Prepared in cooperation with the International Joint Commission

Flood-Inundation Maps for Lake Champlain in Vermont and New York

By Robert H. Flynn and Laura Hayes

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Contents

Figures

Tables

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).

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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 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 USGS Flood Inundation Mapping Science Web site at *http://water.usgs.gov/osw/flood_inundation/*, 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 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 (NWS) Advanced Hydrologic Prediction Service at *http:/water.weather.gov/ahps/*, which also forecasts flood hydrographs at the *Richelieu River (Lake Champlain) at Rouses Point N.Y.*

Static flood boundary extents were determined for Lake Champlain in Addison, Chittenden, Franklin, and Grand Isle Counties in Vt. and Clinton County in N.Y. 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 NWS prediction location. Flood boundary extents for the Lake Champlain static flood inundation map corresponding to the May 2011 flood (103.2 ft NGVD 29) were validated 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 et. al., 2014).

A DEM (Digital Elevation Model) was created by USGS, within a Geographic Information System (GIS), from the recently flown and processed *lidar* (2013-2014) in Vt. and the lake shore area of Clinton County in N.Y. . The lidar data has a vertical accuracy of *0.3 to 0.6*-ft (9.6 to 18.0-cm) and a horizontal resolution of *2.3 to 4.6*-ft (0.7 to 1.4-m). This DEM was used in the determining the flood boundary for *11* flood stages at *0.5*-foot (ft) intervals from 100.0 ft to 104.0 ft (NGVD 29) and 1-ft intervals from 104.0 ft 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, 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 NWS, 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

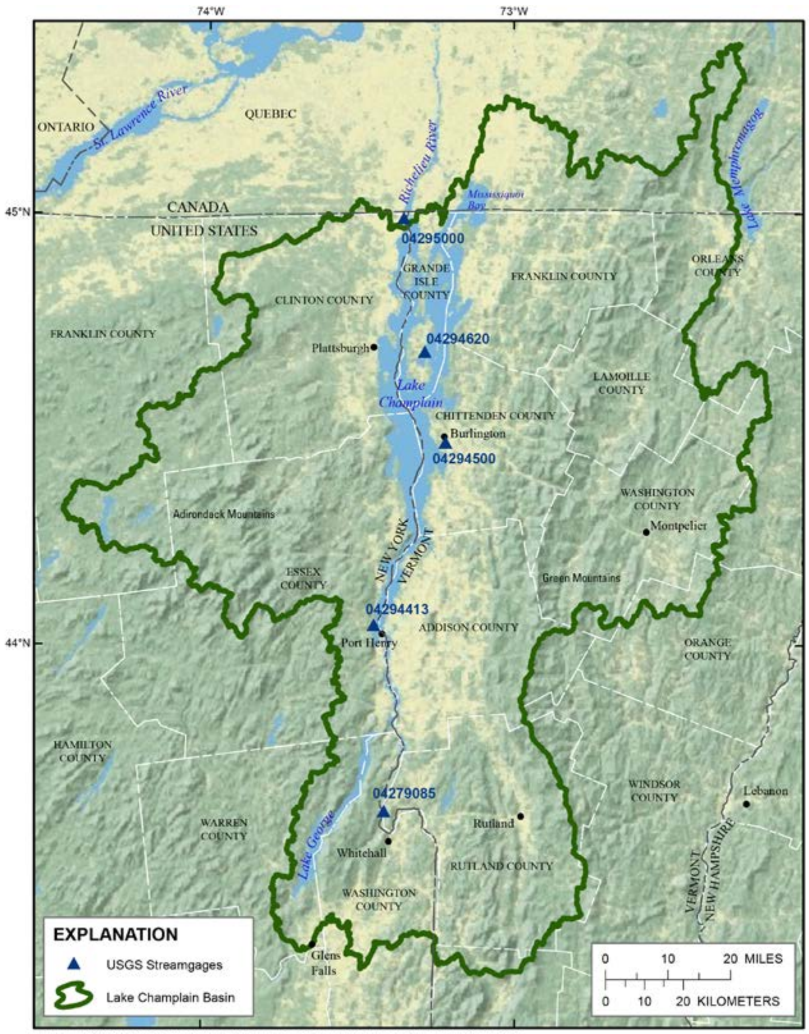
Lake Champlain (fig. 1) is located in a broad valley between the Adirondack Mountains of New York to the west and the Green Mountains of Vermont to the east. During the last glacial period, retreating glaciers left a large body of freshwater that included the Great Lakes, Lake Champlain, and much of 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 mi of shoreline (LCBP, 2013) in New York, Vermont, and Quebec, Canada. The surface area of the lake, at its' mean elevation of 95.5 ft NGVD 29 (LCBP, 2013), occupies only 5.4 percent of the basin (Shanley and Denner, 1999), or approximately 435 sq. mi. of surface area (LCBP, 2015) , excluding islands.

