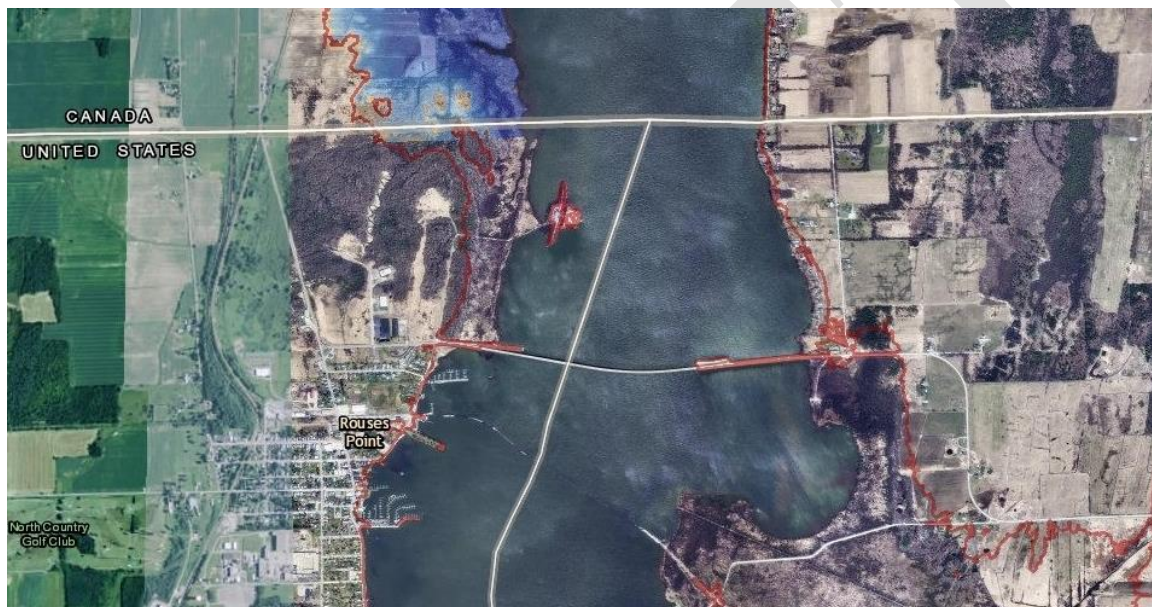


DRAFT REPORT

Toward an operational real-time flood forecasting and flood inundation mapping system for the Lake Champlain and Richelieu River

Preparatory works and basic static flood maps



Prepared for the
International Joint Commission
by the
International Lake Champlain - Richelieu River
Technical Working Group



October 14, 2015

Executive Summary

In the one year from October 1, 2014 to September 30, 2015 a number of federal and state/provincial agencies worked together to enhance flood preparedness and warnings for Lake Champlain and the Richelieu River (LCRR). This effort was the result of a Directive of the Canadian and United States governments led by the International Joint Commission (IJC) in response to severe flooding in the area in 2011 and a subsequent 2013 Plan of Study (PoS) that identified measures to mitigate flooding and flood impacts in the LCRR watershed.

On July 24 and July 31, 2014 the governments of the US and Canada, in accordance with Article IX of the Boundary Waters Treaty, requested that the IJC assist the two governments in:

1. Addressing and closing data gaps through data collection and harmonization of topographic, bathymetric, aquatic vegetation, soil texture, LiDAR and observed climate and hydrometric data collection (per section 3.1, p. 34 of the July 2013 PoS) as are necessary as a basis for the earliest possible initiation of a real-time flood forecasting and inundation mapping system. This system would consist of the development of new real-time LCRR hydrologic and hydraulic models for predicting lake and river levels, and a precise DEM of the flood plain to delineate the contours of corresponding inundated areas.
2. Creation of static flood inundation maps using a combination of existing and new data and modeling to provide practical information to communities. These maps would show which areas would be affected if LCRR water levels hit different heights.

Under the guidance of the International Lake Champlain-Richelieu River (ILCRR) Technical Working Group (TWG) gaps in specific aspects of the required elements for a future forecasting system were addressed, a suggested pragmatic approach for a future flood forecasting system was developed, and a series of static maps of flood inundation under specific scenarios in response to component 2 of the directive were prepared.

Accomplishments from this collective Canadian-United States effort include:

1. **New LiDAR data** were collected for drainage to Lake Champlain in New York State. When this LiDAR data along with new LiDAR data for Vermont is released, a complete LiDAR data set will be available of the entire LCRR basin.
2. **Hydrologic and watershed data** for areas of the LCRR basin were collected and used to create an experimental two-dimensional hydro-dynamic model of Lake Champlain and the Richelieu River.
3. **Meteorological data evaluation** to assess current abilities to predict short- and long-term precipitation, wind and temperatures for the LCRR basin. Data and predictions from a variety of US and Canadian sources were used in this evaluation. Results indicates it is possible to forecast the North-South component of the wind for three day out periods for flood forecasting purposes, but a calibration/downscaling procedure will be required before wind forecasts can be used by hydrodynamic models. Precipitation forecasts to the 5-day lead-time also provide reliable forecasts for flood modeling purposes.
4. **Vertical datum corrections** were developed for critical lake and river water level measuring points so that a common vertical datum could be used on both sides of the international border. This has been a previous issue when comparing observed Lake Champlain and Richelieu River water levels. This problem is now solved.

5. **Experimental 2-dimensional hydrodynamic lake modeling for Lake Champlain and Richelieu River** was performed using existing and new data collected for this study. Results of the modeling found that high lake levels on Lake Champlain could be reasonably simulated with this model and that the model provides a good foundation for future modeling of the lake and Richelieu River to Chambly. Additional bathymetric data of the Saint-Jean-sur-Richelieu sill and from Chambly downstream to Sorel will be needed to simulate river flows and flooding accurately.
6. **Static Flood Inundation maps for portions of the Lake Champlain shoreline and the Richelieu River above Chambly** were created for 11 flood level scenarios. These maps are designed to show what land areas would be flooded during the 11 scenarios, and are hoped, to be a valuable product for local and state emergency responders and local officials. The maps will be available on the web so locals can get quick access to them. These maps are static and therefore do not reflect actual wind and wave conditions that could influence the extent of flooding. A complete LiDAR Digital Elevation Model available in Canada also allowed for the representation of inundation depths for the 11 flood scenarios.
7. **Future Improved and Coordinated Flood Forecasting** is possible and a pragmatic approach is described. The approach is based on using a probabilistic approach to the modelling system and an international coordination body to issue the best possible joint flood forecast to the agencies responsible for flood warnings and flood plain mapping.

The study also provides specific recommendations for future flood forecasting and preparedness; these recommendations include:

1. To generate flood forecasts and real-time flood mapping system, the TWG recommends that the proposed U.S. - Canada two-pronged probabilistic approach presented in section 5 for the forecasting of floods should be adopted and implemented operationally, including the modelling of wind set-up and wave action.
2. To calibrate and validate a future forecasting system, the TWG recommend that the both the Port Henry and the Grand Isle water level stations installed to support this Study, be kept in operation at a minimum to collect data covering a representative range of water levels supporting the calibration of the hydraulic model, recognising that those stations may or may not be required in the context of an operational system. The TWG also recommends, at least during the calibration phase of a wave model, the installation of wave buoys in both the main part of the lake and in the inland sea.
3. The TWG recommends that a binational coordination body under the auspices of the IJC be instituted to conduct the coordination among agencies involved in real-time forecasts, namely on the development and maintenance of the models, availability of observation data, quality control of the ensemble predictions and generate the bi-national water level predictions and a consistent message to emergency responders and public regarding the bi-national water level predictions for distribution to agencies responsible for dissemination.
4. To allow for a better flood forecasting capacity of the entire LCRR, the TWG recommends that the acquisition of new bathymetric data of the Richelieu River between Sorel and the natural control section near Saint-Jean-sur-Richelieu, and that updated maps of substratum and aquatic plant assemblages be completed.

5. To generate flood forecasts and real-time flood mapping products for the entire Lake Champlain Richelieu River system, as well as static maps, the TWG recommends that a single consistent DEM be created for the entire LCRR basin once all LiDAR and bathymetric data acquisition and quality control is completed.
6. The TWG recommends that the static flood inundation maps be generated for the entire Lake Champlain Richelieu River system.

DRAFT

Acknowledgements

This work has been carried out with the assistance of many individuals, who participated either in the technical workshop, in targeted user meetings, or who worked directly with the members of the International Lake Champlain-Richelieu River Technical Working Group to carry out field work, complete analysis, draft technical reports or create maps. The Working Group expresses its sincere appreciation to each and all.

This Study is respectfully submitted to the International Joint Commission (IJC) by the International Lake Champlain-Richelieu River Technical Working Group composed of:

U.S. Membership

Keith Robinson (Co-Chair)
Blaine Hastings
Fred Dunlap
William Saunders
Stephanie Castle (Secretary)

Canadian Membership

Jean-François Cantin (Co-Chair)
Daniel Leblanc
Richard Turcotte
Vincent Fortin
Madeleine Papineau (French language service)

Table of content

Executive Summary	ii
Acknowledgements.....	v
Table of content	vi
1 Introduction to the Lake Champlain-Richelieu River Study	1
1.1 Background	1
1.2 The scope and organization of this study	3
1.3 Communication of the Study Plans and Results	6
2 Data Gathering and Development.....	7
2.1 Collection and processing of LiDAR Data for Lake Champlain	7
2.2 Collection of new in-lake and watershed data to assist with flood forecasting and inundation mapping system	8
2.3 Collection of new substratum, aquatic plant assemblages and distribution in the Richelieu River between Saint-Jean-sur-Richelieu and Rouses Point on the Lake Champlain	11
2.4 Coordination mechanism to exchange data of interest.....	13
2.5 Consolidation and Harmonization of U.S. Data.....	13
2.6 Address Differences between Vertical Datums along the US/Canada Border	15
3 Studies on Meteorological Forecasting, Lake and River Modeling and Creation of Digital Elevation Models	17
3.1 Assess the quality of surface wind predictions and precipitation analyses	17
3.2 Implement an experimental 2D hydrodynamic model of Lake Champlain, using existing bathymetric data.....	21
3.3 Development of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel	30
3.4 Creation of a quality-controlled Digital Elevation Model from available LiDAR data sets along the Richelieu River and Missisquoi Bay of Lake Champlain.....	32
4 Creation of static flood inundation maps	36
4.1 Selected static scenarios	36
4.2 Creation of static inundation maps.....	38
4.3 Quality control of the mapping products.....	44
4.3.1 Residual flood line contour discrepancies near the border	44
4.3.2 Wind set-up and wave action.....	45
4.3.3 Simulated VS observed 2011 flooding	45
4.4 Availability of the Inundation Maps	46

4.5	Future flood inundation mapping in the LCRR Basin	47
4.6	Comments from targeted users and stakeholders meetings	48
5	A Pragmatic Approach for Flood Forecasting and Inundation Mapping	50
5.1	Vision for the next generation of flood forecasting system and real time flood inundation mapping	50
5.2	Technical workshop key points and other input from informal consultations with experts	53
5.3	A pragmatic approach for a future operational flood forecasting and flood inundation mapping system	55
5.3.1	Coordination	55
5.3.2	Linking model results to inundation Mapping	56
5.3.3	Wave modelling	56
5.3.2	Forecast models options	57
6	Summary of findings and recommendations	58
6.1	Findings related to the real-time flood forecasting and inundation mapping system	58
6.2	Findings on the flood mapping products	60
6.3	Recommendations	61
	ANNEX 1 References from the Governments	63
	ANNEX 2 IJC Directive	69
	ANNEX 3 Members of the International Lake Champlain-Richelieu River Technical Working Group and its technical and secretariat support	72
	ANNEX 4 Experts present at the IAGLR Water Level Prediction Workshop	75
	ANNEX 5 References	76
	ANNEX 6 Cited Organizations and list of Acronyms	78

1 Introduction to the Lake Champlain-Richelieu River Study

This report describes the results of a one year effort from October 1, 2014 to September 30, 2015 to enhance flood preparedness and warnings for Lake Champlain and the Richelieu River (LCRR) system, whose watershed is illustrated in figure 1.1. This effort was the result of a Directive of the Canadian and United States governments led by the International Joint Commission (IJC) in response to severe flooding in the area in 2011 and a subsequent 2013 Plan of Study (PoS) that identified measures to mitigate flooding and flood impacts in the LCRR watershed. The results obtained from these current efforts represent the collective work of a number of federal, state and provincial agencies.

1.1 Background

The extreme flooding in 2011 of the LCRR, in the United States (US) and Canada brought public attention to the need for improved flood warning, preparedness and mitigation of flooding and associated impacts in this international watershed. The 2011 Lake Champlain levels were the highest in recorded history, reaching 103.27 feet (31.477 m above mean sea level, NGVD 29) at the Rouses Point lake gauge in New York. Downstream of the Lake, the Richelieu River flooded extensive areas in the Province of Quebec including the city of Saint-Jean-sur-Richelieu. In total, approximately \$88 million in damages occurred in the US and Canada collectively from this flooding.

The 2011 flooding was not an isolated event. Severe flooding in Lake Champlain and or the Richelieu River has occurred three other times in the past century. Major flood stage in Lake Champlain occurred in 1932, 1972, and 1992. Most of these floods were the result of a combination of melting snowpack with rainfall in the late winter and spring months. Over the last 100 years, a number of flood control strategies and structures have been proposed, but none have been fully implemented. The 2013 PoS for *The Identification of Measures to Mitigate Flooding and the Impacts of Flooding of Lake Champlain and Richelieu River* presents a more detailed description of the history of flooding in the LCRR basin.

The IJC has conducted several studies of flooding and flood mitigation activities and impacts in the LCRR basin since the 1932 floods. The main studies can be found on the IJC website at http://www.ijc.org/en/Reports_and_Publications. Studies followed a major flood event. In response to the 1930s flooding, the IJC performed studies, presented a plan for and approved construction and operation of flood control works in the Richelieu River in Quebec for the reclamation and protection from flooding of lowlands in Quebec. The Fryers Dam, with thirty-one gates, each thirty feet wide was completed at Fryers Island in 1939. Other project components, including the construction of dikes in the vicinity of the dam and the dredging through the rock sill at Saint-Jean-sur-Richelieu were not done. Since all project components were not completed, the Fryers Dam, was never placed into operation. The dam still exists today.

In 1973, the IJC, based on a US and Canada reference, studied the desirability of regulating outflows from Lake Champlain and possible interim measures which could be instituted to alleviate flooding. The Study Board created for this study examined the use of the Fryers Island Dam, a possible new control structure and a number of dredging alternatives in the

Saint-Jean-sur-Richelieu Rapids and published the results in a 1975 and a 1981 report. The Commission concluded that it was technically feasible to build and operate a gated control measure at Saint-Jean-sur-Richelieu in conjunction with dredging the natural control section, however the Commission was unable to determine the desirability of this option. Only a few of the suggested actions were completed, mostly those related to flood plain mapping and a flood forecasting and warning system in the U.S..

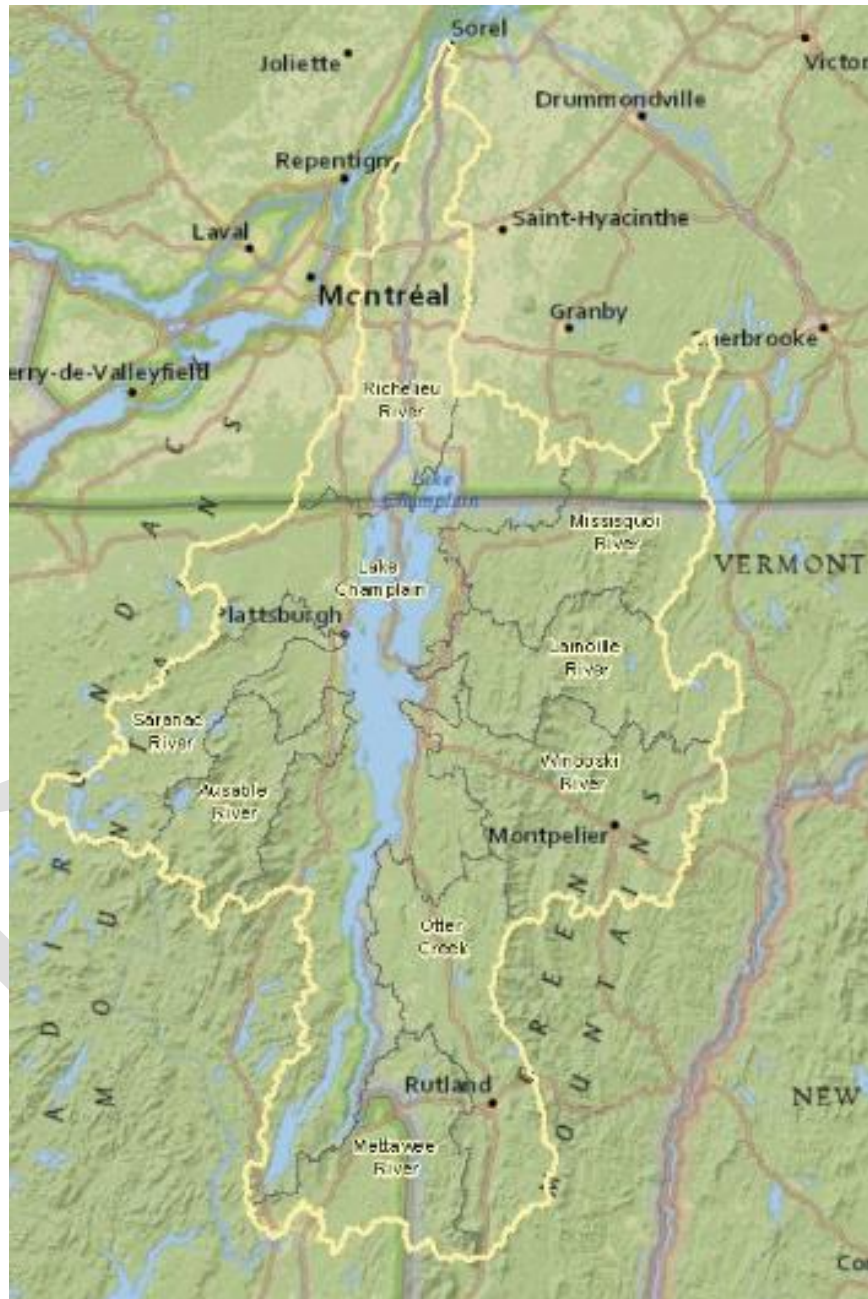


Figure 1.1 – Location of Lake Champlain and the Richelieu River system and its watershed boundaries

In 2013, the IJC developed a Plan of Study (PoS) for the LCRR, following the 2011 floods and peak of record for lake levels in Lake Champlain. This PoS presented a number of options that could be studied for mitigating flooding for the LCRR. Foremost was the recommendation to create a bi-national Study Board to coordinate studies regarding flooding on both sides of the international border and to develop state-of-the-art techniques to monitor and develop physical, social-economic and ecological response models. Local governments were encouraged to take action by implementing best management practices and putting in place a culture of flood preparedness and flood resiliency. Finally, coordinated flood preparedness, forecasting and response actions among local, state, provincial and federal governments were recommended to be strengthened.

Based on the 2013 PoS, the IJC issued a series of recommendations to the Governments, including that hydrologic and hydraulic modelling of the system be implemented. To that end, the PoS identified the basic elements that are required for the operation of a real-time flood forecasting and inundation mapping system, summarized below:

1. Weather forecasts with high resolution wind, precipitation and temperature estimates and a precise evaluation of the snowpack;
2. A Digital Terrain Model (DEM) of the flood plain (horizontal resolution of 1m, vertical resolution of 0.25m) and of the watershed's geophysical characteristics (horizontal resolution of 100m and vertical resolution of 1m);
3. A hydrological modelling capacity for the estimation of water supplies to the watershed with a lead-time as long as possible;
4. A hydraulic modelling capacity to simulate the response of LCRR to predicted water supplies and winds.

1.2 The scope and organization of this study

On July 24 and July 31, 2014 the governments of the US and Canada, in accordance with Article IX of the Boundary Waters Treaty, requested that the IJC assist the two governments in the implementation of two components of the July 2013 LCRR PoS. The two scalable components from the PoS to be initiated and completed by the IJC are:

1. Addressing and closing data gaps through data collection and harmonization of topographic, bathymetric, aquatic vegetation, soil texture, LiDAR and observed climate and hydrometric data collection (per section 3.1, p. 34 of the July 2013 PoS) as are necessary as a basis for the earliest possible initiation of a real-time flood forecasting and inundation mapping system. This system would consist of the development of new real-time LCRR hydrologic and hydraulic models for predicting lake and river levels, and a precise DEM of the flood plain to delineate the contours of corresponding inundated areas.
2. Creation of static flood inundation maps using a combination of existing and new data and modeling to provide practical information to communities. These maps would show which areas would be affected if LCRR water levels hit different heights.

The complete reference letters sent to the IJC by the US and Canadian governments are provided in *Annex 1*.

In response to the government's joint reference, the IJC developed a directive to establish and direct the International Lake Champlain-Richelieu River (ILCRR) Technical Working Group (TWG) to examine and report to the IJC on the matters identified by the governments in their July 24 and July 31, 2014 reference letters to the Commission on LCRR flooding, by September 2015. The directive is provided in *Annex 2*.

The TWG worked to close some gaps in specific aspects of the required elements for a future forecasting system (component 1 of the directive). It should be noted that the actual implementation of a coordinated operational real-time flood forecasting and inundation mapping system on the LCRR is beyond the scope of this directive. The present work has exclusively analyzed the general scientific components and coordination requirements for suitable forecasting systems. Also, a combination of existing and new data and models were used to generate static maps of flood inundation under specific scenarios (component 2 of the directive).

The various tasks completed by this Study are essentially those identified in the work plan approved by the IJC which is posted on the IJC website (http://ijc.org/en/_LCRRTWG).

The specific activities that were identified as required to meet the IJC Directive were:

Task 1-1 Assess the quality of surface wind predictions and precipitation analyses for the LCRR

Task 1-2 Develop an experimental 2D hydrodynamic model of Lake Champlain, using existing bathymetric data

Task 1-3 Establish a coordination mechanism to exchange data of interest

Task 1-4 Recommend a pragmatic approach for the future operational real-time flood forecasting and inundation mapping system for LCRR flood plain

Task 1-5 Collection and processing of LiDAR data for Lake Champlain

Task 1-6 Address Differences between Vertical Datums along the U.S./Canada Border

Task 1-7 Collection of new in-lake and watershed data to assist with the flood forecasting and inundation mapping system

Task 1-8 Collection of new substratum, aquatic plant assemblages and distribution in the Richelieu River between Saint-Jean-sur-Richelieu and Rouses Point on the Lake Champlain

Task 2-1 Consolidation and Harmonization of US Data to be used in lake and river modeling

Task 2-2 Creation of a quality-controlled Digital Elevation Model from available LiDAR data sets along the Richelieu River and Missisquoi Bay of Lake Champlain

Task 2-3 Set-up of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel

Task 2-4 Creation of static inundation maps along the shoreline of LCRR

This final report contains a summary of the tasks performed. The order of task results in this report do not follow the task list above, but each section in this report refers to the task number in the work plan. When appropriate, key working group members produced technical report as the main product for a given task. References for the technical reports are provided in this report.

Flood inundation maps are a second key type of product. The maps are produced in electronic format for posting on the IJC website.

The TWG also developed an approach for a future flood forecasting and floodplain mapping system that would take advantage of recent developments in the numerical weather forecasting in both countries to generate probabilistic flood predictions.

The TWG itself is comprised of an equal number of members from each country, with Co-Chairs appointed by the IJC to organize and execute the work of the TWG and for coordinating with and reporting to the Commission. The members of the working group are listed in *Annex 3*.

The IJC entered into an agreement with the US Geological Survey (USGS), New England Water Science Center, to conduct the US portion of the technical work associated with the Work Plan. The Commission also contracted with the Lake Champlain Basin Program (LCBP) to provide secretariat duties as assigned by the Co-Chairs or the TWG as a whole, including logistical support for meetings, recording meeting minutes, assistance with presentations, communication with local and regional partners, public outreach, and facilitation of data storage and access. The TWG worked with the IJC, providing technical evaluations, support and guidance on how best to complete the reference study within the budget and time frame included in the reference from governments. An additional secretariat member was also provided by the IJC for public French language services where necessary and to complement the TWG's secretariat role.

The reference study took advantage of existing collaborations and government mechanisms already in place on both sides of the border, including work being done at both the state and provincial levels.

Timeline:

The governments tasked the IJC with producing a final report on all the new activities by September 2015. However, the TWG identified the need to consult with a targeted set of stakeholder agencies and end users in the basin on products resulting from their work, including the static flood-inundation maps, prior to finalizing its report to the IJC. Furthermore, prior to holding these meetings, the TWG had to consolidate, review and comment on the various sections of the report, drafted by various members of the binational team, including some that require translation services.

To ensure that the IJC provides the governments with the highest quality product possible, the IJC agreed that the TWG will hold targeted stakeholder and user meeting, which will be held in the first week of November 2015. This means that the final report will be completed

by November 30, 2015. In addition, The IJC will provide governments with an updated timeline for completion of the report at the October IJC Semi-Annual meeting.

1.3 Communication of the Study Plans and Results

General information about the TWG such as the mandate, member composition, the study work plan and activities have been posted for the public in a dedicated section on the IJC website: http://ijc.org/en/_LCRRTWG. The final IJC approved report will also be posted there. The newly produced flood maps will also be available on the IJC website. The interactive maps will show the flood plain contours associated with 11 flood scenarios.

Progress reports on what was being accomplished with respect to the various planned tasks were presented by the co-chairs at the IJC Semi-annual meetings in Washington (April 2015), and in Ottawa (October 2015).

A vision for a future operational flood forecasting and flood plain mapping system was presented to experts during a technical workshop held at the same time as the International Association for Great Lakes Research (IAGLR) May 27, 2015 in Burlington, Vermont. Input from the experts was used to refine the proposed approach.

