Prepared in cooperation with the International Joint Commission

Flood-Inundation Maps for Lake Champlain in Vermont and in Northern Clinton County, New York

Scientific Investigations Report 2016–5060

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

Cover. May 2011 Flood, Lake Champlain. Photograph by Bill Howland, Lake Champlain Basin Program.

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SALLY JEWELL, Secretary

U.S. Geological Survey
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Conversion Factors

Inch/Pound to SI

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)

Vertical coordinate information is referenced to (1) stage, the height above an arbitrary datum established at a lake gage, and (2) elevation, the height above the National Geodetic Vertical Datum of 1929 (NGVD 29) and North American Vertical Datum of 1988 (NAVD 88).

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

Flood-Inundation Maps for Lake Champlain in Vermont and in Northern Clinton County, New York

By Robert H. Flynn and Laura Hayes

Abstract

Digital flood-inundation maps for an approximately 100-mile length of Lake Champlain in Addison, Chittenden, Franklin, and Grand Isle Counties in Vermont and northern Clinton County in New York were created by the U.S. Geological Survey (USGS) in cooperation with the International Joint Commission (IJC). The flood-inundation maps, which can be accessed through the International Joint Commission (IJC) Web site at http://www.ijc.org/en_/, depict estimates of the areal extent flooding corresponding to selected water levels (stages) at the USGS lake gage on the Richelieu River (Lake Champlain) at Rouses Point, N.Y. (station number 04295000). In this study, wind and seiche effects (standing oscillating wave with a long wavelength) were not taken into account and the flood-inundation maps reflect 11 stages (elevations) for Lake Champlain that are static for the study length of the lake. Near-real-time stages at this lake gage, and others on Lake Champlain, may be obtained on the Internet from the USGS National Water Information System at http://waterdata.usgs.gov/ or the National Weather Service Advanced Hydrologic Prediction Service at http:/water.weather.gov/ahps/, which also forecasts flood hydrographs at the Richelieu River (Lake Champlain) at Rouses Point.

Static flood boundary extents were determined for Lake Champlain in Addison, Chittenden, Franklin, and Grand Isle Counties in Vermont and northern Clinton County in New York using recently acquired (2013–2014) lidar (light detection and ranging) and may be referenced to any of the five USGS lake gages on Lake Champlain. Of these five lake gages, USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y., is the only USGS lake gage that is also a National Weather Service prediction location. Flood boundary extents for the Lake Champlain static flood-inundation map corresponding to the May 2011 flood (103.2 feet [ft], National Geodetic Vertical Datum [NGVD] 29) were evaluated by comparing these boundary extents against the inundation area extents determined for the May 2011 flood (which incorporated documented high-water marks from the flood of May 2011) (Bjerklie and others, 2014).

A digital elevation model (DEM) was created by USGS, within a geographic information system (GIS), from the recently flown and processed light detection and ranging (lidar) data (2013–2014) in Vermont and the lake shore area of northern Clinton County in New York. The lidar data have a vertical accuracy of 0.3 to 0.6-ft (9.6 to 18.0-centimeters [cm]) and a horizontal resolution of 2.3 to 4.6 ft (0.7 to 1.4 meters). This DEM was used in determining the flood boundary for 11 flood stages at 0.5-ft intervals from 100.0 to 104.0 ft (NGVD 29) and 1-ft intervals from 104.0 to 106.0 ft (NGVD 29) as referenced to the USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. In addition, the May 2011 flood-inundation area for elevation 103.20 ft (NGVD 29) (102.77 ft, North American Vertical Datum [NAVD] 88) was determined from this DEM. The May 2011 flood is the highest recorded lake water level (stage) at the Rouses Point, N.Y., lake gage. Flood stages greater than 101.5 ft (NGVD 29) exceed the “major flood stage” as defined by the National Weather Service for USGS lake gage 04295000.

The availability of these maps, along with Internet information regarding current stage from the USGS lake gage and forecasted high-flow stages from the National Weather Service, will 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

Lake Champlain (fig. 1) is in a broad valley between the Adirondack Mountains of New York to the west and the Green Mountains of Vermont to the east. During the last glacial period, retreating glaciers left a large body of freshwater that included the Great Lakes, Lake Champlain, and much of the St. Lawrence River Valley (Lake Champlain Research Consortium, 2004). The Lake Champlain Basin area comprises 8,234 square miles (mi^2) and has 587 miles (mi) of shoreline (Lake Champlain Basin Program, 2013) in New York, Vermont, and Quebec, Canada. The surface area of the lake,

Base from U.S. National Park Service, Natural Earth physical map, 500-meter resolution
http://services.arcgisonline.com/ArcGIS/rest/services, 2015
Albers conic projection, North American Datum 1983 (NAD 83)

Figure 1. Lake Champlain Watershed and U.S. Geological Survey lake gages.

at a mean elevation of 95.5 ft (NGVD 29) (Lake Champlain Basin Program, 2013), occupies only 5.4 percent of the basin (Shanley and Denner, 1999), or approximately 435 mi^2 of surface area (Lake Champlain Basin Program, 2015), excluding islands.