During the spring and summer of 2011, the Lake Champlain region experienced historic flooding (Kiah and others, 2013) due to heavy spring rainfall across the Androscoggin, Connecticut, and St. Lawrence Basins in northern N.H. and Vt., on a warm, saturated late spring snowpack. 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 et. al., 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 at all of the lake gages in Lake Champlain. The maximum recorded stage at USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. (USGS, 2015a) was 103.20 ft NGVD 29 on May 6, 2011 while, the maximum recorded stage at USGS lake gage 04294500, Lake Champlain at Burlington, Vt. (U.S. Geological Survey, 2015b) was 103.27 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 (USGS, 2015c). Lake levels as recorded at Rouses Point, N.Y. and Burlington, Vt. gages are generally in close agreement. 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 of up to 0.3 ft (0.1 m) (Shanley and Denner, 1999). On August 28, 2011, during tropical storm Irene, lake levels varied by up to 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). Prior to 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 gage was 101.86 ft (NGVD 29) on April 27, 1993 .

Prior to this study, emergency responders in the N.Y. and Vt. 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 FEMA flood insurance studies (FIS) for the communities surrounding Lake Champlain. These communities are located in the counties of Grand Isle, Franklin, Addison, and Chittenden in Vt. and in Clinton County N.Y. (Federal Emergency Management Agency, 2015). FEMA maps for the towns in Grande Isle County, Vt. were effective in between 1978 and 1988. FEMA maps for the lakeside towns in Franklin County, Vt. were effective in between 1981 and 1988. FEMA maps for the lakeside towns in Addison County, Vt. were effective in between 1979 and 1986. FEMA maps for the lakeside towns in Chittenden County, Vt. were effective in between 1986 and 2011. FEMA maps for the lakeside towns in Clinton County, N.Y. 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 (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 while the Grande Isle, Vt. gage is a new gage that was activated on March 31, 2015. A third source of flood-related information is the 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 (USGS, 2015a) and for Lake Champlain at Burlington Vt. (lake gage 04294500) (USGS, 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).



Base from U.S. National Park Service, Natural Earth physical map, 500-meter resolution, services.arcgisonline.com, 2015
Albers projection, NAD83

Figure 1. Lake Champlain Watershed and U.S. Geological Survey lake gages; from U.S. Geological Survey (2013)

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 lidar (light detection and ranging) data was 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 Vt. and Clinton County in N.Y. and identifies where on the Internet these maps can be found and where ancillary data (e.g. Geographic-Information-System flood lines and polygons) can be downloaded.

The Lake Champlain flood-inundation maps cover a straight-line lake distance of approximately 100 miles in length on the eastern side of the Lake from the Rutland / Addison County line in Vermont north to the Canadian / United States border and one the western side of the Lake from the Essex / Clinton County line in New York north to the Canadian / 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, as such, do not factor in wind and seiche.

The flood-inundation maps cover a range in stage from 100 to 106 feet (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 significant hydrologic activity. The 100.0-ft (NGVD 29, ft) stage is defined by the NWS (2015c) 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 USGS Rouses Point N.Y., Burlington, Vt., and Whitehall, N.Y. lake gages, respectively. These stages exceed the “major flood stage” of 101.5 ft (NGVD 29) as defined by the NWS.

There are 5 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 currently a NWS prediction site. Location of 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.