Selected end users of the forecast and mapping products were invited to special sessions held November 3-4, 2015 in Burlington, Vermont and Saint-Jean-sur-Richelieu, Quebec.

DRAFT

2 Data Gathering and Development

Initial discussions within the TWG have identified specific data gaps that could be addressed immediately to support the implementation of a future operational flood forecasting and inundation mapping system for the LCRR. They include:

- Collection and processing of LiDAR Data for Lake Champlain
- Collection of new in-lake and watershed data to assist with flood forecasting and inundation mapping system
- Collection of new substratum, aquatic plant assemblages and distribution in the Richelieu River between Saint-Jean-sur-Richelieu and Rouses Point on the Lake Champlain
- Creation of a coordination mechanism to exchange data of interest
- Consolidation and Harmonization of US Data to be used in lake and river modeling
- Address the Differences between Vertical Datums used along the U.S./Canada Border so data can be maintained to a common datum

A summary of those activities is provided below.

2.1 Collection and processing of LiDAR Data for Lake Champlain

Note: This work corresponds to Study work plan Task 1-5.

New LiDAR data collection, processing and finalization will result in the complete LiDAR data base for Lake Champlain drainage areas in New York and Vermont. A complete LiDAR database for the Canadian portions of the LCRR basin already exists (figure 2.1.1). The USGS contracted for the collection of high quality LiDAR in portions of the Lake Champlain drainage in New York State; this was part of a larger effort to collect and process LiDAR data sets in Clinton and Essex counties and others areas, totaling approximately 2670 square miles of New York (this effort was also partially supported by LiDAR collection in Washington and Warren Counties under the auspices of the NY-ITS GIS Program). The New York collection project is being completed with 9.25cm vertical accuracy. The resulting DEM produced will be at a resolution of 1.0 m².

LiDAR acquisition in New York was completed on Saturday May 9, 2015. Field work to survey the data to the ground surface was essentially complete by the end of August 2015. The processing and quality control components of the LiDAR data development are planned to be completed in January 2016, with USGS acceptance of the products by the end of February 2016.

In Vermont, data collection for LiDAR projects in the Lake Champlain Basin has been collected over several years from the fall of 2008 to 2015. Some areas remain to be collected and are scheduled to be done in the fall of 2015, weather permitting. Specifications and requirements for LiDAR in Vermont have changed over the course of these projects. The earlier projects were completed to an 18 cm vertical accuracy and produced a DEM with a resolution of 1.6 m². The current effort is being completed with 9.25 cm vertical accuracy. The DEM produced will be at a resolution of 0.7- 1.6 m² since will be mosaicked product from multiple data sources. Presuming that all data collection

efforts are completed in 2015, completion of the Vermont LiDAR processing will occur in 2016.

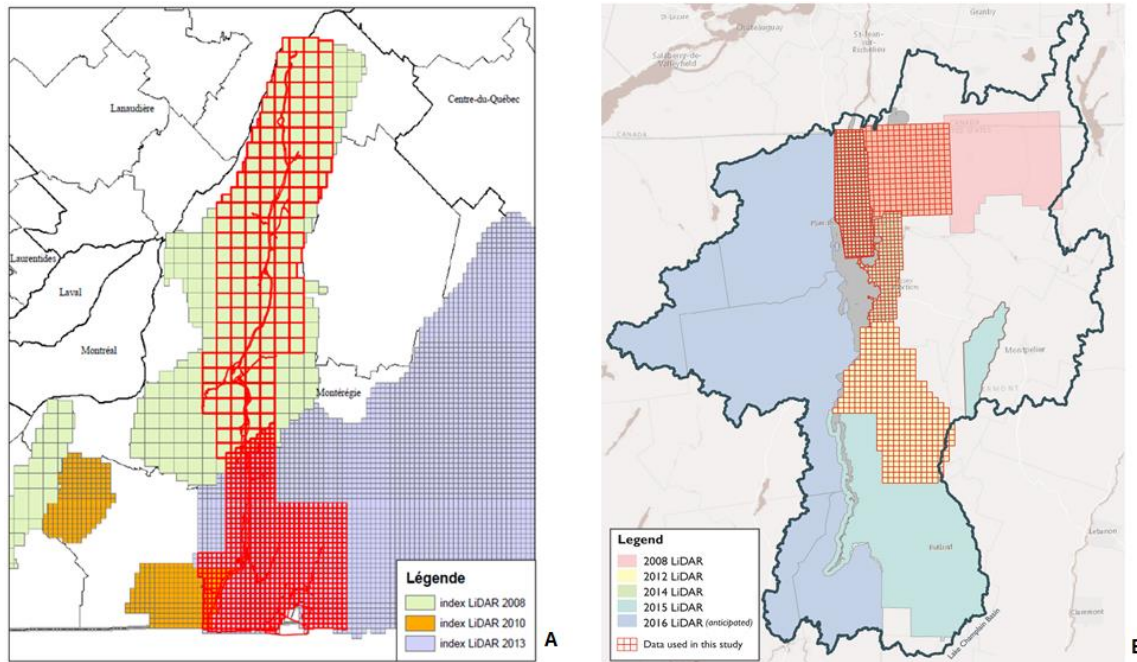


Figure 2.1.1 – Maps of LiDAR data collection efforts and data used in this study for A – Canada and B – United States

Although not all of Vermont is available for use in activities associated with this IJC effort, the direct shoreline areas were processed and delivered as a preliminary product for use with the flood inundation maps. This data, while accurate, will be replaced when the entire project is submitted by the contractor.

When all the LiDAR data is completed for the US side of the basin, additional work will be needed to create a consistent and seamless LiDAR data base for the entire LLCRR basin. Having a single merged data base will facilitate future basin modeling and flood forecasting. The completed LiDAR data will be housed with various state GIS offices and the IJC web site:

<http://ijc.maps.arcgis.com/home/webmap/viewer.html?webmap=512478504bbf4d33a8252710ccdff732>

2.2 Collection of new in-lake and watershed data to assist with flood forecasting and inundation mapping system

Note: This work corresponds to Study work plan Task 1-7.

Two lake and tributary data collection activities were performed that provided data for use in lake modeling and assessment activities. The first was the compilation of existing

tributary flow and lake level data. This was to support EC's stationary simulations for Lake Champlain; USGS provided lake/stream gauge lake elevation and streamflow data for 25 USGS lake/stream gauges to aid EC for determination of flow distributions between major tributaries to Lake Champlain. As part of this effort, USGS provided:

- Daily and 15-minute historical gauge flow data (along with drainage area and latitude/longitude)
- Seasonal and annual flow and stage data statistics (mean and median)
Seasons were defined as follows:
Winter: December 1 to February 28
Spring: March 1 to May 31
Summer: June 1 to August 31
Autumn: September 1 to November 30

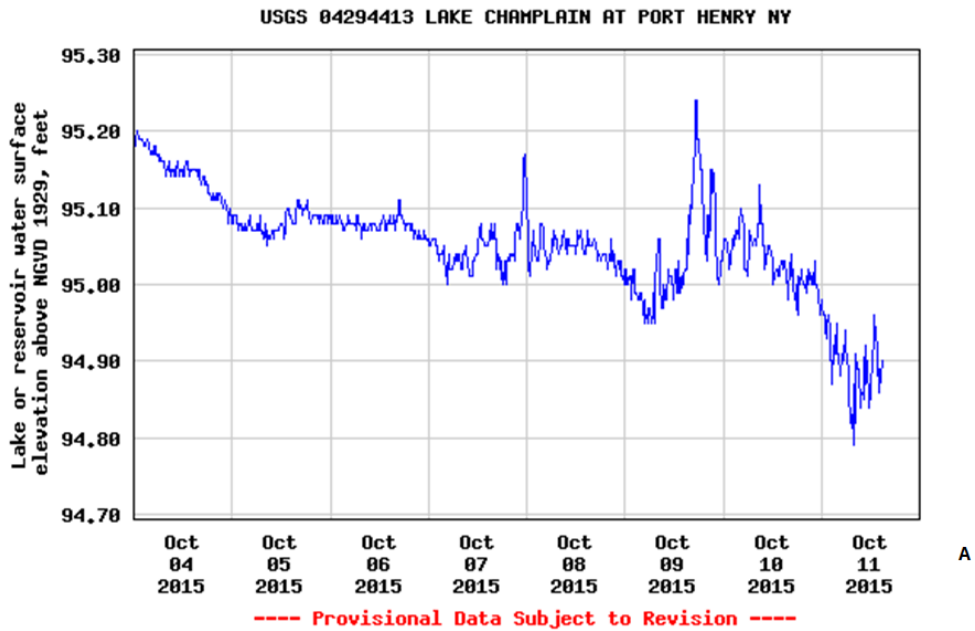
The second activity was installation and operation of two new lake level gauges on Lake Champlain by the USGS. These gauges are located on Lake Champlain at Port Henry NY and on the east side of Grand Isle (or South Hero Island), VT. These locations were endorsed by the TWG as the 2 most desirable for new lake level gauges that would support a 2D Lake Champlain model and future flood forecasting. The Port Henry gauge would fill a spatial gap in data between the USGS lake gauges at Whitehall NY and Burlington VT.

The Grand Isle (or South Hero Island) lake level gauge is located near the southern portion of the so-called "Inland Sea", a large portion on the north-east of Lake Champlain that is hydraulically connected, but reacts differently than the main body of the lake due to the presence of multiple causeways linking some of the Lake Champlain's islands together with the Vermont side of the lake. Combined with the existing Canadian water level gauge located in Philipsburg in the Missisquoi Bay, this lake level gauge will allow for quantification of the wind set-up effects in the "inland sea" area of Lake Champlain. The gauge was installed and operated for the duration of this study.

Both gauges were operational by mid-April 2015. Fifteen minute lake level data has been collected by the gauges, transmitted in near real-time (one hour delay) and posted on the USGS National Water Information System (NWIS) public web page. Figure 2.2.1 presents plots of lake levels at the two sites during the period of data collection. Meteorological data, including wind speed/direction and air temperature and precipitation is being collected at the Port Henry site only, as a local weather monitoring site already exists on Grand Isle.

All of the lake level and meteorology data from the gauges will be reviewed checked and finalized by USGS before being identified as quality assured data in the USGS NWIS data base.

Lake or reservoir water surface elevation above NGVD 1929, feet
 Most recent instantaneous value: 94.90 10-11-2015 14:45 EST



Lake or reservoir water surface elevation above NAVD 1988, feet
 Most recent instantaneous value: 94.55 10-11-2015 16:15 EDT

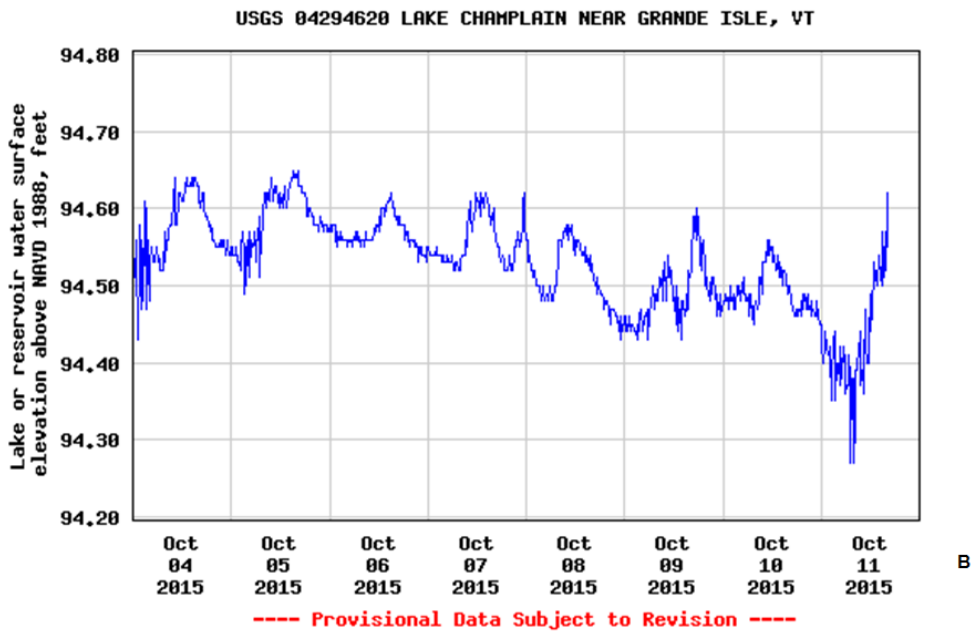


Figure 2.2.1: Hydrography of Lake Champlain water levels at the Port Henry (a) and Grand Isle gauges, October 04, 2015 – October 11, 2015

2.3 Collection of new substratum, aquatic plant assemblages and distribution in the Richelieu River between Saint-Jean-sur-Richelieu and Rouses Point on the Lake Champlain

Note: This work corresponds to Study work plan Task 1-8.

A 7-day field campaign allowed to collect substratum and submerged aquatic plant data along 35 km of the Richelieu River between the Gouin bridge at Saint-Jean-sur-Richelieu and the border near Rouses Point. The field campaign took place between September 8 and 17, 2015.

Cross sections were measured 200 m apart from the Gouin bridge toward the upstream for 2 km. Then, the cross sections were subsequently carried out 400 m apart up to the border because of the simpler topographical set-up. A last day was done on October 5, 2015 to cover the area between Gouin bridge and the control section of Saint-Jean-sur-Richelieu. This area, downstream of the Gouin bridge, is about 1 km long. Figure 2.3.1 illustrates the survey lines for this field effort.

In order to identify the plant species and their density, combinations of the following techniques were used and adapted to local conditions. Those observation techniques are: direct visual observation, observation using an underwater camera, analysis of signals from an echosounder and actual plant sampling. From those observations, plants density, plants composition at the species level, ratio of each species on the plants community and their height in meter were noted along transects sampling points whose GPS coordinates are accurately known. A total of 951 observation points have been done.

Usually, submerged aquatic plants were present in shallow water area but generally absent when the depth exceeded 2.5 m (8 ft) near Saint-Jean-sur-Richelieu. Progressing upstream on the Richelieu River toward the border, the depth to which plants were no longer present increases to 3.5 m (12 ft). The river discharge during the field campaign was around 190 m³/s and the water level at Rouses Point was around 27.80 m (95.20 ft, NGVD 29). Aquatic plant species that have been observed in the field are *Heterothera dubia*, *Vallisneria Americana*, *Myriophyllum spicatum*, *Myriophyllum verticillatum*, *Potamogeton pectinatus*, *Potamogeton richardsonii*, *Alisma gramineum* and *Elodea Canadensis*.

The coverage for the substratum sampling is sparser because its variability is less pronounced and more time was dedicated to submerged aquatic plants. A small amount of grab sampling was made in addition to the camera observations. Generally, the substratum upstream from the Gouin Bridge consists of fine sand and silt. Some small boulders, around 30 cm, were also observed. Precise locations of these samples are also available. The substrate is much coarser downstream from the Gouin bridge where there are lots of boulders in this area where the velocities becomes higher, approaching the natural control section in Saint-Jean-sur-Richelieu.

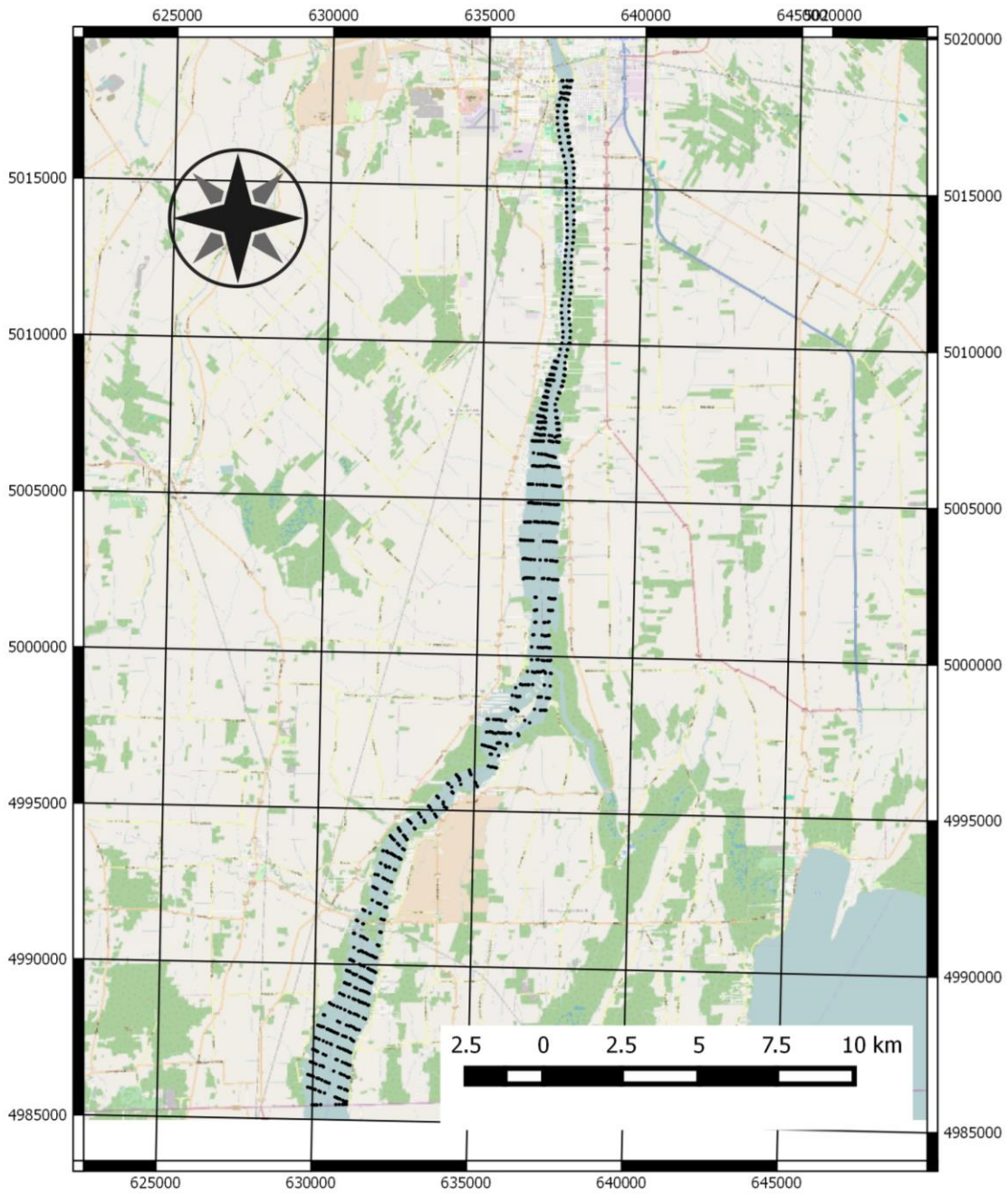


Figure 2.3.1: location of survey lines on the Richelieu River used for aquatic plants observations.

2.4 Coordination mechanism to exchange data of interest

Note: This work corresponds to Study work plan Task 1-3.

The 2013 PoS called for the creation of a common basin-wide geophysical database. The need for a collaborative common data set was reiterated in section 1 of the 2014 IJC reference that established the TWG. To achieve this objective, a coordination mechanism to facilitate the exchange of data produced in both countries, led by the Lake Champlain Basin Program (LCBP), commenced in December 2014. The LCBP was ideally suited for this task, having been established in 1990 with strong partnerships in all three jurisdictions in the watershed. As such, the LCBP can continue facilitating data exchange indefinitely.

A file transfer protocol (FTP) site was set up in January 2015 to facilitate collaboration and sharing of information among the technical working group. Relevant data and information for input into flood forecasting models and static inundation maps were posted to the FTP site by workgroup members. The LCBP facilitated the collection of the highest resolution, most up-to-date earth surface and lake bottom elevation models. Data sets available on the FTP site include: observations of precipitation, temperatures, winds, water levels, inflows, topometric and bathymetric data, precipitation analyses, and results from weather and hydrological and climate forecast models. Due to the limitations of the FTP site, coordination of direct data transfer was also completed, including delivery of all available LiDAR data among workgroup members. Creation of new data sets is discussed in other tasks.

Data were obtained and compiled from varying sources, including federal, state, provincial and non-governmental authorities. Due to the varying nature of the data (both temporal and spatial information were included), no transformations to a common form were completed. However, every effort was made to include harmonized, basin-specific data. Shared data sets are described in more detail in Task 2.1 of this report.

In addition, sharing of all new and derived data sets, model outputs and workgroup communications were coordinated through the LCBP to fulfill the objectives of this task. The LCBP reported data exchange progress and workgroup communications on a monthly basis to the IJC to ensure that all involved parties remained well-informed through the duration of the project. The LCBP also facilitated monthly workgroup meetings and communications throughout the project.

2.5 Consolidation and Harmonization of U.S. Data

Note: This work corresponds to Study work plan Task 2-1.

USGS inventoried, compiled and assessed Lake Champlain watershed data in the US for future lake flood forecasting and modeling. This included data on lake bathymetry, wind, waves, snowpack, lake evaporation, structures influencing lake levels and flows, trends in tributary inflows, and other data recommended by the TWG and others. The LCBP assisted the USGS in compiling these data and making them accessible to the technical working

group. USGS describes the data, sources and limitations below. Data necessary for the development of the flood inundation mapping of Lake Champlain was also gathered so that mapping products reflect a seamless data set.

Shared data sets include:

- National Elevation Data set seamless DEM for the Lake Champlain Basin
 - Data Source: USGS
 - Acquisition Year: 2008
 - Resolution: 10 m horizontal; 1:24,000 Vertical
- LiDAR data for Vermont portions of the Lake Champlain Basin
 - Data Source: USGS
 - Acquisition Year: 2008, 2010, 2012, 2014
 - Resolution: Range 0.7 m-1.6 m (horizontal)
- Bridge/Causeway as-built plans for bridges and causeways crossing Lake Champlain
 - Data Source: Vermont Agency of Transportation
 - Acquisition Year: 2010
- 2012 10 m Bathymetry for Lake Champlain
 - Data Source: Middlebury College
 - Resolution: 10 m (horizontal)
 - Acquisition Year: 2012
- Stream gauge hydrology for all tributary and Lake Champlain gauges within the US portion of the Lake Champlain Basin
 - Data Source: USGS
 - Resolution: 15 minute and daily mean
 - Acquisition Year: 2007-2015
- Hydro-Quebec stream gauge hydrology data for gauges on the Richelieu River
 - Data Source: Hydro-Quebec
 - Resolution: 15 minute and daily mean
 - Acquisition Year: 2007-2015
- Federal Emergency Management Agency (FEMA) Floodplain maps for Vermont and New York
 - Data Source: FEMA
 - Resolution: 10 m horizontal
 - Acquisition Year: 2014
- Meteorological Data for Lake Champlain
 - Data Source: Vermont Monitoring Cooperative
 - Resolution: 15 second, 15 minute and daily
 - Acquisition Year: 2007-2015

2.6 Address Differences between Vertical Datums along the US/Canada Border

Note: This work corresponds to work plan Task 1-6. A detailed description of this work is described in a technical report:

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, 28 p. (<http://dx.doi.org/10.3133/sir/20xxxxxx>).

Due to the vertical datum discontinuity between Canada and the US, a height transformation is required to work in a common vertical datum. This transformation was required in response to the needs of the TWG for hydraulic modeling and flood forecasting on LCRR.

At the end of 2013, Natural Resources Canada released a new geoid-based vertical datum for Canada to replace the Canadian Geodetic Vertical Datum of 1928 (CGVD28) that was defined by mean sea level at tide gauges, namely the Pointe-au-Père gauge. The new Canadian Geodetic Vertical Datum of 2013 (CGVD2013) is a 100% geoid-based datum that is defined by the equipotential surface $W_0 = 62636856.0 \text{ m}^2/\text{s}^2$. This surface, agreed by the US National Geodetic Survey (NGS) and Canadian Geodetic Survey (CGS) in 2012, represents the mean potential of the mean sea level at a series of tide gauges across Canada and US. The new vertical datum is realized by the Canadian Gravimetric Geoid model of 2013 (CGG2013).

In the United States, the hybrid (based on geoid and mean sea level observations) North American Vertical Datum of 1988 (NAVD 88) was selected in 1993 as the official vertical datum of the National Spatial Reference System (NSRS) for the Conterminous US and Alaska and remains the official vertical datum to date, replacing the National Geodetic Vertical Datum of 1929 (NGVD 29). Though, NGS will replace NAVD 88 with a 100% geoid-based vertical datum by 2022 (<http://www.ngs.noaa.gov/datums/newdatums/FAQNewDatums.shtml#WHEN>). NAVD 88 extends to various degrees into Canada, including in the Richelieu River valley.

To develop a fix for the cross-border water level discrepancies, in April 2015, personnel from the USGS, EC and U.S. and Canadian Geodetic Survey conducted field work to create a vertical datum transformation so that all of the water level data in the study area comprised of the LCRR. Selected point locations for making the datum corrections were survey control disks or reference marks at lake- and stream gauges and hydro-sensitive locations within the Champlain-Richelieu floodplain. The survey measurements were used to create a vertical datum transformation so that all the water level data already available in the study area can be referenced to either the NAVD 88 or the CGVD2013 datums. A Global Navigation Satellite System (GNSS) survey was performed to achieve centimeter precision height data.

Seven water level lake/stream gauge survey control locations (Whitehall, NY, US; Burlington, VT, US; Rouses Point, NY, US; Philipsburg, Quebec, Canada; Saint-Paul-de-

l’Ile-aux-Noix, Quebec, Canada; Saint-Jean-sur-Richelieu, Quebec, Canada; and Sorel, Quebec, Canada) and 2 hydro-sensitive locations (Chambly and Saint-Ours dams on the Richelieu River in Quebec, Canada) were surveyed.

