel elevations, lidar data were collected during a period of low flow in the Ottauquechee River and Reservoir Brook; thus, many of the cross-section data points collected within the channel were considered to accurately reflect the channel elevation.

The lidar data covered a 1,000-m corridor and were augmented with 10-m contour interval data in modeled areas outside of the lidar corridor. In flood-inundation areas beyond the extent of the available lidar, 10-m contour interval USGS 15-minute quadrangle topographic digital raster graphics maps produced at a scale of 1:24,000 and referenced to the North American Datum of 1983 and the NAVD 88 were used to augment lidar data to delineate the extent of flooding. The horizontal accuracy of the digital raster graphics maps is one-half of the contour interval ( $\pm 5$  m).

Various manmade drainage structures (bridges, culverts, roadway embankments, levees, and dams) in and along the stream affect or have the potential to affect water-surface elevations during floods along the stream. To properly account for these features in the model, structural dimensions for 23 bridges and 1 dam along the Ottauquechee River and 4 bridges along Reservoir Brook were measured and surveyed in the field concurrently with the stream-channel surveys.

## Energy-Loss Factors

Field observations and high-resolution aerial photographs were used to select initial (precalibration) Manning's roughness coefficients ("*n*" values) for energy-loss (friction-loss) calculations. The final Manning's *n* values used ranged from 0.025 to 0.055 for the main channel and from 0.06 to 0.08 for the overbank areas modeled in this analysis.

## Model Calibration and Performance

The hydraulic model was calibrated to the most current stage-discharge relation at the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) and to high-water marks collected after the August 2011 tropical storm Irene flood (Medalie and Olson, 2013). The estimated peak discharge for the tropical storm Irene flood is 9,070 ft<sup>3</sup>/s at an estimated stage of 14.95 feet (ft) at the streamgage. The measured peak discharges (table 2) at the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900; and stages) for the 1- and 0.2-percent AEP floods are 4,960 ft<sup>3</sup>/s (1,161.87 ft, NAVD 88) and 8,390 ft<sup>3</sup>/s (1,163.32 ft, NAVD 88), respectively. Model calibration was accomplished by adjusting model input such as Manning's *n* values. Differences between measured and simulated water

levels for measured or rated flows at Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) ranged from 0.02 to 0.90 ft (table 3). Absolute value differences between measured and simulated water levels for the model calibrated to tropical storm Irene high-water marks (HWMs) in the study reach averaged 0.49 ft (table 4) with the quality of HWMs rated from "excellent" to "poor." For those HWMs ranked "good" to "excellent," the absolute value difference between measured and simulated water levels for the calibrated model was 0.23 ft. Of the 24 HWMs used in calibrating the model, 3 had a model simulated value that was greater than the surveyed HWM by greater than 1.0 ft. These three surveyed HWMs had a quality rating of "fair" and were based on field observed debris or wash lines that could possibly have reflected the receding flood extent rather than the peak flood of tropical storm Irene.

## Development of Water-Surface Profiles

Profiles were developed (table 5) for the flood of August 28, 2011, from tropical storm Irene (greater than the 0.2-percent AEP discharge) and for the 10-, 2-, 1- and 0.2-percent AEP discharges (also referred to as the 10-, 50-, 100-, and 500-year recurrence interval floods, respectively) as referenced to the Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900) and the Ottauquechee River at North Hartland, Vt. streamgage (station 01151500). Discharges corresponding to the various stages were obtained from the most current stage-discharge relation at the USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900).

## Inundation Mapping

Flood-inundation maps were created for the 1-percent AEP, as referenced to the USGS Ottauquechee River near West Bridgewater, Vt. streamgage (01150900) and the August 2011 flood from tropical storm Irene, using a GIS by combining the water-surface profiles and digital elevation model (DEM) data. The DEM data were derived from lidar data and cover a 1,000-m corridor. In flood-inundation areas beyond the extent of the available lidar, 10-m contour interval USGS 15-minute quadrangle topographic digital raster graphics maps produced at a scale of 1:24,000 were used to augment lidar data to delineate the extent of flooding.

Estimated flood-inundation boundaries for each simulated profile were developed with HEC—GeoRAS software (U.S. Army Corps of Engineers, 2009). HEC—GeoRAS is a set of procedures, tools, and utilities for processing geospatial data in ArcGIS by using a graphical user interface. The interface 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, 2010).

## 8 Analysis of Floods at the Ottauquechee River and Reservoir Brook in Vermont

**Table 3.** Comparison of measured and model simulated water levels at U.S. Geological Survey streamgage 01150900 at Ottauquechee River near West Bridgewater, Vt.

