International Joint Commission


# *A Real-Time Flood Forecasting and Flood Inundation Mapping System for the Lake Champlain-Richelieu River Watershed*

December, 2015

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December 21, 2015

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Mr. Christopher Sandrolini
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Dear Messrs. Wilkie and Sandrolini:

The Commission is pleased to transmit to you the final report of the International Lake Champlain-Richelieu River Technical Working Group in response to the Lake Champlain Richelieu River reference letters of July 24 and July 31, 2014, along with the Commission's recommendations. In this reference, the governments of the United States and Canada, in accordance with Article IX of the Boundary Waters Treaty, requested the Commission's assistance in addressing two issues associated with the 2011 flooding in the Lake Champlain-Richelieu River basin.

The report was produced by a Technical Working Group (TWG) of binational experts established by the Commission in the fall of 2014. It presents the results of the two issues identified in the reference: closing the data gaps towards the initiation of a future real-time flood forecasting and inundation mapping system, and the creation of static flood inundation maps.

The Commission approves the TWG report and endorses all recommendations in the report. The Commission further recommends that governments:

1. Focus on completing an operational, real-time flood forecasting and flood inundation mapping system for the Lake Champlain-Richelieu River watershed and in doing so; provide the necessary resources to fill the data gaps identified in the TWG report. This is consistent with current efforts by governments to have the most current and credible scientific information in hand to mitigate flood risks and to properly plan emergency responses. It is recommended, should governments consider future mitigation measures, that this system be completed for the entire basin.



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2. In transmitting the Technical Working Group's report, the Commission strongly reiterates its recommendation that governments implement the full scope of the 2013 Plan of Study (PoS) to evaluate past impacts, flood plain management practices, and adaptation strategies, and to assess soft (*i.e.*, low impact and cost) to moderate flood mitigation measures and their impacts.

Of the TWG recommendations, numbers 2, 4, 5, 6 and 7 require additional resources to fill necessary data gaps for the development of a real-time forecast. Recommendations numbers 1 and 3 call for a binational approach, and a new binational body to conduct the coordination among agencies involved in real-time forecasting.

Emergency responders, community planners, municipalities, and public security organizations, were invited to information sessions in Burlington, Vermont and Saint-Jean-sur-Richelieu, Quebec to review the work of the TWG. A total of 53 participants were present at both meetings. Useful comments were provided, and a strong expression of interest was shown for an operational real-time flood forecasting and mapping system for the Lake Champlain-Richelieu River Basin. A summary of the meetings and a list of participants are available for review at http://ijc.org/en_/LCRRTWG/Activities.

A month-long public comment period was also held, and a limited number (4) of comments were obtained. Comments focused on the need to address data gaps (*e.g.*, more modeling or the addition of gaging stations in the basin), completing the real-time forecasting system, and improving on flood planning and flood plain management policies. It was determined that a real-time flood forecasting system is necessary as a planning tool for emergency services, to inform the implementation of immediate mitigation measures, and for the evaluation of potential future water control structures and their impacts. The public comments are available for review at http://www.ijc.org/en_/Lake_Champlain-Richelieu_Flood_Forecasting_and_Mapping.

The Technical Working Group report does not evaluate the potential of structural flood mitigation measures, as this was not part of the terms of reference provided by the governments. In order to provide a long term solution to the flooding issues in the Champlain-Richelieu basin. a full evaluation of structural mitigation measures should be conducted, as was contemplated in the 2013 Plan of Study.

The work of the TWG led to the development by the Commission of an inundation mapping tool or application that provides the user with a state-of-the-art display of the data that make up the static inundation maps. It should be noted that the inundation maps are not designed for regulatory purposes, but rather to show flooding potential under different conditions. A preview of these maps is available on the IJC web site at: http://arcg.is/1MhXui2.

The International Joint Commission commends the efforts of the Technical Work Group, and as always, the Commission and members of its Technical Working Group are available to brief governments on these points and the findings in the report. We look forward to receiving the governments' direction on next steps for the Lake Champlain-Richelieu River Basin in the near future.

Sincerely,

Lana B. Pollack
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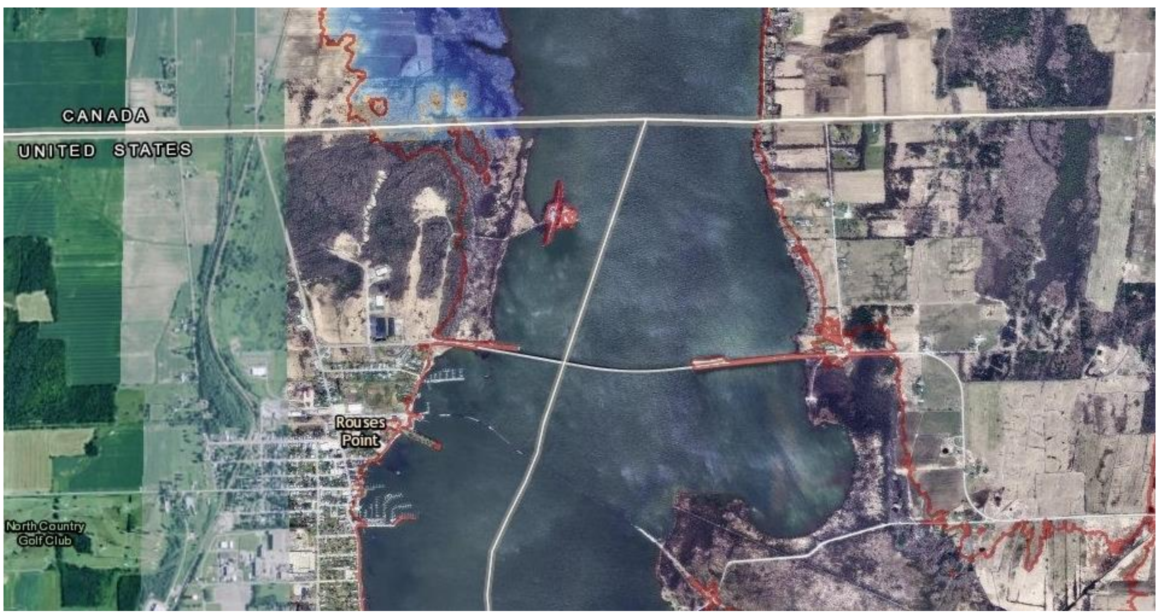
Enclosure:

- International Lake Champlain-Richelieu River Technical Working Group Report

# FINAL REPORT

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

## Preparatory works and static flood inundation maps




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

**November 30, 2015**

**A**

## 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 (US) 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 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 Digital Elevation Model (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 occur at 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 flood inundation maps were prepared under specific scenarios in response to component 2 of the directive.

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 hydrodynamic model of LCRR.
3. **Meteorological forecasts evaluation** was conducted to assess current capabilities 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 indicate it is possible to forecast the North-South component of the wind for the nearest three days in support of short-term flood forecasting, but a bias correction procedure is required before wind forecasts can be reliably used in hydrodynamic models. Precipitation forecasts for 5-day lead-times 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 LCRR 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 project. Results of the modeling found that high lake levels on Lake Champlain could be reasonably simulated with a steady-state application of 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 shoal and from Chambly downstream to Sorel will be needed to simulate river flows and flooding more accurately in those areas.
6. **Static Flood Inundation maps for portions of the Lake Champlain shoreline and the Richelieu River upstream of 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 expected to be a valuable product for local and state emergency responders and local officials. The maps are 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. They constitute however a good first step in helping to characterize the flood threats from future flooding events. A complete LiDAR DEM covering the Canadian portion of the basin 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 modeling 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 report also provides specific recommendations for future flood forecasting and preparedness; these recommendations include:**

1. To generate flood forecasts and real-time flood mapping products, the TWG recommends that the U.S. - Canada two-pronged probabilistic approach presented in section 5 for the forecasting of floods should be adopted and implemented operationally, including the modeling of wind set-up and wave action. This approach will include the development of hydrodynamic models for Lake Champlain that will be used as current Great Lakes model applications are employed, i.e. to provide a U.S. and Canada modeled forecast contribution to the bi-national coordination body for its forecast consideration.

2. To calibrate and validate a future forecasting system, the TWG recommends that both the Port Henry and the Grand Isle water level stations be kept in operation, at a minimum to collect data covering a representative range of water levels supporting the calibration of the hydraulic model. 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 observational data, quality control of the model predictions, and generation of bi-national water level predictions. The establishment of this coordination body will ensure that a consistent message is conveyed to emergency responders and the public regarding the LCRR water level predictions that are disseminated.

4. To generate flood forecasts and real-time flood mapping products for the entire LCRR system, 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.

5. To allow a better and complete flood forecasting capacity for LCRR, the TWG recommends the acquisition of new bathymetric data for 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.

6. The TWG recommends that the static flood inundation maps be generated for the entire LCRR system.
7. The TWG recommends that the newly acquired data, wind observations and models be used to calibrate a dynamic version of the hydraulic model for the entire LCRR system.

## 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. Special thanks go out to the IJC advisors Pierre-Yves Caux, Joe Babb and Mike Laitta, as well as to Benoit Thouin for translation services.

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

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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 services)

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# 1 Introduction to the Lake Champlain-Richelieu River Project

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 (US) 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 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 collective damages occurred in the US and Canada from this flooding event that lasted for over 60 consecutive days.

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://ijc.org/files/publications/Final_PoS_LakeChamplain-RichelieuRiver.pdf. 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 shoal 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 two reports (1975 and 1981). 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.

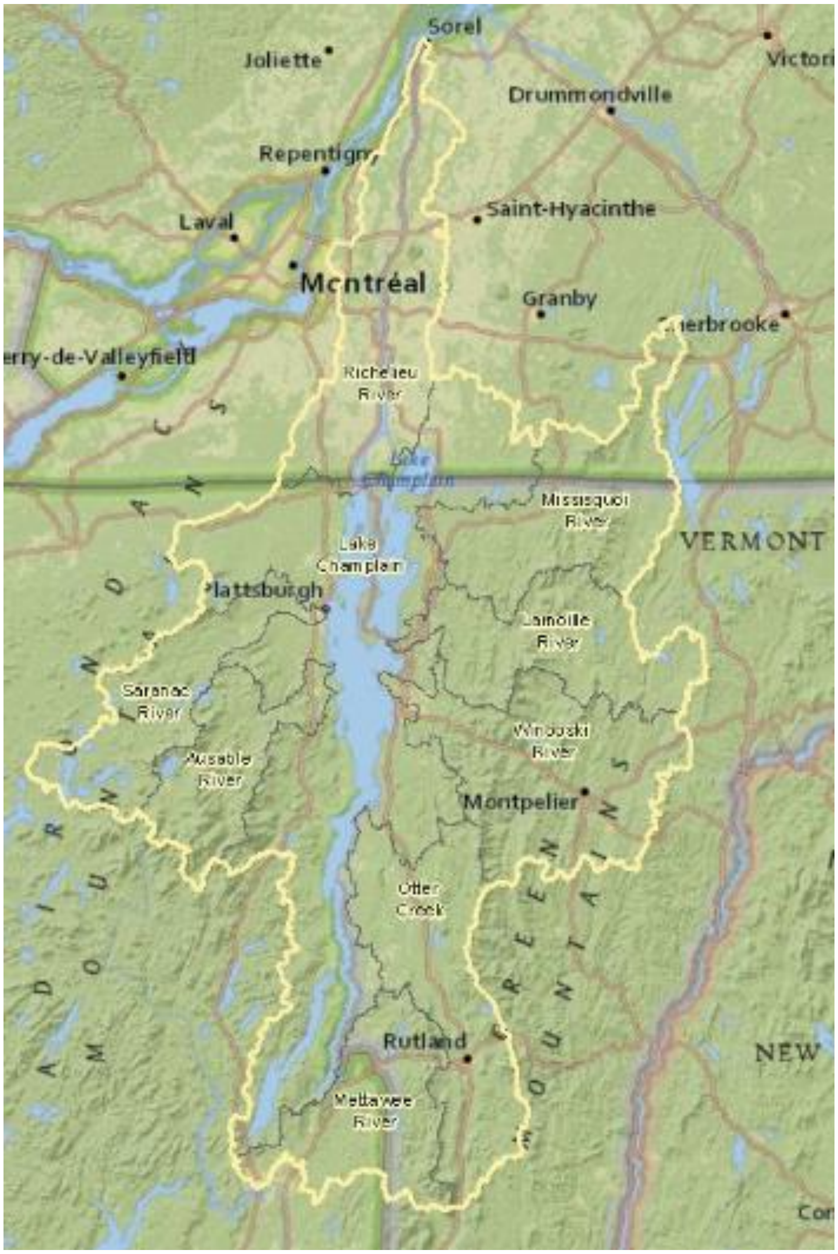



**Figure 1.1 – Location of Lake Champlain and the Richelieu River system and its watershed boundaries**

In 2013, the IJC developed a 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 in 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 modeling 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 Elevation 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 modeling capacity for the estimation of water supplies to the watershed with a lead-time as long as possible;
4. A hydraulic modeling capacity to simulate the response of LCRR to predicted water supplies and winds.

## 1.2 The Scope and Organization of this Work

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 occurred at 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 project were guided by 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 report contains a summary of the tasks performed. The order in which results are presented in this report does not follow the task list above, but each section provides a reference to a 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.

Static flood inundation maps were produced and posted in electronic format and are available for consultation on the IJC website: http://arcg.is/1MhXui2.

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 TWG 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 and conference calls, 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 project 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 project leveraged 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 on or before November 30, 2015. 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 hold targeted stakeholder and user meetings, in the first week of November 2015.

## 1.3 Communication of the Project Plans and Results

General information about the TWG such as the mandate, member composition, the project 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 are available on the IJC website: http://arcg.is/1MhXui2. The interactive static maps show the flood plain contours associated with 11 flood scenarios.

Progress reports on accomplishments associated with 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 (***Annex 4)***. Input from the experts was used to refine the proposed approach.
Selected stakeholders and 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.

# 2 Data Gathering and Development

Initial discussions within the TWG 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 these activities is provided below.

## 2.1 Collection and Processing of LiDAR Data for Lake Champlain

Note: This work corresponds to TWG 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 (NY) and Vermont (VT). 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 NY 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 NY (this effort was also partially supported by LiDAR collection in Washington and Warren Counties under the auspices of the New York GIS program office). The NY collection project is being completed with 9.25cm vertical accuracy. The resulting DEM produced will be at a resolution of 1.0 $m^2$.
LiDAR acquisition in NY 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 VT 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 $m^2$. 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 $m^2$, since it will be a mosaicked product from multiple data sources. Presuming that all data collection efforts are completed in 2015, completion of the VT LiDAR processing will occur in 2016.

