Lake Champlain – Richelieu River Flood Study

Final Report

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

August 2022
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ACKNOWLEDGMENTS

The work of the Lake Champlain – Richelieu River Study Board represents the collaborative effort of over 100 individuals in Canada and the United States, and the culmination of five years of study. This final report benefited from the contributions of the past and present Study Board members, Technical Working Group members, Study Managers, and our writing team. A comprehensive review of the report was conducted by the Independent Review Group (IRG). A full list of Study members is provided in Appendix C. The Board wishes to thank all Study members for their time, expertise, and dedication to this effort.

In addition, the Study Board is grateful for the contributions of numerous individuals and organizations who supported the Study's work and provided valuable input to improve the Study's recommendations and effectively communicate our results, including:

- Members of the Public Advisory Group who consulted with Study members throughout the project and assisted with outreach
- Members of the public who attended public meetings, workshops, and informational sessions, and provided feedback during the public comment period
- Community members from First Nations and Native American Indigenous communities, including in Canada, members of the Grand Conseil de la Nation Waban-aki and the Mohawk Council of Kahnawà:ke, and in the United States, the Nulhegan Band of the Cooksuk Abenaki Nations

- Environmental, economic development and agricultural organizations

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This final report was authored and submitted by John F. Bratton, PhD, PG and Kathy Hall, QEP, LimnoTech.

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A NOTE FROM THE STUDY CO-CHAIRS

Following catastrophic flooding along the shorelines of Lake Champlain and the Richelieu River during the spring of 2011, the governments of Canada and the United States asked the International Joint Commission (IJC) to review the causes and develop potential measures to minimize impacts of future flooding in communities across the basin. The International Lake Champlain-Richelieu River Study Board was established in 2016. Since then, groups of experts have investigated scientific, engineering, environmental and socio-economic aspects of the problem and developed recommendations that can offer real, long-term benefits that reduce flooding and its impacts on the Lake Champlain and Richelieu River communities.

The Study has prioritized learning from past experiences and current perspectives of basin residents, speaking with community leaders and organizations about emergency response, economics, social and environmental concerns, as well as consulting decision-makers in federal, state, and provincial governments. These considerations were integrated with modern scientific models to design flood reduction measures, improve flood forecasting, enhance floodplain management, and evaluate new flood insurance approaches. Ensuring resiliency of proposed measures in the face of climate change was paramount. As a result, the Study's recommendations reflect the concerns of basin communities in both countries and support workable approaches to reduce flooding and its impacts. Water level extremes of a system like the Lake Champlain and Richelieu River watershed can never be completely controlled, especially in the face of a changing climate. Nevertheless, thoughtful structural and non-structural approaches can be implemented over time to improve community resilience and reduce risks to life and property.

Jean-François Cantin, Canada Co-Chair

Deborah H. Lee, United States Co-Chair

The members of the Study Board were appointed by the International Joint Commission to provide the expertise needed to prepare this report. Although some are employed by government agencies in both Canada and the United States, they serve the Commission in their personal and professional capacities and the views they expressed as part of their participation in the Study do not necessarily represent those of their agencies. The report was developed by the Study Board and its contents should not be considered as official opinions, positions, or commitments of any named organizations, agencies or departments.

EXECUTIVE SUMMARY

The Study explored the causes, impacts, risks and solutions for flooding in Lake Champlain and the Richelieu River.

Lake Champlain and the Richelieu River experienced devastating floods in the spring of 2011 that called for a coordinated binational response to increase the resilience of the communities in the basin to future flooding events and decrease risks to human life and property. After the 2011 floods, the governments gave two initial mandates to the International Joint Commission (IJC): (1) to develop a plan of study for exploring potential flood management solutions via a range of structural and non-structural flood prevention and mitigation measures, and (2) to initiate development of tools and products for flood mitigation. In 2016, the governments of Canada and the United States instructed the IJC to implement a plan of study to examine the causes and impacts of the 2011 flooding and develop possible mitigation measures. The IJC established the Lake Champlain – Richelieu River Study Board. The Study Board has overseen the Lake Champlain-Richelieu River Flood Study (the Study) described in this report. The Study was an international collaboration involving more than 100 individuals with expertise in engineering, hydrology, flood management, planning and mitigation, emergency management, economics, communications and public outreach, social sciences and Indigenous knowledge. The Study Board was charged with providing recommendations to the IJC on what should be done to mitigate the flooding issue. This report presents the recommendations that resulted from the Study, as well as the process, including technical and engagement elements, that was used to develop the recommendations. A shorter "highlights" report has also been developed that presents this material in summary form for general audiences (ILCRRSB 2022).

The Study explored the causes, impacts, risks and solutions for flooding in Lake Champlain and the Richelieu River[1]. To do so, a framework was adopted for the Study that included consideration of a variety of structural and non-structural[2] measures. The Study Board's flood mitigation framework focused on four key mitigation themes, which are represented by icons in the report, as shown below:

Structural:

1. Reduce high water levels on the Richelieu River and Lake Champlain through accelerating the evacuation of water.

2. Impede inflows into Lake Champlain or the Richelieu River through wetlands and temporary upstream storage of floodwaters.

Non-structural:

3. Improve flood response (flood forecasting and emergency preparedness).

4. Enhance floodplain management (adaptation to flooding).

Experts identified, developed and evaluated potential flood mitigation measures under each of the four themes. Theme 1 focused on the development of moderate

[1] The Study focused on the reduction of flood impacts on the Richelieu River and Lake Champlain and did not directly address the reduction of flooding and the impact of flooding on tributaries, although the impacts of more localized tributary flooding are recognized as often severe and relatively frequent.
[2] 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 changes to flood levels, velocities, duration, or the environment.) Non-structural measures can be temporary (contingent) or permanent.

structures that lowered flood peaks, while Theme 2 evaluated the effectiveness of storing floodwaters within the watershed. In Theme 3, new flood forecast models were developed, and Theme 4 explored new approaches to floodplain management, flood risk communication and flood insurance. Evaluations of ways to mitigate flooding and its impacts in the LCRR basin included developing and using sophisticated computer models to understand and simulate floods and flood impacts, developing proposed mitigation solutions, and evaluating the feasibility of potential mitigation approaches. The Study applied a powerful tool, the Integrated Social, Economic and Environmental system (ISEE) to assist in understanding flood risk and evaluating potential solutions. ISEE was used to produce a variety of flood impact maps that were tailored to support assessment of the possible mitigation measures. Other discipline-specific methods and models were used by various experts to answer specific questions such as those related to upland storage capacity or the potential effects of climate variability on flood adaptation strategies.

To integrate social, political and economic considerations, social scientists used methods such as conducting focus groups and surveys of the general public; emergency managers and planners; and state, provincial and federal civil servants and elected officials to gauge risk perception, sources of risk communication and flood mitigation behaviors. Matters such as technical feasibility, cost, environmental impact, acceptability, political feasibility and public preferences of specific structural changes were taken into consideration. Through these activities, the experts were able to understand how stakeholders in each region of the basin perceived the risk of lake and riverine flooding, the anticipated impacts on their livelihoods, and their willingness to adopt certain risk mitigation measures and policies, as well as how they received risk communication messages.

The Lake Champlain and the Richelieu River basin has served, and continues to serve, as a resource for food, water, tools and spiritual practices for Indigenous peoples. Hunting, gathering, fishing, boating and recreation are important activities. There are cultural and archeological sites (campsites, villages, meeting sites, burial sites) of traditional and sacred importance to the Indigenous people across the basin. As such, the Study reached out to Indigenous communities with an interest in flood mitigation in the basin and started a dialogue to make certain that the Study Board heard their concerns about cultural resources and practices that have been impacted by past and recent flooding in the basin. New knowledge was also incorporated into the Study's development and use of performance indicators, helping to ensure that the evaluation of flood mitigation measures considered potential impacts on Indigenous communities and their important cultural sites.

Public and stakeholder engagement was an essential component of the LCRR Study and included both direct engagement by the Study Board (for example, through public meetings and interactive webinars) and close collaboration with the Public Advisory Group (PAG). The binational PAG represented various interests within the Lake Champlain-Richelieu River basin. Its members drew on their knowledge, networks and experience to provide advice and encourage broader public participation in the Study.

Based on the data, models and tools, as well as extensive consultation with Study experts, stakeholders and the public, the Board developed recommendations for each Study Theme, as well as several broader recommendations related to climate change, capacity building, legacy data and modeling tools. Recommendations include consideration of a structural measure to reduce water levels, as well as protection of wetland areas, improvements in flood forecasting and ideas for the implementation of improved flood risk management strategies. Moderate structural measures alone cannot keep the waters of Lake Champlain and the Richelieu River within their shorelines under all conditions, but they can provide some relief under high-flow events. To be most effective, however, they need to be used in combination with approaches that reduce exposure to floods, such as adjustment over time in the locations and construction details of buildings and other structures located at or near the shore, preservation of current wetland areas, and improvements in the ways that human and financial risks are communicated, understood and distributed among communities and individuals. This means that there is not a **single solution** to the problem of flooding in the LCRR basin, but rather a complementary suite of approaches that can collectively help LCRR communities become better prepared for future floods.

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.

FIND OUT MORE ABOUT THE STUDY

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

Email lcrr@ijc.org

Access the Study Board's many technical reports, fact sheets and videos on the Study's website: www.ijc.org/lcrr.

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1 INTRODUCTION TO THE REPORT

This report summarizes the evaluations conducted as part of the Study and presents the Study Board's recommendations; further details are provided in the individual Study reports referenced herein.

The Lake Champlain-Richelieu River (LCRR) basin (Figure 1) is an international watershed in southern Québec and northern New York and Vermont. It is a region of diverse geography – a deep lake surrounded by the Adirondacks to the west and the Green Mountains to the east, which flows to the north into flat, fertile farmland along the river that extends to the St. Lawrence River.

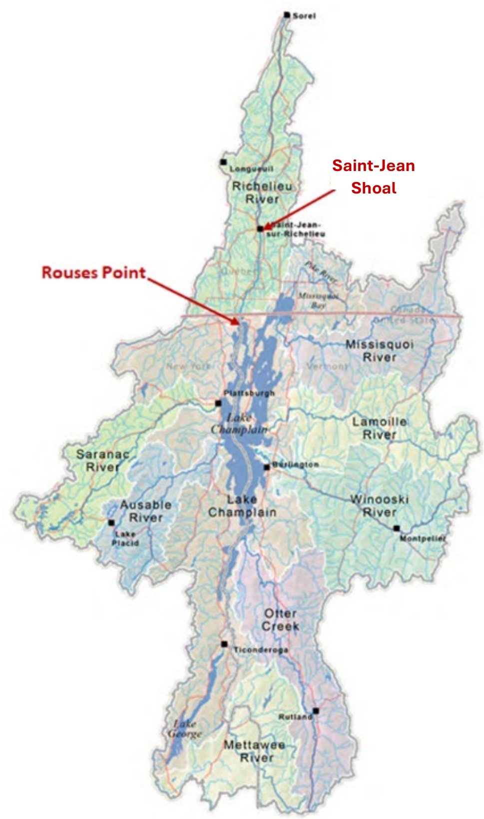

Figure 1. Lake Champlain-Richelieu River watershed.

It is also, as recent history shows, a region highly vulnerable to flooding. Major floods occurred in 1927, 1976, 1983, 1993, 1998 and 2011. A combination of topography and climate makes the LCRR basin naturally prone to extended periods of flooding. In particular, the watershed draining into Lake Champlain is more than 18 times the normal area of the lake itself. The steep mountain slopes of the upper basin, high winter snowfall amounts, the flow regime of the upper Richelieu River, strong winds and large waves, and the frequency of heavy spring rainfall are all key drivers of flooding in this basin. The dominant hydrological event of the year is the spring snowmelt, when nearly one-half of the annual streamflow can occur within an eight-week window. There are also instances of severe summer and fall floods, though these are more likely to be shorter flood events driven by individual storms or sets of storms rather than the longer-duration floods that occur in the spring.

In the spring of 2011, the region experienced flooding well beyond anything ever seen in the almost 200 years for which flood records are available. Lake Champlain's water levels reached 31.23 m (102.46 ft) NAVD 88[3] above sea level (FMMM & HHM, 2021), exceeding the previous historical maximum level of 30.9 m (101.3 ft) (FMMM & HHM, 2021). The Richelieu River rose above flood stage for more than two months. Many farms and an estimated 4,000 homes along the Richelieu River in Québec and along the shoreline of Lake Champlain were damaged. More than 40 communities were directly affected and thousands of residents needed to be evacuated. Damages were initially estimated at more than CDN$104 million (US$78 million)[4] (ILCRRSB 2019); more comprehensive subsequent estimates suggested that damages were about 70 percent higher, or about CDN$188 million (US$141 million) (Moin et al. 2022). The economic damages of the 2011 flood occurred primarily (79 percent) in Québec, with 11 percent of the damages in New York, and 10 percent in Vermont (IJC 2013). There are concerns that such catastrophic flooding could happen again, and that the magnitude, frequency and economic severity of flooding could increase over time due to a changing climate and ongoing development in the floodplain.

