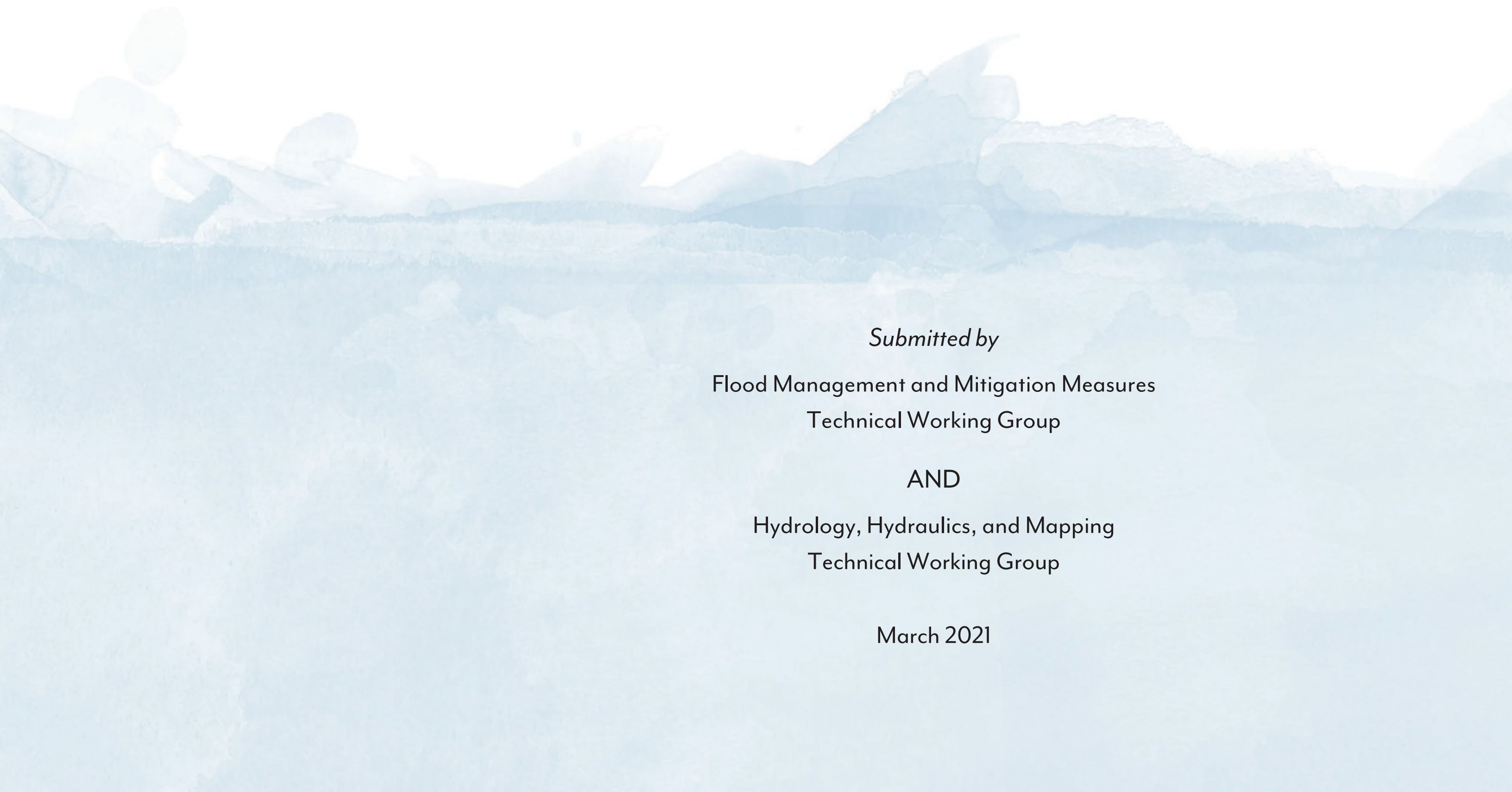
Potential Structural Solutions to Mitigate Flooding in the Lake Champlain-Richelieu River Basin

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION



Submitted by

Flood Management and Mitigation Measures
Technical Working Group

AND

Hydrology, Hydraulics, and Mapping
Technical Working Group

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TECHNICAL WORKING GROUPS

FMMM, Canada

Jan Adamowski

Pascal Marceau

Syed Moin

FMMM, United States

Ben Rose

HHM, Canada

Olivier Champoux

Milena Dimitrijevic

Simon Lachance-Cloutier

Dominic Roussel

HHM, United States

Tim Calappi

Chris Gazoorian

Blaine Hasting

Bill Saunders

FMMM study co-lead, Canada

Ted Yuzyk

FMMM study co-lead, United States

Bill Werick

HHM study co-lead, Canada

Jean Morin

HHM study co-lead, United States

Jesse Feyen

EXECUTIVE SUMMARY

This report documents the formulation and preliminary evaluation of a wide range of structural solutions to reduce extreme water levels in the Lake Champlain-Richelieu River system. The alternatives identified in this report include structural solutions from the 1973 International Joint Commission reference study, ideas for potential structural solutions provided by stakeholders during the current study, and potential solutions identified from a literature scan.

STRUCTURAL SOLUTIONS

Seven potential structural solutions were identified and subjected to a preliminary assessment of their effectiveness in reducing extremely high water levels, while not exacerbating drought water levels; the number of residential buildings that would potentially be spared from flooding; and some economic and environmental implications associated with their implementation. The alternatives are as follows:

1. Excavating of human interventions on Saint-Jean-sur-Richelieu shoal (eel trap, submerged dikes).
2. a. Diverting moderate flow through the Chambly Canal with a conservative diversion scheme.

   b. Diverting significant flow through the Chambly Canal with an optimized diversion scheme.
3. Alternative 2a combined with Alternative 1.
4. Moving the control by installing a fixed weir upstream of Saint-Jean-sur-Richelieu and dredging the channel.
5. Installing an inflatable weir or bladder upstream of Saint-Jean-sur-Richelieu and dredging the channel.
6. Installing an inflatable weir or bladder at the Saint-Jean-sur-Richelieu shoal and dredging the channel.

DECISION CRITERIA

The information compiled by the study to date was used by the Study Board to determine which alternatives warrant a more comprehensive analysis; this will require further significant resources and time to complete. The data and results of analyses presented in this report are those that were available as of July 2020. The decision criteria that were applied are:

1. Within study scope and mandate
2. Implementable
3. Technically viable
4. Economically viable
5. Equitable and fair
6. Environmentally sound
7. Robustness to climate change.

STUDY FOCUS

The Study Board debated the utility, effectiveness in reducing floods, potential impact on drought levels, number of residential buildings that would be spared from flooding and some of the economic and environmental implications of implementing each alternative. Central to the discussions was the need to adhere to the U.S. and Canadian Governments' request to focus on "moderate structural works" as the Study Board aids the International Joint Commission in fulfilling the terms of that reference from the two governments. The Study Board interpreted that Alternatives 4, 5 and 6 were major structural solutions, as they involved the damming of the river with significant effect on the flow regime and the environment. The unsuccessful history of trying to implement a dam further indicated to the Study Board that there still may be little political and social appetite to pursue such a flood control structure. The Study Board determined that no further study resources should be committed to Alternatives 4-6.

The Study Board therefore focused its attention on Alternatives 1, 2 and 3, as these could be considered to be moderate structural solutions. It was concluded that the diversion of water through the Chambly Canal was the most promising solution. The Study Board decided that Alternative 2b particularly warranted the study's further attention, as Alternative 2a was a less effective utilization of the canal.

This alternative has the potential to provide significant flood relief, negligible impact on low water levels, and potentially limited environmental implications. Alternatives 1 and 3 were less appealing to the Study Board, as they would result in permanent water level lowering, which could be problematic if climate change reduces net basin supplies, as some early climate work is predicting. Alternatives 1 and 3 are still in consideration pending the results of the Alternative 2b evaluation.

The Study Board has directed the study team to continue the analysis of the diversion (with a focus on Alternative 2b), provide thorough cost estimates and explore various potential operating plans. The appropriate hydraulic simulations, evaluations, and a benefit/cost analysis also will be done. Moving forward, the Study Board will be working closely with Parks Canada to further evaluate modifying the Chambly Canal as a potentially acceptable diversion scheme.

STAY CONNECTED, BE ENGAGED

Want more information on the Lake Champlain-Richelieu River Study? Have a question for the Study Board?

Email the Study at lcrr@ijc.org

Sign up to receive Study news, such as notices of public meetings, consultations, reports, fact sheets, and other publications

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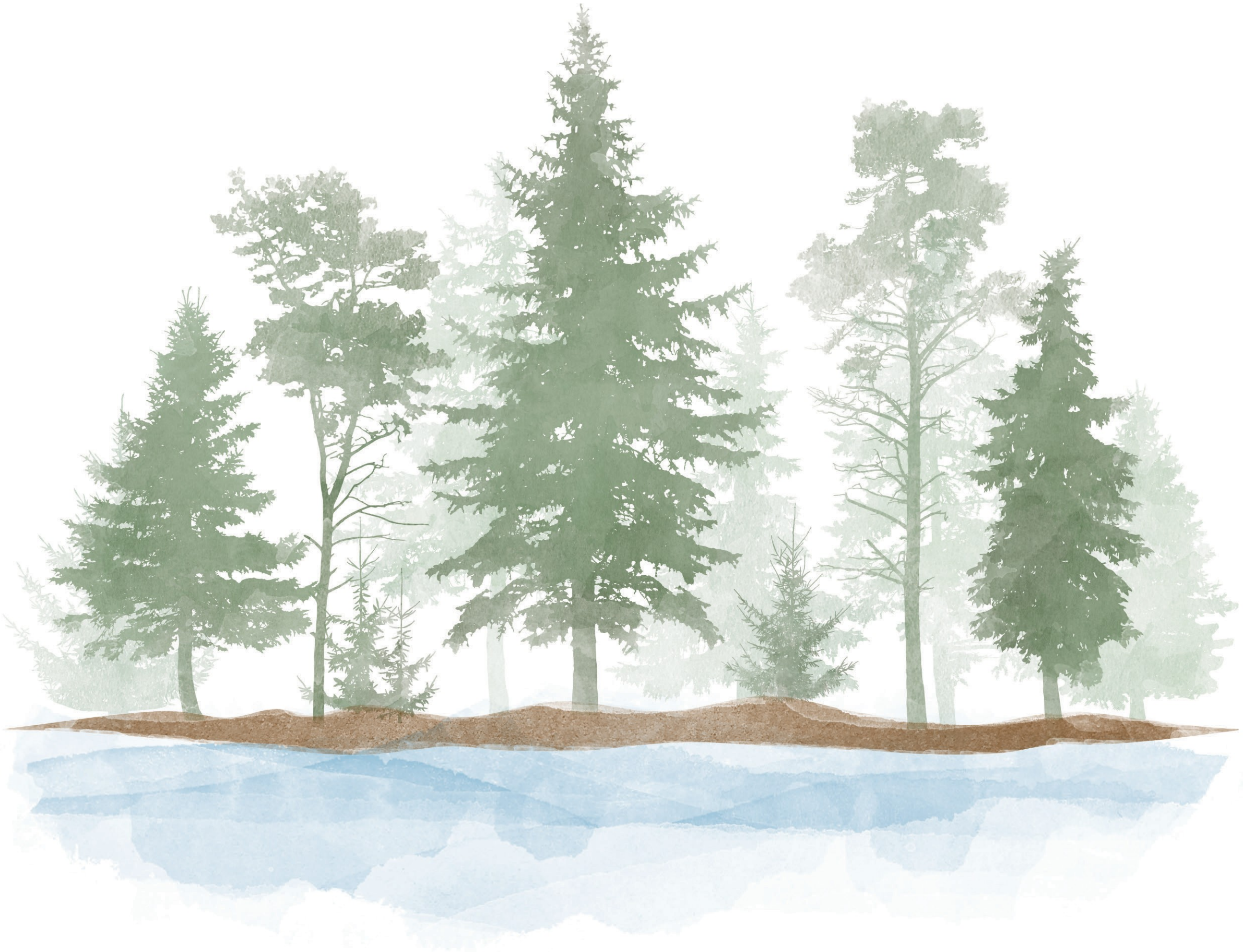

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List of Acronyms

The following is a list of acronyms used in the report:

BWT	Boundary Water Treaty
CAWG	Climate Adaptation Working Group
CDST	Collaborative Decision Support Tool
CLIMEX	Climate Extremes
CMIP	Coupled Model Inter-comparison Project
CORDEX	Coordinated Regional Downscaling Experiment
COVABAR	le Comité de concertation et de valorisation du bassin de la rivière Richelieu
CPR	Canadian Pacific Railway
CRCM	Canadian Regional Climate Model
ECCC	Environment and Climate Change Canada
FMMM	Flood Management and Mitigation Measures
GCM	General Circulation Model
GIS	Geographic Information System
GSC	Geodetic Survey of Canada
H2D2	Two-Dimensional Hydraulic and Dispersion Simulation
HHM	Hydrology, Hydraulics and Mapping
ICRB	International Champlain-Richelieu Board
ICREB	International Champlain-Richelieu Engineering Board
IJC	International Joint Commission

List of Acronyms (continued)

ILCRRSB	International Lake Champlain-Richelieu River Study Board
INRS	Institut national de la recherche scientifique
IPCC5	Fifth Assessment Report of the United Nations Intergovernmental Panel on Climate Change
ISEE	Integrated Social Economic and Environmental
IUGLS	International Upper Great Lakes Study
LCBP	Lake Champlain Basin Program
LCRR	Lake Champlain-Richelieu River
LOSLR	International Lake Ontario - St. Lawrence River Study
NAVD88	North American Vertical Datum of 1988
NBS	Net Basin Supplies
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PI	Performance Indicator
PMF	Probable Maximum Flood
QM	Quarter-month
RCM	Regional Climate Model
SJSR	Saint-Jean-sur-Richelieu
SPE	Social, Political, Economics Advisory Group
TWG	Technical Working Group

List of Acronyms (continued)

USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
USWRC	United States Water Resources Council
WBM	Water Balance Model
WRF	Weather Research and Forecasting

Measurement Units and Datum Conversion Factors

Metric System – United States Customary Measurement System Units

(With abbreviations)

Length

1 millimetre (mm) = 0.0394 inch (in)

1 in = 25.4 mm

1 centimetre (cm) = 0.3937 in

1 in = 2.54 cm

1 metre (m) = 3.2808 feet (ft)

1 ft = 0.3048 m

1 kilometre (km) = 0.6214 mile (mi)

1 mi = 1.6093 km

Area

1 square kilometre (km^2) = 0.3861 square mile ($mile^2$)

1 $mile^2$ = 2.59 km^2

1 hectare (ha) = 2.47 acres

1 acre = 0.405 ha

Volume

1 cubic metre (m^3) = 35.315 cubic ft (ft^3)

1 ft^3 = 0.02832 m^3

1 cubic decametre (dam^3) = 1000 m^3

1 dam^3 = 0.810714 acre-foot (ac-ft)

1 ac-ft = 1.233481 dam^3

Flow rate

1 cubic metre per second (m^3/s) = 35.315 cubic ft per second (ft^3/s)

1 ft^3/s = 0.02832 m^3/s

NAVD88 – NGVD29 Datum Conversion Factor at Rouses Point

Datums are the basis for all geodetic survey work. A geodetic datum is an abstract coordinate system with a reference surface (such as sea level) that provides known locations from which to begin surveys and create maps.

For this report, example of conversion between National Geodetic Vertical Datum of 1929 (NGVD 29) and North American Vertical Datum of 1988 (NAVD 88), which is specific for a given location specified by the latitude and longitude, will be given for Rouses Point that is the geographical outlet of Lake Champlain.

NAVD88 (ft) = NGVD29 (ft) – 0.43 (ft)

NGVD29 (ft) = NAVD88 (ft) + 0.43 (ft)

NAVD88 (m) = NGVD29 (m) – 0.131 (m)

NGVD29 (m) = NAVD88 (m) + 0.131 (m)

1 INTRODUCTION TO THE REPORT

This report documents the formulation and preliminary evaluation of a wide range of structural solutions to reduce extreme water levels in the Lake Champlain-Richelieu River system.

1.1 A CALL TO ACTION

Periodically there are extreme floods in the Lake Champlain-Richelieu River (LCRR) Basin. Extreme flooding in the 1930s, 1970s, and more recently in 2011, have resulted in the governments of Canada and the United States giving a reference[1] to the IJC to provide recommendations on what should be done to mitigate the flooding issue. Lack of implementation of the recommendations from past references, and limited actions being undertaken to reduce flooding, means the issue has yet to be effectively addressed. This general lack of decisive action, along with the record severity of the 2011 flood, has led to a renewed sense of urgency to address the flooding issue.

The economic impacts from these floods have grown over time and are more pronounced in Canada. The economic damages[2] of the 2011 flood were calculated to be approximately $89 M, 79% occurring in Québec, 11% in New York, and 10% in Vermont (IJC, 2013). There are ongoing concerns that the magnitude, frequency, and economic severity of flooding could increase over time due to: a changing climate, encroachment in the river, and development in the floodplain. Some preliminary work by the study suggests that the flooding issue may be of less concern in the United States as a result of the mitigation measures that have been undertaken.

For Quebec, however, the 2011 flood was particularly devastating as flooding extended beyond the regulated floodplain.

As the basin is a transboundary basin, addressing this risk will require a binational approach. It is therefore in both countries' interests to identify and implement effective solutions to address the flooding issue that are commensurate with each nation's respective risks.

1.2 REPORT SCOPE AND STRUCTURE

There is a broad range of actions that can be taken to address flooding; these can be structural or non-structural. This report primarily focuses on the various structural solutions that could be implemented to reduce extreme water levels in Lake Champlain and the Richelieu River. The study is addressing non-structural solutions in various other reports.

Chapter 2 begins with a brief overview of the basin setting and then describes the current Lake Champlain and Richelieu River hydraulic regimes and the implications that a changing climate may have on future water levels.

Chapter 3 explains the importance of the Saint-Jean-sur-Richelieu shoal in controlling water levels and then goes on to elucidate how human interventions in the river

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[1] Formal request from both governments to the International Joint Commission (IJC) to provide recommendations on addressing a specific issue.

[2] All monetary values in this report are in Canadian dollars, reflecting the location of the proposed capital works.

have impacted water levels over time and further exacerbated flood levels.

Chapter 4 provides a history of structural mitigation efforts associated with previous IJC references and provides an understanding of what transpired regarding the implementation of these structural recommendations. Some insight into the political and social acceptability of proposed structural solutions is highlighted to better understand how this might impact acceptability of any currently proposed structural solutions.

Chapter 5 examines a broad range of structural alternatives, and a limited number are identified for consideration by the Study Board.

Chapter 6 describes the study's modelling framework and the application of the Water Balance Model, 2-D Hydrodynamic Model, Integrated Social Economic and Environmental (GIS) System, and Collaborative Decision Support Tool developed by the study to determine the hydraulic and other impacts associated with each of the proposed structural alternatives.

Chapter 7 of the report focusses on seven proposed structural alternatives, assesses their hydraulic effectiveness, and identifies some limited economic and environmental implications associated with implementing each of them. It also identifies the decision criteria that the Study Board used to evaluate the structural alternatives and determine whether any warrant further consideration.

Finally, **Chapter 8** provides a brief summary culminating in the Study Board's decision to further investigate the most promising structural solutions.

THE INTERNATIONAL JOINT COMMISSION

Under the Boundary Waters Treaty of 1909 (the Treaty), the governments of the United States and Canada established the basic principles for managing many water-related issues along their shared international boundary. The Treaty established the IJC as a permanent international organization to advise and assist the governments on a range of water management issues. The IJC has two main responsibilities: regulating shared water uses; and investigating transboundary issues and recommending solutions.

2 LAKE CHAMPLAIN-RICHELIEU RIVER BASIN

2.1 PHYSICAL SETTING

The Lake Champlain-Richelieu River basin is shown in Figure 2-1. The Lake Champlain and Richelieu River system is composed of two interconnected sub-basins: the Richelieu River watershed (downstream of the shoal) and the Lake Champlain watershed (upstream of the shoal). Over the two sub-basins, the average annual precipitation varies from approximately 760 mm (30 in) near the lake and in the valleys to more than 1,020 mm (40 in) in the mountains; snowfall averages 1,020 (40 in) to 1,520 mm (59.8 in). The population of the basin is over one million, with the Lake Champlain sub-basin accounting for 60%. In the area upstream of Rouses Point, New York, about 50% of the basin population depends on the lake for drinking water. Only 5.6% of the basin is occupied by developed areas, and 16% is used for agricultural purposes. The remaining areas are mostly forested land (LCBP 2008, 2015; Stager and Thill, 2010).

For the purposes of this report, the sub-basins will be described separately because, though inter-related, the hydraulic and hydrological responses for the two sub-basins are quite different.

2.1.1 Lake Champlain

Lake Champlain is one of the largest lakes in North America, and is a binational waterbody shared by Vermont, New York, and the province of Québec. Lake Champlain extends from Whitehall, New York, north to its outlet at the Richelieu River in Québec. The lake, carved out during the last glacial advance, is 193 km (120 mi) long and 20 km (12.5 mi) at its widest point. The 21,325 km^2 (8,233 mi^2) watershed drains nearly half the land area of Vermont and portions of northeastern New York and southern Québec. About 56% of the basin is in Vermont, 37% in New York, and 7% in Québec (LCBP 2004, 2015).

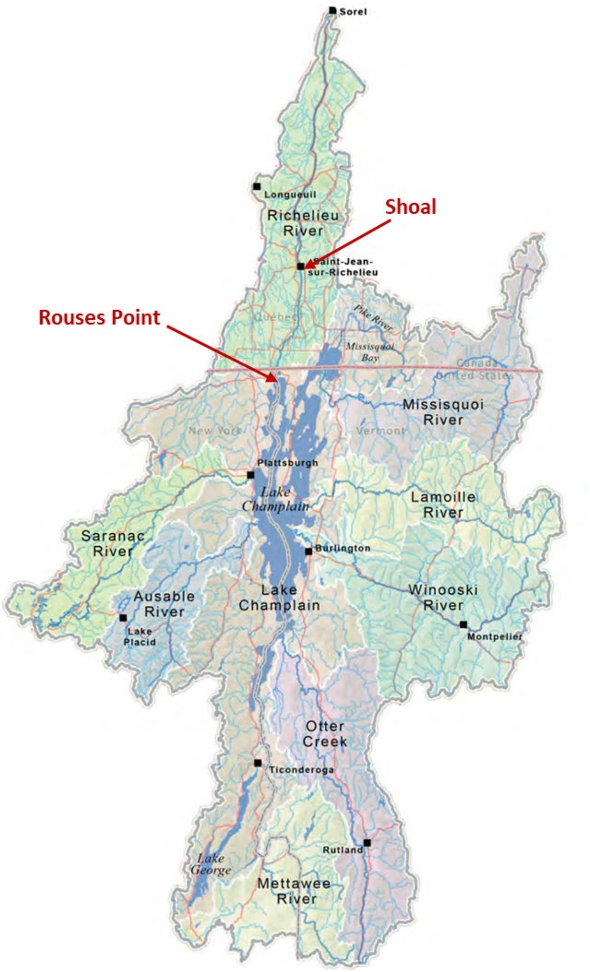

Figure 2-1 | Lake Champlain - Richelieu River Basin

Lake Champlain is in the St. Lawrence River drainage basin. The lake sits in the low point of a valley between the Adirondack Mountains of New York and the Green Mountains of Vermont, with the border between New York and Vermont following the deepest part of the lake. A small portion of the lake resides in Québec. The land use in the basin is 64.3% forest, 16% agriculture, and 5.6% developed land, with the remainder being wetlands and open water (LCBP 2004). The relatively flat, fertile lands that extend to the east between the lake and the Green Mountains contain the highest concentration of agricultural lands. To the west, the Adirondacks are much closer to the lake's shore. The mean monthly temperatures range from 4° to 24° C (39° to 75° F), and the growing season generally lasts about 160 days.

Physically, there are seven physiographic regions that define the sources and delivery of water to the lake. From west to east these regions are Adirondack, Champlain, Hudson Valley, Taconic, Valley of Vermont, Green Mountain, and Vermont Piedmont. Similarly, Lake Champlain is often divided into 13 segments for analysis and simplified into five major lake segments: Missisquoi Bay, Northeast Arm, Mallets Bay, Main Lake, and South Lake. When compared to the other lake segments, Missisquoi Bay and South Lake have the highest watershed to lake area ratios. The Lake Champlain watershed is composed of smaller sub-watersheds with surface areas varying between 115 km^2 (44.4 mi^2) and 2,704 km^2 (1,044 mi^2). The major tributaries feeding into the system are: Missisquoi River, Chazy River, Lamoille River, Saranac River, Winooski River, Ausable River, and Otter Creek. The Lake Champlain Basin has a relief of over 1,500 m (4,921 ft) between the Adirondack Mountains in New York and Rouses Point, the geographical outlet of the lake.

Lake Champlain is the striking water feature of the basin. With a surface area of 1,263 km^2 (488 mi^2), the lake occupies roughly 5% of the total area of the watershed. The lake thus acts as a natural reservoir that dampens the flood wave entering the Richelieu River (Shanley and Denner, 1999).