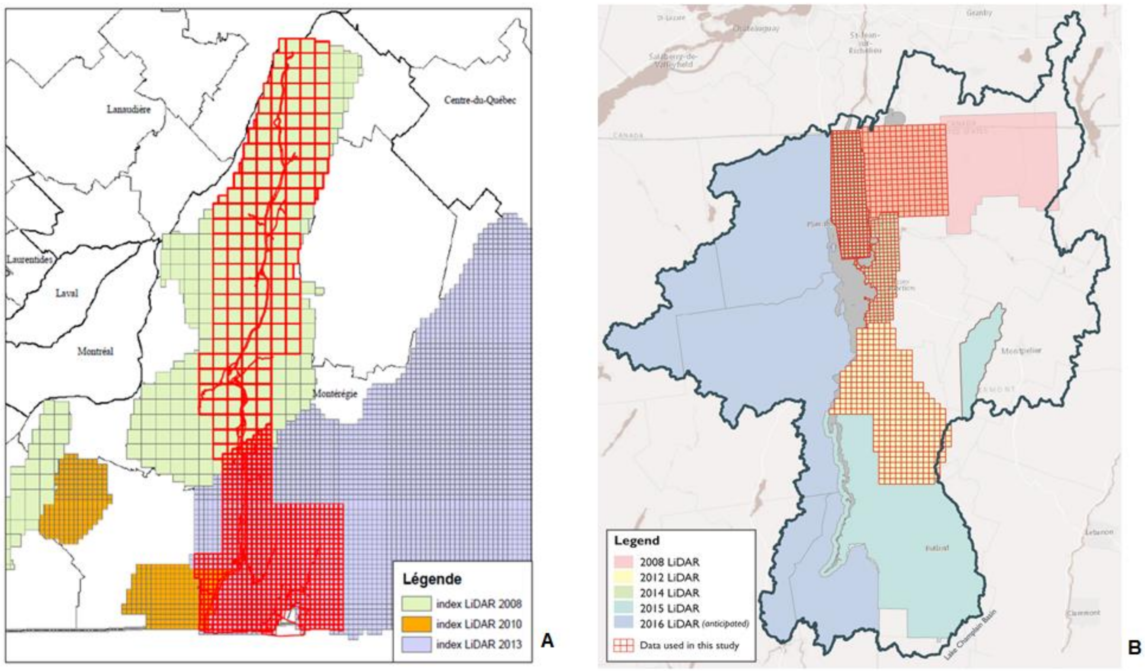



**Figure 2.1.1 – Maps of LiDAR data collection efforts and data used in this project for A – Canada and B – United States**

Although not all of VT is available for use in activities associated with this IJC effort, the direct shoreline areas where LiDAR were collected 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 TWG 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 Environment Canada (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 water level 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 the 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 two most desirable for new lake level gauges that would support a 2-dimensional (2D) Lake Champlain model and future flood forecasting. The Port Henry gauge fills 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 in the northeast 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 Philipsburgh in the Mississquoi Bay, this lake level gauge will allow for quantification of the wind set-up effects in the "Inland sea" area of Lake Champlain.

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 illustrate the installed stations at the A) Port Henry and B) Grand Isle sites, while figure 2.2.2 presents plots of lake levels at the two sites during a 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.

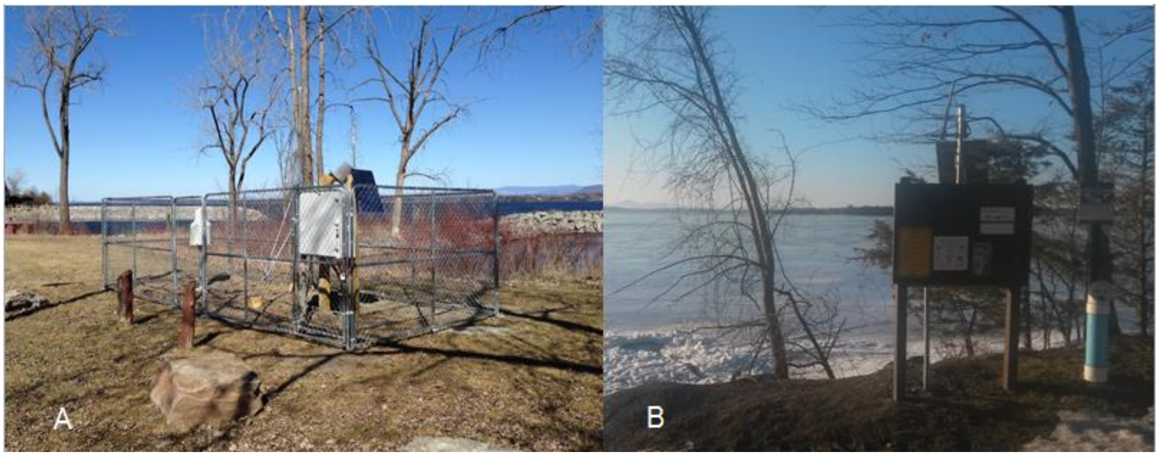
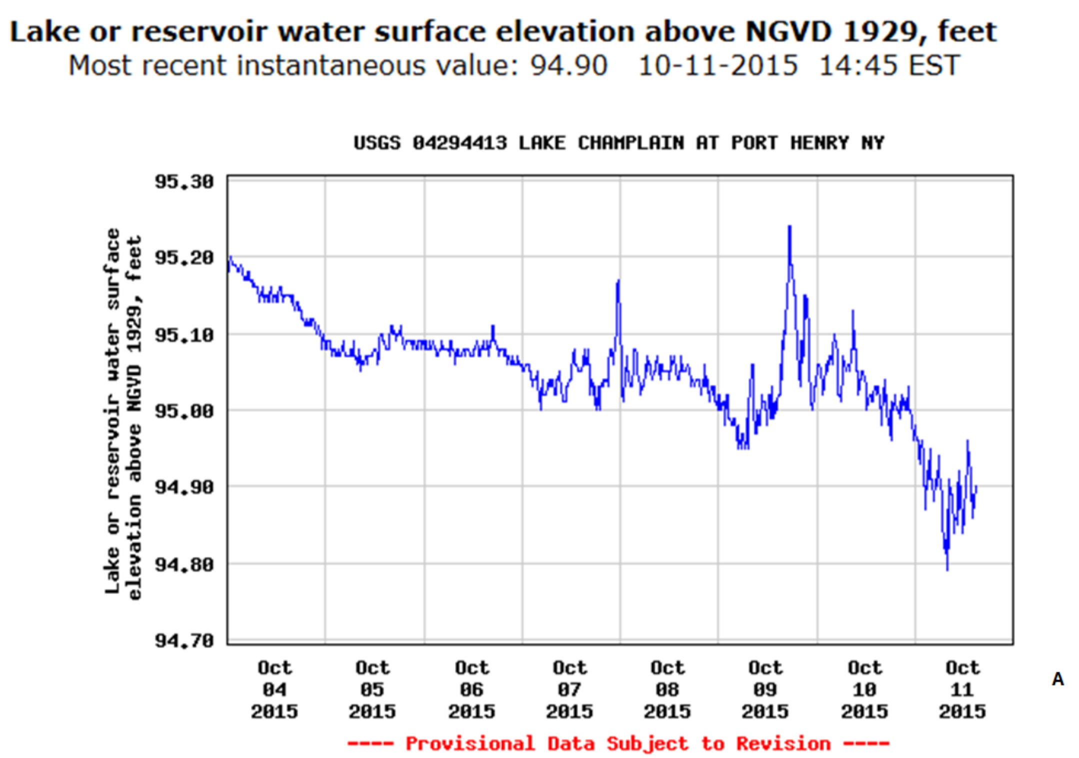



**Figure 2.2.1 – Installed stations at the (A) Port Henry and (B) Grand Isle sites on Lake Champlain**



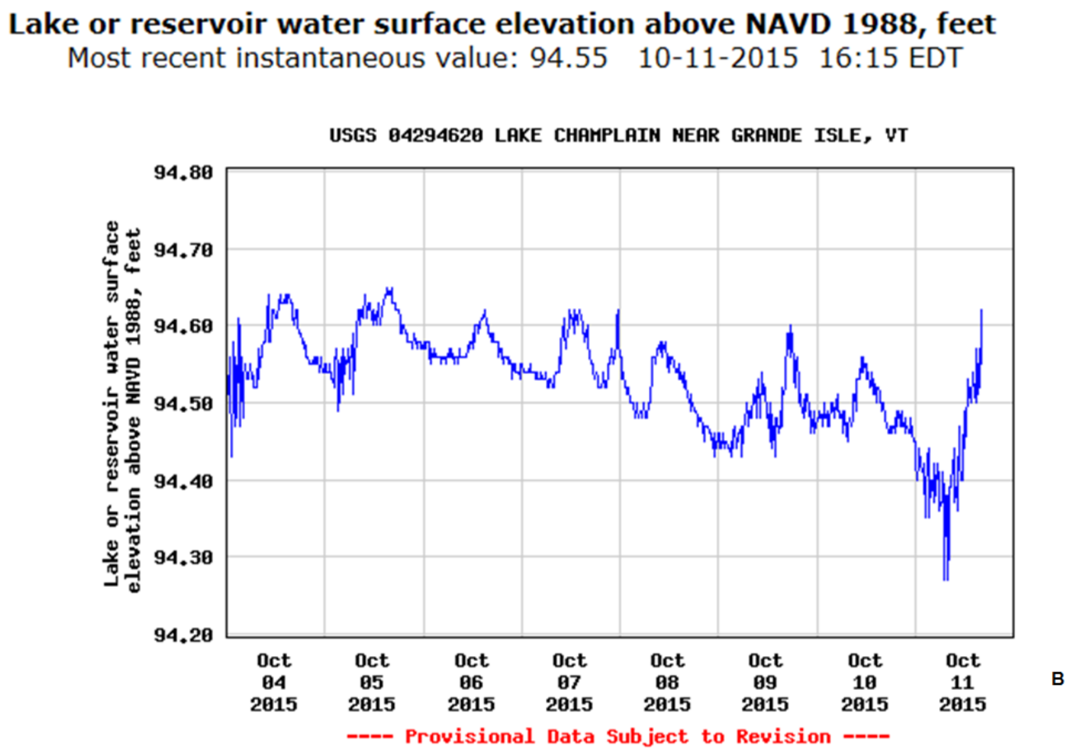



**Figure 2.2.2 – Hydrography of Lake Champlain water levels at the (A) Port Henry and (B) Grand Isle gauges, October 04, 2015 – October 11, 2015**

## 2.3 Collection of New Substratum, Aquatic Plant Assemblages and Distribution in the Richelieu River between Saint-Jean-sur-Richelieu and Rouses Point on Lake Champlain

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

A 7-day field campaign was conducted 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 towards the upstream portion of the River over a distance of 2 km. Then, the cross sections were subsequently carried out 400 m apart up to the border because the topography is simpler. An additional day of data collection was conducted 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.

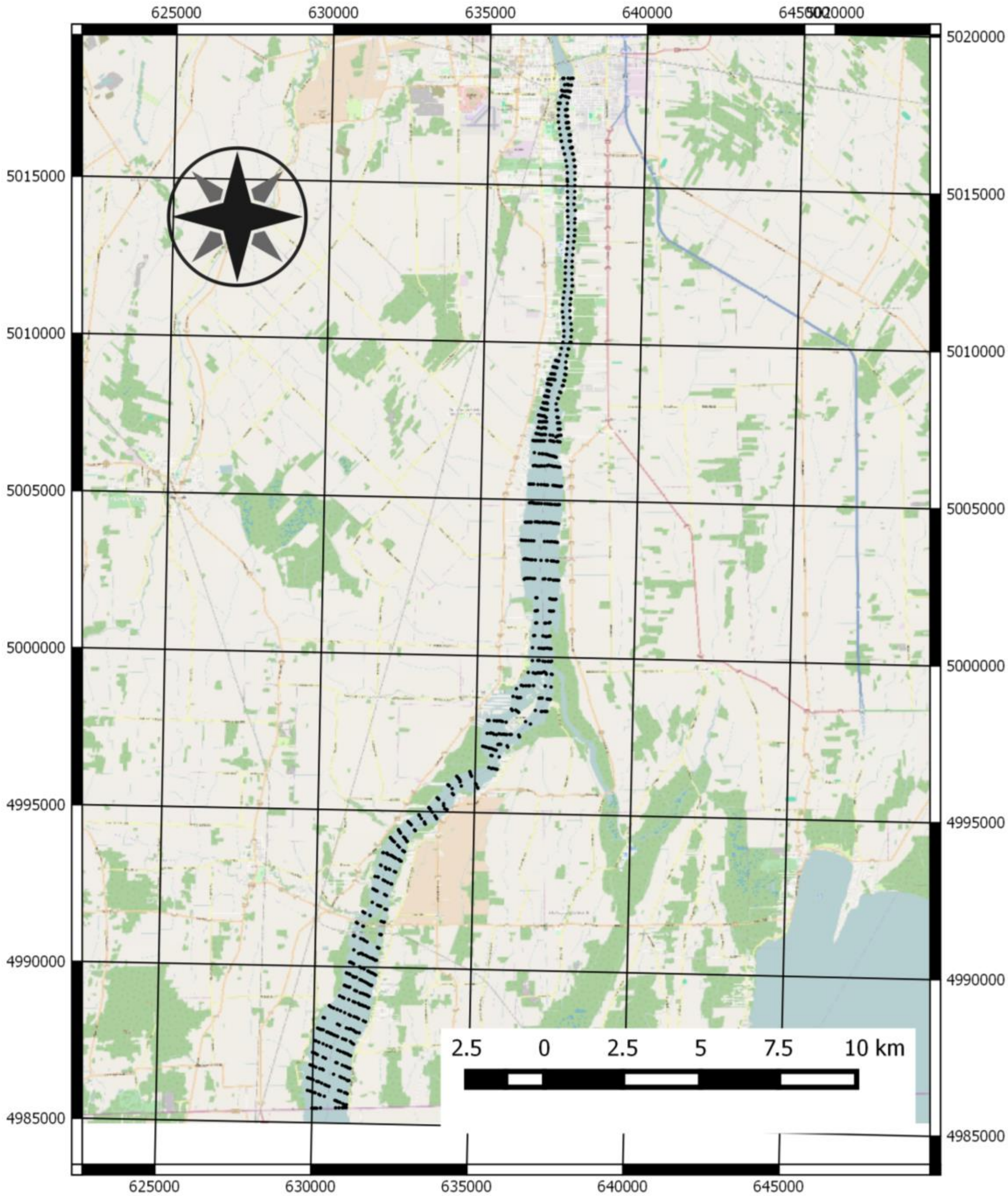



**Figure 2.3.1 – Location of survey lines on the Richelieu River used for aquatic plants observations**

In order to identify the plant species and their density, combinations of the following techniques were used and adapted to local conditions: direct visual observation, observation using an underwater camera, analysis of signals from an echo sounder, and plant sampling (harvesting). From the above, plant density, plant composition at the species level, ratio of each species in the plant community and their height in meters were noted along transect sampling points for which Global Positioning System (GPS) coordinates were accurately known. Data from a total of 951 observation points were collected.

Usually, submerged aquatic plants were present in shallow water areas but they were generally absent when the depth exceeded 2.5 m (8 ft) near Saint-Jean-sur-Richelieu. Upstream on the Richelieu River, progressing towards the border, the depth at which plants were absent increased to 3.5 m (12 ft). The river discharge during the field campaign was around 190 $m^3/s$ and the water level at Rouses Point was around 27.80 m (95.20 ft, NGVD 29). Aquatic plant species that were observed in the field include *Heterethera 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 not as pronounced and more time was dedicated to submerged aquatic plants. A small amount of grab sampling was done 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. The precise locations of these samples are also available. The substrate is much coarser downstream from the Gouin Bridge, approaching the natural control section in Saint-Jean-sur-Richelieu, where there are more boulders due to higher water velocities.

## 2.4 Coordination Mechanism to Exchange Data of Interest

Note: This work corresponds to TWG 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.
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 conference calls and communications throughout the project.

## 2.5 Consolidation and Harmonization of U.S. Data

Note: This work corresponds to TWG 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; 1.55 m 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 Generate Corrections Factors Required to Reference Water Levels According to a Common Vertical Datum

> Note: This work corresponds to TWG work plan Task 1-6. A detailed description of this work is given in the following technical report:
> Flynn, R.H; Rydlund, P.H.; and Martin, D.J., 2015. 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, 25 p.