The catastrophic 2011 flood was a call to action. In the spring of 2012, the governments of Canada and the United States asked the IJC to draft a plan of study to examine the causes and impacts of the 2011 flooding and develop possible mitigation measures. In the fall of 2014, a second mandate from the governments requested the collection of data, development of tools and creation of static floodplain maps. In 2016, the governments instructed the IJC to carry out activities described in the plan of study, leading the IJC to establish the Lake Champlain – Richelieu River Study Board. The Study Board oversaw the Lake Champlain-Richelieu River Flood Study, which was an international collaboration involving individuals with expertise in engineering, meteorology and hydrology, flood management, planning and mitigation, economics, environmental analysis and social sciences. The Study Board was charged with providing recommendations to the IJC on what should be done to mitigate the flooding issue (for details, see the Study's website: https://ijc.org/en/lcrr). This report summarizes the evaluations conducted as part of the Study and presents the Study Board's recommendations; further details are provided in the individual Study reports referenced herein.

As the basin spans an international boundary, addressing flood risk necessarily includes a binational approach. It is therefore in both countries' interests to identify and implement effective solutions in a coordinated way to address the flooding issues; these solutions should be beneficial for reducing respective risks without adversely impacting either country.[5]

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[3] Prior to the LCRR Study, the vertical datum for measuring and reporting water levels in the United States and Canada were to different national standards. Before the occurrence of the 2011 flood, in Canada, the datum used was Canadian Geodetic Vertical Datum of 1928 (CGVD 28); while in the United States, it was National Geodetic Vertical Datum 1929 (NGVD 29). The US Geological Survey (USGS) and National Oceanic and Atmospheric Administration (NOAA) still use this datum for reporting water levels. Realizing the challenges in reporting water levels and forecasts during the flood of 2011, the IJC funded a project to harmonize the datum for the LCRR watershed using the established standard of North American Vertical Datum of 1988 (NAVD 88). The harmonization study procedures and tables that capture the steps and results of the analysis including the conversion tables for various key locations in the basin are reported in Flynn, et. al. (2016). In the collaborative work of the Study, all water levels, bathymetry and related information were referenced to NAVD 88 datum. Where water levels are shown on figures or other references produced by agencies or institutions from either country individually, and used or reproduced in this report, appropriate footnotes indicate the corresponding vertical datum.

[4] Currency values cited in this report reflect those used in the source documents as cited, not present values.

[5] The Study focused on the reduction of flood impacts on the Richelieu River and Lake Champlain and did not directly address the reduction of flooding and the impact of flooding on tributaries, although the impacts of more localized tributary flooding are recognized as often severe and relatively frequent. The reason for not directly considering tributary flooding is the fact that almost all the drainage areas for the tributaries lie in only one country or the other. That implies that the management of tributary floods could be done entirely within Canada or the United States and would not involve the IJC.

2 NATURAL AND HISTORICAL CONTEXT

To move toward a more flood resilient LCRR basin, it is important to first understand the natural setting and the human development history. Also important are the modern drivers that have created the conditions for ongoing risk to property and safety when variable flows and water levels in lakes and rivers impact the built environment.

2.1 NATURAL ENVIRONMENT OF THE LCRR BASIN

The Lake Champlain-Richelieu River basin (Figure 1) covers an area of about 23,900 km^2 (9,277 mi^2). About 84 percent of the basin is in northeastern New York and northwestern Vermont, and 16 percent is in Québec. The international border crosses the outlet at the north end of the lake, close to where the river begins, and also crosses Missisquoi Bay in Lake Champlain. The basin has two distinct types of topography. Around Lake Champlain, the basin is rugged and mountainous. Around the northern part of the lake, the terrain of the basin moderates to plains that continue northward to the confluence of the Richelieu River with the St. Lawrence River.

Lake Champlain (Figure 1) is a relatively large lake, with a surface water area of nearly 1,130 km^2 (about 436 mi^2) (ILCRRSB 2019). The lake, which was carved out of a faulted tectonic lowland during multiple continental glacial advances, is about 193 km (121 mi) long (ILCRRSB 2019) and extends from Whitehall, New York, north to its outlet at the Richelieu River near Rouses Point, New York, close to the United States-Canada border. The Richelieu River is the only outlet. Note that the Champlain Canal and its locks connect the southern part of Lake Champlain to the Hudson River in New York; this is not a natural connection and it does not significantly affect the overall water flow in the basin. The average depth of the lake is 19.5 m (64 ft) (ILCRRSB 2019) and the water level since 1971 has averaged 29.26 m (96.0 ft) (FMMM & HHM, 2021). The Richelieu River extends about 124 km (78 mi) (ILCRRSB 2019) north from its start at the outlet of Lake Champlain at Rouses Point, New York, to the south shore of the St. Lawrence River at Sorel-Tracy, Québec. For its first 37 km (23 mi), the river is wide (up to 1.5 km or 0.9 mi) and there is no significant impediment to flow. Near Saint-Jean-sur-Richelieu, the river becomes much narrower with a steeper gradient, as it meets a long barrier formed by shoals of dense glacial till. These shoals are about 210 m (689 ft) wide, extend for about 3.2 km (2 mi), and serve as the primary hydraulic control for the watershed, regulating Lake Champlain water levels and outflows, as well as flows in the Richelieu River (FMMM & HHM, 2021). Human artifacts in the shoals have also affected the hydraulic control. The average flow in the river is 330 m^3/s (11,650 ft^3/s) (Roy et al. 2022). In addition to static water levels in the lake, strong winds can push water to the north end of the lake at times, resulting in temporary increases in the flow of water over the shoals and down the river.

The Chambly Canal is situated along the west side of the river, approximately 48 km (30 mi) north of the Lake Champlain outlet and facilitates navigation past the rapids at Saint-Jean-sur-Richelieu. In Chambly, the river widens and its velocity decreases, forming the Chambly Basin, a popular boating and recreational area. Water levels in the river channel below the Chambly Basin are influenced by a dam about 50 km (31 mi) downstream at Saint-Ours, Québec (FMMM & HHM, 2021). The river enters the St. Lawrence River approximately 23 km (14 mi) downstream of the dam at a point 40 km (25 mi) northeast and downstream of Montreal. During high flow conditions in the St. Lawrence River, backflow can induce or amplify flooding in the lowermost Richelieu River. Because of the northward flow direction of the Richelieu River, spring melting in the southern upstream part of the basin can also lead to ice-related flooding conditions in the northern downstream reaches before river ice melts.

2.1.1 Hydrology of the LCRR basin

The dynamics of Lake Champlain water levels and corresponding flow in the Richelieu River are influenced by several factors. The key factors are the inflows to the lake, both in volume and temporal distribution; peak intensity of inflows; and lake water levels before a freshet or storm event.

Figure 2 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 averaged water levels, and the line graph shows the maximum observed water levels in each year. The figure also shows the flooding threshold of 30.35 m (99.57 ft) (FMMM & HHM, 2021)[6]. The extensive evaluations completed as part of this study (Ouarda & Charron, 2019; FMMM & HHM, 2021) indicate no significant increasing trends in peak water inflows, streamflow or water levels; however, there are significant increasing trends in annual Lake Champlain mean water levels, inflows and streamflow. After 1971, the mean lake level increased by approximately 26 cm (10 in). Increasing annual mean water levels can be explained by:

1. Wetter water supply regime in the spring and fall shoulder seasons[7];
2. Widening of the Chambly Canal (and narrowing of the river) in the early 1970s, which increased Lake Champlain's level by 10 cm (4 in) and the Richelieu River by 20 cm (8 in) (Moin et al. 2022); and
3. Increased aquatic vegetation growth, as in the Richelieu River, causing additional friction and associated higher water levels from late spring to fall.

A large part of the increase in mean levels can be attributed to the widening of the Chambly Canal.

Figure 3 shows the peak annual outflows from Lake Champlain into the Richelieu River. The figure also presents the inflows into the lake. An important observation from this graph is that the peak outflows are significantly smaller than the peak inflows into the lake, demonstrating the outflow-moderating behavior 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. The lower the initial lake level, the greater its ability to retain inflow without producing a corresponding amount of outflow to the Richelieu River. Hence, trends in water levels have an indirect impact on the potential for flooding. However, the study did not develop and analyze ways to use this buffering capacity of the lake to minimize the impacts of flooding.

[6] Flooding thresholds vary among governments and agencies; the threshold of 30.35 m (99.57 ft) NAVD 88 is considered minor flood stage by the US National Weather Service (NWS), representing minimal property damage and possibly some public threat (FMMM & HHM, 2021). The NWS flood thresholds are provided in Table 1.

[7] For the purposes of this study, 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 (FMMM & HHM, 2021)

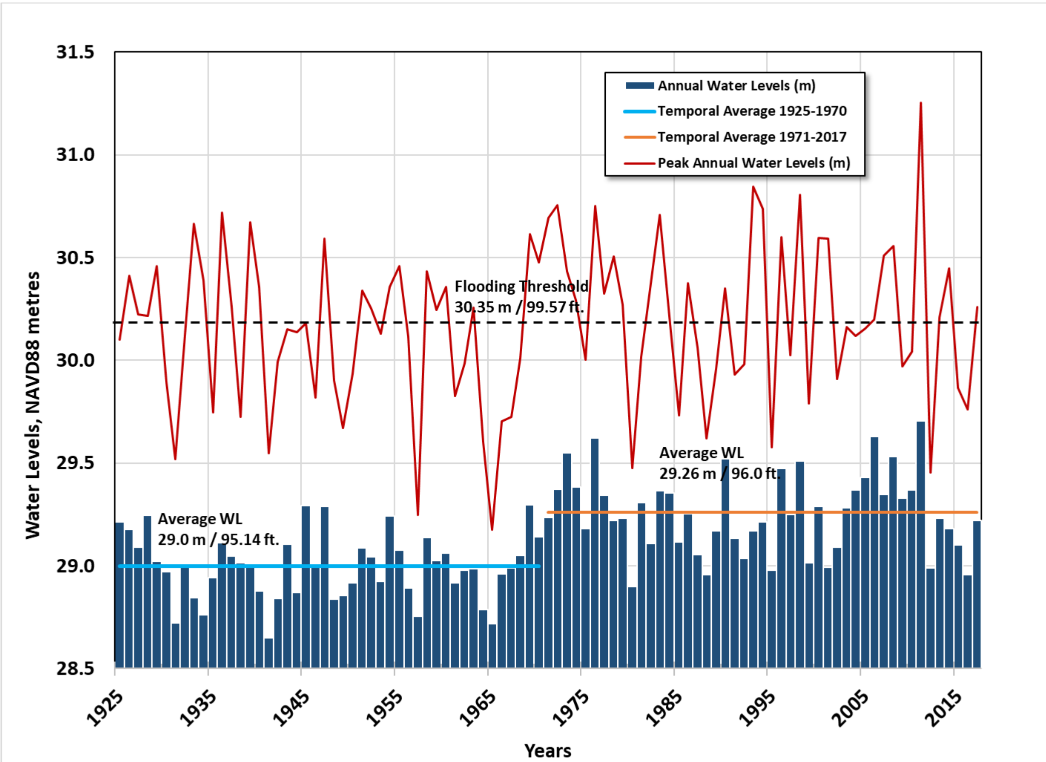


Figure 2. Peak (red line) and average annual (blue bars) Lake Champlain water levels (based on FMMM & HHM, 2021).