2.1.2 Richelieu River

Lake Champlain outflows and four streams form the five main tributaries that drain into the Richelieu River; additionally, there are 14 smaller streams that are part of Richelieu River along with municipal drains that discharge into the Richelieu River directly. The local streams have a drainage area of 2,546 km^2 (968 mi^2). The four sub-basins with drainage areas larger than 100 km^2 include: the Acadie River (530 km^2 or 205 mi^2), the Huron River (334 km^2 or 129 mi^2), the South River (145 km^2 or 56 mi^2) and the Lacolle River (126 km^2 or 49 mi^2) (COVABAR, 2011). The Richelieu River discharge is mainly dependent on the Lake Champlain level, and to a lesser extent on wind surge. The Richelieu River flows over a flat valley, dropping by only 28 m (92 ft) between Rouses Point and Sorel, where it meets the St. Lawrence River. The elevation of the Richelieu River at Rouses Point is 34 m (111 ft) and at its outlet in Sorel is 6 m (19 ft). A longitudinal profile with pictures of key features is shown in Figure 2-2. The key information on the hydraulic features of the Richelieu was drawn from earlier efforts on hydrodynamic modelling by the International Lake Champlain – Richelieu River Technical Working Group (ILCRR TWG 2015a, 2015b).

One of the key morphological features of the Richelieu River is a rock shoal at Saint-Jean-sur-Richelieu some 30 km (18.6 mi) downstream of Rouses Point. The rock shoal is the hydraulic control that regulates the water level of Lake Champlain. From a hydraulic perspective, the outlet of the lake should be considered the Saint-Jean-sur-Richelieu shoal, rather than Rouses Point, which is commonly considered to be the lake outlet. This upper reach of the river therefore can be considered an extension of Lake Champlain. The gradient of the river is low for the upper reach of the river, with a drop of only 0.3 m (about 1 ft).

The shoal section is about 210 m (689 ft) wide and extends for about 3.2 km (2 mi). In this reach of the river, the river drops about 25 m over 12 km (about 82 ft over 7.5 mi). The Chambly Canal passes along the west side of the river to facilitate navigation past the rapids caused by the rock shoal. The canal consists of nine locks over a length of nearly 19 km (12 mi).

In Chambly, the river widens again and its velocity decreases, forming the Chambly Basin. Water levels in the river channel below the Chambly Basin are controlled by a dam about 50 km (31 mi) downstream, at Saint-Ours, Québec.

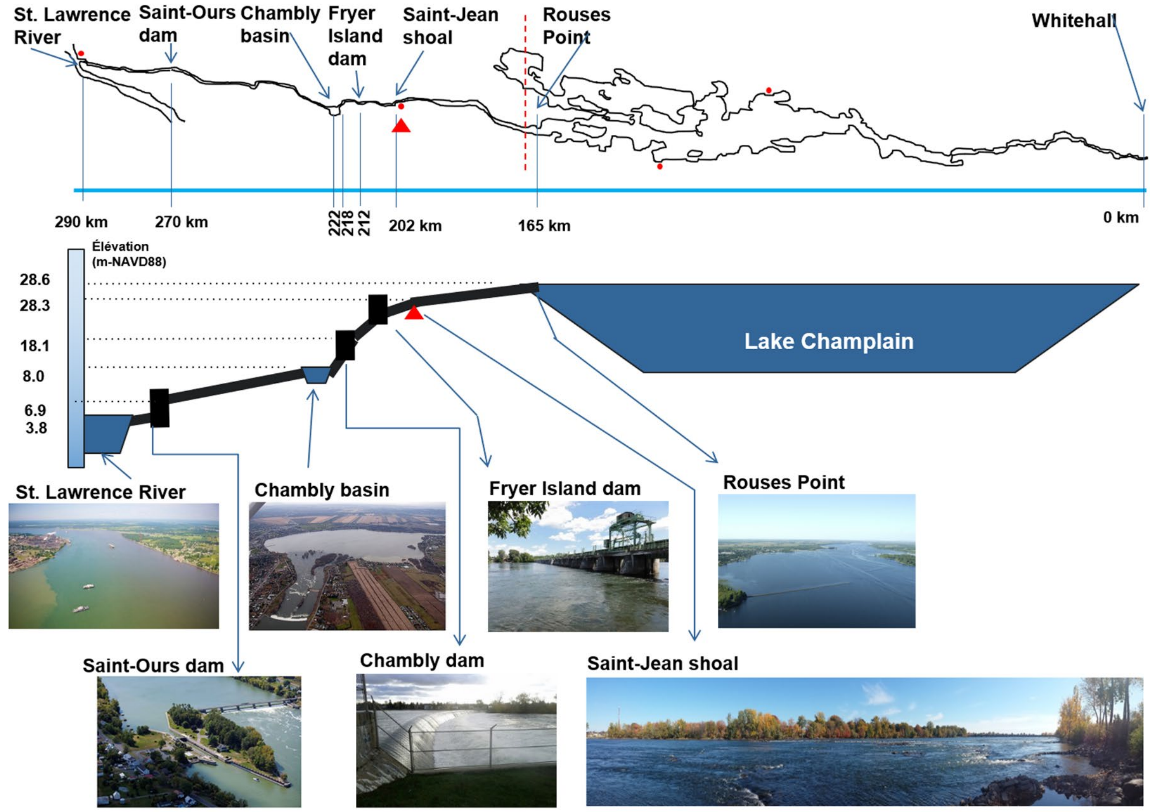

Figure 2-2 | Key features of the Richelieu River (note: the vertical scale on the cross-sectional view is not linear)

2.2 LAKE CHAMPLAIN HYDROLOGY

The dynamics of Lake Champlain water levels are the result of several factors. The key factors are the inflows into the lake, termed "Net Basin Supplies (NBS)", both in volume and temporal distribution; peak intensity of inflow; and the starting lake water levels before a freshet event.

2.2.1 Data Sources

At the outset of the study, it was agreed that all participants and consultants would use standardized and verified data sets. Three of these data sets were the synthesized Net Basin Supplies (NBS) into Lake Champlain, recorded lake-wide averaged Lake Champlain water levels, and recorded Richelieu River discharge at Fryer Dam. All three variables were certified by the Hydrology, Hydraulics and Mapping (HHM) Technical Working Group (TWG) for use in analysis and were used for this report (Boudreau et al. 2019). All the graphics in this section are drawn from these three data sets.

2.2.2 Lake Champlain Water Levels

Figure 2-3 captures two essential features of the peak and average water levels of Lake Champlain for the period of 1925 to 2017. The bar graph depicts the yearly averages of water levels, and the line graphs the maximum observed water levels in the year. The graph also shows the flooding threshold of 30.35 m (99.57 ft) NAVD88 (see section 2.2.3 for flood level designations).

As shown on the graph, both peak (green dashed line in Figure 2-3) and average annual water level (dark blue dashed line in Figure 2-3) exhibit upward trends. The peak water levels demonstrate a negligible trend of 1 mm/decade, whereas the annual water level trend is more dramatic at 30 mm/decade (1.2 in/decade), some

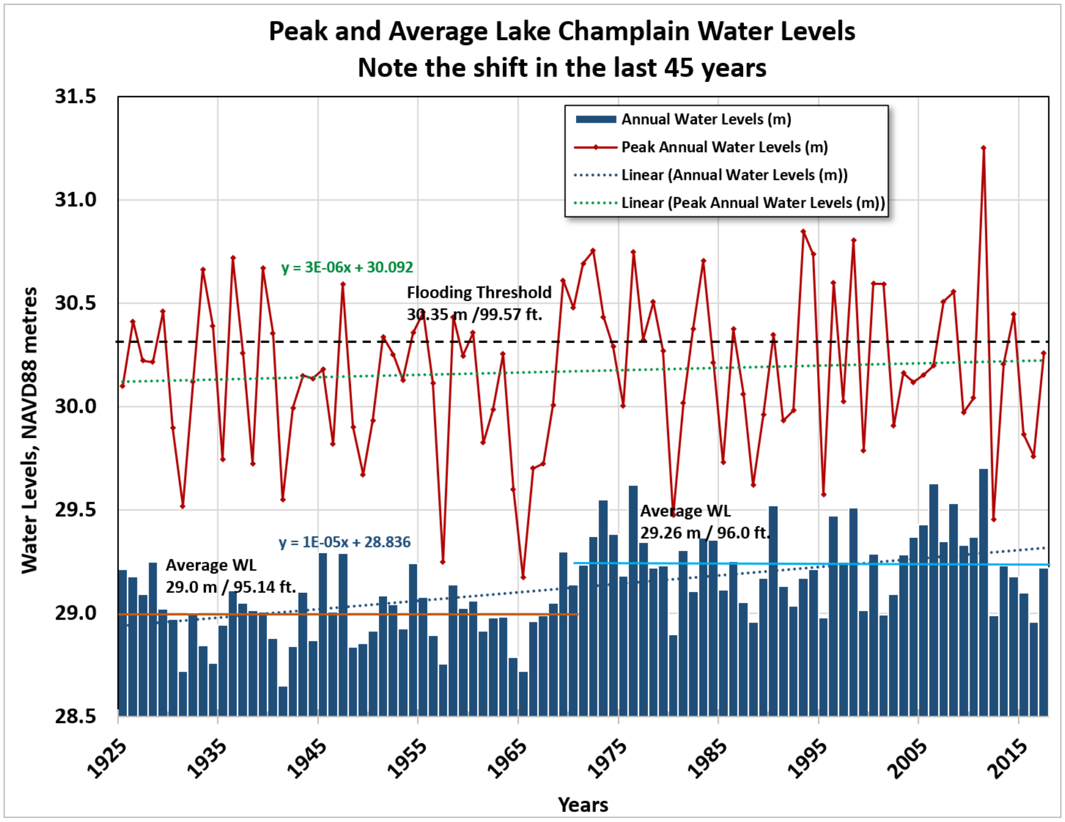

Figure 2-3 | Peak and average Lake Champlain water levels

thirty times higher for the annual water levels series. Furthermore, if the trend evaluation is split between pre- and post-Chambly Canal widening in the early 1970s (the red and light blue trend lines, respectively), an upward shift of about 26 cm (10.2 in) is observed for averaged annual water levels in the post 1971 period. While the widening of the Chambly Canal undoubtedly contributed to this significant shift, the change cannot be completely attributable to the canal widening. Coincidently around 1970, the hydrological regimes in basins throughout north-eastern continental North America faced an increase in precipitation. For Lake Champlain, post-1971 NBS values were almost 24% higher than pre-1971, as will be discussed in Section 2.3. Based on the hydrodynamic modelling conducted by HHM TWG, the shift in averaged annual water levels can be attributed to three factors:

1. Wetter water supply regime in the shoulder seasons [3];
2. Widening of the Chambly Canal (1970 to 1974); and,
3. Increased weed growth in the Richelieu River causing additional friction and associated higher water levels from late spring to fall.

When examining the historical record for NBS into the lake, while 2011 provided the highest flood levels, the peak NBS into Lake Champlain for the 2011 flooding event was just 2,201 m^3/s (77,728 ft^3/s). This was not the highest NBS in the historical series; five other events exceeded the 2011 event. Of these five events, only one event was in the fall; the rest were in the spring season (Table 2-1). The highest NBS occurred in 1936 and was 2,721 m^3/s (96,091 ft^3/s).

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[3] For the purposes of the report, the shoulder seasons are defined as months outside of the traditional spring flood months. It was observed, since 1971, that higher volumes of runoff from summer storms and snowmelt in the late winter period contributed to Lake Champlain staying at higher than average water levels for longer periods.

Table 2-1 also provides relevant information on the flows, volumes, and the initial level of Lake Champlain. A comparison of this information confirms that a combination of causative factors contributes to flooding. These data also demonstrate the self-regulating and storage capacity of Lake Champlain. If a flood event begins at a lower Lake Champlain water level, there is greater storage available within the usual lakebed to absorb the volume of inflow, resulting in smaller immediate increases in outflows.

Two annual flood events reflected in Table 2-1 demonstrate the regulating capacity of the lake. The first is the flood of 1936; the peak outflow was 45.4% (1,235/2,721 as percent) of inflow peak. The starting lake level was relatively low at 28.73 m (94.26 ft), while the 60-day NBS volume was the third largest in the table, a volume of 5.14 x106 dam^3 (4.16 x106 acre-feet). For the 2011 flood event, the peak outflow was 32.3% less than the peak inflow. In 2011, the basin received inflows into the lake from an early freshet which brought the water levels up. The starting water level of 30.5 m (100.06 ft) was already above the flooding threshold of 30.35 m (99.57 ft) at the onset of the combination of extended precipitation, above average snow depth, and warmer than normal temperatures; this event had the highest 60-day NBS volume of 7.64 x 106 dam^3 (6.19 x 106 acre-feet), resulting in record water levels and outflows.

2.2.3 Designation of Lake Floods

For Lake Champlain, water level forecasts are provided by the US National Weather Service (NWS), which is part of the US National Oceanic and Atmospheric Administration (NOAA). The NWS has established target water levels that classify the severity of a flood. They are described in Table 2-2.

Table 2-1 | Highest events since 1925, ranked by NBS

Date of Event	Peak NBS, m^3/s (ft^3/s)	Peak Outflow, m^3/s (ft^3/s)	Starting Lake Level, m (ft), NAVD88	60-Day Volume, dam^3 (ac-ft) x10^6
March 1936	2,721 (96,091)	1,235 (43,614)	28.73 (94.26)	5.14 (4.16)
April 1960	2,443 (86,271)	1,018 (35,950)	28.95 (94.98)	4.14 (3.35)
April 1933	2,437 (86,059)	1,187 (41,919)	30.69 (100.69)	5.48 (4.44)
April 2001	2,397 (84,646)	1,058 (37,363)	28.92 (94.88)	4.70 (3.81)
November 1927	2,352 (83,057)	963 (34,008)	28.74 (94.29)	4.46 (3.61)
April 2011	2,201 (77,725)	1,550 (54,736)	30.50 (100.06)	7.64 (6.19)

Table 2-2 | US National Weather Service's flood classification criteria (https://water.weather.gov/ahps2/hydrograph.php?gage=roun6&wfo=btv)

Flood Severity	Lake Champlain Target Elevation		Expected Flooding Impacts
	(m/ft) NGVD29	(m/ft) NAVD88	
Minor Flood	30.48/100.0	30.35/99.57	Minimal or no property damage, but possibly some public threat.
Moderate Flood	30.78/101.0	30.65/100.57	Some inundation of structures and roads near stream. Some evacuations of people and/or transfer of property to higher elevations.
Major Flood	30.94/101.5	30.81/101.07	Extensive inundation of structures and roads. Significant evacuations of people and/or transfer of property to higher elevations.

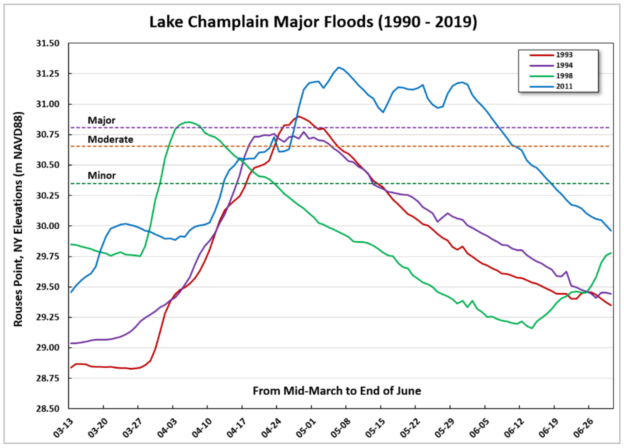


Figure 2-4 | Major floods of the 1990s and 2011 Event

Figure 2-4 shows the significant floods since 1990, including the 2011 flood water level during freshet for a three-month duration. The graph shows the duration of higher lake levels that can be classified in the moderate to major flooding category. When compared to the events in the 1990s, the enormity of the 2011 flood can be visualized by the duration of 41 days it stayed in the major flood zone, meaning above an elevation of 30.81 m (101.08 ft) NAVD88.

2.3 RICHELIEU RIVER HYDROLOGY

The discharge in the Richelieu River is related to the water levels in Lake Champlain. The common understanding is that the outlet of the lake is at Rouses Point. However, the outflow from Lake Champlain is dependent on the physical influence of the shoal at Saint-Jean-sur-Richelieu, so from a hydraulic perspective the outlet is at Saint-Jean-sur-Richelieu.

2.3.1 Richelieu River Peak Discharges

Figure 2-5 shows the peak annual outflows from Lake Champlain into the Richelieu River. The graph also captures the inflows into the lake. The important observation from this graph is that the peak outflows are significantly smaller than the peak inflows into the lake, demonstrating the self-regulating feature of this large lake. The degree of peak flow reduction in the Richelieu River, in the absence of anthropogenic regulation, is a function of the volume of spring runoff and the starting water level in the lake.

Both time series do not exhibit any apparent trend in both inflow and outflow peak flow series. By estimating the linear regression of peak flows over time as noted in Figure 2-5, the observation of a very slight downward trend is verified. The lack of a substantial trend suggests that T-year (return period) estimates based on frequency analysis are appropriate.

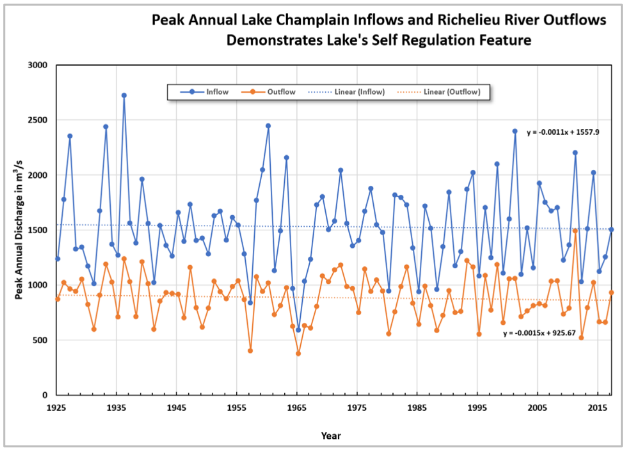


Figure 2-5 | Peak annual Lake Champlain inflows and outflows into the Richelieu River

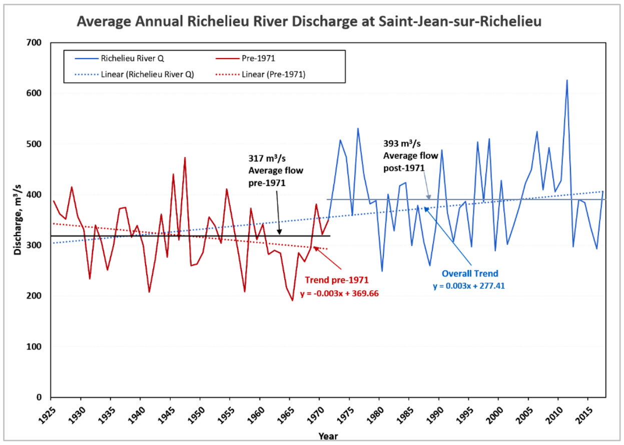


Figure 2-6 | Average annual outflows in Richelieu River, showing a step function and a shift in average flows

For the average annual Richelieu River flow series, Figure 2-6 shows an upward trend when the full time series of 1925 to 2017 is considered. This upward trend is misleading, however. As noted in Section 2.2.2, the total time series consist of two sub-series, one from 1925 to

1970 and the other from 1971 to 2017. Linear regression of pre-1971 records for annual discharge shows a downward trend, while the post-1971 data show no trend.

When the time series is split based on the Chambly Canal widening, along with higher NBS that forced higher annual water levels and associated outflows beginning in 1970, a step function becomes clear (Figure 2-6). After 1971, the average discharge showed a shift from 317 m^3/s (11,195ft^3/s) to 393 m^3/s (13,879 ft^3/s). This is an increase of 76 m^3/s (2,684 ft^3/s), translating into a 24% increase in post-1971 discharges. This also implies that the long-term trend when using all the data can be misleading as to what the future may be with regard to average annual discharges.

2.3.2 2011 Historic Flood

The confluence of warm temperatures, record precipitation, and rapid melting of a near-record snowpack caused historically high flood levels in the basin tributaries and in Lake Champlain and the Richelieu River (Saad et al. 2016). While spring flooding is common along the shores of Lake Champlain, the duration of the 2011 flood period was unprecedented. Lake levels remained above NWS's minor flood elevation of 30.35 m (99.57 ft) NAVD88 for 67 days at Rouses Point, from April 13, 2011 to June 19, 2011.

Over the 2010-2011 winter, snowfall in Burlington, Vermont, measured 326.14 cm (128.4 in), the third highest total since 1883 (NOAA 2011). In addition, no major thaw occurred mid-winter. The mean monthly temperatures from February to June were at or above mean temperatures. Total precipitation in the basin in March was 46 percent above average, while April experienced 174 percent and May 213 percent above average. The three-month spring total was also a record, higher than the previous record by 113.8 mm (4.5 in) (NOAA 2011). Table 2-3 shows the precipitation statistics for spring 2011 as recorded in Burlington, Vermont.

Table 2-3 | Precipitation in Burlington, Vermont, Spring 2011 (Causes and Impacts Report, LCRR 2020)

Month (2011)	2011		Normal		Amount > Normal		Percent increase over normal
	cm	in	cm	in	cm	in	
March	8.59	3.38	5.89	2.32	2.72	1.07	46 %
April	20.02	7.88	7.32	2.88	12.70	5.00	174 %
May	22.02	8.67	7.04	2.77	14.99	5.90	213 %
Three Month Total	**50.65**	**19.94**	**20.24**	**7.97**	**30.40**	**11.97**	**105 %**

An examination of the 2011 flows into Lake Champlain and the Richelieu River is shown in Figure 2-7. The extended period of high lake levels resulted in a flow into the Richelieu River of 1,490 m^3/s (52,619 ft^3/s) over a quarter-month period, or a maximum daily value of 1,550 m^3/s (54,736 ft^3/s). Figure 2-7 shows the lake's capacity to reduce the peak outflow. For the period of high spring inflows, the lake received 7.64 x 106 dam^3 (6.19 x 106 acre-feet) of water and utilized 1.34 x 106 dam^3 (1.09 x 106 acre-feet) of storage space in the lake. The capacity of the lake to provide this storage greatly reduced the flooding potential, notably along the Richelieu River corridor around Saint-Jean-sur-Richelieu. As presented in the graph, for the period where the inflows (blue line) into the lake are greater than the outflows (red line), the excess volumes are stored in Lake Champlain. This happened from start of March to late May. The lake is drained when outflows exceed the inflows. This happened from late May until late August when Hurricane Irene caused high inflows.

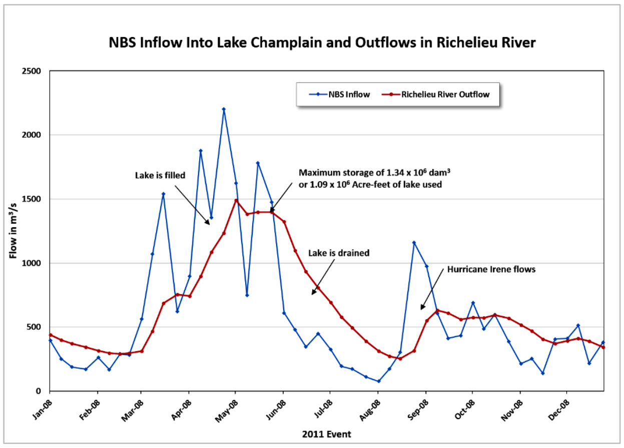


Figure 2-7 | NBS inflows and outflows into Richelieu River for 2011 flood

The flood resulted in a period of record maximum lake levels recorded at all lake gauges on Lake Champlain. The maximum recorded stage at Rouses Point, New York, was 31.32 m (102.77 ft) on May 6, 2011. Before the 2011 flooding, the highest lake level elevation recorded at the Rouses Point, New York, gauge was 30.90 m (101.35 ft) on May 4, 1869.

The record flood of 2011 was further exacerbated, at times, by wind set-up, due to persistent winds from the south. Historical observations of Lake Champlain elevations at the Rouses Point gauge have shown that water levels there can increase by 15.2 to 30.5 cm (6-12 in) when average south wind speeds over the lake range between 46.3 to 64.8 km/hr (25 to 35 knots) for durations of six hours or more. During the spring of 2011, Lake Champlain was in flood status for 67 days. Over that period, there were eight separate wind set-up events that pushed the nominal lake elevation up by between 7.6 and 21.3 cm (3 to 8.4 in). The most dramatic of these events occurred on April 23, 2011, when the lake was in minor flood status, just below the moderate flood level of 30.78 m (101 ft). The ensuing 21.3 cm (8.4 in) rise pushed the Rouses Point elevation into moderate flood and then past the 30.94 m (101.5 ft) major flood threshold. The wind event ended the next day and lake elevations were back down into the minor flood range. (Causes and Impacts Report, LCRR 2020)

The Richelieu River at Fryer Rapids exceeded flood flows of 1,064 m^3/s (37,575 ft^3/s) from April 20 to until June 28, a total of 69 days. This flow at Fryers Rapids corresponds to Rouses Point water level of 30.5 m (100.04 ft) NAVD88, which is slightly more than the flooding trigger of 30.35 m (99.55 ft). Increases in the elevation of Lake Champlain during the flood were translated downstream on the river and the same south winds amplified river stages.

