Prepared in cooperation with the International Joint Commission

Network Global Navigation Satellite System Survey to Harmonize United States and Canadian Datum for the Lake Champlain Basin

By Robert H. Flynn, Paul H. Rydlund Jr., and Daniel J. Martin

Scientific Investigations Report 2016–XXXX

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

U.S. Geological Survey, Reston, Virginia: 20xx
Revised and reprinted: 20xx

Suggested citation:
Flynn, R.H; Rydlund, P.H.; and Martin, D.J., 2016, Network Global Navigation Satellite System Survey to harmonize United States and Canadian Datum for the Lake Champlain Basin: U.S. Geological Survey Scientific Investigations Report 2016-XXXX, xx p. (http://dx.doi.org/10.3133 /sir/20xxxxxx.

Acknowledgments

The authors wish to thank the International Joint Commission for funding the Lake Champlain basin datum harmonization study as well as members of the International Lake Champlain Richelieu River Technical Working Group (TWG), Pierre-Yves Caux (International Joint Commission), Paul Boudreau of Environment Canada, Marc Veronneau (Natural Resources Canada, Canadian Geodetic Survey) and Joe Babb (US State Department detail assignment to International Joint Commission) for their role in determining the scope and design of this study. Members of the TWG include: Jean-Francois Cantin (Canadian co-chair of the TWG and Manager of the Hydrology and Ecohydraulics Section of the National Hydrologic Services of Environment Canada), Keith Robinson (United States co-chair of the TWG and Director of the US Geological Survey (USGS) New England Water Science Center), Richard Turcotte (Office of the Quebec, Canada Ministry of Sustainable Development and the Environment), William Saunders (National Weather Service), Vincent Fortin (Environment Canada), Daniel LeBlanc (Office of the Quebec, Canada Ministry of Sustainable Development and the Environment), Blaine Hastings (Vermont Department of Environmental Conservation), and Fred Dunlap (New York Lake Champlain Basin Coordinator).

The authors wish to thank Guy Morin and Julie Therien (Environment Canada) for providing reference mark and elevation data in Canada and for all of their help in locating and gaining access permission for the GNSS surveys in the Lake Champlain basin in Canada.

The authors wish to thank the following people for their efforts in collecting GNSS survey data from April 14 through April 16, 2015: Ann Chalmers (USGS, Vermont), John ”Duke” Erbland (USGS, South Carolina), Jonathan Graham (USGS, Georgia), Doug Nagle (USGS, South Carolina), and Glenn Berwick (USGS, New Hampshire).

The authors would also like to thank Madeleine Papineau (International Joint commission) and Stephanie Castle (Lake Champlain Basins Program) for administrative and secretarial support for this project.

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Conversion Factors

Inch/Pound to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
Square mile (mi^2)	2.590	Square kilometers (km^2)

Temperature in degrees Farenheit (°F) may be converted to degrees Celcius (°C) as follows:

$$^{o}C = (^{o}F - 32) / 1.8$$

Abbreviations

APC Antenna Phase Center

CGG 2013 Canadian Gravimetric Geoid model of 2013

CGS Canadian Geodetic Survey

CGVD 2013 Canadian Geodetic Vertical Datum of 2013

CGVD 28 Canadian Geodetic Vertical Datum of 1928

CORS Continuously-Operating Reference Station

CSRC Canadian Spatial Reference System

EC Environment Canada

FEMA Federal Emergency Management Administration

GNSS Global Navigation Satellite Systems

GRAV-D Gravity for the Redefinition of American Vertical Datum

IJC International Joint Commission

lidar	Light Detection and Ranging
NAD 83	North American Datum of 1983 (horizontal datum)
NAVD 88	North American Vertical Datum of 1988
NGS	National Geodetic Survey (US)
NGVD 29	National Geodetic Vertical Datum 1929
NOAA	National Oceanic and Atmospheric Administration
NSRS	National Spatial Reference System
NWS	National Weather Service
NRCan	Natural Resources Canada
OPUS	Online Positioning User Service
PPP	Precision Point Processing
RINEX	Receiver Independent Exchange Format
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
WGS 84	World Geodetic System 1984 ellipsoid
WSC	Water Survey Canada

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By Robert H. Flynn,[1] Paul H. Rydlund Jr.,[1] and Daniel J. Martin[2]