During the spring and summer of 2011, the Lake Champlain region recorded historic flooding (Kiah and others, 2013) because of heavy spring rainfall on a warm, saturated late spring snowpack across the Androscoggin, Connecticut, and St. Lawrence River Basins in northern New Hampshire and Vermont. As a result of melting snow and rainfall, historically high flood levels were observed in Lake Champlain beginning in late April through May of 2011. Shoreline erosion and variable lake levels during this period of high water was exacerbated by wind-driven waves associated with local fetch and lake-wide seiche effects (standing oscillating wave with a long wavelength) (Bjerklie and others, 2014). Seiche effects have been previously reported on the lake (Shanley and Denner, 1999) and are created by wind and atmospheric pressure changes.

The flood elevation of May 2011 was a period of record maximum levels at all of the lake gages in Lake Champlain. The maximum recorded stage at U.S. Geological Survey (USGS) lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. (U.S. Geological Survey, 2015a), was 103.20 ft (NGVD 29) on May 6, 2011, whereas, the maximum recorded stage at USGS lake gage 04294500, Lake Champlain at Burlington, Vt. (U.S. Geological Survey, 2015b), was 103.27 ft (NGVD 29) on May 6, 2011. The peak stage at the USGS lake gage 04279085 Lake Champlain north of Whitehall, N.Y., was 103.57 ft (NGVD 29) on May 9, 2011. This lake elevation was affected by seiche (U. S. Geological Survey, 2015c). Lake levels as recorded at Rouses Point, N.Y., and Burlington, Vt., gages are generally in close agreement as both gages are in the northern part of the lake. Although the net difference in lake levels at the Burlington and Rouses Point sites averages near zero, internal seiches in the lake can cause differences in the lake levels to as much as 0.3 ft (0.1 meter [m]) (Shanley and Denner, 1999). On August 28, 2011, during tropical storm Irene, lake levels varied by as much as 4 ft, with a lake elevation of 98.5 ft at the Whitehall, N.Y., gage at the southern end of the lake and a lake elevation of 94.5 ft at the northern end of the lake at Rouses Point, N.Y. (Lumia and others, 2014). Before the flooding of May 2011, the highest lake level elevation recorded at the Rouses Point, N.Y., gage was 102.1 ft (NGVD 29) on May 4, 1869, and the highest lake elevation recorded at the Burlington, Vt., gage was 101.86 ft (NGVD 29) on April 27, 1993.

Before this study, emergency responders in the New York and Vermont communities bordering Lake Champlain relied on several information sources (all of which are available on the Internet) to make decisions on how to best alert the public and mitigate flood damages. One source is the Federal Emergency Management Agency (FEMA) flood insurance studies (FIS) for the communities surrounding Lake Champlain. These communities are in the counties of Grand Isle, Franklin, Addison, and Chittenden in Vermont and in Clinton County, N.Y. (Federal Emergency Management Agency, 2015). For the towns in Grande Isle County, Vt., FEMA maps were effective between 1978 and 1988. For the lakeside towns in Franklin County, Vt., FEMA maps were effective between 1981 and 1988. For the lakeside towns in Addison County, Vt., FEMA maps were effective between 1979 and 1986. For the lakeside towns in Chittenden County, Vt., FEMA maps were effective between 1986 and 2011. For the lakeside towns in Clinton County, N.Y., FEMA maps were effective in 2007 (Federal Emergency Management Agency, 2015). A second source of information are the USGS lake level lake gages: Richelieu River (Lake Champlain) at Rouses Point, N.Y. (lake gage 04295000; U.S. Geological Survey, 2015a), Lake Champlain at Burlington, Vt. (lake gage 04294500; U.S. Geological Survey, 2015b), Lake Champlain North of Whitehall, N.Y. (lake gage 04279085; U.S. Geological Survey, 2015c); Lake Champlain at Port Henry, N.Y. (lake gage 04294413; U.S. Geological Survey, 2015d), and Lake Champlain near Grand Isle, Vt. (lake gage 04294620; U.S. Geological Survey, 2015e) from which current and historical water levels, including annual peak stages, can be obtained. Historical water levels date back to March 1871 at Richelieu River at Rouses Point, N.Y., gage to October 1998 at Lake Champlain North of Whitehall, N.Y., gage and to May 1907 at Lake Champlain at Burlington, Vt., gage. The lake gage at Port Huron, N.Y., was re-activated on April 10, 2015, and has historical water level data from March 16, 1997, to September 20, 2015, whereas the lake gage at Grande Isle, Vt., (04294620) is a new gage that was activated on March 31, 2015. A third source of flood-related information is the National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS), which displays the USGS stage data for the Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 (U.S. Geological Survey, 2015a) and for Lake Champlain at Burlington, Vt. (lake gage 04294500; U.S. Geological Survey, 2015b), and also issues forecasts of stage for the Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 (National Weather Service, 2015a and 2015b).