A recent analysis conducted by Riboust and Brissette (2015b) determined that the return period of the 2011 spring flood exceeded 700 years and can be attributed to the combination of extreme precipitation over the spring season (500 years recurrence) and an important snowpack (15 years recurrence). Their modelling results show that if the snowpack that was recorded in 2008 occurred in 2011, the flood would have been even greater.

2.4 FREQUENCY ANALYSIS OF HYDROLOGICAL DATA

The study contracted INRS (Ouarda, et al. 2019) to investigate the hydrological and statistical properties of the key variables driving water levels and flows in the Lake Champlain – Richelieu River system. The project included evaluating:

1. Annual mean and maximum flows on the Richelieu River for given return periods.
2. Annual mean and maximum water levels for Lake Champlain for given return periods.
3. Annual mean and maximum net basin supplies (NBS) for the Richelieu River basin for given return periods.
4. Presence of trends and change points in the hydrological time series, including determining the links with anthropogenic modifications, natural evolutions, or climate changes; and considering the presence of potential change points and trends in the frequency analysis to remove their effects.
5. Future trends in the hydrological variables of interest.
6. Comparisons with neighboring watersheds.
7. Teleconnection analysis to identify climatic indices that affect the variables of interest and explain the inter-annual variability in these variables.

Some pertinent findings from the project are highlighted for this report. The first are the quantiles or return period estimates of water levels and flows for various time slices as per the report and augmented through personnel communications. The second is the generation of variables of interest for the next 50 years. As this has climate change signals embedded, this is discussed in Section 2.5.

2.4.1 Quantiles Corresponding to Return Periods of Interest

The project explored a variety of estimation methods using combinations of Probability Density Functions (PDF), domains, and estimation methods. A total of 11 different PDF, their associated domains, and four sample statistics estimation methods were employed. The goodness of fit was examined by five different methods, using a combination of PDF and estimation method. This resulted in a total of 180 different combinations of PDF and estimation statistics. By comparing the sample and PDF-based statistics and using established goodness of fit criteria, the most favourable PDF and associated estimation were recorded. For the purposes of this report, the full data set was sliced into four distinct periods to evaluate the impact of various anthropogenic and natural variations on the quantiles in comparison to the observed water levels and flows for the 2011 flood. The four time slices and their rationale are:

1. Full record, 110 years for water level and 93 years for flow – 1908 or 1925 to 2017.
2. Pre-widening and pre-wet period start –1908 or 1925 to 1971.
3. Period used for delineating flood areas on Richelieu River – 1971 to 2000.
4. Post-widening and wetter climate, 46 years of record – 1972 to 2017.

The statistics and quantiles are captured for five different return periods, as shown in Tables 2-4, 2-5, and 2-6. The current regulation of flood risk areas along the Richelieu River are shown for three return period floods; three of these quantiles, 2-year, 20-year, and 100-year, are depicted on the maps. The 20-year flood limits define the floodway zone, and the 100-year shows the flood hazard area (Dubé, 2006). This information will play an important role in determining the level of hazard that is most appropriate for recommended mapping. A comparison of the key statistics of water level and flows for the 2011 event, shown in the right-most columns of Tables 2-4 to 2-6, with the estimated quantiles provides an insight into the return period estimates.

A cursory analysis shows that for the variables attributed on an annual basis, the 2011 flood was close to the 150-year event for the time window of post-Chambly Canal widening and a rarer return period for other time windows analyzed and shown in Tables 2-4 to 2-6.

For the post-Chambly Canal time period, similar comparisons of quantiles with the maximum series show that for the Richelieu River flow (Table 2-5), the 2011 event was close to the 100-year event, and nearer to a 200-year event for the Lake Champlain water levels (Table 2-4).

Interestingly, comparisons of quantiles with the peak NBS series suggest a return period for the 2011 event of no more than 20 years (Table 2-6). The annual volume analysis, while useful on its own, does not reflect the high quarter-month volumes and resulting quantiles. If this NBS is further characterized to reflect a 60-day volume analysis, rather than an annual basis, a longer return period may be revealed. This analysis was not carried out.

Table 2-4 | Lake Champlain water levels - quantiles corresponding to specific return periods (Ouarda, et al., 2019)

Lake Champlain in Water Levels

Quantiles corresponding to return periods of interest

Variable	Return period	T-year WL m NAVD88	T-year WL m NAVD88	T-year WL m NAVD88	T-year WL m NAVD88	Observed m NAVD88
Distribution/Estimate		1908-2017	1908-1971	1908-2000	1972-2017	2011
		GEV/ML	GEV/ML	GEV/ML	GEV/ML	
Mean water level	2	29.11	29.02	29.08	29.25	
	20	**29.49**	**29.29**	**29.44**	**29.59**	
	50	29.59	29.35	29.53	29.67	
	100	**29.65**	**29.38**	**29.58**	**29.72**	**29.70**
	200	29.71	29.41	29.63	29.77	
Distribution/Estimate		N/ML	N/ML	N/ML	N/ML	
Maximum water level	2	30.19	30.15	30.19	30.25	
	20	**30.82**	**30.76**	**30.81**	**30.91**	
	50	30.98	30.91	30.97	31.07	
	100	**31.08**	**31.01**	**31.07**	**31.17**	**31.25**
	200	31.18	31.10	31.17	31.27	
		Full 110 years of record	*Pre-widening & pre-wet period - 64 years of record*	*Period used for floodplain delineation in SJSR*	*Post-widening & wetter climate - 46 years of record*	

GEV - Generalized Extreme Value, N - Normal, ML - Maximum likelihood

Table 2-5 | Richelieu River discharge - quantiles corresponding to specific return periods

Richelieu River Discharge

Quantiles corresponding to return periods of interest

Variable	Return period	T-year Q, m^3/s	T-year Q, m^3/s	T-year Q, m^3/s	T-year Q, m^3/s	Observed m^3/s
Distribution/Estimate		1925-2017	1925-1971	1925-2000	1972-2017	2011
		LN2/ML	LN2/ML	LN2/ML	LN2/ML	
Mean Richelieu River streamflow	2	347	312	336	386	
	20	**504**	**433**	**485**	**540**	
	50	553	470	531	588	
	100	**588**	**496**	**564**	**621**	**626**
	200	623	521	596	654	
Distribution/Estimate		GG/MM	GG/MM	GG/MM	GG/MM	
Maximum Richelieu River streamflow	2	937	972	958	910	
	20	**1270**	**1224**	**1246**	**1301**	
	50	1350	1270	1306	1411	
	100	**1402**	**1298**	**1343**	**1487**	**1550**
	200	1449	1323	1376	1558	
		Full 93 years of record	Pre-widening & pre- wet period - 47 years of record	*Period used for floodplain delineation in SJSR*	Post-widening & wetter climate - 46 years of record	

LN2 - 2 Parameter Log-Normal, GG - Generalized Gamma, MM - Method of moments, ML - Maximum likelihood

Table 2-6 | Net Basin Supplies - quantiles corresponding to specific return periods

Net Basin Supplies

Quantiles corresponding to return periods of interest

Variable	Return period	T-year NBS, m^3/s	T-year NBS, m^3/s	T-year NBS, m^3/s	T-year NBS, m^3/s	Estimated, m^3/s
Distribution/Estimate		1925-2017	1925-1971	1925-2000	1972-2017	2011
		GEV/MM	GEV/MM	GEV/MM	GEV/MM	
Mean water level	2	346	314	336	387	
	20	**504**	**422**	**485**	**543**	
	50	551	450	528	584	
	100	**583**	**468**	**558**	**611**	**610**
	200	613	484	585	634	
Distribution/Estimate		G/ML	G/ML	G/ML	G/ML	
Maximum water level	2	1485	1480	1479	1489	
	20	**2199**	**2236**	**2186**	**2159**	
	50	2406	2456	2391	2352	
	100	**2551**	**2611**	**2534**	**2486**	**2201**
	200	2688	2757	2670	2613	
		Fulf 93 years of record	Pre-widening & pre-wet period - 47 years of record	*Period used for floodpfain delineation in SJSR*	Post-widening & wetter climate - 46 years of record	

GEV - Generalized Extreme Value, G - Gamma, MM - Method of moments, ML - Maximum likelihood

2.5 CLIMATE CHANGE IMPLICATIONS

In the IJC directive, the Study Board was directed to examine the implications of a changing climate on future floods in the basin. To meet this requirement, the Study Board has adopted the IJC framework that includes using a broad range of approaches to determine potential future climate change water supplies. It is important to note that any structural alternatives that are proposed by the study will require a performance evaluation based on future climate change water supplies, to determine their robustness.

2.5.1 IJC's Climate Change Guidance

The IJC has developed a climate change guidance framework for use in the international basins (Figure 2-8). The purpose of the framework is to provide a process for the IJC to maintain, to the extent reasonably possible, the resilience of the ecosystems, economic and social benefits, and impacts of its managed systems despite the uncertainty about future change. The goal of the framework is to provide clear guidance to the boards for addressing climate change using the best available institutional and organizational science and stakeholder input to the boards. The framework prescribes four steps, repeated iteratively: organize, analyze, act, and update. The framework was developed collaboratively by the Climate Adaptation Working Group (CAWG), climate change experts, and IJC Board members from several basins, many of whom are also climate change experts (IJC, 2017). The framework has three major elements:

1. A recommended planning guidance method;
2. A shared information pool; and
3. Assistance in establishing adaptive management.

The recommended planning method is central to the framework; the other two elements (i.e., a shared information pool and assistance in establishing adaptive management) will support each board's successful planning. Many approaches have been used for climate change impact evaluation and adaptation planning in the last twenty years. An initial emphasis on projecting future climate has given way to approaches that focus on first understanding the responsiveness of the system to climate change, describing the context with regard to the full spectrum of possible future uncertainties, and using climate science to inform the analysis, rather than serving as the starting point and focus. The contrast between the early and later approaches is captured in the terminology. Downscaling focused on developing local climate projections from global models; ***decision scaling*** starts with an assessment of how climate change might affect outcomes and then considers the plausibility of those changes occurring.

Figure 2-8 | Climate change guidance framework

Downscaling was used in the study of the regulation of Lake Ontario releases (LOSLR 2006). Decision scaling was first used in the IJC study of the regulation of Lake Superior (IUGLS 2012) after its Study Board considered and rejected the use of downscaling.

In this study, the decision scaling approach will be employed considering the impacts and plausibility of different Net Basin Supplies (NBS) generated using climate models, stochastic analysis, and a Probable Maximum Flood (PMF).

2.5.2 Climate Change Studies

Numerous climate change analyses have been done for the basin in recent years and the study will build on these analyses. Stager and Thill (2010) prepared a technical report for the Nature Conservancy on climate change in the basin. Using output from 16 General Circulation Models (GCMs) and two emissions scenarios, climate change impacts on temperatures and precipitation were developed. By extension, the challenges of extreme precipitation events were noted. The report drew no conclusion about future flood levels, but outlined the need for additional research, some of which is being done by this study:

> *Understanding of hydrological processes in the watershed should be improved to allow more precise near-term forecasting of weather-related changes in lake level, stream flow and other environmentally important factors. More stream-level data are needed. An accurate watershed precipitation- and evaporation-response model could be helpful for both short- and long-term prediction of stream flow and lake level changes. (Stager and Thill, 2010)*

While these hydrological variables were noted, the focus was on the ecological impacts on flora and fauna.

Riboust and Brissette (2015a) concluded that most climate projections indicate the severity of most extreme spring floods may be reduced between 2041 and 2100, but that summer-fall extreme events, such as caused by hurricane Irene in August, 2011, may become more frequent in the future. In their work they used 372 downscaled climate projections from 19 GCM and nine Regional Climate Models (RCMs) with three emission scenarios. A total of 197 simulations covered the period of analysis 2040 to 2070, and 175 for the period 2071 to 2100. The study employed constant scaling and daily scaling methods. The major conclusion from the paper was that future extreme events may be quite different from the historic mean values, with the spring floods following a decreasing trend in lake levels. The study highlighted the challenges with uncertainty in modelling.

A more recent study by Huang et al. (2020) uses the Advanced Weather Research and Forecasting (WRF) model in predicting hydrological variables under climate change in the basin. The paper captured three five-year periods up to 2014 and essentially provides a proof of concept and applicability that is useful, as HHM TWG is using WRF as a forecasting tool for the study's "Theme 3" (flood response) work.

2.5.3 Study's Climate Change Work

A comprehensive climate change analysis was completed for this study by École de Technologie Supérieure (ÉTS). Most of the work reported in this section is captured in an earlier paper by Lucas-Picher et al. (2015) and two recent papers for the current study by Lucas-Picher et al. (2020a, 2020b). The investigation used:

- Two emission scenarios, termed RCP: Representative Concentration Pathways;
- 28 GCM, termed CMIP5 as per IPCC5;
- Six RCM, termed CORDEX, driven by five GCM for nesting purposes; these were operated for RCP 4.5 and 8.5; and
- 50 Canadian RCM #5 (CRCM5), termed CLIMEX, that were run only for RCP8.5.

The resolution varied 100 to 300 km for GCM, 25 to 50 km for RCM and 12 km for CRCM5.

The study employed Hydrotel (Fortin et al. 1995) as the driving hydrological model for representing the dynamics in the system. Hydrotel is the approved model used for all hydrological simulations in Quebec. Based on the multiple simulations, the results indicated the model adequately reproduces the observed events. It should be noted, though, that flood levels and average annual NBS are not well correlated and flood levels have almost no dependence on supplies after June.

The key findings from this analysis are that:

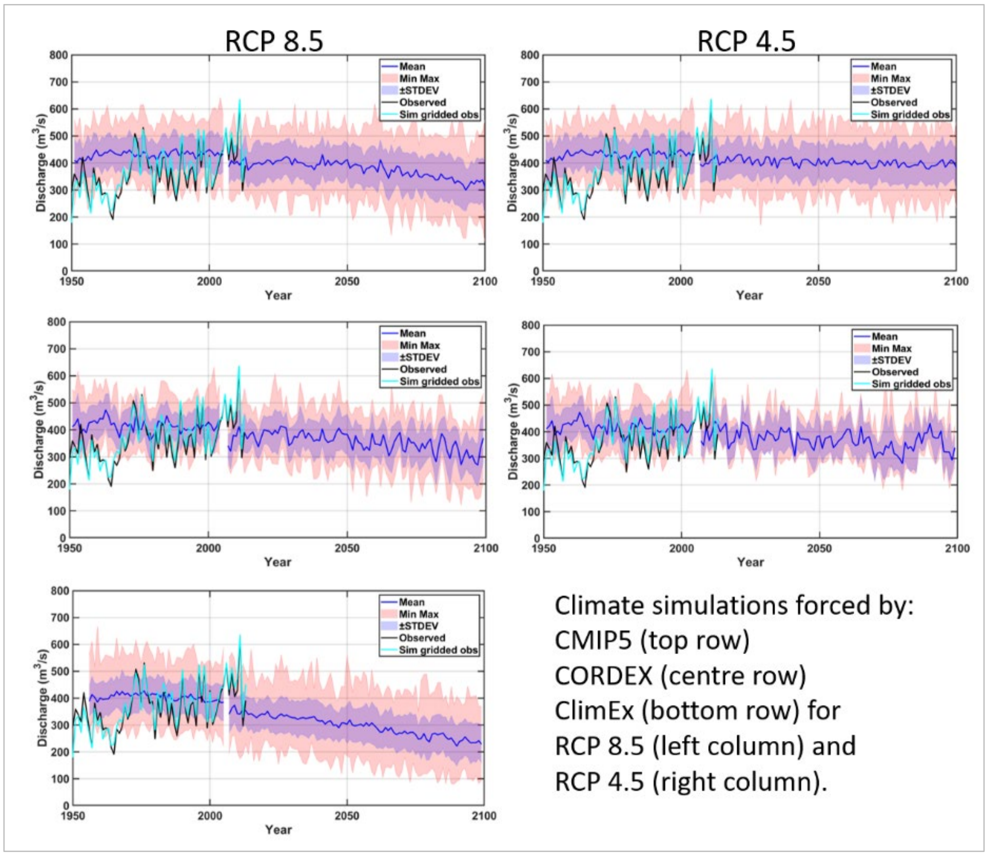
- there is a shift to earlier peak floods;
- the peak exhibits lower amplitudes;
- the volume is lowered with more reductions farther into the future; and
- mean low flows are extended.

Figures 2-9 and 2-10 capture the climate realizations from simulations from 1961 to 2100 of ensemble mean, minimum, maximum, and estimates of one standard deviation values, presented as follows:

- climate forcing by CMIP5 is presented in the top row,
- CORDEX in the centre row, and
- CLIMEX in the bottom row;
- the period covered in the analysis is 1950-2100;
- the results for RCP 8.5 are in the left column and RCP 4.5 in the right column.

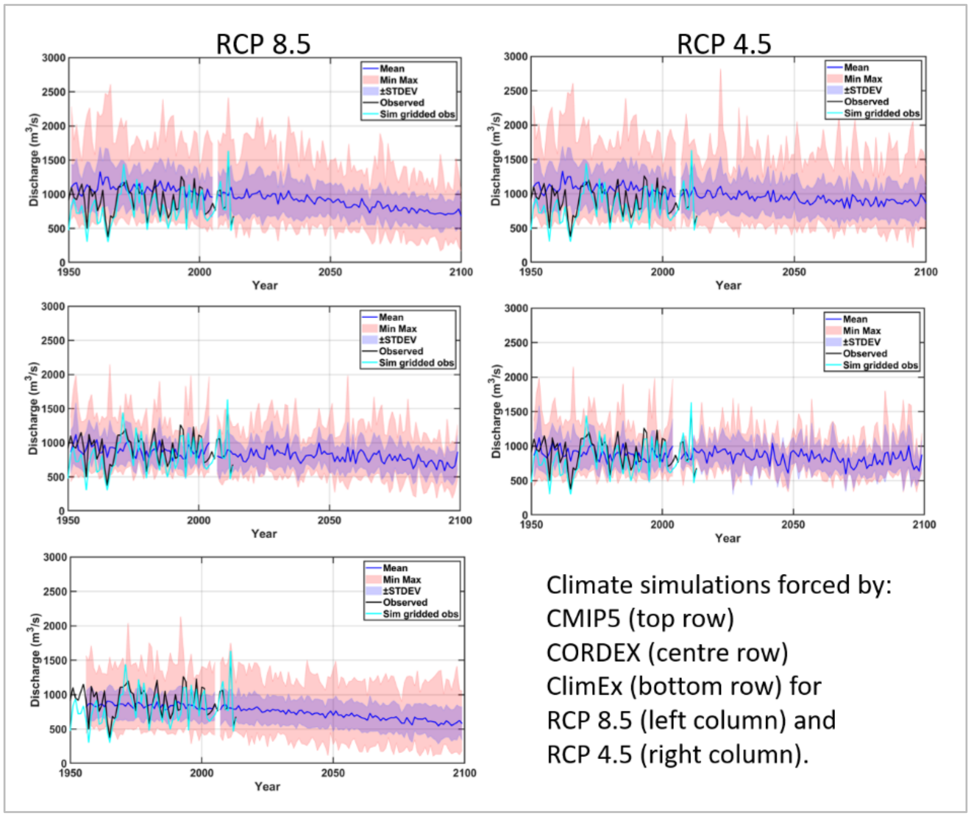
Figure 2-9 presents ensemble mean, minimum, maximum and ±STDEV of the mean annual simulated river discharge at Fryer station. The first year is removed as spin up. The same information for the 1-day spring maximum is captured in Figure 2-10. Only the first members of the CMIP5 models are presented here. The graphic shows the general decline in the average annual NBS and one-day flow in the 21st century.

For this report, only a preliminary assessment of Lake Champlain water levels under various climate change scenarios was made. Table 2-7 captures four such projections using the three outcomes from RCM and CRCM. The first two rows are for RCM and CORDEX. The next two rows are for RCP8.5 and the CLIMEX model. In the last row, the same variables show comparisons to the 2011 flood event.



Climate simulations forced by:
CMIP5 (top row)
CORDEX (centre row)
ClimEx (bottom row) for
RCP 8.5 (left column) and
RCP 4.5 (right column).

Figure 2-9 | Climate simulations of the mean annual flow in Richelieu River



Climate simulations forced by:
CMIP5 (top row)
CORDEX (centre row)
ClimEx (bottom row) for
RCP 8.5 (left column) and
RCP 4.5 (right column).

Figure 2-10 | Climate simulations of the peak annual flow in Richelieu River

Table 2-7 | Potential for a 2011 like flood in Lake Champlain Richelieu River under climate projections

Potential for 2011 Like Floods in Lake Champlain Richelieu River under climate projections					
Climate Change Series	**Peak NBS, m^3/s ft^3/s**	**Richelieu River Peak Outflow, m^3/s ft^3/s**	**Peak Lake Level, m ft NAVD88**	**60-Day Volume, Dam^3 x 10^6 Acre-feet x 10^6**	**Days above Water Level of 30.35 m**
Cordex_MPI-ESM-MR.CRCM5_44_MEMBER1_RCP45	2,594	1,501	31.41	7.40	51
	91,606	53,007	103.05	6.00	
Cordex_CanESM2.RCA4_MEMBER1_RCP85	5,600	1,751	31.77	7.25	36
	197,762	61,836	104.23	5.87	
Climex_kdo	2,938	1416	31.28	6.63	41
	103,755	50,006	102.62	5.37	
Climex_kev	3,450	1,323	31.14	6.34	39
	121,836	46,721	102.16	5.14	
Historic 2011 Flood Event	**2,201**	**1,547**	**31.23**	**7.64**	**67**
	77,728	**54,632**	**102.46**	**6.19**	

While other outcomes may not have a similar pattern, one aspect that stood out in all scenarios is that while the general trend is towards lower peaks, there are several events that are equal to or exceed the observed 2011 flood. Some of these events show significantly higher NBS peaks, longer duration above flooding threshold, and higher volumes of water. In this table, all climate projected events and their key statistics like NBS, peak outflow through the Richelieu River, peak Lake Champlain water levels, 60-day volumes, and the number of days above a peak threshold of 30.35 m (99.57 ft) NAVD88 water level are shown. For comparison purposes, all the climate outcomes are compared with similar statistics for the 2011 events.

Based on this analysis, while exhibiting a general downward trend in Lake Champlain water levels, there may be enough signals that indicate the presence of significant flood events similar to features of the 2011 flood. Much of this will be part of discussion in the decision scaling work for addressing climate change.

2.5.4 Extension of Forecasts for 50 Years

A second key product of the project (Ouarda et al. 2019) is the extension of the time series forecast by 50 years, using the empirical mode decomposition (EMD) method. If there are climate change signals in the full annual data series, this is brought to the fore. As noted in the report,

> *"the level of success of the method depends on the length of the series of the analysis and the phase of the various low frequency climate oscillation indices that influence the series." (Ouarda et al. 2019)*

Using the EMD technique, the project analyzed annual Lake Champlain water levels, Richelieu River flows and NBS, and predicted these variables of interest for the next 50 years. The results are presented in Figure 2-11. From the graph, there is potential for high water levels and flow in the future climate. These observations need to be verified by the current work being undertaken by the study on stochastic analysis and decision scaling (see Section 2.5.5). In Figure 2-11 below, the solid blue line represents the observations; the thick solid line shows the selected Intrinsic Mode Functions (IMF) components and the mean of the generated 200 realizations for the extension of 50 years; and the dotted gray lines represent the 200 realizations.