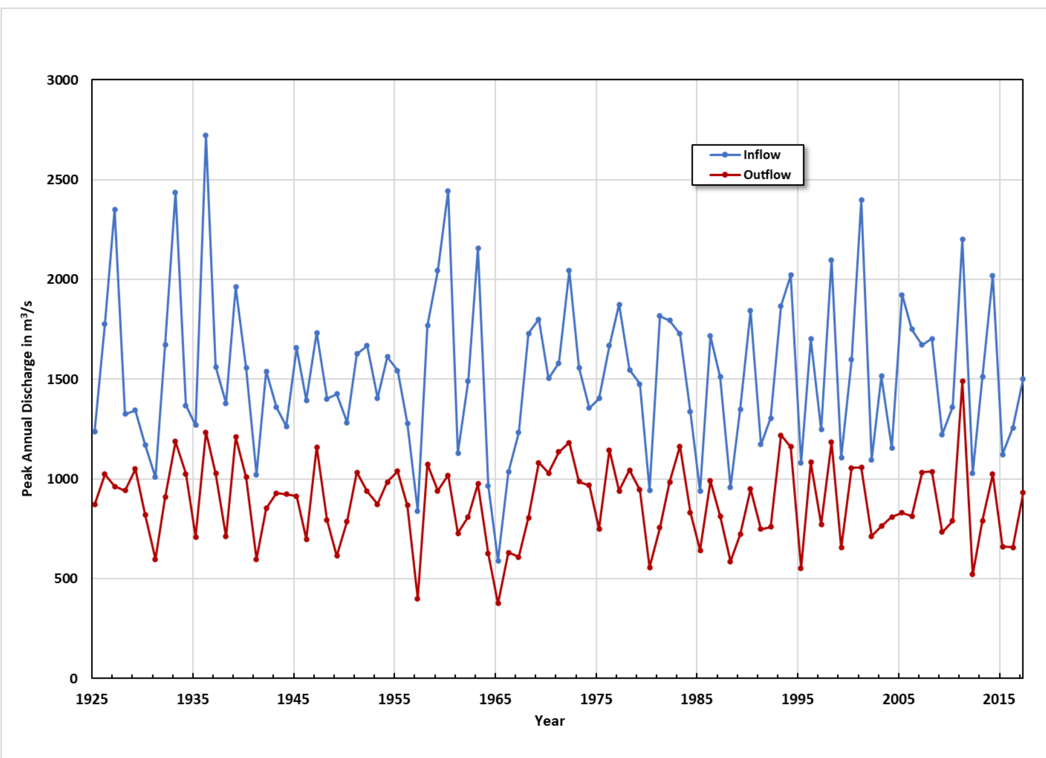


Figure 3. Peak annual inflow to Lake Champlain (blue line) and outflow from the lake into the Richelieu River (red line), demonstrating the lake's self-regulation.

2.1.2 Land cover

About two-thirds of the portion of the LCRR basin that lies within the United States is forested. Other important land uses and land cover in the United States portion of the basin include agriculture (nearly 16 percent); wetlands (nearly six percent); and urban and developed land (about five percent). The remainder of the basin in the United States is occupied by a relatively small proportion of shrubland, grassland and herbaceous vegetation, and barren land (Homer et al. 2015). Agriculture occupies nearly 70 percent of the basin area in Québec, about 8 percent is urban and other developed land, nearly 16 percent is forest, and about 2.4 percent is wetlands (ILCRRSB 2019).

2.1.3 Ecosystems

The LCRR basin supports a diverse range of ecosystems and wildlife and includes rare clayplain forest and a designated Wetland of International Importance under the global Ramsar Treaty that seasonally hosts tens of thousands of migratory waterfowl. Three major ecosystem types are most impacted by hydrological variations: lake and river aquatic environments; shorelines; and floodplains and wetlands. Some of the basin's species and ecosystems are particularly sensitive to changes in water levels. That is, they are indicators or measures of the environmental conditions that exist in a region. Indicator species and ecosystems can help identify possible effects of changes in those environmental conditions. Indicators for the Study were chosen to assess the various flood mitigation measures considered by the Study Board. In modeling and evaluating possible flood mitigation measures in the basin, the Study focused on the predicted impacts and responses of these selected indicators. The use of these indicators was not intended as an exhaustive evaluation of environmental impacts, but rather as a screening-level assessment to inform the Board's recommendations. The Study's indicator species (discussed later in this report), several of which are endangered or threatened, included: the Eastern Spiny Softshell Turtle (*Apalone spinifera spinifera*); Copper Redhorse (*Moxostoma hubbsi*); muskrat (*Ondatra zibethicus*); Northern Pike (*Esox lucius*) and Least Bittern (*Ixobrychus exilis*). Ecosystem indicators used in the Study include wetlands and waterfowl staging habitat. The indicators were selected to help the Board assess a range of potential impacts that are sensitive to water level changes; there are other important ecosystem considerations, such as water quality, that were not included as indicators because their relationships to water levels are less well established.

2.2 HUMAN ACTIVITY IN THE BASIN

2.2.1 Indigenous peoples

The Study area is located in the traditional territories of Haudenosaunee (Iroquoian) and Algonquian peoples, who continue to be present and active on the lands and waters of the region. The lands and waters of Lake Champlain and the Richelieu River have central importance to the cultures and livelihoods of these communities. Although the Canada-United States border cuts across established First Nations and Native American tribal territories, Indigenous Peoples have maintained traditional activities throughout these lands, on both sides of the border. Throughout the study, the Board sought Indigenous peoples' input and worked together to develop the study's performance indicators.

Broadly speaking, the Mohawk (Kanyen'kehà:ka - one of the six member nations of the Haudenosaunee Confederacy) are located west of the Richelieu River and Lake Champlain on both sides of the Canada–United States border, with reserve lands in the provinces of Ontario and Québec and reservation land in the State of New York. The Mohawk communities of Kahnawà:ke, Kanesatake, and Akwesasne are located closest to the Study area and upstream of the confluence of the Richelieu River with the St. Lawrence in the New York-Québec-Ontario border region and near Montreal on the Ottawa River. The St. Regis Mohawk have a designated reservation on the St. Lawrence River in Franklin County, New York, which is adjacent to the Akwesasne reserve in Québec.

The study area is important to the W8banaki nation, whose ancestral territory, the Ndakina, covers areas of Québec, New Brunswick, Maine, Vermont and New Hampshire. It stretches between the Rivière du Loup and the Richelieu River and between the St. Lawrence River and Boston in the United States.

The Stockbridge-Munsee Band of the Mohican Indians resided in the southern portion of the watershed historically, but now primarily resides in Wisconsin.

Archeological evidence indicates the presence of Indigenous peoples in Canada and the United States (including the Champlain valley) continuously over at least the past 12,000 years (GCNWA 2021). Lake Champlain and the Richelieu River served, and continue to serve, as resources for food, water, medicines, tools, economy, and spiritual practices. The lake and river are part of a travel network (transportation route) used by Indigenous people for thousands of years. Hunting, fishing, and gathering of species of plant, fungi and animals have been and continue to be important cultural activities. Over millennia, Indigenous peoples have adapted to the changes in climate, plants, and wildlife of the region as well as human modifications of the landscape of the Richelieu Valley and Lake Champlain, and natural hydrographic dynamics.

In the Champlain Valley, Indigenous peoples established settlements on the floodplains of the lake and major rivers. For thousands of years, Indigenous people have relied on agriculture and built villages along the fertile floodplains of Lake Champlain and the surrounding rivers, growing corn, squash, and beans.

There are archeological sites of traditional and sacred importance to the Indigenous people across the basin. Vestiges of their occupation sites (campsites, villages, meeting sites for exchanges between different Nations, workshops as well as burial sites) have been identified throughout the area. Known or potential archeological sites of importance to the Indigenous communities of the region may be at risk from past and future flooding and have been considered in the Study, as described in subsequent sections of this report. The Study's performance indicators (discussed later in this report) included several indicators important to Indigenous peoples, such as black ash and wild rice.

2.2.2 Population growth and distribution

The LCRR basin spans parts of twelve counties in Vermont, four counties in New York, and five regional county municipalities (RCMs) in Québec. The total population within the basin is estimated at 1,015,000. About 39 percent of the basin population lives in Vermont (about half of this in the Burlington metro area), 38 percent in Québec and nearly 23 percent in New York (ILCRRSB 2019).

The distribution of population and the built environment, which are key factors in considering the social and economic impacts of flooding, vary widely in the basin. Most areas in the United States portion of the basin have a population density of fewer than 85 people per square mile (33 people per km^2). By contrast, population density north of the international border is much higher, increasing northward along the Richelieu River to nearly 550 people per square mile (212 people per km^2). The only county within the United States with a comparable density to the Canadian portion of the basin is Chittenden County, Vermont. This county is home to over a quarter of the state's total population and contains Burlington, the largest city in the state (ILCRRSB 2019).

Population growth can influence land use when the natural land cover in a region is converted for a wide range of new purposes such as agriculture, transportation, housing, and industrial and commercial development. Some outcomes of population growth may include a loss of natural land cover such as wetlands and forest cover, the installation of drainage systems to remove water from fields, straightening of agricultural streams, and an increase in the area of impervious surfaces, such as parking lots and roads. Many of these changes can accelerate water movement through a watershed, particularly during a flood event.

The LCRR basin's population has grown steadily over the past 50 years. Since 2000, the population of the basin in New York and Vermont has grown by about six percent (LCBP 2019). In the Richelieu River portion of the basin, there has been a steady increase in the population of Saint-Jean-sur-Richelieu and other urban areas (for example, the population of Saint-Jean-sur-Richelieu increased by 2.9 percent between 2016 and 2021 (Statistics Canada 2022)). Population growth in the Richelieu River portion of the basin has been concentrated in urban areas along a narrow river corridor, part of the river's natural floodplain.

2.2.3 Human modification of the LCRR

In addition to natural geographical and meteorological factors affecting flooding in the LCRR basin, a range of human activities, both past and present, likely affect lake and river levels to varying degrees. Population growth in the Richelieu River basin has been paralleled by the growth of buildings in areas that can be flooded. As the number of buildings in the floodplain has increased over the years, so has the value of those buildings and the cost of damages due to flooding (ILCRRSB 2019). It is important to note that occupation of the floodplain has a significant effect on the severity of flooding impacts; if humans have not built buildings and infrastructure within the floodplain, flooding impacts are far less frequent and costly.

Over the years, many wetlands that would have held floodwaters were drained for farming or filled to allow the construction of buildings and roads. In some areas, dikes and pumping systems have been set up to protect agricultural land from flooding. Streams flowing into Lake Champlain and the Richelieu River were straightened and dredged, causing the water to flow more rapidly and forcefully. Berms were built along rivers to prevent them from overflowing. This eliminated many floodplains that used to accommodate floodwaters.

The Richelieu River itself has been altered by multiple anthropogenic and natural changes since the beginning of European colonization, including dredging, filling, installation of in-river structures, erosion, and sediment deposition (Thériault et al. 2022). The Chambly Canal opened in 1843 alongside the Richelieu River to allow boats to bypass rapids near Saint-Jean-sur-Richelieu. It was widened in the early 1970s. Instream modifications, such as the establishment of "eel cribs" (to catch eels; Figure 4), rail and road transportation piers, and the widening of the Chambly Canal (and resultant narrowing of the river) tend to impede flows and raise lake water levels. This is particularly true in significant sections of the river such as the Saint-Jean-sur-Richelieu Shoal. In contrast, dredging or removing obstacles tends to accelerate flow passage and decrease water levels.

The Saint-Jean Shoal acts as a natural control affecting water levels in Lake Champlain and has been the site of several modifications. The river reach above the Saint-Jean-sur-Richelieu Shoal behaves like an extension of Lake Champlain due to the hydraulic dam-like control exerted by the shoal. Flow in the Richelieu River is mainly dependent on the Lake Champlain level, and to a lesser extent on wind surge. The Richelieu River flows over a relatively flat valley between Rouses Point and Sorel-Tracy, where it meets the St. Lawrence River. A longitudinal profile with pictures of key features is shown in Figure 5 (FMMM & HHM, 2021). The hydrodynamic characteristics of the lower portion of the river are complex, with water levels depending not only on the river discharge, but also on the level of the St. Lawrence River at Sorel-Tracy.

Figure 4. Remnants of eel traps at Saint-Jean-sur-Richelieu Shoal.