The Lake Champlain static flood-inundation maps are intended to aid residents in assessing the extent of flooding based on the stage as shown on the USGS gage Web sites and, in the case of the Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000, as predicted by NWS. One way to address the informational gaps in flood extent is to produce a library of flood-inundation maps that are referenced to the stages recorded at the USGS lake gage. By referring to the appropriate map, emergency responders can discern the severity of flooding (areal extent), identify roads that are or will soon be flooded, and make plans for notification or evacuation of residents in harm’s way. 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. In 2014–15, the USGS, in cooperation with the International

Joint Commission (IJC), conducted this project to produce a library of static flood-inundation maps for the perimeter of Lake Champlain in which light detection and ranging (lidar) data were available.

Purpose and Scope

This report describes the development of a series of 11 estimated flood-inundation maps for Lake Champlain in Addison, Chittenden, Franklin, and Grand Isle Counties in Vermont and northern Clinton County in New York.

The Lake Champlain flood-inundation maps cover a straight-line lake distance of approximately 100 mi in length on the eastern side of the Lake from the Rutland/Addison County line in Vermont north to the Canada/United States border and on the western side of the Lake from the northern part of Clinton County (Cumberland Bay, north of Plattsburgh) in New York north to the Canada/United States border (upstream to downstream, respectively) (fig. 1). The maps were produced for flood levels referenced to the stage recorded at any of the five lake gages on Lake Champlain (table 1). These flood-inundation maps for Lake Champlain are static and, therefore, do not factor in wind and seiche.

The flood-inundation maps cover a range in stage from 100 ft to 106 ft, referenced to the lake gage datum of NGVD 29. The 99.9-ft (NGVD 29, ft) stage is defined by the NWS (National Weather Service, 2015a and 2015b) as the “action stage” or that stage which, when reached, requires the NWS or a partner to take some type of mitigation action in preparation for possible substantial hydrologic activity. The 100.0-ft (NGVD 29, ft) stage is defined by the NWS (2015a) as the minor “flood stage”. The 103.20-ft, 103.27-ft, and 103.57-ft (NGVD 29) stages are the highest recorded water levels at the lake gages at USGS Rouses Point, N.Y.; Burlington, Vt.; and Whitehall, N.Y., respectively. These stages exceed the “major flood stage” of 101.5 ft (NGVD 29) as defined by the NWS.

There are five USGS lake gages on Lake Champlain (table 1), and of these lake gages, only the Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 is a NWS prediction site. Locations for the U.S. Geological Survey lake gages for Lake Champlain are shown in figure 1. All of the lake gages are referenced to NGVD 29 with the exception of the Lake Champlain near Grande Isle lake gage, which is referenced to NAVD 88. To convert Grande Isle lake gage elevations to NGVD 29, add 0.45 ft to given NAVD 88 stage values.

Study Area Description

Lake Champlain is a freshwater lake of approximately 435 mi^2 of surface area (Lake Champlain Basin Program, 2015) located primarily within the borders of the United States but partially situated in the Canadian province of Quebec. It is the largest freshwater lake in the United States outside of the five Great Lakes (Stickney and others, 2001). Water transiting through Lake Champlain flows north from Whitehall, N.Y., to the United States and Canadian border at its outlet at the Richelieu River in Quebec. The Richelieu River flows into the St. Lawrence River at Sorel, Quebec, in Canada (not shown) which flows into the Atlantic Ocean at the Gulf of St. Lawrence. The Richelieu River extends from Rouses Point, N.Y. downstream to Sorel, Quebec, Canada. Lake Champlain is approximately 120 mi in length, extending from Whitehall, N.Y., in the south to the Richelieu River in Quebec, Canada (Lake Champlain Basin Program, 2015). Visually, there are three distinct regions in the lake (Bjerklie and others, 2014). The southern end (or South Lake, fig. 1) is a narrow river-like region, whereas in the central region (or Main Lake, fig. 1), the lake is wide with some small islands. In the northern

Table 1. Information for U.S. Geological Survey lake gages, Lake Champlain, Vt., and N.Y.

[DA, drainage area; mi^2, square miles; ft, foot; NGVD 29, National Geodetic Vertical Datum of 1929; N.Y., New York; Vt., Vermont; n/a, not applicable; --, no data]

Station name (fig. 1)	Station number	DA (mi^2)	Latitude	Longitude	Period of stage record	Maximum recorded stage (ft, NGVD 29) and date
Richelieu River (Lake Champlain) at Rouses Point, N.Y.	04295000	8,277	44°59′46″	73°21′37″	March 1871 to present (2015)	103.2, May 6, 2011
Lake Champlain at Burlington, Vt.	04294500	n/a	44°28′34″	73°13′19″	May 1907 to present (2015)	103.27, May 6, 2011
Lake Champlain North of Whitehall, N.Y.	04279085	725	43°37′18″	73°25′08″	October 1998 to present (2015)	103.57, May 6, 2011
Lake Champlain at Port Henry, N.Y.	04294413	n/a	44°03′09″	73°27′12″	October 1997 to 1999, April 2015 to present (2015)	--
Lake Champlain near Grand Isle, Vt.	04294620	n/a	44°41′09″	73°17′28″	April 2015 to present (2015)	--

region, the lake is widest with several large islands. Tributaries to Lake Champlain are primarily high-gradient streams that peak within 24 hours in response to precipitation or snowmelt. The dominant hydrologic event during the year is spring snowmelt, when typically nearly one-half of the annual streamflow happens in a 6 to 8 week period (Shanley and Denner, 1999). The response of the Lake Champlain outflow to inflow is not instantaneous and the lake plays an important role in regulating flow to the Richelieu River. Because of the storage capacity of the lake, the lake level peak lags the peak inflow by several days. The Richelieu River and Lake Champlain Basins are dominated by strong spring flooding and more moderate flows throughout the rest of the year. Richelieu River discharge is effectively controlled by the water level in Lake Champlain with approximately 95 percent of the Richelieu River's outlet flow into the St. Lawrence River originating in Lake Champlain (Riboust and Brissette, 2015).