The GNSS survey at the 7 water level lake/stream gauges consisted of simultaneous 12-hour observations on April 15, 2015 followed by simultaneous 6-hour observations on April 16, 2015 for redundancy. The GNSS survey at the 2 hydro-sensitive locations of Chambly and Saint-Ours dams consisted of simultaneous 12 hour observations on April 14, 2015. There was no redundant 6-hour observation for the 2 dam locations at Chambly and Saint-Ours.

GNSS survey data for the 7 water level lake/stream gauge survey control locations and 2 hydro-sensitive locations were processed in the US using the National Geodetic Survey’s OPUS (Online Positioning User Service) and were shared to the OPUS database where their ellipsoid height can be further used to help refine future datum work and models.

The magnitudes of the transformations range from -0.27 to -0.52 ft for NGVD 29 to NAVD 88 conversion and from -0.21 to +0.11 ft for CGVD28 to NAVD 88 conversion (Table 1). It is difficult to say if there is a definitive spatial pattern as it is not known how accurately the datum was surveyed to establish the datum in CGVD 28 (or NGVD 29), nor are there data points to constrain the data in an east and west direction. The results show a -0.06 ft conversion to NAVD 88 at Saint-Jean-sur-Richelieu but a +0.07 ft. conversion to NAVD 88 at Chambly dam to the north and a -0.21 ft. conversion to NAVD 88 at Saint-Paul to the south.

A USGS-led technical report, done in cooperation with EC, describes the study and its results and detailed elevation data for each of the US and Canadian lake/stream gauges, benchmarks, and hydro-sensitive areas surveyed. This technical report is included in the technical compendium to this main report.

Table 1 – Results of Datum Corrections at Seven Surveyed Locations

Station Number	Site Name	Agency	Published Data Type	¹ Offset (to NAVD88)	Units
02OJ022	Sorel, Quebec, Canada	EC	Elevation, CGVD28	+0.115	feet
02OJ016	Saint-Jean-Sur-Richelieu, Quebec, Canada	EC	Elevation, CGVD28	-0.061	feet
02OJ036	Saint-Paul-de-l’Ile-aux-Noix, Quebec, Canada	EC	Elevation, CGVD28	-0.206	feet
02OH001	Philipsburg, Quebec, Canada	EC	Elevation, CGVD28	-0.213	feet
04295000	Rouses Point, NY, USA	USGS	Elevation, NGVD29	-0.431	feet
04294500	Burlington, VT, USA	USGS	Elevation, NGVD29	-0.523	feet
04279085	Whitehall, NY, USA	USGS	Elevation, NGVD29	-0.268	feet

3 Studies on Meteorological Forecasting, Lake and River Modeling and Creation of Digital Elevation Models

The TWG identified four specific studies that would be important to support the development of a future operational flood forecasting and inundation mapping system for the LCRR. They are:

- Assess the quality of surface wind predictions and precipitation analyses for the LCRR
- Develop an experimental 2D hydrodynamic model of Lake Champlain, using existing bathymetric data
- Set-up of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel
- Creation of a quality-controlled Digital Elevation Model from available LiDAR data sets along the Richelieu River and Missisquoi Bay of Lake Champlain

Four technical reports provide details on methodology and results. The main findings are provided below.

3.1 Assess the quality of surface wind predictions and precipitation analyses

Note: This work corresponds to Task 1-1 of the Study work plan. A detailed description of this work is described in a technical report:

Fortin, V., Gaborit, E., and M. Dimitrijevic, 2015. Assessing the Skill of Weather Forecasts for the purpose of Flood Forecasting in Lake Champlain and Richelieu River. Technical report prepared for the International Lake Champlain-Richelieu River Technical Working Group. 37p.

Flood forecasting systems are of most value to the public if they provide sufficient advance warning of the potential for floods to occur or recede. Ability to predict weather conditions that could lead to flooding depends on the number of days in advance needed, the spatial resolution of the forecast, and available computing resources.

Wind speed forecast evaluation

Accurate forecasting of surface wind speed would be an important component of a future lake flood model since wind is known to have an important effect on water levels and waves along lake shorelines. The forecasting of surface wind speed requires numerical weather prediction (NWP) systems running at sufficient resolution to resolve the main topographical features and roughness of the surface. In the case of Lake Champlain, which is about 20-km wide at its largest point and bordered on each side by major mountain ranges, a resolution of 20-km or higher is deemed necessary.

With this constraint in mind, wind speed forecasts from four NWP systems having a horizontal resolution between 2.5-km and 15-km were evaluated against observations. Two weather stations operated by the Vermont Monitoring Cooperative (VMC) were selected based on the quality and representativeness of the data sets: Colchester Reef and Diamond Island. Wind set-up events between 2011 and 2015 were selected for the evaluation based on water level observations at both ends of the lake. Because the lake is narrow and elongated in the North-South direction, the focus was put on the evaluation of the North-South component of the wind, which is expected to have the largest impact on wind set-up.

Two deterministic NWP systems were evaluated: the Canadian Regional Deterministic Prediction System (RDPS) (Fillion et al., 2010), which currently has a horizontal resolution of 10-km (15-km until October 2012), and the High-Resolution Deterministic Prediction System (HRDPS) (Bernier and Bélair, 2012), which has a horizontal resolution of 2.5-km. Both systems currently provide 48-h forecasts and are issued every six hours. The comparison was performed over 36 events and evaluated over a total of 2200 forecast/observation pairs at an hourly time-step.

Results of the NWP modeling found that a higher resolution model (2.5-km vs 10-km to 15-km) leads to a 60% reduction in forecast bias, but not to a large increase in the correlation coefficient between observed and predicted values. Correlation between the forecasted wind and the observed mean hourly wind in the North-South direction was typically 0.90 or higher. Hence, even at 15-km resolution it is possible to obtain skillful deterministic wind forecasts at least for 48-h, although a bias correction step is required in order to provide accurate forcing data to a hydrodynamic model of the lake.

The high performance of the 15-km horizontal resolution NWP systems to provide forecasts of wind speed in the North-South direction is good news because this is the highest resolution available for currently operational ensemble NWP systems in both US and Canada. In the US, the National Oceanic and Atmospheric Administration (NOAA) operates the Short Range Ensemble Forecasting (SREF) system (NOAA EMC, 2004) (<http://www.spc.noaa.gov/exper/sref/>) while EC operates the Regional Ensemble Prediction System (REPS) (http://collaboration.emc.ec.gc.ca/emc/cmoe/product_guide/submenus/reps_e.html). SREF forecasts are updated four times per day and go out to 3.5 days, whereas REPS forecasts are updated twice per day and go out to 3 days. Hourly outputs are available from both systems. Both ensemble NWP systems provide 20 scenarios (ensemble members) that aim to represent the uncertainty in the weather forecast.

A comparison of SREF and REPS forecasts over selected events in 2015 showed that both systems provide forecasts of similar skill to the RDPS, with the SREF providing slightly better forecasts based on correlation analysis. It thus seems possible to forecast the North-South component of the wind out to three days for flood forecasting purposes, but a calibration/downscaling procedure will be required before wind forecasts can be used by hydrodynamic models, especially given that the SREF and REPS forecasts have a very different bias signature

Figure 3.1.1 shows a comparison of observed and forecasted winds (north-south component) at Colchester Reef for five events in April-June 2015 that led to wind set up in the lake. A positive value corresponds to a wind blowing from the south (leading to an

increase in water level and flow at the outlet) whereas a negative value corresponds to a wind blowing from the north (leading to a reduction in water level and flow at the outlet). The black line is the observed 15-min wind speed. The blue line is the deterministic forecast from the HRDPS 2.5-km model, and the red line is the 15-km ensemble forecast obtained by averaging SREF and REPS forecasts. All forecasts have a lead time of 0-24h. Although the HRDPS does capture better the higher wind speeds, the ensemble mean capture the dynamics of the events quite well, and both products (deterministic and ensemble forecasts) would likely benefit from further statistical downscaling aimed at reducing the bias.

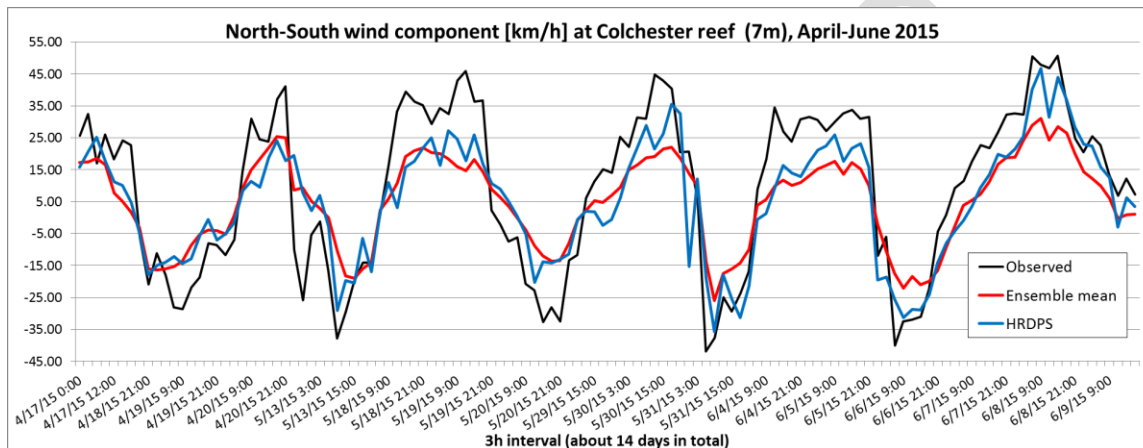


Figure 3.1.1: Time series of observed and forecasted wind (day 1 forecast) at Colchester Reef

Precipitation forecast evaluation

Although unbiased wind forecasts require fairly high horizontal resolution in complex terrain, it is expected that precipitation forecasts can be obtained using models running at lower spatial resolution, and perhaps for a longer advance time period, at least for major storms such as extratropical cyclones or continental frontal systems. In order to perform an evaluation of current abilities to forecast precipitation, all extra-tropical storms which occurred between 2011 and 2014 were analyzed to identify those which affected the Lake Champlain area. Five were found: Irene (2011), Sandy (2012), Leslie (2012), Andrea (2013) and Arthur (2014). The entire watershed of Lake Champlain, subdivided into 12 sub-basins, was considered. Overall, a total of 42 days were considered. Two reference data sets were used to evaluate the precipitation forecasts, namely the U.S. National Centers for Environmental Prediction (NCEP) Stage IV Precipitation Analysis (Lin, Y. and K. Mitchell, 2005) and the Canadian Precipitation Analysis (CaPA) (ref). The precipitation amounts from both sources were in good agreement, so the mean of both daily precipitation amounts was used as the observation to which to compare the forecasts. Maximum daily precipitation amounts observed at each of the 12 sub-basins over these 42 days ranges from 80 to 120 mm/day (approximately 3 to 5 inches of rain).

Canada, US and Mexico jointly participate in the North American Ensemble Forecasting System (https://weather.gc.ca/ensemble/naefs/index_e.html), which combines two-week forecasts from the Canadian Global Ensemble Prediction System (GEPS) and the NOAA Global Ensemble Forecasting System (GEFS). Both systems provide twenty scenarios

(ensemble members) of daily forecasts, plus a control member, with forecasts being updated twice per day.

Verification results indicate that the GEPS forecasts have useful skill up to the 5-day lead-time: correlation for day 1 between observed precipitation and the GEPS control member is very high (0.95), dropping to 0.54 on day 5 (see Figure 3.1.2). Longer lead time forecast show no significant ability to accurately predict daily precipitation. The same type of verification could unfortunately not be done with the GEFS due to time constraints, but in general the error growth of Canadian weather forecasts is similar to that of other centers for North America (http://weather.gc.ca/verification/error_growth_e.html).

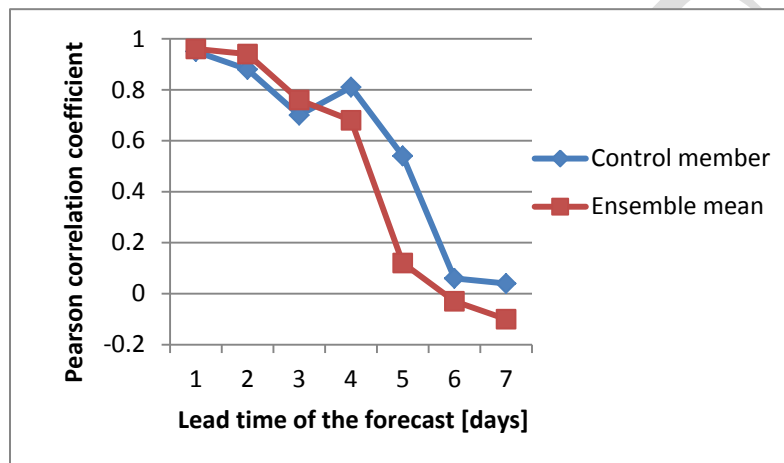


Figure 3.1.2: Median Pearson correlation coefficient between GEPS daily rainfall forecast and observed rainfall for twelve sub-basins of Lake Champlain

Temperature forecast evaluation

Temperature forecasts, especially for periods over 5 days, are typically more robust than precipitation and wind forecasts. Temperature forecasts often have some skill¹ even at seasonal time scale, especially in winter. The GEPS system was used to determine if useful temperature information for lake modeling purposes could be found in monthly forecasts. This could be especially useful to help predict ice melt/loss using weekly forecasts of basin-average degree-days. Hence forecasts that correctly estimates the average number of degree-days observed over a week for the whole watershed would be ideal. Forecasts issued in February, March and April were evaluated over the period of 1995-2012.

Results indicate that there is a similar level of skill for the first week for forecasts issued in all three months. For the second week out, there is skill for all three months but it is more modest. For weeks three and four, we only find see skill for forecasts issued in February. February forecasts for week 3 and 4 are also valid from the second half of February to the second half of March. This assessment is consistent with known characteristics of monthly and seasonal temperature forecasts for this region, where more skill is generally observed

¹ Forecast skill is defined as the performance of a particular forecast system in comparison to some other reference technique

in winter. Whereas the use of monthly temperature forecasts might be warranted in February, for reliable flood forecasting later in the season it might be more appropriate to rely on climatological temperature inputs for week 3 and 4. On the other hand, having the flexibility of using monthly ensemble weather forecasts for all three months might be useful in a warmer climate, since past observations of temperature become less representative of current conditions.

3.2 Implement an experimental 2D hydrodynamic model of Lake Champlain, using existing bathymetric data

Note: This work corresponds to work plan Task 1-2. A detailed description of this work is described in a technical report:

Environment Canada, 2015. Development of an experimental 2D hydrodynamic model of Lake Champlain using existing bathymetric data (Task 1-2). Draft report to the International Joint Commission, 45 p.

Environment Canada's National Hydrological Services developed an experimental 2-dimensional (2D) hydrodynamic model to simulate Lake Champlain and Richelieu River levels associated with static water level scenarios defined as specific water levels at the Rouses Point gauge in Lake »Champlain. This 9 months-long effort aimed at testing the finite element 2-D model's performance using predominately existing data. Results of this effort indicate success in creating this model to determine the Richelieu River discharge and water surface elevations along the Richelieu River corresponding to each of the 11 discrete water level scenarios of interest determined by the TWG (see table 4.1.1). The process and results of the modeling effort are summarized below.

Creating the finite element mesh

The simulations were performed using the H2D2 model, developed at INRS-Eau (now INRS-ETE) with the support of Environment Canada. The approach is based on 2D numerical modeling of the long wave equations also called "shallow water equations" that are solved by the finite element method. This model determines the average flow velocities (speed integrated in the vertical) for all sections of the water body defined by reach nodes. The model also accounts for overbank flows resulting from flood inundation.

The model domain includes Lake Champlain from Whitehall, NY (where the USGS Whitehall lake gauge is located) to the beginning of the Richelieu River, and the Richelieu River downstream to Fryers Dam (coinciding with the Quebec river gauge).

The lake and river models were comprised of a total number of 305,155 nodes and 148,191 elements. The size of the model elements varied from a few meters in areas where better spatial resolution was needed to 700m at the center of Lake Champlain where information needs are less important. A high resolution finite element mesh was required at structures such as bridges piers, docks and culverts that influence the hydrodynamics of the river and lake, as shown in figure 3.2.1 illustrating the mesh capturing the 30 piers of the Fryers Dam structure.

Figure 3.2.2 illustrates the requirement for high resolution mesh on those areas of Lake Champlain where causeways linking islands to the main land present relatively small openings allowing water to flow from one side to the other. Multiple causeways linking some of the Lake Champlain's islands together with the Vermont Side of the Lake create an area known as the "inland sea" that is hydraulically connected, but reacts differently than the main body of the Lake. The model development aimed at capturing this particularity.

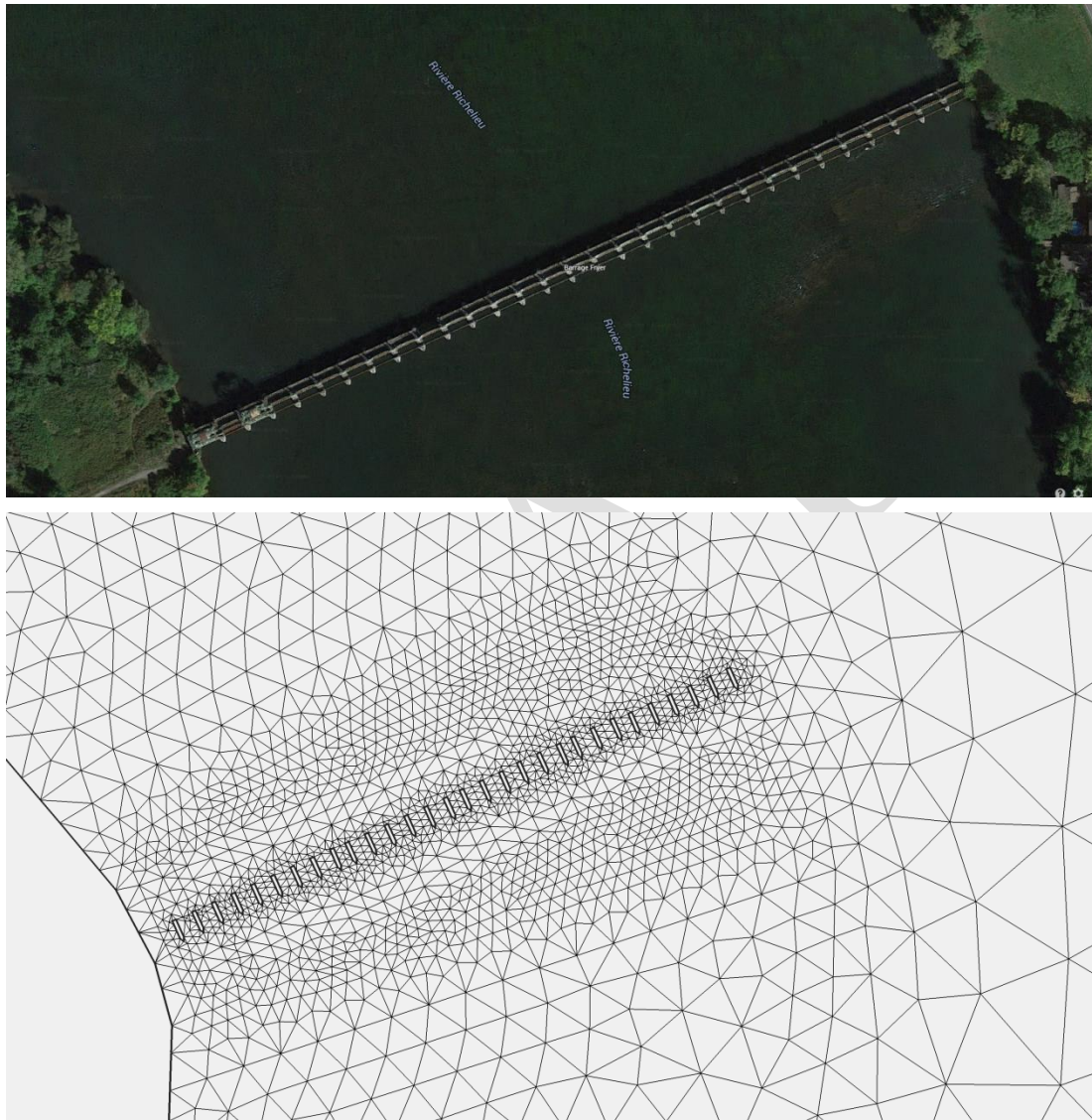


Figure 3.2.1: Fryers Dam and the corresponding mesh

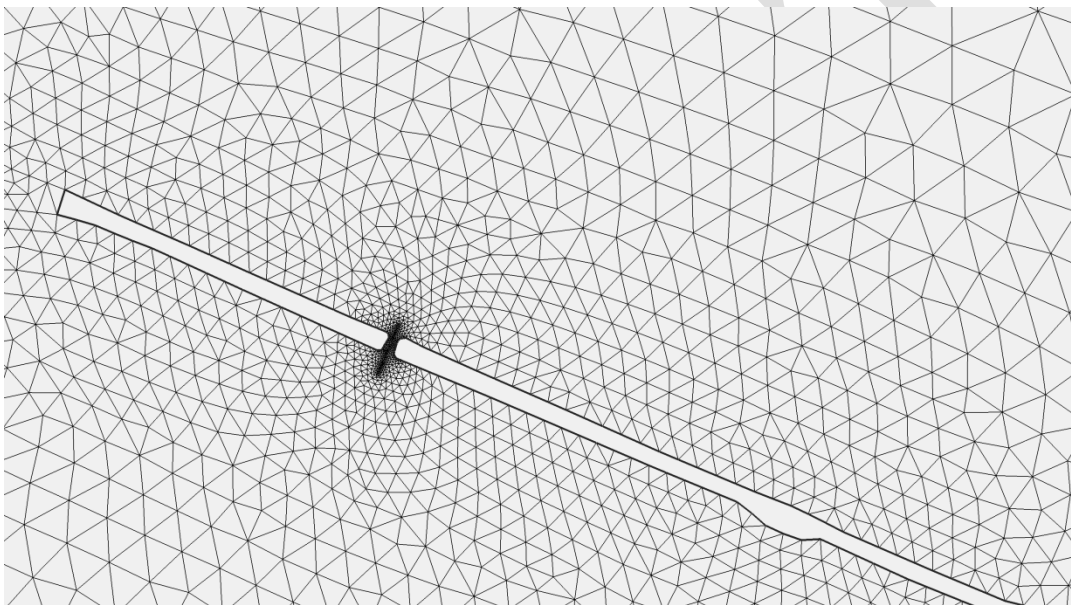


Figure 3.2.2: Highway 2 between South Hero and Colchester and the corresponding mesh

Common vertical datum

Lake shore elevation and bathymetry data were collected to build a DEM of Lake Champlain and its shoreline. Among other, the Middlebury College bathymetry (from Professor Tom Manley), the National Oceanic and Atmospheric Administration (NOAA), different Lidar datasets and the National Elevation Dataset (NED), for areas where Lidar was not available, were used. All elevation and bathymetric data sets that were not initially expressed under the North American Vertical Datum of 1988 (NAVD88) have been adjusted using the transformation grids based on the available online applications

(Vertcon², Geoid12A³, GPS-H). The figure 3.2.3 show the grid used to convert data from CGVD28 to NAVD88⁴). The DEM was transferred to the hydrodynamic mesh ensuring that the model was developed on a cross-border common datum that is NAVD88.

For station level conversions to NAVD88, the high-precision Global Navigation Satellite System (GNSS) observations were used to generate the conversions factors required to convert water levels observed in either NGVD29 in the U.S., or CGVD28 in Canada, to the common NAVD88 vertical datum. Table 3.2.1 presents those conversions factors, and compares them to those available from the on-line applications.