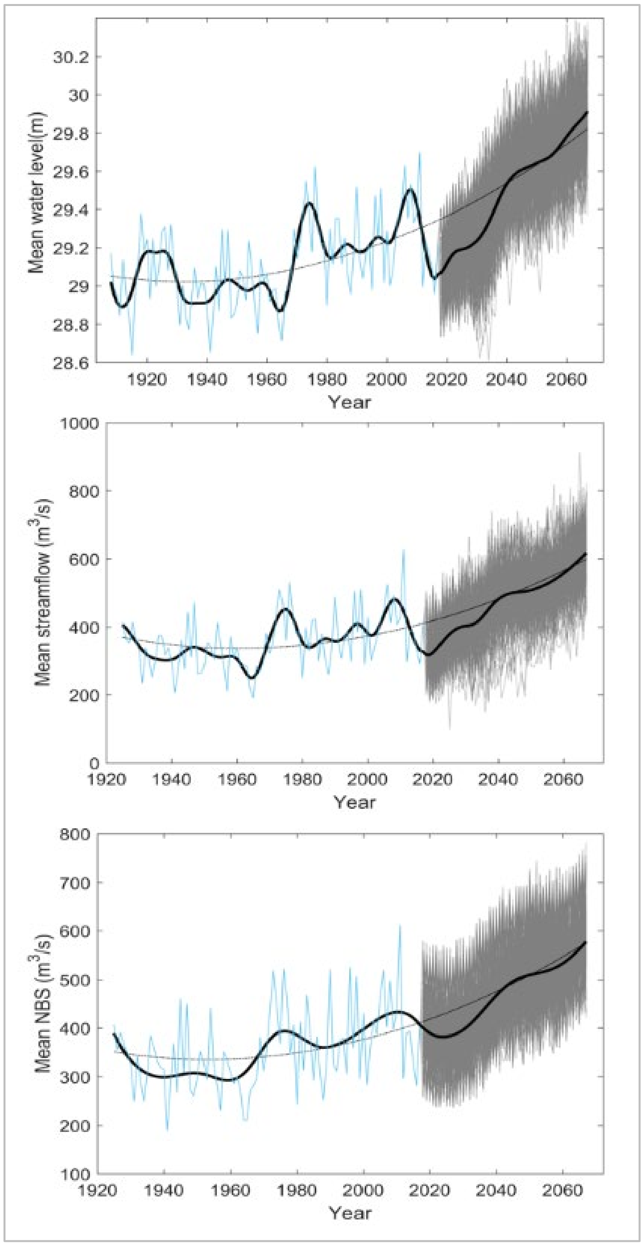


Figure 2-11 | Extension of the time series forecast for 50 years

The 2019 statistical report by Taha Ouarda (INRS) includes non-stationary analysis to demonstrate the non-linearity in the mean and maximum lake levels, NBS, and outflow in the Richelieu River. That is shown in Figure 2-11. While the mean variables demonstrated non-linearity (including shifted mean), the peak values did not. The 2019 report indicates that the impact of the generally higher NBS on flooding is muted by a trend to lower NBS in the spring flood season. This finding is currently being explored to better understand the extent to which trends in the historical record are predictive of flooding, as climate change affects precipitation, evaporation, and snowmelt differently.

2.5.5 Assessment of Climate Change using the IJC Planning Guidance

Research conducted for the study shows that there has been no trend in peak annual water levels, while average annual water levels have risen significantly due to higher levels in non-flooding periods (winter, summer, and fall). The structural flood damage reduction projects are evaluated primarily in terms of damages avoided. The future damages are unknown and must be projected. The frequency of various flood levels in the future is estimated using statistical models based on the assumption that climate was stationary over the planning horizon. If that is not true, statistics cannot be used without caveats. The recent history of Lake Champlain floods makes the point. The empirical mode decomposition method shown in Figure 2-11 shows some promise and is being further explored in the ongoing IJC LCRR stochastic and decision scaling studies.

These recent climate change studies predict a mix of declining trend in lake levels because of climate change for the warm and dry scenario RCP 8.5, a similar trend as in historic observation for RCP 4.5, and an upward trend through empirical mode decomposition. In 2011, the basin experienced the flood of record, much larger than any previous flood, when some climate runs showed a decline in the flood potential. The probabilities of flood events under climate change will be further explored through the decision scaling framework.

3 THE RICHELIEU RIVER

3.1 HYDRAULIC CONTROL SECTION

The Richelieu River discharge is mainly dependent on the Lake Champlain water level, including the effect of any accompanying wind surge.

The north draining Richelieu River, between Rouses Point and Sorel, is a flat valley dropping 28 m (79.1 ft.), punctuated by notable features at the shoal, Fryers Dam, and Chambly basin. The water elevation of the river at Rouses Point is 30.1 m (98.8 ft.) and at its outlet in Sorel, 6.0 m (19.7 ft.).

The key feature of the Richelieu River is a rock shoal, about 37 km (23.1 mi) from the lake, in Saint-Jean-sur-Richelieu. Lake levels are controlled by a series of rapids along a one km (0.6 mi) long reach of the Richelieu River south of this rock sill that defines the Haut-Richelieu region. As will be demonstrated, many characteristics of the reach between Rouses Point and Saint-Jean-sur-Richelieu behave as an extension of the water body of Lake Champlain and can in effect be considered as such.

At several structures across the river, the water level drops between the upstream and downstream faces of the bridges by an amount dependent on the obstruction, type and number of piers, etc. If all these hydraulic losses are removed, that leaves a very mild water level slope of 43 cm (16.9 in) between Rouses Point and the shoal over a distance of 37 km (23.1 mi.). This slope of 1.16 cm/km (0.73 in/mi) and an average channel cross-section can convey a discharge of about 818 m^3/s (28,886 ft^3/s) through this reach. The Saint-Jean-sur-Richelieu shoal is the hydraulic control for the system and naturally regulates the water levels in the river and the lake. Figure 3-1 illustrates the layout of the river and associated longitudinal profiles for three flow conditions.

An examination of hydraulic characteristics of the Richelieu River indicates a series of tranquil stretches punctuated by control points and rapid flow sections at the Fryer Island Dam and Chambly. As the 1970s studies concluded, no alternatives in the downstream reaches of the river will ameliorate flooding between Saint-Jean-sur-Richelieu and upstream to the lake.

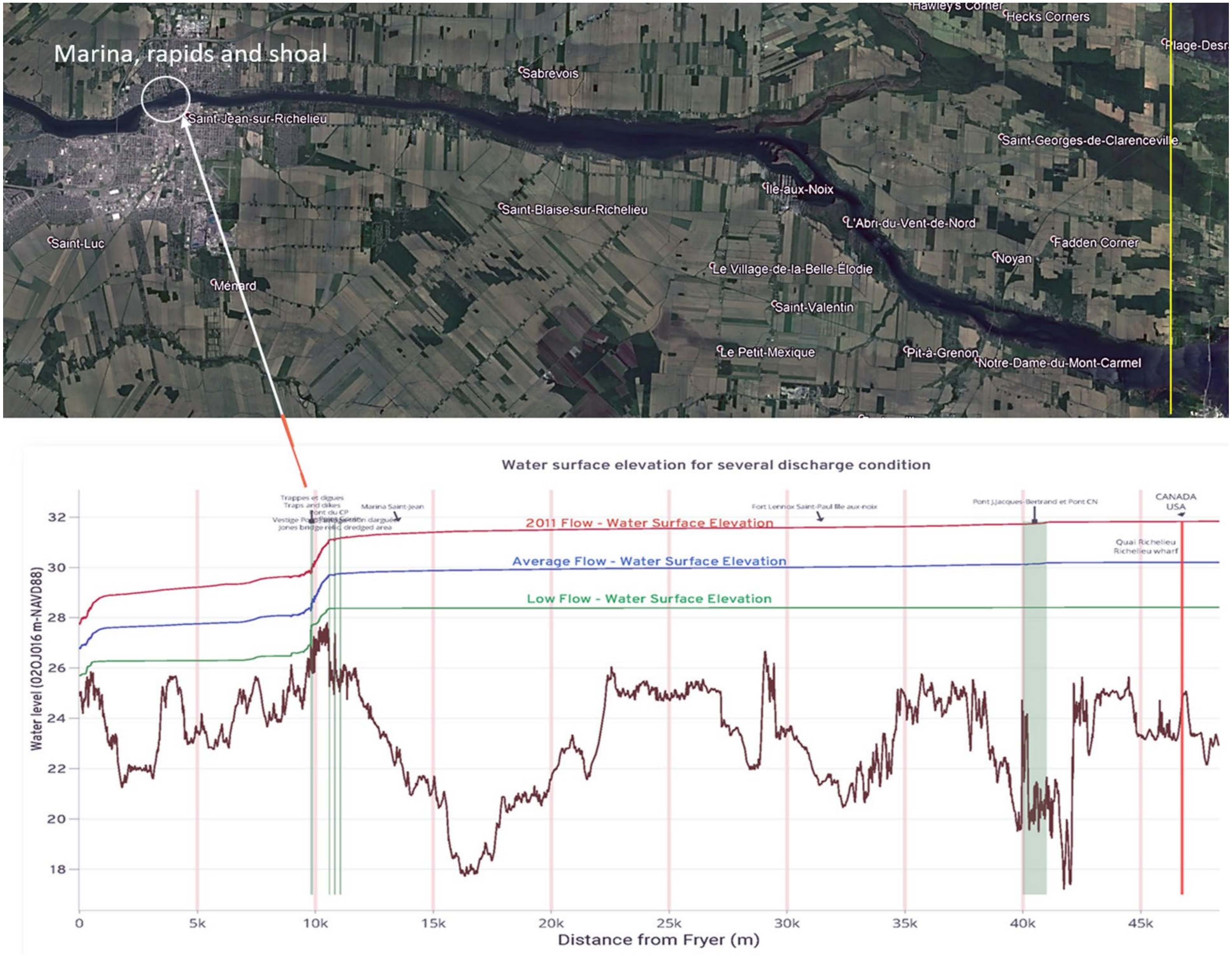


Figure 3-1 | *Longitudinal profile for Richelieu River, Rouses Point to Fryer Island Dam*

3.2 HUMAN INTERVENTIONS IN THE RIVER

A bathymetric map of the shoal (Figure 3-2) shows that there have been numerous human interventions and modifications made to the riverbed. There are submerged dikes that channel the flow to former mill areas; the remnants of an eel trap (Figure 3-3) are clearly visible; and an artificial island was constructed and modified at various times. As the shoal forms the outlet and a control point for the system, the study's focus is on alternatives in and around the shoal area.

Table 3-1 shows the long history of human interventions in the Richelieu River that have impacted the flow and water levels (ILCRRSB 2020). These interventions include the construction of many bridges across the river (primarily the bridge piers), some of which have now been demolished or are in the process of being demolished. Other works include construction or modifications to the Chambly Canal, building of a major eel trap (no longer in use), submerged dikes to divert flow to now obsolete mills and the Fryer Island Dam. There also have been four major dredging episodes in the Richelieu, with the last one conducted in 1939.

Along the whole extent of the Richelieu River there has been encroachment and infilling, not well documented, that is impacting flows and water levels but is not captured in the table.

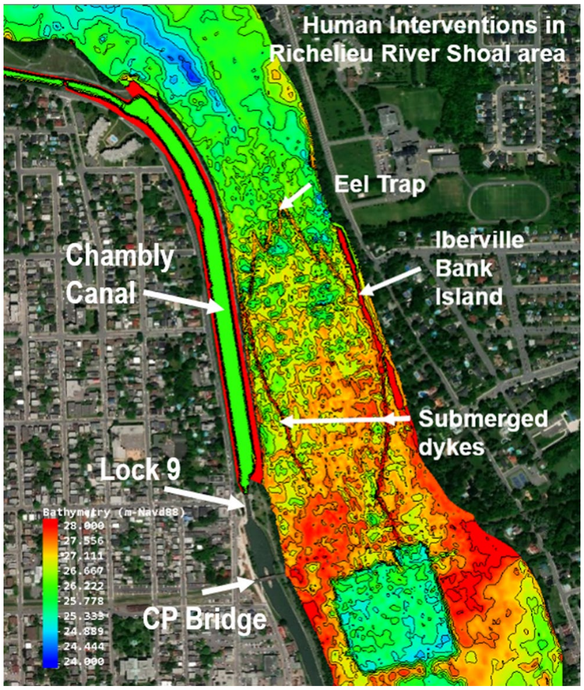


Figure 3-2 | *Human intervention on the shoal*

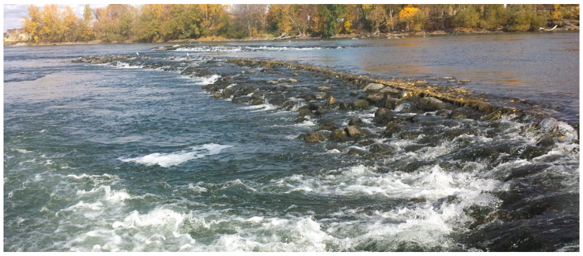


Figure 3-3 | *Eel trap located on the shoal*

Table 3-1 | Selected human interventions in the Richelieu River

Dates	Construction / Modification
1826	Construction of Jones Bridge
1831-1843	Construction of the Chambly Canal
Between 1830 and 1886	Construction of eel trap fisheries and mills with extensive dikes
1874	First dredging work near Ile-aux-Noix
1882	Construction of the old Noyan-Lacolle Bridge
1887	Construction of the Canadian Pacific Railway Bridge at Saint-Jean
1888	Construction of the Atlantic Railway Bridge near Lacolle
1891	Extensive dredging near the port of Saint-Jean
1908	Dredging between Jones Bridge and Central Vermont Bridge
Between 1908 and 1911	Extensive large land filling near the Vermont Central Bridge, now the Saint-Jean-sur-Richelieu Marina
1909-1910	Extensive dredging between Jones Bridge and Central Vermont Bridge (spoil left on the Iberville side upstream of the Central Vermont Bridge)
1915-1918	Construction of the Gouin bridge
1916	Demolition of the Jones Bridge
1928-1930	The Canadian government undertakes dredging works. The Richelieu River is dredged to 3.66 m (12 ft) between Sorel and Saint-Ours
1930-1933	A new lock is constructed at the St. Ours Canal
1938	Construction of the Fryer Island Dam
1939	Dredging to a depth of 3.66 m (12 ft) between Saint-Jean-sur-Richelieu and Rouses Point (Sévigny 1978)
1967	Demolition of the Central Vermont Bridge
1970	Start of expansion work of the Chambly canal downstream of lock number 9
1973	End of extension work of the Chambly Canal
2017-2019	Construction of the new Gouin Bridge
2020	Projected demolition of the 1915 Gouin bridge structure

3.3 HYDRAULIC IMPLICATIONS OF THE HUMAN INTERVENTIONS

Input from various reports and hydraulic modelling were undertaken to quantify the impacts of these various human interactions in the river (Table 3-2). In several cases it was not possible to determine the impacts, due to a lack of information or reliable data. There also is a significant amount of uncertainty associated with the values that have been generated that must be considered. However, this information does serve to illustrate that human interventions have had a significant impact on the Richelieu River and Lake Champlain water levels.

A compilation of these impacts using 2011 flood flow conditions indicates that water levels could have been raised in the Richelieu River by as much as 63.5 cm (25 in) and levels on the lake raised by 46.5 cm (18.3 in) since the mid-1850s. While all of these impacts combined add up to a substantial number, the interventions from the 19th century contributed 24 cm (9.4 in) in the river and 22 cm (8.6 in) on the lake. Of the remaining structures, the widening of the Chambly Canal in the early 1970s and its entrance pier in early 1980s contributed to 22 cm (8.7 in) in Saint-Jean-sur-Richelieu and 12 cm (8.7 in) on Lake Champlain. All figures were obtained from the hydrodynamic modelling conducted by HHM TWG (Champoux 2020).

Table 3-2 reflects discrete human interventions that are documented, but there are others such as increased weed growth and human encroachment that have also contributed to higher water levels for which the impacts have not been quantified (ICRB 1978).

Not all of these impacts can be reversed, but it may be possible to mitigate the impacts from some of them to help reduce water levels. This will be explored as part of this current study.

Table 3-2 | Estimated hydraulic impacts of human interventions on 2011 flood (discharge of 1,537 m^3/s)

Feature	Date Constructed	Impact on River Water Levels	Impact on Lake Water Levels
Eel trap on shoal	1850s	3 cm (1.2 in)	2 cm (0.8 in)
Submerged mill dikes on shoal	1860s	6 cm (2.4 in)	4 cm (1.6 in)
Combined - Eel trap and submerged mill dikes		6 cm (2.4 in)	6 cm (2.4 in)
Artificial Island at Saint-Jean-sur Richelieu	1860s	7 cm (2.8 in)	5 cm (2 in)
CMQR (CPR) Railroad Bridge at St. Jean	1887	11 cm (4.3 in)	11 cm (4.3 in)
Fryer Island Dam	1939	6 cm (2.4 in)	4 cm (1.6 in)
Chambly Canal Entrance Pier	1970s	2 cm (0.8 in)	2 cm (0.8 in)
Widening of the Chambly Canal	1970-1974	20 cm (7.9 in)	10 cm (3.9 in)
Gouin Bridge at Saint-Jean-sur Richelieu	2018	2.5 cm (1.0 in)	2.5 cm (1.0 in)
Total Impacts		**63.5 cm (25 in)**	**46.5 cm (18.3 in)**

These impacts were computed from hydrodynamic modelling by the study

4 HISTORY OF PROPOSED STRUCTURAL MITIGATION MEASURES

4.1 1930S IJC REFERENCE

Following severe flooding in the 1930s, in 1937 the IJC received its first reference from the governments to address the flooding problem in the basin. The IJC determined that flood control structures were the most effective way of addressing the flooding (IJC 1938). At that time, the primary focus was on socio-economic benefits, with little consideration given to potential environmental issues related to the regulation of flow. However, it is interesting to note that both Québec and Vermont raised the issue of possible environmental impacts, although this received little consideration at that time (Brande and Lapping, 1979).

The governments agreed with the IJC's proposed course of action and the Canadian government submitted an application (i.e., formal request to undertake specific engineering work in boundary waters) to the IJC. In 1938, the IJC approved the application and construction of the dam, which is the Fryer Island Dam, located about 8 km (5 mi) downstream of Saint-Jean-sur-Richelieu (IJC, 1938).

Construction of the Fryer Island Dam was completed in 1939. With the outbreak of World War II, the remedial works and dredging of the shoal in the river near Saint-Jean-sur-Richelieu were put on hold, and even after the war ended, these supporting works were never completed. Eventually, the project was abandoned; it is unclear exactly why. The deteriorating abutments of the Fryer Island Dam in the Richelieu River are a reminder of this unsuccessful effort to address the flooding issue (Figure 4-1). In 2016, the pathway across Fryer Island Dam was closed off and further work is being done from a safety perspective.

Figure 4-1 | Fryer Island Dam (https://www.pc.gc.ca/en/lhn-nhs/qc/chambly/culture/ingenierie-engineering/barrage-fryer-dam)

4.2 1970S IJC REFERENCE

Major flooding in the early 1970s resulted in a second reference to the IJC in 1973. This reference focused on assessing potential structural solutions to the flooding problem. The governments requested the IJC:

> *"... investigate and report upon the feasibility and desirability of regulation of the Richelieu River in the Province of Quebec for the purpose of alleviating extreme water conditions in the Richelieu River and in Lake Champlain, and for other beneficial purposes."*
> *(reference letter dated March 29, 1973)*

Given the severity of flooding, the governments requested the IJC produce its report within one year of receipt of the reference, an extremely ambitious timeline.

The International Champlain-Richelieu Engineering Board (ICREB) submitted its report to the IJC in March 1974. The report concluded that a regulatory structure located in the shoal at Saint-Jean-sur-Richelieu would effectively address the flooding issue and was cost-effective (ICREB 1974). The board did assess utilizing the existing Fryer Island Dam and concluded that it would be significantly more costly to fully implement this option and it would not achieve all the desired results.

Public meetings were held in the fall of 1974 to determine support for pursuing a regulatory structure to mitigate flooding in the basin. Two major concerns were raised in these public meetings:

- environmental consequences of regulation needed to be more fully assessed; and
- the economic evaluation and the projected net benefits that would be achieved through regulation were challenged.

In March 1975, the IJC submitted an interim report to the governments. The report concluded that, aside from the undetermined environmental consequences, regulation was desirable and could be achieved by means of a dredged channel and a gated control structure in the shoal section at Saint-Jean-sur-Richelieu (IJC 1975). However, the IJC recognized the two principal weaknesses of the ICREB's report. It therefore recommended to the governments that the ICREB undertake a comprehensive environmental assessment and prepare an accurate determination of the net benefits of regulation to each country, applying uniform criteria and methodology. The report also pointed out that an application would need to be submitted to the IJC prior to any construction being initiated.

In April 1975, the IJC dissolved the ICREB and appointed the International Champlain-Richelieu Board (ICRB) with a revised mandate. The new ICRB was directed to develop a plan of study and focus on providing the IJC with recommendations as to the most practical method of regulation that would limit the adverse environmental effects, while achieving flood control benefits in the basin.

Prior to the 1973 reference, the government of Québec had conducted a number of studies to address the flooding issue at Saint-Jean-sur-Richelieu. In collaboration with Environment Canada, Québec completed a report that concluded that a viable and cost-effective solution involved the dredging of the shoal and the installation of a fixed crest weir. It was determined that this would provide a certain measure of flood control while maintaining low water levels on Lake Champlain at or near their natural levels (Environment Canada and Department of Natural Resources (Québec), 1975). This bypassed the issue of getting agreement on a regulation plan that would be necessary with a gated structure.

In January 1976, the Government of Canada, with the concurrence of Québec, submitted an application to the IJC to dredge the Saint-Jean-sur-Richelieu shoal and construct a fixed crest weir (Figure 4-2). In February 1976, the IJC responded that that it would be deferring its decision until after the ICRB had completed its assessment.

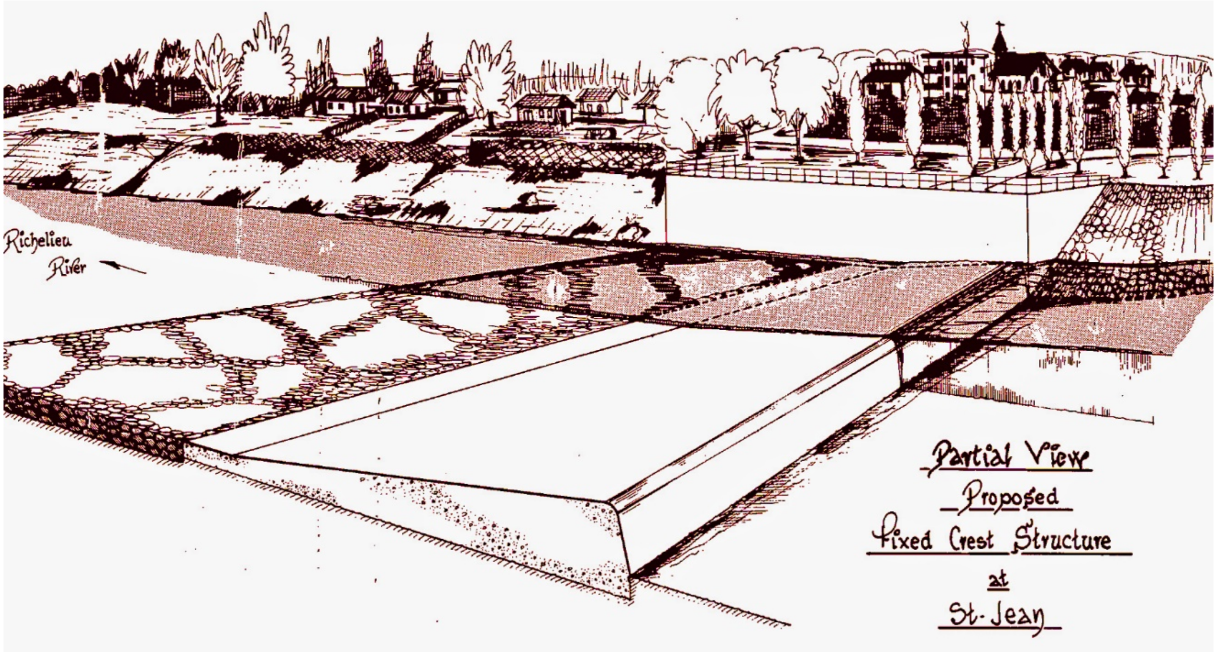


Figure 4-2 | Fixed crest weir at Saint-Jean-sur-Richelieu

The IJC (1981) after further study determined that the fixed crest weir was not an acceptable solution because it was not capable of regulating water levels on Lake Champlain and therefore could not meet the environmental criteria it had established for evaluation purposes.

4.2.1 International Champlain-Richelieu Board

Considerable work was conducted by the ICRB in the selection of a regulatory structure and in developing a regulation plan that would minimize the environmental impacts while still ensuring the flood reduction benefits. Three technical reports were prepared to address key aspects:

- Regulation of Lake Champlain and Upper Richelieu River: Technical Report of the Physical Aspects Committee (1977a);
- Regulation of Lake Champlain and Upper Richelieu River: Technical Report of the Net Benefits Committee (1977b); and
- Regulation of Lake Champlain and Upper Richelieu River: Technical Report of the Environmental Impact Committee (1977c).

The ICRB submitted its final report, "Regulation of Lake Champlain and the Upper Richelieu River", to the IJC in 1977 (ICRB 1977d). The report concluded that the ICRB could not recommend non-structural alternatives alone because, at best, only 20% of the flood damage could be eliminated. The 20% would be achieved through the implementation of the flood forecasting and warning system in conjunction with flood plain regulation that focused on preventing development in flood-prone areas.

The ICRB therefore recommended that:

- a combination of structural and non-structural solutions be implemented to reduce damages to shoreline and agricultural interests on Lake Champlain and the upper Richelieu River to the maximum extent possible while maintaining the seasonal rhythm of lake levels and protecting the ecosystem of the lake and river;
- a new six gated structure (Figure 4-3) be constructed near Saint-Jean-sur-Richelieu, managed with a regulation scheme (referred to as Scheme FCE-1) that would reduce the average maximum water level during the spring by about 37 cm (1.2 ft.) to fully meet environmental and downstream criteria;
- a flood forecasting and warning system be implemented, and flood plain regulation be adopted as an essential addition to the recommended new gated structure; and
- United States and Canada equally share the costs of constructing, operating and maintaining the gated structure and the capital costs of the flood forecasting and warning system.

