Environment Canada Environnement Canada

Development of an experimental 2D hydrodynamic model of Lake Champlain using existing bathymetric data (Task 1-2)

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Technical report prepared by Environment Canada for the
International Lake Champlain – Richelieu River Technical Working Group

October , 2015

Canada

Aussi disponible en français

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Introduction

According to the Final Workplan of January 23, 2015, Task 1-2 consists of developing an experimental 2D hydrodynamic model of Lake Champlain, using existing bathymetric data. The objectives are described as follows:

A 2D finite element (FE) model of Lake Champlain is expected to simulate the hydraulic response, more specifically the water levels, under a variety of inflowing waters and wind scenarios. The wind set-up for Lake Champlain significantly influences the flooding on the Lake itself and also on the Richelieu River. Wave set-up, run-up and over-topping are not part of this experimental model, nor are the 3D complexity of the flows in areas where it's not forced by gravity (i.e., winds etc.). The essential objective of this task is to assess the responsiveness of a 2D model to Lake Champlain water supplies and wind input, and its capacity to adequately simulate water levels at an appropriate spatial resolution on the Lake Champlain, while providing seamless upper limit boundary conditions to the Richelieu River hydraulic model (see task 2-3), creating a continuous hydraulic model of the Lake Champlain and Richelieu River. The downstream limit of the Lake Champlain model will be placed below the Saint-Jean shoal , to ensure that the shoals critical section actually serves as the hydraulic control of the entire Lake Champlain – Richelieu River system, overlapping with the upstream portion of the Richelieu River hydraulic model. This task will start in early 2015.

The main activities are described below:

1. *A scenario analysis will be carried out that will include an identification of the main tributaries that will be included into the model domain. All water inflows to the lake will be distributed among those tributaries. Collation of datasets for calibration purpose (coincident water levels and longitudinal water surface profiles for Richelieu River flows between 550m^3/s and 1500m^3/s, wind speed, inflow). Determination of the upstream boundary location between Port Henry and Whitehall. A database of all required U.S. and Canadian inflows will be developed, in collaboration with the USGS (see task 2-1).*
2. *Digital elevation model (DEM): Lakeshore elevation data and the Lake Champlain bathymetry shall be collected or obtained and processed to be incorporated into the hydraulic model. Bathymetric datasets from Middlebury College and the Vermont Center for Geographic Information will be gathered with the assistance of the Lake Champlain Basin Program and the USGS. The observed difference between the vertical datums used by Canada and the U.S. will be addressed in its simplest form by use of a constant transformation, or according to a more sophisticated protocol that Task 1-6 may establish.*
3. *Digitization of man-made structures such as bridges, piers, causeways, etc. which can affect the hydrodynamics will be incorporated in the FE mesh.*
4. *Development of a finite element mesh for production of the hydrodynamic mesh for Lake Champlain respecting the criteria of the preceding tasks.*
5. *Calibration and validation of the hydrodynamic model simulations will be carried out, especially for wind input. Performance measures will be used to assess model performance at locations where observations are also collected. These performance measures will include (a) mean error between simulations and observations, (b) mean*

absolute error between simulations and observations, (c) root mean error between simulations and observations, and (d) Pearson correlation coefficient (r) of observed to simulated elevations.

6. *Report: description of the hydrodynamic modeling work that was done and results of the model calibration.*

To cover the above activities, this report contains the following sections: scenario analysis, water supply, incorporation of terrain data under a single vertical datum, digital elevation model, 2D hydrodynamic model of Lake Champlain, and a conclusion.

1. Scenario analysis

The first step was to determine the location of the upstream and downstream limits of the 2D hydrodynamic model of Lake Champlain. Whitehall was selected as the upstream limit, with the result that the entire lake was modeled. This enables use of the Whitehall gauging station and it also ensures that the model will respect the conservation of mass principle for the water in the lake when transient wind event simulations are made. Water levels are affected by wind, but the volume of water in the lake remains the same, leaving aside flows into and out of the lake. It would be very difficult to respect mass conservation if only a portion of the lake were modeled. As for the downstream limit, it is located near the Fryers Rapids station (02OJ007), just below the Fryer Dam. This makes it possible to disregard the influence of whatever water level is imposed downstream from the model area since the bedrock sill at Saint-Jean-sur-Richelieu is what controls the level in Lake Champlain: the level imposed downstream of the model area can vary without that affecting the result upstream of the sill. The sill serves as a hydraulic control and blocks the influence of the level imposed downstream. It is therefore possible to simulate a non-stationary event involving wind without first knowing the levels that will result at Saint-Jean-sur-Richelieu and at Rouses Point.

Concerning the model's sources of inflow, it was decided to include the 10 main tributaries of Lake Champlain on the American side of the border, as well as Lake George / LaChute River. The tributaries in question are the Winooski, Missisquoi, Lamoille, Bouquet, Ausable, Saranac, Chazy, Mettawee and Poultney Rivers and Otter Creek. On the Canadian side, the Aux Brochets and De La Roche Rivers (in the Missisquoi Bay area) are included. These are the 13 locations where inflows to the lake are imposed. Inflows associated with other smaller tributaries, as well as non-point flows into the lake or direct over-lake precipitation, are distributed among the 13 entry points.

The Working Group established 11 scenarios (reference events) using levels at the Rouses Point gauging station in New York State. These scenarios correspond to the following levels at Rouses Point that are based on the National Geodetic Vertical Datum of 1929 (NGVD29): 100.0, 101.0, 101.5, 102.0, 102.5, 103.0, 103.2, 103.5, 104.0, 105.0 and 106.0. The scenarios are described in section 5 below (2D model of Lake Champlain).

2. Water supply

2.1 Methodology for calculating inflows to Lake Champlain

Once the entry points of the model had been established, a database of all American and Canadian inflows was created to provide inputs to the model when simulating historical events. The drainage areas of the gauged and ungauged contributing areas used to calculate the inflows were taken mainly from Shanley and Denner (1999).

First, all data available for the period 1970-2015 at gauging stations on the tributaries were extracted so as to have as much data as possible for calculating the inflow to Lake Champlain. The Lake Champlain stations are shown on figure 6.

For each day of the time period under study and for each gauged tributary, the daily flow entering the lake from that tributary was calculated using the following priorities:

- If the data for the main station (the most downstream gaging station) are available, the ratio R_S of the flow at the station to the station's watershed area is used to calculate the inflow to the lake, by multiplying the ratio by the tributary's watershed area A_T. $Q_T = R_S*A_T$
- If the data are not available for the main station but are available for another station on the same tributary (e.g. the Mettawee), these data are used to estimate the inflow to the lake using the method just described. QT = RS*AT
- If no data at all are available for a tributary but there are other gauged tributaries having the same entry point, the mean ratio R_B for that entry point is used to estimate the inflow to the lake from that tributary. $Q_T = R_B*A_T$
- If no data at all are available for any tributary having that entry point, the mean ratio R_{BV} for an entry point in the vicinity is used to estimate the inflow to the lake from the tributary in question. $Q_T = R_{BV}*A_T$
- In the rare cases where no data are available for entry points in the vicinity, the mean ratio R_L, calculated from all the data available from stations, is used to estimate the inflow to the lake from the tributary in question. $Q_T = R_L*A_T$

Where

A_S	Area of the station watershed in km^2
Q_S	Flow at the station in m^3s^{-1}
R_S	Ratio Q_S / A_S for a station and its watershed in $m^3s^{-1}km^{-2}$
A_T	Area of the tributary watershed in km^2
Q_T	Tributary flow at the lake in m^3s^{-1}
R_T	Ratio Q_T / A_T for a tributary and its watershed in $m^3s^{-1}km^{-2}$
A_B	Area of an entry point to the lake in km^2

Q_B Flow at the lake = R_S*A_B or R_B*A_B if R_S is not available, in m^3s^{-1}
R_B Ratio Σ Q_S / Σ A_S for all of an entry point's stations $m^3s^{-1}km^{-2}$
R_{BV} Ratio Σ Q_S / Σ A_S for all stations of an entry point in the vicinity in $m^3s^{-1}km^{-2}$

A_L Area of all entry points to the lake in km^2
Q_L Flow entering the lake Σ Q_B or R_L*A_L in m^3s^{-1}
R_L Ratio Σ Q_B / Σ A_B for all entry points to the lake in $m^3s^{-1}km^{-2}$,
$Q = A*R$

See table 1 for details on the stations used. The data were extracted in March-April 2015.

Here, along with pertinent information, are the gauging stations that were used for each entry point of the model, along with the entry points in the vicinity that were used when data was missing.

Mettawee entry point
Two stations were available for the Mettawee River. Priority was given to the Mettawee River At Middle Granville station because it is nearer to the lake.
Stations available:

- Mettawee River At Middle Granville, NY (1990-2015)
- Mettawee River Near Pawlet, NY (1984-2009)
- Mount Hope Brook at South Bay Near Whitehall, NY (1990-1996)
- Mill Brook at Putnam, NY (1990-1999)

Entry points in vicinity: Otter, Poultney

Poultney entry point
Stations available:

- Poultney River Below Fair Haven, VT (1970-2015)

Entry points in vicinity: Otter, Mettawee

LaChute entry point
The LaChute River station was not included in the calculation of the ratio because the flow is regulated.
Stations available:

- La Chute At Ticonderoga, NY (1970-1979)
- Putnam Creek East of Crown Point Center, NY (1990-2014)
- Mill Brook at Port Henry, NY (1990-1999)
- Hoisington Brook at Westport, NY (1990-1996)

Entry points in vicinity: Mettawee, Bouquet

Otter entry point
Stations available:
- Otter Creek At Middlebury, VT (1970-2015)
- Little Otter Creek At Ferrisburg, VT (1990-2015)
- Lewis Creek At North Ferrisburg, VT (1990-2015)

Entry points in vicinity: Poultney, Winooski

Bouquet entry point
Data are available from 1990 on. Where no data were available, the ratio for the Saranac entry point was used to estimate the flows.
Stations available:
- Bouquet River At Willsboro, NY (1990-2015)
- Highlands Forge Lake Outlet Near Willsboro, NY (1990-1996)

Entry points in vicinity: Ausable, Saranac

Ausable entry point
Data are available from 1990 on. Where no data were available, the ratio for the Saranac entry point was used to estimate the flows.
Stations available:
- Ausable River Near Au Sable Forks, NY (1990-2015)
- Little Ausable River Near Valcour, NY (1991-2015)
- Salmon River At South Plattsburgh, NY (1990-2015)

Entry points in vicinity: Bouquet, Saranac

Winooski entry point
Stations available:
- Laplatte River At Shelburne Falls, VT (1990-2015)
- Winooski River At Essex Junction, VT (1970-2015)

Entry points in vicinity: Otter Creek, Lamoille

Lamoille entry point
Stations available:
- Lamoille River At East Georgia, VT (1970-2015)
- Stone Bridge Brook Near Georgia Plains, VT (1970-2000)

Entry points in vicinity: Missisquoi, Winooski

Saranac entry point
No data available for early 2014; the lake's mean ratio was used to estimate the inflow to the lake since the two entry points in the vicinity had no data for the period in question.
Stations available:
- Saranac River At Plattsburgh, NY (1970-2015)

Entry points in vicinity: Ausable, Chazy

Chazy entry point
No data available for early 2014; the lake’s mean ratio was used to estimate the inflow to the lake since the two entry points in the vicinity had no data for the period in question.
Stations available:

- Saranac River At Plattsburgh, NY (1970-2015)
- Little Chazy River Near Chazy, NY (1990-2014)
- Great Chazy River At Perry Mills, NY (1990-2015)

Basin in vicinity: Saranac

Missisquoi entry point
Two stations were available for the Missisquoi River. The Missisquoi River At Swanton station was given priority since it is nearer to the lake.
Stations available:

- Missisquoi River At Swanton, VT (1990-2015)
- Missisquoi River Near East Berkshire, VT (1970-2015)

Basin in vicinity: Lamoille

Aux Brochets entry point
The available stations are listed below in order of priority.
Stations available:

- Aux Brochets, à Notre-Dame-De-Stanbridge (Pont Couvert), QC (2001-2015)
- Aux Brochets 0.7 km Aval Du Ruisseau Groat (Bedford), QC (1979-2012)
- Aux Brochets, à Bedford, QC (1976-1979)

Entry points in vicinity: De la Roche, Missisquoi

De la Roche entry point
Stations available:

- De La Roche, à Saint-Armand, QC (2001-2015)