Table 3.2.1: Difference between station level conversions to NAVD88 calculated using online tools and those calculated using high-precision GNSS observations

Station	Conversion to NAVD88 using online tools (m)	Conversion to NAVD88 using GNSS observations (m)	Difference (m)
Rouses Point (NGVD29)	-0.138	-0.131	0.006
Burlington(NGVD29)	-0.146	-0.159	-0.012
Whitehall(NGVD29)	-0.156	-0.081	0.074
Phillipsburg (CGVD28)	-0.055	-0.064	-0.009
Saint-Paul-de-L'Ile-aux-Noix (CGVD28)	-0.085	-0.064	0.020
Saint-Jean-Sur-Richelieu (CGVD28)	-0.042	-0.018	0.023
Sorel (CGVD28)	0.004	0.033	0.029
Barrage Chambly (CGVD28)	-0.007	0.024	0.031
Saint-Ours (CGVD28)	0.014	0.033	0.019

² Vertcon : http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl

³ Geoid12A : http://www.ngs.noaa.gov/cgi-bin/GEOID_STUFF/geoid12B_prompt1.prl

⁴ GPS-H : <http://webapp.geod.nrcan.gc.ca/geod/tools-outils/gpsh.php?locale=en>

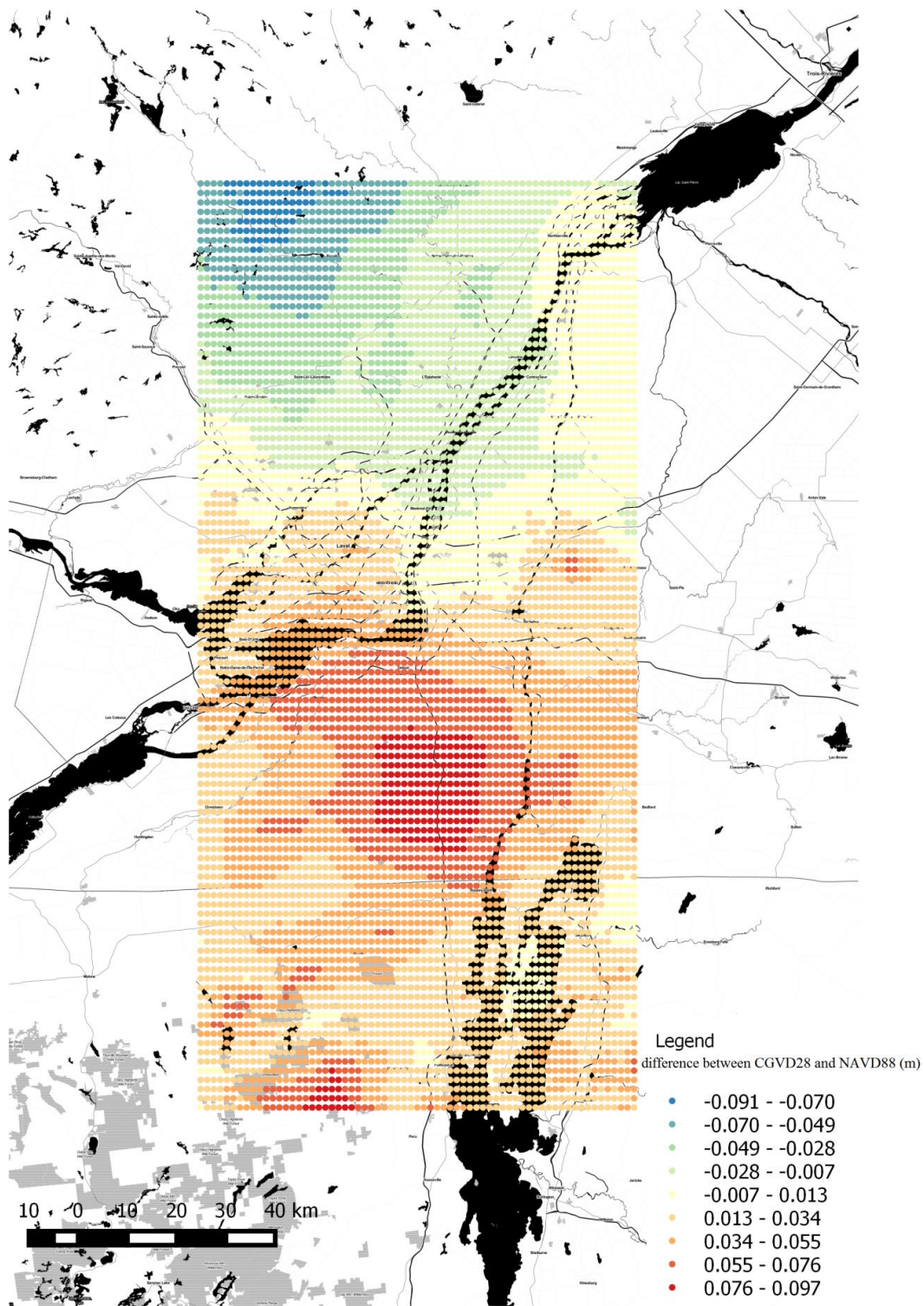


Figure 3.2.3: Grid (in meters) for converting CGVD28 to NAVD88

Hydrologic database

The Lake Champlain's 13 lateral inflows entry points for which the inflows are imposed correspond to the Lake's principal tributaries: the Winooski, Missisquoi, Lamoille, Bouquet, Au Sable, Saranac, Chazy, Mettawee, Poultney, and LaChute Rivers, Otter Creek, and the rivière aux Brochets (Pike River) and rivière de La Roche (Rock River), which both drain directly to Missisquoi Bay. Inflows associated with other smaller tributaries, as well as non-point flows into the lake, are distributed among the 13 entry points according to a methodology adapted from Shanley and Denner, 1999 and based on the relative proportions of gauged and ungauged areas of the watersheds. A database of all US and Canadian daily water inflows needed to operate the hydrodynamic model was created, covering the years 1970-2015. This was done to gain historical quantitative estimations of the Lake Champlain Richelieu River hydrologic supplies

Figure 3.2.4 illustrates the attenuating effect Lake Champlain has on the system and the limited discharge capacity of the Richelieu River. Lake Champlain's water levels rise as consequence of total Lake inflows being larger than the Richelieu River outflows capacity.

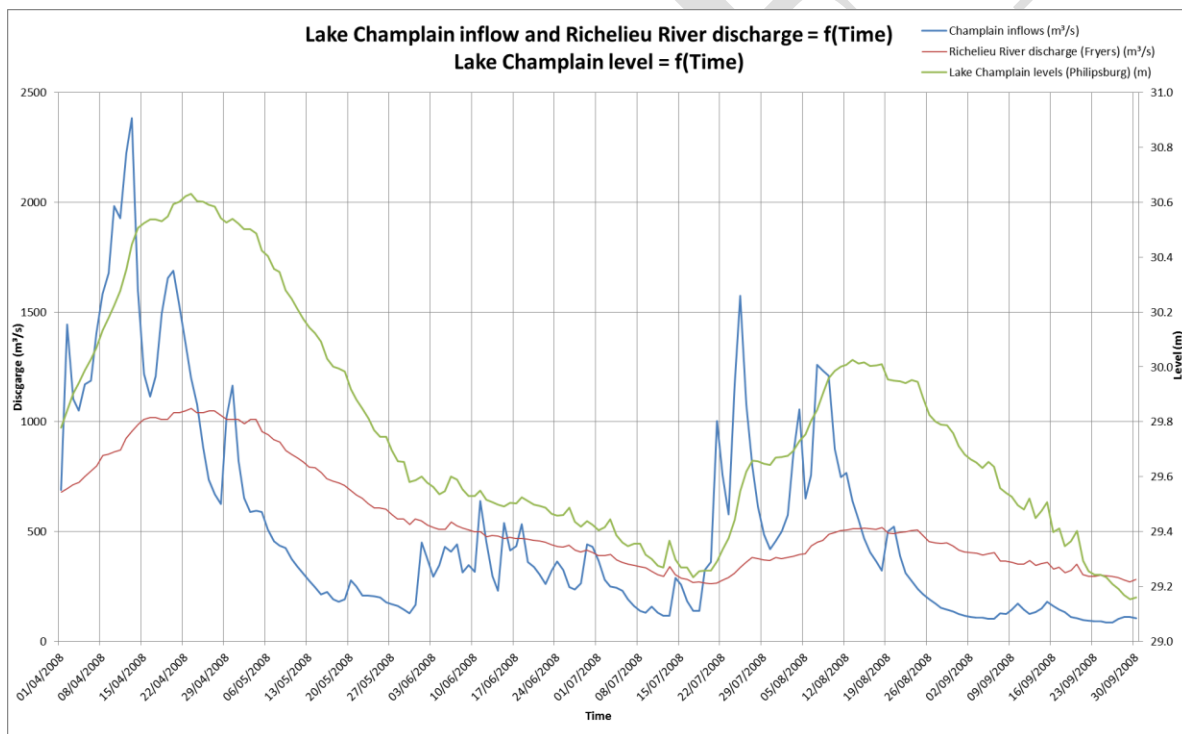


Figure 3.2.4: Influence of flows entering and exiting Lake Champlain on lake level. Spring-summer 2008.

Calibration procedure

Water levels at a given moment on Lake Champlain are dynamic and are the result of total Lake inflows over time, the Richelieu River outflows, and the wind set-up effect, as illustrated by figure 3.2.4. Given the water level of the Lake Champlain is not associated

solely to the total Lake inflows and that the wind set-up effect is still not incorporated in the experimental model, performing the calibration of a steady state model is not an easy task.

However, the flow passing at Saint-Jean-sur-Richelieu on the natural control section is proportional to the water level at Saint-Jean-sur-Richelieu and Rouses Point. With a steady state simulation, it is possible to calibrate the flow passing through the natural control section, so it corresponds with the observed water level in Saint-Jean-sur-Richelieu. Doing so, it's important to keep in mind that those observations are submitted to the wind and that definitive calibration will only occur at a later step, after wind forcing, and hourly inflows would be incorporated in the experimental model. Calibrations were performed in steady state by distributing the flow measured at Fryers station for an event between the different entry points of the model.

The model was calibrated by comparing measurements of water levels along the Richelieu River and at the Rouses Point water level station. As a first step, an average flow and a high flow event were chosen for the calibration. The two events selected were the one on April 4, 2003, with discharge of $593 \text{ m}^3/\text{s}$ at Fryers Rapids gauging station, and the one on May 6, 2011, with discharge of $1550 \text{ m}^3/\text{s}$ at the same station. The latter event was the peak flood day in 2011, when the discharge in the river reached its historical maximum.

For the 2003 event, water level measurements all along the river were available for the calibration, from a campaign conducted by the CEHQ, and for the 2011 event, only water levels at stations were available.

Calibration was done by adjusting the friction coefficient (Manning). Differences between simulated and measured at Saint-Jean gauge of -0.08 m were achieved for the April 4 event and $+0.12 \text{ m}$ for May 6, 2011. It was not possible to achieve a calibration of the model within 5 cm of the observed water levels, using a single set of friction coefficients.

The man-made structures in the Saint-Jean-sur-Richelieu sill area that are not properly captured by the available bathymetry may cause this problem and documentation was found concerning remnants of old channels that were used to bring water to mills on both banks. Those old channels are now part of the river bed, as well as V-shaped rock structures used for eel-fishing on the river, as shown in figure 3.2.5.

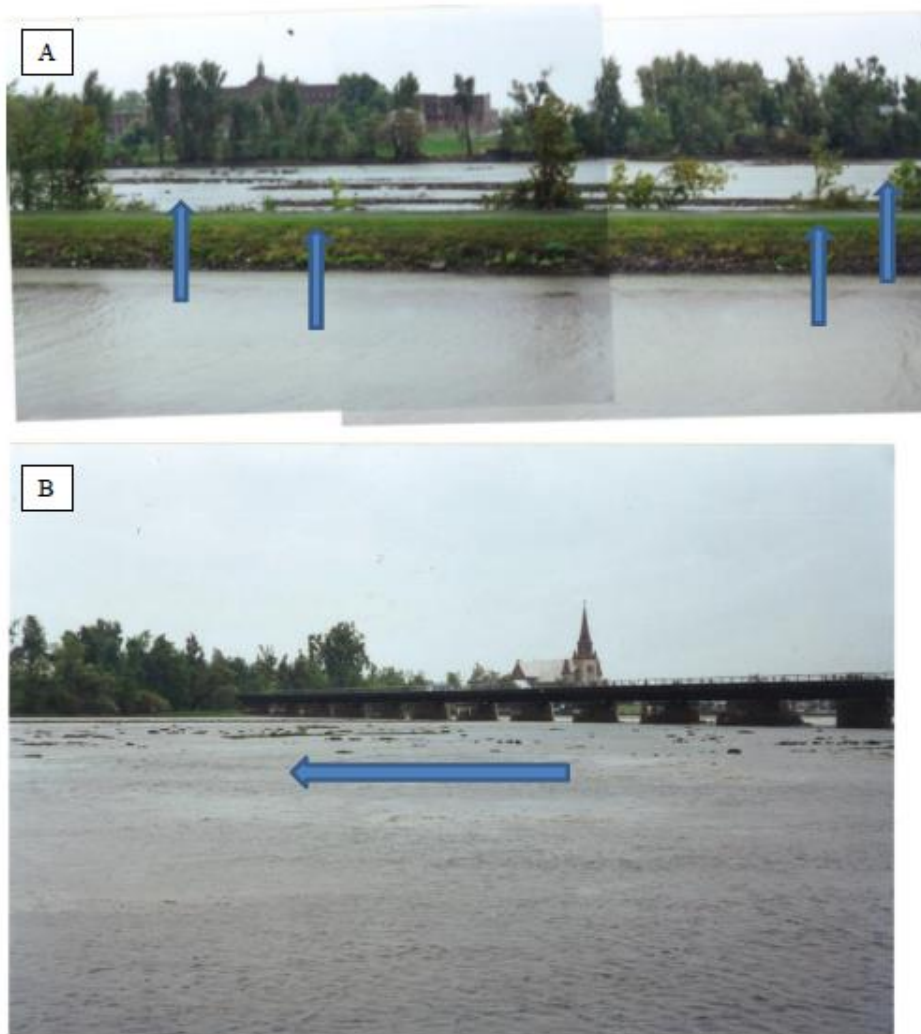


Figure 3.2.5: a) Arrows indicate vestiges of eel traps b) Arrow indicates vestiges of millrace on the right bank

Collection of new river bathymetry information in the Saint-Jean-sur-Richelieu sill area in June 2015 did not really help to improve model performance, and the results remained unacceptable (not within 5 cm of the measurement). There is still some part of the sill that does not have an accurate bathymetry particularly the old channels that used to bring water to mills on both banks.

Therefore, since a better bathymetry is not currently available, the steady state model, without wind forcing, was calibrated solely with the high water event of May 6, 2011, using an observed daily average of 30.676m at Saint-Jean-sur-Richelieu. The “no-wind” calibration appears reasonable, as for May 6, 2011, the average daily wind measured at the Burlington meteorological station was 3.1 m/s (light breeze) and the fastest 2-minute wind gust was 8 m/s (moderate breeze). Table 3.2.1 presents the calibration results, expressed as

the difference between observed and simulated water levels for the flooding period in 2011. The differences at Rouses Point, Phillipsburg, Burlington and Whitehall are provided only for reference but were not used in the calibration of the model.

Table 3.2.1: Calibration of the hydrodynamic mesh for May 6, 2011

Station	NAVD88 Measurement (m)	NAVD88 Calibration (m)	Difference (m)
Saint-Jean	30.686	30.676	-0.010
Rouses Point	31.301	31.283	-0.018
Phillipsburg	31.323	31.295	-0.028
Burlington	31.292	31.290	-0.002
Whitehall	31.304	31.311	0.007

Although some difference at Saint-Jean-sur-Richelieu is 1 cm, those results are deemed acceptable, indicating this experimental model reproduces high flows reasonably well, under steady-state conditions. It is anticipated that the model will provide reasonable water surface required to generate the static flood plain mapping products of this study with an objective to support intervention in flood situations. It should be noted that a single event calibration is generally not sufficient for an application in flood plain delineation for land use planning.

Using the calibration done for the high water levels, the 11 discrete water level scenarios of interest determined by the TWG (see table 4.1.1) have been simulated in a steady state way by adjusting the inflows to provide the desired Lake Champlain water level at the Rouses Point gauging station.

The key issue to have a good hydrodynamic model is the Saint-Jean-sur-Richelieu sill because that is what controls the lake levels. Improved bathymetry covering the Saint-Jean-sur-Richelieu sill will be needed to achieve a good calibration for the entire range of discharge from low to high. After improvement of the model to properly simulate the natural control section in Saint-Jean-sur-Richelieu, the calibration/validation with unsteady, hourly inflows and wind forcing should be done.

Furthermore, the experimental hydrodynamic model did not include simulation of wind set up and waves on water levels in the lake and river. Additional work will be required to address this important feature of flooding and high flows.

3.3 Development of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel

Note: This work corresponds to Study work plan Task 2-3. A detailed description of this work is described in a technical report:

Environment Canada, 2015. Set-up of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel (Task 2-3). Draft report to the International Joint Commission, 25 p.

A 2D hydraulic model of the Richelieu River between Saint-Jean-sur-Richelieu and Sorel (Quebec) was developed for use in creating water level profiles for the flood inundation maps. Results of this modelling indicate that the portion of the river between Saint-Jean-sur-Richelieu and Chambly Dam could be adequately modeled.

Existing elevation and bathymetry data were collected to build a DEM for the Richelieu River and its shoreline. For those areas where structures such as bridges piers and dams influencing the hydrodynamics are present, the “as-built” plans and other pertinent information was compiled and incorporated into the hydrodynamic model mesh.

Using Rouses Point as the upstream limit of the model of the Richelieu River proven to be problematic; when the level of Lake Champlain is very high, as in 2011, flood waters from Missisquoi Bay inundate wetlands and flows directly to the Rivière du Sud, and back into the Richelieu just downstream of Île-aux-Noix, effectively “bypassing” the Richelieu River between Rouses Point and Saint-Paul-de-l’Île-aux-Noix. Since the Lake Champlain model discussed in section 3.2 already covers the upper Richelieu River reach, including the Missisquoi Bay flood plains and its “bypass”, and the Richelieu River downstream of the bedrock sill at Saint-Jean-sur-Richelieu, it was therefore decided to set the Richelieu River model’s upper limit just upstream of the Saint-Jean-sur-Richelieu sill, down to the river’s mouth at Sorel. So doing, the entire domain was covered with the combination of the Lake and River model.

Poor bathymetric datasets for the area of the Chambly Dam were noticed and a section of about 1 km between the Chambly Basin and the Chambly Dam could not be modeled at all. This resulted in dividing the model domain in two: one section from above the sill at Saint-Jean-sur-Richelieu downstream to the Chambly Dam, and the other section from the Chambly Basin to Sorel.,

As described in section 3.2, a database covering the years 1970-2015 was developed to include all the daily inflows needed for the hydrodynamic model of the Richelieu River. The entry points to the hydrodynamic model include the following seven tributaries between Saint-Jean-sur-Richelieu and Sorel: the Des Iroquois, Des Hurons, L’Acadie and Amyot rivers and Laplante, Coderre and Beloeil creeks.

The simulations were performed using the H2D2 model, developed at INRS-Eau (see description in section 3.2). The hydrodynamic mesh for the reach from Saint-Jean-sur-Richelieu to Chambly was developed and calibrated. The mesh contains 79,181 nodes and 38,539 elements. The size of the elements varies from a few meters, in certain areas where a large amount of detail is required to 150 m to cover plains that may be flooded where less

detail is required. Typically, a mesh element size of 25 m was used. The 11 scenarios developed by the TWG have been simulated for this reach.

A hydrodynamic model was also developed for the reach from Chambly to Sorel, but the attempts to calibrate the model revealed some major problems. Model performance was poor, to the point that the validity of the bathymetry was questioned. EC technicians were sent out to conduct additional bathymetric surveys to verify the existing bathymetric data sets, essentially from the Canadian Hydrographic Service (CHS). Comparing the points measured by EC with those from the existing bathymetry revealed an average difference of about 50 cm. The differences varied in space and were greater at some locations but the points measured by EC were consistently deeper than those from the existing bathymetry. Figure 3.3.1 presents the longitudinal differences In a stretch of river near Saint-Ours, while figure 3.3.2 presents both the CHC bathymetry and the EC observations along a cross-section located some 7 km upstream of Sorel.

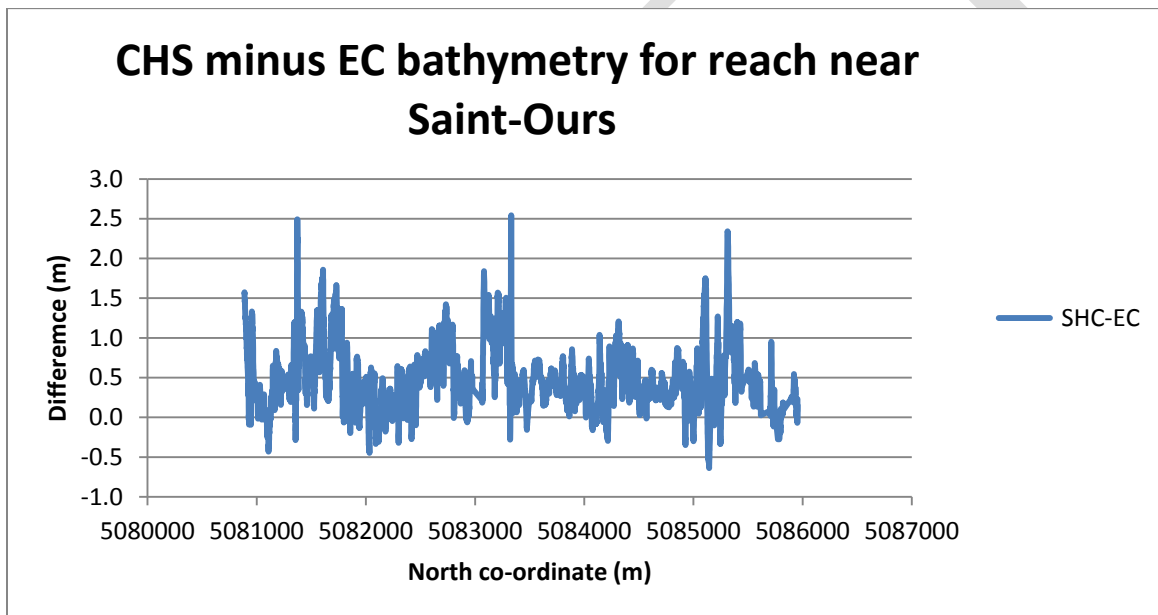


Figure 3.3.1: Difference between CHS and EC depth measurements for longitudinal transect near Saint-Ours

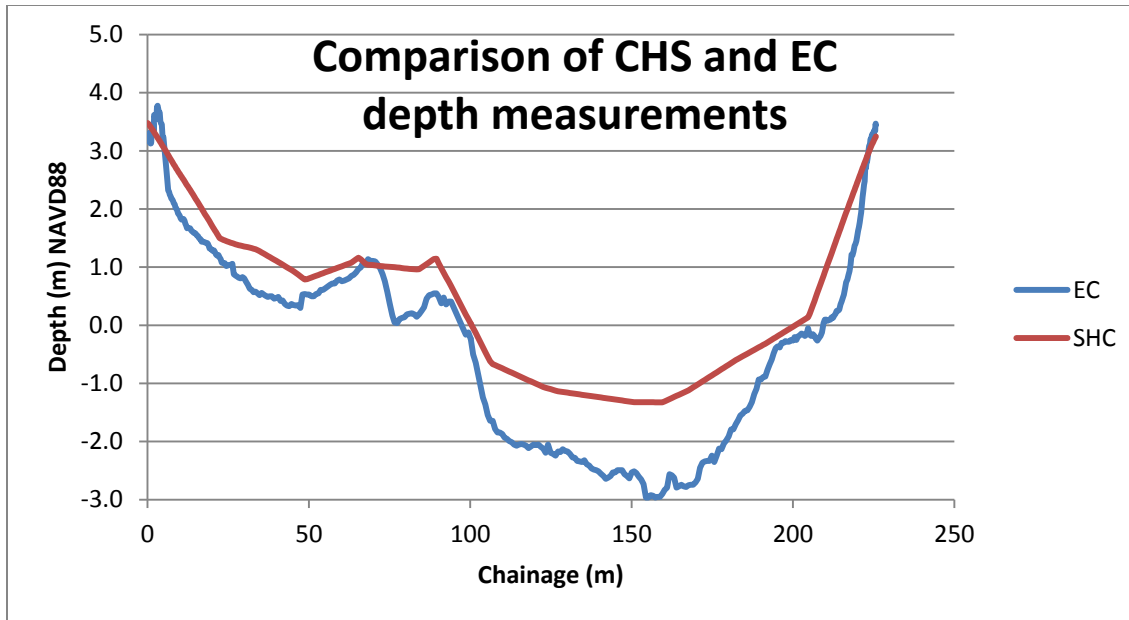


Figure 3.3.2: CHS and EC depth measurements for a cross-section located about 7 km upstream from Sorel

These problems prevented the accurate modeling of this reach. The 11 scenarios developed by the Working Group were not simulated. The work for this reach of the river thus has not been completed and cannot be completed unless a new bathymetric dataset can be obtained.

The Lake 2D model described in the previous section, combined with a short reach from Saint-Jean-sur-Richelieu to Chambly dam where the model performed well were used to simulate the 11 selected scenarios described in table 4.1.1 and to generate the associated water surfaces to be used for the mapping of the inundated areas.

3.4 Creation of a quality-controlled Digital Elevation Model from available LiDAR data sets along the Richelieu River and Missisquoi Bay of Lake Champlain

Note: This work corresponds to Study work plan Task 2-2. Detailed description of the Canadian portion of this work is described in a technical report:

Ministère du Développement durable, de l'Environnement et de la Lutte aux Changements Climatiques, 2015. Contribution to the Creation of Flood Zone Maps for the Quebec Portion of the Lake Champlain/ Richelieu River System: Production of a Digital Terrain Model of the Shoreline Transformation of Water Surfaces into Flood Zone Limits. July 2015 Draft report to the International Joint Commission. 18 p

Two separate topographic data sets were created for this study; one each on both the Canadian and US sides of the border. The topographic data are based on LiDAR technology. The LiDAR data is the highest resolution data available on a regional scale for characterizing the vertical elevation of the land surface and are most appropriate data for use in flood or hydraulic modeling studies. The LiDAR data are then used to create a DEM of the land surface which is used in lake modeling and flood inundation map generation. Additional work will be needed in future studies to merge the Canadian and US LiDAR data into a single DEM data set.

Canadian LiDAR and DEM Data:

Three LiDAR data sources have been pooled to create a topographic data base for the Richelieu River Basin in Canada. These data are derived from three separate LiDAR data collection efforts in 2008, 2010 and 2013. Technical specifications for the LiDAR data collected from each effort are the same. Figure 3.4.1 shows the area covered by each of the collection efforts.