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

[Station locations are shown in figure 1. DA, drainage area; mi^2, square miles; ft, feet; ft^3/s, cubic feet per second]

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

Study Area Description

Lake Champlain is a freshwater lake of approximately 435 sq. mi. of surface area (LCBP, 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 et. al., 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, Canada 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 miles in length, extending from Whitehall, N.Y. in the south to the Richelieu River in Quebec, Canada (LCBP, 2015). Visually, there are three distinct regions in the lake (Bjerklie et. al., 2014). The southern end is a narrow river-like region, while in the central region, the lake is wide with some small islands and in the northern region, the lake is widest with several large islands. Tributaries to Lake Champlain are primarily high-gradient streams which peak within 24 hours in response to precipitation or snowmelt. The dominant hydrologic event during the year is spring snowmelt, when typically nearly half of the annual streamflow occurs 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. Due to 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% 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 sq. miles with 56% of the basin in Vermont, 37% in New York, and 7% in the province of Quebec, Canada. The population distribution in the drainage basin consists of 68% in Vermont, 27% in New York, and 5% 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 in/yr (760 and 1,270) mm/yr depending on location within the watershed (Howland et. al., 2006). The mean air temperature within the basin is 7 deg. C. (45 deg. F) (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, Lake Champlain, and much of the St. Lawrence River valley (Lake Champlain Research Consortium, 2004). The length of the Lake Champlain is approximately 120 miles with 587 mi of shoreline. The lake is 12 miles at its widest point with an average depth of 64 feet, 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 an average 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 located in the physiographic province of the Champlain Lowlands. 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 three years in the Main Lake and less than two months in the South Lake (LCBP, 2015). With a population of 42,284, Burlington, Vermont 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 et. al., 2014). In Vt., the largest rivers that flow into Lake Champlain include the Missisquoi, Lamoille, Poultney, and Winooski Rivers and Otter Creek while in New York, they include the Ausable, La Chute (outflow of Lake George), Saranac, and Bouquet .

At U.S. Geological Survey (USGS) lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, major flood stage, as designated by the National Weather Service(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 et. al., 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, while 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 6.70 ft above its mean level of 96.5 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 6.77 ft above its mean level of 95.5 ft. The lakes' minimum observed elevation 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. 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 two 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 USD while on the US side, the estimated cost due to flood damage in N.Y. and Vt. was approximately 20 million inUnited States dollars (International Joint Commission, 2013).

The flood-inundation mapping extent includes the shoreline of Lake Champlain in Vt. and northeast N.Y.. 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% (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 et. al., 2014) and calibrated to high-water marks (Medalie and Olson, 2013).

Previous Studies

There are four Vt. counties and one N.Y. county having shoreline on Lake Champlain and included in this study. FISs are available for each of these counties. The current FIS for towns in Grand Isle, Franklin, Addison, and Chittenden Counties in Vt. were completed between 1980 and 2011 (Federal Emergency Management Agency, 2015). The current FIS for towns in Clinton County 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: (1) collection of lidar topographic data, (2) verification of 2011 Lake Champlain flood extent from a study using satellite imagery (Bjerklie et. al., 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

Model (DEM) created from lidar within a Geographic Information System (GIS), (4) preparation of the maps, as shapefile lines and polygons that depict the areal extent of flood inundation for display on a USGS flood-inundation mapping application (U.S. Geological Survey, 2015f) and 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 (2013-2014). 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 Vt. and Clinton County in N.Y..

Hydrologic Data

The study area includes 5 Lake Champlain lake gages (Table 1.). Three of the lake gages were in operation prior to 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 IJC 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 (NWS, 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 04295000has been in operation since March 1871 and was a non-recording gage prior to 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 et. al., 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 N.Y. (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 and Franklin Counties. 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 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).