Abstract

Historically high flood levels were observed during flooding in Lake Champlain and the Richelieu River from late April through May, 2011. Flooding was caused by record spring precipitation and snowmelt from the third highest cumulative snowfall year on record, which included a warm, saturated late spring snowpack. Flood stage was exceeded for a total of 67 days from April 13, 2011 until June 19, 2011. During this period of high water, shoreline erosion and lake flood inundation were exacerbated by wind-driven waves associated with local fetch and lake-wide seiche effects. In May,2011, a new water surface elevation record was set for Lake Champlain. Peak lake level elevations varied at the three USGS lake level gages on Lake Champlain in 2011. The May 2011 peak elevations for Lake Champlain ranged from 103.20 ft. National Geodetic Vertical Datum 1929 at the northern end of Lake Champlain, at its outlet into the Richelieu River at Rouses Point, NY, to 103.57 ft NGVD 29 at the southern end of the Lake in Whitehall, NY. The water surface elevations for the Richelieu River in Canada are referenced to a different vertical datum from those in Lake Champlain in the United States,

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[1] U.S. Geological Survey

[2] National Oceanic and Atmospheric Administration

thus making an assessment of real-time flood water surface elevations and comparison of flood peaks in the Lake Champlain basin in the United States and Canada difficult.

On March 19, 2012, as a result of the flood event of April and May, 2011, the governments of Canada and the United States asked the International Joint Commission to draft a plan of study to examine the causes and the impacts of the spring of 2011 flooding on Lake Champlain and the Richelieu River and develop potential mitigation measures. Specific challenges noted by the work group included harmonization of vertical datum within the entire watershed. Harmonization of the vertical datum discrepancy is needed for flood assessment and future efforts to model the flow of water through the Lake Champlain basin in the United States and Canada.

In April 2015, the U.S. Geological Survey and Environment Canada began a joint field effort with the goal of obtaining precise elevations representing a common vertical datum for select reference marks used to determine water level elevations throughout Lake Champlain and the Richelieu River. In order to harmonize the datum difference between the United States and Canada, a Global Navigation Satellite System survey was conducted at nine locations in the Lake Champlain basin to collect simultaneous satellite data. These data were processed to produce elevations for two reference marks associated with dams and seven reference marks associated with active water-level gages (lake gages in Lake Champlain and streamgages in the Richelieu River) to harmonize vertical datum throughout the Lake Champlain basin. The GNSS surveys took place from April 14-16, 2015, at locations ranging from southern Lake Champlain near Whitehall, New York, to the northern end of the Richelieu River in Sorel, Quebec at its confluence with the St. Lawrence River in Canada.

Lake-gage elevations determined during the three-day survey were converted to elevations referenced to the North American Vertical Datum of 1988 using calculated offsets, and historic elevations. In this report, an “offset” refers to the adjustment that needs to be applied to published data from a particular gage to produce elevation data in the North American Vertical Datum of 1988. Offsets presented in this report can be used in the evaluation of water surface elevations in a common datum for Lake Champlain and the Richelieu River. In addition, the common datum referenced water level data (as determined from the offsets) may be used to calibrate flow models and support future modeling studies developed for Lake Champlain and the Richelieu River.

Introduction

During the spring and early summer of 2011, the Lake Champlain region experienced historic flooding because of a warm, saturated late spring snowpack coupled with spring rainfall across the St. Lawrence Basin (not shown). As a result of melting snow (from the third highest snowfall year on record (National Oceanic and Atmospheric Administration, 2012)) and rainfall, historic high flood levels were observed in Lake Champlain beginning in late April and continuing through May of 2011. Shoreline erosion and variable lake levels during this period of high water were exacerbated by wind-driven waves associated with local fetch and lake-wide seiche effects (Bjerklie et. al., 2014). Seiche effects (standing oscillating wave with a long wavelength) have been previously reported on the lake (Shanley and Denner, 1999) and are created by wind and atmospheric pressure changes.

In May, 2011, a new water surface elevation record was set for Lake Champlain. The maximum recorded stage at USGS lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point, NY (U.S. Geological Survey, 2015a) (fig. 1) was 103.20 ft as referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) on May 6, 2011.The maximum stage at USGS lake gage 04294500, Lake Champlain at Burlington, VT (U.S. Geological Survey, 2015b) (fig. 1) was 103.27 NGVD 29, also recorded May 6, 2011. The maximum recorded stage at the USGS lake gage 04279085, Lake Champlain North of Whitehall N.Y. (U.S. Geological Survey, 2015c) (fig. 1) was 103.57 ft (NGVD 29) on May 9, 2011. This lake elevation at Whitehall, NY was affected by wind and seiche. The water surface elevations for the Richelieu River in Canada are referenced to different vertical datums from those in Lake Champlain in the United States, thus making an assessment of real-time flood water surface elevations and comparison of flood peaks in the Lake Champlain basin in the United States and Canada difficult.