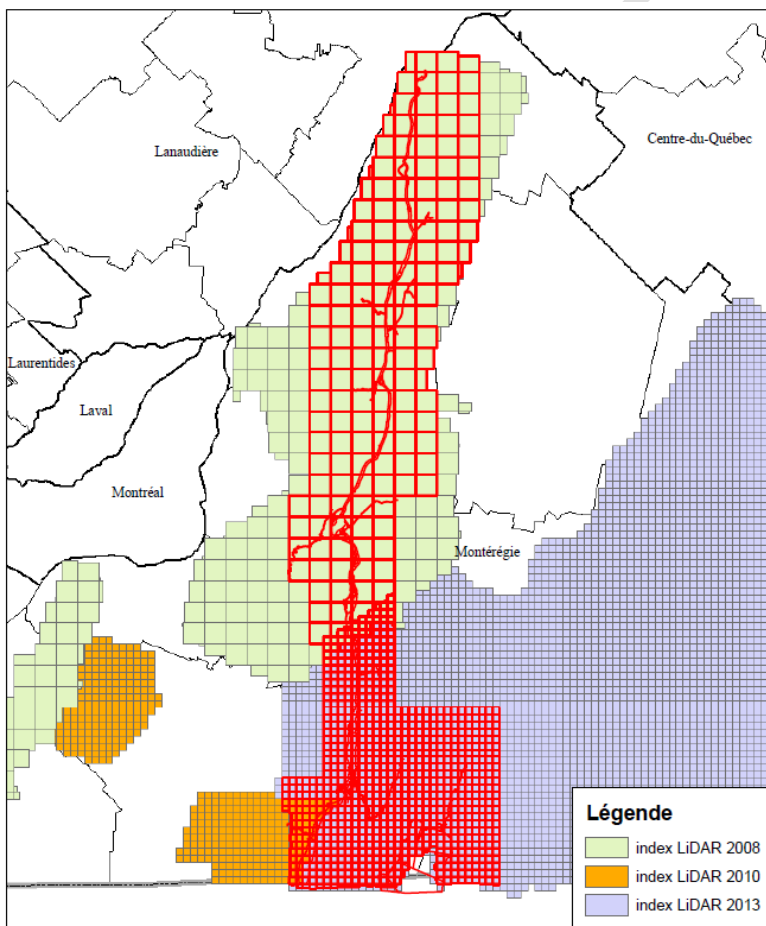


Figure 3.4.1: Spatial domain covered by each of the three measuring campaigns (green, blue, and orange areas) and map sheets for which data were used in this study (red squares)

A DEM is distinguished from a Digital Terrain Model (DTM) as it does not take into account objects located above the surface such as buildings, plants or bridges. Figure 3.4.2 illustrates the DEM produced from existing data sets for the Richelieu River. Similarly, for application in hydraulics, it is essential to combine the topographic elevations of the land with bathymetric depths of the water course. The hydraulic model serves to assess the water level and the water depth for different conditions of flow above the terrain model. The data used has a vertical accuracy of approximately ± 15 cm in open terrain and ± 25 cm in forests. The DEM is based on 1 m^2 grid cells.

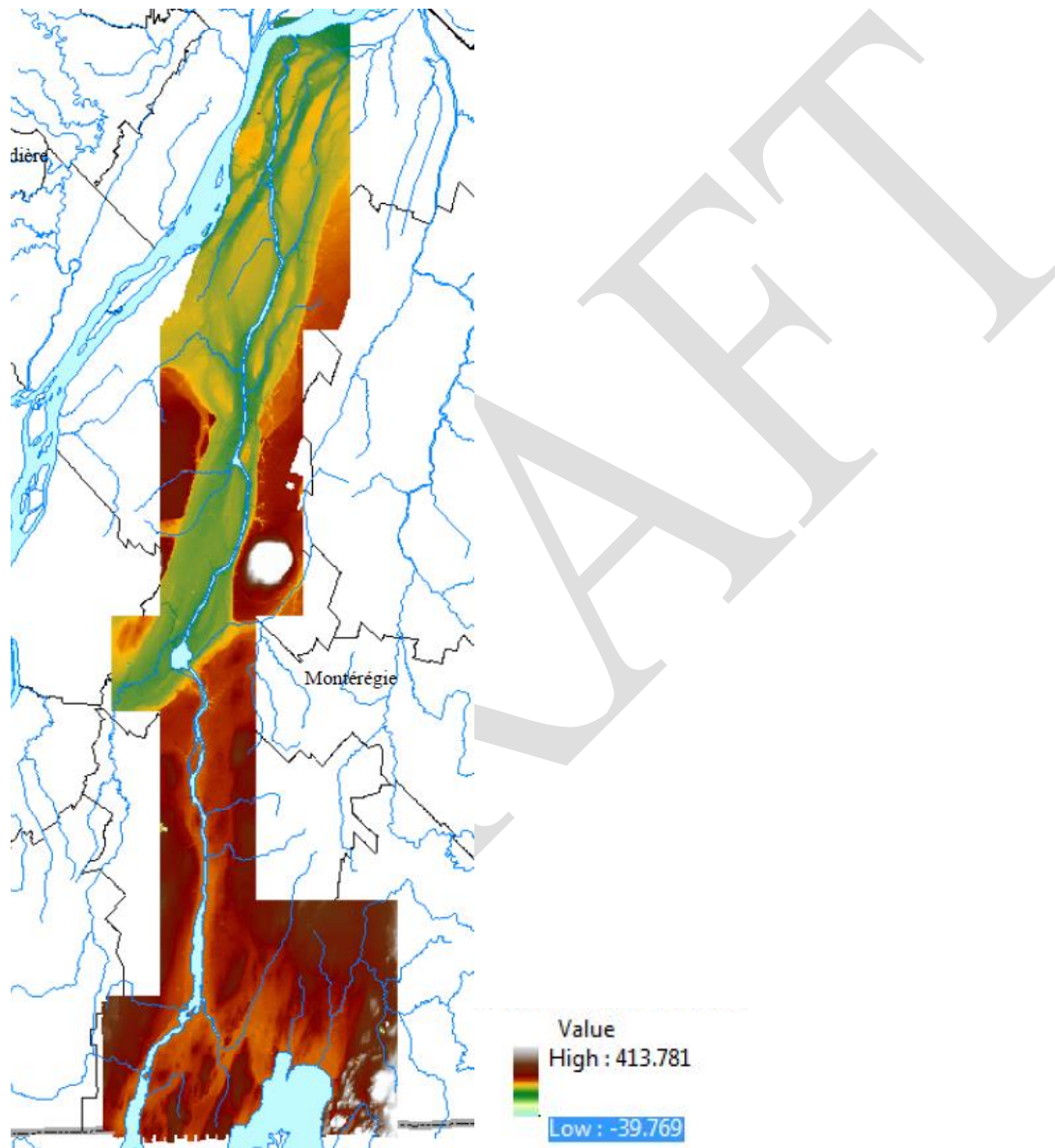


Figure 3.4.2: Overview of the DEM for the shorelines of the Richelieu River and the Missisquoi Bay portion of Lake Champlain. Unit: metres

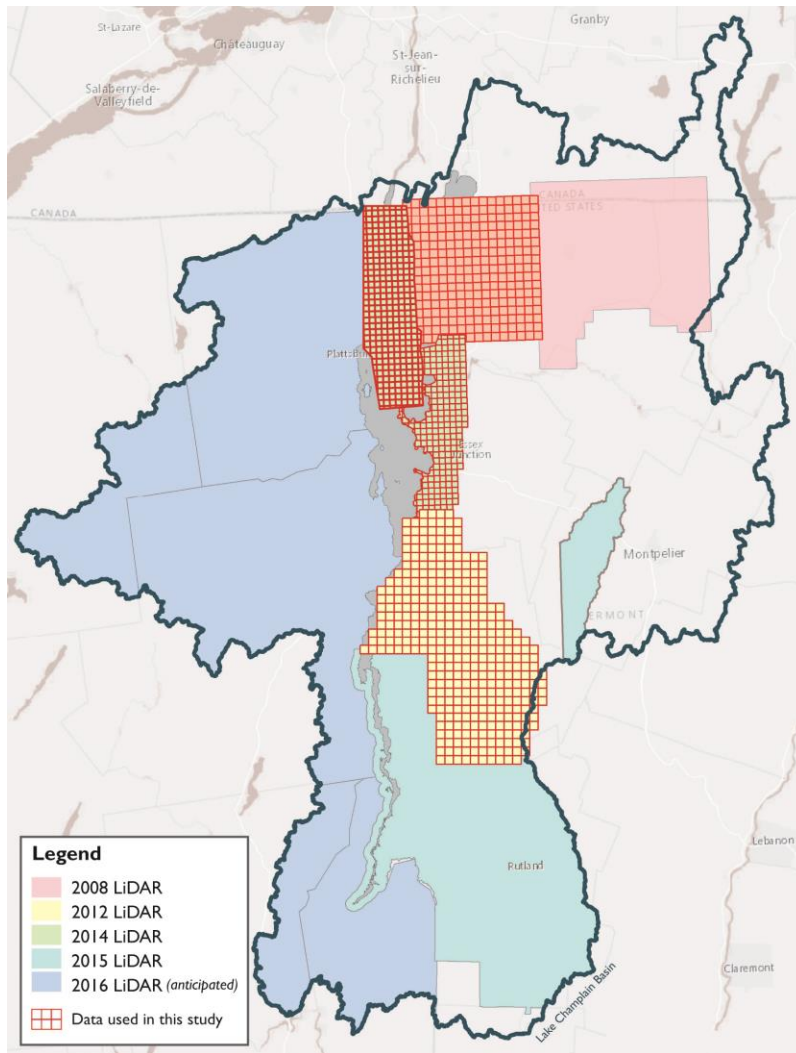


Figure 3.4.3: Spatial domain covered by each of the measuring campaigns and map sheets for which data were used in this study (red squares)

United States DEM and LiDAR Data: Elevation data were obtained from a digital elevation model (DEM) that was derived from LiDAR data on the Vermont (Addison, Chittenden, Franklin and Grande Isle counties) and New York (Clinton County) sides of the lake, as illustrated in figure 3.4.3. The LiDAR data was collected during 2013 and 2014, by Photo Science of Lexington, Kentucky. Post processing of these data was completed in 2014. The LiDAR data have a 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. As with the Canadian LiDAR for the Richelieu River, the U.S. LiDAR for Lake Champlain data specifications support production of 1-ft contours through use of a DEM.

4 Creation of static flood inundation maps

An important product of this study is the creation of maps showing the land areas along parts of the Lake Champlain and the Richelieu River (LCRR) shoreline that would be flooded (inundated) if lake levels reached specific elevations at the Rouses Point NY lake level gauge, and assuming a horizontal lake surface. These maps, known as flood inundation maps, are expected to be a useful tool for example for emergency preparedness for future floods.

The USGS, EC and Ministère du Développement durable, de l'Environnement et de la Lutte aux changements climatiques (MDDELCC) created the flood inundation maps as a collaborative effort for this study. The production of the maps was dependent on a number of specific tasks; these tasks included:

- determining the specific Rouses Point NY lake levels to be used as the basis of the flood inundation maps;
- creation for a high resolution topography data set that would serve of the land surfaces of the maps;
- hydraulic modeling of the Richelieu River downstream of the Rouses Point gauge so that downstream river water levels are accurately related to the lake levels used for the inundation maps; and
- defining the utility and limitations of the flood inundation maps so that local and regional authorities clearly understand how to properly use the maps.

Tasks are summarized below and details are available in two technical reports.

4.1 Selected static scenarios

The TWG selected 11 specific lake water levels to create the flood inundation maps (tables 4.1.1, 4.1.2 and 4.1.3). These water levels are based on designated National Weather Service (NWS) flood stages at the Rouses Point lake gauge, two historic lake levels (103.2 and 102.1 ft), and 0.5 or one-foot increments to 106 feet. These water levels can also be related to threshold values in Quebec as defined by the Quebec's Ministère de la Sécurité publique (MSP).

Table 4.1.1: Eleven scenarios for Lake Champlain water levels at Rouses Point, expressed according to NGVD29 and NAVD88 reference systems, in feet and metres, and approximate corresponding flow of the Richelieu River. The levels shown in bold in the second column are those used in the report text.

Scenario	NGVD29 Level (feet)	NAVD88 Level (feet)	NGVD29 Level (metres)	NAVD88 Level (metres)	Estimated Flow (m ³ /s)
1	100.000	99.570	30.480	30.349	937
2	101.000	100.570	30.785	30.654	1106
3	101.500	101.070	30.937	30.806	1195

4	102.000	101.570	31.090	30.959	1294
5	102.500	102.070	31.242	31.111	1393
6	103.000	102.570	31.394	31.263	1492
7	103.200	102.770	31.455	31.324	1539
8	103.500	103.070	31.547	31.416	1612
9	104.000	103.570	31.699	31.568	1710
10	105.000	104.570	32.004	31.873	1958
11	106.000	105.570	32.309	32.178	2204

Table 4.1.2: Relevancy of IJC Lake Champlain flood elevations used for inundation maps

NGVD29 Elevation (ft.)	NAVD88 Elevation (ft.)	Narrative
100.0	99.57	US NWS designated flood stage at USGS Rouses Point NY stream gauge 04295000
101.0	100.57	US NWS designated moderate flood stage at USGS Rouses Point NY stream gauge
101.5	101.07	US NWS designated major flood stage at USGS Rouses Point NY stream gauge
102.0	101.57	Flood elevation Increment (Flood elevation of 102.1 ft on May 4, 1869 at Rouses Point is the second highest peak of record)
103.2	102.77	Peak lake level elevation (May 6, 2011) at USGS Rouses Point NY stream gauge ever recorded

Table 4.1.3: Relationship between some of the 11 scenarios and flood threshold levels used by Quebec's public safety ministry

Station	Local* water level at station, in metres (NGVD29)	Flow	Flood threshold level	Scenario(s) that correspond approximately
02OJ007 (Fryers Rapids, Carignan, QC)	27.07	1064	Minor	2
	27.25	1221	Moderate	3
	27.37	1335	Major	3 and 4

02OJ016 (Marina, Saint-Jean-sur-Richelieu, QC)	30.10	1070**	Minor	2
	30.32	1225**	Moderate	3
	30.47	1330**	Major	3 and 4
030430 (Outdoor recreation centre, Saint-Paul, QC)	30.56	1150**	Minor	2 and 3
	30.89	1415**	Moderate	5
	31.06	1560**	Major	7 and 8
02OH001 (Lake Champlain, Saint-Armand, QC)	30.61	-	Minor	1 and 2
	30.92	-	Moderate	3
	31.12	-	Major	4

* Not to be confused with the level of Lake Champlain for the 3 first stations

** Approximate value derived empirically from the local level

Lake levels greater than the peak lake level of 103.2 ft are used to create inundation maps that represent possible future flooding levels and or the influence of wind set-up on lake levels at a distance from the Rouses Point gauge.

4.2 Creation of static inundation maps

Note: This work corresponds to Study work plan Task 2-4. Detailed description of the Canadian and U.S. portion work are described in technical reports:

Ministère du Développement durable, de l'Environnement et de la Lutte aux Changements Climatiques, 2015. Contribution to the Creation of Flood Zone Maps for the Quebec Portion of the Lake Champlain/ Richelieu River System: Production of a Digital Terrain Model of the Shoreline Transformation of Water Surfaces into Flood Zone Limits. July 2015 Draft report to the International Joint Commission. 18 p

Flynn, R.H., and Hayes, L., 2015. Flood inundation maps for Lake Champlain in Vermont and New York. Canada: U.S. Geological Survey Scientific Investigations Report. September Draft report to the International Joint Commission, 23 p

Static flood inundation maps were produced by EC and CEHQ for the Richelieu River from US/Canadian border downstream to Saint- Jean- sur- Richelieu, and by the USGS for those portions of the Lake Champlain shoreline where LiDAR data are available. Maps for each waterbody were created for the 11 scenarios of lake level at the USGS Rouses Point NY gage (table 4.1.1).

Static Flood Inundation Maps for the Richelieu River:

Environment Canada utilized the H2D2 modeling results of Lake Champlain to produce river levels for the 11 lake scenarios. The model results provided river elevations for each model node which were then converted to a GIS surface data set. This GIS surface data was used as the inundation layer for the inundation maps. The inundation maps for the Richelieu River also contain water depth information under the surface, obtained by subtracting the local elevation of the ground (provided by the DEM), from the water surface elevation provided by the 2D hydraulic model.

Figure 4.2.1 shows the 11 scenarios for the Quebec portion of the study area. Without being able to see all the details, one can note that water surfaces cover the banks of the Richelieu River and those of Missisquoi Bay of Lake Champlain. Similarly, for scenarios with the highest water levels and stream flows, a hydraulic connection between Missisquoi Bay and the Richelieu River via the South River is clearly shown on the maps.

DRAFT

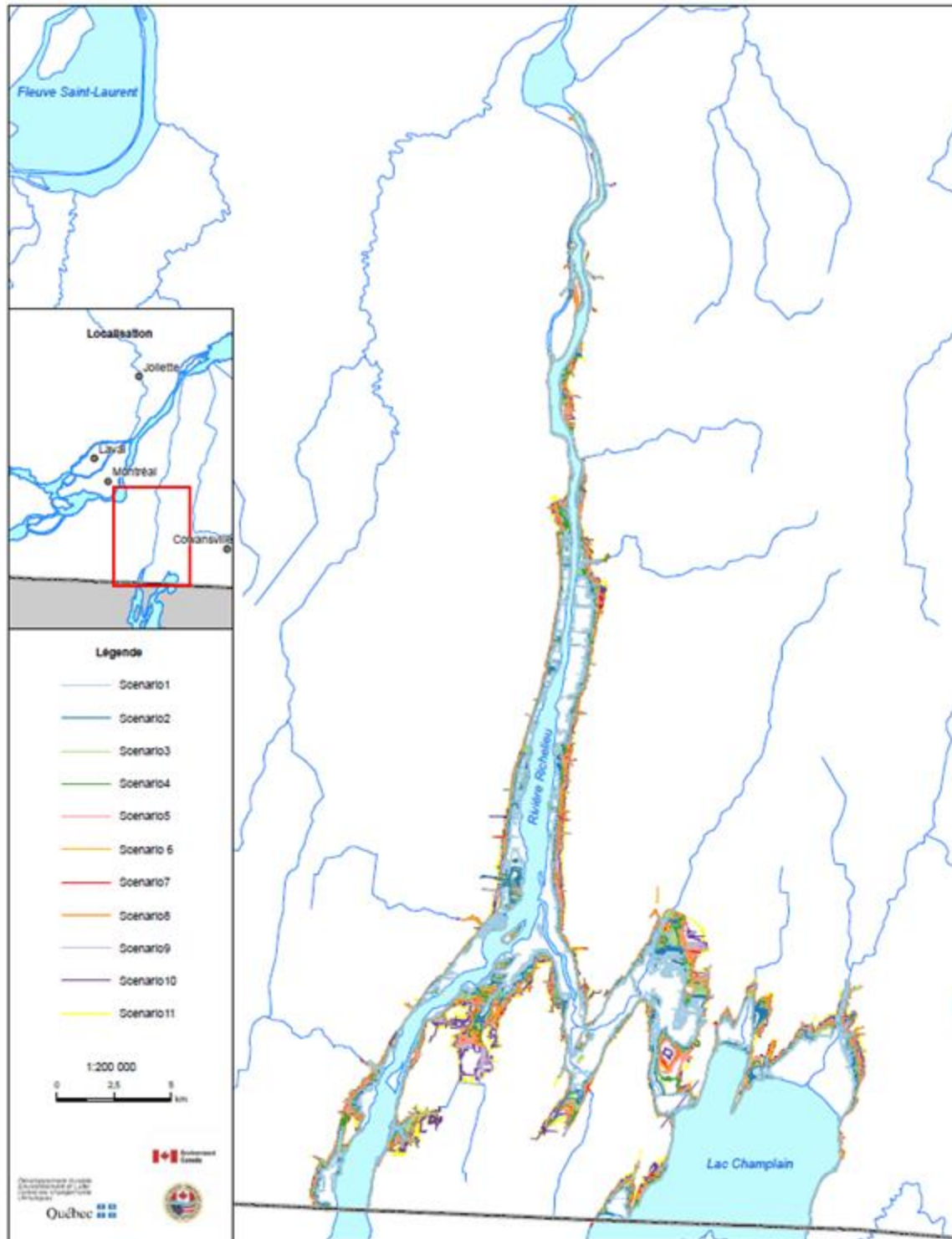


Figure 4.2.1 Areas of the Richelieu River where 11 static flood inundation maps were prepared.

Figure 4.2.2 present a close-up view of the contour maps in the vicinity of Saint-Paul-de-l’Ile-aux-Noix. The progression of the size of the flooded areas from lowest streamflow scenarios to higher streamflow scenarios is evident on these figures. The boundaries of the areas that can be reached by water depending on the scenario are clearly located on the figures.

Figure 4.2.3 presents the flooding depths as simulated for scenario 7 of the flooded area corresponding to a discharge of 1539 m³/s and a water level at Rouse-Point of 31.32 m (NAVD88), in the vicinity of Saint-Paul-de-l’Ile-aux-Noix.

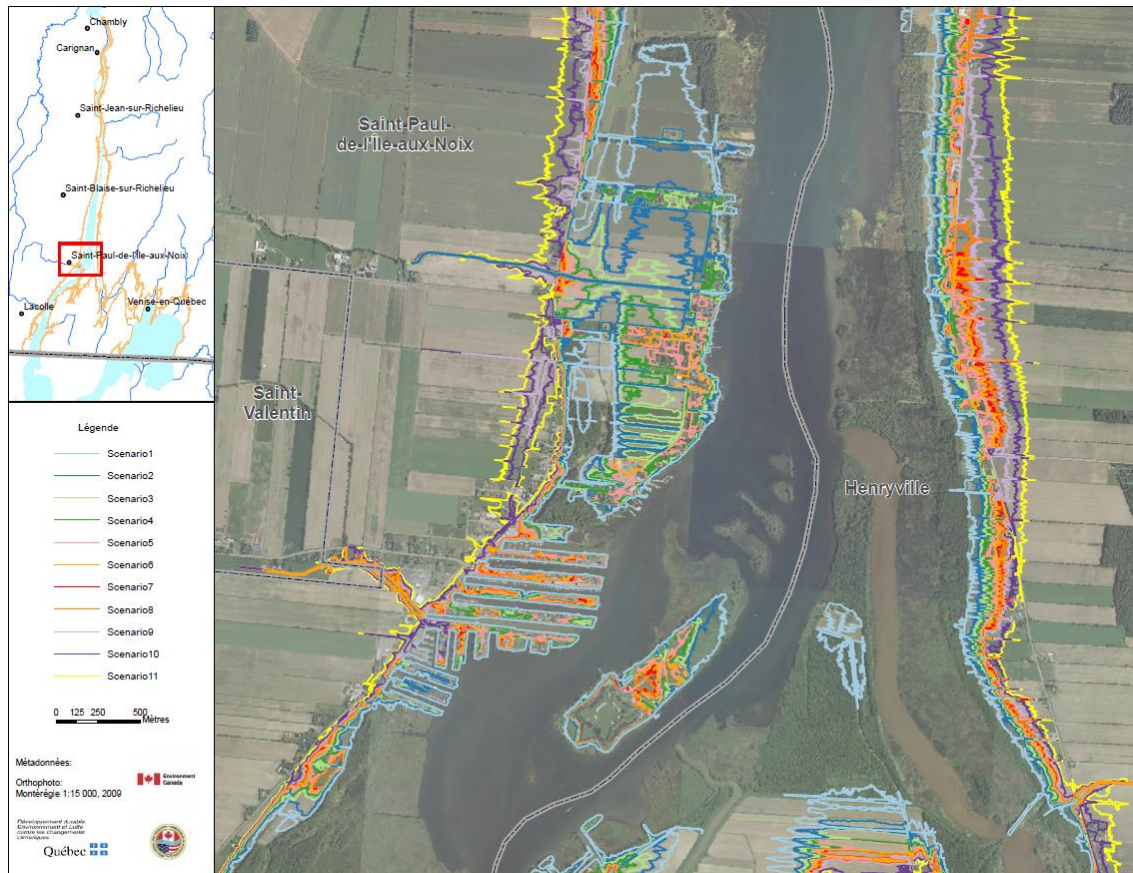


Figure 4.2.2 – Close-up view of the flood inundation profiles for the Richelieu River in the vicinity of Saint-Paul-de-l’Ile-aux-Noix

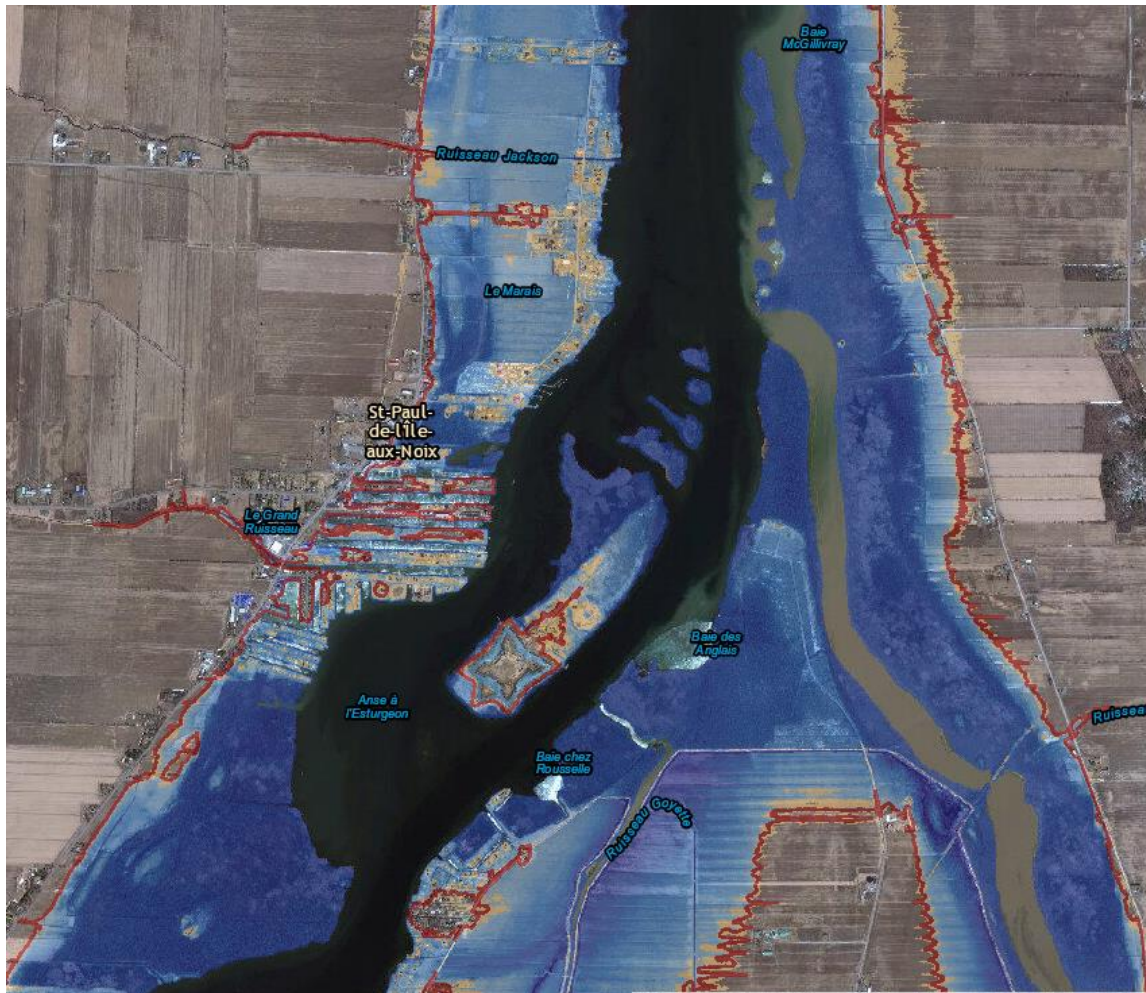


Figure 4.2.3 Flooding depths as simulated for scenario 7, in the vicinity of Saint-Paul-de-l'Île-aux-Noix.