Due to the vertical datum discontinuity between Canada and the US, a height transformation for the water levels 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. Correction factors determined by this effort were used to adjust water levels observations in the hydraulic modeling effort described in section 3.2 of this report.

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 percent geoid-based datum that is defined by the equipotential surface $W_0 = 62636856.0\ m^2/s^2$. 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 U.S., 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 CGS conducted field work to create a vertical datum transformation so that all of the water level data in the project area comprised of the LCRR could be shown in a consistent manner between the two nations. 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 datum. 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 were no redundant 6-hour observations 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 2.6.1). It is difficult to say if there is a definitive spatial pattern as it is not known how accurately the datums were originally surveyed during their respective establishments, 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.

The USGS-led technical report, done in cooperation with EC, describes the work and its results and detailed elevation data for each of the US and Canadian lake/stream gauges, benchmarks, and hydro-sensitive areas surveyed.

**Table 2.6.1: Results of Datum Corrections at Seven Surveyed Locations**

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

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

The TWG identified four specifics 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, Precipitation and Temperature Predictions

> Note: This work corresponds to Task 1-1 of the TWG work plan. A detailed description of this work is given in the following 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 forecasts are 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.cmc.ec.gc.ca/cmc/cmoi/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 (defined as 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.

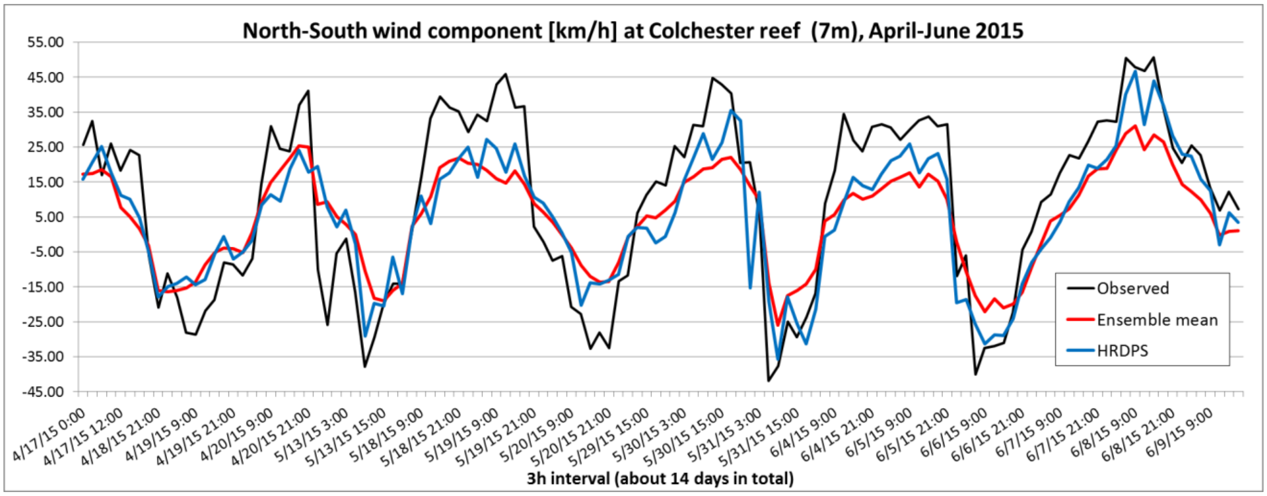



**Figure 3.1.1 – Time series of observed and forecasted wind (day 1 forecast) at Colchester Reef**

### *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). 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 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 (correlation of 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).

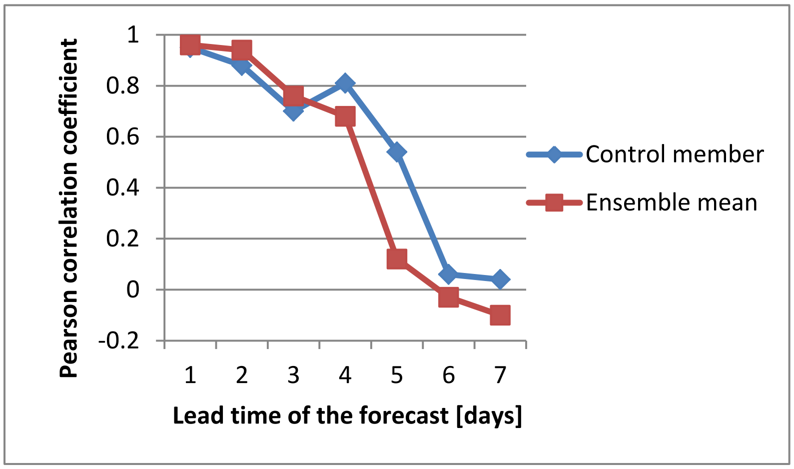



**Figure 3.1.2 – Median Pearson correlation coefficient between GEPS daily rainfall forecast and observed rainfall for twelve sub-basins of Lake Champlain**

### *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 skill[1] 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 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 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 (i.e. Summer and Fall), since past observations of temperature become less representative of current conditions.

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

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

> Note: This work corresponds to TWG work plan Task 1-2. A detailed description of this work is given in the following technical report: Environment Canada, 2015. Development of an experimental 2D hydrodynamic model of Lake Champlain using existing bathymetric data (Task 1-2). Report to the International Joint Commission, 46 p.

EC'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 effort aimed at testing the finite element 2-D model's performance using predominately existing data. Results of this effort indicate success in creating and applying 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.

<u>Creating the finite element mesh</u>

The simulations were performed using the H2D2 model, developed at Institut national de la recherche scientifique – Centre Eau Terre Environnement (INRS-ETE) with the support of EC. 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 Province of 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 peculiarity.

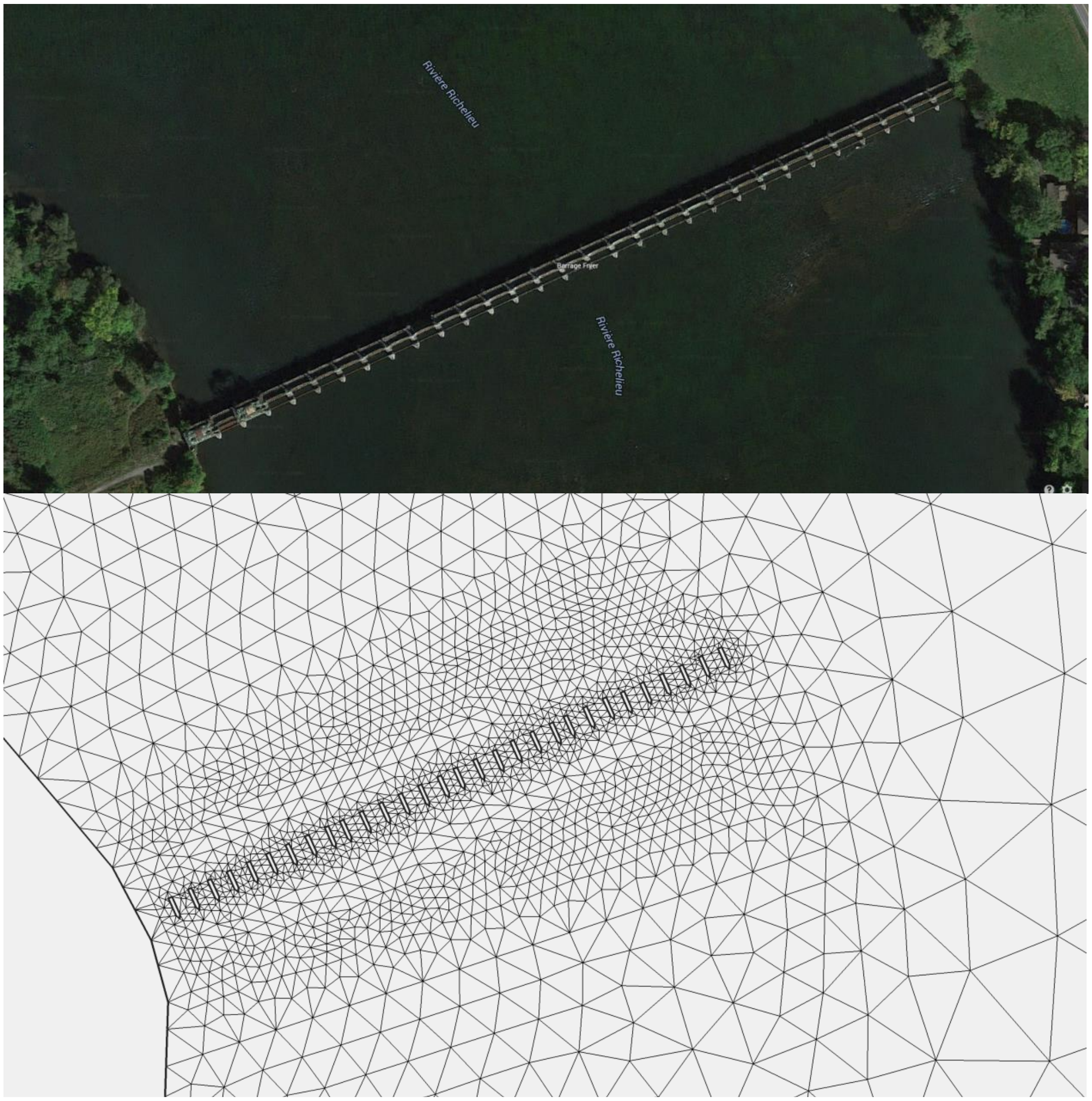


**Figure 3.2.1 – Fryers Dam and the corresponding mesh**

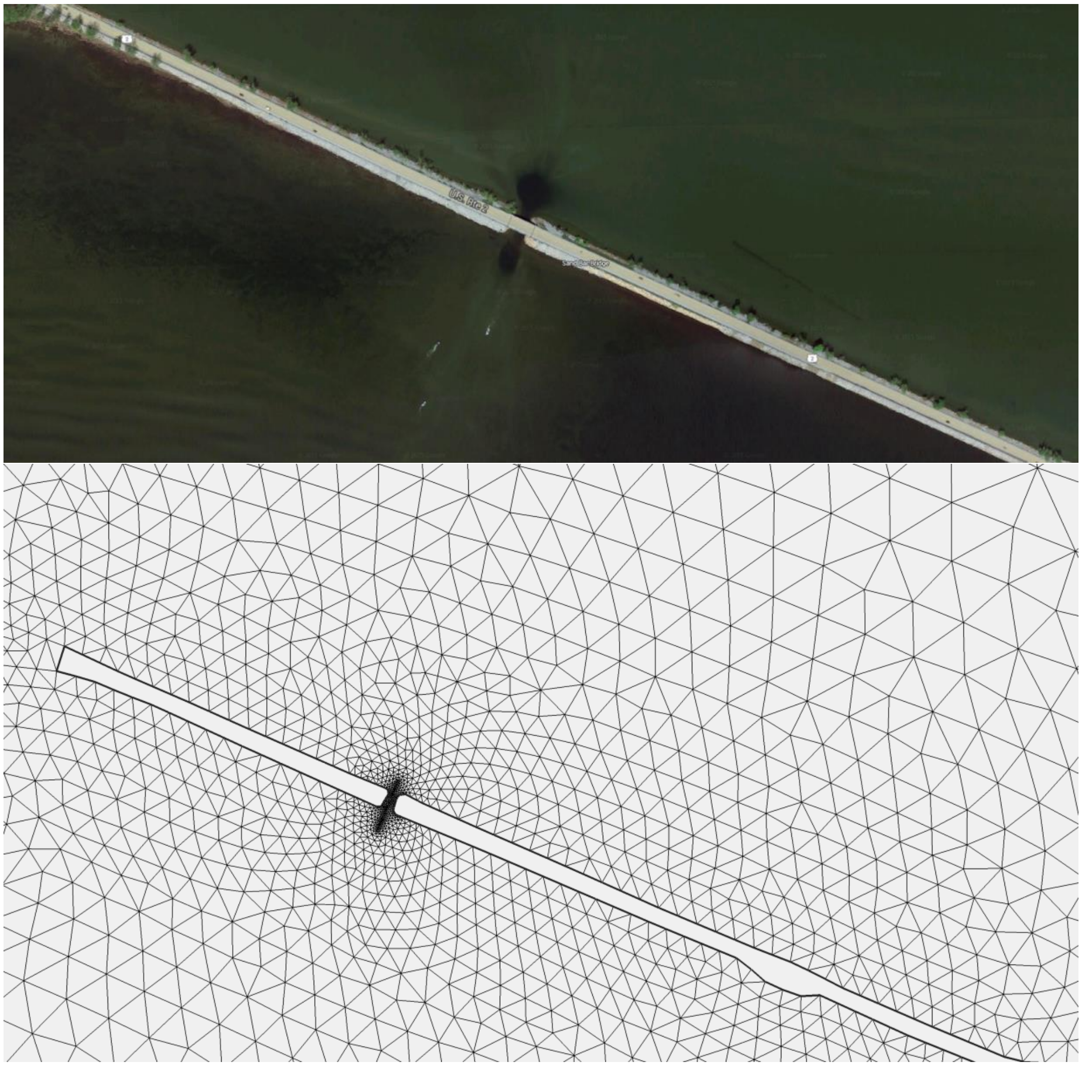

**Figure 3.2.2 – Highway 2 between South Hero and Colchester and the corresponding mesh**

<u>Common vertical datum</u>

Lake shore elevation and bathymetry data were collected to build a DEM of Lake Champlain and its shoreline. Among others, the Middlebury College bathymetry (Manley, 2005), the ElevationDEM_LKCHDEM bathymetry from the Vermont Center for Geographic Information (VCGI, 2010), 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 (Vertcon[2], Geoid12A[3] , GPS-H[4]). Figure

[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

3.2.3 shows the grid used to convert data from CGVD28 to NAVD88. 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 conversion 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 conversion 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 |
| Philipsburg (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 |

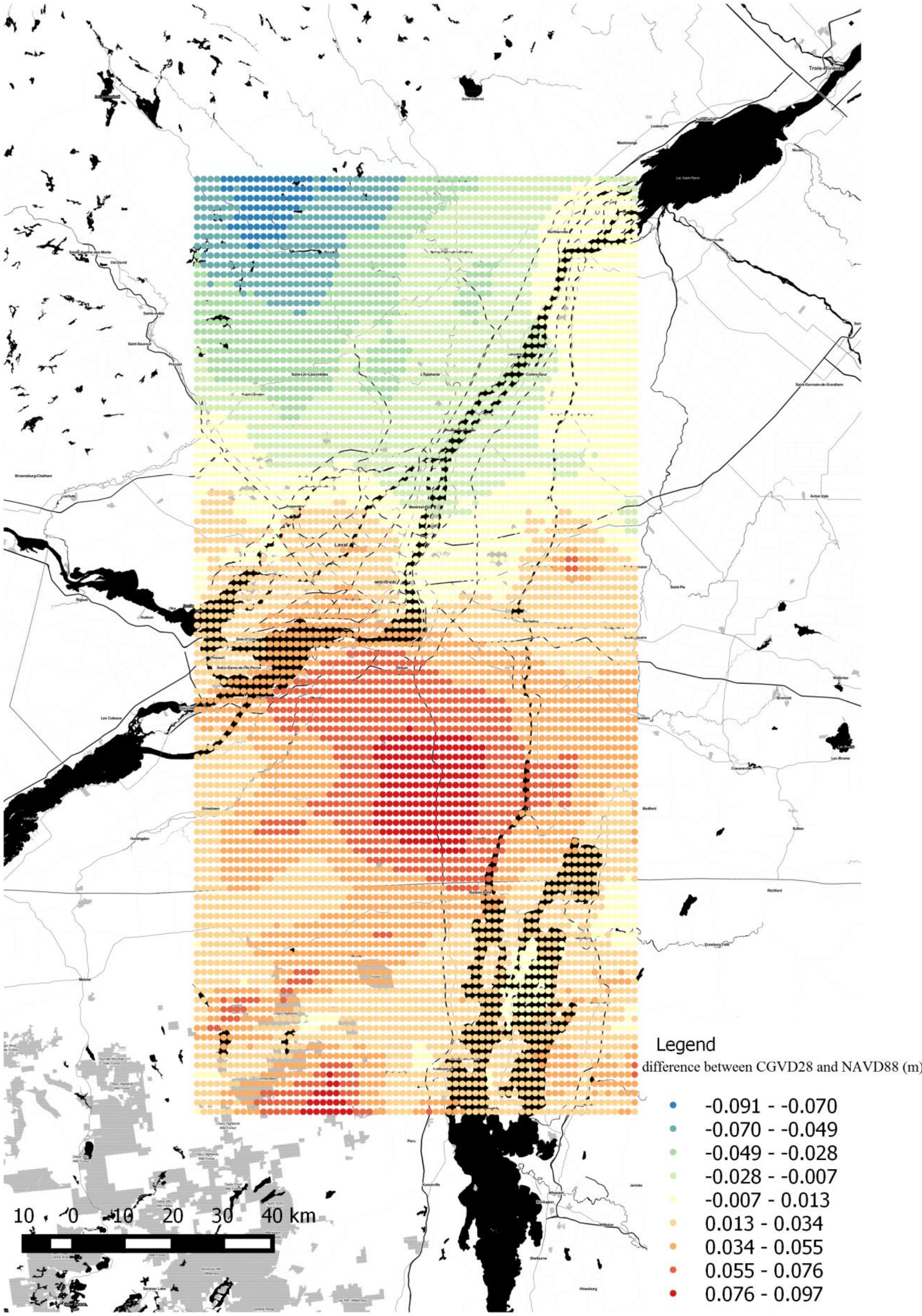


**Figure 3.2.3 – Grid (in meters) for converting CGVD28 to NAVD88**

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 LCRR 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 level rises when the total of the inflows into the lake are larger than the Richelieu River outflow capacity.