The drainage basin area for Lake Champlain is 8,234 mi^2 with 56 percent of the basin in Vermont, 37 percent in New York, and 7 percent in the province of Quebec, Canada. The population distribution in the drainage basin consists of 68 percent in Vermont, 27 percent in New York, and 5 percent in Quebec (Lake Champlain Basin Program, 2015). Lake Champlain is surrounded by mountains, with the Green Mountains to the east in Vermont, the Adirondacks to the west in New York and the Taconic Mountains to the south. Mean precipitation over the Lake Champlain watershed varies between 30 and 50 inches per year (760 and 1,270 millimeters per year, respectively) depending on location within the watershed (Howland and others, 2006). The mean air temperature within the basin is 7 degrees Celsius (45 degrees Fahrenheit) (Shanley and Denner, 1999).

Lake Champlain was formed approximately 11,000 years ago as the last glacial period ended and left behind a large body of freshwater that included the Great Lakes (not shown), Lake Champlain, and much of the St. Lawrence River valley (Lake Champlain Research Consortium, 2004). The lake is 12 mi at its widest point with an average depth of 64 ft, although the deepest point is between Charlotte, Vt. and Essex, N.Y. with a depth of 400 ft (Lake Champlain Land Trust, 2015). Average annual water level is 95.5 ft (NGVD 29) with a typical annual variation between high and low average water levels of approximately 6 ft and a maximum range of 9.4 ft, since 1870s when daily records (Lake Champlain Basin Program, 2015). After floods in the 1930s, a dam was built in 1939 at Fryers Island to regulate the Richelieu River flow (Riboust and Brissette, 2015). However, levees around the dam and dredging of the shoals at St-Jean-sur-Richelieu were never done (International Joint Commission, 2013). The dam was never put into service and the Richelieu River remains unregulated (Riboust and Brissette, 2015).

Lake Champlain is in the physiographic province of the Champlain Lowlands (not shown). Although visually there are three distinct regions in the lake (Bjerklie and others, 2014), based on different physical and chemical characteristics and water quality, the lake is divided into five distinct areas (Lake Champlain Basin Program, 2015). The lake areas include: the South Lake, the Main Lake (or Broad Lake), Malletts Bay, the Inland Sea (or Northeast Arm), and Missisquoi Bay. Water retention time is approximately 3 years in the Main Lake and less than 2 months in the South Lake (Lake Champlain Basin Program, 2015). With a population of 42,284, Burlington, Vt., is the largest city on the lake (in 2013, U.S. Bureau of Census, 2015a). The second and third most populated cities are Plattsburgh, N.Y., and Colchester, Vt., with populations of 19,898 (in 2013, U.S. Bureau of Census, 2015b) and 17,299 (in 2013, U.S. Bureau of Census, 2015c), respectively.

In the spring, snowmelt and the inflows to Lake Champlain become greater than the outflow into the Richelieu River in Quebec, Canada (Shanley and Denner, 1999). Many of the lake tributaries are high-gradient streams that peak within 24 hours in response to precipitation or snowmelt (Bjerklie and others, 2014). In Vermont, the largest rivers that flow into Lake Champlain include the Missisquoi, Lamoille, Poultney, and Winooski Rivers and Otter Creek, whereas in New York, they include the Ausable, La Chute (outflow of Lake George), Saranac, and Bouquet Rivers.

At USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, major flood stage, as designated by the NWS (National Weather Service, 2015a), is 101.5 ft (NGVD 29), moderate flood stage is 101.0 ft (NGVD 29) and minor flood stage is 100.0 ft (NGVD 29). As a result of the rainfall and runoff events of April and May 2011, Lake Champlain was above flood stage for 67 consecutive days, reaching its peak stage on May 6, 2011. Lake Champlain was above the NWS designated major flood stage for the entire month of May, 2011 (Bjerklie and others, 2014). Shoreline erosion and damage was exacerbated by high winds, which resulted in wave heights in excess of 3 ft (Lake Champlain Basin Program, 2013). As a result of the May 2011 flooding, Vermont declared a state of emergency and a presidential disaster declaration (declaration number 1995-DR: http://www.fema.gov/pdf/news/pda/1995.pdf) was made on June 15, 2011).