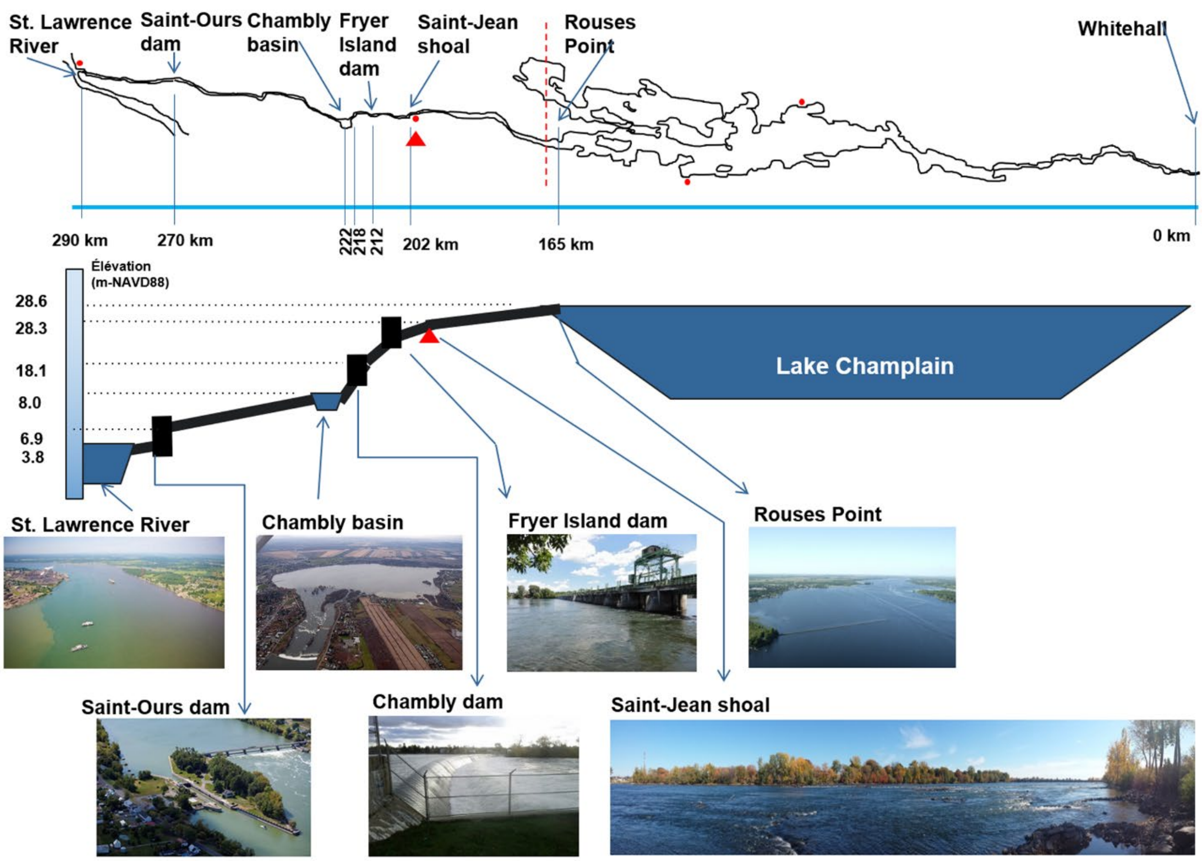


Figure 5. Longitudinal profile of the Richelieu River showing key features, with the north end on the left and the south end on the right

Note: the vertical scale on the cross-sectional view is not linear and the overall vertical dimension is exaggerated relative to the horizontal. The top panel provides a plan view of the system to orient the reader. (FMMM & HHM, 2021).

2.3 HISTORY OF PAST FLOODS IN THE LCRR BASIN

A combination of topography and climate makes the LCRR basin naturally prone to extended periods of flooding. The steep mountain slopes of the upper basin, the flow regime of the upper Richelieu River, high winter snowfall amounts, above-normal spring temperatures and the frequency of heavy spring rainfall are all key drivers of flooding in this basin, as is the size of the watershed: the watershed draining into Lake Champlain is more than 18 times the normal area of the lake. In most of the basin's mountainous areas, a high percentage of the winter precipitation is stored in the snowpack, which can be rapidly melted and enter the lake during the spring, when annual streamflow tends to peak over a period of weeks. Annual lake level peaks typically occur in spring as well. Streamflow in the upper Richelieu River is a direct function of water levels in Lake Champlain and thus, in the upper reach of the river between Lake Champlain and Saint-Jean-sur-Richelieu, flooding occurs simultaneously in the lake and river. In general, flooding impacts on the Lake Champlain shoreline are not as severe as flooding impacts on tributaries or the Richelieu River. However, some areas along the lake can be strongly impacted by waves and have experienced significant wind-driven flooding.

Over the last century, there have been numerous flood events, including several disastrous regional floods in the last 25 years affecting Lake Champlain and the upper Richelieu River (LCBP 2013). Figure 6 highlights four floods between 1990 and 2019 that reached the Lake Champlain water levels characterized by the US National Weather Service as "moderate" or "major" floods (Table 1). The figure shows water levels at Rouses Point from mid-March through June and illustrates both the magnitude and duration of these events. Several notable flood events in the basin that have occurred over the last century are discussed in the Study's Causes & Impacts Report (ILCRRSB 2019).

Causes of Flooding

In a 2019 evaluation of the causes of flooding in the Basin, the Study Board found that:

1. Severe floods occurred multiple times in Lake Champlain and the Richelieu River, including the extreme spring flood of 2011.
2. Factors contributing to these floods include both natural forces, such as geography and weather, and anthropogenic (human-caused) changes in the basin, such as land use changes, channel modifications and the construction of infrastructure.
3. A heavy snowpack, coupled with significant warm spring rains, commonly drives the most severe flood conditions by rapidly contributing large volumes of water to Lake Champlain. Additional factors contributing to flooding in Lake Champlain include wind intensity and direction, and associated lake seiche waves.
4. Since the early 1970s, Lake Champlain has experienced an increase in the average of annual maximum water levels of approximately 0.30 m (0.98 ft). This increase is primarily due to the widening of the Chambly Canal in the 1970s.
5. Over the decades, the basin has undergone changes due to anthropogenic modifications. These include the conversion of wetlands to agriculture and the loss of natural land cover through urbanization and expansion of impervious surfaces, particularly in floodplains.

Table 1. US National Weather Service flood classification criteria.

Flood Severity	Lake Champlain Target Level		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.

Source: https://water.weather.gov/ahps2/hydrograph.php?gage=roun6&wfo=btv

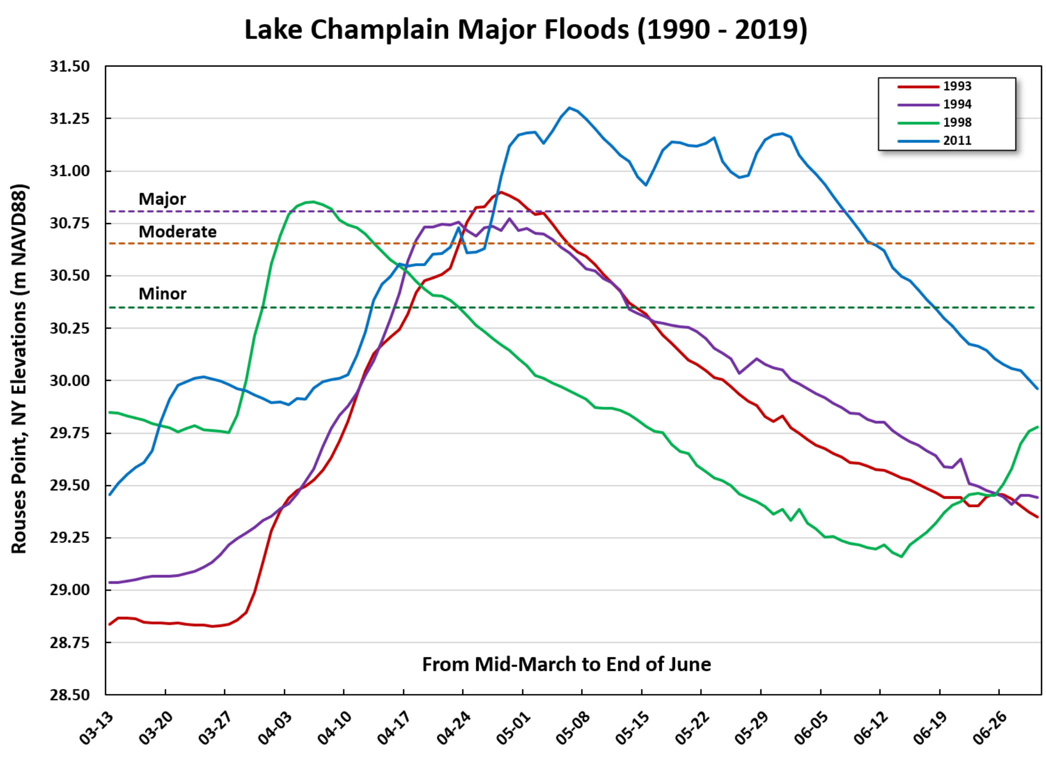
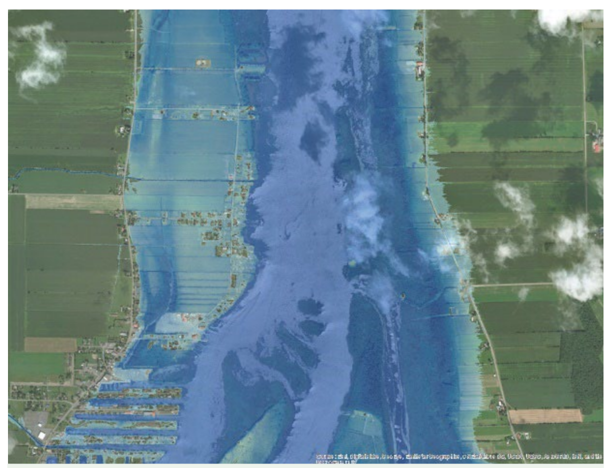


Figure 6. Moderate and major Lake Champlain floods, 1990-2019. (FMMM & HHM, 2021)

The floods that have occurred over the past century have often triggered studies and recommendations of mitigation measures. For example, in the 1930s the implementation of a dam project in the Richelieu River was recommended. Construction was initiated near what is now known as the Fryers Island Dam, about 8 km (5 mi) downstream of Saint-Jean-sur-Richelieu, Québec, and excavation upstream of the shoal was started. However, work was halted at the outbreak of World War II, and the dam project was never completed. In the 1970s, it was determined that regulating Lake Champlain with a new structure would be an effective means of flood control (IJC 1974); however, there were significant environmental concerns for the lake (Riboust and Brissette, 2016). After the widening of the Chambly Canal in the early 1970s constricted the river and increased water levels during high flows, the International Champlain-Richelieu Board conducted limited evaluations involving routing additional high flows through the canal (ICRB 1979). However, there was significant opposition to the proposed regulation of flows, especially in the United States (FMMM & HHM, 2021). After extensive public consultation, the IJC did not recommend regulation of the LCRR system (IJC 1981) The Commission recommended the development of flood forecasting, however, which was implemented in the United States first and in Canada much later, and flood plain mapping, which was carried out in both countries. Other policy actions were also taken to reduce flood damages. Although there have been prior studies and recommendations regarding flooding in the basin, the lack of implementation of proposed measures has limited the ability to address the problem.

2.3.1 The spring flood of 2011

Snowfall during the 2010-2011 winter was heavy, with Burlington, Vermont measuring the third-highest total since 1883 (NOAA 2011). In addition, no major thaw occurred to start melting the snow in mid-winter. With cold winter temperatures, the large snowpack remained through the winter months and into spring. The spring brought rainfall that was well above average (ranging from 46 percent above average in March to 213 percent above average in May). The warm spring temperatures and rain caused the snow in the mountains to melt quickly and increase flow into Lake Champlain, resulting in period-of-record (starting in 1827) maximum lake levels recorded at all lake gauges on Lake Champlain. The narrow, shallow nature of the Richelieu River meant that persistent high waters in Lake Champlain could quickly cause long-lasting floods in the river. While spring flooding is common along the shores of Lake Champlain, the duration of the 2011 flood period was unprecedented. Lake levels remained above the US National Weather Service (NWS) minor flood stage of 30.35 m (99.57 ft)[8] for 67 days at Rouses Point, from April 13, 2011, to June 19, 2011. While the evaluation of the return period of large floods involves substantial uncertainty, analyses have indicated that the 2011 spring flood has a statistical return period of somewhere between 200 and 1,000 years (Ouarda and Charron, 2019).



Flooding near Île-aux-Noix, 2011.
(Source: Canadian Coast Guard, 2018)

[8] US National Weather Service flood stages are provided in Table 1.

The record flood in the spring of 2011 was further exacerbated, at times, by persistent winds from the south. Historical observations of Lake Champlain levels at the Rouses Point gauge have shown significant increases in water during sustained wind events. A typical large wind set-up event with winds from the south pushing water to the north end of the lake can result in an increase of around 15 to 25 cm (6 to 10 in) at Rouses Point, which can make the difference between a minor and a major flood in the Richelieu River due to increased water flows from the lake into the river (Loiselle et al. 2021). During the spring flood of 2011, eight separate wind set-up events pushed the nominal lake level up by between 7.6 and 21.3 cm (3.0 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 stage of 30.65 m[9] (100.57 ft). The ensuing 21.3-cm (8.4 in) rise pushed the Rouses Point lake level into moderate flood stage and then past the 30.81 m (101.07 ft) major flood stage threshold. The wind event ended the next day and lake levels receded back into the minor flood range.

2011 flooding, Colchester Point, Vermont (Photo credit: Matt Sutkoski).

The Richelieu River at Fryer Rapids exceeded flood flows of 1,064 m^3/s (37,575 ft^3/s) from April 20 until June 28, a total of 69 days, including a maximum recorded flow of 1,539 m^3/s (54,349 ft^3/s). Increases in the level of Lake Champlain during the flood were translated downstream on the river and the south winds amplified river stages[10].