At U.S. Geological Survey (USGS) lake gage 04295000, Richelieu River (Lake Champlain) at Rouses Point (fig. 1), major flood stage, as designated by the National Oceanic and Atmospheric Administration (NOAA) - National Weather Service (NWS), 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 (NOAA-NWS, 2015). 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 recorded maximum 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). During this period of high water, shoreline erosion, flood inundation and damage were exacerbated by wind-driven waves associated with local fetch and lake-wide seiche effects resulting in wave heights in excess of three 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; FEMA, 2011) was made on June 15, 2011.

The flood event of April and May, 2011, resulted in governmental requests to the International Joint Commission to investigate options for flood mitigation. On March 19, 2012, the governments of Canada and the United States asked the International Joint Commission to draft a plan of study to examine the causes and the impacts of the spring 2011 flooding on Lake Champlain and the Richelieu River and develop potential mitigation measures. The International Joint Commission established the International Lake Champlain-Richelieu River Work Group to develop the requested plan of study (International Joint Commission, July 2013). Specific challenges noted by the work group included a harmonization of vertical datum within the entire watershed.

Discrepancies in the vertical datum for lake and stream gage data were observed at the border between the Canadian Geodetic Vertical Datum of 1928 (CGVD 28), the North American Vertical Datum of 1988 (NAVD 88), and the National Geodetic Vertical Datum of 1929 (NGVD 29), requiring geospatial datum harmonization for consistency and continuity. Published water levels indicate that the Missisquoi Bay water surface, as referenced to the CGVD 28, would be lower than at Rouses Point, in United States as referenced to the NGVD29, by approximately 0.354 ft. (10.8 cm) (where NGVD 29 – CGVD 28 = 0.354 ft) and greater than at Rouses Point as referenced to the NAVD 88 by approximately 0.098 ft. (3 cm) (where CGVD 28-NAVD88 = 0.098 ft.) (International Joint Commission, 2013). Harmonization of the vertical datum discrepancy was needed for flood assessment and future efforts to model the flow of water through the Lake Champlain basin in the United States and Canada. In April 2015, the U.S. Geological Survey and Environment Canada began a joint field effort with the goal of obtaining precise elevations representing a common vertical datum for select reference marks used to determine water level elevations throughout Lake Champlain and the Richelieu River.

Elevations as defined by ellipsoids, geoids, and topography are all attempts to model the shape of the earth using real world coordinates. An ellipsoid is spherical with a polar radius that is shorter in length than the equatorial radius. Its center coincides with the earth's predicted center and is best-fitted to the overall shape of the earth. The geoid is a model that represents the Earth's mean global sea level under the influence of gravitation and rotation alone. The vertical distance between the geoid and the ellipsoid is called the geoid height and it can be either positive or negative. Topographic heights are usually created using satellite, lidar or aerial photography with elevations computed relative to average sea level. The difference between the topographic elevation and the ellipsoid is called the ellipsoid height. The difference between the topographic elevation and the geoid is called the orthometric height (GISTutor, 2015).

In 2013, a new vertical datum for Canada was released by Natural Resources Canada (NRCan) to replace the CGVD 28 that was defined by mean sea level at tide gages on the Canadian east and west coasts. The new Canadian Geodetic Vertical Datum of 2013 (CGVD 2013) is a geoid-based datum (Natural Resources Canada, 2013). This surface, agreed to by the U.S. NGS and CGS in 2012, represents the mean potential of the mean sea level at a series of tide gages across Canada and USA.

The new Canadian vertical datum is evolved from the Canadian Gravimetric Geoid model of 2013 (CGG2013) (Natural Resources Canada, 2013).

In 1993, NAVD 88 was federally registered as the official vertical datum of the National Spatial Reference System (NSRS) for the Conterminous United States and Alaska and remains the official vertical datum to date. However, it should be noted that, with the exception of the recently (April 2015) established Lake Champlain near Grande Isle, VT lake gage 04294620, the U.S. lake gages on Lake Champlain have remained referenced to the older NGVD 29. NGS plans to replace NAVD 88 with a gravity-based vertical datum in 2022 under the GRAV-D (Gravity for the Redefinition of the American Vertical Datum) proposal in accordance to their 10-year plan (NOAA-NGS, 2014). NAVD 88 extends into Canada as do U.S. Geoid models (currently Geoid12A), but NAVD 88 was never adopted in Canada.

Purpose and Scope

The purpose of this report is to describe the data collection methods and the adjusted water-level data for the Lake Champlain basin such that all of the water level gages in the basin can be referenced to a single datum. The objective of this study was to obtain precise elevations for the nine Lake Champlain basin benchmarks (fig. 1), seven of which are part of the level circuit for active gages that provide real-time, continuous water-level data for Lake Champlain and continuous water level and discharge data for the Richelieu River. These gages are operated by the USGS in the United States and by Environment Canada (EC) in Canada. Water-level gages throughout the Lake Champlain Basin System (fig. 1) are used in the regulation of water levels. However, different vertical datum are used in the U.S. and Canada to determine water levels at these gages (table 1). In the U.S., Lake Champlain water surface elevation data are referenced to NGVD 29 and NAVD 88 while in Canada, the Richelieu River streamgages are referenced to CGVD 28. Comparable elevation data are needed for flood assessment and to develop accurate digital elevation models or hydraulic models that describe the movement of water through the Lake Champlain basin. Therefore, obtaining accurate elevation data in a uniform vertical datum is critical to understanding and managing water levels in Lake Champlain.