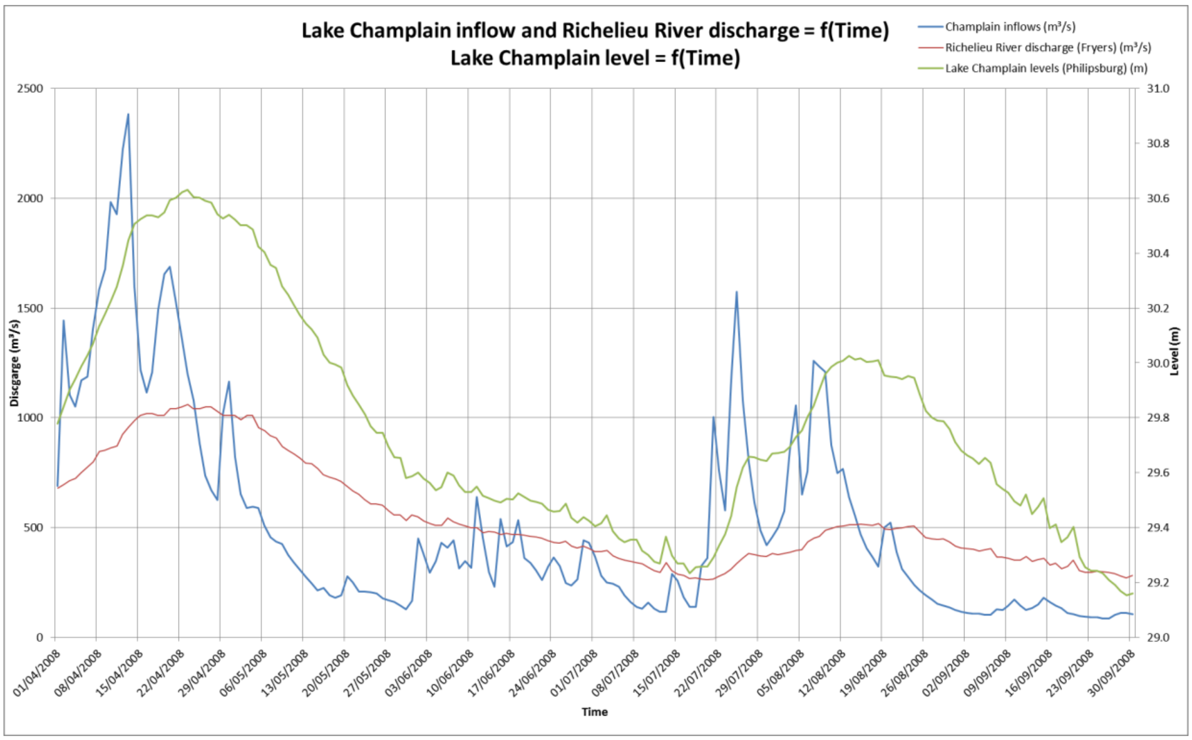


**Figure 3.2.4 – Influence of flows entering and exiting Lake Champlain on lake level. Spring-Summer 2008**

Calibration procedure

Water levels at any given moment on Lake Champlain are dynamic and are the result of total Lake inflows over time, the Richelieu River outflow, and the wind set-up effect, as illustrated by figure 3.2.4. Given that (a) the water level of the Lake Champlain is not associated solely with the total lake inflows and (b) the wind set-up and wave effects are still not incorporated in the experimental model, calibrating this steady state application of the hydrodynamic model is not an easy task.

However, the flow passing the natural control section at Saint-Jean-sur-Richelieu is proportional to the water level at Saint-Jean-sur-Richelieu and Rouses Point. With a steady state application of the model, it is possible to simulate the flow passing through the natural control section, so it corresponds to the observed water level in Saint-Jean-sur-Richelieu. In doing so, it’s important to keep in mind that those observations are affected by the wind set-up and that definitive calibration will only occur at a later step, after wind forcing and hourly inflows are explicitly incorporated in the experimental model. Simulations 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 steady state application of 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 $m^3/s$ at Fryers Rapids gauging station, and the one on May 6, 2011, with discharge of 1550 $m^3/s$ 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 Centre d’expertise hydrique du Québec (CEHQ), and for the 2011 event, only water levels at gauging stations were available. Calibration was done by adjusting the friction (Manning) coefficient. Differences between simulated and measured at the Saint-Jean gauge of -0.08 m were achieved for the April 4, 2003 event and +0.12 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 shoal area that are not properly captured by the available bathymetry may be causing 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.

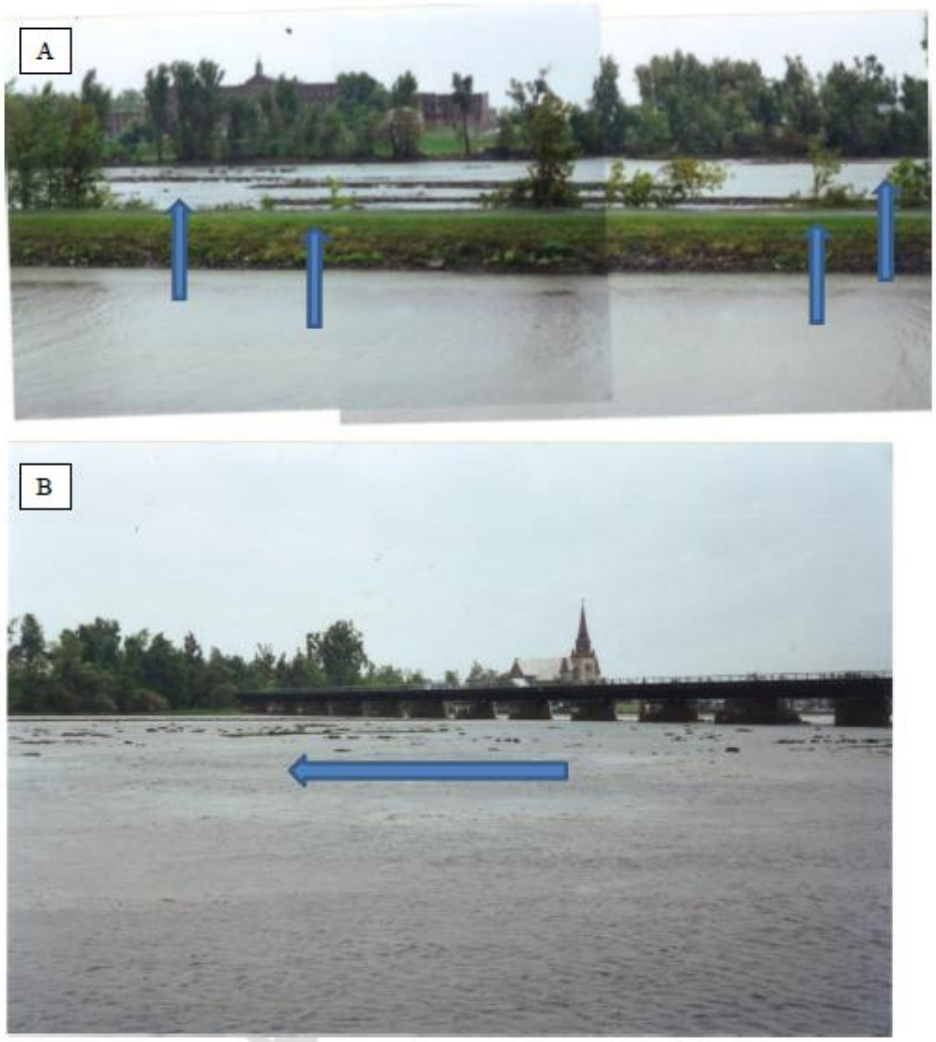


**Figure 3.2.5 –: a) Arrows indicate vestiges of eel traps b) Arrow indicates vestiges of millrace on the right bank**

Collection of new river bathymetry information in the Saint-Jean-sur-Richelieu shoal area in June 2015 did not help improve model performance, and the results remained unacceptable (not within 5 cm of the measurement). There are still some parts of the shoal for which accurate bathymetry is not available, particularly near the old channels that were used to bring water to the 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 30.676 m 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 3.2.2 presents the calibration results, expressed as the difference between observed and simulated water levels for the flood period in 2011. The differences at Rouses Point, Philipsburg, Burlington and Whitehall are provided only as a reference but were not used in the calibration of the model.

**Table 3.2.2: 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** |
| Philipsburg | 31.323 | 31.295 | **-0.028** |
| Burlington | 31.292 | 31.290 | **-0.002** |
| Whitehall | 31.304 | 31.311 | **0.007** |

Although some differences within the hydrodynamic mesh model are in the 1-3 cm range, the results are deemed acceptable, indicating this experimental model reproduces high flows reasonably well, under steady-state conditions. It is anticipated that the model will reasonably provide the water surfaces required to generate the static flood plain mapping products of this project with an objective to support actions taken during 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) were 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 that must still be resolved to achieve a good hydrodynamic model is the acquisition of accurate bathymetry covering the Saint-Jean-sur-Richelieu shoal area, because the shoal is what controls the lake levels. Improved bathymetry in this area will help to establish a good calibration for the entire range of discharges. 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 contributing to 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 TWG work plan Task 2-3. A detailed description of this work is given in the following technical report:

Environment Canada, 2015. Set-up of a 2D hydraulic model of the Richelieu River between Rouses Point and Sorel (Task 2-3). 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 modeling 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 were compiled and incorporated into the hydrodynamic model mesh.

Using Rouses Point as the upstream limit of the model of the Richelieu River proved to be a problem; when the level of Lake Champlain is very high, as in 2011, flood waters from Missisquoi Bay inundate wetlands and flow directly to the Rivière du Sud, which flows back into the Richelieu just downstream of Île-aux-Noix, effectively "bypassing" the Richelieu River between Rouses Point and Saint-Paul-de-l'Ile-aux-Noix. Since the Lake Champlain model discussed in section 3.2 already covers the upper Richelieu River reach, including the Missisquoi Bay flood plain and its "bypass", and the Richelieu River downstream of the bedrock shoal 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 shoal, down to the river's mouth at Sorel. With this approach, the entire LCRR domain was covered with the combination of the lake and river models.

Poor bathymetric datasets for the area of the Chambly Dam were noticed at the start of this work 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 shoal 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-ETE (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 150m to cover plains that may be flooded where less detail is required. Typically, a mesh element size of 25m was used. The 11 scenarios developed by the TWG were 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 put into question. 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 50cm. The difference varied on the ground and was greater at some locations than others 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 CHS bathymetry and the EC observations along a cross-section located some 7 km upstream from Sorel.

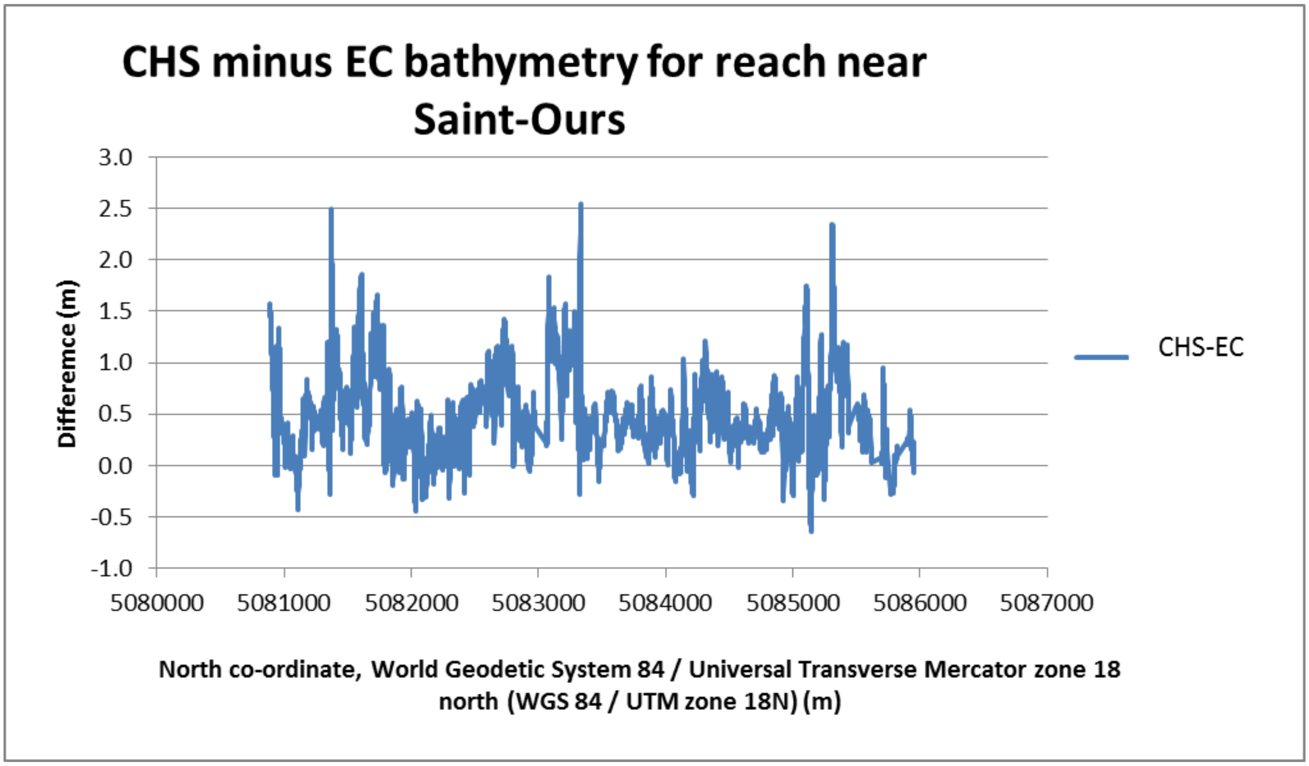


**Figure 3.3.1 – Difference between Canadian Hydrographic Service (CHS) and Environment Canada (EC) depth measurements for longitudinal transect near Saint-Ours**