[9] As noted previously, water levels in this report are referenced to NAVD88 unless otherwise noted. Flood stages cited are referenced to NAVD88. Table 1 provides flood stages referenced to both NGVD29 and NAVD88; note that some governmental agencies, such as NOAA, cite flood stages referenced to NGVD29.
[10] It should be noted that large floods of rare statistical frequency can occur several times in a short period of time; as an example, historical floods along the Ottawa River and in the greater Montreal area occurred in both 2017 and 2019.

2.4 SOCIAL, POLITICAL AND ECONOMIC CONTEXTS OF FLOODS

The impacts of the spring 2011 flood were severe. About 1,310 homes were damaged in New York and Vermont, and more than 2,500 homes in Québec. It is estimated that more than 100 bridges and roads were damaged in Québec. In both countries, flooding in the basin led to the inundation of low-lying roads, causing transportation disruption, and isolating or threatening to isolate individuals and some communities. More than 1,600 residents were forced to evacuate in Québec. People also faced numerous health risks that were beyond the scope of this study, such as mold in wet buildings, dangerous electrical hazards and contaminated drinking water. Many businesses were impacted, including campgrounds and marinas. Much of the area bordering Lake Champlain and the Richelieu River is farmland. Many crops were lost directly because of the long duration of flooding that impacted planting, and crop yields were down because of heavy rains. All of these repercussions have affected Aboriginal communities, particularly with regard to the availability of hunting and fishing territories. Total economic losses from the 2011 flood were initially estimated at more than CDN$104 million (US$82 million), with most (CDN$86 million; US$67 million) in Québec. These reported values primarily included recorded residential damages, and not a broader set of impacts. A subsequent, more comprehensive evaluation indicated that damages were about 70 percent higher, or about CDN$188 million (US$141 million) (Moin et al. 2022).

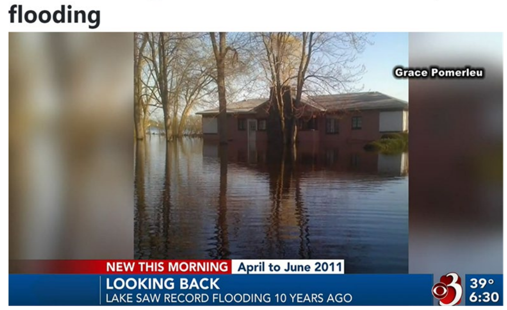
Figure 7 depicts these losses by sector and shows the severe impacts on residential areas, with 64 percent of the total losses by dollar value.

The severe flooding in the Lake Champlain-Richelieu River basin in 2011 was a catalyst for the government of Québec to re-evaluate flood management policies and practices throughout the province. Indeed, the provincial government established "special intervention zones"

"There wasn't a whole lot you could do. It was just sit and wait until it receded. The house had to be completely gutted right down to the framing..."

— Terry Pomerlau, South Burlington, Vermont resident recalling 2011 flooding when he was 22 in 2021 interview

Remembering historic 2011 Lake Champlain flooding



https://www.wcax.com/2021/04/23/looking-back-10-years-ago-to-historic-lake-champlain-flooding/

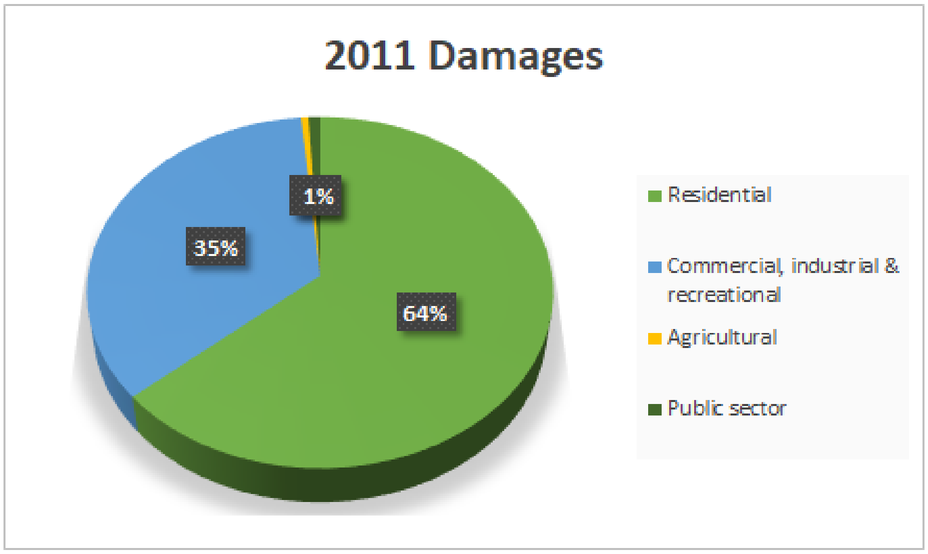


Figure 7. Economic losses by sector due to 2011 flood; estimated damages totaled (based on Roy et al. 2022).

(SIZ) for all municipalities along the Richelieu River just after the flood. The SIZ designations banned reconstruction in the 0-2-year flood zone and allowed reconstruction within the 2-20-year flood zone only if certain protective measures were adopted (Henstra, 2022).

The urgency to explore policy reforms was underscored by major flooding in several regions of Québec in the spring of 2017, which prompted the Ministry of Public Security to draft a Plan d'action en matière de sécurité civile relatif aux inondations (Civil Protection Flood Action Plan). Recommended actions included, for example, mandatory civil protection plans for all municipalities, financial support to improve municipal disaster preparedness, a framework of intermunicipal mutual aid, better management of flood zones and better flood risk communication with the public. One major initiative that emerged from the plan in 2018 was the INFO-Crue project, which aims to identify and map flood zones in southern Québec. The project will incorporate climate change projections to develop tools and a flood forecasting system to support land use planning in several watersheds (Québec 2018).

Severe spring flooding occurred again in several regions of Québec in 2019, after which the SIZ development restrictions were strengthened and extended. Beyond this application of the province's regulatory power, in recent years the Government of Québec has initiated a program of buyouts for severely damaged properties, undertaken a comprehensive effort to replace outdated flood maps using aerial photography and satellite remote sensing, and funded an interdisciplinary network of government scientists and academic researchers (Réseau Inondations InterSectoriel du Québec[11], RIISQ) to improve Québec's flood protection and preparedness. A new, comprehensive framework for flood management called Plan de protection du territoire face aux inondations (Flood Protection Plan) has been developed (Gouvernement du Québec 2020), which proposes 23 specific actions the provincial government would consider to strengthen flood management. These include changes to provincial policy on land use along rivers and in known floodplains, as well as the creation of ten

[11] Québec InterSectoral Flood Network

"project offices" on flood management that will lead planning at the watershed scale (Therrien et al. 2021). At the federal level, there have also been changes in disaster prevention and mitigation programs, such modifications to the Disaster Financial Assistance Arrangements and establishment of a Task Force on Flood Insurance and Relocation.

On the US side of the border, policy and program changes have occurred at both the national and state levels that are relevant for the Study Board's findings and conclusions. Notably, significant changes to the National Flood Insurance Program (NFIP) that have been underway for several years began taking effect in 2021. Dubbed "Risk Rating 2.0," this policy change is designed to impose flood insurance premium rates that reflect an individual property's flood risk, rather than the prior approach, whereby a nationwide rating system was used to calculate expected losses for groups of structures with similar flood risk and structural features and the same rate was applied to all policies in these groups.

In 2018, New York State officials launched the Resilient NY program to improve community resilience to extreme weather that results in flooding (New York 2021). Administered by the Department of Environmental Conservation, the program models flood risk across the state and identifies high-priority watersheds to target for flood mitigation measures. Based on a series of analyses, high-priority communities are considered for risk reduction measures including floodplain restoration, floodwater storage, small structural protections such as dikes and levees, and buyout programs to relocate people and property out of exposed areas. The list of high-priority watersheds includes several tributaries to Lake Champlain.

In Vermont, the state legislature passed several pieces of legislation between 2010 and 2014 that underpinned a River Corridor and Floodplain Management Program, which was adopted to protect the health, safety, and welfare of the public from flood hazards (Vermont Agency of Natural Resources 2017). In coordination with the Federal Emergency Management Agency (FEMA) and local municipalities, the Department of Environmental Conservation was charged with mapping the areas around and adjacent to river channels where fluvial erosion and channel evolution are most likely to occur. The maps have since been used by state floodplain managers to encourage municipalities to adopt river corridor protection bylaws as part of an "accommodate" approach to give the river channel space to evolve over time. Accommodation typically refers to adaptation strategies designed to continue using floodplains, but reduce the vulnerability or exposure of users by selecting uses that are less sensitive to floods (Alberti-Dufort 2022b). In addition, Vermont created an Emergency Relief Assistance Fund (ERAF) to provide support to municipalities that adopt measures to strengthen their resilience to floods in the aftermath of a federally declared disaster (Vermont 2021). This program appears to have been effective in reducing flood risk: between 2014 and 2017, the number of municipalities with emergency management plans nearly tripled, and those with hazard mitigation plans nearly doubled (Pew Charitable Trusts 2019).

2.5 HISTORY OF IJC INVOLVEMENT IN THE LCRR BASIN

In response to multiple flooding events over the past century, the governments of Canada and the United States have made a series of requests or "references" to the IJC to study and provide recommendations to mitigate flooding.

THE 1930s: The first flood reference from the governments to the IJC was convened in the 1930s following severe flooding in the basin. During that time, the IJC determined that flood control structures would be the most effective way of addressing flooding. The issue of environmental impact was raised by both United States and Canadian partners, although little action was taken on that front. The result of the reference was the construction of the Fryer Island Dam, located approximately 8 km (5 mi) downstream of Saint-Jean-sur-Richelieu (ILCRRSB 2019). Construction was completed in 1939. The remedial works required to make the dam functional, however, were delayed due to the outbreak of World War II, and the work was never completed.

THE 1970s: A second flood study was convened for the LCRR basin in 1973 after major regional flooding. Study results prompted the IJC to propose that a gated structure be built in the section of the river at Saint-Jean-sur-Richelieu to regulate flows but it remained up to the federal governments to determine the political desirability of this structural solution. This proposed structure was not supported by the states of Vermont and New York. Though federal governments did not agree on implementing a structural solution for the flooding problem, each was supportive of the IJC recommendation to implement a binational flood forecasting and warning system along with other non-structural actions to address flooding. A flood forecasting system has since been implemented in the United States, and floodplain mapping has been implemented in the LCRR basin. Floodplain mapping was accomplished in some sections of the river in the 1970s, as well as from the lake to Chambly in 2005 and from Chambly to Sorel in 2013.

THE 2010s: A third flood reference was convened for the LCRR basin in 2017, following the catastrophic spring flooding of 2011. Leading up to the 2017 Study, the IJC created the International Lake Champlain Richelieu River Plan of Study Workgroup, which in 2013 developed a Plan of Study to explore the causes, impacts, risks and potential solutions to flooding in the basin. To address the Plan of Study, the IJC created the International Lake Champlain-Richelieu River Technical Working Group in 2014, which identified that data are needed to develop both a flood forecasting system and static maps that show where flooding would occur at different lake levels. In response to an additional reference from the Canadian and US governments to continue their study of flooding in the basin, the IJC in 2016 created the International Lake Champlain Richelieu River Study Board to conduct a five-year study of ways to mitigate flooding in the basin.

In 2012, the governments of Canada and the United States instructed the IJC to "fully explore the causes, impacts, risks and solutions to flooding in the Lake Champlain - Richelieu River basin."

3 LCRR STUDY APPROACH

The LCRR Flood Study was an international collaboration involving external and local individuals with expertise in complementary disciplines. The Study has explored the causes, impacts, risks, and solutions for flooding in Lake Champlain and the Richelieu River. The inclusion of a team to study, from the onset, the social, political, and economic drivers associated with flood mitigation was new to IJC studies and has provided a model for how insights from these disciplines can improve future watershed studies.

This section of the report describes the study objectives and organization, and the technical approach and social, political, and economic assessment methods used to develop the Study's findings and recommendations.