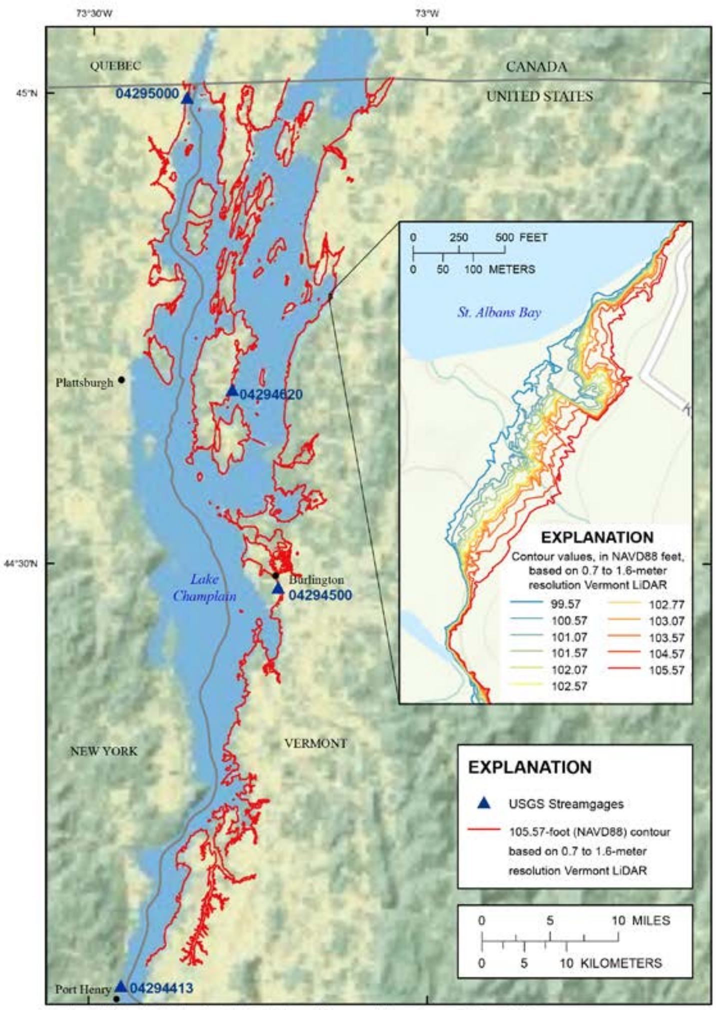
Development of Water-Surface Flood Extents

The DEM, generated from the Vt. and northeastern N.Y. 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).

AN.Y. 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 and polygons are overlaid on high-resolution, geo-referenced, 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 106.0 ft (NGVD 29), along with an inset of St. Albans Bay showing the 11 flood-inundation stages, is presented in figure 2.



Base from U.S. National Park Service, Natural Earth physical map, 500-meter resolution, services.arcgisonline.com, 2015
Albers projection, NAD83

Figure 2. Flood-inundation map for Lake Champlain in N.Y. and Vt., corresponding to a stage of 106.0 feet (NGVD 29) at the U.S. Geological Survey Lake elevation gage at Richelieu River (Lake Champlain) at Rouses Point N.Y. (station number 04295000) and inset of eleven flood-inundation stages at St. Albans Bay.

Flood-Inundation Map Delivery

The current study documentation and shapefiles of the flood-inundation boundaries are available online at the U.S. Geological Survey Publications Warehouse (*http://pubs.usgs.gov/sir/ xxxx /xxxx*). Also, a *Flood Inundation Mapping Science Web site* (U.S. Geological Survey, *2015f*) has been established to make USGS flood-inundation study information available to the public. The flood-inundation maps are also available on a Lake Champlain flood inundation web site established by the IJC (International Joint Commission , 2015). The USGS 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*. A link on this Web site connects to the USGS National Water Information System (U.S. Geological Survey, *2015a*), which presents the current stage at the USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, N.Y. to which the inundation maps are referenced. A second link connects to the NWS AHPS site (National Weather Service, *2015a*) so that the user can obtain applicable information on forecasted peak stage. The estimated flood-inundation maps are displayed in sufficient detail so that preparations for flooding and decisions for emergency response can be performed efficiently. Bridges are shaded—that is, shown as inundated—regardless of the flood magnitude. A shaded building should not be interpreted to mean that the structure is completely submerged; rather that bare earth surfaces in the vicinity of the building are inundated.

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 not static maps, for a given flood event, the lake stage and its' associated flood boundary extent at one USGS lake gage may not correspond to the lake stage and its' 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 National Weather Service (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 reaches 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*. 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 depth and 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 Vt. and Clinton in N.Y. - a length of approximately 100- mi 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 ft., NGVD 29) was compared to high-water mark data (Medalie and Olson, 2013), the stage USGS lake gage 04295000, Richelieu River

(Lake Champlain) at Rouses Point, N.Y., and to inundation map as determined from satellite imagery (Bjerklie et. al., 2014). 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 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 (Flynn, et. al., 2016, in review) 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 NWS forecast locations. The simulated water-surface flood elevation extents were created within a Geographic Information System (GIS) to delineate the estimated flood-inundation areas as shapefile polygons and lines. These flood-inundation polygons and 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 USGS Flood Inundation Mapping Science Web site (U.S. Geological Survey, 2015f).

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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