At USGS Richelieu River (Lake Champlain) at Rouses Point, N.Y. lake gage 04295000, a record flood elevation of 103.20 ft (NGVD 29) was observed on May 6, 2011, whereas a minimum elevation of 92.17 ft (NGVD 29) was recorded on October 23, 1941. This lake level is 1.10 ft above the previous record of 102.10 ft (NGVD 29), set on May 4, 1869, and 7.70 ft above its mean level of 95.5 ft. A record flood elevation of 103.27 ft (NGVD 29) was reached at USGS Lake Champlain at Burlington lake gage 04294500 on May 6, 2011. This lake level is 1.41 ft above the previous record of 101.86 ft (NGVD 29), set on April 27, 1993, and 7.77 ft above its mean level of 95.5 ft. The minimum observed elevation for the lake was 92.61 ft, which was recorded on December 4, 1908, at USGS Lake Champlain at Burlington lake gage 04294500. The highest lake elevation for Lake Champlain occurred at the USGS Lake Champlain north of Whitehall, N.Y., lake gage 04279085 with a peak flood elevation of 103.57 ft (NGVD 29) on May 9, 2011 (USGS, 2015a). This elevation was affected by seiche.

Recurring flooding is an issue for the Richelieu River and Lake Champlain but, the 2011 flood was an outlier in the historical records. May and June monthly precipitation was at record levels and this was coupled with an above average snowpack that resulted in lake levels that took more than 2 months to fall below the flood level (Lake Champlain Basin Program, 2015) with approximately 3,000 homes flooded (Riboust and Brissette, 2015). The Canadian government estimated the cost of the 2011 flood at 70 million U.S. dollars, whereas on the U.S. side, the estimated cost because of flood damage in New York and Vermont was approximately 20 million in U.S. dollars (International Joint Commission, 2013).

The flood-inundation mapping extent includes the shoreline of Lake Champlain in Vermont and northeast New York. A hydraulic model was not developed for the Lake Champlain inundation mapping effort instead, the 11 static and discrete inundation flood maps were created for Lake Champlain to represent a range of hydraulic scenarios from the average spring flood stage to greater than the extreme high water flood stage observed in May 2011. The flood of May 2011, as recorded at the Richelieu River (Lake Champlain) at Rouses Point, N.Y. lake gage, was estimated to have an annual exceedance probability less than or equal to 0.2 percent (Olson and Bent, 2013; equal or greater than the 500-year recurrence interval). The inundation maps represent 11 stages as referenced to USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. This lake gage is also a NWS Advanced Hydrologic Prediction Service (AHPS) site (National Weather Service, 2015a) so that the user can obtain applicable information on forecasted peak stages. The 11 stages (NGVD 29) are: 100, 101, 101.5, 102, 102.5, 103, 103.2 (May 2011 flood), 103.5, 104, 105, and 106.

The inundation map for the flood of May 2011 (103.20 ft, NGVD 29, which is 102.77, NAVD 88) was referenced to the stage at USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y., and compared to a flood map created from satellite imagery (Bjerklie and others, 2014) and calibrated to high-water marks (Medalie and Olson, 2013).

Previous Studies

There are four Vermont Counties (Grand Isle, Franklin, Addison, and Chittenden) and one New York County (Clinton) having shoreline on Lake Champlain and included in this study. Flood insurance studies are available for each of these counties. The current FIS for towns in Grand Isle, Franklin, Addison, and Chittenden Counties in Vermont were completed between 1980 and 2011 (Federal Emergency Management Agency, 2015). The current FIS for towns in Clinton County in New York were completed between 1977 and 2004 (Federal Emergency Management Agency, 2007).

Creation of Flood-Inundation-Map Library

The USGS has standardized the procedures for creating flood-inundation maps for flood-prone communities (U.S. Geological Survey, 2015f) so that the process followed and products produced are similar regardless of which USGS office is responsible for the work. Tasks specific to development of the flood-inundation maps for Lake Champlain included the following: (1) collection of lidar topographic data, (2) comparison of 2011 Lake Champlain flood extent with a study using satellite imagery (Bjerklie and others, 2014) and from high-water mark data (Medalie and Olson, 2013), (3) determination of flood extent for 11 static flood-inundation maps at various lake stages for Lake Champlain based on digital elevation models (DEM) created from lidar within a geographic information system (GIS), (4) preparation of the maps, as shapefile lines that depict the areal extent of flood inundation for display on the IJC Web site (International Joint Commission, 2015), and (5) installation of a lake gage at Grand Isle, Vt. (lake gage 04294620), and re-establishment of a lake gage at Port Henry, Vt. (lake gage 04294413), to have a suite of five lake gages on Lake Champlain to aid users of the inundation maps in determining the variability of water surface elevations for estimating lake levels for specified locations around Lake Champlain (table 1)

Computation of Water-Surface Flood-Inundation Extents

The study area flood-inundation maps focus on the shoreline areas of Lake Champlain (Addison, Chittenden, Franklin, and Grand Isle Counties) in Vermont and New York (Clinton County), which have recently flown lidar (2013–14). The static water-surface extents of the 11 flood-inundation maps in this study were determined for Lake Champlain from a DEM created from recently acquired lidar data for Addison, Franklin, Chittenden, and Grand Isle Counties in Vermont and Clinton County in New York.