3.1 LCRR STUDY OBJECTIVES AND ORGANIZATION

The Study was an international collaboration involving more than 100 individuals[12] with expertise in flood management, engineering, planning and mitigation, environmental analysis, economics, social sciences and Indigenous knowledge (Appendix C). It was led by a Study Board with representatives from Canada and the United States. The Study Board was supported by binational groups addressing key analytical, communications, outreach and data product and information management tasks (Figure 8), along with independent reviewers. These groups included:

- an *Independent Review Group (IRG)* comprised of experts in related disciplines; the IRG provided independent technical review of Study products and reports;
- a *Public Advisory Group (PAG)* representing various areas of interest and regions across the LCRR basin. Its members drew on their knowledge, contacts, and experience to provide advice and to encourage public participation in the study;
- an *Information Management/Information Technology (IM/IT) Support Group* that provided tools and online space to facilitate communication and data sharing among Study members, data management, and other technological support to the Study;
- a *Communication Working Group* in charge of organizing public meetings and developing various communication tools, including newsletters, fact sheets and other materials for distribution to stakeholders and the public; and
- a *Social, Political and Economic (SPE) Analysis Group* to advise the Study Board on many of the complex social, political, and economic issues that form a critical component of the challenge of flood mitigation and management;

[12] These individuals were engaged based on their own expertise and the views they expressed as part of their participation in the Study do not necessarily represent those of their organizations.

- a *Hydrology, Hydraulics and Mapping (HHM) Technical Working Group (TWG)* that created hydrological, hydraulic and water balance models to consider the impacts of future climate change and other factors, and developed several decision-making tools, including flood forecasting and flood mapping models;

- a *Resource Response (RR) TWG* to develop the indicators needed to assess various flood management and mitigation options in terms of impacts on the environment, people, and the economy, as well as the system to integrate those; and

- a *Flood Management and Mitigation Measures (FMMM) TWG* that designed and evaluated flood management and mitigation options.

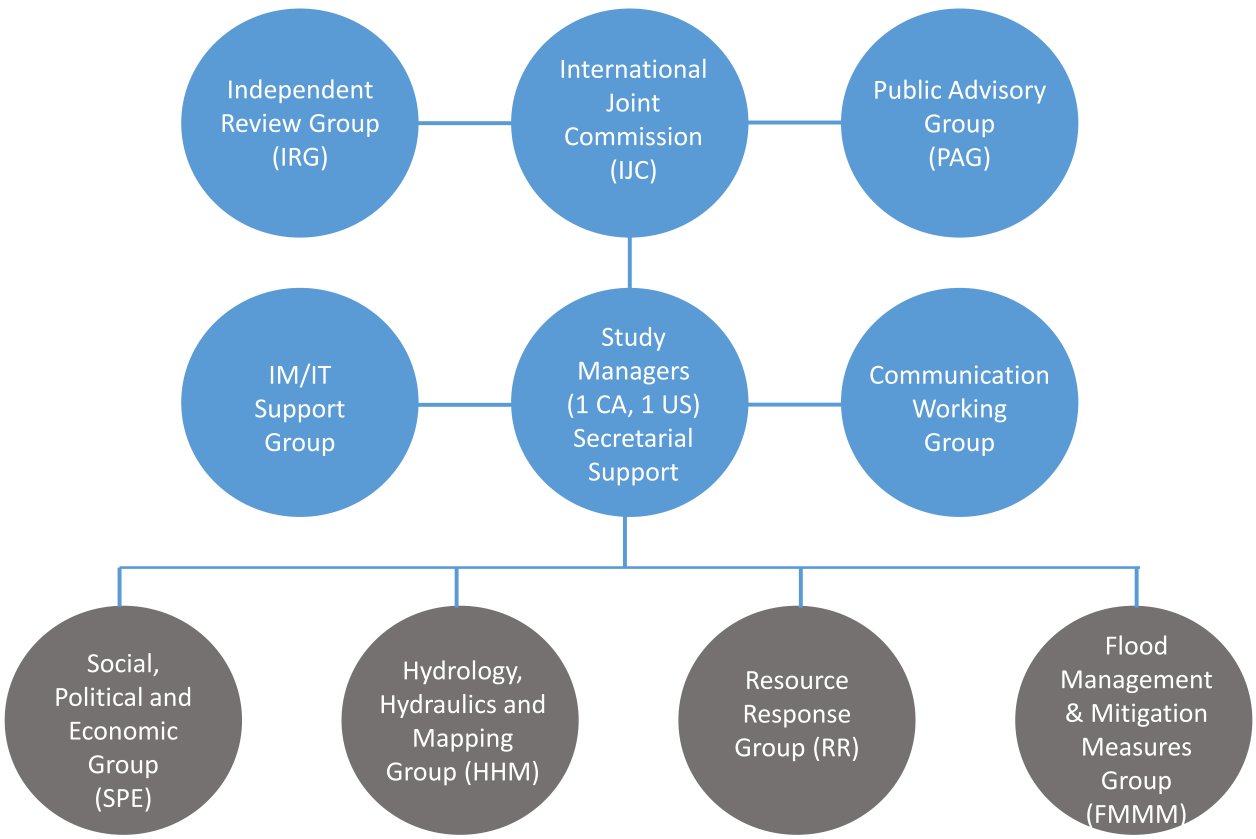


Figure 8. Study organization.

Additional details about the Study Board and its technical and advisory groups are available on the Study website (https://ijc.org/en/lcrr) and in the Study's Work Plan (ILCRRSB 2017). A complete list of Study participants is provided in Appendix C of this report.

Under the letters of reference from the governments of Canada and the United States to the IJC, the Study Board undertook seven key tasks in support of the Study's objective (https://ijc.org/en/lcrr):

1. Evaluating the causes and impacts of past floods, and in particular, the events of 2011;
2. Assessing the possibilities offered by floodplain best management practices;
3. Evaluating possible adaptation strategies to address expected future variability in water supplies;
4. Developing and making recommendations for implementing a real-time flood forecasting and flood inundation mapping system for the basin;
5. Strengthening understanding of current social and political perceptions of proposed structural and other mitigation measures to support and confirm the desirability of potential structural mitigation solutions;
6. Undertaking a comprehensive assessment of potential flood management and mitigation measures, and the impacts of these measures on the natural environment, water uses, the built environment and agriculture; and,
7. Developing resource response models that include basic indicators for water resource response to water level fluctuations, to support the planning, evaluation and ranking of potential flood mitigation solutions.

The Board grouped these seven tasks into two primary goals and four Themes (Figure 9) that guided the Study's work. The first goal concerns reducing the impacts of flooding by reducing high water levels, through moderate structural solutions (Theme 1), or watershed storage options (such as enhancing wetlands) to impede flows to the lake (Theme 2). The second goal centers on reducing vulnerability to high water levels and building flood resiliency, through improved flood response (Theme 3) and floodplain management (Theme 4). Issues of climate change and assessing the social, economic, and political acceptability of potential recommendations are overarching principles in all Themes. The activities conducted related to these tasks have supported the development of recommendations to reduce flooding impacts, which are described later in this report.

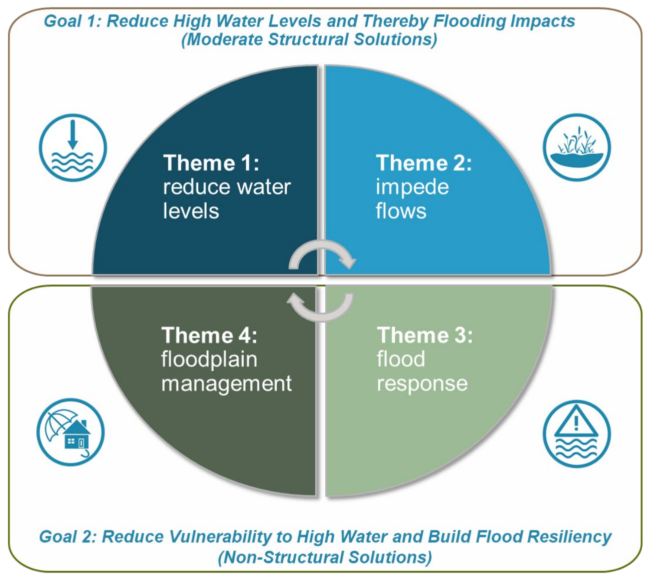


Figure 9. LCRR Study flood mitigation framework.

Structural measures are designed to pass water through the system more quickly or to retain it upstream. The governments of Canada and the United States directed the IJC to evaluate "moderate" structural mitigation measures. Non-structural measures differ from structural measures in that they focus on reducing the consequences of flooding instead of reducing the magnitude of flooding (they generally cause no changes to flood levels, velocities, or duration). Non-structural measures can be temporary (contingent) or permanent.

3.2 DEVELOPMENT AND USE OF STUDY TOOLS, METRICS AND CRITERIA

The Study developed and applied several innovative tools and approaches in its assessment, including high-resolution modeling and advanced information technology (Figure 10). These tools supported the Study's evaluations and will provide value to future studies of the LCRR basin, as well as studies of other watersheds. The tools, metrics or indicators, sets of criteria, or approaches used are described below.

3.2.1 Digital elevation model (DEM)

An accurate and precise characterization of the terrain is a critical component of the modeling of the LCRR system. The hydrodynamic model requires elevation information for each node of the finite element grid to provide accurate water levels and currents. The Integrated Social, Economic and Environmental (ISEE) system also uses elevation to estimate water depths across the study area at any given time step of the reference period. Elevation data are also used to derive different terrain attributes that affect the environmental performance indicators. These tools and indicators are discussed in subsequent sections of this report.

To provide the necessary characterization of the terrain, a high-definition Digital Elevation Model was created from a vast collection of topographic LiDAR and bathymetric datasets provided by multiple governmental sources in the United States and Canada. At critical locations, field surveys were conducted to collect additional elevation data. In particular, a precise bathymetric survey of the Saint-Jean-sur-Richelieu shoal was carried out by the ECCC during the exceptionally low water conditions in the fall of 2016.

Where necessary, a vertical datum transformation was performed so all datasets could be merged to a common datum[13], the North American Vertical Datum of 1988 (NAVD 88). An evaluation was necessary for each proposed flood mitigation measure that required modifications of the bathymetry of the Saint-Jean Shoal area. Therefore, separate DEMs of this area were created for each Theme 1 measure (ECCC 2022).

A DEM of the upper Richelieu River was reconstructed to approximate its natural state before anthropogenic changes were made. The reconstituted DEM was established by using bathymetry from old topographic maps and comparing it with the current DEM. Figure 11 shows the differences between historic (1887) and present (2021) conditions in the Saint-Jean Rapids area (Thériault et al. 2022). These evaluations identified numerous human interventions and modifications made to the riverbed. There are submerged dikes that channel the flow to former mill areas; the remnants of eel traps; an artificial island that was constructed and modified at various times; and the construction of the Chambly Canal itself, on the west side of the Richelieu River shoal area.

3.2.2 Hydrologic modeling of inflows

The study employed the PHYSITEL/HYDROTEL hydrological modeling platform (Fortin et al. 1995) as the driving hydrological model for representing the dynamics in the system. HYDROTEL is the model used for operational hydrological simulations in numerous governmental applications in Québec. The PHYSITEL/HYDROTEL platform is designed to represent a watershed by breaking it into individual river segments and hillslopes, simulating the effect of land cover on flows, and providing inflow or basin supply to a lake/reservoir water balance model or a hydrodynamic model to predict lake or river water levels.

[13] As noted previously, water levels in this report are referenced to the North American Vertical Datum of 1988 (NAVD88).

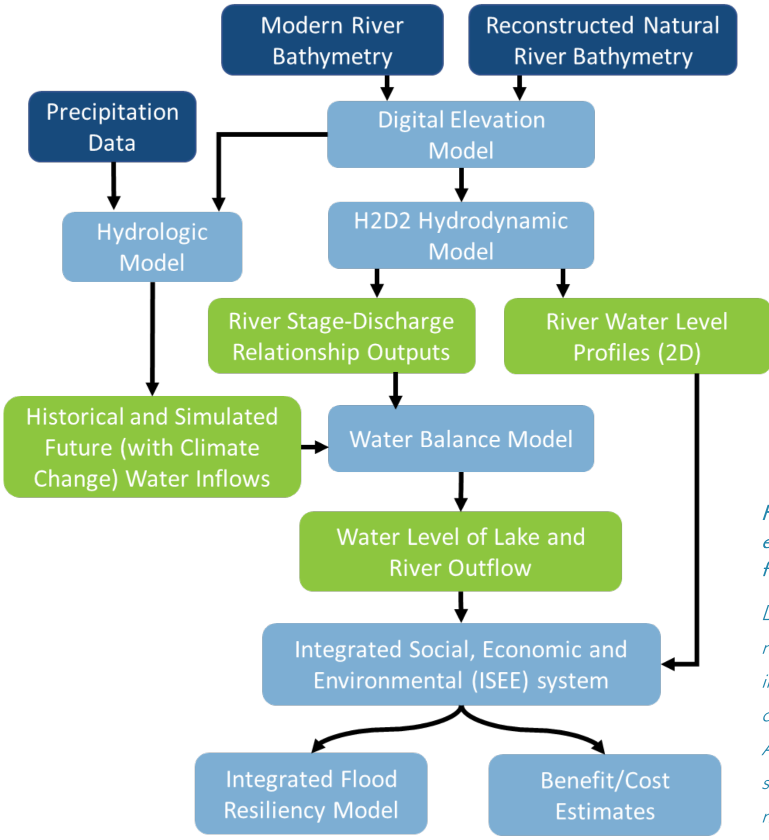


Figure 10, Relationships of models and data used to evaluate flows and water levels to assess potential flood mitigation measures.