Static Flood Inundation Maps for Lake Champlain: Digital flood-inundation maps for an approximately 100-mile length of the Lake Champlain shoreline in Addison, Chittenden, Franklin, and Grand Isle Counties in VT and Clinton County in NY were created by the USGS – see figure 4.2.4. The lake surfaces shown in the flood-inundation maps reflect a flat linear surface for the entire lake tied to the Rouses Point gage. Flood profiles for the Lake Champlain static flood maps were calibrated by comparing the static 103.20 ft, NGVD29 (102.77 ft, NAVD88) flood inundation map created for this study against the inundation area determined for the May 2011 flood which incorporated satellite imagery and documented high-water marks. Conditions at other lake gages were not reflected in the maps, and wind set-up effects were not taken into account.

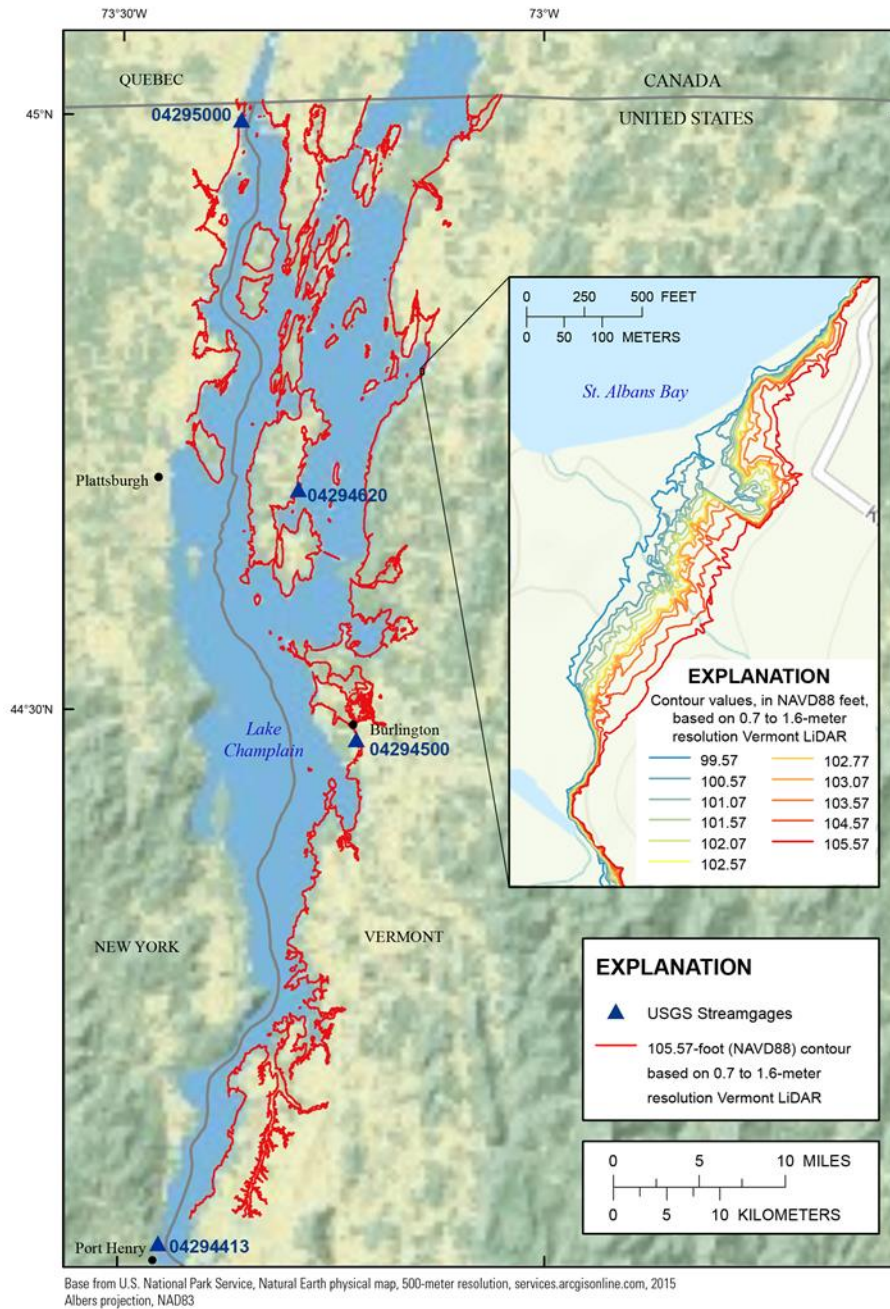


Figure 4.2.4 – Areas of the Lake Champlain where flood inundation maps were created and a detailed map showing areas of flood inundation for the 11 lake level scenarios.

4.3 Quality control of the mapping products

4.3.1 Residual flood line contour discrepancies near the border

Although great care has been applied to assess and compensate for the effects of the two different vertical datums through GNSS observations on the entire domain, the final contours lines produced by the CEHQ and the USGS shows some residual spatial misalignment at the border. For the same water level scenario, the lines produced by the two agencies are spatially off by 1-2 meters (figure 4.3.1 (A) and (B)). These spatial differences can be explained by the fact that the two agencies used different datasets and different techniques to produce the contour lines. The horizontal resolution of the CEHQ LiDAR dataset is at one meter and the USGS one is at 0.70 meter resolution.

The different techniques used by the two agencies to produce contour lines are also a source of uncertainty. EC and CEHQ used water level surfaces produced by a 2D hydrodynamic model, while the USGS used an horizontal plane representing the water level at Rouse's Point gauging station. However, those two different techniques are not significant enough (1- 2 mm) to create the spatial misalignment of the contours lines observed near the border.

Proposed approach to integrate the contour lines produced by USGS and CEHQ near the border

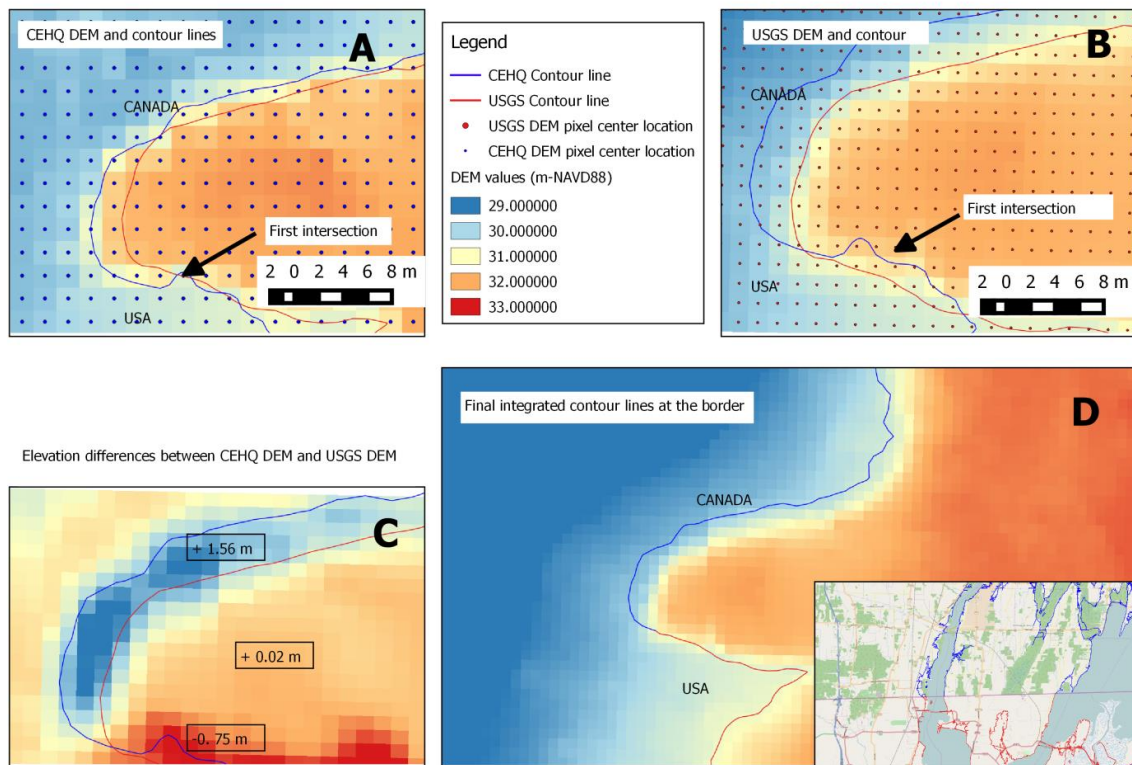


Figure 4.3.1 flood contour line discrepancies at the border

Upon cursory analysis, the most probable cause of the differences observed in the contours lines is related to the use of different LiDAR data sets. The figure 4.3.2 (C) illustrates the differences between the CEHQ and USGS LiDAR dataset. The differences in elevation values can be explain in two ways. The first one is each of the dataset has its own accuracy and uncertainty. Each dataset was acquired at a different time by different methods and calibration resulting in different elevation data. The second possible cause is a slight horizontal shift in the dataset. On the river and lake banks one or two meter is horizontal shift between datasets can results in larger differences in elevation data.

To address the problem at the border, the following procedure was applied for each contour line. For each water level scenario, the contours lines from CEHQ and USGS were mapped. At the border or within few meters of it, and for each water level scenario, the first intersection between the CEHQ and USGS lines was selected has the official line splitter locations. From this location all the USGS north of the line was deleted and only the CEHQ were used and south of the location, all the CEHQ lines were deleted and only the USGS line were used. The final product is shown in figure 4.3.2 (D) were a continuous spatially homogenous line is drawn near the border.

4.3.2 Wind set-up and wave action

Although the flood-inundation maps represent the boundaries of inundated areas with a distinct line, some uncertainty is associated with these maps. The flood boundaries shown were estimated on the basis of water stages at the USGS Rouses Point, NY lake gauge and therefore cannot accurately reflect all local conditions. Unique meteorological factors (timing and distribution of precipitation), wind induced waves and lake level variability may cause actual water level elevations to vary from the assumed static flood elevations depicted at the Rouses Point lake gauge, 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.

The flood-inundation maps should not be used for navigation, regulatory, permitting, or other legal purposes.

4.3.3 Simulated VS observed 2011 flooding

A cursory analysis of the performance of the models in replicating the 2011 flood simulation was performed by EC and CEHQ for the Richelieu River. Figure 4.2.4 shows areas considered inundated during the spring 2011 floods by Quebec authorities superimposed with scenario 7 – the scenario that most closely resembles the most extreme conditions of the 2011 flood. While there are some differences between the two estimates of inundation, they match reasonably well, as shown in figure 4.3.2. Differences are thought to be due to the effects of wind, the inherent incertitude of $\pm 20\text{cm}$ or the contributions of local tributaries.

The cursory analysis leads to the belief that the 2D hydrodynamic modeling coupled with the LiDAR DEM mapping procedures represents reasonably well the flooded areas,

although the 2D model currently operated in steady state mode doesn't have the capacity to incorporate the wind set-up, nor local wave action.

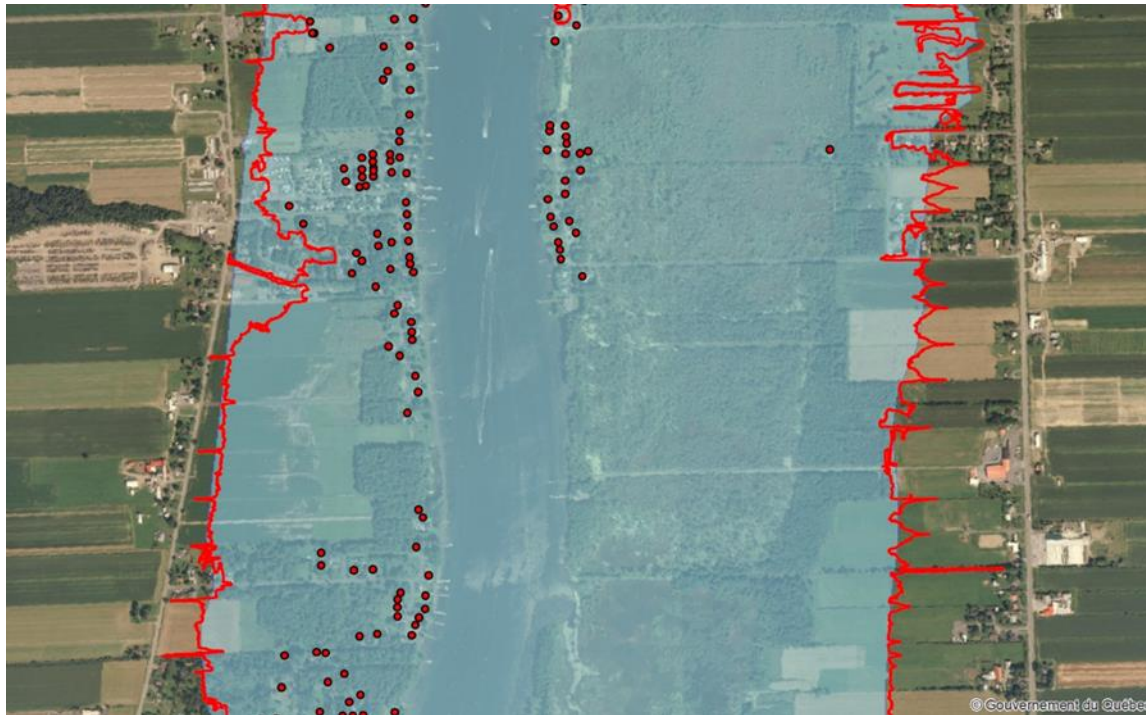


Figure 4.3.2. Example of a comparison between flood inundation for scenario 7 (103.2 ft, NAVD27) and the extent of the flood of 2011 according to data from the Ministry of Public Security of Quebec. Approximate water surface derived from a analysis of remote sensing image taken on May 2011; red dots refer to sites identified as having been flooded.

4.4 Availability of the Inundation Maps

The Richelieu River inundations maps are available on the IJC dynamic mapping web page <http://arcg.is/1MhXui2> as a series of individual maps or a single GIS data set (coverage).

The Lake Champlain maps can also be found on the IJC site, as well as through the USGS Flood Inundation Mapping Science Web site at http://water.usgs.gov/osw/flood_inundation/, 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 NY (station number 04295000) and the Lake Champlain at Burlington, VT (station number 04294500) sites. Figures 10 and 11 present examples of both the Richelieu River and Lake Champlain maps.

Figure 4.3.1 present different views extracted from the IJC dynamic flood plain mapping webpage for the entire Lake Champlain Richelieu River System (<http://arcg.is/1MhXui2>) and showcasing the seamless flood plain delineation at the border.

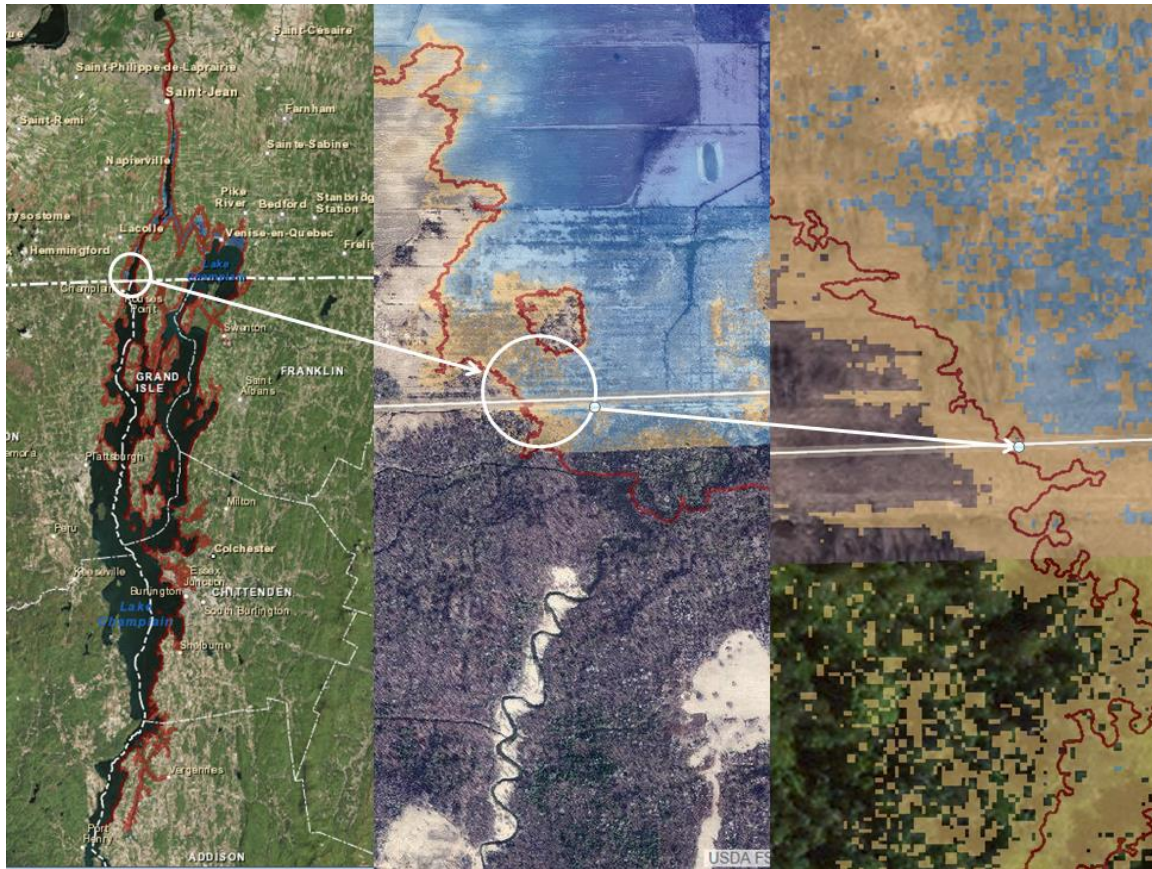


Figure 4.3.1 Seamless Canada – US flood maps of the Lake Champlain Richelieu River System – scenario 7 example

4.5 Future flood inundation mapping in the LCRR Basin

The creation of static flood inundation maps for LCRR as part of this study is a good first step in helping to characterize the flood threats from future flooding events. Not all areas could be mapped around the lake and along the river due to a lack of necessary data (LiDAR for the NY side of the lake and bathymetry data for the Richelieu River below Chambly Dam). The LiDAR data for the NY shoreline will be available in 2016 which will allow completion of the NY side of the lake.

In the future, as lake and river modeling and forecasting improves, enhanced inundation maps that are updated dynamically with flood predictions could be possible. These future efforts would account for the effects of wind set-up and waves which is not possible now.

4.6 Comments from targeted users and stakeholders meetings

Summary of Targeted Users and Stakeholders Meetings

Two stakeholder meetings were held on November 3 and 4 in Burlington Vermont USA and Saint-Jean-sur-Richelieu Quebec Canada, respectively. These meetings presented study results, showcasing the flood inundation map products on the IJC web site. Participants were able to use the web pages and experience the maps and to provide comments on study products. A total of 53 participants were present at both meetings representing emergency responders, community planners, and a host of government agencies.

Participants expressed support for study products and had a number of helpful comments. They liked the flood inundation maps and felt they would be useful in their work.

Comments on the mapping application and the draft maps included:

- It would be important to add an explicit context to each scenario tabs (flood type, frequency, probability, explanatory notes).
- Access to “data/metadata/layers” and not only the maps was requested; however, concerns were also raised about any interpretation of the maps by the general public (*i.e.* non-specialists).
- Land imagery should be added to the Compare feature. The ability to compare two scenarios would also be appreciated.
- People would like to find specific places quickly (for example Rouses Point).
- The visual effect of the uncertainty area on the map was very effective.
- Flood depths for the Lake Champlain area of the maps should be added.
- It was felt that accessibility during disasters and emergency situations will be important.
 - There was some concern about the ability of the mapping server to handle many users during flooding. This would have to be tested to see if the server could handle many users at once.
 - Power and/or internet can be to be out, or decision-makers on the road so access via mobile devices could give the tools more utility during the type of extreme circumstances for which they were developed to help.
- This could be a good tool to build public awareness of watershed dynamics and the interconnectivity of the Lake and River.

Further developments:

People see this past year’s effort as a good first step to be built upon. They would like the work to continue towards both an operational real-time flood forecasting and mapping system for the whole are. They would like also that governments continue to implement

the recommendations contained in the 2013 PoS so as to identify measures to mitigate flooding and the impacts of flooding.

- Participants felt it was very important to add the New York side of the Lake to the map application and the static maps when the LiDAR data becomes available. There was also a lot of interest in obtaining flood maps for the area from Chambly to Sorel along the Richelieu River.
- Participants would like the work to continue with respect to incorporating the effects of wind and waves. This was mentioned at both the Burlington and Saint-Jean-sur-Richelieu meetings.
- Eventually, with further work, several users expressed an interest in using the maps and models to generate flood protection management scenarios so that flood mitigation options (including costs) could be assessed for flood impacts.
- Good communication of end products will be important.

DRAFT

5 A Pragmatic Approach for Flood Forecasting and Inundation Mapping

5.1 Vision for the next generation of flood forecasting system and real time flood inundation mapping

Flood forecasting can be used to provide estimates of flows and water levels for a lead time of a few days to a few weeks. This forecasting also needs to be linked in a dynamic fashion to what shoreline and adjacent lands may flood. Collectively the flood and inundation forecasting should provide accurate information for emergency managers, and local officials, residents and businesses on how to best to respond to threatening condition.

Current situation:

Current forecasts of Lake Champlain water levels are produced in real-time and disseminated by the U.S. National Weather Service (NWS) for 3-day horizons and are based on hydrological modeling of lake's inflows, 1D-hydraulic modelling of the lake, and rules-of-the-thumb appreciation of wind-induced effects. These forecasts predict water levels at the USGS gauge at Rouses Point NY.

Since 2014, NWS forecasts serve, together with real-time monitoring data collected by Environment Canada (EC) and hydrological modeling of the Richelieu River lateral inflows performed by Quebec, as input for predictions of stream flows of the Richelieu River produced and disseminated by the Centre d'expertise hydrique du Quebec (CEHQ). The current flood forecast system is operated by forecast teams in both the NWS and CEHQ who manually assimilate the most recent water level and flow observations to issue deterministic forecasts.

Gaps:

The current system is based on one dimensional riverine models that do not incorporate the effects of lake circulation, wind, or other atmospheric inputs other than precipitation. Furthermore, no explicit linkage is currently in place between forecast lake/river levels and adjacent inundated land areas, hence no dynamic mapping of the flood plain is now issued.

Future improvements:

The TWG identified that the following improvements to the current system should be pursued for the entire Lake Champlain and Richelieu River system:

1. incorporation of wind effect for wind set-up (surge and seiche) and wave action, on the Lake and River;
2. increase in the forecast lead time;
3. inclusion of a formal evaluation of forecast uncertainties, and
4. development of flood inundation flood maps dynamically linked to forecast models.

In order to achieve those improvements, the TWG further identified that the modelling capacities of both countries should contribute to generate diversity, reduce model-specific biases and quantify uncertainties over the range and variability of the conditions that influence flooding .

1. The Canadian and U.S.-generated weather, hydrological and hydraulic model flood forecasts would be post-processed by an international coordination body responsible for producing a single bi-national probabilistic flood forecast covering the 0 – 30 days range with an estimation of uncertainties.
2. The probabilistic flood forecast would be made available to the agencies responsible for their use and dissemination at the federal, provincial, state and local levels of governments.

The approach considered by the TWG is based on similar efforts in the Great Lakes, is robust and can be implemented using different models, as they become available and refined. Although preliminary choices of models have been identified, those are certainly not definitive. Figure 5.1.1 outlines some components of the suggested flood forecasting and flood inundation mapping system.