Hydrologic Data

The study area includes 5 Lake Champlain lake gages (Table 1.). Three of the lake gages were in operation before this study, 1 gage (Lake Champlain near Grand Isle, Vt.) was established, and 1 gage (Lake Champlain at Port Henry, N.Y.) was re-activated for this study, of which, flood-inundation maps are one component of the study. As the 11 study area flood-inundation maps are static maps, they can be referenced to any of the lake gages on Lake Champlain. The flood elevation of 103.2 ft, NGVD 29 is, however, referenced to Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 (Table 1.) as this is the flood elevation of record at that gage. In addition, lake gage 04295000 is a

NWS prediction site (National Weather Service, 2015a) and users can reference this information along with the appropriate flood-inundation contour, to determine extent of predicted flooding for the Lake Champlain location of interest.

The Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 has been in operation since March 1871 and was a nonrecording gage before 1939. Stage is measured every 15 minutes, transmitted hourly by a satellite radio in the lake gage, and made available on the Internet through the USGS National Water Information System (U.S. Geological Survey, 2015a). Stage data from this lake gage are referenced to datum of NGVD 29 but, can be converted to water-surface elevations referenced to the NAVD 88 by subtracting 0.43 ft from the NGVD 29 elevation. The conversion value of 0.43 ft was determined from a Global Navigation Satellite System (GNSS) survey (Flynn and others, 2016).

Topographic Data

All topographic data in this study are referenced vertically to NAVD 88 and horizontally to the North American Datum of 1983. The 11 static flood-inundation maps are referenced to NGVD 29 with a datum conversion value of 0.43 applied (to create contours in NAVD 88) as determined at Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000. The vertical datum adjustment between NAVD 88 and NGVD 29 varies across the study area. As the conversion value of 0.43 ft as determined at the Rouses Point gage was used to convert between NAVD 88 and NGVD 29, there is up to 0.16 ft error (in the southern area of the lake) in the converted NAVD 88 values. Elevation data were obtained from a DEM that was derived from lidar data on the Vermont (Addison, Chittenden, Franklin and Grande Isle) and New York (Clinton County) side of the lake. The lidar data was collected during 2013 and 2014 by Photo Science of Lexington, Kentucky. Postprocessing of these data was completed by Photo Science on January 28, 2014, for Addison County and August 29, 2014, for Chittenden County, and Grand Isle County, and Franklin County. The lidar data acquired for Grande Isle County also included the shore line of Clinton County, N.Y. The lidar data have horizontal resolution of 2.3 to 4.6 ft (0.7 m for Chittenden County and 1.4 m for Addison, Franklin, and Grand Isle Counties) and vertical accuracy of 0.3 to 0.6 ft (9.6 centimeters [cm] for Chittenden County, 12.7 cm for Addison County, and 18 cm for Franklin and Grand Isle Counties) at a 95-percent confidence level for the "open terrain" land-cover category (root mean squared error of 0.04 to 0.3 ft (6.5 cm for Addison County, 9.4 cm for Grand Isle County, 1.1 cm for Chittenden County, and 8.2 cm for Franklin County) (Photo Science, 2014). The lidar data specifications support production of 1-ft contours (Dewberry, 2012).

Development of Water-Surface Flood Extents

The DEM, generated from the Vermont and northeastern New York lidar was used to generate water-surface profiles for a total of 11 stages at 0.5-ft intervals between 100.0 ft and 104 ft and 1-ft intervals from 104.0 ft to 106.0 ft as referenced to NGVD 29 of the USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. The stages of 100 ft to 106 ft, NGVD 29 at lake gage 04295000 correspond to elevations of 99.57 ft to 105.57 ft, NAVD 88, respectively.