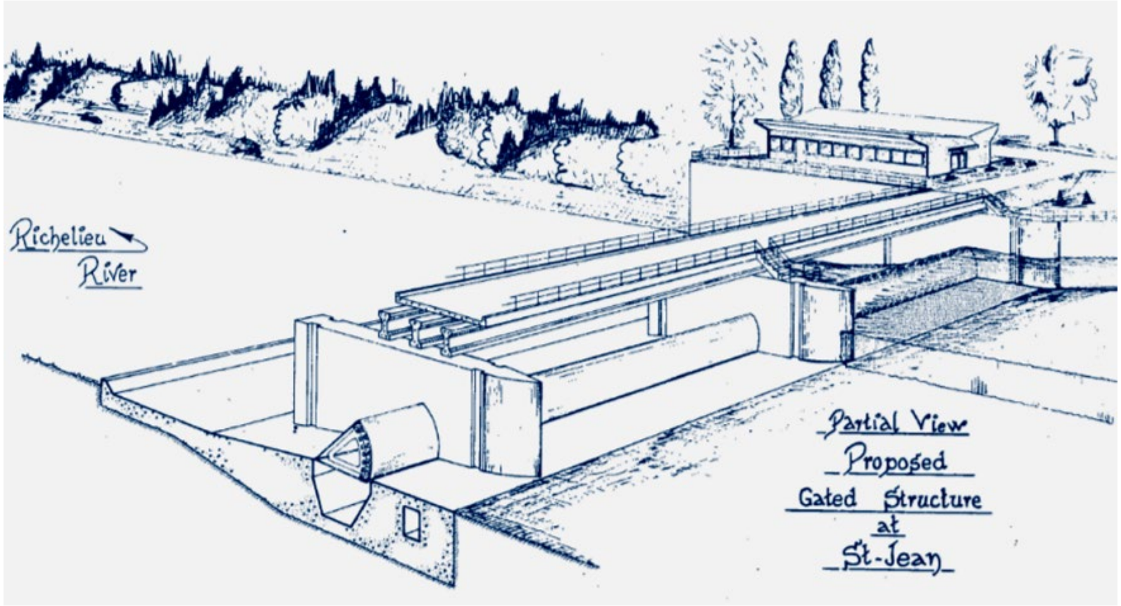


Figure 4-3 | Six-gated structure near Saint-Jean-sur-Richelieu

In addition, the ICRB concluded that while a measure of flood control and maintenance of environmental quality are compatible, additional environmental studies and monitoring were necessary for the initial 10 years of operation to evaluate and refine environmental and downstream criteria. It further recommended that any board of control established by the IJC should include representatives of environmental management agencies on the lake and river.

During its work, the ICRB learned that the Chambly Canal had recently been widened. It concluded that the consequences of this work on the Richelieu River's flows and water levels needed to be fully examined as part of any overall plan to address flood protection and mitigation (IJC 1977d).

4.2.2 Chambly Canal Issue

In early 1970, Transport Canada (Chambly Canal responsibilities later transferred to Parks Canada) proceeded with widening the canal along the Saint-Jean-sur-Richelieu reach by about 30 m (100 ft) into the main channel. The Quebec canal division of the Federal Department of Indian and Northern Affairs carried out certain construction involving the upper portion of the Chambly Canal between March 1970 and April 1971 and from July 1971 to March 1973 (ICRB 1978).

It is not clear that it was understood that widening the canal, which would result in raising upstream water levels, would consequently require review under Article IV of the Boundary Waters Treaty (1909), which states:

> *"The High Contracting Parties agree that, except in cases provided for by special agreement between them, they will not permit the construction or maintenance on their respective sides of the boundary of any remedial or protective works or any dams or other obstructions in waters flowing from boundary waters or in waters at a lower level than the boundary in rivers flowing across the boundary, the effect of which is to raise the natural level of waters on the other side of the boundary unless the construction or maintenance thereof is approved by the aforesaid International Joint Commission."*

The widening of the canal proceeded in stages over four years and finally was completed in 1974. Figure 4-4 shows the extent of the widening of the Chambly Canal and the associated reduction in the width of the main river channel (IJC, 1977d).

Figure 4-4 | Chambly Canal widening

As part of its work, the ICRB undertook several studies to quantify the hydraulic impacts of the widening using different scientific approaches (Table 4-1).

Table 4-1 | Estimated water level changes in Lake Champlain due to the widening of the Chambly Canal (Ad Hoc Committee, ICRB, 1979)

Method of Analysis	Effect at High Flow (cm)	Effect at High Flow (in)
Mathematical model	+9.1	+3.6
Physical model	+3.0	+1.2
Hydrometric gauge stage-discharge relationships	+4.3 to +10.06	+1.7 to +4.0

In general, the three different methods produced results indicating an increase in water level ranging from 3-10 cm (1.2-4 in). The stage-discharge relationships methodology produced slightly higher and more variable results, which was attributed to increased weed growth impacting the water levels during this period. The fact that the different methods of analysis produced comparable results provided the ICRB with a high level of confidence in the assessment of the hydraulic implications of the widening of the canal. Although the impact was relatively small, efforts were made to determine how the impact could be mitigated.

The ICRB also considered modifying the canal so it could be used to pass flows during floods. In the spring of 1979, a field study was conducted by an ad hoc Committee of ICRB. The objective was to test the structural integrity of the canal to pass higher flows through it. If higher flows could be routed through the canal, then this solution could be used to help mitigate the impacts caused by the canal widening (Ad Hoc Committee, ICRB, 1979).

To address the issue, a limited field test was conducted over a 2-day period. Flows of up to 65 m^3/s (2,285 ft^3/s) were routed through the canal with that maximum flow only sustained for one hour. The flow in the Richelieu at that time was not particularly high, 803 m^3/s (28,364 ft^3/s). Based on these limitations, a full prototype verification of the hydraulic behaviour of the canal as a bypass channel was not able to be obtained (Ad Hoc Committee, ICRB, 1979).

Mitigation of the effects of the canal widening was a source of contention, particularly in the United States. This, in turn, prompted the IJC to send an alerting letter to the Canadian government on July 6, 1979, with a copy to the U.S. government. In the letter, the IJC requested that the Government of Canada:

> *"...should take the necessary steps to have an application filed with the Commission for approval of these works by the appropriate party, in order that the Commission carry out its responsibilities under the Treaty."*

It would appear that this letter was sent by the IJC to make it clear that no application was received, under the Boundary Waters Treaty, for the canal widening. No formal response was given by the Government of Canada to the IJC's alerting letter.

4.2.3 IJC Perspective on Regulation and Advice to the Governments

After the ICRB's report was submitted, the IJC engaged in extensive public consultations over a two-year period. It convened four sets of hearings and deliberated over the numerous submissions that were received. Key issues raised included the potential loss of wetlands, particularly in the United States, fish habitat loss, and issues concerning the benefit-cost analysis. The environmental issues were an overriding concern for the United States and resulted in little support for regulation, even though the proposed regulation plan that was selected to a large degree addressed the environmental criteria. In Québec, the views were mixed but in general there was support for the proposed regulation option.

In 1981 the IJC submitted its report to governments that addressed the various issues that were raised. The report concluded with this final assessment:

> *"Although the Commission has concluded that it is technically feasible to operate a gated structure at Saint-Jean that accommodates the proposed environmental criteria, the Commission was unable to determine the desirability of the gated structure and therefore is unable to make recommendations regarding the regulation of Lake Champlain and the Richelieu River. However, the Commission does recommend that a flood forecasting and warning system be instituted as soon as practicable and that flood plain regulation be implemented by the appropriate jurisdictions as a matter of urgency."(IJC 1981)*

4.2.4 Response to IJC 1981 report

Media releases following the release of the report indicated some support for the proposed regulatory structure in Québec. However, the proposed structural solution was not supported by Vermont and New York constituents.

The governments of Canada and the United States never officially provided a response to the IJC's report. It was clear from the extensive press at that time that there was little desire by Vermont or New York for the proposed regulatory structure (Rutland Daily Herald, 1978).

After the 2011 spring flood, there was renewed interest in strengthening the existing flood forecasting and warning system in the basin that was recommended in the 1981 report.

4.3 STRUCTURAL MITIGATION LEGACY

Implementing a structural solution to address wide-spread flooding in this shared basin has been challenging, as the history shows. A structural solution (notably a dam), in the past, had twice been determined to be the most effective measure for addressing the flooding issue (IJC 1938, 1981). However, implementing this solution has either been unsuccessful as in the first reference, or met with opposition as in the second reference.

The IJC has directed the current study to focus on non-structural and only moderate structural solutions, given the history regarding construction of a significant dam. This is based on the reference provided by the governments:

> *"...a quantitative and qualitative assessment of potential flood management and mitigation measures (non-structural and/or moderate structural works) and their impacts on important resources of the system: the wetland and fauna, recreational, domestic, industrial and municipal uses of water, shoreline and floodplain built environment and agriculture." (reference letter dated September 16, 2016).*

There is some ambiguity as to what "moderate" entails, so this review explored the broad range of structural measures that could be employed in an effort to find an acceptable structural solution to address the flooding issue. The Study Board will ultimately be responsible to make the judgment as to what is moderate in light of the solutions proposed in this report and what structural alternatives should be brought forward for a comprehensive evaluation.

5 STRUCTURAL FLOOD MITIGATION MEASURES

5.1 STUDY FLOOD MITIGATION FRAMEWORK

The Study Board has adopted a Flood Mitigation Framework (Figure 5-1) to ensure that flooding in the LCRR Basin is addressed in a comprehensive manner and a broad range of solutions are considered.

It addresses the two key fundamental approaches to flooding: structural and non-structural solutions. These two approaches are covered under the four key mitigation themes:

Structural:

1. Reduce extreme water levels on the Richelieu River, and by extension Lake Champlain.
2. Reduce inflows into Lake Champlain or Richelieu River.

Non-structural:

3. Flood response (emergency preparedness).
4. Floodplain management (adaptation to flooding).

A literature scan of more recently employed structural solutions for flooding produced mostly structures that could be used in Theme 3 or arguably Theme 4, including many alternatives to temporarily control overland flow. There are a few Theme 1 and 2 innovations, but governments around the world have been much more reluctant to implement permanent water control measures (Theme 1) than they were in the last century. This report focusses on Theme 1 and, to a lesser extent, Theme 2 structural measures. Theme 3 and Theme 4 mitigation measures will be covered extensively in separate reports, but work has begun on identifying best management practices in these two areas (Flood Management and Mitigation Measures Technical Working Group, 2018; Henstra and Shabman, 2020).

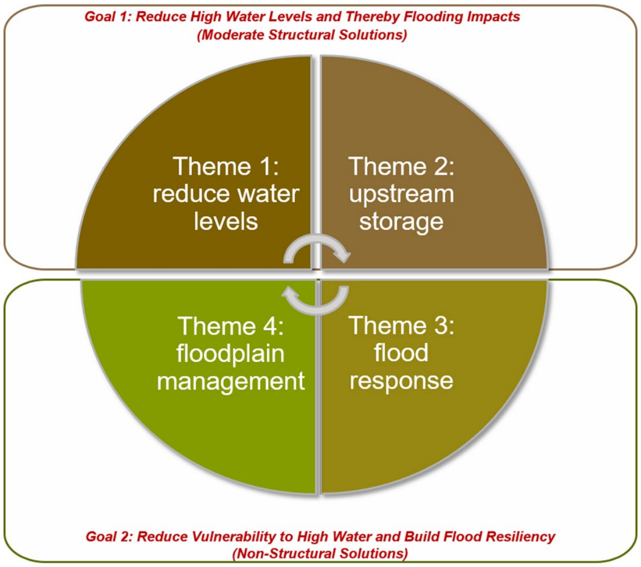


Figure 5-1 | Study flood mitigation framework

The term 'non-structural" as a type of flood solution was initially used by the Corps of Engineers in the early 1970s (US WRC 1973). Non-structural measures differ from structural measures in that they focus on reducing the consequences of flooding instead of reducing the probability of flooding (they generally cause no adverse changes to flood levels, velocities, duration, or the environment.) Nonstructural measures can be temporary (contingent) or permanent.

Similarly, from US Federal Agencies (Executive Office of the President 1998): "The key characteristic of a non-structural approach is that it modifies susceptibility to flooding, as opposed to simply attempting to control flooding through structural methods such as dams, levees and channels. However, non-structural approaches may include use of some structural elements." This terminology can be somewhat problematic because nonstructural measures are often applied to a structure (building) and/or its contents, such as elevating, floodproofing, and relocating. Also, while often associated with more natural and less obtrusive means of addressing flood risks, engineered nature-based approaches that affect the flood hazard are structural rather than nonstructural.

For the purposes of this report, structural solutions encompass the following activities: constructing structures that impact the flow regime, modifications of existing instream structures, dredging or removal of instream obstructions to increase flow (all Theme 1), and construction of barriers to impede or divert overland flow (Theme 2). Ring levees and elevations of structures are considered Theme 4 solutions.

5.2 SCAN OF INNOVATIVE STRUCTURAL SOLUTIONS TO ADDRESS FLOODING

An internet scan was conducted to determine if there were new or innovative structural solutions that have been identified by other countries that warrant the study's consideration. This scan focused on the United States, United Kingdom, Netherlands, Japan, and Australia, as these countries have undertaken major national policy reviews that look at addressing flooding in a comprehensive manner.

It is clear from this scan that most of the focus has been on non-structural solutions (Themes 3 and 4) in recent decades. The innovative structural solutions that were identified from this scan related to structures that addressed special types of flooding: tidal, storm surges, and flash flooding. These all tended to be large-scale structures. These structural solutions are not particularly relevant to the LCRR Basin flooding, which is lake flooding driven by snowmelt and spring precipitation.

Nonetheless, the scan produced some additional ideas for consideration. The most significant is the use of inflatable weirs or bladders to regulate flow. This approach has been gaining popularity as the technology has been implemented in numerous rivers and streams that are somewhat comparable to the Richelieu River (Figures 5-2 and 5-3).

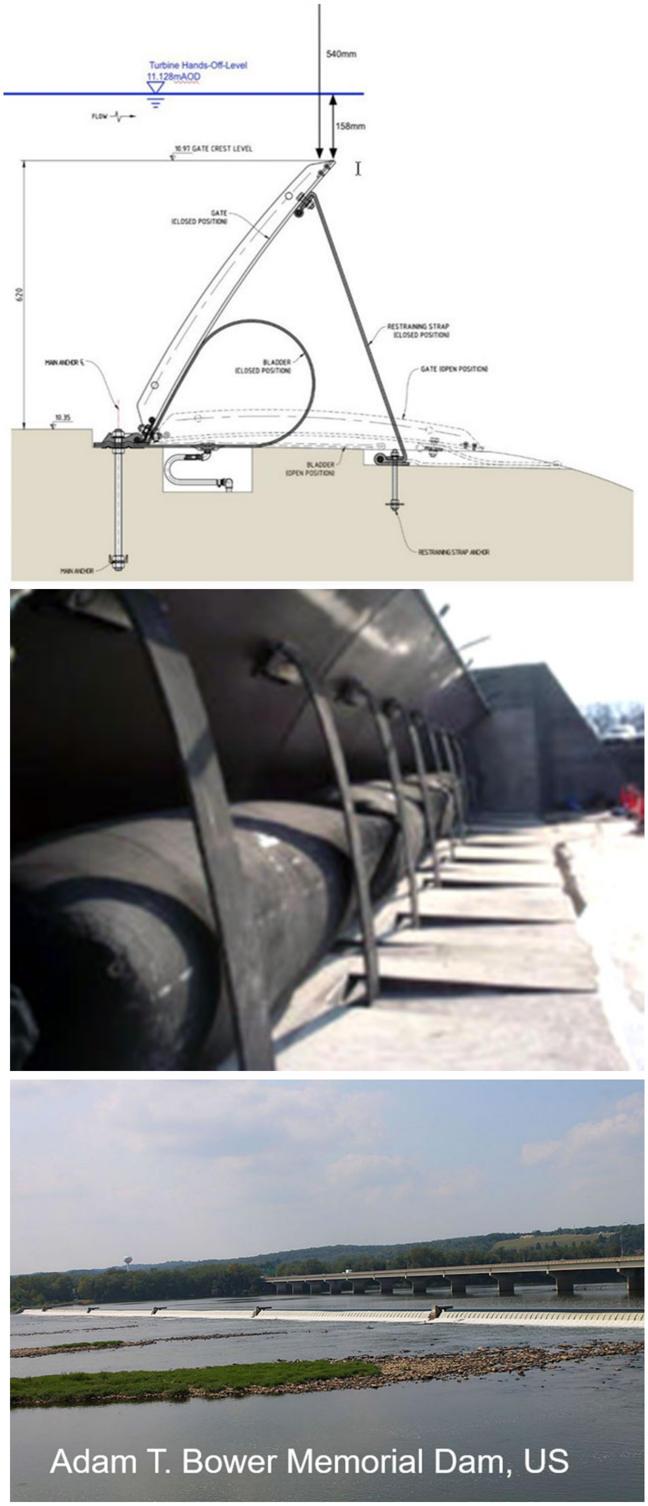


Figure 5-2 | Inflatable weir or bladder used to regulate flow

Figure 5-3 | *One section of an inflatable dam, not inflated*

A weir structure, in combination with dredging, can be operated to moderate the extreme flows, particularly the high flows. If required, it could also help moderate extreme low water levels. The width of the variable-height weir, the operating plan, and the elevation of the weir crest when inflated and deflated would determine its influence on water levels. Except when flooding was occurring or imminent, the bladder would be inflated to keep the weir crest at a level that is hydraulically equivalent to the current control (the shoal at St. Jean-sur-Richelieu), so that water levels would be as they are now. The current shoal elevation is a few feet under the water at historically low flows (with a water surface in St. Jean-sur-Richelieu of about 28.2 m or 92.6 ft). The crest of the weir would be lower than the water surface. A weir differs from a dam, which blocks the flow of water and trains it through released gates or hydropower penstocks. A weir has a key advantage in that it does not obstruct the movement of fish throughout the year as would be the case for a traditional dam. Even when inflated, the bladders will always provide enough water depth to allow fish passage and maintain a minimum flow. An inflatable weir or bladder also would not be the large, highly visible, concrete structure that has been traditionally proposed for regulating flow, and therefore may be more acceptable.

On the negative side, there have been issues with the weir or bladder not functioning properly. The Adam T. Bower Memorial Dam in Augusta, Pennsylvania, (Figure 5-2) was built in 1966. In 2007, it was deflated to replace some of its inflatable bags. Another bag was damaged in 2019. The "Daily Item" reported on July 9, 2019 that:

> *"...the inflatable bags have a life expectancy of 25 years. Bag one on the Sunbury side and bag seven on the Shamokin Dam side were installed in 1985 and replaced in 2017, and bags two and three were installed in 2000. Sherlock said bag six was installed around 2010. When the last two bags were replaced in 2017, the boating season was cut short by more than a month, which affected seasonal businesses, boaters and the docks at the Sunbury Riverfront Park."*

5.3 POTENTIAL STRUCTURAL ALTERNATIVES

The different structural alternatives that have been identified are captured under four general categories: addressing human interventions in the Richelieu River (primarily dredging), application of instream flow modification structures, water diversion schemes, and flood-related engineering modification on the floodplain.

The structural solutions that are proposed in this report come from past IJC reports, ideas put forth from residents and organizations in the basin, and a scan of potential innovative structural alternatives implemented outside of the basin. Many of the solutions that are identified are specific to the existing channel morphology, the hydraulic regime, and the basin hydrology.

5.3.1 Addressing Human Interventions in the Richelieu River

As noted in Chapter 3, over time there have been many human interventions in the Richelieu River that have impacted the river's flow regime and exacerbated flood levels. These specific works have contributed to raising water levels to some degree in the Richelieu River, and by extension, in Lake Champlain. There also have been other broad-based anthropogenic activities that have further impacted water levels and that cannot be realistically addressed due to lack of reliable data or information. These include building encroachment and infilling along the river, increased nutrient loading stimulating aquatic plant growth over time and thus impeding flow, and drainage modifications in the basin.

Over the last couple of decades, support has grown and actions have been taken toward restoring river regimes to their more natural state. Removal of human-made instream obstructions to flow, making room for the river, and restoring the sinuosity in river reaches that have been straightened have been gaining popularity. In some basins, removal of dams (e.g., Glines Canyon Dam, Washington State) is being undertaken in an effort to return a river regime to its natural state.

It is not possible or reasonable to address all the human interventions in an effort to get back to the original state-of-nature for the Richelieu River. However, a promising and reasonable structural alternative that warrants the Study Board attention would be the removal of some of the various human interventions on the Saint-Jean-sur-Richelieu shoal.

5.3.2 Application of Instream Flow Modification Structures

There are primarily two broad types of flow regulating structures that, when combined with dredging/excavating, would reduce flooding around Lake Champlain and along the banks of the Richelieu River:

1. A fixed instream structure (fixed crest submerged weir) that focuses on reducing high water levels, while avoiding lower drought levels.
2. A regulatory structure (dam) that has greater control over the full range of water levels.

Both types of structures were examined in the 1970s (see Chapter 4) and detailed engineering analyses produced.

Application of a fixed crest weir was thoroughly examined as a potential solution (Environment Canada and Department of Natural Resources (Québec), 1975). The fixed crest weir was determined to be a viable solution at that time with its relatively low capital cost, which resulted in a high benefit-cost ratio. It addressed a preferred regulation plan of the International Champlain-Richelieu Engineering Board in its 1974 report that focused on maintaining natural lake levels and outflows throughout the year, except for the period of the spring flood (referred to as P-5).

The 1975 report concluded that the preliminary results obtained from the analytical and hydraulic model studies demonstrated the practicability and desirability of a limited regulation scheme under what was known as Plan XAA. Plan XAA included a concrete weir at crest elevation of 28.3 m (92.85 ft) GSC, equivalent to 28.4 m (93.20 ft NGVD29) and located in the shoal, about 183 m (600 ft) upstream of the CPR bridge. Among all the flow regulation schemes to control floods in the Richelieu-Champlain basin studied at that time, Plan XAA offered the best possibility of rendering a measure of flood control benefit at minimum cost and with minimum environmental disruption. Environmentally, the plan does not impact the timing of the peak flow but does extend the flood period longer. The lake levels at low flows are generally maintained close to natural water levels. It was suggested that further analysis with different dredging configurations and weir design could further decrease the capital costs of this scheme.

The fixed crest weir was analyzed more thoroughly over the course of the reference and against the more restrictive criteria that were established by the IJC. The weir came close to duplicating the natural rhythm of water levels. It would reduce extreme lake water levels by 30-58 cm (1-1.9 ft), while maintaining the average levels and slightly raising extreme low levels. Even though it proved to be the lowest cost option with the highest benefit-cost ratio, it was not selected as a viable solution because it did not meet the environmental criteria established by the IJC (IJC 1981).

The fundamental issue with the fixed crest weir is that it is not capable of regulating the levels of Lake Champlain, which may continue to be a key requirement as it was in the 1970s assessment. In light of uncertainty in climate change impacts on lake levels at this point in time, this solution was considered to be viable.

The option that received the most attention in the 1970s was the six-gated structure that was proposed by the IJC in their final report to the governments (IJC 1981). This structure provided the most flexibility, and based on the proposed regulation plan, the capability to achieve socio-economic benefits while also meeting the environmental criteria. The plan at time, referred to as Scheme FCE-1, would reduce the average maximum water level during the spring by about 37 cm (1.2 ft) and be able to reduce extreme low water levels on Lake Champlain. The cost was double the cost of the fixed weir; it had a much lower but still acceptable benefit-cost ratio.

A flow regulation structure today is still probably the most effective structural solution to address the broader flooding issue in the LCRR Basin. It offers the most flexibility for addressing evolving criteria and the changing hydrological conditions associated with climate change. There may be a potential to develop a regulation plan that produces a better mix of outcomes based on the better data and knowledge that we possess today and covered in another study report. The challenge is ascertaining whether there is any appetite before investing the resources that would be required to complete a comprehensive assessment.

Any flow modification structure will require dredging of the shoal to allow lowering of Lake Champlain. It was estimated for the above structures that the shoal would need to be excavated to an elevation of 25.9 m or 85 ft. A trench 213 m wide by 2,438 m long (700 ft by 8,000 ft) would be required, amounting to 244,658 m^3 (320,000 yd^3) of material to be removed (IJC 1981).

These two structural alternatives are still technically viable solutions today and are capable of significantly reducing flooding in the basin. Both instream structures warrant Study Board consideration and therefore are included in the suite of potential structural alternatives for consideration.

5.3.3 Water Diversion Schemes

Several major diversion or water transfer schemes have been raised over the years as potential solutions to address the LCRR Basin flooding issue. Two have received much attention and were raised at public meetings as being a possible solution:

1. Flow diversion from Lake Champlain into the Hudson River,
2. Flow diversion from Lake Champlain into the Yamaska River.

(1) Flow diversion from Lake Champlain to Hudson River through Champlain Canal.