Figure 1. Map showing Lake Champlain Drainage Basin including GNSS surveyed lake gage, streamgage and dam benchmark locations.

Table 1. Lake Champlain and Richelieu River water level gages and dam benchmarks used in the GNSS Survey.

[ID, Identification; EC, Environment Canada; CGVD28, Canadian National Vertical Datum of 1928; USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum of 1929]

Benchmark ID	Station Name	Site Name	Agency	Vertical Datum	Gage Start Date	Gage End Date
92KSP76	02OJ022	Saint Lawrence River at Sorel, Quebec, Canada	EC	CGVD 28	1912	2011
78L264	-	Richelieu River at Saint-Ours Dam at Saint-Ours, Quebec, Canada	EC	CGVD 28		
732306	-	Richelieu River at Fryers dam at Chambly, Quebec, Canada	EC	CGVD 28		
Established	02OJ016	Richelieu River at Saint-Jean-Sur-Richelieu, Quebec, Canada	EC	CGVD 28	1972	Present
Established	02OJ036	Richelieu River at Saint-Paul-de-I'Ile-aux-Noix, Quebec, Canada	EC	CGVD 28	2011	Present
77L9003	02OH001	Lake Champlain at Philipsburg, Quebec, Canada	USGS	NGVD 29	1964	Present
USGS RM5	04295000	Richelieu River (Lake Champlain) at Rouses Point, NY, USA	USGS	NGVD 29	1871	Present
Established	04294500	Lake Champlain at Burlington, VT, USA	USGS	NGVD 29	1907	Present
Established	04279085	Lake Champlain North of Whitehall, NY, USA	USGS	NGVD 29	1999	Present

From April 14-16, 2015, personnel from USGS, EC and the U.S. National Geodetic Survey (NGS) and Canadian Geodetic Survey (CGS), took part in a joint effort to create a vertical datum transformation such that all water-surface elevation data in the Lake Champlain basin study area (comprised of the Lake Champlain, Richelieu River, and their floodplains) could be converted to either

NAVD 88, CGVD 28 or Canadian Geodetic Vertical Datum of 2013 (CGVD2013). A Global Navigation Satellite System (GNSS) survey was performed at 7 gage (4 lake gages and 3 streamgages) and 2 dam locations to collect simultaneous satellite data that were processed to obtain elevations with centimeter precision level ellipsoid heights referenced to the latest United States realization of the North American Datum of 1983 (NAD 83), currently NAD 83(2011) epoch 2010.00 (this geometric reference frame is equivalent to the Canadian NAD83(CSRS) epoch 2010.0). NAVD 88 or CGVD2013 orthometric heights were determined by applying either GEOID12A or CGG2013 geoid heights.

Study Area Description

Lake Champlain is a freshwater lake with approximately 435 square miles (sq. mi.) 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 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 (mi.) 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 region is narrow and river-like, the central region is wide with some small islands, and the northern region is the 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, 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 sq. miles 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 in New York and Vermont. Mean precipitation over the Lake Champlain watershed varies between 30 and 50 inches per year (in/yr) (between 760 and 1,270 millimeters per year) depending on location within the watershed (Howland et. al., 2006). The mean air temperature within the basin is 7 degrees Celcius (45 degrees Farenheit) (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). Lake Champlain has approximately 587 mi of shoreline and 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 an average annual variation between high and low average water levels of approximately 6 ft. and a maximum range of 9.4 ft, since the 1870s when daily records began (Lake Champlain Basin Program, 2015) .

After floods in the 1930s, a dam was built in 1939 at Fryers Island (not shown) 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 (fig. 1) were never done (International Joint Commission, 2013). The dam at Fryers Island 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.