Entry points in vicinity: Aux Brochets, Missisquoi

Table 1: Details of watersheds and gauging stations, Lake Champlain

Entry point	Area (km²)	Portion of watershed (%)	Watercourse	Area (km²)	Portion of watershed (%)	ID	Station	St/Pr	Source	Area at station (km²)	Watershed ratio
Winooski	2965	16.0%	Winooski River	2828	95.4%	04290500	Winooski River At Essex Junction	VT	USGS	2704	1.05
			Laplate River	137	4.6%	04282795	Laplatte River At Shelburne Falls	VT	USGS	116	1.18
Missisquoi	2223	12.0%	Missisquoi	2223	100.0%	04294000	Missisquoi River At Swanton	VT	USGS	2202	1.01
						04293500	Missisquoi River Near East Berkshire	VT	USGS	1240	1.79
Aux Brochets	654	3.5%	Aux Brochets	654	100.0%	030424	Aux Brochets, À Notre-Dame-De-Stanbridge	QC	CEHQ	584	1.12
						030420	Aux Brochets 0.7Km Aval Du Ruisseau Groat	QC	CEHQ	404	1.62
						030420	Aux Brochets, à Bedford	QC	CEHQ	383	1.71
De la Roche	152	0.8%	De la Roche	152	100.0%	030425	De La Roche, À Saint-Armand	QC	CEHQ	73	2.08
Otter Creek	2856	15.4%	Otter Creek	2462	86.2%	04282500	Otter Creek At Middlebury	VT	USGS	1925	1.28
			Lewis Creek	185	6.5%	04282650	Lewis Creek At North Ferrisburg	VT	USGS	148	1.25
			Little Otter Creek	209	7.3%	04282780	Little Otter Creek At Ferrisburg	VT	USGS	200	1.05
Lamoille	1941	10.5%	Lamoille River	1909	98.4%	04292500	Lamoille River At East Georgia	VT	USGS	1777	1.07
			Stone Bridge Brook	32	1.6%	04292700	Stone Bridge Brook Near Georgia Plains	VT	USGS	22	1.45
Bouquet	742	4.0%	Bouquet River	712	96.0%	04276500	Bouquet River At Willsboro	NY	USGS	712	1.00
			Highland Forge Lake	30	4.0%	04276069	Highlands Forge Lake Outlet Near Willsboro	NY	USGS	28	1.07
Ausable	1687	9.1%	Ausable River	1323	78.4%	04275500	Ausable River Near Au Sable Forks	NY	USGS	1160	1.14
			Little Ausable River	189	11.2%	04273800	Little Ausable River Near Valcour	NY	USGS	176	1.07
			Salmon River	175	10.4%	04273700	Salmon River At South Plattsburgh	NY	USGS	160	1.09
Saranac	1575	8.5%	Saranac River	1575	100.0%	04273500	Saranac River At Plattsburgh	NY	USGS	1575	1.00
Chazy	908	4.9%	Great Chazy River	769	84.7%	04271500	Great Chazy River At Perry Mills	NY	USGS	640	1.20
			Little Chazy River	139	15.3%	04271815	Little Chazy River Near Chazy	NY	USGS	137	1.01
Mettawee	1155	6.2%	Mettawee River	1098	95.1%	04280450	Mettawee River At Middle Granville	NY	USGS	433	2.54
						04280350	Mettawee River Near Pawlet	VT	USGS	182	6.03
			Mill Brook	27	2.3%	04279040	Mill Brook at Putnam	NY	USGS	27	1.00
			Mount Hope Brook	30	2.6%	04279125	Mount Hope Brook at South Bay Near Whitehall	NY	USGS	30	1.00
Poultney	692	3.7%	Poultney River	692	100.0%	04280000	Poultney River Below Fair Haven	VT	USGS	484	1.43
LaChute	963	5.2%	La Chute River	702	72.9%	04279000	La Chute At Ticonderoga	NY	USGS	606	1.16
			Putnam Creek	160	16.6%	04276842	Putnam Creek East of Crown Point Center	NY	USGS	134	1.19
			Mill Brook	73	7.6%	04276770	Mill Brook at Port Henry	NY	USGS	70	1.04
			Hoisington Brook	28	2.9%	04276645	Hoisington Brook at Westport	NY	USGS	17	1.65
	18513	**100.0%**		**18513**							

Estimates of ungauged flows

For the remaining ungauged area of 2637 km², the mean ratio R_L was used to estimate the inflow. For modeling purposes, the result was distributed in proportion to the area of each watershed. The ungauged area is the difference between the known area of the Lake Champlain basin, i.e. 21,150 km² (Shanley and Denner 1999) and the total area of all the gauged watersheds, i.e. 18,513 km² (see table 1).

The results of our method of calculating the ungauged flows were compared to the results of the method used by the NOAA National Weather Service (NWS) with 2011-2014 data. Figure 1 shows the outcome of the comparison: on average, the difference between our method and the method used by the NOAA NWS with their Hydrologic Engineering Centers River Analysis System (HEC-RAS) model is 8.2%. This difference is largely due to the peak flood, where the NOAA NWS gives much greater values than Environment Canada (EC). For verification purposes, the gauged flows were added so as to have a single basis of comparison. Part of the difference may be due to the fact that the NOAA NWS includes the Aux Brochets and De la Roche Rivers in its estimate of ungauged flows, whereas we used data from the Centre d’expertise hydrique du Québec (CEHQ) stations located in these watersheds.

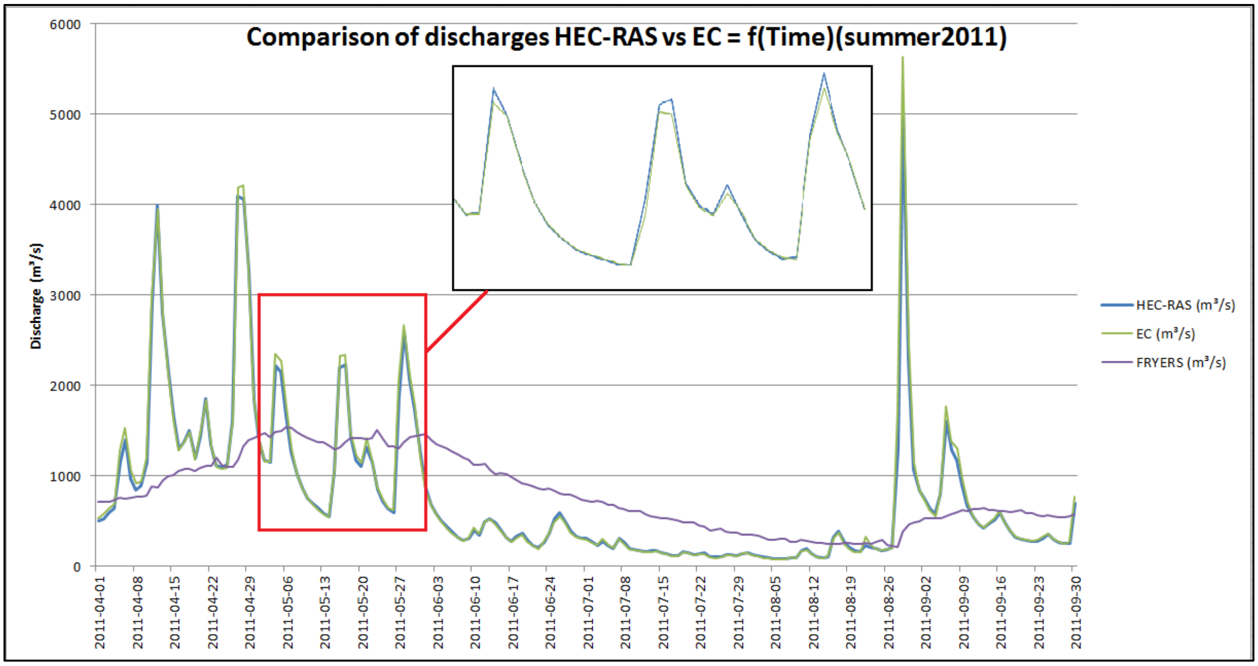

Figure 1: Comparison of methods for estimating daily inflows to Lake Champlain. The flow at Fryers Rapids has been added as a reference. May 2011 has been enlarged to give a better idea of the differences.

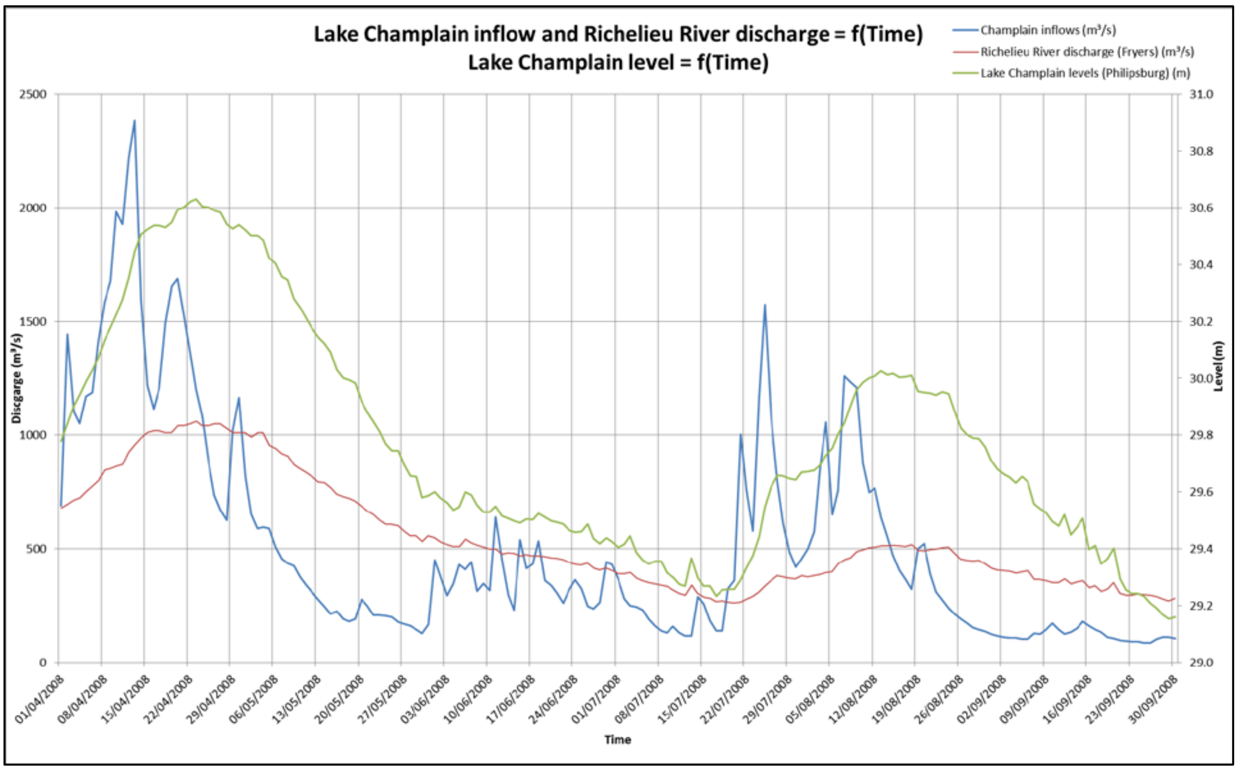

Figure 2: Influence of flows entering Lake Champlain on lake level. Spring-Summer 2008.

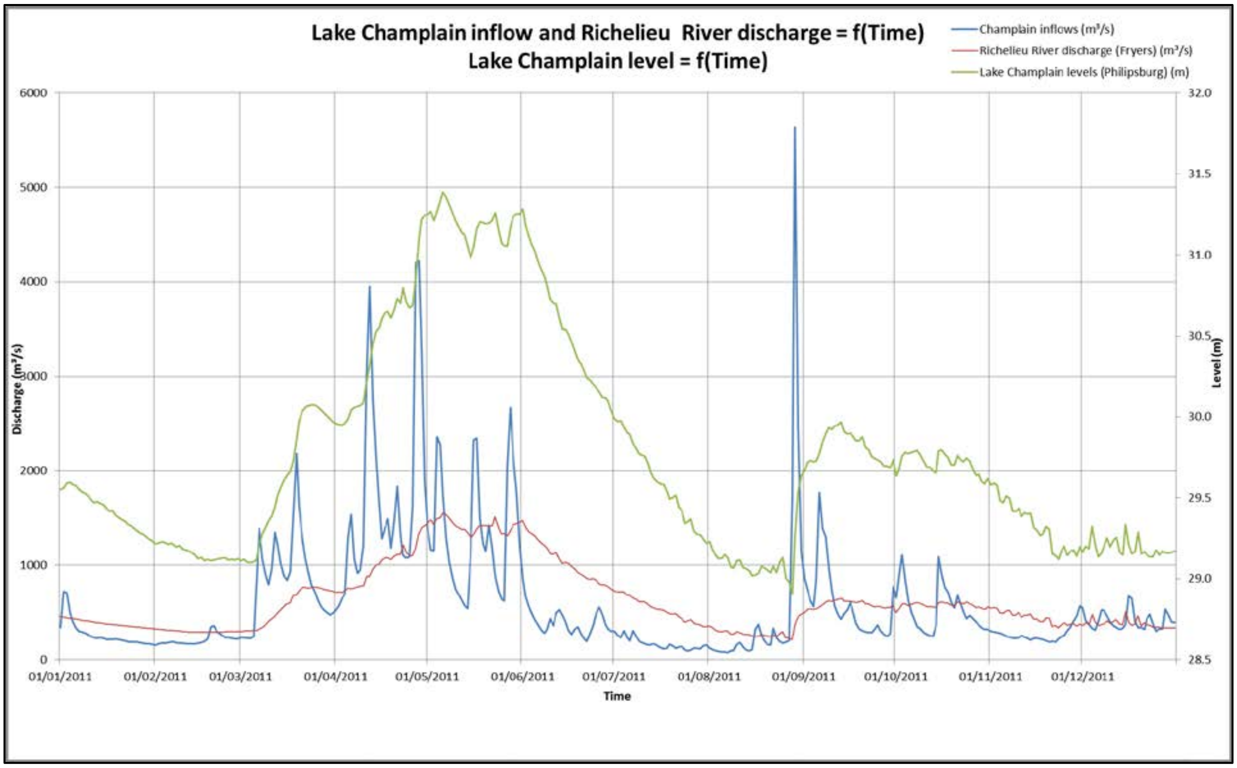

Figure 3: Influence of flows entering Lake Champlain on lake level. 2011.

Figure 2 and figure3 show the attenuating effect of the lake on the outflow from it. The inflow to Lake Champlain can sometimes be several times greater than the outflow. When the inflow is greater than the outflow, the lake level increases. The lake stores a volume of water which will be gradually released once the inflow drops below the outflow. The figures also show that the outflow from the lake depends on the lake level, as shown by the similarity of the two curves. The outflow from the lake is thus not directly related to the inflow at any given time.