Dark blue boxes represent model inputs, light blue boxes represent models or tools, and light green represent intermediate model outputs. Arrows represent the direction of flow of data or output through the network. Arrow width or length are not intended to convey any sense of the relative magnitudes of data or output moving from box to box.

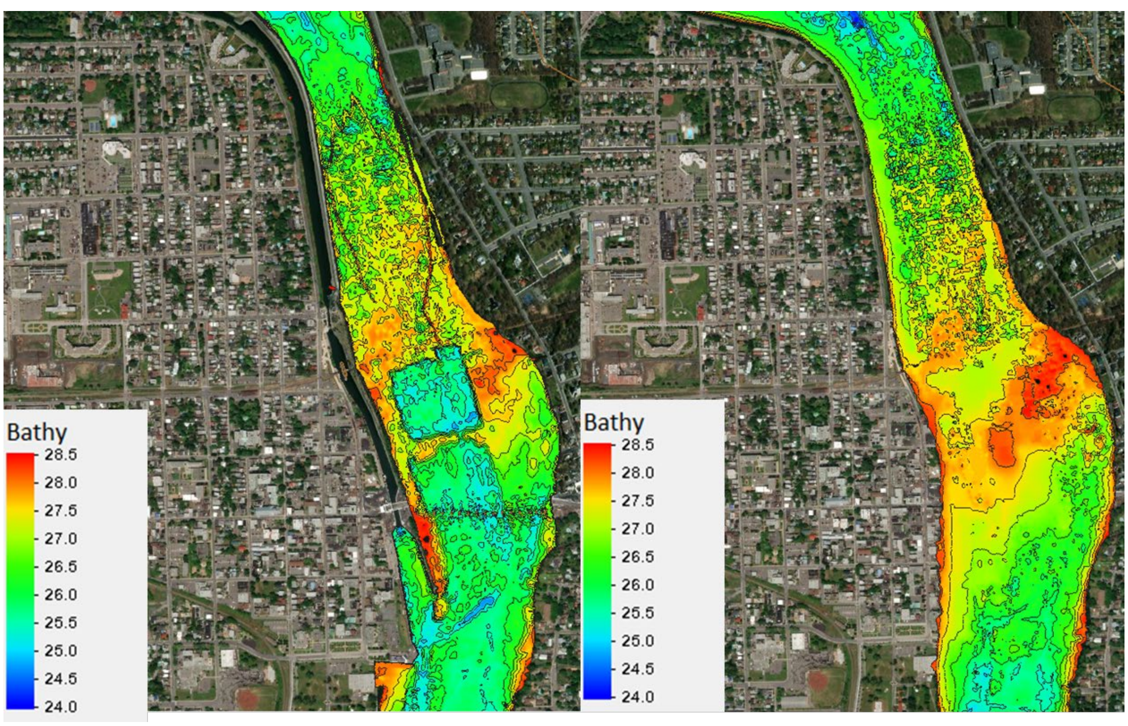


Figure 11. Current (2021) digital elevation model (DEM; left) and natural state (1887) DEM (right) for the Saint-Jean Rapids area. Elevations shown are in meters.

PHYSITEL is a specialized geographic information system (GIS) (Turcotte et al. 2001; Rousseau et al. 2011; Royer et al. 2006) that has been developed to determine the complete drainage structure of a watershed using a DEM and digitized river and lake networks. HYDROTEL is a distributed hydrological model that simulates stream flows and variables such as snow water equivalent and water saturation using basic meteorological variables. Two different implementations of HYDROTEL were made for the Study. The first one was done for climate change analysis (Lucas-Picher et al. 2020) and the second one was done for studying watershed storage. Data from 25 hydrometric stations and 64 years of gridded meteorological data were used in model development and calibration.

HYDROTEL imposes a rectangular cell grid over the Lake Champlain drainage basin; the hydrologic processes operating in each cell are calculated and then applied to surrounding cells. Water moves through the grid in time, producing flows in tributaries to Lake Champlain. Inputs can be historical or projected, which creates an opportunity to estimate basin supplies (inflows) to Lake Champlain with a projected distributed set of precipitation and temperatures. HYDROTEL calculates the following for each computational unit and reach: meteorological conditions, evapotranspiration, snow accumulation/melt, infiltration, recharge, surface flow, subsurface flow and channel routing. These were computed using a daily time step for this study.

3.2.3 Two-dimensional hydrodynamic model (H2D2)

The Study employed a two-dimensional hydrodynamic model, H2D2, to generate water levels and flows within the lake and river system for input to the Water Balance Model and the Integrated Social, Economic and Environmental (ISEE) system described later in this report. Study researchers updated the hydrodynamic model initially developed 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 H2D2 hydrodynamic model was developed at INRS-Eau (now INRS-ETE), with the assistance of Environment and Climate Change Canada. The model utilizes the conservative form of the mass and momentum conservation equations, with friction losses accounted for by the presence of variable substrates, aquatic vegetation, ice, etc. The conservation of mass and conservation of momentum equations are solved using the finite element technique. The H2D2 model has been used in several studies, with many of these feeding into other IJC studies. Several components of the models were developed that span the entire study area from Whitehall, New York at the south end of Lake Champlain to Sorel-Tracy, Québec at the north end of the Richelieu River, and that account for the presence of geomorphological features like the rapids at Chambly Basin and Fryer Island Dam.

The Richelieu River was divided into two reaches for hydrodynamic modeling purposes: 1) from Rouses Point, New York, to the dam at Chambly, approximately 16 km (10 mi.) north of Saint-Jean -sur-Richelieu, a total distance of approximately 53 km (33 mi); and 2) the downstream section of the Richelieu River to its mouth at the St. Lawrence River near Sorel-Tracy (approximately 72 km or 45 mi.). The entire water area was divided into triangular elements that form the “mesh” or “finite element grid”. The shape and size of the elements were modified to represent the shape and complexity of the terrain, the substrate, aquatic vegetation, and any other spatial variable. The more complex the terrain or shoreline, the finer the mesh, and the greater the number of elements. The bathymetry and topography were projected onto the hydrodynamic mesh using a digital elevation model combining bathymetric surveys and LiDAR[14] elevation datasets. The friction at the channel bottom, characterized by the Manning coefficient, was calibrated based on steady one-dimensional hydraulics,

[14] Light Detection and Ranging; a remote sensing method for mapping.

and by considering the geomorphology of the river, field observations, and low-water aerial photography.

The main purpose of the hydrodynamic model supporting this study was to produce gridded water levels to support the calculation of values for performance indicators used to assess flood mitigation measures. This was done by making multiple steady-state runs for a given range of discharge at the Fryer Island Dam and a range of water levels at Rouses Point. Water levels of the St. Lawrence River influenced water levels up to the Chambly Basin. In addition, the hydrodynamic outputs provided the stage-discharge relationships at Saint-Jean-sur-Richelieu that were used by the Water Balance Model (described in the next section), under the different flood mitigation measures of the Study.

3.2.4 Water Balance Model

The purpose of the Lake Champlain Water Balance Model (WBM) was to provide water level and discharge values, based on water inflows, current and potential shoal configurations in the vicinity of Saint-Jean-sur-Richelieu, for a desired time period. The model used basin supplies (inflows) as inputs, a single flow rate for each time step that incorporated precipitation onto and evaporation from the lake surface, and runoff and tributary contributions into the lake. The historical series of average daily water inflows to Lake Champlain, based on historical records of flows and levels, is the primary input to the model. The model is based on the equilibrium of the changes in the volume of the lake and the Richelieu River outflow, and the inflows for the current day. The outflow from Lake Champlain at each time step was estimated using a stage-discharge relationship (a function that defines the outflow in terms of the lake level) and an estimated channel roughness. These were derived from analyses carried out with the 2D hydrodynamic model and historical water level measurements for the seasonal friction variation in the upper Richelieu.

The LCRR WBM was calibrated to emulate the effect of the current hydraulic control section ("bottleneck") at Saint-Jean-sur-Richelieu on Lake Champlain outflows. This is the "baseline" channel condition, which reflects the encroachment of the widened Chambly Canal into the Richelieu River (narrowing the river channel). The WBM allows the reproduction of historical water levels at key locations along the water body based on the inflows. It calculated pairs of lake elevations and corresponding river elevations in Saint-Jean-sur-Richelieu; the ISEE system interpolated between the different hydrodynamic scenarios, based on the levels and flows produced by the WBM. The Richelieu River outflow was based on the stage-discharge relationship presented in Champoux et al. (2018) and Gosselin et al. (2022). The WBM was calibrated through an iterative process, and results compare well with historical observations (Boudreau et al. 2022).

The Study's models provide insight into the 2011 spring flood. Figure 12 (François and Brown 2022) shows meteorological conditions, flows and water levels for the spring-summer flood period. These data were taken from a dataset that distributed meteorological data from point data to a grid that was suitable for input into HYDROTEL (François and Brown 2022). The top panel shows maximum and minimum temperatures (red and light blue lines) and daily snowfall and rainfall (yellow and blue bars). The middle panel shows the surface contribution to runoff, with the orange line representing the Snow Water Equivalent (SWE), which tracks the amount of water stored as snow across the watershed, while the blue line shows the contribution of rainfall and snowmelt to runoff. Notice the spike in runoff around the middle of March, even though there was little rain, as temperatures rose above freezing and the SWE dropped, turning snow into runoff. The bottom panel shows the Lake Champlain inflow and outflow, and the water levels in the lake and in the Richelieu River at Saint-Jean-sur-Richelieu. Snowmelt drove the lake into moderate flooding by the middle of April, with a succession of intense rainfall events in April and May providing the additional inflow that created record water levels and river flows.

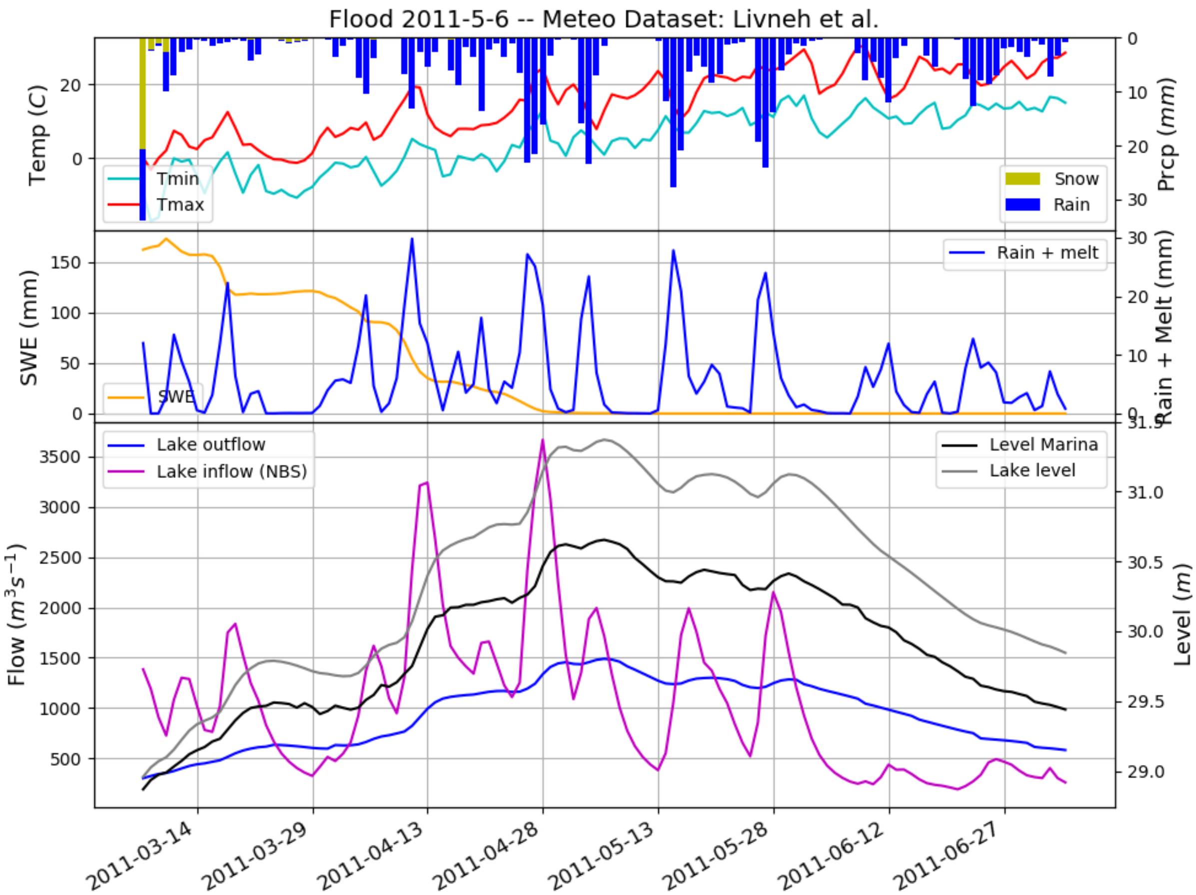


Figure 12. Illustration of the factors contributing to the 2011 flood, using the Water Balance Model (François and Brown 2022).