Methods

In this study, the USGS, in cooperation with EC, NGS, and CGS, deployed dual-frequency survey-grade GNSS receivers, to conduct simultaneous static surveys (Canadian Geodetic Survey, 2003; Rydlund and Densmore, 2012; Canadian Geodetic Survey, 2013) at seven gage benchmarks on Lake Champlain and the Richelieu River and two benchmarks associated with two dams on the Richelieu River in Canada. Because of the different vertical datums in the U.S. and Canada, a height transformation was required to establish a common vertical datum for a study of flood elevations of the

Lake Champlain basin, which includes Lake Champlain and the Richelieu River. This transformation was required as a response to the Lake Champlain and Richelieu River Working Group data needs for hydraulic modeling and flood forecasting of Lake Champlain and the Richelieu River. The GNSS surveys were conducted at survey control disks (benchmarks) at lake gages, streamgages, and two dam locations within the Champlain-Richelieu floodplain. The survey measurements were used to create a vertical datum transformation such that all of the data available in the study area can be converted to either NAVD 88 or CGVD2013.

The approach to datum harmonization for Lake Champlain involved measuring the ellipsoid height to centimeter-level with GNSS static observations at seven lake and stream gaging locations in Whitehall, N.Y., USA; Burlington,Vt., USA; Rouses Point, N.Y., USA; Philipsburg, Quebec, Canada; Saint-Paul de l'Ile aux Noix, Quebec, Canada; Saint-Jean-sur-Richelieu, Quebec, Canada; and Sorel, Quebec, Canada along with two dam locations at Fryers dam at Chambly, Quebec, Canada and Saint-Ours dam at Saint-Ours, Quebec, Canada (figure 1). Orthometric heights, or elevations, were calculated from the ellipsoid heights using current geoid models (GEOID12A and CCG2013).

GNSS observations at benchmarks and differential levels were used to obtain precise elevations representing a common vertical datum for the targeted lake gage or streamgage reference marks. For this report, a benchmark is defined as the mark where the geodetic elevation was determined from the GNSS survey, a reference mark is defined as the mark that represents a perpetuated elevation used to determine water level at the lake gage or streamgage, and survey control refers to a mark with published vertical and horizontal datum. Reference marks were updated to the common vertical datum using differential levels to perpetuate the GNSS surveyed elevations from the benchmarks. In some cases the benchmark was also the reference mark.

GNSS observations were conducted over survey reference marks that represented the origin of a differential leveling circuit at each of the nine locations described above. Benchmarks were established at two Lake Champlain lake gage locations and two Richelieu River streamgage locations because of their lack of suitability for GNSS satellite observations, distance of established monuments from survey control, or absence of survey control. Benchmarks were established for GNSS observations on April 14, 2015 at the following lake gage locations: USGS lake gage 04279085, Lake Champlain North of Whitehall N.Y. and USGS lake gage 04294500, Lake Champlain at Burlington, VT; and at the following streamgage locations: EC streamgage 02OJ016 Saint-Jean-sur-Richelieu, Quebec and EC streamgage 02OJ036 Saint-Paul-de-I'Ile-aux-Noix, Quebec. Elevations from all established benchmarks or available reference marks were perpetuated to the established leveling network (Kenney, 2010 and CGS, 2013) of the lake gage or streamgage by way of differential leveling. The remaining sites had pre-established benchmarks that were acceptable for the GNSS survey and the differential leveling survey to tie to the reference marks in the established lake gage or stream gage level network.

GNSS observations at lake gages and stream gages consisted of simultaneous twelve-hour observations on April 15, 2015 followed by simultaneous six-hour observations on April 16, 2015, for redundancy. GNSS observations at Fryers dam at Chambly (seven-hours) and Saint-Ours dam at Saint-Ours (six-hours) consisted of simultaneous five-hour observation on April 14, 2015. There was no redundant observation the following day (April 15, 2015) at Fryers dam at Chambly and Saint-Ours dam.

Although four-hour observations are generally sufficient for geodetic control nationwide, along with recommended redundant four-hour observations to increase confidence, the observation sessions for this study consisted of twelve-hour observations with redundant six-hour observations for additional precision. Observations longer than four hours yield a small improvement in precision (Eckl et. al.,

2001)   It is commonly accepted that longer observations will yield more precise results of the NAD 83 ellipsoid height which translates to a greater precision of the NAVD 88 orthometric height estimate.

Although the GNSS antennas were all micro-centered, all antennas were oriented to north for added precision. The orientation plays a part in the precision when using the absolute antenna phase center (APC) models since they include not only the elevation but also the azimuth of the satellite. Continuously Operating Reference Station (CORS) network antennas are also oriented to north.

GNSS observations for the lake gage and stream gage locations, along with the locations at the dams were initially post-processed in the U.S. using the NGS Online Positioning User Service (OPUS; National Geodetic Survey, 2015b). OPUS solutions will be shared to the OPUS database. The GNSS observations were also processed by the Canadian Geodetic Survey (CGS) using NRCan Canadian Spatial Reference System - Precise Point Positioning (CSRS-PPP).