Sample calculation (for Mettawee entry point, April 4, 2011):

This entry point brings in water from three tributaries: the Mettawee River, Mill Brook and Mount Hope Brook. There are two stations for the Mettawee River and one each for the other two tributaries. The Mill Brook and Mount Hope Brook stations have no data for the day in question. The calculation is made as follows:

For the Mettawee entry point, the only station available is the main station (Middle Granville), where:

$A_S = 433\ km^2$

$Q_S = 14.017\ m^3s^{-1}$

$R_S = 14.017 / 433 = 0.03237\ m^3s^{-1}km^{-2}$

For the Mettawee tributary:

$A_T = 1098\ km^2$

$Q_T = R_S \text{ X } A_T = 0.03237 \times 1098 = 35.54\ m^3s^{-1}$

$R_T = 35.54 / 1098 = 0.03237\ m^3s^{-1}km^{-2}$

And for the entry point (given that Middle Granville is the only station available):

$R_B = \Sigma Q_S / \Sigma A_S = 14.017 / 433 = 0.03237$ m³s^{-1}km^{-2}

For Mill Brook:

$A_T = 27$ km²

$Q_T = R_B \text{ X } A_T = 0.03237 \times 27 = 0.874$ m³s^{-1}

For Mount Hope Brook:

$A_T = 30$ km²

$Q_T = R_B \text{ X } A_T = 0.03237 \times 30 = 0.971$ m³s^{-1}

The total (not counting the distribution of the ungauged flows) is 37.385 m³s^{-1}

On the day in question, the ratio for the lake as a whole was:

$R_L = \Sigma Q_B / \Sigma A_B = 608 / 18513 = 0.03284$m³s^{-1}km^{-2}

Thus the total ungauged flow was:

$Q_{NJ} = R_L \times A_{NJ} = 0.03284$ m³s^{-1}km^{-2} x 2637 km² = 86.6 m³s^{-1}

The Mettawee entry point represents 1155 km² / 18513 km² = 6.2% of the area.

Thus the ungauged flow attributed to the Mettawee entry point was 86.6 x 6.2% = 5.4 m³s^{-1}

This yields a grand total for the day in question of 37.385 + 5.4 **= 42.785 m³s^{-1}**

2.2 Methodology for compiling water level data for Lake Champlain and the Richelieu River

Data were extracted for nine stations (see table 2) on Lake Champlain and the Richelieu River. Data from the U.S. stations were converted to the metric system. The Canadian data were based either on the Canadian Geodetic Vertical Datum of 1928 (CGVD28) for Lake Champlain and the Richelieu River, or on the International Great Lakes Datum of 1985 (IGLD85), for the St Lawrence River. The U.S. data were based on the National Geodetic Vertical Datum of 1929 (NGVD29). All the data were converted to the North American Vertical Datum of 1988 (NAVD88) using the Global Navigation Satellite System GPS surveys made by the USGS in April 2015. The Lake Champlain/ Richelieu River gauging stations are shown in figure 6.

Table 2: Lake level gauging stations on Lake Champlain and the Richelieu River

Station	ID	Source	Lat	Long	Conversion to NAVD88 (m)
Lake Champlain North Of Whitehall	04279085	USGS	43.621667	-73.418889	-0.08230
Lake Champlain at Port Henry	04294413	USGS	44.052500	-73.453333	-0.18715
Lake Champlain At Burlington	04294500	USGS	44.476111	-73.221944	-0.15850
Champlain (Lac) A Philipsburg	02OH001	EC	45.039722	-73.079722	-0.06401
Richelieu R (L Champlain) At Rouses Point	04295000	USGS	44.996111	-73.360278	-0.13106
Richelieu, À Saint-Paul-De-L'Île-Aux-Noix	030430	CEHQ	45.077222	-73.325556	-0.06401
Richelieu (Rivière) À Saint-Jean	02OJ001	EC	45.313333	-73.251667	-0.01829
Richelieu (Rivière) Amont Écluse St-Ours	02OJ018	CH	45.863055	-73.147777	0.03353
Saint-Laurent (Fleuve) A Sorel	02OJ022	FOC	46.046944	-73.116111	0.03353

Volume of water in Lake Champlain

Figure 4 shows the relationship between the level of Lake Champlain and the volume of water it contains. Overall, one centimetre in the level corresponds to an average of 11,000,000 m³ of water. To observe an increase in lake level of 1 cm, the difference between inflows and outflows would have to be about +125 m³/s over an entire day. The volume of water in the lake was calculated by adding the volumes over each bathymetry point (of the regular 10m grid).

For a level at Rouses Point between 27 and 29.1 m, the relationship between level and volume of water is represented by the following exponential equation:

$$V = 7\,817\,113\,182 * e^{0.04196*H} \qquad R^2 = 0.999965$$

Where

V Volume of water in m^3
H Level of Lake Champlain in m NVGD29

For a level at Rouses Point between 29.2 and 32 m, the relationship between level and volume of water is represented by the following polynomial equation:

$$V = 26\,752\,873 * H^2 - 445\,853\,397 * H + 16\,819\,451\,730 \qquad R^2 = 0.999971$$

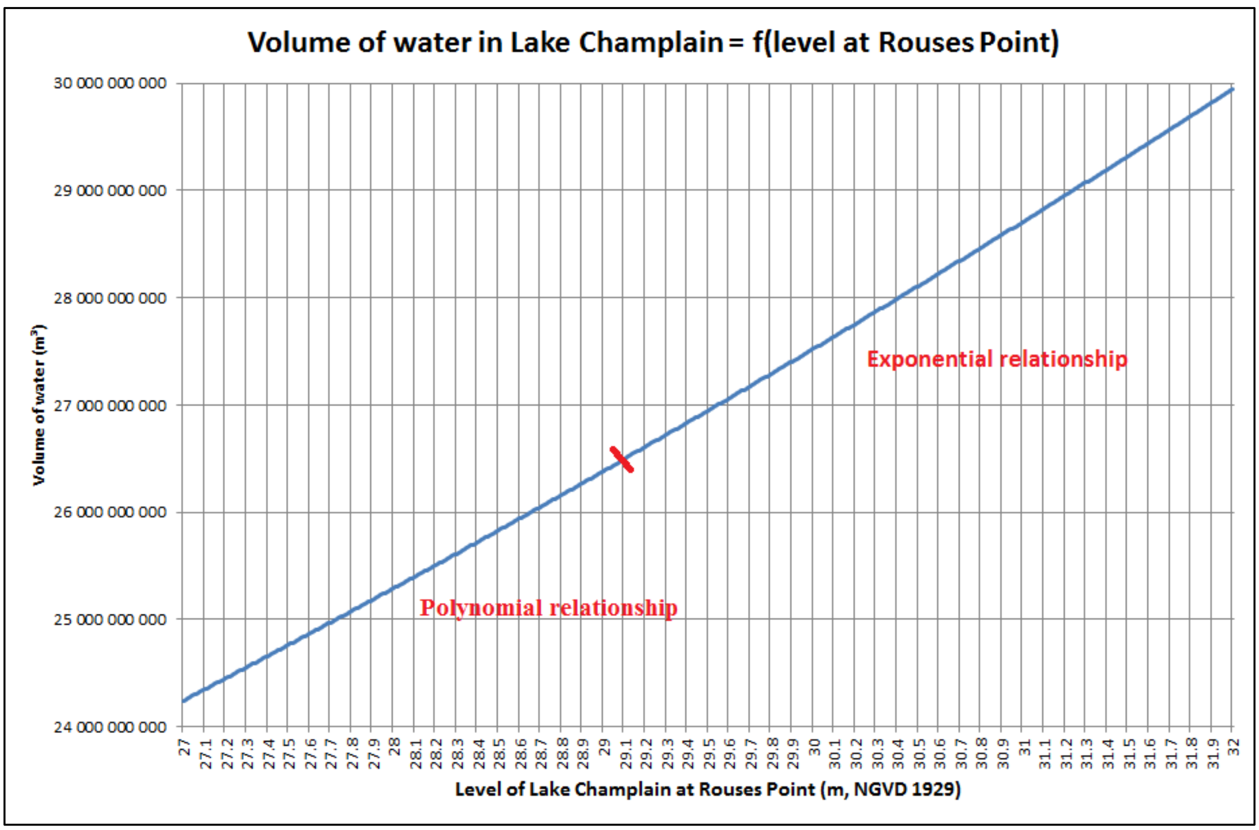

Figure 4: Volume of water in Lake Champlain in relation to the water level at Rouses Point based on NVGD29

Table 3: Volume of water (m³) in Lake Champlain in relation to the water level (m) at Rouses Point based on NVGD29

Level (m)	Volume (m³)	Level (m)	Volume (m³)
27.0	24,284,254,428	29.6	27,056,061,619
27.1	24,384,402,131	29.7	27,167,900,318
27.2	24,485,084,892	29.8	27,280,559,187
27.3	24,586,302,710	29.9	27,394,043,493
27.4	24,688,055,586	30.0	27,508,563,648
27.5	24,790,343,519	30.1	27,624,363,776
27.6	24,893,166,509	30.2	27,741,446,050
27.7	24,996,524,557	30.3	27,859,509,663
27.8	25,100,417,663	30.4	27,978,534,833
27.9	25,204,845,826	30.5	28,098,364,515
28.0	25,309,809,046	30.6	28,218,776,889
28.1	25,415,307,324	30.7	28,339,713,936
28.2	25,521,340,659	30.8	28,461,120,695
28.3	25,627,909,052	30.9	28,582,987,443
28.4	25,735,012,502	31.0	28,705,323,334
28.5	25,842,651,010	31.1	28,828,147,515
28.6	25,950,824,575	31.2	28,951,528,136
28.7	26,059,533,197	31.3	29,075,502,548
28.8	26,168,776,878	31.4	29,200,004,807
28.9	26,278,555,615	31.5	29,324,983,906
29.0	26,388,869,410	31.6	29,450,406,119
29.1	26,499,718,262	31.7	29,576,261,237
29.2	26,611,102,172	31.8	29,702,549,630
29.3	26,724,433,120	31.9	29,829,274,019
29.4	26,834,464,703	32.0	29,956,434,018
29.5	26,944,979,580		

2.3 Strategy for calculating flows in the Richelieu River

The Fryers Rapids station was used as a reference point for the flow in the Richelieu River. For comparison purposes, the Richelieu watershed flow occurring above the Rapids was added to the outflow from Lake Champlain. The watershed flow occurring downstream of the Rapids was then used to calculate the total outflow into the St Lawrence River. Table 4 and table 5 provide details on the stations and tributaries used for the calculations, as well as the estimating methods. The areas associated with the tributaries include the areas of nearby ungauged watersheds. Thus the total area of the Richelieu watershed from the border to the river's mouth is distributed over the tributaries that are included in the model. Figure 7 shows the model's stations and tributaries.

Above Fryers Rapids
Stations available:
None. Flows in ungauged watercourses were estimated from data for the following stations:

- Des Hurons (Rivière) En Aval Du Ruisseau Saint-Louis (CEHQ 030415)

- L'Acadie (Rivière) Près De L'Autoroute No. 10 (CEHQ 030421)
- Noire (Rivière), à 7,6km de la rivière Yamaska (CEHQ 030304)

Flows were estimated for the following rivers:

- Rivière des Iroquois (Saint-Jean-sur-Richelieu)
- Rivière du Sud (Henryville)
- Rivière Lacolle (Lacolle)

Fryers Rapids

The flow at Fryers Rapids is the reference flow for the model.
Stations available:

- Richelieu (Rivière) Aux Rapides Fryers (EC 02OJ007)

Below Fryers Rapids

Stations available:

- Des Hurons (River) En Aval Du Ruisseau Saint-Louis
- L'Acadie (River) Près De L'Autoroute No. 10

Flows in ungauged watercourses were estimated in the same way as those upstream:

- Ruisseau Laplante (Saint-Ours; Pierre-De Saurel)
- Ruisseau Coderre (Saint-Antoine-sur-Richelieu)
- Rivière Amyot (Saint-Charles-sur-Richelieu)
- Ruisseau Beloeil (Saint-Marc-sur-Richelieu)

Special cases: When data from the Des Hurons and L'Acadie stations were not available, data from the Noire station was used to estimate flows.