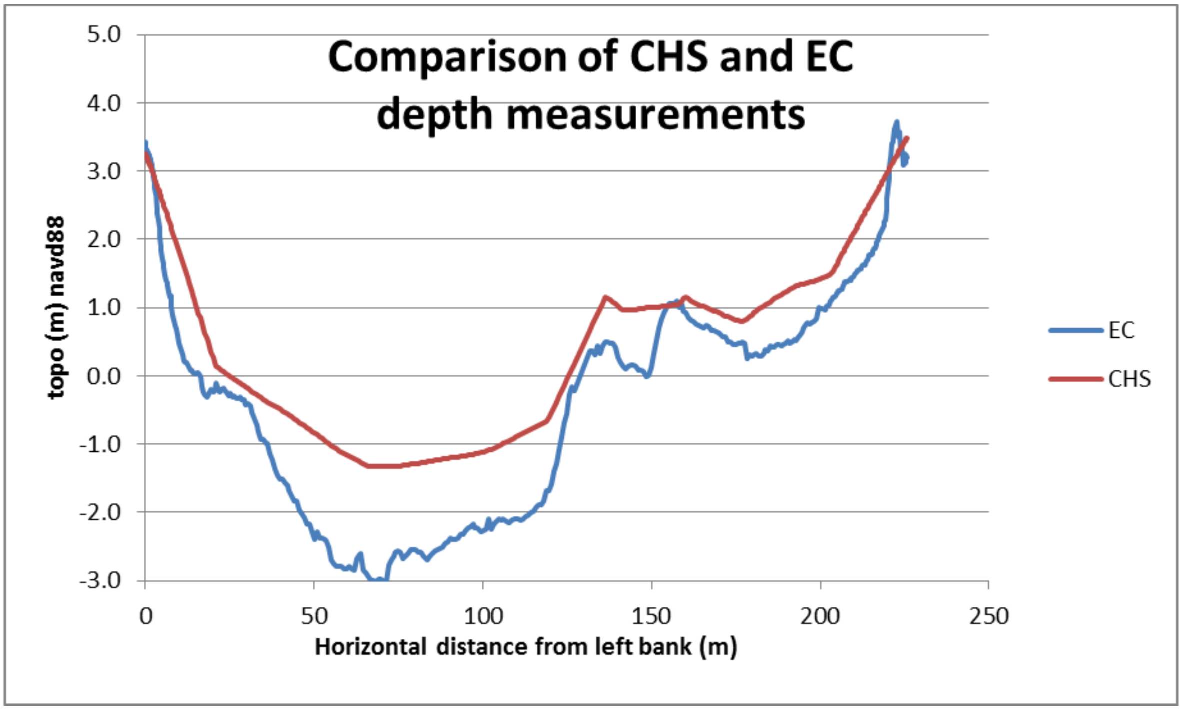


**Figure 3.3.2 – Canadian Hydrographic Service (CHS) and Environment Canada (EC) depth measurements for a cross-section located about 7 km upstream from Sorel**

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 is 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 TWG work plan Task 2-2. A detailed description of the Canadian portion of this work is given in the following technical report:
> Ministère du Développement durable, de l'Environnement et de la Lutte contre les 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 Elevation Model of the Shoreline, Transformation of Water Surfaces into Flood Zone Limits. Report to the International Joint Commission. 22 p

Two separate topographic data sets were created for this project; one on each side of the Canada/US 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 the 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 (Note: this map was produced in French).

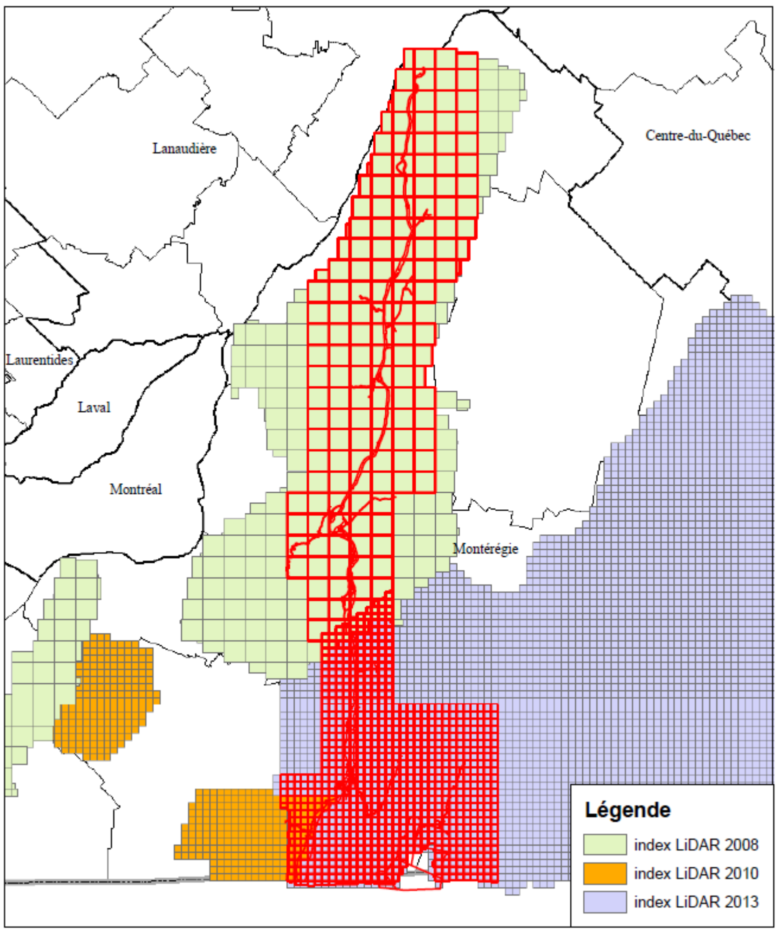


**Figure 3.4.1 – Spatial domain covered by each of the three measuring campaigns** (green, blue, and orange areas) **and map sheets for which data were used in this project** (red squares)

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.

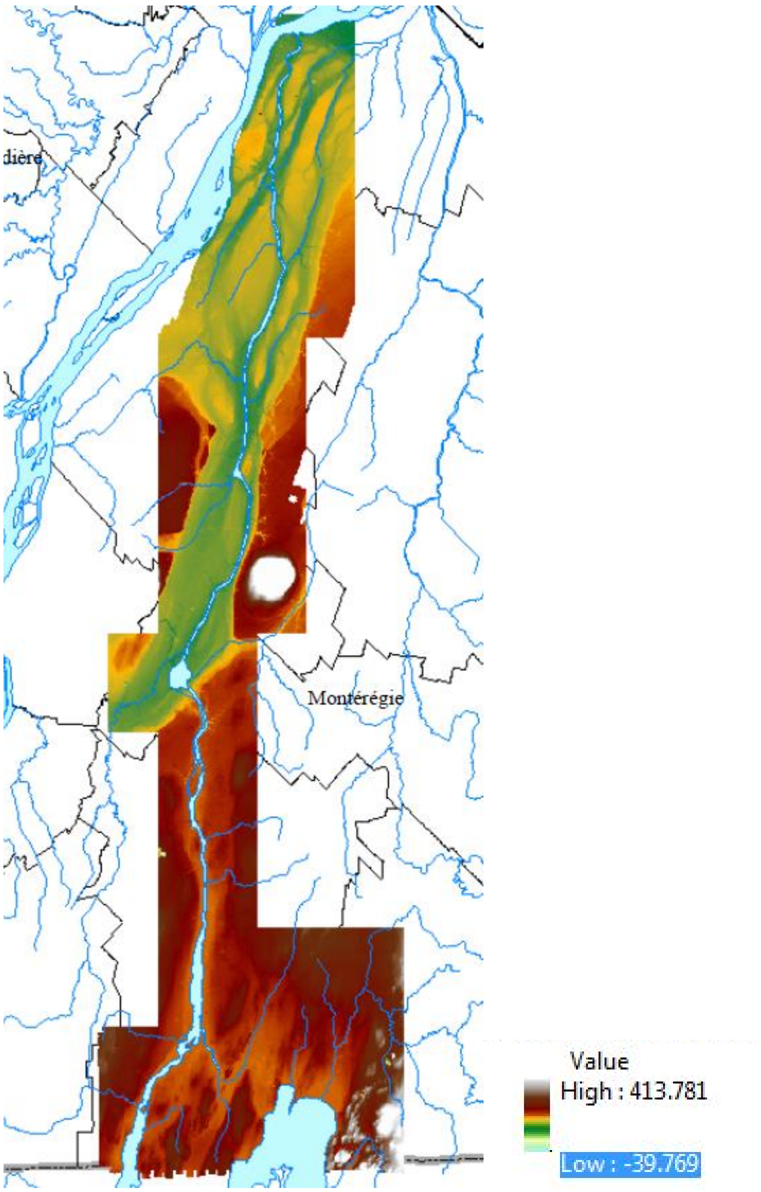


**Figure 3.4.2 – Overview of the DEM for the shorelines of the Richelieu River and the Missisquoi Bay portion of Lake Champlain.** Unit: meters

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.

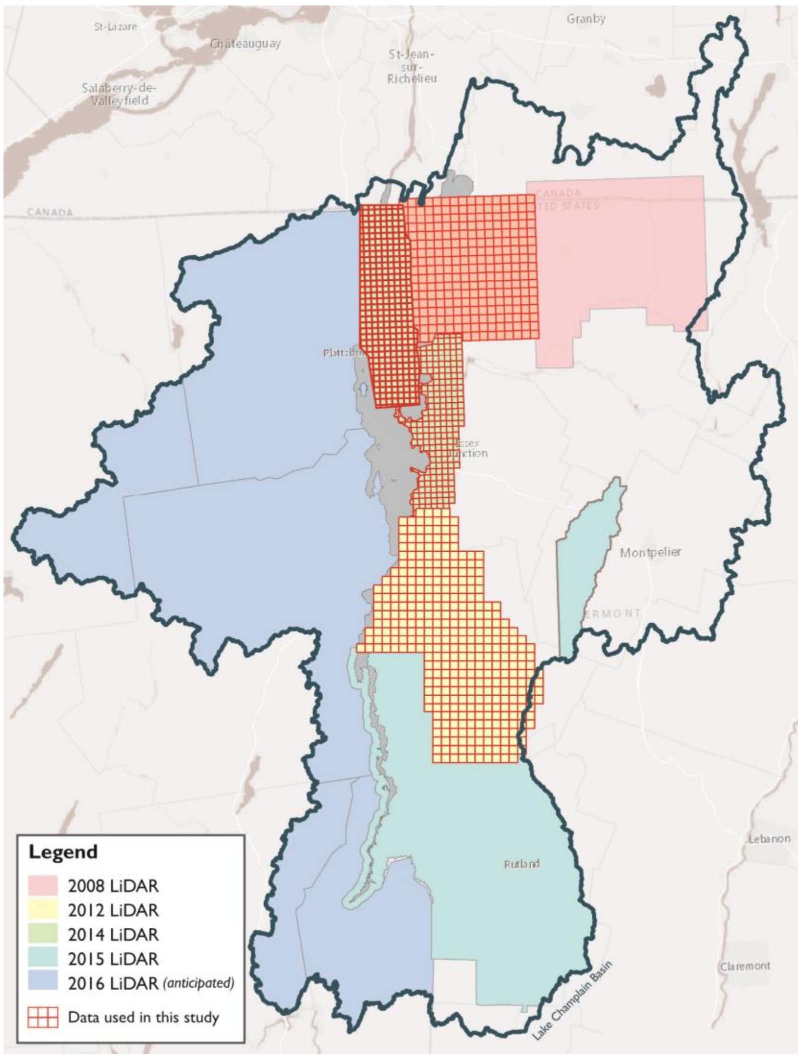


**Figure 3.4.3 – Spatial domain covered by each of the measuring campaigns and map sheets for which data were used in this project (red squares)**

# 4 Creation of static flood inundation maps

An important product of this project 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 contre les changements climatiques (MDDELCC) created the flood inundation maps as a collaborative effort for this project. 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 as 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.

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

## 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 U.S. 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 meters, 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** | NAVD88 Level | NGVD29 Level | NAVD88 Level | Estimated Flow |
|---|---|---|---|---|---|

| | **(feet)** | (feet) | (meters) | (meters) | ($m^3/s$) |
|---|---|---|---|---|---|
| 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 minor flood stage at USGS Rouses Point NY lake gauge 04295000 |
| 101.0 | 100.57 | US NWS designated moderate flood stage at USGS Rouses Point NY lake gauge |
| 101.5 | 101.07 | US NWS designated major flood stage at USGS Rouses Point NY lake gauge |
| 102.0 | 101.57 | Flood elevation Increment (Flood elevation of 102.1 ft on May 4, 1869 at Rouses Point NY lake gauge is the second highest peak of record) |
| 103.2 | 102.77 | Peak lake level elevation (May 6, 2011) at USGS Rouses Point NY lake 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 meters (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 | 30.10 | *1070*** | Minor | 2 |
| | 30.32 | *1225*** | Moderate | 3 |

| | | | | |
|---|---|---|---|---|
| (Marina, Saint-Jean-sur-Richelieu, QC) | 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 TWG work plan Task 2-4. A detailed description of the Canadian and U.S. portions of this work are given in the following technical reports:
Ministère du Développement durable, de l'Environnement et de la Lutte contre les 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 Elevation Model of the Shoreline, Transformation of Water Surfaces into Flood Zone Limits. Report to the International Joint Commission. 22 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 2016-XXXX. Draft report to the International Joint Commission, 26 p

Static flood inundation maps were produced by EC and MDDELCC for the Richelieu River from the 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).
<u>Static Flood Inundation Maps for the Richelieu River</u>:
EC utilized the H2D2 modeling results for 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 Geographical Information System (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 project area. Even at this 1:200,000 map scale, one can see 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 streamflows, a hydraulic connection between Missisquoi Bay and the Richelieu River through the South River can clearly be seen on the maps.