Field Data Collection

USGS field crews deployed 7 static GNSS units in the U.S. and Canada for GNSS data collection from April 15, 2015 (Julian day 105) through April 16, 2015 (Julian day 106) at specified lake and streamgage locations (table 1, fig. 1). Field crews deployed static GNSS units in Canada for satellite data collection on April 14, 2015 (Julian day 104) at two dam locations (table 1, fig. 1). Field data-collection procedures used during the GNSS surveys followed guidelines established for static network surveys as described in NRCan (Canadian Geodetic Survey, 2013) and USGS guidelines (Rydlund and Densmore, 2012). A clear view of the sky was available during GNSS observations at all locations on the dates of April 14 through April 16, 2015. Four benchmarks were established and differential levels were used to measure elevation differences between GNSS observation benchmarks and gage reference marks. Log files from the GNSS surveys are available in Appendixes 1 and 2, and contain details such as antenna height during data collection and descriptive location of the benchmarks.

Instantaneous water levels were obtained at each site using readings from active gages as disseminated from the National Water Information System Web Interface (NWIS-Web) (NWIS, 2015) and Environment Canada Wateroffice (Environment Canada, 2015) or measured directly from the established reference mark using differential levels.

Potential limitations to the GNSS survey were poor satellite data quality, errors in leveling between GNSS survey benchmarks and reference marks and GNSS multipath errors. Multipath errors are a result of reflected signals to the GNSS receiver and may be due to proximity of the GNSS units to the water surface combined with surrounding tree cover. In reviewing the data, satellite and data quality were determined to be good.

Data Processing

Environment Canada, (in cooperation with the CGS) and USGS (in cooperation with U.S. NGS)processed GNSS observations independently using different methods. Canadian Geodetic Survey staff processed the static GNSS survey data using CSRS-PPP (Kouba and Heroux, 2001) to obtain ellipsoid heights. The Canadian Gravimetric Geoid model of 2013 (CGG 2013) was applied to post-process data from CSRS-PPP to obtain orthometric heights in CGVD 2013 (Huang and Veronneau, 2013; Veronneau and others, 2014a; Veronneau and others, 2014b). NOAA-NGS personnel processed the GNSS static survey data through the NGS OPUS software (OPUS; NGS, 2015b) to establish survey grade geographic and grid coordinates, along with ellipsoid heights (NGS, 2012b). NAVD 88 orthometric heights were calculated using GEOID12A (NGS, 2012a) for each benchmark. A network adjustment of all benchmarks relative to the CORS network (National Geodetic Survey, 2015a) was conducted using OPUS Projects (National Geodetic Survey, 2014c). Results of data processing using OPUS Projects are presented in Appendix 4 of this report for converting water surface elevation data at a gage to a single, uniform vertical datum (Huang and Veronneau, 2013; Veronneau and others, 2014a; Veronneau and others, 2014b).

Gage Datum Offsets

The Canadian streamgage and U.S. lake gage vertical datums used for water surface elevation determination are presented in table 1. GNSS-derived elevation data were used to develop offsets for conversion of published water levels to NAVD 88 elevations, either through GNSS observations at gage reference marks or differential leveling between established monuments with GNSS observations and gage reference marks. Offset elevation data presented are based on conversion of datum to NAVD 88 from published datum in either NGVD 29 or CGVD 28.

Results

The measured ellipsoid and orthometric heights of all survey points computed with the NGS OPUS Projects software (OPUS; NGS, 2015b) are presented in table 2. Results of the OPUS static data processing can be found in Appendix 2. Leveling information between GNSS-surveyed points and gage reference marks can be found in Appendix 3.

Table 2. Global Navigation Satellite System benchmark survey results from OPUS-Projects network adjustment.

[ID, identification; OPUS, Online Positioning Users Service; ft, feet; WGS 84, World Geodetic System 1984; NAVD 88, North American Vertical Datum of 1988]

Benchmark ID	Station Name	Site Name	(1)OPUS Ellipsoid Height (ft)	Geoid Height, N_{12} (ft)	OPUS Orthometric Height (ft)
			WGS 84	GEOID12A	NAVD 88
92KSP76	02OJ022	Saint Lawrence River at Sorel, Quebec, Canada	-75.889	-102.812	26.923
78L264	-	Richelieu River at Saint-Ours Dam at Saint-Ours, Quebec, Canada	-56.486	-102.073	45.587
732306	-	Richelieu River at Fryers dam at Chambly, Quebec, Canada	-30.463	-99.636	69.173

Established	02OJ016	Richelieu River at Saint-Jean-Sur-Richelieu, Quebec, Canada	0.758	-98.747	99.505
Established	02OJ036	Richelieu River at Saint-Paul-de-I'Ile-aux-Noix, Quebec, Canada	11.499	-97.316	108.816
77L9003	02OH001	Lake Champlain at Philipsburg, Quebec, Canada	5.755	-96.667	102.421
USGS RM5	04295000	Richelieu River (Lake Champlain) at Rouses Point, NY, USA	5.558	-96.572	102.129
Established	04294500	Lake Champlain at Burlington, VT, USA	7.169	-95.364	102.533
Established	04279085	Lake Champlain North of Whitehall, NY, USA	6.066	-96.745	102.812