Table 4: Principal tributaries of the Richelieu River

Watercourse	Location	Watershed area (km²)	Zone	ID	Station	Station area (km²)	Source
Rivière des Iroquois	Saint-Jean-sur-Richelieu	381.6	Above Fryers	-			
Rivière du Sud	Henryville	210.1	Above Fryers	-			
Rivière Lacolle	Lacolle	163.6	Above Fryers	-			
Rivière Richelieu	Fryers Rapids		Fryers				EC
Ruisseau Laplante	Saint-Ours; Pierre-De Saurel	292.7	Below Fryers	-			
Ruisseau Coderre	Saint-Antoine-sur-Richelieu	91.48	Below Fryers	-			
Rivière Amyot	Saint-Charles-sur-Richelieu	152	Below Fryers	-			
Ruisseau Beloeil	Saint-Marc-sur-Richelieu	216.9	Below Fryers	-			
Rivière l'Acadie	Saint-Jean-sur-Richelieu	561.3	Below Fryers	030421	L'Acadie	345	CEHQ
Rivières des Hurons	Saint-Mathias-sur-Richelieu	403.5	Below Fryers	030415	Des Hurons	309	CEHQ
Rivière Noire	Saint-Pie		-	030304	Noire	1505	CEHQ

Table 5: Ratios used for ungauged tributaries and for cases of missing data

Watercourse	Estimate1	Ratio	Estimate2	Ratio	Estimate3	Ratio	Lat	Long
Rivière des Iroquois	Des Hurons	1.2350	L'Acadie	1.1061	Noire	0.2536	45.359440	-73.268890
Rivière du Sud	Des Hurons	0.6799	L'Acadie	0.6090	Noire	0.1396	45.136111	-73.252222
Rivière Lacolle	Des Hurons	0.5294	L'Acadie	0.4742	Noire	0.1087	45.066667	-73.331667
Rivière Richelieu							45.398333	-73.258889
Ruisseau Laplante	Des Hurons	0.9472	L'Acadie	0.8484	Noire	0.1945	45.834722	-73.137222
Ruisseau Coderre	Des Hurons	0.2961	L'Acadie	0.2652	Noire	0.0608	45.731667	-73.194167
Rivière Amyot	Des Hurons	0.4919	L'Acadie	0.4406	Noire	0.1010	45.709167	-73.188611
Ruisseau Beloeil	Des Hurons	0.7019	L'Acadie	0.6287	Noire	0.1441	45.645278	-73.207500
Rivière l'Acadie	L'Acadie	1.6270	Des Hurons	1.8165	Noire	0.3730	45.389722	-73.370833
Rivières des Hurons	Des Hurons	1.3058	L'Acadie	1.1696	Noire	0.2681	45.490278	-73.186944
Rivière Noire								

2.4 Comparison of inflow to Lake Champlain and flow measured at Fryers Rapids

From a theoretical point of view, the following equation applies for a given time-step:

Volume of water entering the lake + Volume of water entering the Richelieu above Fryers Rapids + over lake Precipitation – over lake Evaporation + Variation in the volume of the lake – Volume of water measured at Fryers Rapids = 0

To compare the inflow to the lake with the flow at Fryers Rapids, the flow entering the Richelieu above Fryers Rapids must be added to the flow entering the lake. Three watercourses were used to calculate the former: Rivière des Iroquois, Rivière du Sud and Rivière Lacolle. Since there are no stations on any of these rivers, their flows were estimated from data on the Des Hurons, L'Acadie and Noire rivers.

To take into account variation in the lake volume, the average of the water level data from available lake stations was used.

Figure 5 shows the annually calculated volumes. The annual inflow is the sum of the daily volumes entering the lake (see section 2.1 Methodology for calculating inflows to Lake Champlain), the daily volumes above Fryers Rapids (see section 2.3 Methodology for compiling water level data for Lake Champlain and the Richelieu River) and the annual variation in the lake level, while the annual outflow is the sum of the daily volumes at Fryers Rapids. Daily volumes are calculated from average daily flows.

Over the period 1970 to 2014, the calculated volume entering the lake was on average 5.33% greater than the volume measured at Fryers Rapids. To complete the water balance it would be necessary to consider precipitation over the lake and evaporation from it. In view of the uncertainty in the calculation of flows from ungauged areas, the uncertainty of flow measurements at Fryers Rapids and at the other stations in the basin, and the exclusion of precipitation and evaporation affecting the lake, the figure of 5.33% is quite acceptable.

To carry out simulations of historical events, inflows will be corrected on the basis of flows at Fryers Rapids as well as the observed variation in lake level, so that zero mass balance is achieved. The effects of precipitation and evaporation will thus be captured indirectly via the model's imposed inflows. Precipitation and evaporation cannot be introduced directly with this model.

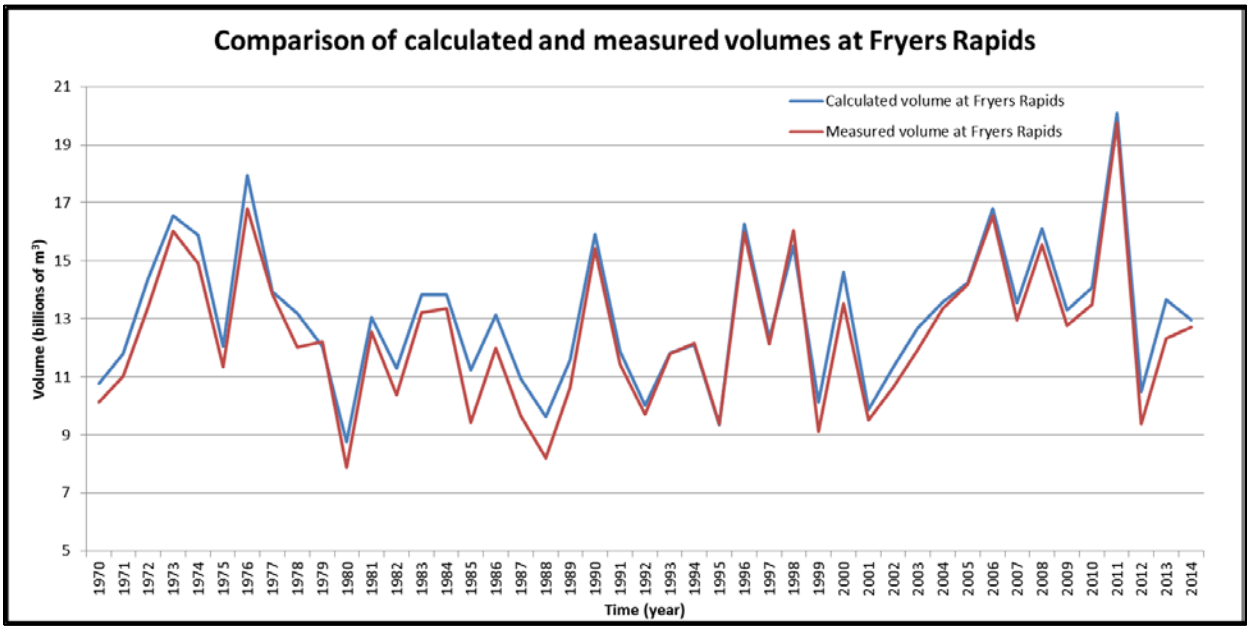

Figure 5: Volume entering and exiting Lake Champlain by year

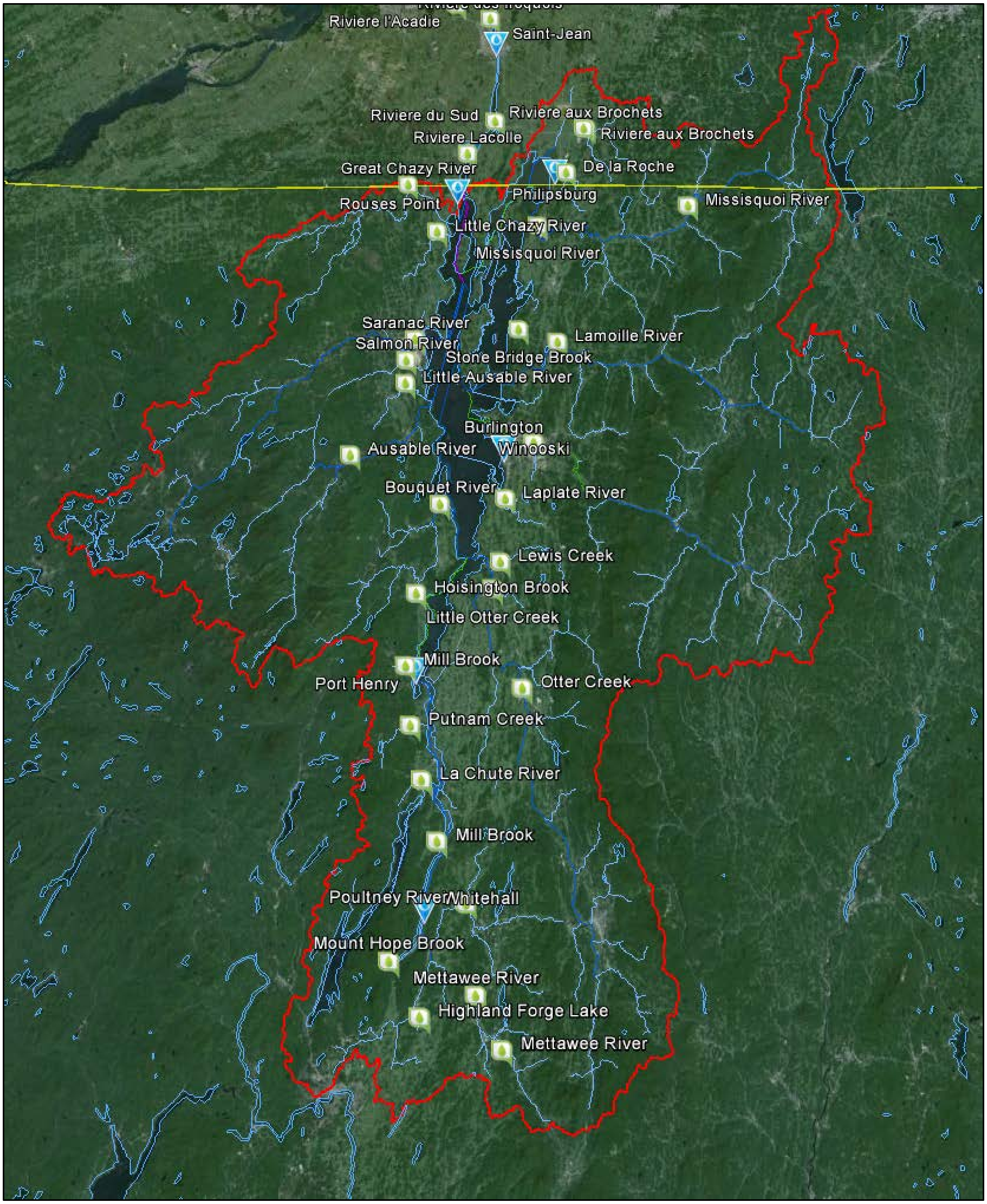

Figure 6: Location of stations in Lake Champlain basin and on the Richelieu River

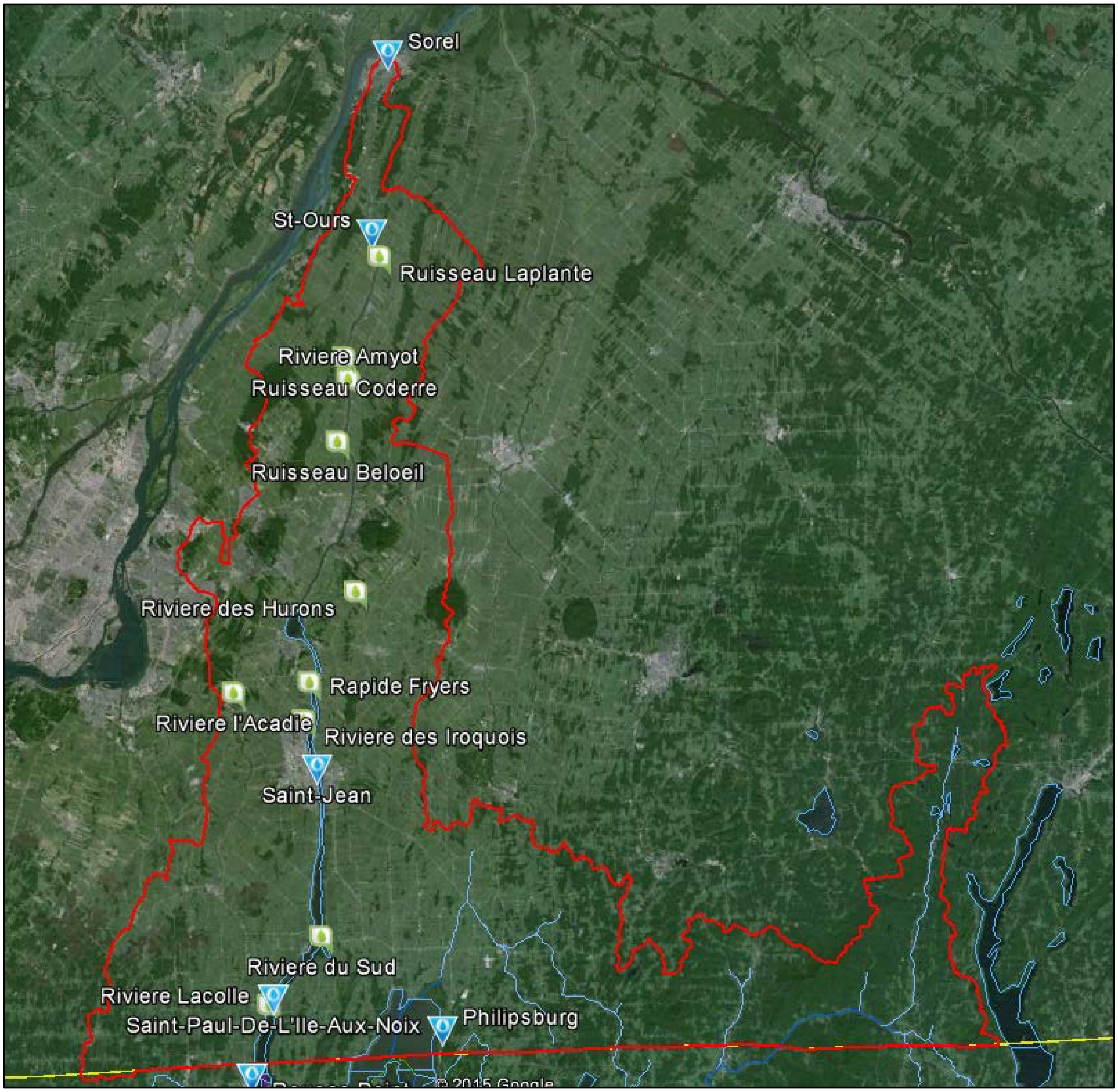

Figure 7: Location of stations and tributaries, Richelieu River Basin

3. Incorporation of terrain data under a single vertical datum

Background

The vertical datums for the model area are the new Canadian vertical datum CGVD2013, the old Canadian vertical datum CGVD28, the old American vertical datum NGVD29 and the current American datum NAVD88. All these vertical references may be taken to be orthometric heights, i.e. elevations above mean sea level. Unfortunately, the different datums do not use the same definition of mean sea level, or the same technique for estimating orthometric height. As a result, all the heights in the datasets had to be converted to a homogenous dataset based on a single datum. The Working Group decided that either NAVD88 or CGVD2013 would be used for the project. NAVD88 was chosen because the information for transforming the gauging station data was initially provided for NAVD88.