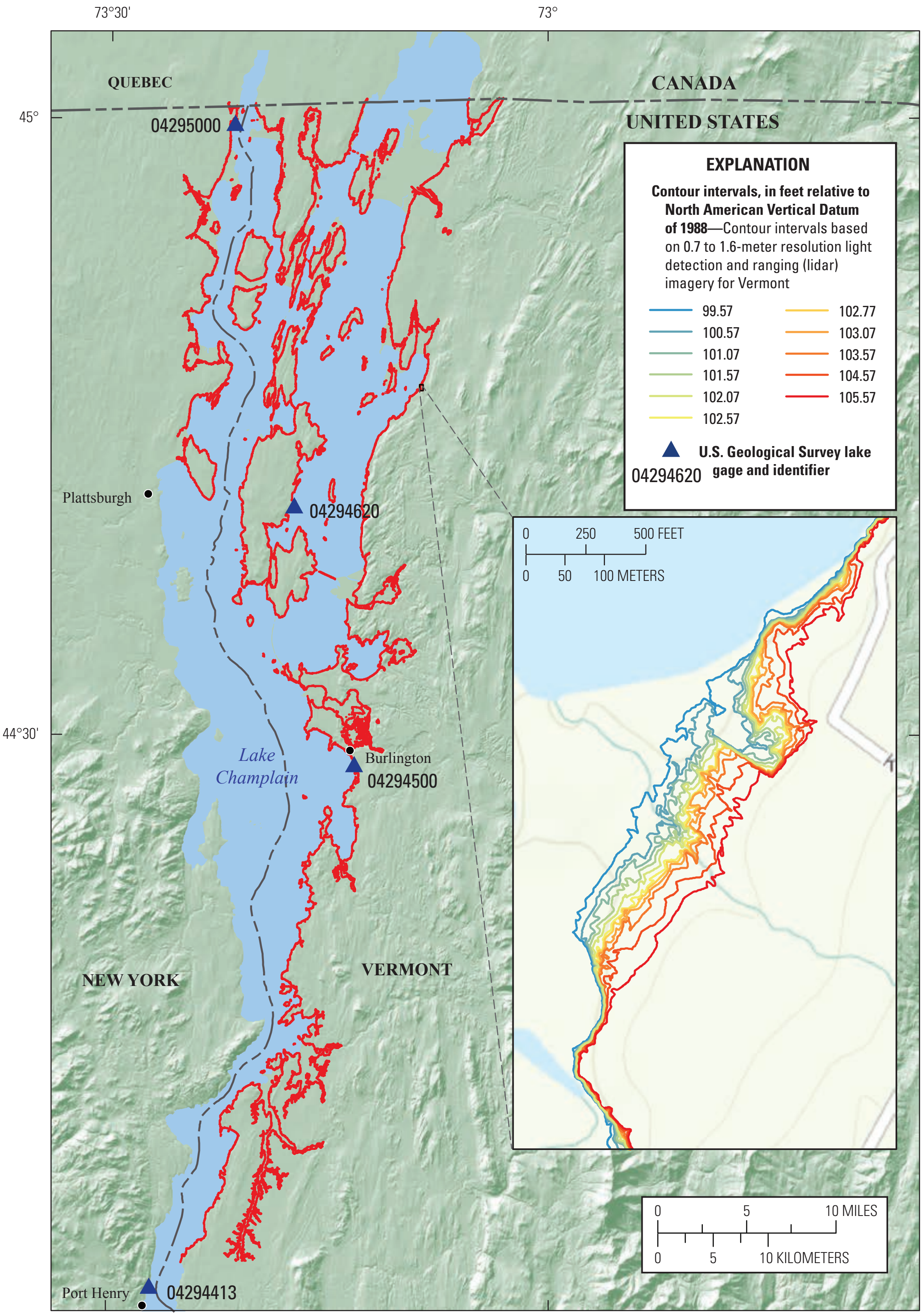
Development of Flood-Inundation Maps

Flood-inundation maps were created for Lake Champlain and can be referenced to any of the five USGS lake gages on Lake Champlain. Lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y., has been designated as a NWS flood-forecast location (National Weather Service, 2015a and 2015b). Flood-inundation maps were created within a GIS for the 11 water-surface elevations by combining the static flood-inundation profiles and DEM data created from lidar data. Estimated flood-inundation boundaries for each simulated profile were developed with the ArcMap application of ArcGIS (Esri, 2015).

Inundated areas that were detached from Lake Champlain were examined to identify connections with the lake, 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. The flood-inundation lines are overlaid on high-resolution, georeferenced, aerial photographs of the study area. Bridge surfaces are displayed as inundated regardless of the actual water-surface elevation in relation to the lowest structural chord of the bridge or the bridge deck. The flood map corresponding to the highest simulated water-surface elevation, a stage of 105.57 ft, NAVD 88 [106.0 ft (NGVD 29)], is presented in figure 2 along with an inset showing the 11 flood-inundation extents at St. Albans Bay.

Flood-Inundation Map Delivery

A Lake Champlain flood-inundation Web site has been established by the IJC (International Joint Commission, 2015) to make USGS flood-inundation study information available to the public. The IJC Web site links to a mapping application that presents map libraries and provides detailed information on flood extents for modeled sites. The mapping application enables the production of customized flood-inundation maps from the map library for Lake Champlain. The user can open another Web site for the USGS National Water Information System (U.S. Geological Survey, 2015a-e), which presents the current stage at the five USGS lake gages for which the inundation maps are referenced. Another Web site connects to the NWS AHPS site (National Weather Service, 2015a) so that



Base from U.S. Geological Survey, National Elevation Dataset, 1 arc-second resolution (approximately 30 meters), http://nationalmap.gov, February 2013
Albers conic projection, North American Datum 1983

Contours prepared based on Photo Science Inc. lidar data, 2009–2014

Figure 2. Flood-inundation map for Lake Champlain in Vermont and in northern Clinton County, New York corresponding to a stage of 105.57 ft, NAVD 88 at the U.S. Geological Survey Lake elevation gage at Richelieu River (Lake Champlain) at Rouses Point, N.Y. (station number 04295000).

the user can obtain applicable information on forecasted peak stage at USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y.. The estimated flood-inundation maps are displayed in sufficient detail so that preparations for flooding and decisions for emergency response can be performed efficiently.

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. In addition, as these flood-inundation maps are static, they do not account for the effects of wind and seiche on lake levels.