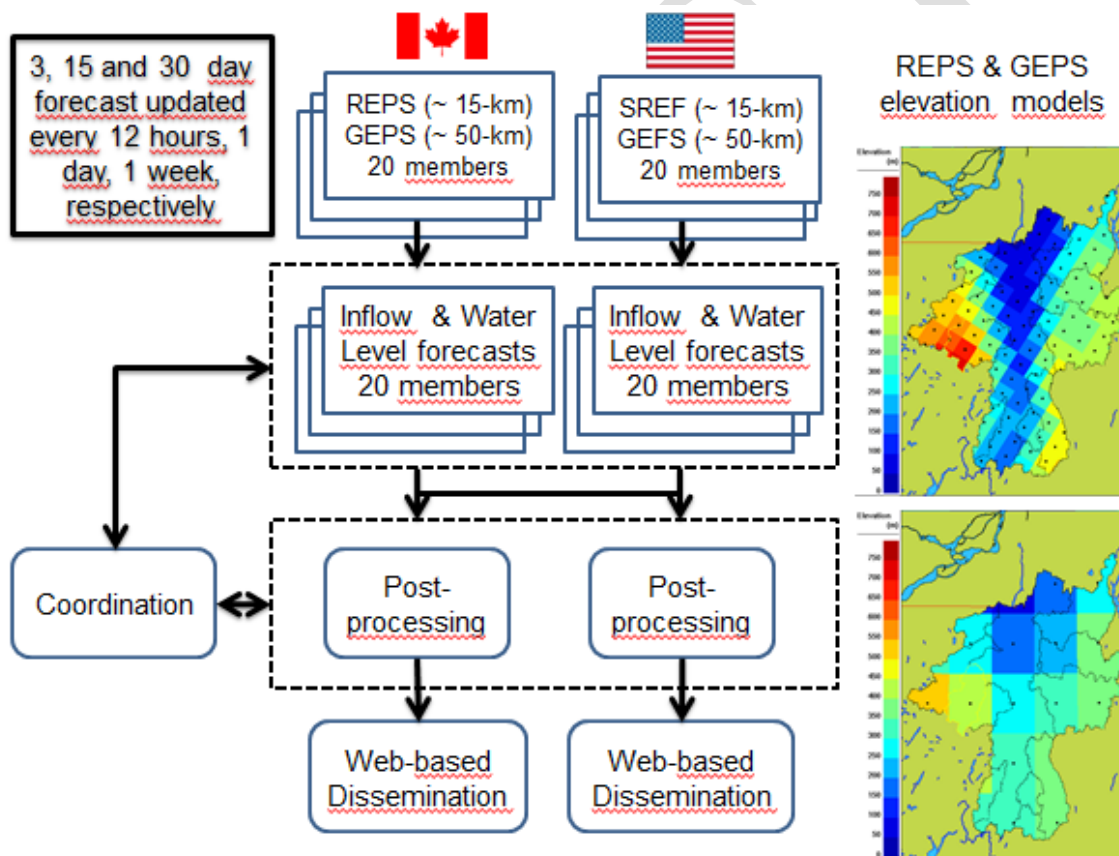


Figure 5.1.1 Components of the flood forecasting and flood inundation mapping system

More specifically,

- The probabilistic weather forecast systems of both countries should be used. In the current configuration, this would represent 40 distinct members: 20 from Canada and 20 from the U.S.
- The forecast range should take advantage of both the short term (0-3 days), higher spatial resolution ensemble forecast systems and the longer term (4-30 days) lower spatial resolution systems. Table 5.1.1 outlines the temporal and spatial resolutions of the currently available products. The North America Ensemble Forecast System (NAEFS) websites provides further information on the products: https://weather.gc.ca/ensemble/naefs/index_e.html, and <http://www.nco.ncep.noaa.gov/pmb/products/naefs/>.

Table 5.1.1 Temporal and spatial resolutions of the US and Canada ensemble prediction systems

T = 0 - 3 days		T = 4 - 30 days	
Canada	U.S.	Canada	U.S.
Regional Ensemble prediction System (REPS) 15 km, 20 membres	Short Range Ensemble forecasting System (SREF) 20membres 16km	Global Ensemble prediction System (GEPS) 50 km, 20 membres	Global EnsembleForecasting System (GEFS) XX km, 20 membres
Hourly outputs, refresh rate of 12 hours	Outputs every 3 hours, refresh rate of 6 hours	Outputs every 6 hours, refresh rate of 12 hours during weeks 1 and 2, weekly refresh for weeks 3 and 4	Outputs every 6 hours, refresh rate of 12 hours during weeks 1 and 2, weekly refresh for weeks 3 and 4

- In order to generate individual runoff and inflow scenarios, the hydrological models operated by both Canada and the U.S. would be forced by atmospheric members for short term and long term predictive ranges, including predictions on air temperatures, snowfall and rainfall for the initial weeks, and wind forcing for the initial 0-3 days. In Canada the land-surface and hydrological models under consideration are a combination of EC's GEM-Hydro land-surface and hillslope model, coupled to a river routing system, and HYDROTEL, the hydrological model currently used by the Centre d'Expertise Hydrique du Québec (CEHQ). These models provide simulation of snowmelt, vertical water budget and overland and river flows.
- The LCRR water levels and flows would be simulated using the respective models operated in the U.S. and Canada, forced by their respective members of tributary inflows and wind forcing (for the short-term 3 day range), thus creating a probabilistic envelope of potential lake and river local water levels and flows. Models under consideration are, in Canada, H2D2, a finite element model developed at Institut National de la Recherche Scientifique – Centre Eau-Terre-Environnement (INRS-ETE) with support from EC, and in the U.S., an application of the Finite Volume Community Ocean Model (FVCOM), currently in use for the Great Lakes. This model is presently used for nowcasting and forecasting of two- and three-dimensional currents, elevations, winds, waves, and ice in the Great

Lakes domain. The NOAA Great Lakes Environmental Research Laboratory (GLERL) develops applications of this model. The NOAA Center for Operational Oceanographic Products and Services (CO-OPS) maintains and operates the model. A similar application of FVCOM would be developed for the LCRR system.

- The initiation of each simulation cycle would start with an assimilation procedure during which the internal state variables of the models would be modified in order to better represent current hydrological and hydraulic conditions and ensure a smooth transition between observed and predicted lake and river water levels and flows, tributary inflows, wind speed and direction. The assimilation procedure would be developed to take full advantage of the available information and expertise.
- With the availability of the complete LiDAR DEM expected for the entire system by 2016, the predictive flood mapping products could describe the predicted contours of any flood, as well as the local predicted inundation depth over the land surface at any location. This product is viewed as having potential use in optimizing the flood preparedness, but also as a communication tool to raise awareness about local severity of floods.

Similarities exist with the modeling approach that provides accurate simulations and predictions of water surface elevations across trans-boundary waters for the Great Lakes. Under this Great Lakes approach, the U.S. and Canada run parallel sets of atmospheric and hydrodynamic models. Environment Canada and NOAA conduct the model runs independently and then share model results. In the case of Lake Ontario and the Saint-Lawrence River, the International Saint-Lawrence River Board of Control takes advantage of the availability of both atmospheric and hydrodynamic model runs executed by both countries to conduct its activities.

Adopting a similar approach for the LCRR system provides the most likely path to improved forecast performance in the system.

5.2 Technical workshop key points and other input from informal consultations with experts

The vision for a flood forecasting and floodplain mapping system described in section 5.1 was presented to experts in a special technical workshop held during the Conference on Great Lakes Research in May 2015 in Burlington, Vermont. Annex 4 lists the experts that attended the workshop. The TWG engaged the experts with specific questions and listened to experts input on those and other issues deemed important.

The questions asked to experts were:

Weather and hydrological forecasts

1. Is a forecast time horizon of 0-3 days reasonable?
2. Is it feasible to have wind forecasts for time horizons beyond 3 days?
3. Should we be looking at a probabilistic or a deterministic approach?

Hydraulics of the LCRR

4. What is the expected accuracy of the flood forecast predictions?
5. Should we add wave action (height, period, run-up, overtopping) or ice components on top of seiche effects?

Whole prediction system

6. How do we best communicate flood forecasts and flood inundation maps? What are the desirable features?
7. Should we consider adding value to automated forecasts? If so, how?
8. Desired flood mapping products:
 - a. Delineation of the flood plain only?
 - b. Add depth information?
 - c. Add terrain features (buildings, roads, etc.)?
9. Is it desirable to use one common set of flood forecasts to generate both the Canadian and U.S. flood inundation maps? Should a board / committee be set up?
10. What type of coordination mechanism makes sense: a board / committee? Do we need coordination?
11. Are we missing something important?
12. Are there other options we should consider?

Essentially, the approach proposed by the TWG received support from the group of experts, who also provided insight on specific points. The highlights of experts' input are:

- The probabilistic approach presents many advantages over the deterministic solutions: Probabilistic products with communicated uncertainty provide the users the ability to make decisions based on their own acceptable levels of risk; it also allows for the definition of confidence intervals on flood map depictions and potentially limits legal issues and liabilities.
- Predictions on flooded areas and local depths was viewed as a good idea, potentially very useful as an awareness tool when discussing rebuilding homes at same locations after a major flood.
- Experts indicated that the forecast updates could be done at a higher frequency than the suggested 12 hours, provided that the greater frequency could be shown to improve flood warning and preparedness.
- The wind set-up (surges and seiche) effects should be incorporated into the model, as its effect on flooding is significant and can change rapidly. The “Inland Sea” portion of Lake Champlain also reacts differently to wind forcing from the main body of the lake, due to the presence of multiple causeways with small “pinch-point” openings, isolating portions of the lake.
- The effects of wave action (height, period, run-up, overtopping) should be considered in the modelling effort as it has demonstrated significant impacts in the past.
- Ice effects should be documented with historical data to evaluate the magnitude and locations of their impacts on the flooding, if any.
- Performance indicators to assess the flood forecasting system skill should be developed, used in future events, and refined with experience in the future. Some packages are already in use by NOAA and other agencies.

- Experts confirmed that the federal, state and provincial agencies that are responsible for the flood plain mapping often have developed their own standards and procedures. The responsibilities of an eventual LCRR coordinating body would essentially related to the production of flood forecasts – water levels and floods – to be disseminated by the responsible agencies as per their own standards for the packaging of the forecast products.
- Experts also mentioned that caution must be used when combining data sets from different sources to create flood mapping products and ensure that the combined errors are accounted for in the confidence intervals and quantification of uncertainties.

5.3 A pragmatic approach for a future operational flood forecasting and flood inundation mapping system

In order to achieve improved forecast performance in the future, a modeling system that combines atmospheric, hydrologic, hydraulic, wind set-up and wave action is required. In addition, a methodology that more readily connects lake/river levels to adjacent flooded shoreline is necessary to ensure that inundated areas become part of the forecasts.

The TWG suggests that the modelling approach described in section 5.1 would provide the required information for the generation of the best possible flood forecasts, and further convey the consulted experts’ appreciation to the effect that the probabilistic products with communicated uncertainty would provide the users with the ability to make decisions based on their own acceptable levels of risk.

The TWG further suggests that the following aspects be addressed by an eventual flood forecasting and real-time floodplain mapping system:

5.3.1 Coordination

The implementation of a bi-national coordinating body including members from the U.S., Canada, New York, Vermont, and Quebec is proposed to ensure the coordination of the forecast activities on the Lake Champlain – Richelieu River system. The group would coordinate activities between the agencies responsible for execution of the respective modeling ensemble systems, taking advantage of the diversity and redundancy of the ensemble flood predictions to issue the best possible joint probabilistic flood forecast. This forecast would be mutually agreed to and made available to the agencies responsible for flood warnings and flood plain mapping in each applicable country, state, and province.

The bi-national coordinating body would become annually more active during the months preceding the spring freshet, until flows and water levels recede to low risk status, and during high flows events triggered by heavy storms (such as Hurricane Irene in 2011), or in response to other events for which precise water levels and flows are required.

The coordination body should engage the forecasting agencies and aim at facilitating the exchange of up-to-date scientific knowledge and organizational development activities on

LCRR. The coordination structure could also encourage agencies to share common goals, development priorities and agendas and some compatible forecasting tools for LCRR. Development, implementation and maintenance of the models, availability and analysis of observation and forecast data, benchmarking of forecast performances are examples of common activities. Finally, the coordination structure should also address how operational agencies should work together for the production of day-to-day flood forecasts.

The coordination body should also facilitate exchanges of information and best practices among agencies that disseminate and interpret forecasts for end-users needs such as safety purposes. These agencies should exchange operationally, especially on flood situations, about the different forecast products available and should produce coherent and useful messages for end-users making the best of available data. Each agency should stay responsible for disseminating and interpreting the forecast for its respective customers.

5.3.2 Linking model results to inundation Mapping

The development of a near-real time inundation mapping delivery should be accomplished in close collaboration with the lake and river forecasting system development. Results from the lake and river forecasts would be seamlessly linked to the U.S. and Canada DEMs to generate the flood inundation maps in real-time, and fed to on-line delivery applications that would display detail topographic maps in near real-time fashion.

This would then allow local, state and federal emergency agencies to package the flood mapping products as per their own standards and disseminate it to their respective customers with added value such as identification of potential flood impacts on properties and critical infrastructures, roads, bridges, sewage, drinking water facilities, and others.

The inundation maps are not designed for flood planning and regulatory purposes, but rather for emergency and flooding potential due to current and future conditions.

5.3.3 Wave modelling

Although wave action alone is not expected to significantly alter flow at the outlet of Lake Champlain and certainly does not change the mean water level, wave action can certainly cause additional local damage to infrastructure. Storms passing through Lake Champlain can cause significant wave heights of up to 2 meters (http://www.weather.gov/media/btv/lake/Science_behind_the_forecast.pdf). The National Weather Service currently runs a simple wave model developed for fetch-limited conditions (<http://onlinelibrary.wiley.com/doi/10.1029/JC089iC03p03586/pdf>) but both Canada and the US are in the process of replacing their national wave forecasting models by the NOAA WaveWatch III model (<http://polar.ncep.noaa.gov/waves/wavewatch/>), which is a third generation model applicable to a broad range of conditions, benefits from long-term support by the NOAA and EC and is continuously being improved by the community. It is proposed to include a wave forecasting tool based on WaveWatch III in the future flood forecasting system of Lake Champlain. It could be used to lower the threshold at which flood warnings would be issued for the lake. A challenge for calibrating WaveWatch III on Lake Champlain is that no wave observation station is currently

operating on the lake. It would be useful to install, at least during the calibration phase of the model, wave buoys in both the main part of the lake and in the inland sea.

5.3.2 Forecast models options

As mentioned previously in section 5.1, although preliminary choices of models have been identified, those are certainly not definitive. Some additional options are presented here, but final choices should be part of an eventual next phase in the development of the operational flood forecasting and real-time mapping of the flood plains.

Atmospheric models: For the U.S. simulation of Lake Champlain, an integrated system linking the atmospheric model(s) (e.g. the SREF/GEFS combination outlined in Table 5.1.1) to a three-dimensional hydrodynamic model of the lake (e.g. FVCOM) would ultimately be implemented. FVCOM is currently used in the Great Lakes Coastal Forecasting System (GLCFS) and the Great Lakes Operational Forecasting System (GLOFS). The models provide predictions of water levels, surface winds, seiche effects, wave heights, surface currents and temperatures, temperature profiles, and ice thickness. As currently operated by NOAA, the GLCFS provide forecasts twice daily.

Hydrologic and hydraulic models: For the Canadian simulation of LCRR, the regional and global prediction systems outlined in Table 5.1.1 would be connected to a combination of Environment Canada's GEM-Hydro land-surface and hillslope model coupled to a river routing system and/or HYDROTEL, the hydrological model currently used by the Centre d'expertise hydrique du Québec (CEHQ). The predicted inflows and winds ensembles would be used to force a 2D hydrodynamic model such as H2D2 to generate the water level forecasts twice daily.

Accounting for uncertainties: in order to help quantify the uncertainty associated with perturbations to atmospheric and/or hydrodynamic model parameters, multiple model runs incorporating these perturbations (typically one perturbation per model run) can be executed. The resultant range of model outputs (i.e. considering all model runs) helps to quantify the potential effects of the perturbations. Automated approaches to conducting these multiple model runs are commonly referred to as "ensemble runs" of the model(s). Future operational models for Lake Champlain should be implemented to take advantage of the ensemble approach, so that the models can communicate not just a forecast, but the uncertainties associated with that forecast.

6 Summary of findings and recommendations

6.1 Findings related to the real-time flood forecasting and inundation mapping system

On the weather forecasts

A comparison of SREF and REPS forecasts over selected events in 2015 showed that both systems provide forecasts of similar skill⁵ to the RDPS, with the SREF providing slightly better forecasts. It thus seems possible to forecast the North-South component of the wind out to three days for flood forecasting purposes, but a calibration/downscaling procedure will be required before wind forecasts can be used by hydrodynamic models, especially given that the SREF and REPS forecasts have a very different bias signature.

Verification results indicate that the GEPS forecasts have useful skill up to the 5-day lead-time: correlation for day 1 between observed precipitation and the GEPS control member is very high (0.95), dropping to 0.54 on day 5. Longer lead time forecast show no significant skill. The use of the ensemble mean instead of the GEPS control member did not allow to extend the useful lead time of the forecast, but did increase correlation slightly for the first two days.

Whereas the use of monthly temperature forecasts might be warranted in February, for reliable flood forecasting later in the season it might be more appropriate to rely on climatological temperature inputs for week 3 and 4. On the other hand, having the flexibility of using monthly ensemble weather forecasts for all three months might be useful in a warmer climate (summer and fall), since past observations of temperature become less representative of current conditions.

On the vertical datums in use in Canada and the U.S.

Cross border datum discrepancies have existed in the LCRR Basin and prevented comparisons of water level elevations and flooding between the two nations. To correct these data discrepancies, in April 2015, personnel from USGS, EC and U.S. and Canadian Geodetic Surveys conducted a study to create a vertical datum transformation so that all of the water level data in the LCRR could be shown in a consistent manner between the two nations. Selected point locations at lake and stream gauges and hydro-sensitive locations within the Champlain-Richelieu floodplain were intensely surveyed over a 2-day period. This resulted in vertical corrections allowing to represent the water levels in any of the two geoid-based vertical datums (NAVD 88 or CGVD2013). These corrections now allow water levels on both sides of the border to be converted to a single consistent value that is essential in creating consistent flood plain maps for the lake and river.

⁵ Forecast skill is defined as the performance of a particular forecast system in comparison to some other reference technique

On the implementation of two new water level gauges

Two new water level gauges were installed on the Lake Champlain, in Port Henry and on the East Side of Grand Isle. The one in Port Henry is considered a valuable long-term gauge for the lake because it provides lake level data for an area of the lake that is not represented by the other active gauges on the lake. Moreover, the Port Henry gauge better describes southern mid-lake conditions than the one in Whitehall, at the extreme south end of the lake, and preliminary modeling of the lake indicates it is more useful for the estimation of wind impacts on the lake. The Grand Isle water level station will likely become essential for the calibration of the “inland sea” portion of the hydraulic model, as it is the only gauge measuring water levels in the southern portion of this enclosed area.

On the collection of new substratum and aquatic plants distribution in the Richelieu River between Rouses Point and Saint-Jean-sur-Richelieu

The new data sets of substratum and submerged aquatic plants acquired between the Gouin Bridge at Saint-Jean-sur-Richelieu and the border near Rouses Point in September 2015. The field campaign took place between September 8 and 17, 2015. These new data sets could be used to generate updated maps of the substrate, as well as the aquatic plants assemblage and density, which in turn could be used to refine the model’s friction coefficient.

On the experimental 2D hydraulic modelling of Lake Champlain

A 2D finite element hydraulic model has been created for Lake Champlain between Whitehall NY and Saint-Jean-sur-Richelieu Quebec. The model is based on a single vertical datum (NAVD88) and a hydrological database has been created to represent the inflows of 13 tributaries, including an estimation of the un-gauged areas. This experimental model can accurately predict high lake and river levels to Chambly. Preliminary simulations also find that lake water levels in the main lake and that area of the inland sea can be significantly different due to wind effects. Preliminary simulations of water levels show significant differences to wind forcing between the main body of the lake and its “inland sea” portion, connected through relatively small openings in a series of causeways. The use of a 2D model is expected to allow for a more precise prediction of the water levels in the various areas of the LCRR than the current 1D approach, especially if a dynamic version of the hydraulic model is implemented in the future.

Significant gaps and errors in the currently available bathymetric data were observed, essentially in the area comprised between Saint-Jean-sur-Richelieu and Sorel and the calibration of the hydraulic model proved impossible to complete for that area. Additional bathymetry was acquired on the natural control section near Saint-Jean-sur-Richelieu, but a finer description is still required to complete the calibration of the hydraulic model on the whole range of possible flows.

On the creation of a Combined LiDAR data base and Digital Elevation Model for the Basin

Collection of new LiDAR data was accomplished with this study in New York State. Once formally completed and delivered, together with on-going LiDAR data collection and processing in Vermont, a complete LiDAR data base will be available for the entire LCRR basin. The NY and VT data will be available in 2016.

Future efforts will be needed to create a single seamless LiDAR and DEM data base for the basin. Currently the Canadian and US LiDAR/DEM data sets are not totally matched and consistent for creating a single DEM that can be used for basin-wide modeling and flood inundation mapping.

On the best possible approach for Flood Forecasting and Inundation Mapping

The approach presented in section 5.1 has been developed by the TWG members, submitted to other experts, and further refined accordingly. The TWG considers that its operational implementation will generate the best possible bi-national flood forecasting and real-time flood plain mapping system for the entire Lake Champlain – Richelieu River system.

In short, a probabilistic approach cascading down from the atmospheric models, to hydrological models, to hydrodynamic models with real-time assimilation of observations, taking advantage of both the U.S. and Canada's capacities to generate probabilistic flood plain mapping products with communicated uncertainty is recommended by the TWG. This approach would provide the users with the ability to make decisions based on their own acceptable levels of risk, as well as allowing for the definition of confidence intervals on flood mapping products and potentially limits legal issues and liabilities.

A coordinating body would conduct the coordination among agencies involved in the forecasts, namely on the development and maintenance of the models, post-processing of the forecasts to produce a single bi-national probabilistic flood forecast covering the 0 – 30 days range with an estimation of uncertainties, quality control and availability of the forecast products.

6.2 Findings on the flood mapping products

Static Flood Inundation Maps

The current effort greatly moved forward the creation of flood-inundation maps for the LCRR. These maps provide an emergency planning tool for authorities and the general public on land that may flood during high water events. Static inundation maps were created for the Vermont side of Lake Champlain and a portion of the New York northeastern shore line were created on the US side, and for the Richelieu River from the border, downstream to the Fryers Rapids on the Canadian side. These maps are available from the IJC web site at: <http://arcg.is/1MhXui2>. A complete LiDAR Digital Elevation Model available in Canada also allowed for the representation of inundation depths for the 11 flood scenarios.

A series of 11 water level scenarios for the Rouses Point NY Lake level gauge were used to create the static inundation maps. These scenarios range from 100 feet to 106 feet (30.480 to 32.308 meters) and are expected to cover the full range of flood conditions to be expected on the lake. These maps have their limitations however and do not reflect actual dynamic conditions throughout the lake and river associated with constantly-varying wind set-up and waves inducing local variations in water levels. For creating the Lake Champlain maps, the entire lake surface was assumed to be horizontal upstream from the Rouses Point gauge. And for the Richelieu River, the sloped water surface was established through the use of a 2D hydraulic model.

Other areas that need to be mapped that have not been done yet include:

- New York State shoreline along Lake Champlain: This can be done when the New York State LiDAR is completed in 2016. For now, the New York shoreline cannot be mapped for flood inundation purpose. A small section of southern Vermont in Rutland County will also need to be mapped once LiDAR is completed for that area.
- The water levels and flows of the Richelieu River from the entrance of the Chambly basin to the Saint-Lawrence River could not be modeled accurately due to poor bathymetric data sets. Acquiring a new bathymetric data set for the lower Richelieu should be essential for the hydraulic modelling of this portion of the system and to allow for the creation of flood inundation maps from the dam downstream to Sorel.

Displaying the flood inundation maps in a consistent and common format in both Canada and the US that is readily accessible via the web would be valuable for emergency responders, local officials and flood plain managers.

In the future, as improved lake and river forecast models are created and a new system is in place for flood forecasts, these forecasted results will need to be linked to real-time inundation maps that show current conditions and future forecasted conditions, and how wind set-up and waves are impacting flood levels. This is unlike the current maps that are static and so do not show current conditions.

6.3 Recommendations

1. To generate flood forecasts and real-time flood mapping system, the TWG recommends that the proposed U.S. - Canada two-pronged probabilistic approach presented in section 5 for the forecasting of floods should be adopted and implemented operationally, including the modelling of wind set-up and wave action.
2. To calibrate and validate a future forecasting system, the TWG recommend that the both the Port Henry and the Grand Isle water level stations installed to support this Study, be kept in operation at a minimum to collect data covering a representative range of water levels supporting the calibration of the hydraulic model, recognising that those stations may or may not be required in the context of an operational system. The TWG also recommends, at least during the calibration phase of a wave model, the installation of wave buoys in both the main part of the lake and in the inland sea.

3. The TWG recommends that a binational coordination body under the auspices of the IJC be instituted to conduct the coordination among agencies involved in real-time forecasts, namely on the development and maintenance of the models, availability of observation data, quality control of the ensemble predictions and generate the bi-national water level predictions and a consistent message to emergency responders and public regarding the bi-national water level predictions for distribution to agencies responsible for dissemination.
4. To allow for a better flood forecasting capacity of the entire LCRR, the TWG recommends that the acquisition of new bathymetric data of the Richelieu River between Sorel and the natural control section near Saint-Jean-sur-Richelieu, and that updated maps of substratum and aquatic plant assemblages be completed.
5. To generate flood forecasts and real-time flood mapping products for the entire Lake Champlain Richelieu River system, as well as static maps, the TWG recommends that a single consistent DEM be created for the entire LCRR basin once all LiDAR and bathymetric data acquisition and quality control is completed.
6. The TWG recommends that the static flood inundation maps be generated for the entire Lake Champlain Richelieu River system.

ANNEX 1 References from the Governments

Reference letter provided to the IJC by the U.S. government



United States Department of State

*Bureau of Western Hemisphere Affairs
Washington, D.C. 20520-6258*

July 24, 2014

Mr. Chuck Lawson
Secretary, U.S. Section
International Joint Commission
2000 L St. NW, Suite 615
Washington, D.C. 20440

Lake Champlain and Richelieu River Reference

Dear Mr. Lawson:

The Governments of Canada and the United States thank the International Joint Commission (IJC) for its July 2013 Plan of Study: “The Identification of Measures to Mitigate Flooding and the Impacts of Flooding of Lake Champlain and Richelieu River” which the IJC undertook in response to our governments’ request in a March 19, 2012, letter to investigate flood mitigation solutions following devastating floods in that region in the spring of 2011.