Methodology

Mapping, whether paper-based or digital, requires representing the Earth on a plane surface. Since the planet's real shape is too complicated, it has to be reduced to a rotation ellipsoid—a sort of sphere slightly flattened at the northern and southern extremities. The reduction causes the details of the Earth's surface geography to disappear. At one time, the only way to obtain mean sea level heights was conventional levelling based on a location with known orthometric height. This limited the ability to measure orthometric heights because heights were known only at certain locations and not very precisely or accurately.

Nowadays, however, results can be obtained through high-precision mapping using a Global Navigation Satellite System, the best known of which is GPS. This approach can be combined with levelling by taking a GNSS observation as a point with known orthometric height. When a point to be observed is not in a suitable location for a GNSS antenna, the antenna is moved to a suitable site, which is then used for the levelling.

The GNSS positions an observed point on the ellipsoid rather than on the actual surface of the Earth, and as a result the topography is expressed in terms of ellipsoidal height rather than orthometric height. An ellipsoidal height can be converted to an orthometric height using a geoid model. The difference between the ellipsoid and the geoid, known as the geoid undulation, is known for given geographical coordinates (see figure 8).

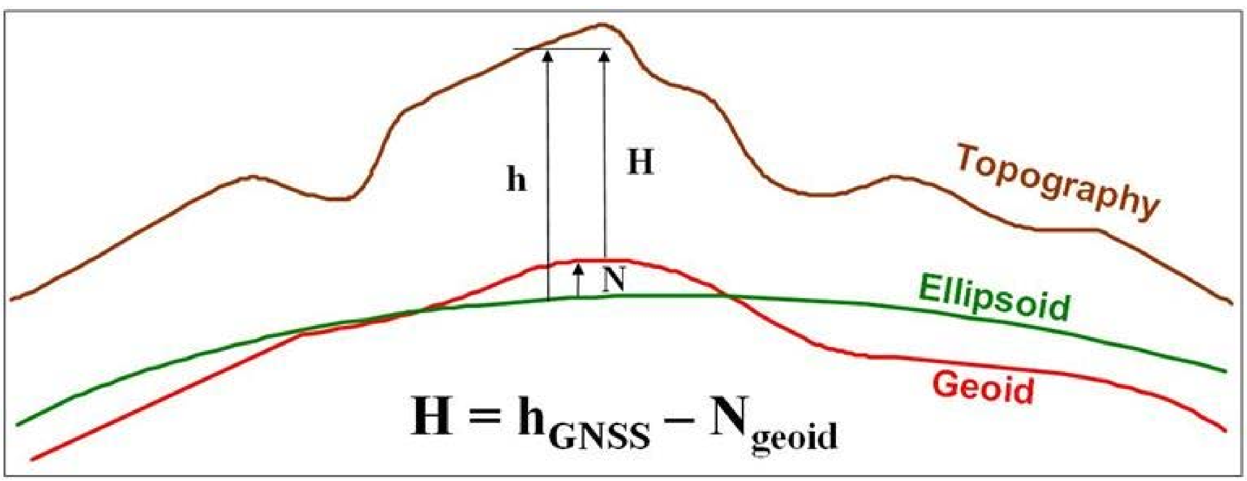

Figure 8: Orthometric height (H), ellipsoidal height (h) and geoid undulation (N)

Source: Department of Natural Resources Canada

NAVD88 uses a hybrid geoid model, GEOID12A, with which the required values for the Richelieu area can be obtained. An online application giving the geoid undulation values for chosen points is available at the USGS site (http://www.ngs.noaa.gov/cgibin/GEOID_STUFF/geoid12A_prompt1.prl). Another application converts data from NGVD29 to NAVD88 (http://www.ngs.noaa.gov/PC_PROD/VERTCON/). The same hybrid geoid model has been developed in Canada for CGVD28 (HTv2) and CGVD2013 (CGG2013).

To convert topometric data for the study area, we established a regular grid with a spatial resolution of 1 arc minute (a little less than 1 km) covering the entire simulated area, and the geoid (or hybrid geoid) undulation was obtained for each vertical datum. Then the geoid undulation for each point was compared with the GEOID12A undulation. The difference is the difference in height between NAVD88 and the other datums (CGVD28 and NGVD29), i.e. the value for the conversion (see figure9 and figure 10).

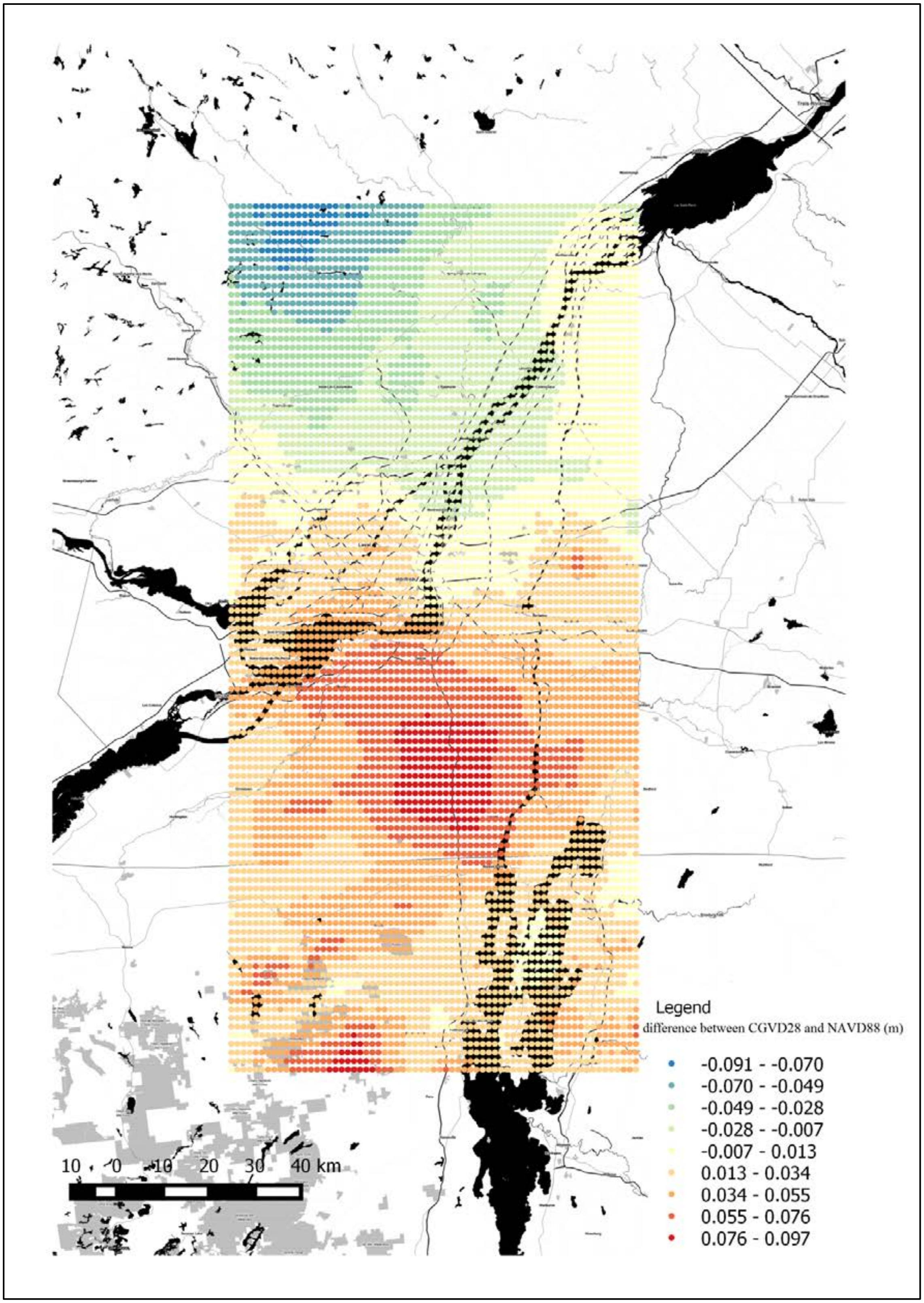

Figure 9: Grid for converting CGVD28 to NAVD88

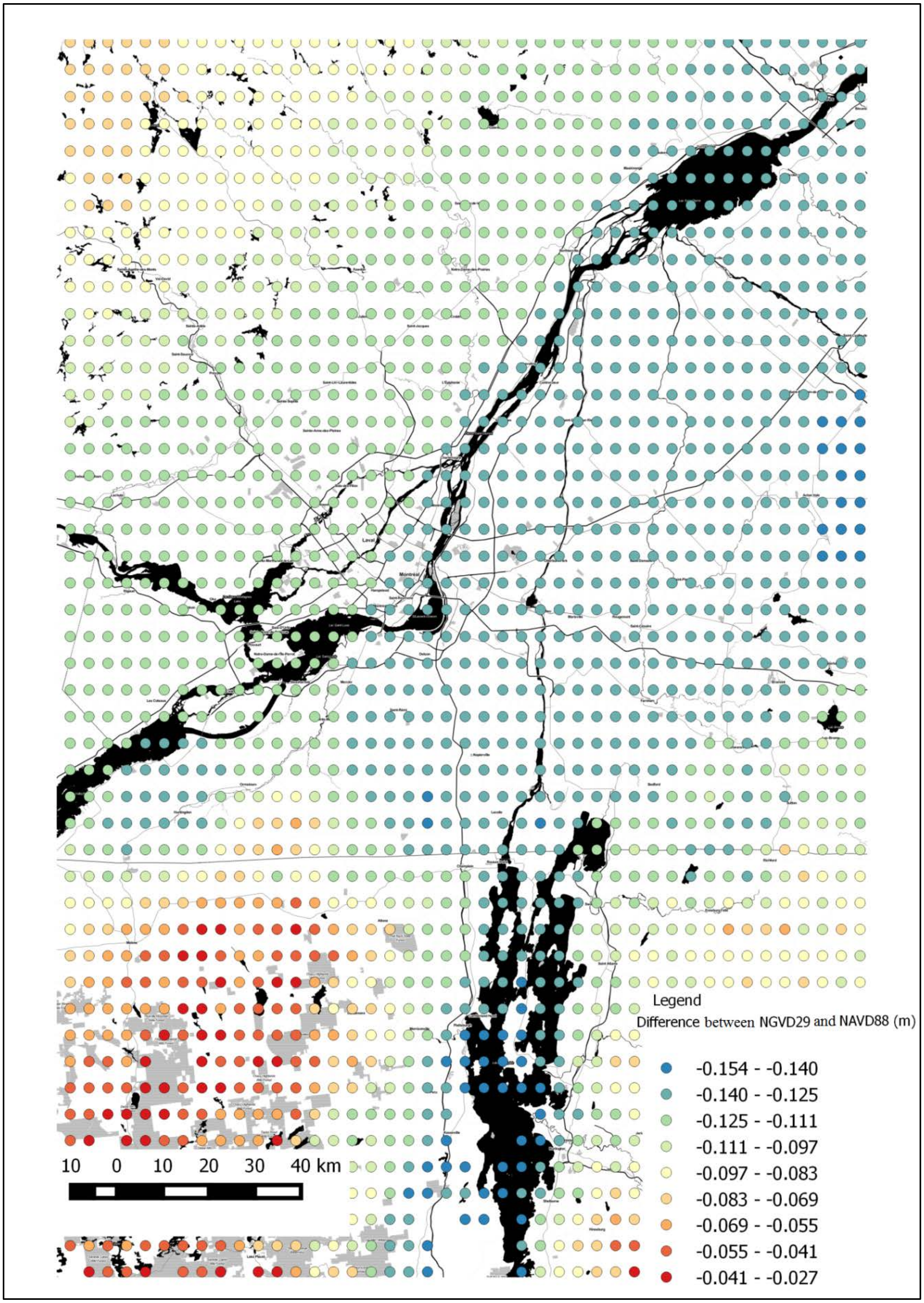

Figure 10: Grid for converting NGVD29 to NAVD88

To convert station water levels, the USGS undertook a GNSS survey, which enabled use of the above-mentioned combination method (high-precision measurement of the ellipsoidal heights of known points in the gauging network, along with conventional leveling based on those points). The results were checked by Natural Resources Canada and by the USGS, and for most points (see appended table), the difference between the Canadian and American results was less than 2 cm. This outcome was expected in view of the number of satellites involved and the duration of the observations. However the quality of the observations is questionable for two stations: Saint-Paul and Chambly. Here the difference between the Canadian and American results was greater than 2 cm, probably because of poor signal reception on the ground. When the Canadian team noticed the problem, they recommended redoing the surveys so as to improve quality in the future. Once again, the geoid undulation gives us all water levels based on the NAVD88 datum at the observation points; it is then simply a matter of applying conventional levelling values.

Hybrid geoid models are constrained at locations where benchmarks are available, and as a result a model may be of varying quality over a given region depending on the quality and quantity of points on which the model was based. Shortcomings will only be noticed with the assistance of high-precision measurements. To check the quality of the hybrid models, station water level values obtained using GNSS observations were compared with the values obtainable online for the various models at the sites' geographical coordinates. The differences ranged between 0 and 3 cm at all stations except Whitehall (see table 6). The difference at Whitehall can be explained by an adjustment to the station level in the metadata; it does fall within the range of precision of a conventional LiDAR survey. The comparison confirms that using the differences among hybrid geoid models as a way of converting topographical values near the stations yields a satisfactory conversion value with a precision of between 0 and 3 cm, which is within the range of precision of the LiDAR survey that was used to develop the terrain model.