[1]WGS 84 as part of NAD83(2011) Epoch 2010.00

Offsets between published gage water levels and NAVD 88 elevations were developed using GNSS-derived elevations and differential leveling information (Appendix 4). Daily mean, maximum, and minimum water levels (NAVD88) for the data collection period (Julian days 104-106) at USGS instantaneous lake elevation gages in Lake Champlain were calculated (fig. 2). The average water-surface elevation at Whitehall, N.Y., in the southern part of Lake Champlain, was higher than the water surface elevation in the northern part of the lake (Rouses Point, N.Y. and Burlington, Vt.) (fig. 2). Wind and seiche were contributing factors to the higher elevation in the southern part of the lake.

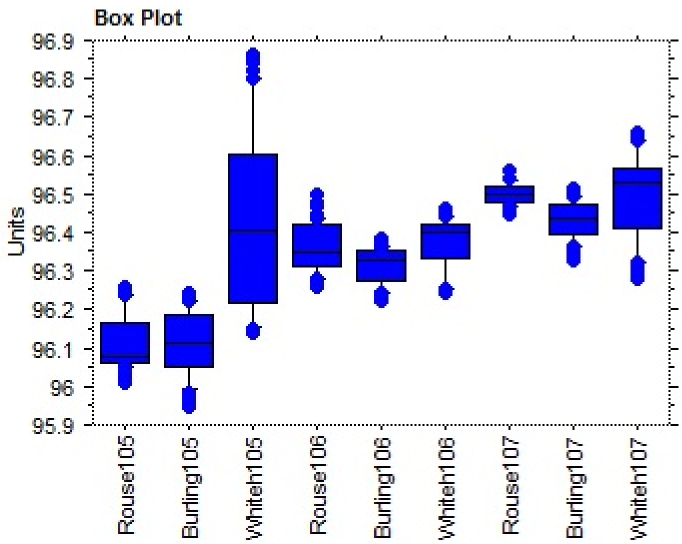
Instantaneous lake level gages for Lake Champlain are located in Philippsburg, Quebec, Canada (EC streamgage 02OH001), Rouses Point, NY (USGS lake gage 04295000), Burlington, VT (USGS lake gage 04294500), and Whitehall, NY (USGS lake gage 04279085). Instantaneous streamgages in the Richelieu River in Quebec, Canada are located at Sorel (EC streamgage 02OJ022), Saint-Jean-Sur-Richelieu (EC streamgage 02OJ016), Saint-Paul-de-I'Ile-aux-Noix (EC streamgage 02OJ036) (fig. 1). Elevation offset information between GNSS-derived benchmarks and gage reference marks can be found in table 3 and Appendix 4.

Table 3. Offsets for conversion of published water levels to water surface elevations in the North American Vertical Datum of 1988 for stream and lake gages in Lake Champlain and the Richelieu River.

[Offset, the amount added or subtracted to convert published gage data to elevations in NAVD 88; Units, the unit of the corresponding correction which also corresponds to units of published data; ft., feet; NAVD 88, North American Vertical Datum 1988; EC, Environment Canada; CGVD 28, Canadian Geodetic Vertical Datum of 1928; USGS, U.S. Geological Survey; NGVD 29, National Geodetic Vertical Datum 1929]

Station Name	Site Name	Agency	Datum of Published Elevation Data	[1]Offset (ft.) to convert Published Elevation Data to NAVD 88
02OJ022	Saint Lawrence River at Sorel, Quebec, Canada	EC	Elevation, CGVD 28	+0.115
02OJ016	Richelieu River at Saint-Jean-Sur-Richelieu, Quebec, Canada	EC	Elevation, CGVD 28	-0.061
02OJ036	Richelieu River at Saint-Paul-de-I'Ile-aux-Noix, Quebec, Canada	EC	Elevation, CGVD 28	-0.206
02OH001	Lake Champlain at Philipsburg, Quebec, Canada	EC	Elevation, CGVD 28	-0.213
04295000	Richelieu River (Lake Champlain) at Rouses Point, NY, USA	USGS	Elevation, NGVD 29	-0.431
04294500	Lake Champlain at Burlington, VT, USA	USGS	Elevation, NGVD 29	-0.523
04279085	Lake Champlain North of Whitehall, NY, USA	USGS	Elevation, NGVD 29	-0.268

[1] The number of decimal places shown corresponds to the number of decimal places published for the site



[graph to be updated to USGS publications unit standards]

Figure 2. Daily mean, maximum, and minimum water levels in North American Vertical Datum of 1988 elevations, from GNSS survey, for the data collection period (Julian days 105-106) at USGS lake Gages in Lake Champlain.