[USGS, U.S. Geological Survey; AEP, annual exceedance probability; ft<sup>3</sup>/s, cubic feet per second; ft, feet; NAVD 88, North American Vertical Datum of 1988]

AEP flood	Discharge, in ft <sup>3</sup> /s	Streamgage stage, in ft above NAVD 88	Model simulated stage, in ft above NAVD 88	Elevation difference, in ft
10 percent	2,140	1,159.57	1,160.01	-0.44
2 percent	3,910	1,161.24	1,161.39	-0.15
1 percent	4,960	1,161.87	1,162.15	-0.28
0.2 percent	8,390	1,163.32	1,163.34	-0.02
Tropical storm Irene	9,070	1,163.54	1,163.53	+0.01

**Table 4.** Comparison of water-surface elevations from hydraulic model and surveyed high-water mark elevations from the flood of tropical storm Irene on August 28, 2011, on the Ottauquechee River, Vermont.

[mi, miles; ft, feet; HWM, high water mark; NAVD 88, North American Vertical Datum of 1988]

River station, in ft <sup>1</sup>	HWM elevation, in ft above NAVD 88	Model water-surface elevation, in ft above NAVD 88	Elevation difference, in ft above NAVD 88	HWM quality rating <sup>2</sup>
22,269	693.53	693.44	-0.09	Poor
41,148	749.86	749.7	-0.16	Fair
58,717	816.53	816.53	0.00	Fair
58,830	819.41	820.05	0.64	Poor
66,664	846.56	846.64	0.08	Fair
68,115	850.34	849.94	-0.4	Poor
69,880	862.18	862.23	0.05	Good
70,243	865.19	865.92	0.73	Fair
81,682	917.74	919.15	1.41	Fair
81,831	920.18	920.41	0.23	Good
84,510	939.7	940.42	0.72	Good
84,682	940.26	940.88	0.62	Good
88,090	960.22	961.93	1.71	Fair
88,364	964.67	963.99	-0.68	Poor
91,192	983.67	983.87	0.2	Poor
91,336	987.04	987.91	0.87	Fair
92,277	993.88	993.88	0.00	Good
92,735	997.68	997.45	-0.23	Fair
94,779	1,012.18	1,014.05	1.87	Fair
101,073	1,055.8	1,055.8	0.00	Poor
102,583	1,083.88	1,083.88	0.00	Fair
110,981	1,157.79	1,157.79	0.00	Fair
111,035	1,161.49	1,161.49	0.00	Excellent
132,476	1,205.09	1,205.09	0.00	Good

<sup>1</sup>River station distances are in ft upstream of Woodstock, Vt., downstream corporate limit.

<sup>2</sup>HWM quality rating is from Medalie and Olson (2013).

**Table 5.** Stages and water-surface elevations for the streamgage at USGS Ottauquechee River near West Bridgewater, Vt. streamgage (sta. no. 01-150900), with corresponding discharge estimates at the USGS Ottauquechee River at North Hartland, Vt. streamgage (sta. no. 01-151500).

[AEP, annual exceedance probability; %, percent; ft, feet; NAVD 88, North American Vertical Datum of 1988]

Location	10% AEP flood	2% AEP flood	1% AEP flood	0.2% AEP flood	Tropical storm Irene flood
Streamgage 01150900 at Ottauquechee River near West Bridgewater, Vt.					
Stage, in feet above streamgage datum of 1,148.59 feet NAVD 88	10.96	12.65	13.28	14.73	14.95
Elevation, in feet above NAVD 88	1,159.55	1,161.24	1,161.87	1,163.32	1,163.54
Discharge, in cubic feet per second	2,140	3,910	4,960	8,390	9,070
Corresponding estimated unregulated discharge at streamgage 01151500 at Ottauquechee River at North Harland, Vt.					
Discharge, in cubic feet per second	18,700	34,300	43,400	72,200	38,200

## Ottawaquechee River and Reservoir Brook, Vermont Flood-Inundation Map Data

Digital flood-inundation maps for the 1-percent AEP and the August 2011 flood from tropical storm Irene are also available at the USGS Flood Inundation Mapper (<http://wim.usgs.gov/FIMI/>). Flood inundation maps of the Ottauquechee River and Reservoir Brook for the 1-percent AEP (100-year) flood and flood of tropical storm Irene in Woodstock, Bridgewater, Sherburne, and Plymouth are presented in appendix 1. Profiles for the 10-, 2-, 1-, and 0.2-percent AEP floods and the tropical storm Irene flood of August 2011 are presented in appendixes 2 through 5. The estimated flood-inundation maps can be displayed in sufficient detail to note the extent of flooding with respect to individual structures so that preparations for flooding and decision making for emergency response can be performed efficiently.