Table 6: 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 (SI)	Conversion to NAVD88 using GNSS observations (SI)	Difference(SI)
Rouses Point	-0.1380744	-0.1313688	0.0067056
Burlington	-0.1469136	-0.1594104	-0.0124968
Whitehall	-0.1560576	-0.0816864	0.0743712
Philipsburg	-0.055	-0.064008	-0.009008
Saint-Paul-de-L'Ile-aux-Noix	-0.085	-0.064008	0.020992
Saint-Jean-Sur-Richelieu	-0.042	-0.018288	0.023712
Sorel	0.004	0.033528	0.029528
Barrage Chambly	-0.007	0.024384	0.031384
Saint-Ours	0.014	0.033528	0.019528

Note that the same conversion method, but using CGG2013 instead of GEOID12A, will convert data to CGVD2013 if necessary.

4. Digital elevation model

Available elevation datasets

Several datasets were available to construct the digital elevation model (DEM) for Lake Champlain and the Richelieu River. However, there was a problem of heterogeneity of horizontal and vertical spatial resolutions and of vertical datums from one dataset to another (see table 7). The problem was greater on the American side, where a great variety of datasets were available. The datasets in italics on table 7 are those for which the vertical datum was changed to the North American Vertical Datum of 1988 (NAVD88).

Table 7: Bathymetric and topometric datasets used

Name	Source	Horizontal resolution	Vertical datum
National Elevation Dataset	USGS	10 m	NAVD88
Manley Bathymetry		regular 10 m grid	Depth with zero set at 93 feet (lake reference level)
NOAA Bathymetry	NOAA	Bathymetry point cloud	Depth with zero set at 93 feet (lake reference level)
Addison		LiDAR point cloud (multiple points per metre)	NAVD88
Grande Isle		LiDAR point cloud (multiple points per metre)	NAVD88
Rock River		LiDAR point cloud (multiple points per metre)	NAVD88
Chittenden		LiDAR point cloud (multiple points per metre)	NAVD88
CEHQ LiDAR		LiDAR point cloud (multiple points per metre)	CGVD28
CHS	CHS	Bathymetry point cloud for Richelieu River	Chart datum
MSC	MSC-HOE	Bathymetry point cloud for Richelieu River	CGVD28
GENIVAR	GENIVAR	Bathymetry point cloud for Richelieu River	CGVD28

Figure 11 shows the spatial distribution of the datasets used.

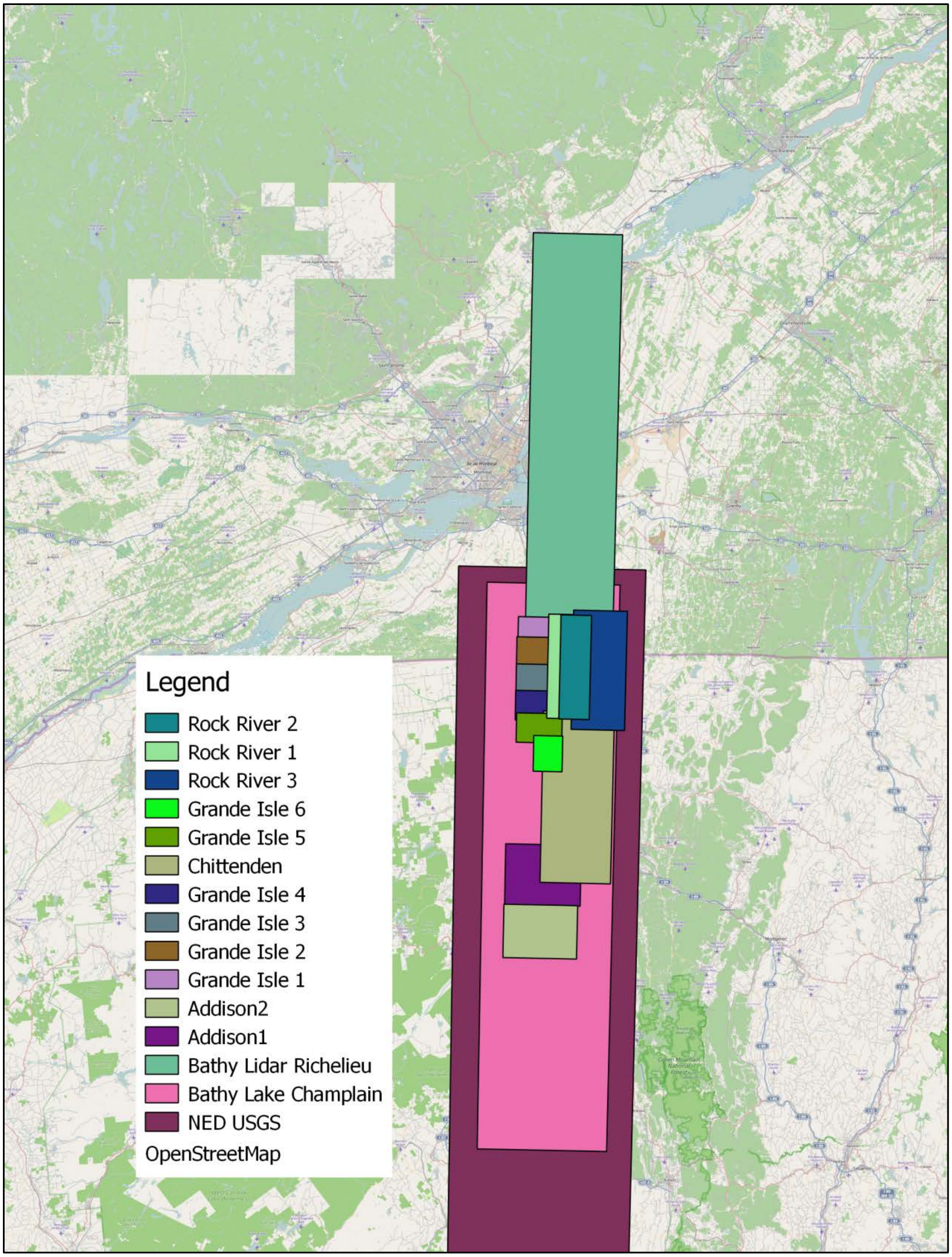

Figure 11: Spatial distribution of datasets used to assemble the DEM

Transformation of vertical datums

The vertical datum for the final DEM was NAVD88. Consequently some of the datasets had to undergo transformation. Details of the different transformations, depending on the dataset in question, are set out below.

Middlebury College and NOAA bathymetry

The Middlebury College bathymetry data (Manley, T.O., P.L. Manley and G.B. Fisher, (2005)) are actually depths with zero set at the lake's reference level of 93 feet (no datum involved). Since the water level data from the lake's gauging stations were based on NGVD29, it was concluded that the reference level of 93 feet was also based on that datum. As for the data from the National Oceanic and Atmospheric Administration, the hydrographic charts bear the words: "plane of reference of this chart (Low Water Datum) 93 ft. Referred to mean water level at Rimouski, Quebec. International Great Lakes Datum (1985)".

The NOAA data set used was the ElevationDEM_LKCHDEM, 2010 download from the Vermont Center for Geographic Information (VCGI). This data layer includes all bathymetric points from the RF 40,000 scale NOAA charts for Lake Champlain. For Mallets Bay north and for the Crown Point bridge south, the Vermont Center for Geographic Information added data for these missing areas in 2003 by taking points from the Lake Champlain Basin Program (LCBP) data bundle (LAKEBATH). VCGI also replaced the shoreline points in 2010 using the shoreline as defined in the VHDCARTO dataset.

Both of these datasets underwent the same two transformations. First, imperial units were converted to metric units by applying the following equation:

$$1)\ \ Depth\ (m) = Depth\ (ft) * 0.3048$$

The depth data in metres were turned into elevation values. For this purpose, the 93 feet was first converted to metres in the above manner. The resulting elevation value was 28.3464 m (NGVD29). For each depth in the dataset, an NGVD29 elevation was then obtained by subtraction. For example, a depth of 1 m became an elevation of 27.3464 m (NGVD29).

Finally, the NGVD29 value was turned into an NAVD88 value, by applying the appropriate conversion grid (see figure 10).

CHS bathymetry

The data from the Canadian Hydrographic Service cover the navigable portion of the Richelieu between the entrance to the Chambly Canal and Lake Champlain. The data are expressed as depths in relation to the chart datum, which is constant for this portion of the river, with a value of 28.35 m. See table 8 for the chart datum values.

Table 8: Chart datum values in upstream portion of Richelieu River

Station number	Station name	Chart datum (MSL (m))
15905	Cantic	28.350
15910	Saint-Paul-de l'Ile-aux-Noix	28.349
15913	Saint-Jean-sur-le-Richelieu	28.350

The CHS depth data were subtracted from 28.35 to obtain elevation values based on CGVD28.

For the remaining datasets, i.e. CEHQ LiDAR, CHS, MSC (Meteorological Service of Canada) and GENIVAR, the only transformation was conversion between CGVD28 and NAVD88, using the conversion grid for these two datums.

Regular grid
The final DEM used for the hydrodynamic simulations is supported by a regular grid with a spatial resolution of 10 metres. The grid was developed by GIS geoprocessing.

Sampling of datasets at model points
The next step was to sample available datasets near the model points of the regular grid. For example, in areas where LiDAR data was available, as in some counties in Vermont, the USGS National Elevation Dataset was also available. In these cases, two or more values were thus available for a grid point on the final DEM. The procedure was carried out using the Point Sampling Tool plug-in of QGIS.

Assembly of elevation data at grid points based on dataset priorities
Once the available datasets had been sampled for all grid points, a final filter was used to yield a single elevation value for each grid point. The filter sets priorities for which dataset to use. To use the preceding example, where both a LiDAR value and a NED value were available, priority was given to the LiDAR value. For most of the grid points, only one dataset was available.
The final DEM was developed in this way by programming. The following table lists the datasets by order of priority.

Table 9: Priority of datasets for assembling the DEM

Dataset	Priority
Lake Champlain bathymetry	1
Richelieu River bathymetry	2
CEHQ LiDAR	3
Rock River LiDAR	4
Addison LiDAR	5
Grande Isle LiDAR	6
Chittenden LiDAR	7
USGS NED	8

5. 2D model of Lake Champlain

System hydrology
See section 2 above.

Bathymetry and topography
The bathymetry and topography were assembled on the hydrodynamic mesh using the digital elevation model described in section 4 above.

Substrate and friction
The friction value used to develop a hydrodynamic model is usually spatially variable and inferred from substrate samples. However in this case, no substrate data were available to produce friction maps.

The Manning coefficient was used to capture the roughness of the river. This coefficient is used in equations to generate a value for friction acting on the flow. An increase in the coefficient yields a slower flow and a higher water level. Adjusting the coefficient for a reach of the river enables model calibration. A uniform coefficient of 0.02 was initially applied over the entire model area. When the model was calibrated, the values were adjusted to fit the water levels.

Hydrodynamic model
The hydrodynamic modeling was carried out with the H2D2 software developed at INRS-Eau (now INRS-ÉTÉ), with the assistance of Environment Canada. This involves 2D digital modeling of long-wave equations, also known as shallow-water equations, which are solved by the finite element method. The model uses the conservative form of the mass and momentum conservation equations and takes into account local friction parameters due to substrates, aquatic vegetation and ice. The outputs are the (x, y) components of the mean (vertically integrated) velocity at all nodes. The entire domain of the simulation is thus described either directly at the nodes or by interpolation between the nodes. The model takes covering and uncovering (wetting and drying) of the banks into account, based on water flow and level. The equations are shown in figure 12.

Conservation of mass equation

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0$$

Conservation of momentum equation

$$\frac{\partial}{\partial x}\left(\frac{q_x q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{H}\right) + c^2 \frac{\partial h}{\partial x} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx}) + \frac{\partial}{\partial y}(H\tau_{xy}) - \tau_x^b - \tau_x^s\right) - f_c q_y = 0$$

$$\frac{\partial}{\partial x}\left(\frac{q_y q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_y q_y}{H}\right) + c^2 \frac{\partial h}{\partial y} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx}) + \frac{\partial}{\partial y}(H\tau_{yy}) - \tau_y^b - \tau_y^s\right) + f_c q_x = 0$$

$\boldsymbol{x}(x,y)$ = coordinates (x to the east, y to the north)
q_x , q_y = specific discharge in the x and y directions (m^3/s)
h = water height (level)
H = water column depth ($=h-z_f$) (m)
c = wave velocity ($c = \sqrt{gH}$) (m/s)
r = water density (10^3 $kg/m)^3$
$\boldsymbol{u}(u,v)$ = component of velocity (m/s) where:
$u = q_x /H$ (m/s)
$v = q_y /H$ (m/s)

f_c = Coriolis force ($f_c=2\omega\sin\phi$) (s^{-1})
τ_{ij} = Reynolds stresses (kg/s^2m)
τ_x^b , τ_y^b = bottom friction in x and y directions (kg/s^2m)
τ_x^s , τ_y^s = surface friction in x and y directions (kg/s^2m)

Figure 12: Shallow water equations (conservative form) for permanent regime solved with H2D2 finite element software

Finite element mesh

The reach being simulated is divided into triangular elements that form the "mesh" or "finite element grid". The shape and size of the elements can be modified to represent the shape and complexity of the terrain, the substrate, aquatic vegetation and any other variable. The more complex the terrain, the finer the mesh, and the greater the number of elements. However a mesh with too many elements can result in excessive calculation time. One objective of the modeller is to optimize the mesh based on requirements for precision as well as the calculation time on available computers.