The existing Champlain Canal allows small amounts of water to transit between the Hudson River and Lake Champlain (Figure 5-4). Modifying the 97 km (60 mi) of canal would be an expensive undertaking for a number of reasons. The narrow canal system (shown in Figure 5-4) would have to be significantly widened and changes would need to be made to the series of locks. But more important would be the significant excavation costs associated with dredging the entire canal and overcoming the rise in elevation that peaks at 42.7 m (140.1 ft) above mean sea level at lock C-9, a vertical rise of 12.2 m (40 ft) above Lake Champlain levels. Also, given the historical significance of the canal system, there would be resistance to making such significant changes. In addition, recent concerns over the canal being a pathway for invasive species make expanding this diversion highly unlikely from an environmental perspective (LCC 2019).

(2) Flow Diversion from Lake Champlain into the Yamaska River.

The Yamaska River flows into the St. Lawrence River at Lac St. Pierre, well below the discharge of the Richelieu River into the St. Lawrence. Its course is generally east of the Richelieu River. The Pike River (a tributary flowing into Missisquoi Bay) could be potentially used to divert flow into the Yamaska River, thereby lowering the peak flows in the Richelieu River. The potential diversion would flow through a developed area and significant land acquisition would be required that would be costly. Substantial excavation would also be required, including the deepening of the upper reaches of the Pike River to reverse the flow and install measures to address the 10-12 m (33-39 ft) of vertical rise in elevation between the two rivers. This, in turn, would make the costs for this proposed diversion extremely high. There also would be the added environmental consequences associated with the transfer of water between basins which would greatly impact the viability of this proposed option. The layout is captured in Figure 5-4 as well.

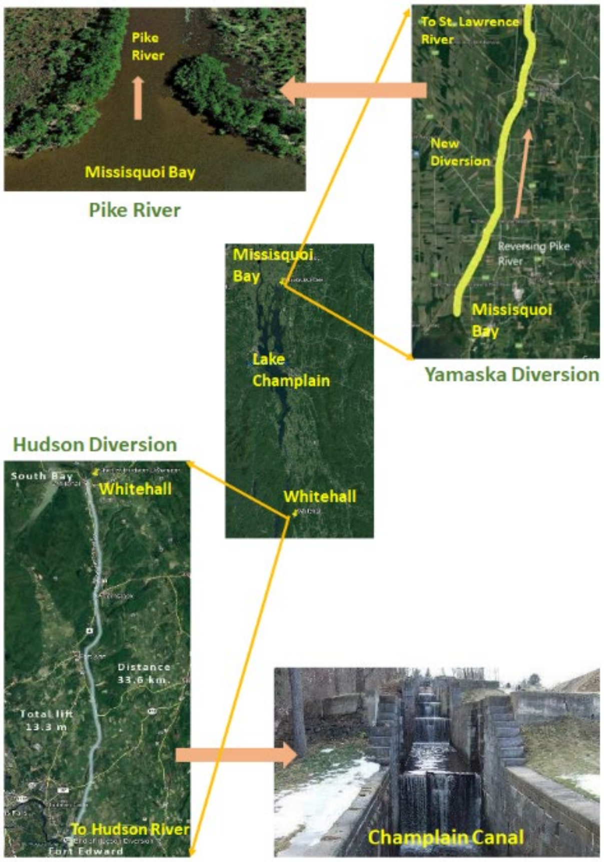


Figure 5-4 | Hudson and Yamaska proposed diversions

It is highly unlikely that any major water diversions from one basin to another would be considered to be a viable solution today for a number of reasons:

1. The recipient basin would have to be able to receive the water without inducing its own flooding issues. The probability of high Lake Champlain levels being concurrent with low water levels in adjacent basins is low.

2. Diverting water could introduce exotic species and other environmental issues from one basin to another.

3. Basins are divided by high ground. Absent an existing connecting channel, diversions would generally require a substantial amount of excavation and reinforcement works to create a connecting channel. This makes this type of solution extremely expensive.

4. Diversions could well require extensive acquisition of private property, the construction of new bridges, the rerouting of existing infrastructure, the issuances of permits, and other challenges under the various State and Provincial laws.

Based on the current IJC reference from the governments, major out-of-basin water diversions, such as these schemes, are beyond this study's mandate. To examine this approach in any further detail would require another reference from the governments.

For the reasons described above, it is highly unlikely that there would be significant support for such schemes. It is also widely recognized that the governments of Canada and the United States have moved away from diversions and water transfer in favor of other water management practices.

A small-scale diversion within the same river does not have the implications associated with a major water diversion between basins and therefore would be considered within this Study Board's mandate.

It may be possible to divert higher flows through the Chambly Canal during the spring freshet prior to the canal opening, which is typically at the end of May. Some preliminary field work to address this issue was conducted in 1979, but the field test proved to be inconclusive (Ad-Hoc Committee 1979).

Besides the engineering considerations, it will be important to determine whether any modifications can be made to the canal, given its historical designation status.

Diverting flow through the Chambly Canal is a viable structural alternative that requires the Study Board's consideration.

5.3.4 Flood-related Engineering Modifications on the Floodplain

Under this category there are a number of different potential structural solutions to address flooding: nature-based (i.e., creating wetlands), temporary flooding of marginal or agricultural land, and dyking or levees to protect flood prone areas. The first two relate to Themes 1 and 2 and are consistent with the approach being undertaken in the Netherlands, referred to as "make room for the river" (USACE, 2011). Dyking and levees are arguably grouped in Theme 3 if the dike is used only when floods are imminent or Theme 4 if the dike, levee, or floodwall is permanently in place. This type of solution has been extensively used and has the potential to be a cost-effective solution. There are two types of solutions: permanent structure or temporary structure.

A permanent levee is costlier than a temporary levee such as sandbags or an Aquadam®. It would require regular maintenance and if breached could result in more significant damages because development was allowed based on the presumption of flood protection. The US Army Corps of Engineers and the Province of Quebec have both documented the potential vulnerability created by confidence of the public in the levees, which, unbeknownst to them, have declining protection over time. In addition, the levee design and economic justification cannot be separated from projections about the effect of climate change on future flooding. If the flood threat from climate variabilities and change declines, the levee may be unnecessary; if the flood threat increases, the levee may be under-designed. There may be the need for such solutions to augment a flow regulation structure on the Richelieu River, but that will depend on whether there is support for such a solution.

Temporary water barriers could be effectively and efficiently deployed using the study's models and verified by working closely with community, state, and provincial flood responders. This is a Theme 3 solution and there is a broad range of potential technologies that can be used. Sandbags are used in both states and in Quebec now to provide temporary protection. Since 2017, New York State's Departments of Homeland Security and Transportation have deployed Aquadam®[4][5] in towns under threat of flooding. The use of Aquadam® is less dependent on the estimation of the effect of climate change on future flooding. The specific locations where temporary water barriers could effectively and efficiently be deployed can be determined using the study's models and maps. At the ground level it will be verified by working closely with community, state and provincial flood responders.

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[4] https://www.governor.ny.gov/news/governor-cuomo-announces-deployment-additional-state-resources-protect-upstate-communities-lake

[5] https://orleanshub.com/2-aqua-dams-installed-in-kendall-to-protect-shoreline-property/

6 MODELLING OF STRUCTURAL ALTERNATIVE IMPACTS

6.1 EVALUATION FRAMEWORK

The Study Board will test proposed structural alternatives virtually. A series of computer models (Figure 6-1) will be used to create those virtual tests, with each model specialized for its purpose. This chapter focuses on how structural alternatives will be modelled.

The Study Board will practice making its decision on structural alternatives. The practice decisions have two main goals. The first goal is to familiarize the Study Board with the performance of each alternative to inform their assessment based on the decision criteria. Unless one alternative is superior to all others for every criterion, the board will have to decide which mix of performance scores it favours. The second goal of the practice decisions will be to support and document the Study Board's trade-off process. The Study Board will use the Collaborative Decision Support Tool (CDST) to capture the results of the modelling system and present the performance of the alternatives in simple, straightforward terms.

The key underlying models used in this assessment are described in the following sections.

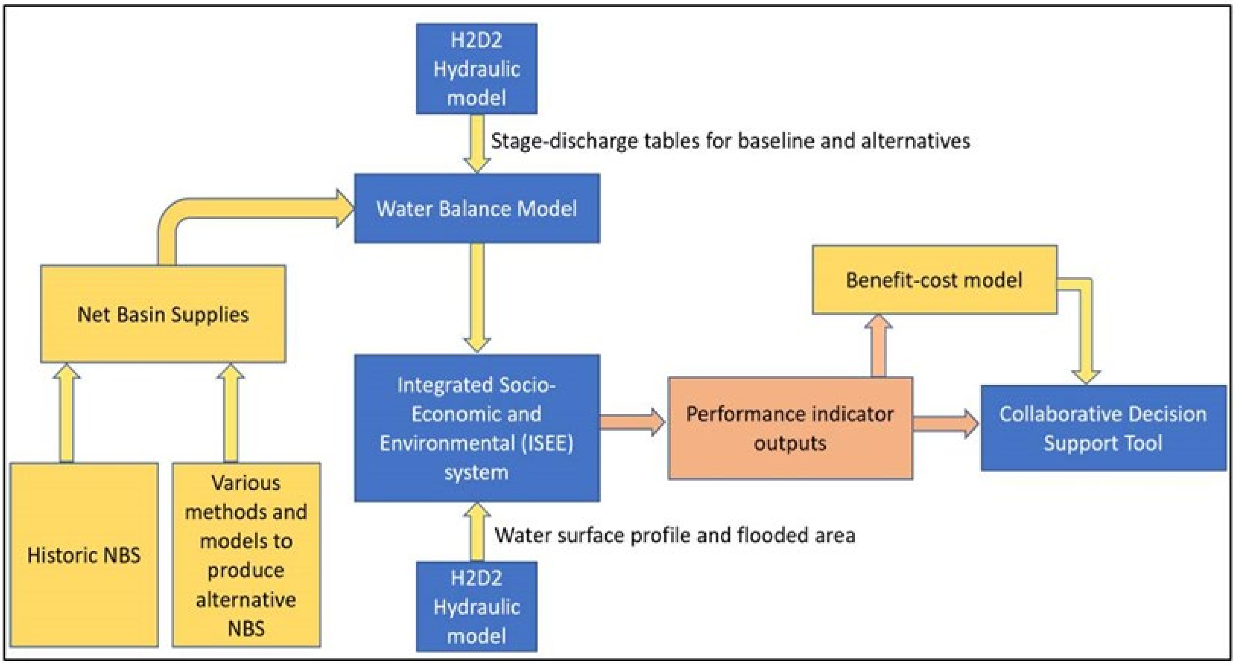


Figure 6-1 | Models used to generate alternative evaluations

6.2 CALIBRATED WATER BALANCE MODEL

There are two modelling components that are key to analyzing the hydraulic impact of structural alternatives. The first is the Water Balance Model (WBM) that is described in this section and the second is the hydrodynamic model that is covered in the next section (Boudreau et al, 2019, Boudreau et al., 2015a).

The study's Lake Champlain WBM is based on the conservation of mass equation. This equation reflects the balance between the change in lake volume, the outflow from the Richelieu River, and the Net Basin Supplies (NBS) from Lee (1992) and Bruxer (2011):

$$\Delta S \pm \Delta S_{th} = P + R \pm G - E - O - C \qquad (1)$$

Where:

ΔS = change in lake volume
ΔS_{th} = thermal expansion and contraction, which can be neglected
P = precipitation on the lake

R = runoff and contributions from tributaries to the lake

G = groundwater flow

E = lake evaporation

O = outflow to the Richelieu River

C = water withdrawal

NBS can be defined in terms of its components:

$$\mathrm{NBS} = P + R \pm G - E \qquad (2)$$

Because records of these components are incomplete or not measured, NBS can more usefully be defined as the inflow (less evaporation) volume, which must equal the change in the lake volume plus the volume of water that flows out of the lake:

$$\mathrm{NBS} = \Delta S + O \qquad (3)$$

The WBM noted in equation (3) is first used in establishing the historical NBS series at a quarter-month (QM) time step. In other words, the NBS corresponds to the sum of the variation in lake level as translated into flow (positive for an increase in water level and negative for a decrease) and the average outflow into the Richelieu River, on a QM basis. This established the historical NBS that is considered a certified series for the basis of comparison for any other data generated by stochastic analysis or from climate forcing.

In the second stage, the same equation is used in evaluating the impact of structural alternatives by adjusting the stage-discharge function based on the results of multiple simulations with the H2D2 two-dimensional hydraulic model (described in Section 6.3).

Water level fluctuations in Lake Champlain are slow due to the large storage capacity of this water body. The quarter-month time step is therefore considered adequate to quantify the effect on lake levels of the different outflow situations. An iterative process is used to solve the mass conservation equation.

From an initial state, a first level of Lake Champlain, at the end of the QM period, is calculated from the outflow from the Richelieu River at the beginning of the QM period and the NBS for the QM period considered. The level of Lake Champlain (Rouses Point) is then reported at Saint-Jean-sur-Richelieu by estimating the difference in elevation of the water surface, which depends on the flow of the river, the presence of ice, as well as the aquatic vegetation encountered along this 37 km (23 mi) section.

The Manning-Strickler formula, noted below, is used to define discharge in terms of channel geometry, roughness parameters, bed/water surface slope, etc.

$$V = \frac{1}{n} R^{2/3} \sqrt{S} \qquad (4)$$

With $R = \frac{A}{P}$ (5)

The term Slope is given as

$$S = \frac{h_{RP} - h_{SJV}}{L} \qquad (6)$$

Finally:

$$\mathrm{Q = V\ x\ A} \qquad (7)$$

Where:

n is the Manning coefficient

R is the hydraulic radius (m)

S is the hydraulic slope (m/m)

A is the cross-sectional area of the flow (m^2)

P is the wetted perimeter (m)

hRP is the average level of Lake Champlain (m)

hSJV is the level at the Saint-Jean-sur-Richelieu virtual station (m)

L is the distance between Rouses Point and the Saint-Jean-sur-Richelieu virtual station (m), equal to 36889 m

Q is the discharge (m^3/s)

By reorganizing equations (4) through (7), the Manning coefficient is estimated as:

$$n = \frac{A}{Q}\left(\frac{A}{P}\right)^{\frac{2}{3}}\left(\frac{h_{RP} - h_{SJV}}{L}\right)^{\frac{1}{2}} \qquad (8)$$

Using known discharge and a measured cross-section at the Saint-Jean-sur-Richelieu virtual station, the variation of Manning's n is computed for the most recent period 2010 to 2016. This varied from a low of 0.071 in quarter-month 14 to a high of 0.14 in quarter month 33.

Operation of the Water Balance Model

First, an initial state of the system is established with a level of Lake Champlain and a flow from the Richelieu River representing the situation at the beginning of the first QM.

Step 1: A level of Lake Champlain (end of QM) is calculated based on the average of the flows of the Richelieu River at the end and beginning of QM, as well as the NBS for the QM considered. During the very first iteration of a given QM, the flows of the Richelieu River at the end and beginning of the QM are identical.

Step 2: A level from the Richelieu to the virtual station at Saint-Jean-sur-Richelieu (end of QM) is calculated using the Manning-Strickler formula based on the lake level (end of QM) and the flow of the Richelieu River (end of QM).

Step 3: The stage-discharge is computed with 2D hydraulic model simulations. The water level at the virtual station is calculated with it (Step 4). The Manning-Strickler equation is used to "transfer" the water level of the virtual station to the Lake during the iterative process at Step 2. The final WL of the QM is calculated at Step 4.

Step 4: A new flow of the Richelieu River (end of QM) is calculated using the level-flow relationship at the Saint-Jean-sur-Richelieu virtual station. There is iteration for Steps 2 to 4 to obtain a convergence on the level and flow at Saint-Jean-sur-Richelieu. The next action is a return to Step 1.

The iterative process (Steps 1 to 4) continues until Lake Champlain level convergence is achieved (end of QM). The process is repeated for the next QM, until the series is fully processed.

All these variables are interdependent of each other. Therefore, these iterative processes are necessary to achieve a balance every quarter-month. For its part, the historical NBS series is fixed. Figure 6-2 illustrates the iterative process of the WBM.

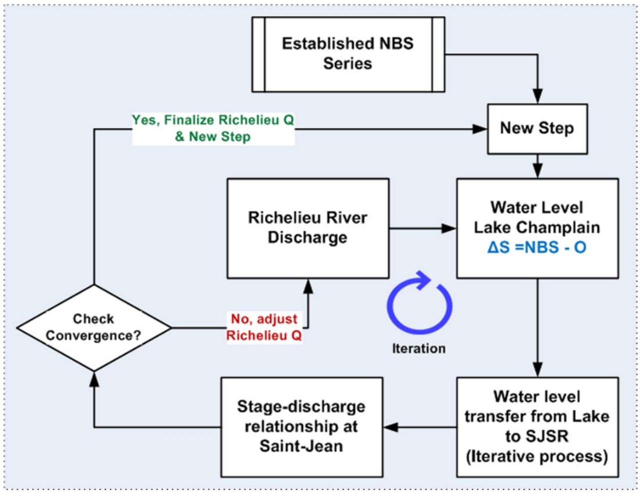


Figure 6-2 | Iterative process in the Water Balance Model

6.3 2-D HYDRODYNAMIC MODEL

The study employed the hydrodynamic model developed earlier in 2015 as part of the demonstration of an operational forecasting toolkit by the International Lake Champlain – Richelieu River Technical Working Group (Boudreau et al. 2015a, 2015b). The task group produced flood maps for various flow and water level scenarios from Rouses Point as a point on Lake Champlain to Fryer Island Dam downstream of this point. The downstream limit for the initial study was dictated by the quality of bathymetric data. Once better bathymetry became available north of the Fryer Island Dam, the model was extended to its downstream boundary at Sorel.

The hydrodynamics of the system were represented by a two-dimensional hydraulic model H2D2 developed at INRS-Eau (now INRS-ETE) with assistance of Environment and Climate Change Canada. The model solves the Navier-Stokes (Saint-Venant) two-dimensional long-wave equations. Like all two-dimensional models, H2D2 uses depth integrated information and only allows variation in the cartesian x and y directions. The model utilizes the conservative form of the mass and momentum conservation equations, with friction losses accounted by the presence of substrates, aquatic vegetation, ice, etc. The model is governed in a mathematical form as shown in the conservation of mass (Equation 9) and conservation of momentum (Equations 10 and 11) equations.

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0 \qquad (9)$$

$$\frac{\partial}{\partial x}\left(\frac{q_x q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_x q_y}{H}\right) + c^2 \frac{\partial h}{\partial x} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{xx}) + \frac{\partial}{\partial y}(H\tau_{xy}) - \tau_x^b - \tau_x^s\right) - f_c q_y = 0 \qquad (10)$$

$$\frac{\partial}{\partial x}\left(\frac{q_y q_x}{H}\right) + \frac{\partial}{\partial y}\left(\frac{q_y q_y}{H}\right) + c^2 \frac{\partial h}{\partial y} - \frac{1}{\rho}\left(\frac{\partial}{\partial x}(H\tau_{yx}) + \frac{\partial}{\partial y}(H\tau_{yy}) - \tau_y^b - \tau_y^s\right) - f_c q_x = 0 \qquad (11)$$

Where:

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) (m)

H = water column depth (=h-zf) (m)

c = wave velocity (c = g·H) (m/s)

r = water density (1,000 kg/m^3)

u (u, v)= component of velocity (m/s) where: u = qx/H and v=qy/H

f_c = Coriolis force (fc = 2wsinj)(1/s)

t = Reynold stresses (kg/m^2)

t_x^b, t_y^b = bottom friction in x and y directions (kg/m^2)

t_x^s, t_y^s = surface friction in x and y directions (kg/m^2)

These equations are solved by the finite element technique. The H2D2 model has been used in several studies, many of these feeding into other IJC studies. Several components of the models were developed that span the entire study area from Whitehall at the south end of Lake Champlain to Sorel in the north. Given the presence of several geomorphological features like the rapids at Chambly Basin and Fryer Island Dam, separate hydraulic models of relevant stretches were made to avoid the singularities in the solution.

For most of the work feeding into this report, the hydrodynamic model used covered the reach from Rouses Point, NY to Fryer Island Dam about 10 km (6.25 mi) north of Saint-Jean-sur-Richelieu, a total of about 49 km (30.6 mi). The reach 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. The bathymetry and topography were assembled on the hydrodynamic mesh using the digital elevation model. The friction at the channel bottom was captured by using the Manning coefficient, borrowed from steady one-dimensional hydraulics and developed based on the geomorphology of the river, field observation, and low water aerial photography. The iterative process of calibration produced the final version of the friction coefficient.

The main purpose of the hydrodynamic model supporting this study was to make multiple steady state runs for a given range of discharge at the Fryer Island Dam and a range of water levels at Rouses Point. In total, 37 profiles were generated for a water level range from 28.1 m to 31.8 m (92.19 ft to 104.33 ft) NAVD88 at Rouses Point and corresponding flows from 55 to 2,011 m^3/s at Fryer Island Dam. These values can be used for developing rating curves at any point within the reach. The output from the hydrodynamic model runs were in turn used in driving the water balance model, described above, and in the development of the Collaborative Decision Support Tool (CDST) and Integrated Social Economic and Environmental system (ISEE).

The process noted in the previous paragraph is appropriate when a structural alternative would modify the bathymetry, remove instream features, or add structural alterations. By repeating the above effort, a new stage-discharge function is developed and when it is used with the water balance model and CDST, would provide a change in water levels and flows for the alternatives. A comparison between the base case and an alternative is a measure of hydraulic relief for a flood mitigation measure computed by the CDST.

6.4 INTEGRATED SOCIAL ECONOMIC AND ENVIRONMENTAL (GIS) SYSTEM

ISEE uses water levels and flows as inputs to algorithms that calculate performance indicators geographically throughout the study area. ISEE relies on a georeferenced database specialized for modelling aquatic and riparian areas connected to a script library to calculate performance indicators (PIs) based on a hydrological dataset using a quarter-month time step (water discharge or level). ISEE allows the integration of numerous layers of information (inputs) on the same grid (10 m by 10 m). The information set describes the hydraulics, land use, infrastructure, socio-economic variables, and the natural environment, especially wetland distribution (Figure 6-3). As a result, all relevant physical variables, such as water depth, currents velocities, shear stress, Reynolds and Froude number, etc., are available at each point of the ISEE grid. All of these variables can be used to create simple PIs such as stage-damage curve or more complex models (combination of water saturation, currents, and wave erosion models) over different periods if needed. PIs addressing various concerns of stakeholders are then computed to evaluate any combination of alternatives from the four themes. The PI values for each scenario (outputs) are then compared to a baseline condition scenario (present management conditions) for each Net Basin Supply series. Figure 6-4 shows a pair of Google Earth screen captures based on .kmz files showing water surface elevations near Maple St. in Burlington, Vermont. This is a visualization of the water surface elevation layer in ISEE that would drive (for example) inundation damage functions for buildings near the water.