We particularly appreciate the IJC’s presentation of individually scalable options for study implementation. We understand that the IJC recommends Option C at \$14 million (to be funded jointly by Canada and the United States) as the best option for a thorough understanding of the causes and solutions for flood mitigation through a long-term study. Our governments are not at this time, however, able to commit to such a large scale, long-term undertaking, and thus cannot make a reference including that option now.

Instead, in accordance with Article IX of the Boundary Waters Treaty, the Governments of Canada and the United States request that the International Joint Commission assist our governments in the implementation, with existing 2014 funding, of two scalable components in the study. These components will provide valuable information to assist affected communities in floodplains in a practical and immediate fashion and also provide a basis for a future real-time flood forecasting and inundation mapping system.

This reference is limited to initiating and completing work on the following, which will be organized and implemented by a small technical working group, to be convened by the IJC:

1. Addressing and closing data gaps through data collection and harmonization of topographic, bathymetric, aquatic vegetation, soil texture, Light Detection and Ranging (LiDAR) and observed climate and hydrometric data collection (per section 3.1, page 34 of the July 2013 Plan of Study) as are necessary as a basis for the earliest possible initiation of a real-time flood forecasting and inundation mapping system. This system would consist of the development of new real-time Lake Champlain and Richelieu River hydrologic and hydraulic models for predicting lake and river levels, and a precise Digital Elevation Model of the flood plain to delineate the contours of corresponding inundated areas.
2. Creation of static flood inundation maps using a combination of existing and new data and modeling to provide practical information to communities. These maps would show which areas would be affected if Lake Champlain and Richelieu River water levels hit different heights.

Subject to each government's national appropriations process, Canada and the United States may consider a subsequent reference on other components of the 2013 Plan of Study, including using data from this work to produce a real time flood forecasting and inundation mapping system.

In examining and collecting data, the IJC-assembled working group should build on the technical data gap analysis outlined in the IJC July 2013 plan of study and decide early on which government agency will take leadership on the different elements. The study should incorporate and take advantage of existing systems and government mechanisms already in place on both sides of the border. These include the bilateral agreement that the NOAA has with Environment Canada, the Canada-Quebec St. Lawrence Action Plan, and a Vermont river management/river easement program that deals with river stability and other elements. The group should also assess and use data from the U.S. national initiative to promote better soil health through management to increase water infiltration and water holding capacity on a landscape basis and wetland restoration, among other things. The working group should also take into account and build on work done at the state and provincial levels.

Although the political-social study component identified in the 2013 Plan of Study cannot be undertaken at this time, the workgroup should be sensitive throughout this process to local stakeholders' concerns as expressed during the previous plan of study.

The Commission is requested to pursue its activities expeditiously and to report periodically to the Governments. This should include an initial work plan by August 2014 and interim briefings at the October 2014 and April 2015 semi-annual meetings. The final report should be completed by September 2015.

The United States and Canada underscore their joint commitment to the principle of parity, including funding, under the Boundary Waters Treaty. To undertake the work described above, the United States Government commits \$487,000 of appropriated 2014 fiscal year funds. The Government of Canada commits a minimum of \$150,000 of existing Canadian Section IJC funds and in-kind contributions (the dollar value of which shall be mutually agreed by the Governments), with the understanding that ultimate funding of all references relating to this matter will, in cumulative total, be funded by the two Governments on a basis of parity.

Canada's total contribution of resources over the course of this and any future references will equal those of the United States, subject to national appropriations.

The governments of Canada and the United States welcome the opportunity to collaborate and assist the Commission in its work. An identical letter is being sent to the Secretary of the Canadian Section of the Commission by the Canadian Department of Foreign Affairs, Trade and Development.

Sincerely,



Sue Saarnio
Acting Deputy Assistant Secretary
Bureau of Western Hemisphere Affairs
United States Department of State

Reference letter provided to the IJC by the government of Canada



Foreign Affairs, Trade and
Development Canada

Affaires étrangères, Commerce
et Développement Canada

July 31, 2014

125 Sussex Drive
Ottawa, Ontario
K1A 0G2

Ms. Camille Mageau
Secretary, Canadian Section
International Joint Commission
234 Laurier Avenue West, 22nd Floor
Ottawa, Ontario
K1P 6K6

Lake Champlain and Richelieu River Reference

Dear Ms. Mageau:

The Governments of Canada and the United States thank the International Joint Commission (IJC) for its July 2013 Plan of Study: “The Identification of Measures to Mitigate Flooding and the Impacts of Flooding of Lake Champlain and Richelieu River” which the IJC undertook in response to our governments’ request in a March 19, 2012, letter to investigate flood mitigation solutions following devastating floods in that region in the spring of 2011.

We particularly appreciate the IJC’s presentation of individually scalable options for study implementation. We understand that the IJC recommends Option C at \$14 million (to be funded jointly by Canada and the United States) as the best option for a thorough understanding of the causes and solutions for flood mitigation through a long-term study. Our governments are not at this time, however, able to commit to such a large scale, long-term undertaking, and thus cannot make a reference including that option now.

Instead, in accordance with Article IX of the Boundary Waters Treaty, the Governments of Canada and the United States request that the International Joint Commission assist our governments in the implementation, with existing 2014 funding, of two scalable components in the study. These components will provide valuable information to assist affected communities in floodplains in a practical and immediate fashion and also provide a basis for a future real-time flood forecasting and inundation mapping system.

.../2

Canada

This reference is limited to initiating and completing work on the following, which will be organized and implemented by a small technical working group, to be convened by the IJC:

1. Addressing and closing data gaps through data collection and harmonization of topographic, bathymetric, aquatic vegetation, soil texture, Light Detection and Ranging (LiDAR) and observed climate and hydrometric data collection (per Section 3.1, page 34 of the July 2013 Plan of Study) as are necessary as a basis for the earliest possible initiation of a real-time flood forecasting and inundation mapping system. This system would consist of the development of new real-time Lake Champlain and Richelieu River hydrologic and hydraulic models for predicting lake and river levels, and a precise Digital Elevation Model of the flood plain to delineate the contours of corresponding inundated areas.
2. Creation of static flood inundation maps using a combination of existing and new data and modeling to provide practical information to communities. These maps would show which areas would be affected if Lake Champlain and Richelieu River water levels hit different heights.

Subject to each government's national appropriations process, Canada and the United States may consider a subsequent reference on other components of the 2013 Plan of Study, including using data from this work to produce a real time flood forecasting and inundation mapping system.

In examining and collecting data, the IJC-assembled working group should build on the technical data gap analysis outlined in the IJC July 2013 plan of study and decide early on which government agency will take leadership on the different elements. The study should incorporate and take advantage of existing systems and government mechanisms already in place on both sides of the border. These include the bilateral agreement that the NOAA has with Environment Canada, the Canada-Quebec St. Lawrence Action Plan, and a Vermont river management/river easement program that deals with river stability and other elements. The group should also assess and use data from the U.S. national initiative to promote better soil health through management to increase water infiltration and water holding capacity on a landscape basis and wetland restoration, among other things. The working group should also take into account and build on work done at the state and provincial levels.

Although the political-social study component identified in the 2013 Plan of Study cannot be undertaken at this time, the workgroup should be sensitive throughout this process to

.../3

local stakeholders' concerns as expressed during the previous plan of study.

The Commission is requested to pursue its activities expeditiously and to report periodically to the Governments. This should include an initial work plan by August 2014 and interim briefings at the October 2014 and April 2015 semi-annual meetings. The final report should be completed by September 2015.

The United States and Canada underscore their joint commitment to the principle of parity, including funding, under the Boundary Waters Treaty. To undertake the work described above, the United States Government commits \$487,000 of appropriated 2014 fiscal year funds. The Government of Canada commits a minimum of \$150,000 of existing Canadian Section IJC funds and in-kind contributions (the dollar value of which shall be mutually agreed by the Governments), with the understanding that ultimate funding of all references relating to this matter will, in cumulative total, be funded by the two Governments on a basis of parity.

Canada's total contribution of resources over the course of this and any future references will equal those of the United States, subject to national appropriations.

The governments of Canada and the United States welcome the opportunity to collaborate and assist the Commission in its work. An identical letter is being sent to the Secretary of the United States Section of the Commission by the U.S. Department of State.

Sincerely,

A handwritten signature in black ink, appearing to read "C. Wilkie", with a long horizontal flourish extending to the right.

Christopher Wilkie
Director
U.S. Transboundary Affairs Division

ANNEX 2 IJC Directive

DIRECTIVE TO THE INTERNATIONAL LAKE CHAMPLAIN-RICHELIEU RIVER TECHNICAL WORKING GROUP

The purpose of this directive is to establish and direct the International Lake Champlain-Richelieu River Technical Working Group (TWG) to examine and report to the International Joint Commission on the matters identified by the governments in their July 24 and July 31, 2014 reference letters to the Commission on Lake Champlain and Richelieu River flooding. (copies attached) As stated in these letters, the governments requested that the Commission initiate and complete two scalable components from the 2013 Lake Champlain-Richelieu River Plan of Study (PoS). The 2013 PoS was prepared in response to the floods of 2011 in the Richelieu River and the Lake Champlain basin and built upon IJC's long history investigating water management in this system including the 1937 order of approval and the 1973 reference by the US and Canadian governments to "investigate and report on the feasibility and desirability of regulation of the Richelieu River ... for the purpose of alleviating extreme water conditions in the Richelieu River and in Lake Champlain..." (see Dockets 38A, 98R). The PoS recommended a comprehensive study of measures to mitigate flooding and the impacts of flooding in the basin. Work on two scalable components identified in the PoS is to be completed by the IJC within existing funding limits.

These components are:

1. Addressing and closing data gaps through data collection and harmonization of topographic, bathymetric, aquatic vegetation, soil texture, Light Detection and Ranging (LiDAR) and observed climate and hydrometric data (per section 3.1, page 34 of the July 2013 Plan of Study) as are necessary as a basis for the earliest possible initiation of a real-time flood forecasting and inundation mapping system. This system would consist of the development of new real-time Lake Champlain and Richelieu River hydrologic and hydraulic models for predicting lake and river levels, and a precise Digital Elevation Model of the flood plain to delineate the contours of corresponding inundated areas.
2. Creation of static flood inundation maps using a combination of existing and new data and modeling to provide practical information to communities. These maps would show which areas would be affected if Lake Champlain and Richelieu River water levels hit different heights.

To assist the Commission in the organization and implementation of the work outlined in the July reference letters, the Commission will appoint members to a Technical Working Group and Co-Chairs to lead the Technical Working Group's efforts. The co-chairs shall convene and preside at meetings of the Technical Working Group and shall jointly take a leadership role in planning and implementing the Group's work. The Technical Working Group will be binational,

2

with an equal number of members from each country. The Commission shall arrange for provision of secretariat support to carry out such duties as are assigned by the Co-Chairs or

the Technical Working Group as a whole. The Commission will provide guidance to the TWG and will pursue technical assistance from the two governments, as identified by the TWG. Members of the TWG and any committees or work groups created by it will be responsible for their own expenses unless otherwise arranged with the Commission.

The Technical Working Group is to work with the IJC, and the agencies that are identified by the IJC to perform work tasks, providing those agencies and IJC staff with technical determinations, evaluations and guidance on how best to complete IJC-designated tasks within the budget and time frame included in the reference from governments. Given that the envisioned work tasks contain unknown factors related to the extent and resolution of existing data, the scope of data collection needed to close data gaps, and the nature of computer modeling and graphical products or interfaces needed to make the data useful to the public and government, the Technical Working Group may suggest to the IJC modifications to the work tasks.

To facilitate public outreach, the Technical Working Group shall make information related to its work plan as widely available as practicable, including data, its reports and other materials, as appropriate. The Technical Working Group in collaboration with the IJC shall develop and maintain a web-site hosted by the IJC as a means for disseminating information related to implementation of its tasks. To the extent practicable, the Technical Working Group shall make available on the web-site all documents that are available for public information under the Commission's Rules of Procedure.

The Technical Working Group shall keep the Commission fully informed of its progress and direction. The Technical Working Group shall also maintain an awareness of basin-wide activities and conditions and shall inform the Commission about any such activities or conditions that might affect its work. In addition to regular contact with designated Commission personnel, the Technical Working Group shall be prepared to meet with the Commission at least semi-annually if requested by Commissioners, and if so requested, it shall submit written progress reports to the Commission at least three weeks in advance of those meetings.

The Technical Working Group shall act as a unitary body. The members of the work group shall serve the Commission in their professional capacity, in an impartial manner for the common good of both countries, and not as representatives of their countries, agencies, organizations, or other affiliations. The Technical Working Group will strive to reach decisions by consensus and will immediately notify the Commission of any irreconcilable differences. Any lack of clarity or precision in instructions or directions received from the Commission shall be promptly referred to the Commission for clarification.

3

The Technical Working Group shall within one month of its creation submit for the Commission's approval an initial work plan with a schedule of tasks, products and budget based on this directive. The work plan shall include a proposal that will describe how public consultation will be undertaken. The consultation plan shall discuss how the TWG will collaborate with federal governments, provinces, states as well as the wider body of stakeholders and the public. The TWG will compile the data necessary as a basis for initiation of a real-time flood forecasting and inundation mapping system, complete the static flood inundation maps and submit its final report no later than September 15, 2015. The final report should contain the TWG's findings, conclusions and recommendations regarding the matters raised by the governments.

Documents, letters, memoranda and communications of every kind in the official records of the Commission are privileged and become available for public information only after their release by the Commission. The Commission considers all documents in the official records of the TWG or any of its committees to be similarly privileged. Accordingly, all such documents shall be so identified and maintained as separate files.

September 12, 2014

DRAFT

ANNEX 3 Members of the International Lake Champlain-Richelieu River Technical Working Group and its technical and secretariat support

ILCRR Working Group

<p>Jean-François Cantin, ing., M.Sc. Canadian co-chair</p> <p>Manager, Hydrology and Ecohydraulics Section, National Hydrologic Services Meteorological Service of Canada Environment Canada 1550, avenue d'Estimauville Québec (Québec), G1J 0C3 Telephone 418-649-6565 Cellular phone 418-564-0521 Facsimile 418-648-5643 E-mail jean-francois.cantin@ec.gc.ca</p>	<p>Keith Robinson United States co-chair</p> <p>Director, New England Water Science Center US Geological Survey 331 Commerce Way, Suite 2 Pembroke NH 03244 Telephone 603-226-7807 Cellular phone 603-986-2327 Facsimile 603-226-7894 E-mail kwrobins@usgs.gov</p>
<p>Vincent Fortin Federal member</p> <p>Chercheur en prévision numérique environnementale Environnement Canada 2121, route Transcanadienne Dorval, Québec H9P 1J3 Telephone : 514-421-4630 E-mail : vincent.fortin@ec.gc.ca</p>	<p>William (Bill) Saunders Federal Member</p> <p>Senior Hydrologist National Weather Service Northeast River Forecast Center 445 MylesStandishBlvd Taunton, MA 02780 Telephone: 508-824-5116 x260 Email: william.saunders@noaa.gov</p>
<p>Daniel Leblanc, ing. M.Sc.A. Quebec member</p> <p>Directeur adjoint Ministère du Développement durable, de l'Environnement et de la Lutte contre les</p>	<p>Blaine Hastings Vermont member</p> <p>Hydrologist Vermont Department of Environmental Conservation</p>

<p>changements climatiques</p> <p>Direction régionale de l'analyse et de l'expertise de l'Estrie et de la Montérégie</p> <p>201, place Charles-Le Moyne, 2ième étage</p> <p>Longueuil (Québec) J4K 2T5</p> <p>tél.:450-928-7607 poste 305</p> <p>télééc.: 450-928-7625</p>	<p>Watershed Management Division</p> <p>1 National Life Drive, Main 2</p> <p>Montpelier, VT 05620-3522</p> <p>Telephone: 802-490-6156</p> <p>Email: Blaine.Hastings@state.vt.us</p>
<p>Richard Turcotte, ing, Ph.D.</p> <p>Quebec member</p> <p>Conseiller scientifique</p> <p>Direction de l'expertise hydrique</p> <p>Centre d'expertise hydrique du Québec</p> <p>Développement durable, Environnement et Lutte contre les changements climatiques</p> <p>675, boulevard René Lévesque Est</p> <p>Québec (Québec) G1R 5V7</p> <p>Tél: 418 521-3993 poste 7145</p> <p>Fax: 418 643-6900</p> <p>Courriel: www.cehq.gouv.qc.ca</p>	<p>Fred Dunlap</p> <p>New York member</p> <p>NY Lake Champlain Basin Coordinator</p> <p>New York State Dept of Environmental Conservation</p> <p>1115 NYS Rte 86 - Box 296</p> <p>Ray Brook, NY 12977</p> <p>Telephone: 518-897-1241</p> <p>Email: fred.dunlap@dec.ny.gov</p>

Technical support

<p>Paul Boudreau</p> <p>Hydraulic Engineer</p> <p>National Hydrologic Services</p> <p>Meteorological Service of Canada</p> <p>Environment Canada</p> <p>1550, avenue d'Estimauville</p> <p>Québec (Québec), G1J 0C3</p> <p>E-mail paul.boudreau@ec.gc.ca</p>	<p>Robert Flynn</p> <p>Hydrologist-Engineer</p> <p>New England Water Science Center</p> <p>US Geological Survey</p> <p>331 Commerce Way, Suite 2</p> <p>Pembroke NH 03244</p> <p>Telephone 603-226-7824</p> <p>Facsimile 603-226-7894</p> <p>E-mail rflynn@usgs.gov</p>
---	---

Secretariat support

<p>Additional secretariat support for French language services</p> <p>Madeleine Papineau E-mail: Papineaum@ottawa.ijc.org</p>	<p>Secretariat support from LCBP</p> <p>Stephanie Castle Lake Champlain Basin Program NEIWPC Environmental Analyst LCPB Technical Associate 54 West Shore Rd., Grand Isle, VT 05458 p: 802-372-3213; f: 802-372-3233 scastle@lcbp.org</p>
--	--

DRAFT

ANNEX 4 Experts present at the IAGLR Water Level Prediction Workshop

Attendees to IAGLR Technical Workshop, May 27, 2015 in Burlington, VT			
Participant	Organization	Email	Area of Expertise
Tom Manley	Middlebury College	tmanley@middlebury.edu	Hydrodynamics and bathymetry
Dmitry Beletsky	University of Michigan	beletsky@umich.edu	3D Hydrodynamic Modeling
Alvaro Linares	University of Wisconsin	alvaro.linares@wisc.edu	
Adam Bechle	University of Wisconsin	bechle@wisc.edu	Great Lakes High Frequency Water Level Oscillations
Jamie Dickhout	Environment Canada	Jamie.Dickhout@ec.gc.ca	St Lawrence and Lake Superior Regulation
Jeanette Fooks	Environment Canada	jeanette.fooks@ec.gc.ca	Hydrometric Monitoring and Hydraulics
Wendy Leger	Environment Canada	wendy.leger@ec.gc.ca	Great Lakes-St Lawrence Adaptive Management
Cherie-Lee Fietsch	Bruce Power	cherie-lee.fietsch@brucepower.com	Aquatic Ecology, Modelling, Benthic Ecology
Francis Chua	Bruce Power	francis.chua@brucepower.com	
Jiangtao Xu	NOAA/NWS/CO-OPS	jiangtao.xu@noaa.gov	Hydrodynamic and Ecosystem Modeling
Martin Mimeault	MDDELCC	martin.mimeault@mddelcc.gouv.qc.ca	Lake Champlain
Zachary Hanson	Notre Dame	zhanson@nd.edu	Hydrology
Chun-Mei Chiu	Notre Dame	cchiu2@nd.edu	Hydrology
David Fay	IJC	fayd@ottawa.ijc.org	Water Quantity Management
Duncan Mueller	Aquatic Informatics	duncan.meuller@aquaticinformatics.com	Hydrology
Jamison Romano	Aquatic Informatics	jamison.romano@aquaticinformatics.com	Hydrometrics
Lauren Fry	US Army Corps of Engineers	lauren.fry@usace.army.mil	Hydrology
Alan Hamlet	Notre Dame	hamlet1@nd.edu	Hydrologic Modelling
Marie-Amelie Boucher	University of Quebec at Chicoutimi	marie-amelie-boucher@uqac.ca	Hydrology (ensemble forecasting)
Aubert Michaud	IRDA	aubert.michaud@irda.qc.ca	Hydrologic Modelling
Etienne Gaborit	Environment Canada	etienne.gaborit.s@gmail.com	Hydrologic Modelling
Richard Sanfacon	Retired from Canadian Hydrologic Service	rsanfacon@reformar.ca	Hydrography/Water Levels

ANNEX 5 References

Environment Canada, 2015. Development of an experimental 2D hydrodynamic model of Lake Champlain using existing bathymetric data (Task 1-2). Draft report to the International Joint Commission, 45 p.

Environment Canada, 2015. Set-up of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel (Task 2-3). Draft report to the International Joint Commission, 25 p.

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, 28 p. (<http://dx.doi.org/10.3133/sir/20xxxxxx>)

Flynn, R.H., and Hayes, L., 2015. Flood inundation maps for Lake Champlain in Vermont and New York. Canada: U.S. Geological Survey Scientific Investigations Report. September Draft report to the International Joint Commission, 23 p

Fortin, V., Gaborit, E., and M. Dimitrijevic, 2015. Assessing the Skill of Weather Forecasts for the purpose of Flood Forecasting in Lake Champlain and Richelieu River. Technical report prepared for the International Lake Champlain-Richelieu River Technical Working Group. 37p.

International Joint Commission, 2013. Plan of Study for The Identification of Measures to Mitigate Flooding and the Impacts of Flooding of Lake Champlain and Richelieu River An IJC report to the governments of Canada and the United States. 128 p.

International Joint Commission, 1981. Regulation of the Richelieu River and Lake Champlain. An IJC report to the governments of Canada and the United States. 40 p.

International Joint Commission, 1975. Interim Report on the Regulation of the Richelieu River and Lake Champlain. Docket 98 Interim Report to Gov. 22 p.

Lin, Y. and K. E. Mitchell, 2005. The NCEP Stage II/IV Hourly Precipitation Analyses: Development and Applications. Preprints, 19th Conference on Hydrology, American Meteorological Society, San Diego, CA, 9-13 January 2005, Paper 1.2, 4 p.

Ministère du Développement durable, de l'Environnement et de la Lutte aux Changements Climatiques, 2015. Contribution to the Creation of Flood Zone Maps for the Quebec Portion of the Lake Champlain/ Richelieu River System: Production of a Digital Terrain Model of the Shoreline Transformation of Water Surfaces into Flood Zone Limits. July 2015 Draft report to the International Joint Commission. 18 p.

National Oceanic and Atmospheric Administration (NOAA) Environmental Modeling Center (EMC), 2004. Overview of the NOAA/NWS/NCEP Short Range Ensemble Forecast (SREF) System, <http://www.emc.ncep.noaa.gov/mmb/SREF-Docs/SREF-TPB2004.pdf>, 22 p.

Natacha B. Bernier and Stéphane Bélair, 2012: High Horizontal and Vertical Resolution Limited-Area Model: Near-Surface and Wind Energy Forecast Applications. *J. Appl. Meteor. Climatol.*, **51**, 1061–1078.
doi: <http://dx.doi.org/10.1175/JAMC-D-11-0197.1>

Luc Fillion, Monique Tanguay, Ervig Lapalme, Bertrand Denis, Michel Desgagne, Vivian Lee, Nils Ek, Zhuo Liu, Manon Lajoie, Jean-François Caron, and Christian Pagé, 2010: The Canadian Regional Data Assimilation and Forecasting System. *Wea. Forecasting*, **25**, 1645–1669.
doi: <http://dx.doi.org/10.1175/2010WAF2222401.1>

DRAFT

ANNEX 6 Cited Organizations and list of Acronyms

CaPA	Canadian Precipitation Analysis
CEHQ	Centre d'expertise hydrique du Québec
CGG2013	Canadian Gravimetric Geoid model of 2013
CGS	Canadian Geodetic Survey
CGVD28	Canadian Geodetic Vertical Datum
CHS	Canadian Hydrographic Service
CO-OPS	Center for Operational Oceanographic Products and Services
DEM	Digital Elevation Model
DTM	Digital Terrain Model
EC	Environment Canada
FEMA	Federal Emergency Management Agency
FTP	File transfer protocol
FVCOM	Finite Volume Community Ocean Model
GEFS	Global Ensemble Forecasting System (US)
GEPS	Canadian Global Ensemble Prediction System (Canada)
GIS	Geographical Information System
GLCFS	Great Lakes Coastal Forecasting System
GLERL	Great Lakes Environmental Research Laboratory
GLOFS	Great Lakes Operational Forecasting System.
GNSS	Global Navigation Satellite System
HRAP	Hydrological Rainfall Analysis Project (US)
HRDPS	High-Resolution Deterministic Prediction System
IAGLR	International Association for Great Lakes Research
IJC	International Joint Commission
ILCRRTWG	International Lake Champlain-Richelieu River Technical Working Group
LCBP	Lake Champlain Basin Program
LCRR	Lake Champlain and the Richelieu River
LiDAR	Light Detection And Ranging

MDDELCC	Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques
MSC	Meteorological Service of Canada
NAD 83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NAEFS	North America Ensemble Forecast System
NED	National Elevation Data set
NGS	National Geodetic Survey (US)
NGVD	National Geodetic Vertical Datum
NOAA	National Oceanic and Atmospheric Administration
NSRS	National Spatial Reference System
NY	New York
NWIS	National Water Information System
NWP	Numerical weather prediction
NWS	National Weather Service
OPUS	National Geodetic Survey's Online Positioning User Service
POM	Princeton Ocean Model
PoS	Plan of Study
RDPS	Regional Deterministic Prediction System (Canadian)
REPS	Regional Ensemble Prediction System
SREF	Short Range Ensemble Forecasting
TWG	Technical Working Group
US	United States
USGS	United States Geological Survey
VMC	Vermont Monitoring Cooperative
VT	Vermont