Summary

During the spring and early summer of 2011, the Lake Champlain region experienced historic flooding due to a warm, saturated late spring snowpack coupled with spring rainfall across the St. Lawrence Basin. As a result of melting snow (from the third highest snowfall year on record) and rainfall, historic high flood levels were observed in Lake Champlain beginning in late April through May of 2011. Flood stage was exceeded for a total of 67 days from April 13, 2011 until June 19, 2011. Shoreline erosion and variable lake levels during this period of high water were exacerbated by wind-driven waves associated with local fetch and lake-wide seiche effects (Bjerklie et. al., 2014). May 2011 peak elevations for Lake Champlain ranged from 103.2 ft. National Geodetic Vertical Datum 1929 (NGVD 29) at the northern end of Lake Champlain, at its outlet into the Richelieu River at Rouses Point, NY, to 103.57 ft. NGVD 29 at the southern end of the Lake in Whitehall, NY. An assessment of flood water surface elevations in the basin was difficult as the water surface elevations for the Richelieu River in Canada are referenced to a different vertical datum from those in the United States, thus making an assessment of real-time flood elevations and comparison of flood peaks in the Lake Champlain basin difficult.

As a result of the flood event of April and May, 2011, the governments of Canada and the United States asked the International Joint Commission to draft a plan of study to examine the causes and the impacts of the spring of 2011 flooding on Lake Champlain and the Richelieu River and develop potential mitigation measures. Specific challenges noted by the work group included a harmonization of vertical datums within the entire watershed for future efforts to model the flow of water through the Lake Champlain basin.

In April 2015, the U.S. Geological Survey (USGS) and Environment Canada began a joint field effort with the goal of obtaining precise elevations representing a common vertical datum for select reference marks used to determine water level elevations throughout Lake Champlain and the Richelieu River. In order to harmonize the datum difference between the United States and Canada, a Global Navigation Satellite System survey was conducted at nine locations to collect simultaneous satellite data that were processed to produce elevations for two reference marks associated with dams and seven reference marks associated with active water-level gages (lake gages in Lake Champlain and streamgages in the Richelieu River) throughout the Lake Champlain basin. The GNSS survey occurred April 14-16, 2015, at locations ranging from southern Lake Champlain near Whitehall, New York, to the northern end of the Richelieu River in Sorel, Quebec (at its confluence with the St. Lawrence River in Canada).

Precise elevations were obtained in a uniform vertical datum of North American Vertical Datum of 1988 (NAVD 88) at benchmarks used in the Global Navigation Satellite System (GNSS) survey for datum harmonization of water levels at seven gage sites and two dam locations located in Lake Champlain and the Richelieu River. Environment Canada, in cooperation with the Canadian Geodetic Survey processed raw static GNSS survey data using NRCan Canadian Spatial Reference System - Precise Point Positioning (CSRS-PPP). United States Geological Survey (USGS), in cooperation with United States National Oceanic and Atmospheric Administration - National Geodetic Survey (NOAA-NGS) processed static data independently using Online Positioning User Service (OPUS) Projects. Results from the network adjustment of the static GNSS survey data processed using OPUS-Projects were selected for calculating offsets that convert published gage water levels to NAVD 88 elevations.

Lake-gage elevations determined during the three-day survey were converted to elevations referenced to the North American Vertical Datum of 1988 using calculated offsets, and elevations demonstrated good hydrologic agreement among gages. Water-level offsets, determined as a result of the GNSS survey in the Lake Champlain basins, can be used in the evaluation of flow from Lake Champlain in the US through the Richelieu River in Canada. Water level corrections will provide the information needed to calibrate flow models developed by EC for the Richelieu River and Lake Champlain. Furthermore, improved accuracy of water elevations will enhance a digital elevation model being developed by Environment Canada and will benefit other modeling studies designed to assess the effects of flooding in the Lake Champlain basin.

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Appendixes

Appendix 1. Global Navigation Satellite System data collection information for all benchmarks surveyed in this study; the appendix is available electronically and is not included in the body of this report.

Appendix 2. Files from processing of raw data collected at benchmarks using global navigation satellite systems; the appendix is available electronically and is not included in the body of this report.

Appendix 3. Surveyor leveling information for sites with benchmarks that could not be surveyed directly using global navigation satellite systems; the appendix is available electronically and is not included in the body of this report.

Appendix 4. Elevation offset information for benchmarks surveyed directly using global navigation satellite systems; the appendix is available electronically and is not included in the body of this report.