Discretization

The terrain model data are incorporated in the model using the finite element method. The elements are triangles with six nodes (P1-iso-P2 interpolation), all of which are involved in calculating the mean velocities. The nodes provide information on friction and topography. The topography and water level are provided by the 3 top nodes; linear interpolation yields these variables for any element.

Mesh covering Lake Champlain and Richelieu River

The mesh covers the Richelieu River, from the Fryers Rapids station, as well as Lake Champlain as far as the Whitehall locks in New York State. The location of the downstream limit allows correct modeling of the Saint-Jean-sur-Richelieu sill, which controls the level of water in the lake. The mesh contains 305,155 nodes and 148,191 elements. The size of the elements varies from a few metres, in certain areas where a large amount of detail is required, to 700 metres at the centre of Lake Champlain, where there is a lesser requirement for detail. Special attention was paid to certain physical and structural features in both the river and the lake.

Some parts of the bathymetry of the river were captured in greater detail in the mesh, such as the Saint-Jean-sur-Richelieu sill and the various narrows that control flow during periods of heavy inundation of the floodplain north of Missisquoi Bay. For both the river and the lake, the mesh covers the range of very high water levels that may arise.

A number of man-made structures significantly restrict flow in the river and the lake. Pillars of bridges over the Richelieu as well as the numerous causeways across the bays of Lake Champlain were discretized in detail. Figures 13, 14 and 15 show details near some of the structures in question.

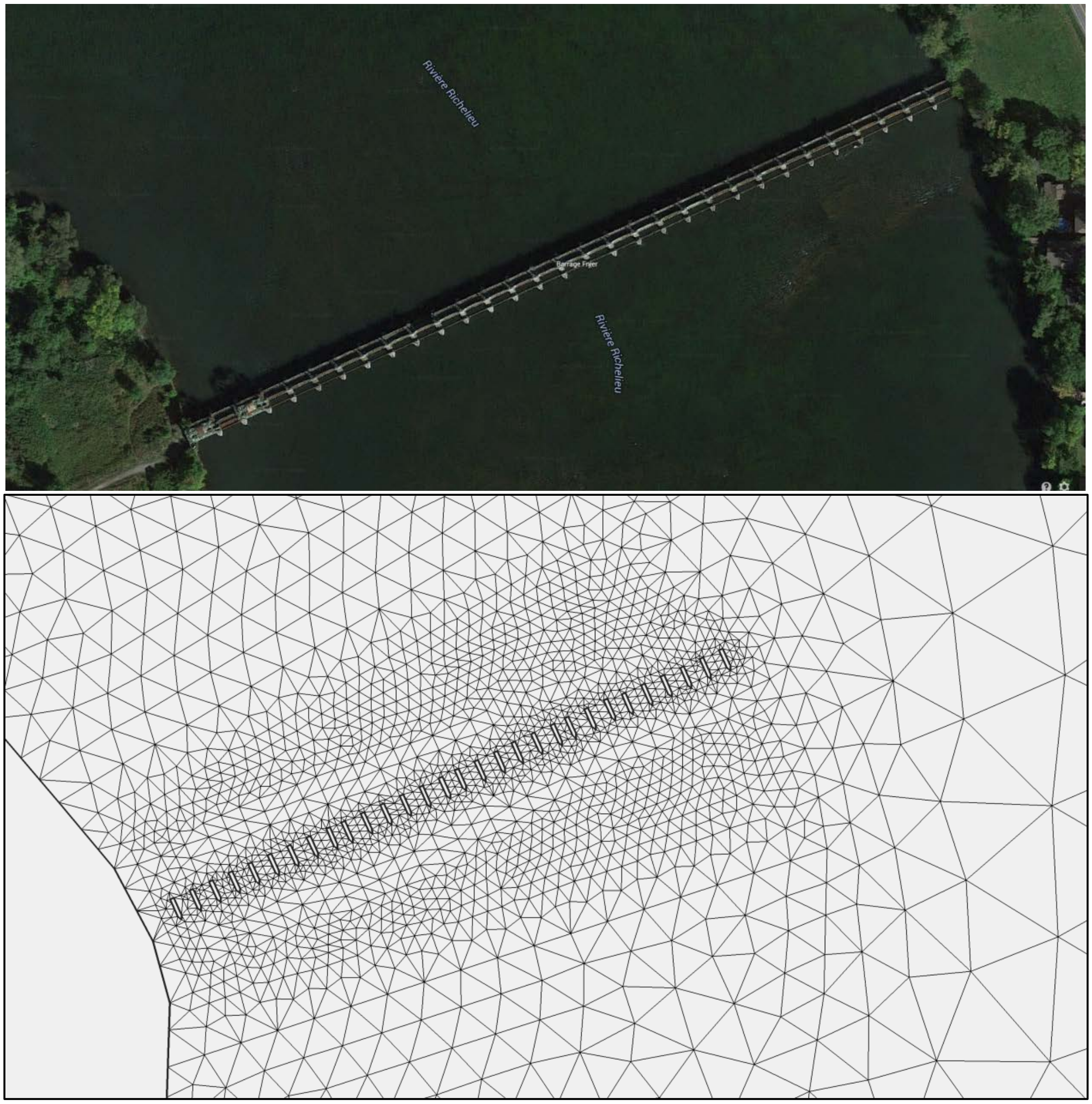

Figure 13: Fryer Dam and the corresponding mesh

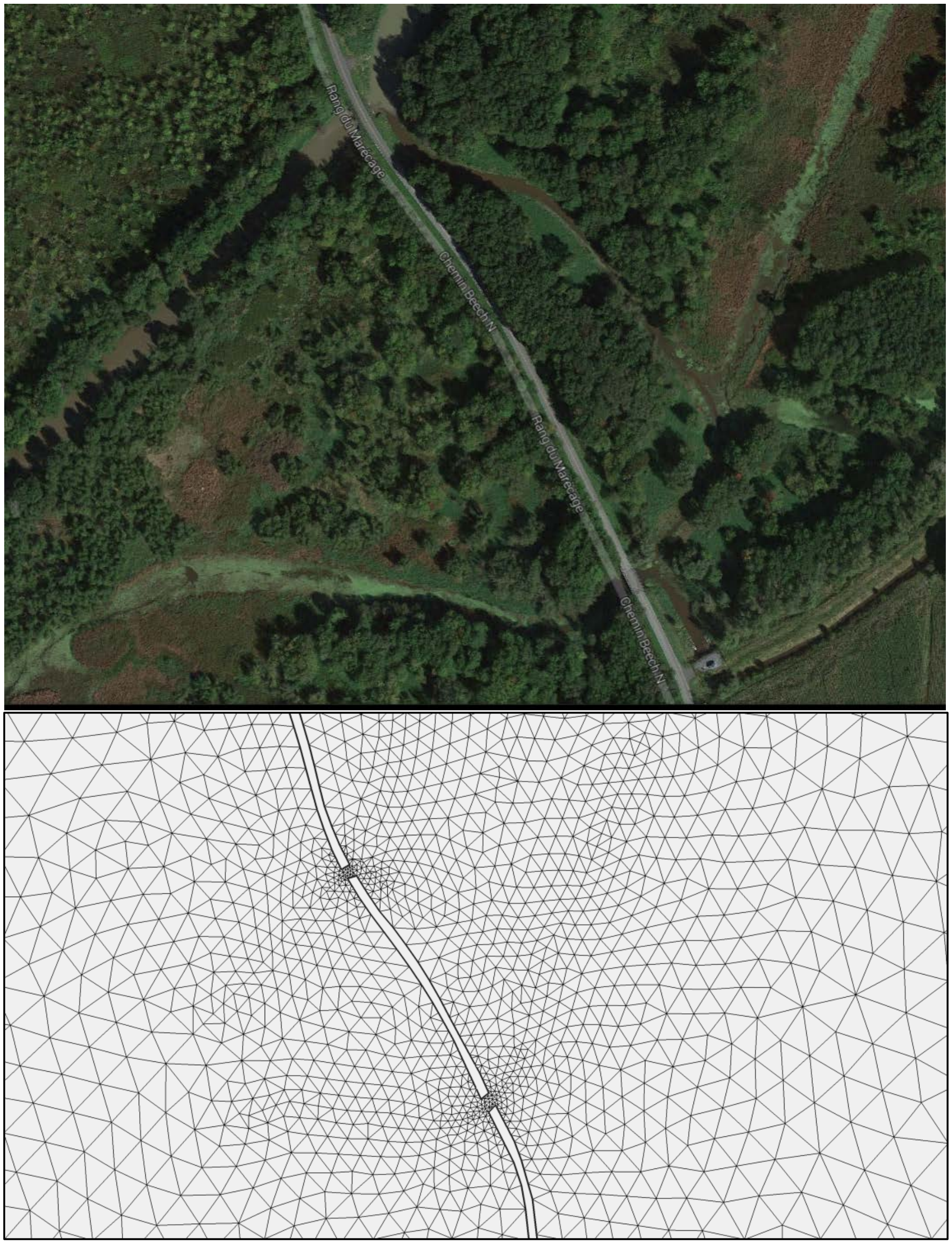

Figure 14: Chemin Beech Nord (North Beech Way) between Missisquoi Bay and the Richelieu River and the corresponding mesh

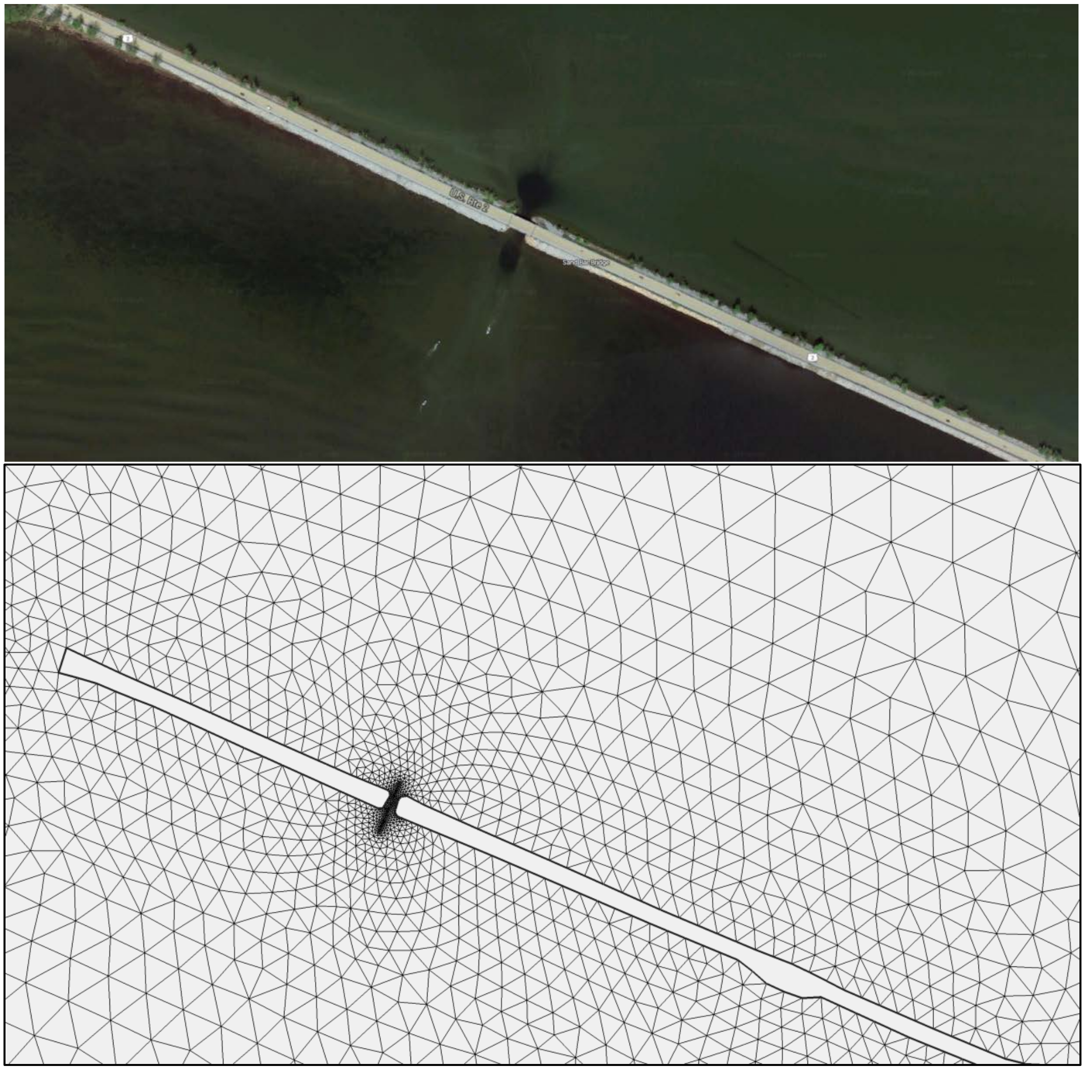

Figure 15: Highway 2 between South Hero and Colchester and the corresponding mesh

Calibration events

Water levels at a given moment on Lake Champlain are dynamic and are the result of total Lake inflows over time, the Richelieu River outflows, and the wind set-up effect. Given the water level of the Lake Champlain is not associated solely to the total Lake inflows and that the wind set-up effect is still not incorporated in the experimental model, performing the calibration of a steady state model is not an easy task.

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

The model was calibrated by comparing measurements of water levels along the Richelieu River and at the Rouses Point water level station. As a first step, an average flow and a high flow event were chosen for the calibration. The two events selected were the one on April 4, 2003, with discharge of 593 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 CEHQ, and for the 2011 event, only water levels at stations were available.