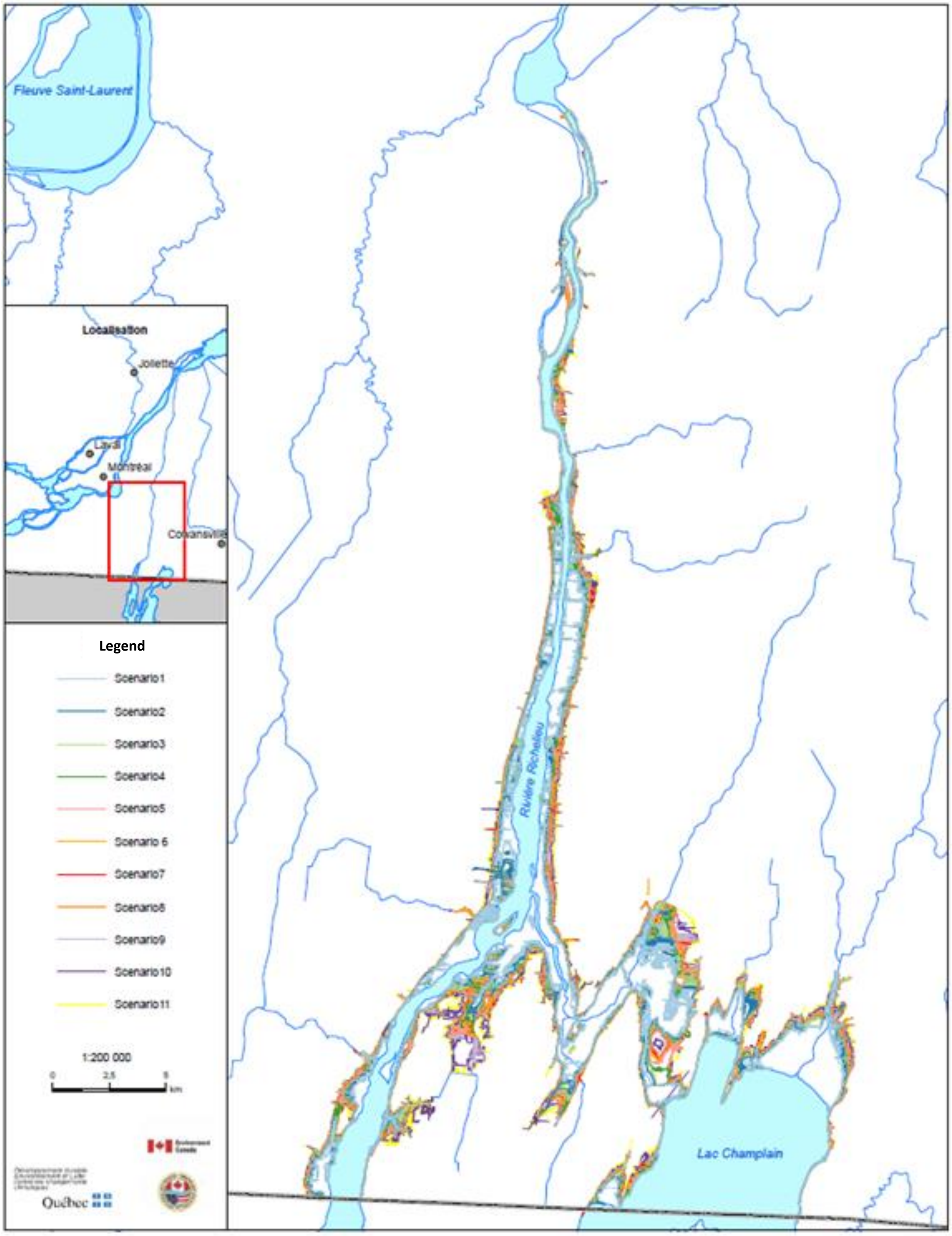


**Figure 4.2.1 – Areas of the Richelieu River where 11 static flood inundation maps were prepared**

Figure 4.2.2 presents a close-up view of the contour maps in the vicinity of Saint-Paul-de-l'Ile-aux-Noix. The increase in the size of the flooded areas when moving from the lowest streamflow scenario to higher streamflow scenarios is obvious on this figure. It also shows the extent and the boundaries of where water can reach for each scenario. Figure 4.2.3 provides flood depths and areas during a simulation using scenario 7 also in the vicinity of Saint-Paul-de-l'Ile-aux-Noix. This corresponds to a discharge of 1539 $m^3/s$ and a water level at Rouses Point of 31.32 m (NAVD88).

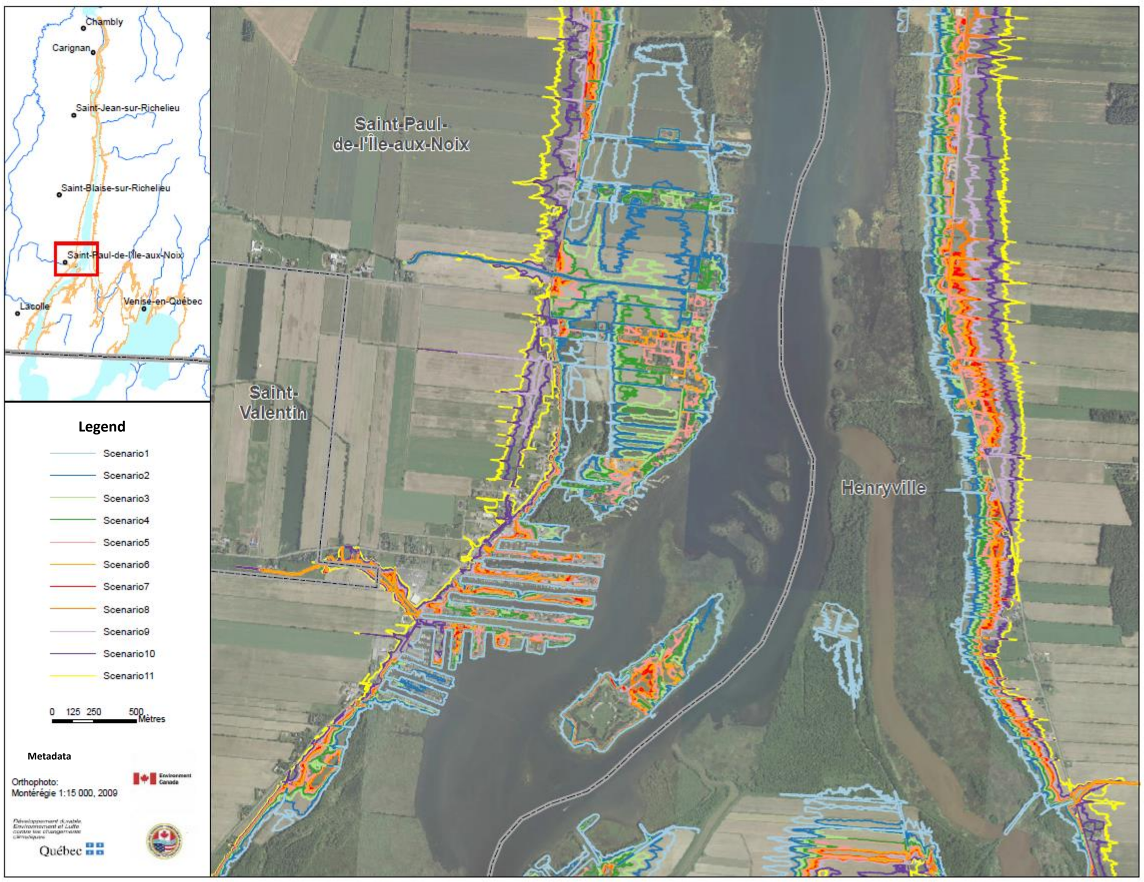


**Figure 4.2.2 – Close-up view of the flood inundation profiles for the Richelieu River in the vicinity of Saint-Paul-de-l'Ile-aux-Noix**

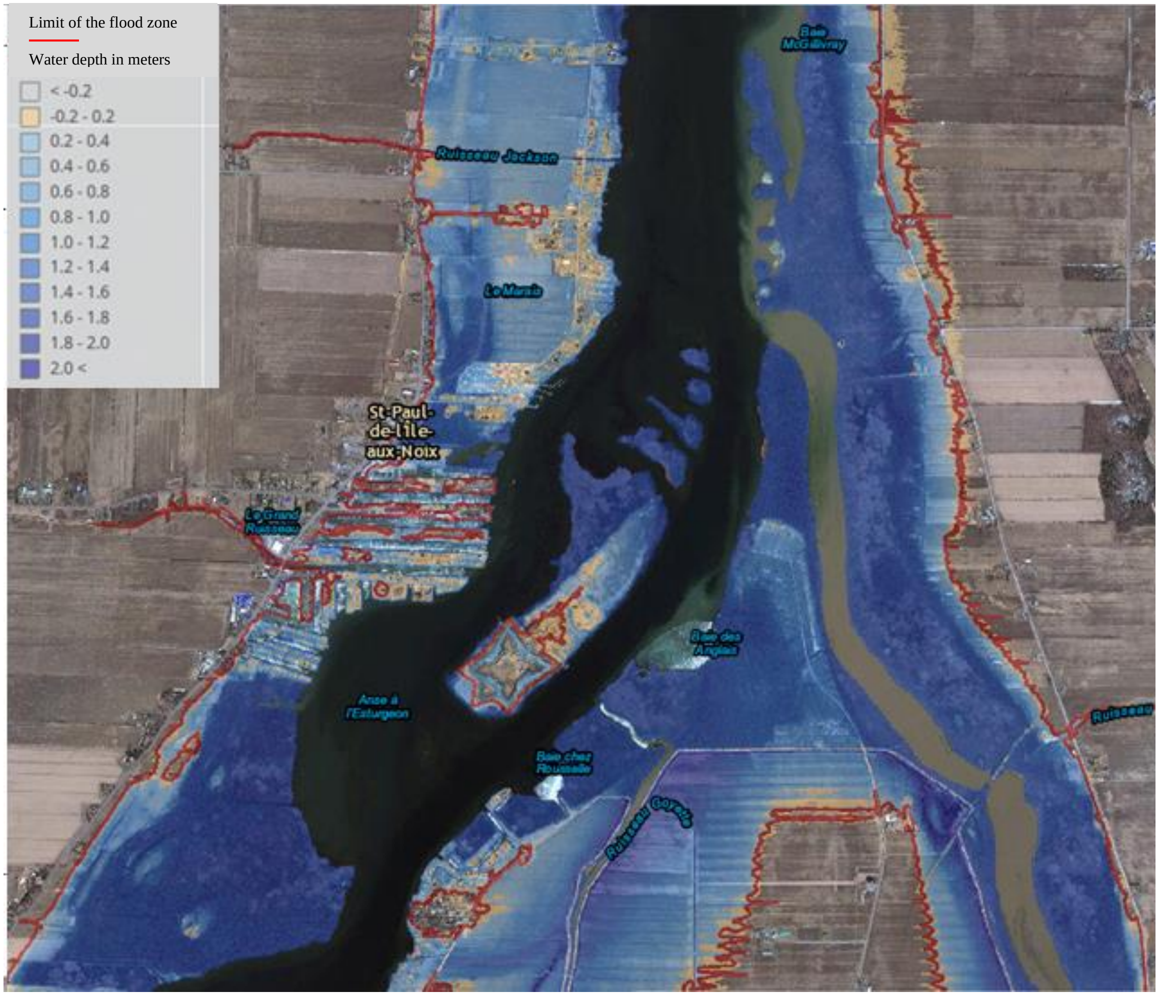


**Figure 4.2.3 – Flooding depths as simulated for scenario 7, in the vicinity of Saint-Paul-de-l'Ile-aux-Noix**

<u>Static Flood Inundation Maps for Lake Champlain</u>: Digital flood-inundation maps for an approximate 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 gauge. 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 project against the inundation area determined for the May 2011 flood which incorporated satellite imagery and documented high-water marks. Conditions at other lake gauges were not reflected in the maps, and wind set-up effects were not taken into account.

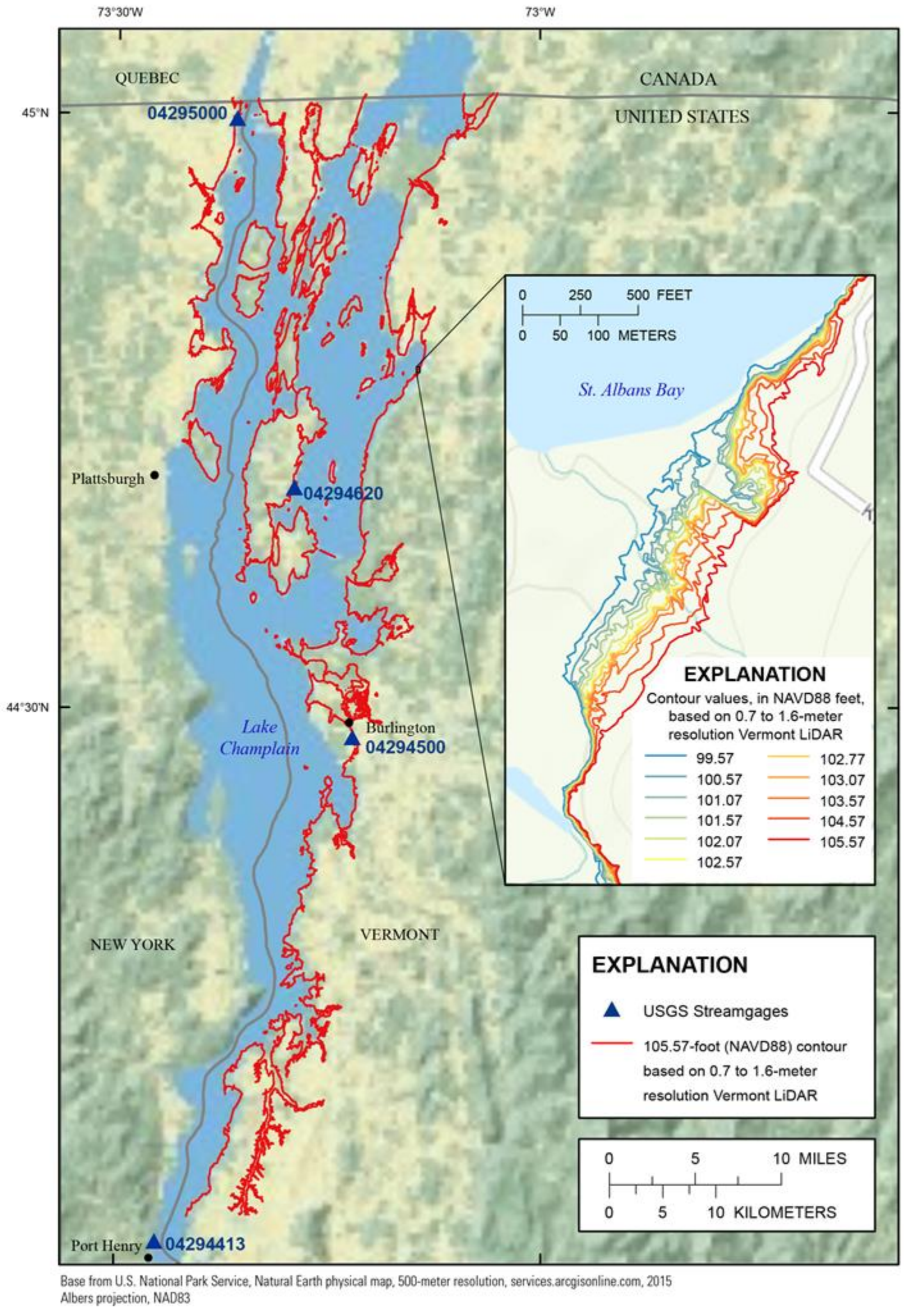


**Figure 4.2.4 – Areas of the Lake Champlain where flood inundation maps were created and a detailed map showing areas of flood inundation for the 11 lake level scenarios**

## 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 contour lines show some minor residual spatial misalignment at the border. For the same water level scenario, the two lines are spatially off by 1-2 meters (figure 4.3.1 (A) and (B)). These spatial differences can be explained by the fact that two different datasets and different techniques to produce the contour lines. The horizontal resolution of the LiDAR dataset in Canada is one meter and the U.S. resolution is 0.70 meter.