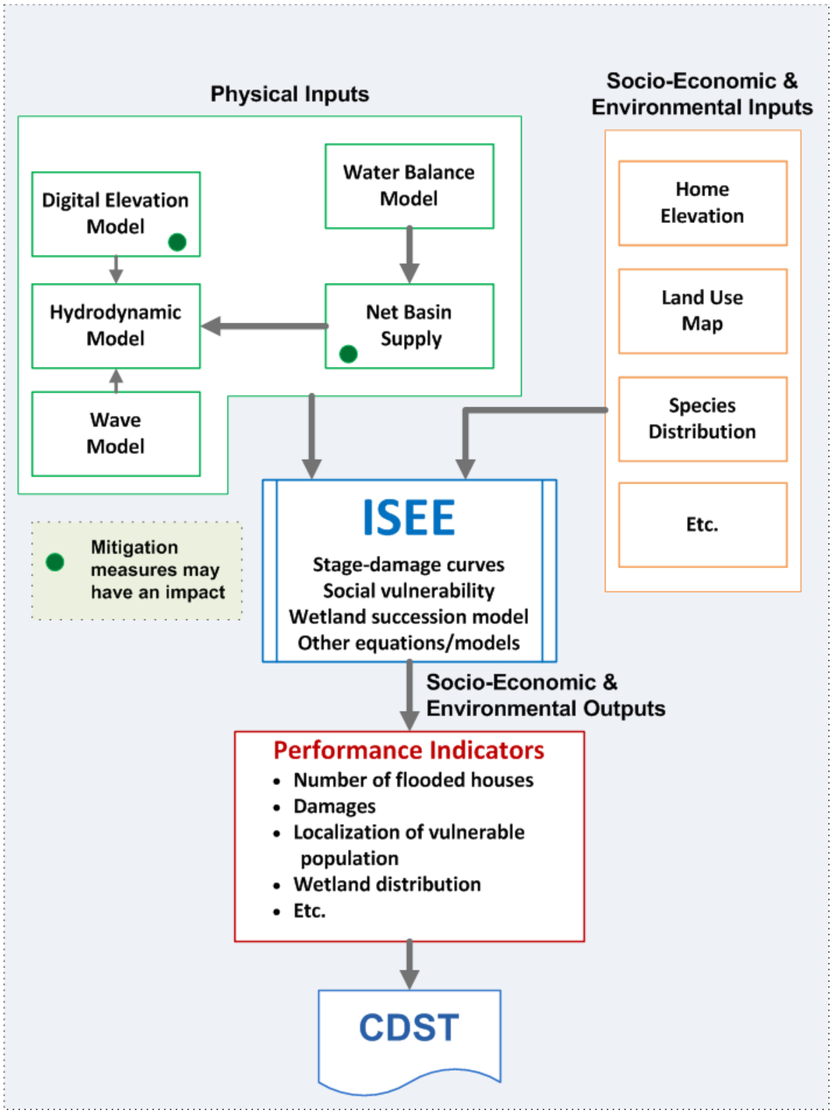


Figure 6-3 | Integrated Social Economic and Environmental System

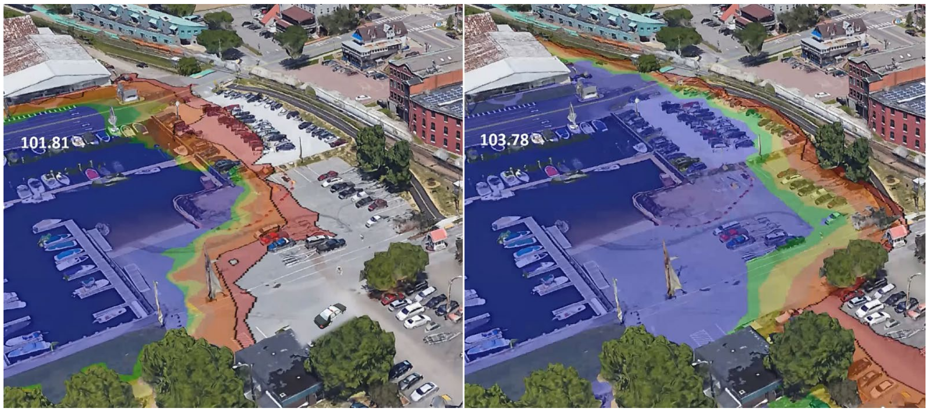


Figure 6-4 | A visualization of the flood layer in ISEE showing Burlington, VT near the corner of Maple Street and Island Line Trail

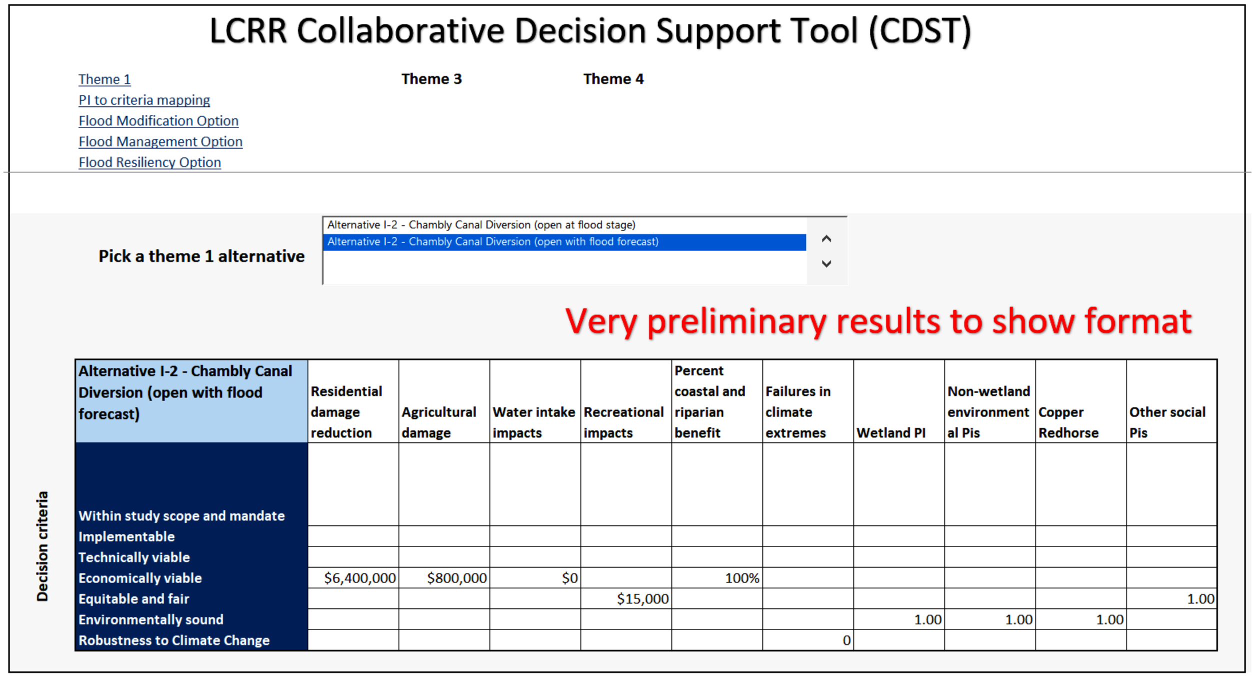
6.5 COLLABORATIVE DECISION SUPPORT TOOL

The CDST is an Excel model that will hold selected and summarized ISEE output data and combine the results in ways that map into and support the Study Board's decision criteria. The CDST will translate the immense amount of data produced by ISEE into summary results tailored to support the assessment of how well the Study Board decision criteria have been met.

The choice of data and the specific mappings used will be developed over time in practice decisions. For example, ISEE will produce damages for every parcel at all selected flood elevations. The basin totals for different hydrologic scenarios might be used in the CDST to support the cost-effectiveness criterion, but for the "equity" criterion, the CDST might be programmed to look for areas that received no flood damage reductions. For the criterion "economically viable", the recreation benefits might be highlighted, as some Theme 1 alternatives might have net benefits because of flood damage reduction but lower recreation benefits because of lower lake levels during droughts, making it difficult to use sail boats. A mock-up of the CDST is shown in Figure 6-5, showing PI results for one NBS scenario apportioned among the appropriate criteria.

The CDST is based primarily on the many ISEE simulations run for each alternative. Figure 6-4 is an illustrative mock-up that shows one of the windows that might be available from the planned simulations of the preferred Theme 1 alternative, diversion of flood water through the Chambly Canal.

The PIs shown in Figure 6-5 will quantify the extent to which the alternative meets the criteria developed by the Study Board (see section 7.9). The results will primarily be quantifiable but could include some non-quantifiable PIs to provide additional impacts.



LCRR Collaborative Decision Support Tool (CDST)

Theme 1
PI to criteria mapping
Flood Modification Option
Flood Management Option
Flood Resiliency Option

Theme 3

Theme 4

Pick a theme 1 alternative

Alternative I-2 - Chambly Canal Diversion (open at flood stage)
Alternative I-2 - Chambly Canal Diversion (open with flood forecast)

Very preliminary results to show format

Decision criteria

Alternative I-2 - Chambly Canal Diversion (open with flood forecast)	Residential damage reduction	Agricultural damage	Water intake impacts	Recreational impacts	Percent coastal and riparian benefit	Failures in climate extremes	Wetland PI	Non-wetland environmental Pis	Copper Redhorse	Other social Pis
Within study scope and mandate										
Implementable										
Technically viable										
Economically viable	$6,400,000	$800,000	$0		100%					
Equitable and fair				$15,000						1.00
Environmentally sound							1.00	1.00	1.00	
Robustness to Climate Change						0				

Figure 6-5 | Collaborative Decision Support Tool (CDST)

7 PRELIMINARY EVALUATION OF PROPOSED STRUCTURAL ALTERNATIVES

7.1 CONTEXT FOR SELECTIONS

In Chapter 5, a selection of potential structural alternatives was identified using different sources. Seven of these were selected to provide the Study Board with a range of structural alternatives for flood relief, and estimated costs and projected utility. The list of alternatives is ordered generally from lower cost alternatives providing less flood relief to more costly alternatives that provide substantial flood relief. The alternatives are as follows:

1. Excavating of human interventions on Saint-Jean-sur-Richelieu shoal (eel trap, submerged dikes).
2. a. Diverting flow through the Chambly Canal with a conservative diversion scheme.

   b. Diverting flow through the Chambly Canal with an optimized diversion scheme.
3. Alternative 2a combined with Alternative 1.
4. Moving the control through installing a fixed weir upstream of Saint-Jean-sur-Richelieu and channel dredging.
5. Installing an inflatable weir or bladder upstream of Saint-Jean-sur-Richelieu and channel dredging.
6. Installing an inflatable weir or bladder at the Saint-Jean-sur-Richelieu shoal and channel dredging.

Alternatives 1 to 3 have not been considered or effectively addressed in previous flooding studies. A fixed weir and a gated structure to regulate flow in the Saint-Jean-sur-Richelieu area were examined in the 1970s (ICRB 1977a), but the regulation structures in Alternatives 4 and 5 considered in this study would be located upstream of Saint-Jean-sur Richelieu, thereby providing greater flood relief. Some previous cursory work was done to examine siting upstream of Saint-Jean-sur Richelieu, but it received limited attention at that time. Alternatives 5 and 6 propose employing a new technological advancement, an inflatable weir/bladder, to regulate flow.

These seven proposed alternatives were simulated using the Water Balance Model described in Chapter 6. The hydraulic implications of each alternative were assessed to determine the level of flood relief it would provide on the Richelieu River and Lake Champlain based on the 2011 flood. The impacts these structures could have on low water levels (based on the historical low water level of 1964) on the Richelieu River and Lake Champlain are assessed as well. The Integrated Social Economic Environmental (ISEE) System is being used to determine the number of residential buildings that would be spared from flooding based on the water level reduction that is achieved with each alternative.

For this report, most of the quantities of dredging, volumes of material, etc. were brought forward from the 1970s study that explored the same or similar flood relief measures and layouts (ICRB, 1977a). Using the Engineering News Record (ENR) cost index method, the cost of construction in 1973 dollars was updated to 2018 estimates using a factor of 4.55. To estimate costs for features and actions considered in this study, information was expressed as unit costs for activities like dredging, engineering for control gates, disposal of dredged material, etc. These unit costs were then used to estimate elements of the alternatives not considered in the earlier IJC study. Typically, these costs include construction facilities, lands and damages, excavations, appurtenances, preliminary directed studies, engineering supervision, and administration and contingencies.

For example, with the ENR construction index and inflation included and stricter environmental considerations for dredging and removing material, the cost was estimated at about $\$200/m^3$.

These estimates are considered to be very preliminary but help to provide a relative comparison of cost for each alternative.

7.2 ALTERNATIVE 1: EXCAVATING OF HUMAN INTERVENTIONS ON THE SAINT-JEAN-SUR-RICHELIEU SHOAL

7.2.1 Description

As noted in Chapter 3, several human interventions have taken place over the years that impeded flow and raised water levels. The impact of these interventions can be partially addressed by excavation and removal of materials. This alternative focuses on the Saint-Jean-sur-Richelieu shoal and proposes that the eel trap and submerged dikes and Iberville Islands be removed to help lower high-water levels (Figure 7-1).

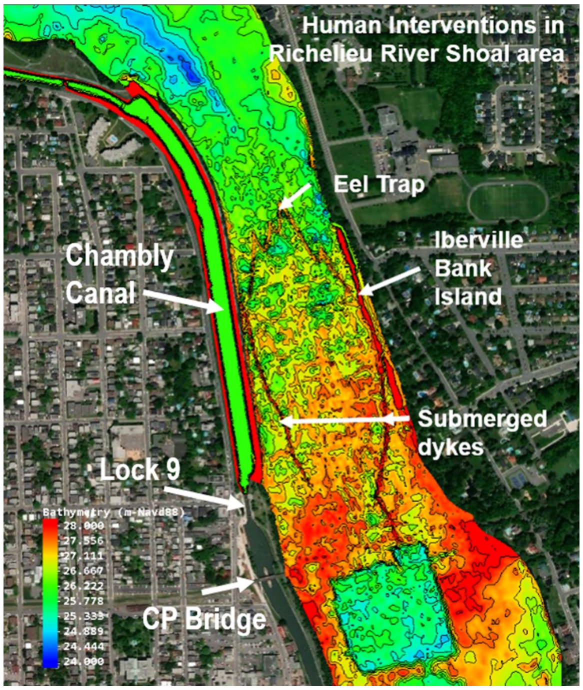


Figure 7-1 | Human interventions removed from Saint-Jean-sur-Richelieu Shoal under Alternative 1

The following are the estimated volumes of riverbed material that would need to removed:

- eel trap: 2,197 m^3 (2,743 yd^3);
- submerged shoal mill dikes: 1,456 m^3 (1,904 yd^3); and
- Iberville Bank Islands: 6,333 m^3 (8,283 yd^3).

In total this would result in the removal of 9,986 m^3 (13,060 yd^3) of material. This alternative would disturb about 1.2 ha (3.0 acres) of the riverbed for removal of the eel trap, 1.6 ha (4.0 acres) for the submerged shoal mill dikes, and 1.65 ha (4.1 acres) of the Iberville Bank Islands. The total area disturbed for this alternative is 4.45 ha (11.1 acres).

7.2.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

The exploratory analysis done by ISEE shows that the removal of the proposed human interventions would result in lowering the water level in the Richelieu River at St-Jean-sur-Richelieu marina, located 1.7 km (1.06 miles) upstream of the lip of the shoal, by about 9 cm (3.5 in) for a flood similar to the 2011 flood. This would result in the permanent lowering of Lake Champlain by about 6 cm (2.4 in) for all floods, including the 2011 flood.

In terms of low flow impacts, this could result in lowering the water level on both the lake and river by 8 cm (3.1 in) based on 1964 drought conditions.

7.2.3 Considerations

The integrity of the shoal would be maintained, as the dredging would be limited to the removal of only the instream anthropogenic interventions. The only cost would be for the removal and disposal of dredged material. Based on very preliminary estimates, it is expected that this work could cost between $3-5 million.

This alternative would provide limited flood relief, and based on the ISEE modelling results would prevent the flooding of 110-170 residential buildings during a flood similar to that which occurred in 2011

As the water level reduction is small, producing a profile more similar to conditions before the widening of the canal, it is expected that the environmental impacts would be low or unmeasurable and primarily localized to the shoal. Dredging would be conducted in a manner designed to minimize sediment transport.

7.3 ALTERNATIVE 2A: DIVERTING MODERATE FLOW THROUGH THE CHAMBLY CANAL WITH A CONSERVATIVE DIVERSION SCHEME

7.3.1 Description

This alternative utilizes diverting flow through the Chambly Canal during the freshet period to lower high-water levels. It would require installing a series of gates below Lock 9 for this small-scale diversion (Figure 7-2). The diversion entrance would involve excavating a 40 m (131 ft) opening in the canal wall (identified as location 1 in Figure 7-2) The flow is then regulated through a set of gates (locations 2 and 3 in Figure 7-2).

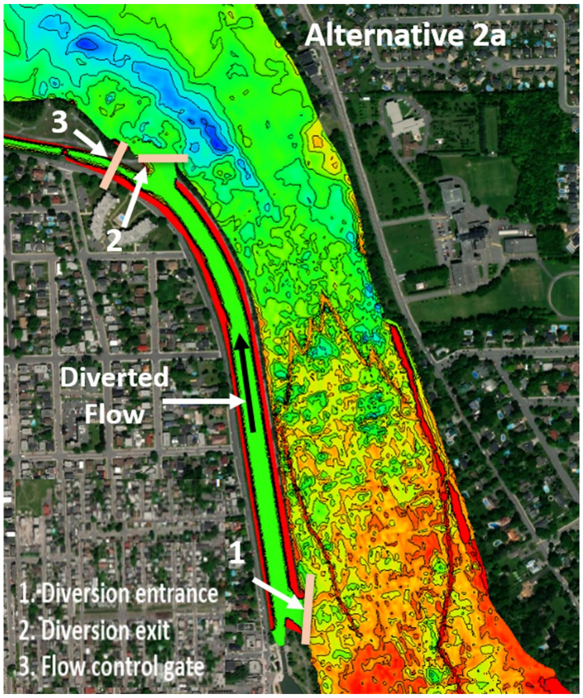


Figure 7-2 | Alternative 2a - Diversion below Lock 9 of Chambly Canal

Based on the current canal dimensions and hydraulic conditions, it was determined that the canal could accommodate a flow up to 270 m^3/s (9,535 ft^3/s), recognizing that the canal would need to be reinforced and the bed armoured. There would be some dredging of the riverbed to divert the flow to pass through the canal. It is estimated that 13,741 m^3 (17,972 yd^3) of material would have to be excavated from the main channel for this purpose of river training. There would also be dredging upstream of the entrance: 5,055 m^3 (6,611 yd^3); and downstream of the exit: 8,686 m^3 (11,360 yd^3). This alternative will disturb about 0.26 ha (0.64 acres) of the riverbed at the diversion entrance, and 0.93 ha (2.3 acres) at the diversion exit location. The total area disturbed for this alternative is 1.19 ha (2.94 acres).

The human interventions discussed in Alternative 1 would primarily remain in place, as the dredging emphasis is on efficient river training.

An initial simple rule for the operation of the diversion is proposed, based on a targeted water level upstream at Rouses Point of 30.35m (99.57 ft) NAVD88 (minor flood level). Once the water level reaches that target water level, the diversion would go into effect. The diversion would be primarily limited to seasonal operation prior to the opening of the canal to boat traffic, which is the end of May. However, it could be used outside this window, if required.

7.3.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

If this proposed simple diversion scheme is employed, it would result in lowering the peak water level by 19 cm (7.5 in) in the river and 8 cm (3.2 in) in the lake. After the diversion ended, water levels would return to normal and there would be no long-term impact on water levels.

This alternative would have negligible impacts on low flows for both the river and lake.

7.3.3 Considerations

Based on preliminary analysis from ISEE, this would prevent flooding of 230 to 350 residential buildings during a flood similar that which occurred in 2011. Based on preliminary estimates, it is expected that this work would cost between $22-27 million.

The historical designation of the canal could present design issues that would affect the feasibility of this project. To proceed further with this alternative will require the Study Board to work closely with Parks Canada, the federal agency responsible for managing the Chambly Canal.

It is anticipated that the environmental impacts would not be significant, as only the peak flow would be lowered; there could be localized impacts, but this would need to be assessed (ICRB 1977c).

7.4 ALTERNATIVE 2B: DIVERTING SIGNIFICANT FLOW THROUGH THE CHAMBLY CANAL WITH AN OPTIMIZED DIVERSION SCHEME

7.4.1 Description

This alternative explores modifying the canal to optimize the capacity to divert flow. The river training is also more extensive in order to be able to route this greater amount of flow into the canal. This scheme reflects what is possible theoretically, but further work may reflect that this alternative may not be achievable due to various limitations, and it may need to be scaled back accordingly. The Chambly Canal modifications to achieve a higher diversion rate than in Alternative 2a consist of the following key features: (all elevations are referred to NAVD88 datum)

1. Dredging in the shoal area to 25.2 m (82.7 ft).
2. Construction of a submerged dike with a crest elevation of 26.4 m (86.6 ft).
3. Upstream canal wall training at an elevation of 30.5 m (100 ft).
4. 40 m (131 ft) diversion control gates at a new entrance below Lock #9.
5. Chambly Canal control gates below the exit of diverted waters.
6. Downstream canal wall training at an elevation of 30.5 m (100 ft).
7. 45 m (148 ft.) diversion exit control gates with dredging in the main river to 24.35 m (80 ft).

Along with this optimization, other modifications required include dredging and reshaping the canal cross-section, adjusting the slope, and armouring of the bed.

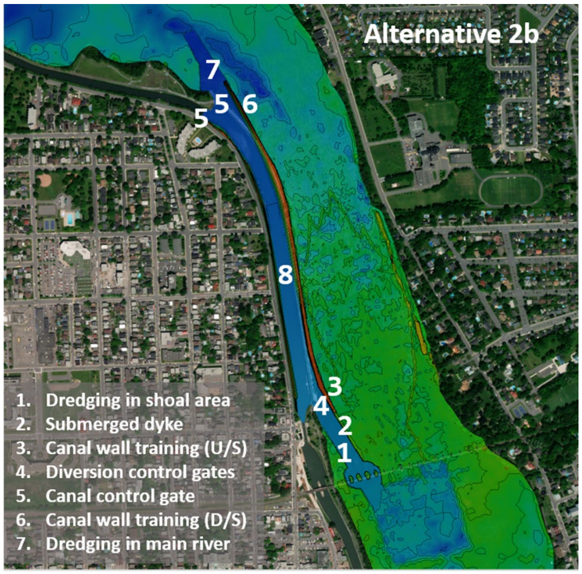


Figure 7-3 | Alternative 2b - Modified and optimized configuration of diversion

It is estimated that 126,516 m^3 (4,467,708 yd^3) of material would have to be excavated from the main channel for river training, plus an additional 44,193 m^3 (1,560,604 yd^3) upstream of the entrance and 82,323 m^3 (2,907,103 yd^3) downstream of the exit, including canal slope changes. This alternative will disturb about 1.37 ha (3.38 acres) of the riverbed for the river training at the diversion entrance, 4.32 ha (10.7 acres) to reshape the Chambly Canal, and 0.94 ha (2.32 acres) for stream training at the diversion exit and the Richelieu River. The total area disturbed for this alternative is 6.62 ha (16.36 acres).

7.4.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

If this proposed diversion scheme is employed, it would result in lowering the peak water level by up to 33 cm (13 in) in the river and 15 cm (5.9 in) in the lake. This would not have any long-term impact on water levels.

The Chambly Canal diversion will carry 395 m^3/s during peak flow conditions.

This alternative would have negligible impacts on low flows for both the river and lake.

7.4.3 Considerations

Based on preliminary analysis from ISEE, this would prevent flooding of 410 to 610 residential buildings during a flood similar that which occurred in 2011. Based on preliminary estimates, it is expected that this work would cost between $60-75 million.

The historical designation of the canal could present design issues that would affect the feasibility of this project. To proceed further with this alternative will require the study to work closely with Parks Canada, the federal agency responsible for managing the Chambly Canal.

The environmental impacts of this significant reduction in peak flow would have to be assessed.

7.5 ALTERNATIVE 3: ALTERNATIVE 2A COMBINED WITH ALTERNATIVE 1

7.5.1 Description

This alternative utilizes diverting flow through the Chambly Canal during the freshet period to lower high-water levels (Alternative 2a), in combination with the removal of the eel trap, submerged dikes, and Iberville Islands (Alternative 1). The total dredging volumes is the sum for the first two alternatives, about 23,727 m^3 or 31,033 yd^3, although the dredging related to Alternative 1 may need to be modified to further support efficient river training in support of Alternative 2a. Figure 7-4 depicts this layout. This alternative will disturb an area for Alternative 1 of 4.45 ha (11.1 acres) and Alternative 2a of 1.19 ha (2.94 acres). The total area disturbed for this alternative is 5.64 ha (14.04 acres).

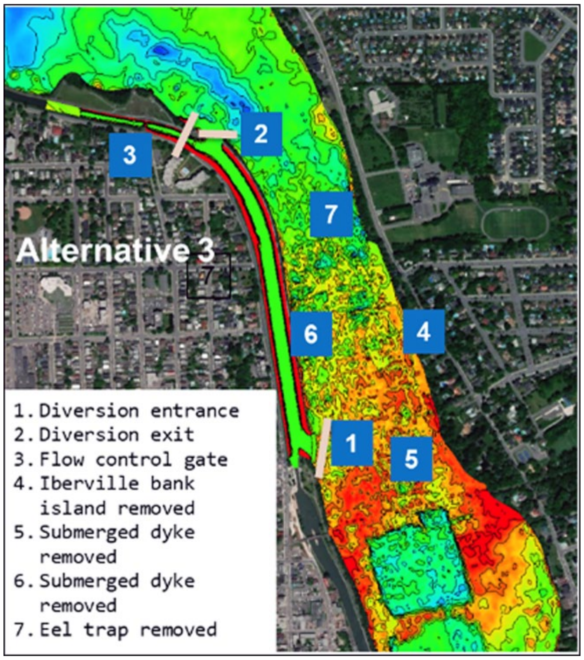


Figure 7-4 | Dredging of human interventions and Chambly Canal diversion

7.5.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

This alternative would result in a reduction in water level by 23 cm (9 in) on the river at St-Jean-sur-Richelieu and 12 cm (4.7 in) on the lake for a flood similar to the 2011 flood. As noted previously, the reduction in water level could be further increased if the diversion plan is modified.

In terms of low flow impacts, this could result in lowering the water level on both the lake and river by 8 cm (3.1 in) based on 1964 drought conditions.

7.5.3 Considerations

Based on ISEE preliminary analysis, this alternative would prevent flooding of 290 to 430 residential buildings in Saint-Jean-sur-Richelieu during a flood similar that which occurred in 2011. The preliminary estimate of costs is on the order of $25-30 million.

The considerations are those that were described for Alternatives 1 and 2.

7.6 ALTERNATIVE 4: FIXED WEIR UPSTREAM OF SAINT-JEAN-SUR-RICHELIEU

7.6.1 Description

As discussed in Chapter 4, installing a fixed weir in the shoal was considered under the 1973 reference. The basic premise in this alternative is to dredge so that the control section moves upstream of St. Jean-sur-Richelieu, substantially lowering levels in the reaches where damages occur now. A fixed submerged weir would be installed in the Richelieu River at the new control point (Figure 7-5) with a crest elevation of 28.0 m (91.86 ft) NAVD88. The elevation of the fixed weir was selected to reduce extreme high-water levels while not significantly exacerbating low water levels. It would require the dredging/excavating of 244,658 m^3 (320,000 yd^3) of material and the lowering of the natural control at the shoal. This alternative will disturb about 12.5 ha (30.9 acres) of the riverbed at the location of submerged dike, and 57.5 ha (142.1 acres) for dredging in the shoal area. The total area disturbed for this alternative is 70.0 ha (173 acres).