Calibration was done by adjusting the friction coefficient (Manning). Differences between simulated and measured at Saint-Jean gauge of -0.08 m were achieved for the April 4 event and +0.12 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 shoal area that are not properly captured by the available bathymetry may cause this problem and documentation was found concerning remnants of old channels that were used to bring water to mills on both banks. Those old channels are now part of the river bed, as well as V-shaped rock structures used for eel-fishing on the river, as shown in figure 20.

Bathymetry problem at Saint-Jean-sur-Richelieu sill
In its 2012 report, GENVIAR also mentioned a problem calibrating the 1D model when discharge values were low. They put the blame on control structures acting only with low discharges, and they identified structures that might be responsible on satellite images. Among these were old channels that used to bring water to mills on both banks, as well as V-shaped structures used for eel-fishing on the river (see figure 17). Such eel traps are still in use today, for example on the Delaware River in New York State (see figure 16). The vestiges of such traps probably act as natural sills when discharges are low.

Figure 16: Satellite image of an eel trap on the Delaware River (NY)

Vestiges of the millraces cause a further problem. At very low discharges, they fill with water but do not contribute to the flow in the river, since the velocities are very low. As a result they increase water levels because the width of the river is reduced.

In their model, GENIVAR eliminated these locations (areas that can fill up with water but where velocities are very low) to avoid overestimating the hydraulic capacity of the river.

Figure 17: Vestiges of man-made structures at the Saint-Jean-sur-Richelieu sill (from GENIVAR 2012)

We made a more thorough analysis to determine the possible impact of the structures at the sill. The first step was to look at the bathymetric data at that location. This showed that data do not cover—or barely cover—these structures, the effect of which is visible on satellite images. There are only a few data points that may correspond to them. We then used available LiDAR data to examine the water surface to confirm the impact of the structures on water levels. These data were acquired when discharges were low or moderate, between 500 and 600 m^3/s. Since the LiDAR signal barely penetrates the water, the data should make it possible to represent the relative elevation of the water surface. Figure 18 shows the effect of the eel traps and the vestiges of the millraces.

A longitudinal profile of the LiDAR values from downstream to upstream across the structures clearly showed an impact on water levels at low discharges (figure 19).

Figure 18: Water surface represented by LiDAR data at the Saint-Jean-sur-Richelieu sill

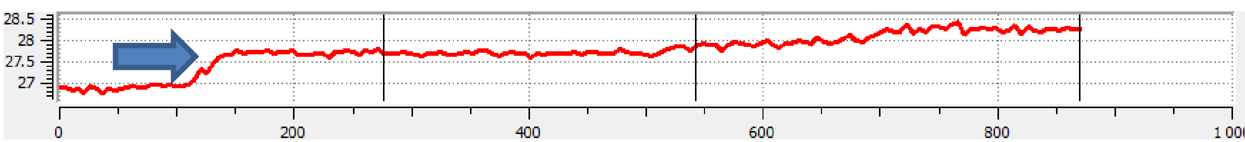

Figure 19: Longitudinal profile of LiDAR data at the Saint-Jean-sur-Richelieu sill. The blue arrow shows the location of the vestiges of the V-shaped eel traps (dimensions in metres).

A set of satellite images taken at different times, but during higher discharges, showed an attenuation of the effect of these structures on surface levels.

Our last step was physical validation. We managed to find some fairly specific photographs of the V-shaped structures and the old millraces. The photographs in figure 20 were taken in 1999 by Guy Morin, an Environment Canada hydrometric technician, during an event featuring unusually low discharge in the river. The low discharge combined with high north winds had partially dried out the Saint-Jean-sur-Richelieu sill for a few hours. On the photographs, the structures stand out clearly in relation to the local bathymetry.

Figure 20: 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 St. Jean shoal area in June 2015 not really helped to improve model performance, and the results remained unacceptable (not within 5 cm of the measurement). There is still some part of the shoal that does not have an accurate bathymetry particularly the old channels that used to bring water to mills on both banks.

Therefore, since a better bathymetry is not currently available, the steady state model, without wind forcing, was calibrated solely with the high water event of May 6, 2011, using an observed daily average of 30.676m at Saint-Jean-sur-Richelieu.

The “no-wind” calibration appears reasonable, as for May 6, 2011, the average daily wind measured at the Burlington meteorological station was 3.1 m/s (light breeze) and the fastest 2-minute wind gust was 8 m/s (moderate breeze).

The calibration involved changing the Manning's roughness coefficients along the Richelieu. In Lake Champlain, the coefficients stayed at their base value of 0.02, but along the river, they were changed in areas with sills or where the bathymetry suggested a coarser substrate. We attempted as much as possible to re-use some of the values from GENIVAR (2012). Figure 21 shows the calibrated coefficients up to Rouses Point.

Table 10 presents the calibration results, expressed as the difference between observed and simulated water levels for the flooding period in 2011. The differences at Philipsburg, Burlington and Whitehall are provided only for reference but were not realy used in the calibration of the model.

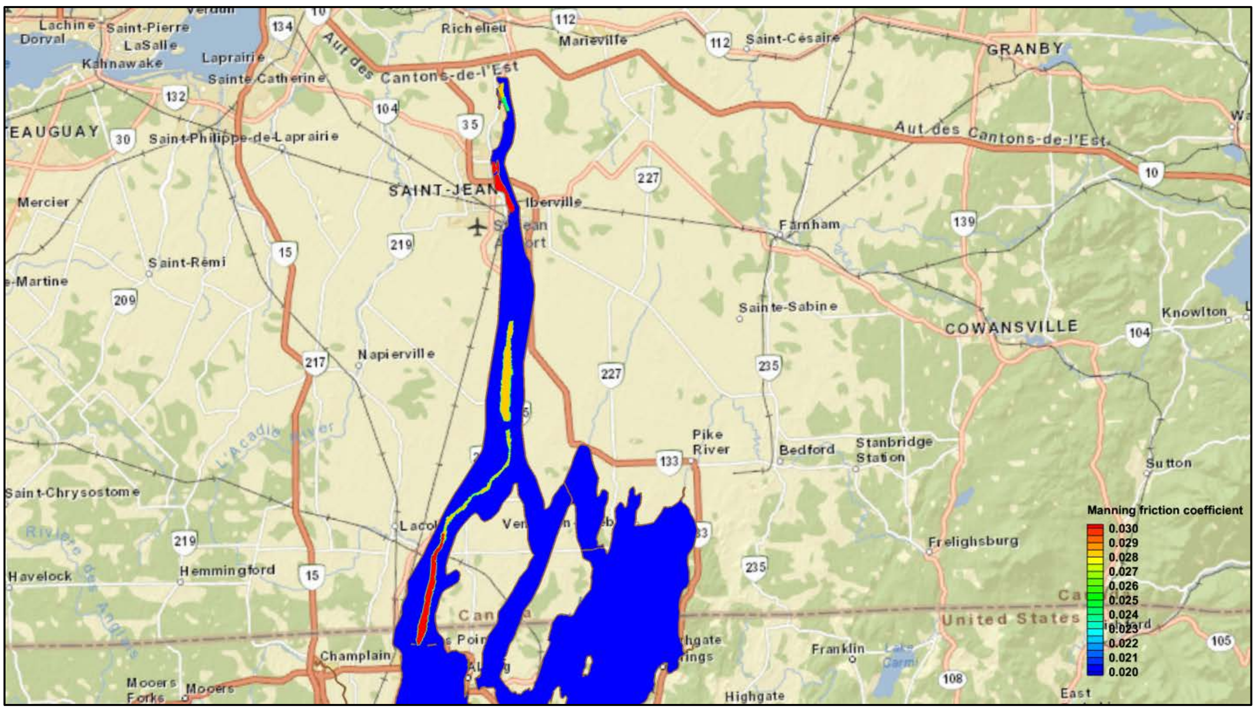

Figure 21: Roughness coefficients up to Rouses Point

Table 10: Calibration for May 6, 2011

STN	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**

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

Reference scenarios

The Working Group developed 11 reference scenarios for this study, using the water level of Lake Champlain at the Rouses Point gauging station in New York State as the point of reference in each case. Scenario 1 reflects the known inundation threshold for the lake. Scenario 7 reflects the peak flood on May 6, 2011 (as measured every 15 minutes). The interval between scenarios was selected so as to be significant in light of the terrain model. Table 11 shows the water levels for the two datums and for both the imperial and metric systems.

Table 11: Water levels defining the scenarios

Scenario	H_NGVD29(ft)	H_NAVD88(ft)	H_NGVD29(m)	H_NAVD88(m)
1	100.000	99.570	30.480	**30.349**
2	101.000	100.570	30.785	**30.654**
3	101.500	101.070	30.937	**30.806**
4	102.000	101.570	31.090	**30.959**
5	102.500	102.070	31.242	**31.111**
6	103.000	102.570	31.394	**31.263**
7	103.200	102.770	31.455	**31.324**
8	103.500	103.070	31.547	**31.416**
9	104.000	103.570	31.699	**31.568**
10	105.000	104.570	32.004	**31.873**
11	106.000	105.570	32.309	**32.178**

For each scenario, the inflows from the tributaries were adjusted to give the outflow into the Richelieu River corresponding to the appropriate water level at Rouses Point. The flows in the tributaries were distributed in proportion to the areas of their watersheds.

Table 12 summarizes the results of the 11 event simulations. The simulated station water levels as well as the outflows into the Richelieu River are shown. The simulated levels at Rouses Point are very good reflections of the levels which the Working Group established for each of the scenarios. **Note that these are static simulations in which surface winds are not considered.**

Table 12: Results of simulations of the 11 NAVD88 reference events

STN	***Scenario1***	***Scenario2***	***Scenario3***	***Scenario4***
St-Jean (m)	29.834	30.102	30.238	30.385
RousesPoint (m)	**30.350**	**30.651**	**30.800**	**30.958**
Philipsburg (m)	30.362	30.662	30.812	30.970
Burlington (m)	30.355	30.656	30.806	30.964
Port Henry (m)	30.355	30.656	30.806	30.964
Whitehall (m)	30.373	30.674	30.823	30.982
Outflow (m^3/s)	**937.488**	**1105.720**	**1194.500**	**1293.590**
STN	***Scenario5***	***Scenario6***	***Scenario7***	***Scenario8***
St-Jean (m)	30.528	30.667	30.731	30.829
RousesPoint (m)	**31.111**	**31.256**	**31.321**	**31.423**
Philipsburg (m)	31.123	31.268	31.334	31.435
Burlington (m)	31.118	31.263	31.329	31.430
Port Henry (m)	31.117	31.263	31.329	31.430
Whitehall (m)	31.136	31.282	31.348	31.450
Outflow (m^3/s)	**1392.830**	**1492.360**	**1538.960**	**1611.680**
STN	***Scenario9***	***Scenario10***	***Scenario11***	
St-Jean (m)	30.975	31.273	31.571	
RousesPoint (m)	**31.567**	**31.876**	**32.174**	
Philipsburg (m)	31.579	31.889	32.187	
Burlington (m)	31.574	31.884	32.183	
Port Henry (m)	31.574	31.884	32.183	
Whitehall (m)	31.595	31.905	32.206	
Outflow (m^3/s)	**1709.950**	**1958.360**	**2204.440**	

Conclusion

The main objectives of Task 1.2 have been met. Elevation and bathymetry data were collected to build a DEM for Lake Champlain and its shores. The various datums were reconciled. Where information was available on structures such as bridges, piers and causeways influencing the hydrodynamics, this was compiled and incorporated in the mesh model. A database was developed of all American and Canadian water supply sources needed for the hydrodynamic model. The model's limits and entry points were identified.

A hydrodynamic mesh was developed and calibrated for high water levels. The 11 scenarios developed by the Working Group were simulated and the results were shared with the Group's members.

The key issue to have a good hydrodynamic model is the Saint John shoal because that is what controls the lake levels. Improved bathymetry over the Saint-Jean shoal will be needed to achieve a good calibration for the entire range of discharge from low to high. An improved version of the model should not significantly change the results of the 11 scenarios since the calibration was done with a hight flow event. 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.

The water inflow database is currently an Excel file that will have to be migrated to a proper database to make it useable.

References

GENIVAR. 2012. Impact du barrage Fryer sur les niveaux d'eau du Richelieu – Étude hydraulique. Report to Parks Canada. 33 pp. + annexes.

Manley, T.O., P.L. Manley and G.B. Fisher, (2005), Bathymetry of Lake Champlain, Map, Middlebury College.

Shanley, J.B. and J.C. Denner, 1999. "The Hydrology of the Lake Champlain Basin" in *Lake Champlain in Transition: From Research Toward Restoration*. AGU, Washington, D.C., pp. 41-66.

Hydrologic Engineering Center of the US Army Corps of Engineers, HEC-RAS
http://www.hec.usace.army.mil/software/hec-ras/

Centre d'Expertise Hydrique du Québec (CEHQ)
https://www.cehq.gouv.qc.ca/suivihydro/ListeStation.asp?regionhydro=03&Tri=Non

Fisheries and Oceans Canada, Tides and Water Levels Data Archive
http://www.isdm-gdsi.gc.ca/isdm-gdsi/twl-mne/index-eng.htm

U.S. Geological Survey, USGS Water Data for the Nation, National Water Information System
http://nwis.waterdata.usgs.gov/nwis

Environment Canada (Water), Tides and Water Levels Data Archive, HYDAT database
http://www.isdm-gdsi.gc.ca/isdm-gdsi/twl-mne/index-eng.htm - s5

ANNEX

Results of GNSS survey to resolve vertical datum problem

Richelieu Valley GPS
Comparision Summary

Comparison