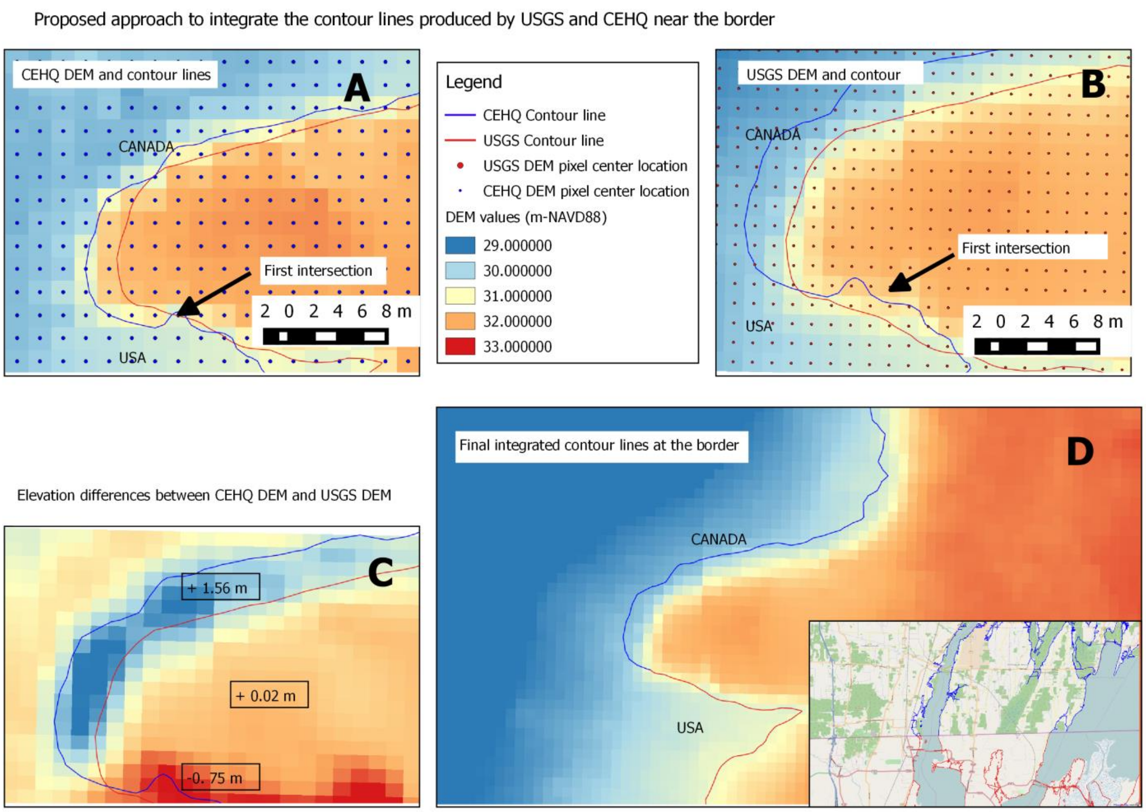


**Figure 4.3.1 – Flood contour line discrepancies at the border**

The most probable cause of the differences observed in the contour lines is related to the use of different LiDAR datasets. The figure 4.3.2 (C) illustrates the differences between LiDAR datasets in the U.S. and Canada. Two possible explanations for the differences in elevation values have been suggested. The first possible explanation is that each dataset has its own accuracy and uncertainty. The datasets were acquired at different times by different methods and calibrations, resulting in different elevation data. The second possible explanation is a slight horizontal shift in one (or both) of the datasets. On river banks and lake shores, a one or two meter horizontal shift between datasets can result in differences in elevation data.

To address this problem at the border in first approximation, a procedure was developed and applied for each contour line. For each water level scenario, the two contour lines were mapped. At the border (or within a few meters of it), and for each water level scenario, the first intersection between the lines was selected as the official location of contour transition. From this location all the U.S. contours north of the line were deleted and only the contours produced for Quebec were used. South of the location, all the Quebec lines were deleted and only the contours produced for the U.S. were used. The final product is shown in figure 4.3.2 (D), where a continuous spatially homogenous line is drawn near the border.

The actual source of discrepancy was not conclusively identified. In order to avoid future problems in cross-border elevation estimations, this residual discrepancy between the two LiDAR datasets will have to be addressed by the creation of a single consistent DEM for the entire LCRR basin.

### 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. These maps provide an emergency planning tool for authorities and the general public on land that may flood during high water events.

### 4.3.3 Simulated versus observed 2011 flooding

A cursory analysis of the performance of the models in replicating the 2011 flood simulation was performed by EC and the CEHQ for the Richelieu River. Figure 4.3.2 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, the figure shows that they match reasonably well. Differences are thought to be due to the effects of wind, the inherent uncertainty of ±20cm, or the contributions of local tributaries.

The cursory analysis leads to the conclusion that the 2D steady-state modeling, coupled with the LiDAR DEM mapping procedures, represents the flooded areas reasonably well, although the 2D model, as currently operated, doesn't incorporate wind set-up or local wave action.

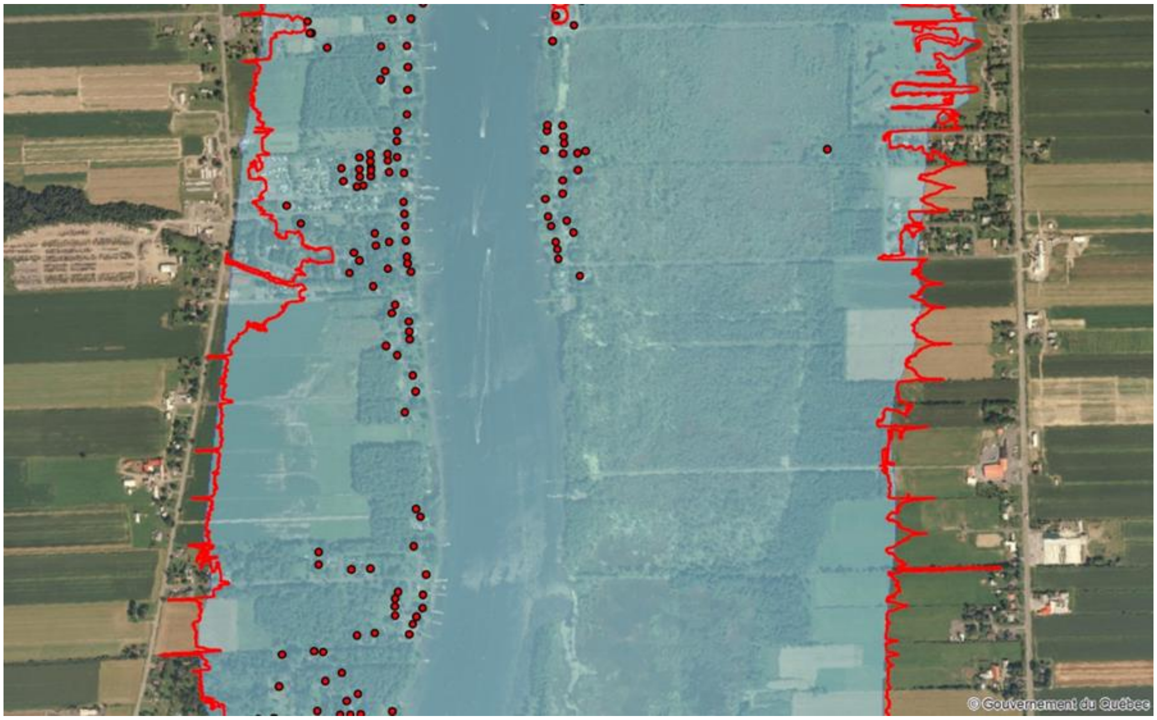

**Figure 4.3.2** – **Example of a comparison between flood inundation for scenario 7 (103.2 ft, NGVD29, blue shaded area) and the extent of the flood of 2011 (red contour line) according to data from the Ministry of Public Security of Quebec**. Approximate water surface derived from a analysis of remote 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 inundation maps are available on the IJC dynamic mapping web page http://arcg.is/1MhXui2as a series of individual maps or a single GIS data set.
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 provides forecast flood hydrographs for the Richelieu River (Lake Champlain) at Rouses Point NY (station number 04295000) and the Lake Champlain at Burlington, VT (station number 04294500) sites.
Figure 4.4.1 present different views extracted from the IJC dynamic flood plain mapping webpage for the entire Lake Champlain Richelieu River System (http://arcg.is/1MhXui2) near the border – scenario 7 example.

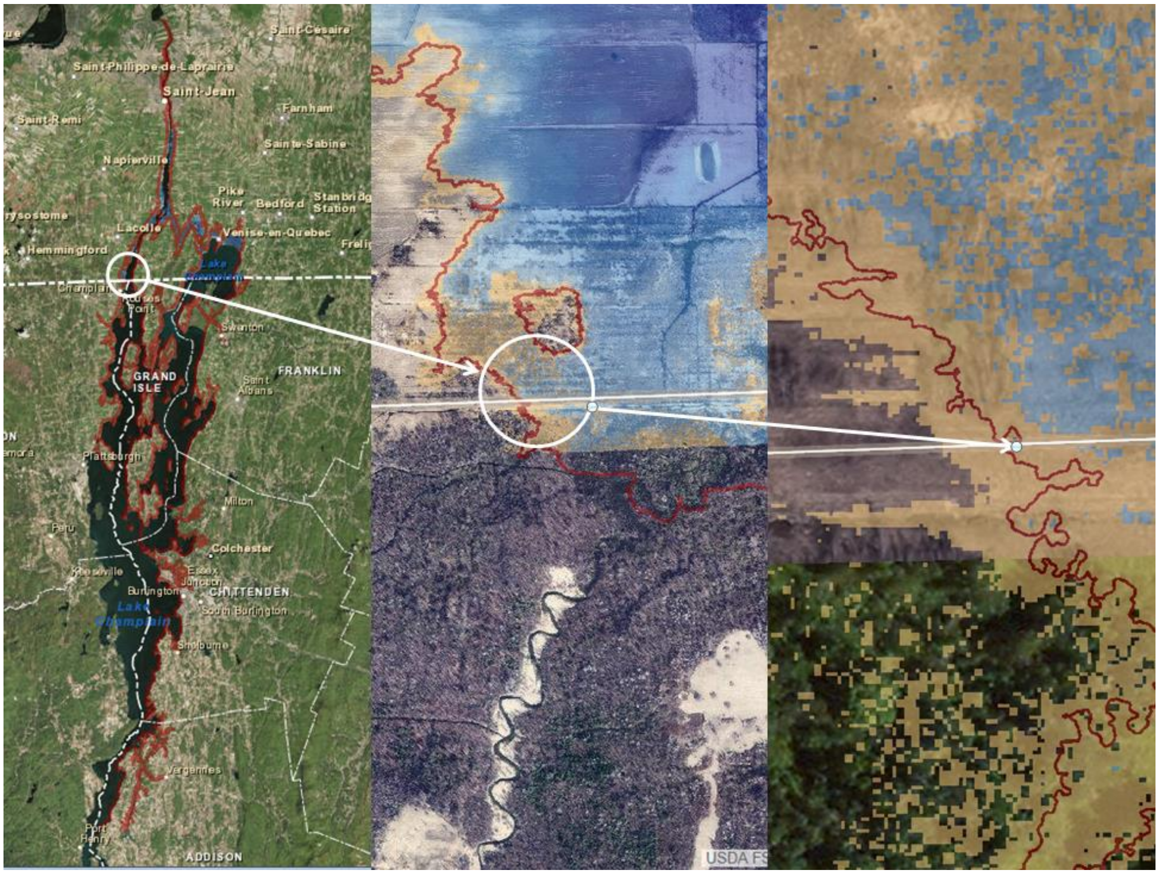


**Figure 4.4.1 – Canada – US flood maps of the Lake Champlain Richelieu River System – scenario 7 example**

## 4.5 Future flood inundation mapping in the LCRR Basin

The creation of static flood inundation maps for LCRR as part of this project 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 improve, 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

Two stakeholder meetings were held on November 3 and 4 in Burlington VT USA and Saint-Jean-sur-Richelieu Quebec Canada, respectively. These meetings presented project 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 the products. A total of 53 participants were present at both meetings representing emergency responders, community planners, and a host of government agencies - see participant list in ***Annex 5.***

Participants expressed support for project 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 in Canada 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 area. They would also like 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 seemed particularly important during the Burlington meeting.
- 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.

# 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, local officials, residents and businesses on how to best to respond to threatening conditions.

Current situation:

Current forecasts of Lake Champlain water levels are produced in real-time and disseminated by the U.S. NWS for 3-day horizons and are based on hydrological modeling of lake's inflows, 1D-hydraulic modeling of the lake, and rules-of-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 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 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 maps dynamically linked to forecast models.

In order to achieve those improvements, the TWG further identified that the modeling 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.

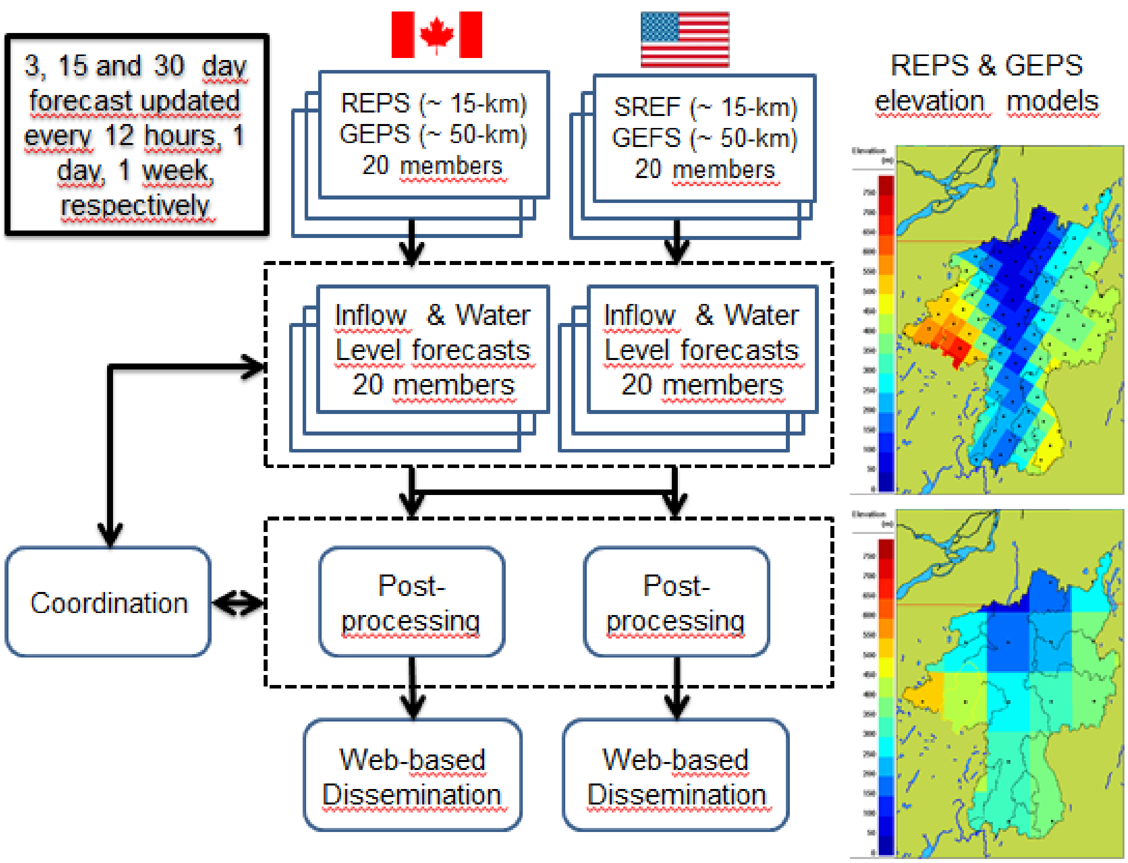


**Figure 5.1.1 – Components of the proposed flood forecasting and flood inundation mapping system**

More specifically,

- The probabilistic weather forecast systems of both countries should be used. In the current configuration, this would represent 40 distinct predictions (defined as ensemble 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 provide 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 Ensemble Forecasting System (GEFS) 32 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 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 CEHQ. These models provide simulation of snowmelt, vertical water budget and overland 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 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. EC and NOAA conduct the model runs independently and then share model results. In the case of Lake Ontario and the St. Lawrence River, the International St. 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 and coordinated 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 modeling 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 responsible for the flood plain mapping often have developed their own standards and procedures. The responsibilities of an eventual LCRR coordinating body would essentially be 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 shorelines is necessary to ensure that inundated areas become part of the forecasts.