7.6.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

Alternative 4 would reduce the peak water level on the river at St-Jean-sur-Richelieu by 113 cm (44.5 in) and 40 cm (15.4 in) on the lake during a flood similar to the 2011 flood.

Alternative 4 would also have a potentially significant adverse effect on low water levels on the river and lake, varying with the weir elevation selected.

7.6.3 Considerations

Based on preliminary analysis from ISEE, this alternative would prevent flooding of 1,400 to 2,100 residential buildings in Saint-Jean-sur-Richelieu during a flood similar that which occurred in 2011.
The preliminary estimate of the cost is about $80-100 million.

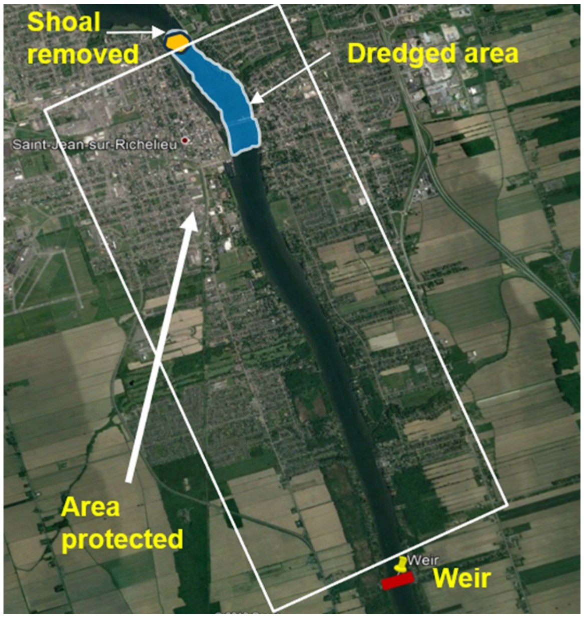


Figure 7-5 | Fixed submerged weir in the Richelieu River upstream of Saint-Jean-sur-Richelieu

Significant effort would be required to determine the environmental impacts in the river and lake. More detailed and accurate cost estimates would be required to determine the economic viability of such a large-scale effort.

7.7 ALTERNATIVE 5: INFLATABLE WEIR OR BLADDER UPSTREAM OF SAINT-JEAN-SUR-RICHELIEU

7.7.1 Description

Alternative 5 proposes the use of a technology (i.e., inflatable weir or bladder) that was not considered in past studies to regulate flows and water levels. The inflatable weir (Figure 7-6) would primarily be used to reduce high water levels while still safeguarding extreme low water levels. It would be installed at the same location as the Alternative 4 weir. The regulation plan (referred to as scheme FCE-1) that was developed in the 1970s was used to provide these initial results for illustrative purposes (ICRB 1978).

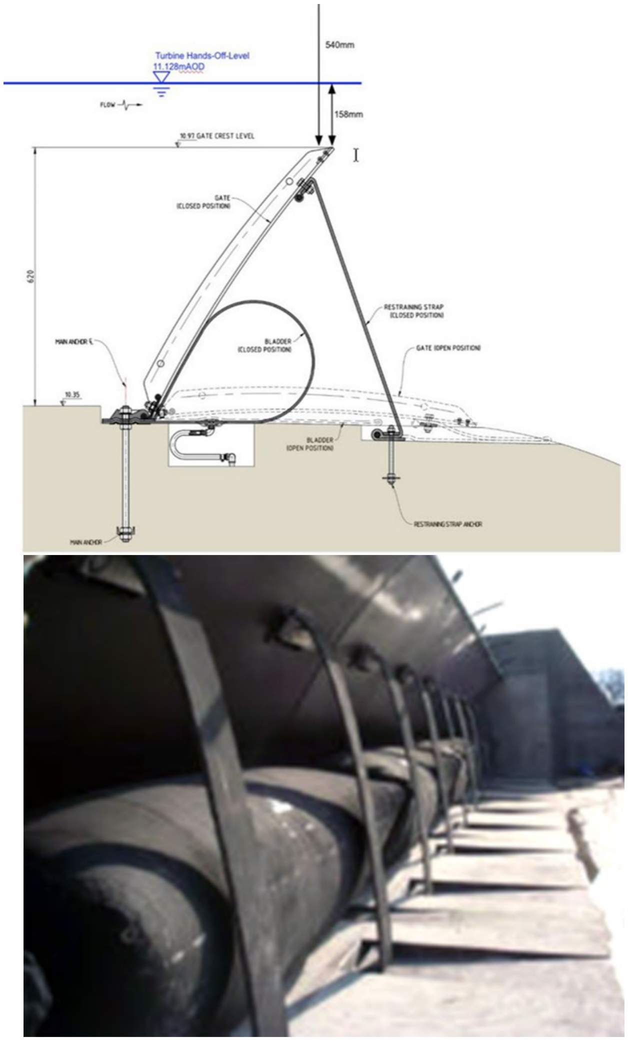


Figure 7-6 | Inflatable weir or bladder

7.7.2 Hydraulic Implications (river, lake, based on 2011 flood and 1964 drought)

Preliminary results from ISEE show that this alternative would result in the lowering of the river by 113 cm (44.5 in) and by 40 cm (15.7 in) on the lake as was the case for Alternative 4. The inflatable weir would allow greater control over low water levels, so Alternative 5 would be more effective than Alternative 4 at preserving adequate boating depths during droughts.

7.7.3 Considerations

Based on preliminary analysis from ISEE, this alternative would prevent flooding of 1,400 to 2,100 residential buildings in Saint-Jean-sur-Richelieu during a flood similar that which occurred in 2011. The preliminary estimate of the cost is about $100-120 million.

Significant effort would be required to determine the environmental impacts in the river and the lake. More detailed and accurate cost estimates would be required to determine the economic viability of such a large-scale effort.

7.8 ALTERNATIVE 6: INFLATABLE WEIR OR BLADDER AT SAINT-JEAN-SUR- RICHELIEU

7.8.1 Description

Alternative 6 also would use the same technology (i.e., inflatable weir or bladder) as Alternative 5. However, in this case it would be constructed on the shoal, as was proposed in the 1970s. This alternative also uses the regulation plan (referred to as scheme FCE-1) developed at that time for illustrative purposes. This would not provide as much protection as Alternative 5, but it would result in considerably lower construction costs, as the amount of dredging would be significantly less, at 9,986 m^3 (13,060 yd^3). This alternative would disturb about 32 ha (79.1 acres) of the shoal bed.

7.8.2 Hydraulic implications (river, lake, based on 2011 flood and 1964 drought)

This alternative would lower the river at St-Jean-sur-Richelieu by around 44 cm (17.3 in) and the lake by 27 cm (10.6 in) or more for a flood similar to the 2011 flood. A more optimized pre-regulation plan could help provide additional flood relief.

Low water levels would not be significantly affected by this alternative, as the inflated weir height could be selected to maintain or even improve water levels during periods of drought.

7.8.3 Considerations

Alternative 6 would prevent flooding of 370 to 560 residential buildings in Saint-Jean-sur-Richelieu during a flood similar that which occurred in 2011 at a cost of some $55-65 million.

Significant effort would be required to determine the environmental impacts in the river and lake if the Study Board should consider pursuing evaluating this alternative. More detailed and accurate cost estimates would be required to determine the economic viability of such a large-scale effort.

7.9 STUDY BOARD EVALUATION AND RANKING OF THEME 1 ALTERNATIVES

On March 24, 2020, the Study Board began a practice decision online with two major objectives. The first was to continue to refine the criteria by applying them in practical circumstances to see where adjustments might be warranted. The second objective was to decide how much more work to do on any or all of the Theme 1 alternatives described above. Over the next week, each board member evaluated how well each alternative met each criterion. The workshop "practiced" the use of the Board's criteria to rank alternatives. The Board used preliminary information to do so, as is usually the case with practice decisions earlier in a study process. The Board did not yet have estimates of expected damages under the baseline or alternatives.

The Board used very preliminary cost estimates and a simple measure of effectiveness, the number of homes removed from the flooded outline. The Study Board scores were then compared and combined. The act of practicing the decision also provided the Board with useful information to manage limited study resources, and in a later session; the Study Board directed the study team to focus on one alternative[6], the diversion of flood water through the Chambly Canal. The Board did not decide to recommend the diversion or to not recommend the other alternatives, and it will return to these questions in the writing of the final report.

7.9.1 Decision Criteria

Table 7-1 summarizes the Study Board's decision criteria. Board members were asked to score each alternative for each decision criterion.

The scoring was simple, reflecting the limited amount of information about each alternative at this initial stage (Table 7-2).

The possible scores were:

1 = Positive,

0 = Neutral,

-1 = Negative, and

? = Not sure at this time.

The scoring template is shown in Figure 7-7; a summation of the scores is tabulated in Figure 7-8. For example, a score of 25 for Alternative 1, in Figure 7-8, is arrived by arithmetically summing the number of positives, 34, and subtracting the number of negatives, 9 (+34 – 9 = 25). Other sums of scores were computed accordingly.

The two approaches under Alternative 2 were scored as one option.

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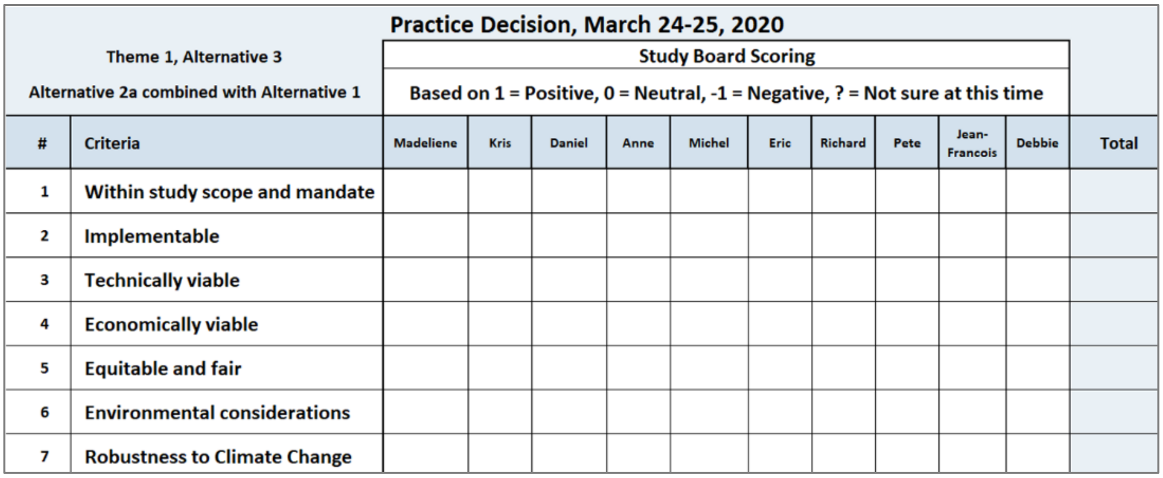
[6] From the **LCRR Record of Decisions**. Decision number 139 2020-04-20. Approval of structural alternatives (Theme 1). The Study will focus on alternative 2 (a & b) moving forward. The motion was approved following substantial debate. The other alternatives will still be evaluated for inclusion in the final report, but at a more general level.

Table 7-1 | Study Board decision criteria

#	Criterion	Context	Evaluation	Performance Indicators (PIs) or other documentation
1	**Within study scope and mandate.**	International study focuses on solutions that reduce Lake Champlain and Richelieu River flood damages, not local flooding problems.	Based on the reference from governments and the IJC's directive and continuing advice to the study, which stipulates only moderate structural solutions will be studied.	Recorded Study Board decision.
2	**Implementable.**	Because governments alone can implement study recommendations, the Board prefers alternatives that meet the requirements governments impose for such alternatives.	Only governments can determine with certainty; the Board estimates implementability based on surveys of the public and stakeholders, input from public and stakeholder meetings, input from Provincial and Federal Coordinating Committees, State and Federal agency representatives and elected officials in both countries.	Metrics from SPE surveys. Study meeting notes with various groups.
3	**Technically viable.**	Is the alternative engineering sound and effective in reducing flood damages?	Based on technical and scientific assessment and input by study's experts, including estimates of flood level reductions.	Study reports. ISEE PIs
4	**Economically viable.**	Benefits exceed the costs. Implementers can fund the required work, not potentially cost prohibitive. Sustainable – will not require subsidization for its ongoing operation.	Based on the application of sound economic evaluation practices. Based on cost-benefit analyses completed by the study.	SPE's economic evaluation.
5	**Equitable and fair.**	The solution broadly benefits society and not just a particular group or interest (e.g., urban vs rural). Does not result in transferring any disproportionate negative impacts to another interest.	Based on the application of principles determined by the Study Board.	Criteria established by the Board.
6	**Environmentally sound.**	Increases environmental benefits, or as a minimum, limits detrimental impacts. Protection and restoring of ecosystem services.	Based on applying ISEE's suite of environmental performance indicators to assess impacts.	Suite of ISEE's environmental PIs.
7	**Robustness to Climate Change.**	Works about as well as or better than other solutions across a wide range of possible climatic scenarios and futures.	Based on applying the decision scaling approach that is central to the IJC's Climate Change Guidance Framework. This information will not be available until Fall, 2020.	Decision scaling analysis results.

Table 7-2 | Data presented to the Study Board for evaluating the seven alternatives

Alternatives	Estimated Cost	Flood relief at record high at SJSR (2011)	Impacted Residential Buildings	Flood relief at record high in Lake Champlain (2011)	Decrease in water level at low flow (1964) at SJSR	Decrease in water level at low flow (1964) in Lake Champlain
Alternative 1: Dredging Shoal of Human Interventions	$3 to $5M	9 cm (3.5 in)	110-170 houses	6 cm (2.4 in)	8 cm (3.1 in)	8 cm (3.1 in)
Alternative 2a: Conservative Chambly Canal Diversion	$22 to $27M	19 cm (7.5 in)	230-350 houses	8 cm (3.1 in)	Negligible	Negligible
Alternative 2b: Optimized Chambly Canal Diversion	$60 to $75M	33 cm (13.0 in)	410-610 houses	15 cm (5.9 in)	Negligible	Negligible
Alternative 3: Alternatives 1 and 2a combined	$25 to $30M	23 cm (9.1 in)	290-430 houses	12 cm (4.7 in)	8 cm (3.1 in)	8 cm (3.1 in)
Alternative 4: Fixed submerged Weir upstream of SJsR	$80 to $100M	113 cm (44.5 in)	1400-2100 houses	40 cm (15.7 in) (or more)	170 cm (66.9 in)	Based on selected weir elevation
Alternative 5: Inflatable Weir upstream of SJsR	$100 to $120M	113 cm (44.5 in)	1400-2100 houses	40 cm (15.7 in) (or more)	170 cm (66.9 in)	Based on selected weir elevation
Alternative 6: Inflatable Weir at the Shoal	$55 to $65M	44 cm (17.3 in)	370-560 houses	27 cm (10.6 in)	Negligible	Based on selected weir elevation



Practice Decision, March 24-25, 2020

Theme 1, Alternative 3

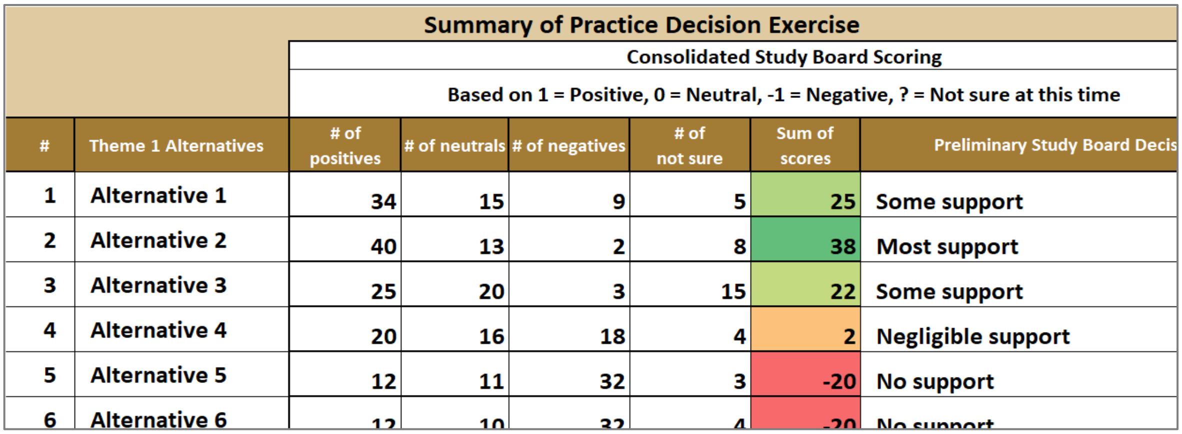
Alternative 2a combined with Alternative 1

Study Board Scoring

Based on 1 = Positive, 0 = Neutral, -1 = Negative, ? = Not sure at this time

#	Criteria	Madeliene	Kris	Daniel	Anne	Michel	Eric	Richard	Pete	Jean-Francois	Debbie	Total
1	Within study scope and mandate											
2	Implementable											
3	Technically viable											
4	Economically viable											
5	Equitable and fair											
6	Environmental considerations											
7	Robustness to Climate Change											

Figure 7-7 | Decision criteria scoring template for Theme 1 alternatives



Summary of Practice Decision Exercise

Consolidated Study Board Scoring

Based on 1 = Positive, 0 = Neutral, -1 = Negative, ? = Not sure at this time

#	Theme 1 Alternatives	# of positives	# of neutrals	# of negatives	# of not sure	Sum of scores	Preliminary Study Board Decis
1	Alternative 1	34	15	9	5	25	Some support
2	Alternative 2	40	13	2	8	38	Most support
3	Alternative 3	25	20	3	15	22	Some support
4	Alternative 4	20	16	18	4	2	Negligible support
5	Alternative 5	12	11	32	3	-20	No support
6	Alternative 6	12	10	32	4	-20	No support

Figure 7-8 | Summary of the Study Board's scores

7.9.2 Alternatives 4, 5, and 6

Alternative 4 received negligible support and Alternatives 5 and 6 received no support, as per the Study Board exercise results (i.e., Figure 7-8). These results are consistent with those of earlier practice decisions conducted with the Study Board.

These three alternatives were the most expensive and required the greatest physical disruptions, but also provided the greatest water level reductions. Under the first decision criterion, the Study Board had to determine whether or not these alternatives would be considered "moderate" and thus consistent with the directions provided by the governments and the IJC. The Study Board considered the history of the rejection of dams in the basin and the opinions provided in a series of meetings with Quebec officials in December 2019. Based on this, Alternatives 4, 5 and 6 scored low. For Alternative 4, the results were split as to whether this alternative was within the Study Board's mandate; for Alternatives 5 and 6 it was clear that most felt these two are outside the mandate.

In regards to criterion 2, technical viability, the Study Board expressed concerns about the reliability of the inflatable weir/bladder to be implemented in Alternatives 5 and 6. The fact that Alternative 4 uses a fixed rather than an inflatable weir/bladder made it less of a concern.

These three alternatives are very costly alternatives and some preliminary analysis (none of these alternatives have yet been fully evaluated in ISEE) suggested that benefits might not exceed costs (Criterion 4). Given the disruption these alternatives would cause in the hydrologic regime and the environment (Criterion 6), they generated no support.

The Study Board has not heard support or even interest in structural solutions in the United States There was widespread resistance to the six-gate structure proposed in the 1980s, and the resistance to structural solutions was articulated in public meetings in Vermont and New York during this study. At this point in the study analysis, based on field surveys, it appears that the flooding issue is less significant in the United States. Therefore, there appears to be limited interest in pursuing any significant structural solution.

Based on all of the above considerations, the Study Board determined that no further study resources should be committed to evaluate these alternatives.

7.9.3 Alternatives 1, 2a, 2b, and 3

Alternatives 1- 3 were scored positively by the Study Board members. They all agreed that these alternatives are considered to be clearly within the scope of the IJC directive and the governments' reference (Criterion 1). These alternatives focus primarily on reducing extreme flows and not on the regulation of the full flow regime. From this perspective, they also would only have limited, if any, environmental impacts and therefore, overall, they were viewed positively.

Alternative 1 received support because it addressed undoing past human interventions in the river, and this was viewed as positive from an environmental perspective (Criterion 6). However, there are three drawbacks that make this alternative less appealing. The first is that it provides limited flood relief (9 cm) (3.5 in), which is not significant in terms of addressing flooding (Criterion 3). The second is that this will result in a permanent lowering of water levels, which would negatively impact low flows during a drought period, on the order of 8 cm (3.1 in) (Criterion 5). The third is concern about triggering erosion (Criterion 6).

The Study Board was most supportive of the canal diversion solution, either Alternative 2a or 2b. Alternative 2a provided flood relief of some 19 cm (7.5 in), which was considered to be significant. It also would not impact low flows. Alternative 2b provides additional flood relief (33 cm) (13 in) through further optimizing of the canal diversion scheme, making this approach even more appealing from the Study Board's perspective.

The diversion involves utilizing an existing structure with some modifications. It has been proven that the canal encroachment in the 1970s resulted in the increasing high-water levels and is responsible for exacerbating the flooding issue. Now its utilization could be used to help mitigate the flooding issue. The environmental impacts would be limited, as just the peak water levels would be reduced in extreme years. There has been general support for this alternative.

Alternative 2a provided flood relief of some 19 cm (7.5 in), which was considered to be significant. It also would not impact low flows.

Alternative 3 is less attractive, as it requires the costs of both alternatives, but the flood level reduction is less than the sum of the two independently.

7.9.4 Board Direction on Theme 1 Alternatives

The Study Board issued a formal decision on further analysis of Theme 1 alternatives at its 26 May 2020 meeting (Figure 7-8). The Study Board directed some additional development of Alternative 2 (includes 2a and 2b), the diversion of flood waters from the main channel through a section of the Chambly Canal. This additional work will include:

- Cursory design of gate technology and dimensions suitable to the Chambly Canal, and cost estimations of materials, construction, and maintenance;
- Cursory cost estimates of the construction of the canal configuration and maintenance;
- Development of one or two water management plan(s) to ensure the alternative will not create worse hydraulic conditions upstream and downstream of the diversion. Plan(s) should include the use of short-term forecast, seasonal climate outlook, and/or other information and proxy, in addition to the current plan opening/closing at fixed water levels;
- The appropriate hydraulic simulations and evaluations in ISEE;
- A recommendation to the Study Board about which PIs should be used to assess the benefits/impacts of this measure; and
- A benefit/cost analysis after developing the required parameters and processes compatible with the decision criteria and processes of the LCRR study.

8 SUMMARY

An extensive search was undertaken to identify potential structural solutions to reduce water levels in the Lake Champlain-Richelieu River system. This involved taking into account structural solutions identified under the 1973 IJC reference, getting input from residents in the basin for other ideas, a literature scan, and finally the application of new engineering designs tailored to the hydrology/hydraulics of the system.

As noted in this report, implementing any structural solutions will face considerable challenges for a variety of reasons. Changing climate and evolving floodplain management policies create much uncertainty in terms of assessing the economic viability of any structural solution. Potential environmental impacts continue to be the other major reason for limiting the implementation of structural solutions. Society, in general, is more supportive of non-structural solutions than structural solutions. There is a myriad of laws, regulations, and other mechanisms that would need to be addressed before moving forward with a structural solution that could result in significant delays in implementation, possibly extending for decades.

The Study Board is also very cognizant of the early unsuccessful attempts to implement a structural solution on the Richelieu River and the general lack of support for implementing a flood control structure. However, there is support for structural solutions from some stakeholders and therefore a viable solution is being pursued. Accordingly, the Study Board undertook this initial exploratory review of structural solutions, leading to a more detailed formulation and evaluation of these seven alternatives:

1. Excavating of human interventions on Saint-Jean-sur-Richelieu shoal (eel trap, submerged dikes).
2. a. Diverting flow through the Chambly Canal with a conservative diversion scheme.

   b. Diverting flow through the Chambly Canal with an optimized diversion scheme.
3. Alternative 2a combined with Alternative 1.
4. Moving the control through installing a fixed weir upstream of Saint-Jean-sur-Richelieu and channel dredging.
5. Installing an inflatable weir or bladder upstream of Saint-Jean-sur-Richelieu and channel dredging.
6. Installing an inflatable weir or bladder at the Saint-Jean-sur-Richelieu shoal and channel dredging.

The Study Board evaluated these alternatives using the decision criteria the Study Board established, to determine whether any should be pursued further.

The Study Board determined that the most promising structural alternative involves the canal diversion, in particular Alternative 2b. Alternatives 1 and 3 are still in consideration pending the results of the Alternative 2b evaluation. The diversion is appealing, as it reduces extreme flood levels but has little or no effect on normal or low water levels. The Study Board provided direction to the study team to enhance the specification of the canal diversion and evaluate its benefits and impacts with the modelling tools developed by the study.

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