## Disclaimer for Flood-Inundation Maps

Inundated areas shown are not meant to 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. The flood boundaries shown were estimated on the basis of water stages and streamflows at the two USGS streamgages on the Ottauquechee River. Water-surface elevations along the stream reaches were estimated using steady-state hydraulic modeling, assuming unobstructed

flow, with streamflows and hydrologic conditions anticipated at the USGS streamgages. The hydraulic model reflects the land-cover characteristics and any bridge, dam, levee, or other hydraulic structures existing as of February 2014. Unique meteorological factors (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 deviations in the water-surface elevations and inundation boundaries shown. Additional areas may be flooded owing to 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 or ice jams. The accuracy of the floodwater extent portrayed on these maps will vary with the accuracy of the DEM used to simulate the land surface.

## Summary

Estimated flood-inundation maps were developed by the U.S. Geological Survey USGS in cooperation with the U.S. Army Corps of Engineers, New York District for a 25-mile (mi) reach of the Ottauquechee River from the River Road Bridge in Killington, Vermont, to the Taftsville Dam in village of Taftsville, Vt., located in the town of Woodstock, Vt., and for a 2-mi reach of Reservoir Brook from a location downstream from Woodward Reservoir in Plymouth, Vt., to the confluence with the Ottauquechee River in Bridgewater, Vt. These maps, in conjunction with the annual peak-flow data analyses of the U.S. Geological Survey Ottauquechee River near West Bridgewater, Vt. (station 01150900) and Ottauquechee River at North Hartland, Vt. (station 01151500) streamgages will help guide the general public in taking individual safety precautions and will provide city officials with a tool to efficiently manage emergency flood operations and flood mitigation efforts.

The maps were developed by using the U.S. Army Corps of Engineers HEC—RAS model and HEC—GeoRAS program to compute water-surface profiles and to delineate estimated flood-inundation areas for selected floods of the 1-percent annual exceedance probability (AEP) and for the tropical storm Irene flood of August 2011. The model was calibrated using documented high-water marks (Medalie and Olson, 2013) of the peak of the tropical storm Irene flood of August 2011 as well as stage discharge data as determined for USGS Ottauquechee River near West Bridgewater, Vt. streamgage (station 01150900). The simulated water-surface profiles were combined with a digital elevation model (DEM) within a geographic information system (GIS) to delineate the areas flooded during tropical storm Irene and for the 1-percent AEP water-surface profile. The DEM data were derived from light detection and ranging (lidar) data obtained for a 3,281-foot (ft; 1,000-meter [m]) corridor along the Ottauquechee River study reach and were augmented with 33 ft (10-m) contour interval data in the modeled flood-inundation areas outside of the lidar corridor. The 33 ft (10-m) contour interval USGS 15-minute quadrangle topographic digital raster graphics map used to augment lidar data was produced at a scale of 1:24,000. The digital map files show georeferenced, estimated (shaded) flood-inundation areas in the study area for these two events, whereas the graphs in the appendixes of this report show the flood profiles for the 10-, 2-, 1- and 0.2-percent AEP floods, also known as the 10-, 50-, 100-, and 500-year floods, respectively. Digital flood elevation maps for the 1-percent AEP and the August 2011 flood from tropical storm Irene are also available at the U.S. Geological Survey Flood Inundation Mapper (<http://wim.usgs.gov/FIMI/>).

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## **Appendixes 1–5**

[Available at <http://pubs.usgs.gov/sir/2014/5214/>.]

**Appendix 1. Ottauquechee River and Reservoir Brook Flood Inundation Maps of the 1-Percent Annual Exceedance Probability (100-Year) Flood and Flood of Tropical Storm Irene in Woodstock, Bridgewater, Sherburne, and Plymouth, Vermont**

**Appendix 2. Profiles of the 10-, 2-, 1-, and 0.2-Percent Annual Exceedance Probability Floods for the Ottauquechee River, Vermont**

**Appendix 3. Profiles of the 1-Percent Annual Exceedance Probability Flood and the Flood of Tropical Storm Irene of August 2011 for the Ottauquechee River, Vermont**

**Appendix 4. Profiles of the 10-, 2-, 1-, and 0.2-Percent Annual Exceedance Probability Floods for the Reservoir Brook, Vermont**

**Appendix 5. Profiles of the 1-Percent Annual Exceedance Probability Flood and the Flood of Tropical Storm Irene of August 2011 for the Reservoir Brook, Vermont**

Prepared by the Pembroke Publishing Service Center.

For more information concerning this report, contact:

Office Chief  
U.S. Geological Survey  
New England Water Science Center  
New Hampshire-Vermont Office  
331 Commerce Way, Suite 2  
Pembroke, NH 03275  
dc\_nh@usgs.gov

or visit our Web site at:  
<http://nh.water.usgs.gov>