The TWG suggests that the modeling approach described in section 5.1 would provide the required information for the generation of the best possible flood forecasts, and would also convey the consulted experts' appreciation that probabilistic products (with communicated uncertainty) 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 systems, taking advantage of the diversity and redundancy of the 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 the LCRR basin. Development, implementation and maintenance of the models, availability and analysis of observational and forecast data, benchmarking of forecast performances are examples of common activities. The coordination structure should also encourage agencies to share common goals, development priorities, and compatible forecasting tools for LCRR. Finally, the coordination structure should also provide support to the operational agencies and encourage bi-national cooperation in 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-user needs such as for safety purposes. These agencies should exchange operationally, especially in 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 model results on detailed topographic maps in near real-time fashion. This near real-time integration of lake and river forecasts to the DEMs would then allow local, state, provincial 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.

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

### 5.3.3 Wave modeling

Although wave action alone is not expected to significantly alter flow at the outlet of Lake Champlain and 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 NWS 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 with 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 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.

### 5.3.4 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 plain.

**Atmospheric models**: In support of current weather forecast requirements, NOAA runs multiple atmospheric models, at various detail scales and frequencies, throughout a typical day. For the next iteration of the Lake Champlain forecast model, it is envisioned that atmospheric inputs will be provided from an ensemble forecast system. The main ensemble forecast systems that are currently run by NOAA include the Global Ensemble

Forecast System (GEFS) and the Short Range Ensemble Forecast (SREF) Model. In order to provide a comprehensive set of inputs to the eventual receiving water model, a combination of short-term (SREF) and longer-term (GEFS) atmospheric inputs has been suggested. Other models may be considered in place of these models, as they become available.

EC runs a similar set of ensemble prediction systems, namely the Regional Ensemble Prediction System (REPS) for short-term forecasts and the Global Ensemble Prediction System (GEPS) for long-term forecast (up to 30 days). EC plans to force hydrological models with a combination of REPS and GEPS forecasts in order to obtain a single hydrological ensemble forecast.

It should be noted that EC and NOAA both contribute to the North American Ensemble Prediction System (NAEFS), which currently combines GEFS and GEPS forecasts and should soon include the SREF and REPS systems as well. Hence a coordinated atmospheric ensemble forecasting system exists and could be used as well, making it possible to force each hydrological and hydrodynamic model from EC and NOAA with atmospheric forecasts from both countries.

**Hydrologic and hydraulic models**: For the U.S. simulation of Lake Champlain, a three-dimensional hydrodynamic model of the lake (e.g. FVCOM) could ultimately be implemented. FVCOM is currently used in the Great Lakes Coastal Forecast 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.

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 EC's GEM-Hydro land-surface and hillslope model coupled to a river routing system and/or HYDROTEL, the hydrological model currently used by the 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. Further uncertainties associated to wind set-up and wave action could be communicated as well.

# 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 skill[5] 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 (correlation of 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 the U.S. and CGS conducted a project 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 the representation of water levels in either 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.

On the implementation of two new water level gauges

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

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, which is at the extreme south end of the lake. Preliminary modeling of the lake indicates the Port Henry gauge 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.

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

New data sets of substratum and submerged aquatic plants were 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 coefficients.

<u>On the experimental 2D hydraulic modeling of Lake Champlain</u>

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 ungauged areas. This experimental model can accurately predict high lake and river levels throughout the model domain under steady state conditions. 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 when 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.

<u>On the creation of a Combined LiDAR data base and Digital Elevation Model for the Basin</u>

Collection of new LiDAR data was accomplished with this project 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 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 LCRR 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 inundation 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, allow for the definition of confidence intervals on flood mapping products, and potentially limit legal issues and liabilities.

A bi-national 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 static flood mapping products

Static Flood Inundation Maps

The current effort greatly advanced 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. In Canada, static inundation maps were created for the Richelieu River from the border downstream to the Fryers Rapids. These maps are available from the IJC web site at: http://arcg.is/1MhXui2. A complete LiDAR DEM 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 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. For the Richelieu River, the sloped water surface was established through the use of a 2D hydraulic model and the complete LiDAR coverage of the flood plain also allowed for the generation of local estimations of inundation depths associated with each flood scenario.

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 purposes. 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 St. Lawrence River could not be modeled accurately due to poor bathymetric data sets. Acquiring a new bathymetric data set for the lower Richelieu is essential for the hydraulic modeling 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 put in place for flood forecasts, these forecast results will need to be linked to real-time inundation maps that show current conditions and future forecast 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 products, the TWG recommends that the U.S. - Canada two-pronged probabilistic approach presented in section 5 for the forecasting of floods should be adopted and implemented operationally, including the modeling of wind set-up and wave action. This approach will include the development of hydrodynamic models for Lake Champlain that will be used as current Great Lakes model applications are employed, i.e. to provide a U.S. and Canada modeled forecast contribution to the bi-national coordination body for its forecast consideration.
2. To calibrate and validate a future forecasting system, the TWG recommends that both the Port Henry and the Grand Isle water level stations be kept in operation, at a minimum to collect data covering a representative range of water levels supporting the calibration of the hydraulic model. 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 observational data, quality control of the model predictions, and generation of bi-national water level predictions. The establishment of this coordination body will ensure that a consistent message is conveyed to emergency responders and the public regarding the LCRR water level predictions that are disseminated.
4. To generate flood forecasts and real-time flood mapping products for the entire LCRR system, 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.

5. To allow a better and complete flood forecasting capacity for LCRR, the TWG recommends the acquisition of new bathymetric data for 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.
6. The TWG recommends that the static flood inundation maps be generated for the entire LCRR system.
7. The TWG recommends that the newly acquired data, wind observations and models be used to calibrate a dynamic version of the hydraulic model for the entire LCRR 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



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.

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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

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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 word 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,

C. Wilkie

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, 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.

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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

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

**ILCRR Working Group**

| | |
|---|---|
| **Jean-François Cantin, ing., M.Sc.**<br>Canadian co-chair<br><br>Manager, Hydrology and Ecohydraulics Section, National Hydrologic Services<br>Meteorological Service of Canada<br>Environment Canada<br>1550, avenue d'Estimauville<br>Québec (Québec), G1J 0C3<br>Telephone 418-649-6565<br>Cellular phone 418-564-0521<br>Facsimile 418-648-5643<br>E-mail jean-francois.cantin@canada.ca | **Keith Robinson**<br>United States co-chair<br><br>Director, New England Water Science Center<br>US Geological Survey<br>331 Commerce Way, Suite 2<br>Pembroke NH 03244<br>Telephone 603-226-7807<br>Cellular phone 603-986-2327<br>Facsimile 603-226-7894<br>E-mail kwrobins@usgs.gov |
| **Vincent Fortin**<br>Federal member<br><br>Chercheur en prévision numérique environnementale<br>Environnement Canada<br>2121, route Transcanadienne<br>Dorval, Québec H9P 1J3<br>Telephone : 514-421-4630<br>E-mail : vincent.fortin@ec.gc.ca | **William (Bill) Saunders**<br>Federal Member<br><br>Senior Hydrologist<br>National Weather Service<br>Northeast River Forecast Center<br>445 MylesStandishBlvd<br>Taunton, MA 02780<br>Telephone: 508-824-5116 x260<br>Email: william.saunders@noaa.gov |
| **Daniel Leblanc, ing. M.Sc.A.**<br>Quebec member<br><br>Directeur adjoint<br>Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques<br>Direction régionale de l'analyse et de l'expertise de l'Estrie et de la Montérégie<br>201, place Charles-Le Moyne, 2ième étage<br>Longueuil (Québec) J4K 2T5<br>tél.:450-928-7607 poste 305<br>téléc.: 450-928-7625<br>E-mail: daniel.leblanc@mddelcc.gouv.qc.ca | **Blaine Hastings**<br>Vermont member<br><br>Hydrologist<br>Vermont Department of Environmental Conservation<br>Watershed Management Division<br>1 National Life Drive, Main 2<br>Montpelier, VT 05620-3522<br>Telephone: 802-490-6156<br>Email: Blaine.Hastings@state.vt.us |
| **Richard Turcotte, ing, Ph.D.**<br>Quebec member | **Fred Dunlap**<br>New York member |

| | |
|---|---|
| Conseiller scientifique<br>Direction de l'expertise hydrique<br>Centre d'expertise hydrique du Québec<br>Développement durable, Environnement et Lutte contre les changements climatiques<br>675, boulevard René Lévesque Est<br>Québec (Québec) G1R 5V7<br>Tél: 418 521-3993 poste 7145<br>Fax: 418 643-6900<br>E-mail:<br>Richard.Turcotte2@mddelcc.gouv.qc.ca | NY Lake Champlain Basin Coordinator<br>New York State Dept of Environmental Conservation<br>1115 NYS Rte 86 - Box 296<br>Ray Brook, NY 12977<br>Telephone: 518-897-1241<br>Email: fred.dunlap@dec.ny.gov |

**Technical support**

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

**Secretariat support**

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

# 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.gc.ca | Lake Champlain |
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| Chun-Mei Chiu | Notre Dame | cchiu2@nd.edu | Hydrology |
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| Jamison Romano | Aquatic Informatics | jamison.romano@aquaticinformatics.com | Hydrometrics |
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| 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 Participants present at the End-User meetings in November 2015

| Participant | Organization | Location of the event |
|---|---|---|
| Eric Day | Clinton County, Emergency Services | Burlington |
| Wallace Day | Observer, New York | Burlington |
| Rob Evans | Vermont Agency of Natural Resources (ANR) | Burlington |
| Emily Harris | Vermont Emergency Management and Homeland Security | Burlington |
| Greg Hanson | National Weather Service | Burlington |
| Bill Howland | Lake Champlain Basin Program | Burlington |
| Nathaniel Neider | St. Alban Town (planner) | Burlington |
| Rebecca Pfeiffer | Vermont ANR | Burlington |
| Dean Pierce | Town of Shelburne | Burlington |
| Meghan Sullivan | Department of Foreign Affairs, Trade and Development Canada (DFATD) | Burlington and Saint-Jean-sur-Richelieu |
| Ned Swanberg | Vermont Department of Environmental Conservation (DEC) River Program | Burlington |
| Sylvain Arteau | St-Jean-sur-Richelieu | Saint-Jean-sur-Richelieu |
| Claudine Beaudoin | Ministère des Affaires municipales et de l'Occupation du territoire du Québec (MAMOT) | Saint-Jean-sur-Richelieu |
| Denis Bourdon | Saint-Denis-sur-Richelieu | Saint-Jean-sur-Richelieu |
| Luc Castonguay | Ville de St-Jean-sur-Richelieu | Saint-Jean-sur-Richelieu |
| Daniel de Brouwer | Ville de Richelieu | Saint-Jean-sur-Richelieu |
| Chantale Chatelain | Comité de concertation et de valorisation du bassin de la rivière Richelieu (COVABAR) | Saint-Jean-sur-Richelieu |
| Michelle Chabot | Municipalité régionale de comté (MRC) du Haut-Richelieu | Saint-Jean-sur-Richelieu |
| Andrée Clouâtre | Municipalité de Henryvillle | Saint-Jean-sur-Richelieu |
| Marcel Comiré | COVABAR | Saint-Jean-sur-Richelieu |
| Chantal Couture | Parcs Canada | Saint-Jean-sur-Richelieu |
| Eric Desbiens | St-Jean-sur-Richelieu | Saint-Jean-sur-Richelieu |
| François Ferrer | Parcs Canada | Saint-Jean-sur-Richelieu |
| Jean-Sébastien Forest | Ministère de la Sécurité publique du Québec (MSP) | Saint-Jean-sur-Richelieu |
| Yannick Gignac | MAMOT | Saint-Jean-sur-Richelieu |
| Yvan Giroux | Ville de Richelieu | Saint-Jean-sur-Richelieu |
| Gerardo GolloGil | Ministère de l'Agriculture, des | Saint-Jean-sur-Richelieu |

| | | |
|---|---|---|
| | Pêcheries et de l'Alimentation du Québec (MAPAQ) | |
| Simon Lajeunesse | MRC Brome-Missisquoi | Saint-Jean-sur-Richelieu |
| Ana Claudia de Oliveira | Agence Parcs Canada | Saint-Jean-sur-Richelieu |
| Francis Pelletier | MRC du Haut-Richelieu | Saint-Jean-sur-Richelieu |
| Jonathan Pelletier | Université du Québec à Montréal (UQAM) | Saint-Jean-sur-Richelieu |
| Gilbert Prichonnet | UQAM (à la retraite- retired) | Saint-Jean-sur-Richelieu |
| Francis Provencher | MRC de Rouville | Saint-Jean-sur-Richelieu |
| Caroline Roberge | MRC du Haut-Richelieu | Saint-Jean-sur-Richelieu |
| Renée Rouleau | Clarenceville | Saint-Jean-sur-Richelieu |
| Nouri Sabo | Ressources naturelles Canada | Saint-Jean-sur-Richelieu |
| Philippe Thiberge | MRC de Rouville | Saint-Jean-sur-Richelieu |

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## ANNEX 7 Cited Organizations and list of Acronyms

| | |
|---|---|
| 2-D | 2-Dimensional |
| 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 |
| EC | Environment Canada |
| EDT | Eastern Daylight Time |
| EST | Eastern Standard Time |
| FEMA | Federal Emergency Management Agency |
| FTP | File transfer protocol |
| FVCOM | Finite Volume Community Ocean Model |
| GEFS | Global Ensemble Forecasting System (US) |
| GEM | Global Environmental Multiscale Model |
| GEPS | Canadian Global Ensemble Prediction System (Canada) |
| GIS | Geographical Information System |
| GLCFS | Great Lakes Coastal Forecast System |
| GLERL | Great Lakes Environmental Research Laboratory |
| GLOFS | Great Lakes Operational Forecasting System. |
| GNSS | Global Navigation Satellite System |
| GPS | Global Positioning System |
| HRDPS | High-Resolution Deterministic Prediction System |
| HYDROTEL | Hydrologie et Télédétection |
| IAGLR | International Association for Great Lakes Research |
| IJC | International Joint Commission |
| ILCRRTWG | International Lake Champlain-Richelieu River Technical Working Group |
| INRS-ETE | Institut national de la recherche scientifique – Centre Eau Terre Environnement |
| 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 |
| MSP | Ministère de la sécurité publique du Québec |
| NAVD88 | North American Vertical Datum of 1988 |
| NAEFS | North America Ensemble Forecast System |
| NCEP | National Centers for Environmental Prediction |
| 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 |
| PoS | Plan of Study |
| QC | Quebec |
| 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 |
| VCGI | Vermont Center for Geographic Information |
| VMC | Vermont Monitoring Cooperative |
| VT | Vermont |