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. Flood-inundation boundary extents were estimated from lidar data collected in 2013 and 2014. As the flood-inundation maps are static maps, for a given flood event, the lake stage and associated flood boundary extent at one USGS lake gage may not correspond to the lake stage and associated flood boundary extent at another USGS lake gage. In addition, a NWS predicted flood stage at the Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage 04295000 may not be the same flood stage at another location on the lake. Unique meteorological factors (timing and distribution of precipitation), wind and seiche may cause actual lake level elevations in Lake Champlain to vary from the assumed static flood elevations depicted, which may lead to deviations from the inundation boundaries shown. Additional areas may be flooded due to unanticipated conditions such as backwater from localized debris or ice jams.

If this series of flood-inundation maps will be used in conjunction with NWS river forecasts, the user should be aware of additional uncertainties in the maps and that may be inherent or factored into NWS forecast procedures. The static flood-inundation maps for Lake Champlain do not factor in wind and seiche and were produced for flood levels referenced to the stage recorded or forecasted at the USGS lake gage on the Richelieu River (Lake Champlain) at Rouses Point, N.Y. lake gage 04295000. Current and forecasted stages for other locations on Lake Champlain may or may not be the same as shown at lake gage 04295000. The NWS uses forecast models to estimate the quantity and timing of water flowing through selected stream and lake locations in the United States. These forecast models (1) estimate the amount of runoff generated by precipitation and snowmelt, (2) simulate the movement of floodwater as it proceeds downstream, and (3) predict the flow and stage (and water-surface elevation) for a water body at a given location (AHPS forecast point) throughout the forecast period (every 6 hours and 3 to 5 days out in many locations). For more information on AHPS forecasts, please see http://water.weather.gov/ahps/pcpn_and_river_forecasting.pdf. In addition, although the flood inundation boundary extents are shown in tributaries to the lake, hydraulic analyses of the tributaries were not done as part of this study and, as such, these boundary extents do not reflect the stream water-surface, only the lake water-surface. Additional uncertainties and limitations pertinent to this study may be described elsewhere in this report.

Estimating Potential Losses Due to Flooding

The flood-inundation maps provide general information relative to the areal extent of flooding. These data can aid in assessing populations and infrastructure at risk and estimating potential losses from disasters such as floods and hurricanes. Government planners, GIS specialists, and emergency managers can use these flood-inundation maps to calculate losses from floods and to assess the most beneficial mitigation approaches to minimize these losses.

Summary

A series of 11 digital flood-inundation maps were developed for Lake Champlain by the U.S. Geological Survey (USGS) in cooperation with the International Joint Commission (IJC). The maps include the Lake Champlain bordered counties of Addison, Chittenden, Franklin and Grand Isle in Vermont and northern Clinton in New York—a length of approximately 100 miles from the Rutland/Addison County corporate limit to the Canadian/United States border. The maps were developed using lidar data collected in 2013 and 2014. The lidar data was used to determine static water-surface elevations and to delineate estimated flood-inundation extents and can be referenced to any of the five lake gages on Lake Champlain. The inundation map for the flood of 2011 (103.20 feet [ft], National Geodetic Vertical Datum [NGVD 29]) was compared to high-water mark data, the stage USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y., and to an inundation map as determined from satellite imagery. The lidar was used to generate water-surface profiles for a total of 11 stages at 0.5-ft intervals between 100.0 ft and 104 ft and 1-ft intervals from 104.0 ft to 106.0 ft as referenced to NGVD 29 of the USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. With the exception of the USGS Lake Champlain near Grande Isle, Vt., lake gage which is referenced to North American Vertical Datum (NAVD 88), the USGS lake gages on Lake Champlain are referenced to NGVD 29. Because of this, the datum of NGVD 29 was also used for the inundation maps. Conversion to NAVD 88 at the reference lake gage (lake gage 04295000, Richelieu River (Lake Champlain) requires subtraction of 0.43 feet from the NGVD 29 referenced elevations. The maximum recorded stage at USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y., was 103.20 ft NGVD 29) on May 6, 2011, and 103.27 ft (NGVD 29) at Lake Champlain at Burlington, Vt., lake gage 04294500 on May 6, 2011. The Richelieu River (Lake Champlain) at Rouses Point, N.Y., lake gage is also a National Weather Service forecast location. The simulated water-surface flood elevation extents were created within a geographic information system (GIS) to delineate the estimated flood-inundation areas as shapefile lines. These flood-inundation lines were overlaid on high-resolution, georeferenced aerial photographs of the study area. The flood maps are available through a mapping application that can be accessed on the International Joint Commission Lake Champlain Flood Inundation Mapping Web site.

These maps, in conjunction with the real-time stage data from the USGS lake gage, Richelieu River (Lake Champlain) at Rouses Point, N.Y. (station number 04295000), and forecasted flood stage data from the National Weather Service Advanced Hydrologic Prediction Service will help to 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 post-flood recovery efforts.

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For more information concerning this report, contact:
Director, New England Water Science Center
U.S. Geological Survey
331 Commerce Way, Suite 2
Pembroke, NH 03275
dc_nweng@usgs.gov
or visit our Web site at:
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