The top panel shows the meteorological forcing. The red and cyan curves show, respectively, the daily maximum and minimum temperatures (left y-axis). The blue and yellow bars show the daily liquid (rain) and solid (snow) precipitation (right y-axis, inverted).

The middle panel shows the surface contribution to runoff. The orange line shows the Snow Water Equivalent (SWE), which is the variable used to track the snowpack across the watershed. The blue line shows the combined contribution to runoff from rainfall and snowmelt.

The bottom panel shows the inflow or net basin supply (NBS, purple) to Lake Champlain, the lake outflow (blue), the lake level (grey) and the water level at the Saint-Jean-sur-Richelieu marina (black).

The WBM was first calibrated for the Baseline scenario (representing existing conditions at the time of the study, without mitigation measures or climate change impacts). The resultant stage-discharge relationship was then modified to simulate different structural flood mitigation measures. The Saint-Jean shoal controls the outflow and the water level of Lake Champlain, and modifications to the shoal result in changes in those variables. Thus, by changing the stage-discharge relationship to reflect a change in the Saint-Jean-sur-Richelieu flow control section, it is possible to assess the impacts of such a change on water levels over the entire reference period.

3.2.5 Integrated Social, Economic and Environmental System (ISEE)

To evaluate the benefits, costs and feasibility associated with various flood mitigation measures, the LCRR Study developed a powerful integrative tool allowing quantification of flood impacts: the Integrated Social Economic and Environmental (ISEE) system. This platform is a georeferenced database that is optimized for modeling aquatic and riparian areas. It allows for the simulation of floods and estimates the impacts of water level variations over decades. Impacts can be quantified using various performance indicators (PIs), which describe the relationships between water level changes and key components of society, the economy and the environment.

The ISEE system was developed to meet the following objectives:

- Re-creating water levels, throughout the year, over a reference period (1925-2017) that allows for quantification of the baseline natural variability of the system, including spring floods and summer low flows.

- Quantifying the effects of the mitigation measures from a hydraulic perspective throughout the year, with a particular focus on flood relief and variations at low flows.

- Analyzing the entire study area with similar PIs and algorithms, where applicable, including the Richelieu River and Lake Champlain, on both sides of the US-Canada boundary.

- Integrating high-resolution geospatial datasets over a large area (up to 250,000 hectares), including water flow, water depth, water velocity, slopes, land use and detailed information such as buildings and crops.

- Modeling the benefits of flood mitigation measures on population vulnerability and social risk.

- Quantifying the reduction in economic effects provided by the flood mitigation measures using performance indicators of structural damage and income loss to the residential, commercial, industrial, recreational, agricultural, and government sectors.

- Modeling the benefits and impacts to the natural environment caused by the changes to the water level regime associated with the flood mitigation measures using a selection of PIs representing wetlands and fish and wildlife habitats, including key and endangered species.

- Assessing the effects of potential flood mitigation measures on Indigenous communities using indicators of cultural importance.

ISEE allows the integration of numerous layers of information (inputs) on the same grid (10 m by 10 m). The inputs describe the hydraulics, land use, infrastructure, socio-economic variables, and the natural environment, including wetland distribution (Figure 13). As a result, all relevant physical variables, such as water depth, water velocities and water flows are available at each point of the ISEE grid. All of these variables can be used to create simple PIs, such as stage-damage curves, or more complex models over different periods.

The ISEE model calculated a water level at every property from the water elevations in each of its grid cells and used that to drive the various performance indicator functions. The primary example is the flooding performance indicator. For each property, damage begins at some elevation and then increases according to a depth-damage formula for that property.

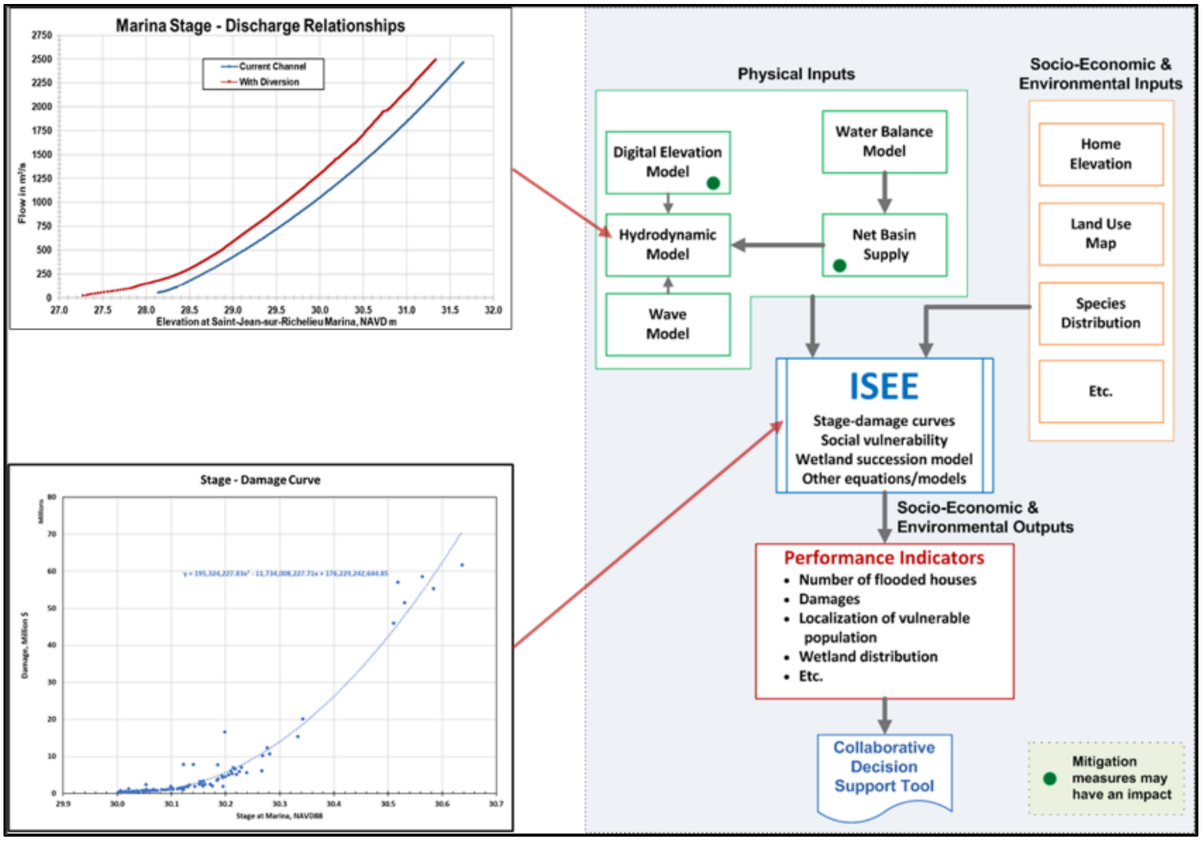


Figure 13. Integrated Social, Economic and Environmental (ISEE) system framework (FMMM/HHM 2022).

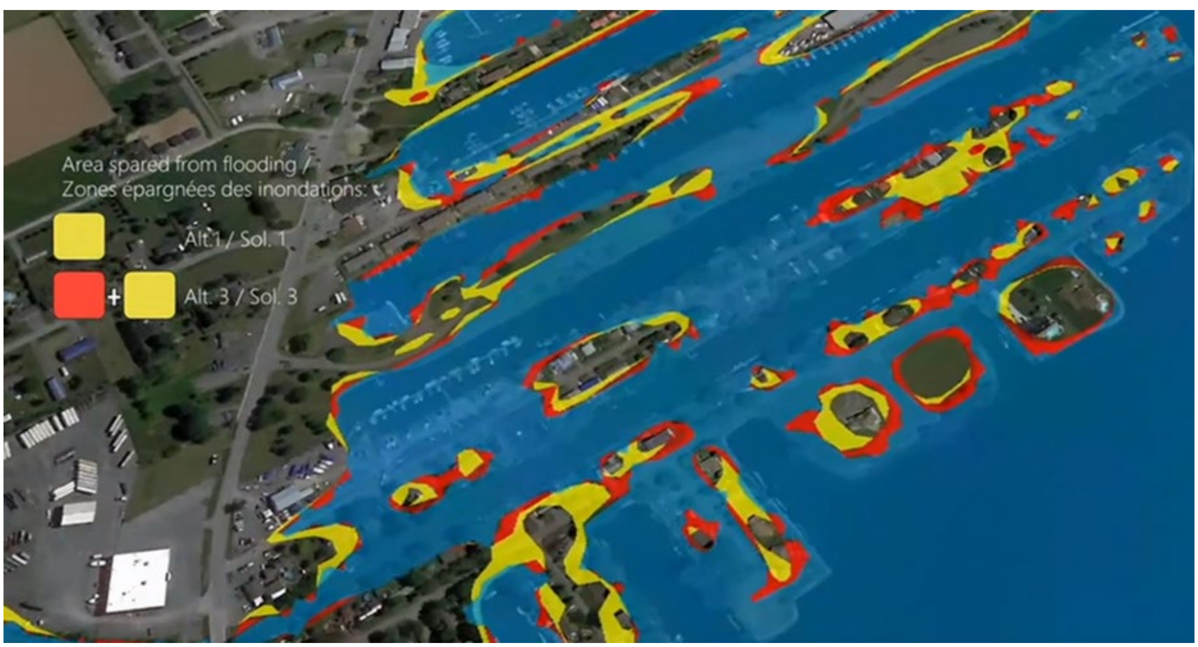


Figure 14. Example visualization of flooding in ISEE under different potential mitigation measures (shown in red and yellow).

PIs addressing potential impacts of flood mitigation measures were then computed to evaluate any combination of measures from the four themes. The PI values for each scenario (outputs) were then compared to a baseline condition scenario representing present management conditions.

Figure 14 shows an example visualization of the water surface level layer in ISEE that would drive inundation damage functions for buildings near the river.

The outputs from the ISEE model runs were displayed and analyzed in the Collaborative Decision Support Tool (CDST) described below, and used to produce benefit-cost estimates for different mitigation measures by two separate methods. One method (Bouchard St-Amant and Dumais, 2022) incorporated a separate water level and flow generator beyond the ISEE step, using the 1924-2017 water levels from ISEE to generate its own, much larger set of synthetic water levels. The intended purpose was to provide a wider range of water levels than ISEE that represented the long-term distribution of high and low levels. Both methods incorporated ISEE output related to performance indicators.

3.2.6 Integrated Flood Resiliency Model (IFRM)

The Integrated Flood Resiliency Model (IFRM) was developed to compare two ways to mitigate the financial damage property owners may incur because of floods: (1) a disaster relief program similar to the program offered in Québec, and (2) a three-layered flood insurance program. The IFRM calculated the estimated damages over time for the government, property owners and insurance providers under a range of possible future flood scenarios. The model used individual damage-frequency tables generated in the ISEE model, but only for the upper Richelieu River as a proof of concept. Payout maximums for each of the three parties (government, property owners and insurance providers) could be altered to examine how flood insurance premiums might be affected, and the resulting cost apportionment could be determined.

Insurance is not an effective method for reducing financial risk if people do not buy the policies because the premiums are perceived as cost-prohibitive. Therefore, rules to reduce the premiums paid by low-income property owners were incorporated, with government providing the difference to insurance companies. The model calculated the estimated insurance payouts for thousands of individual properties and a benefit-cost ratio for floodproofing each house, providing an assessment of which homes could be floodproofed most cost-effectively. A second set of damage-frequency tables representing the upper Richelieu risk profile after the construction of a proposed structural mitigation measure was incorporated, allowing model users to combine this structural measure with floodproofing and relocation to formulate a multi-theme alternative. The model allowed calculation of the dynamic interactions of program costs and risks, including the cost reductions in the government program to make insurance affordable, providing the unique ability to support an analysis of how measures from different Study themes would interact.

Evaluations of the potential mitigation measures included the use of performance indicators (PIs) and benefit/cost ratios; these are described below. ISEE's output provided flooding maps, flood damage information and values for other PIs that were used both to assess the potential impacts of mitigation measures and to develop benefit/cost ratios (Figure 15).

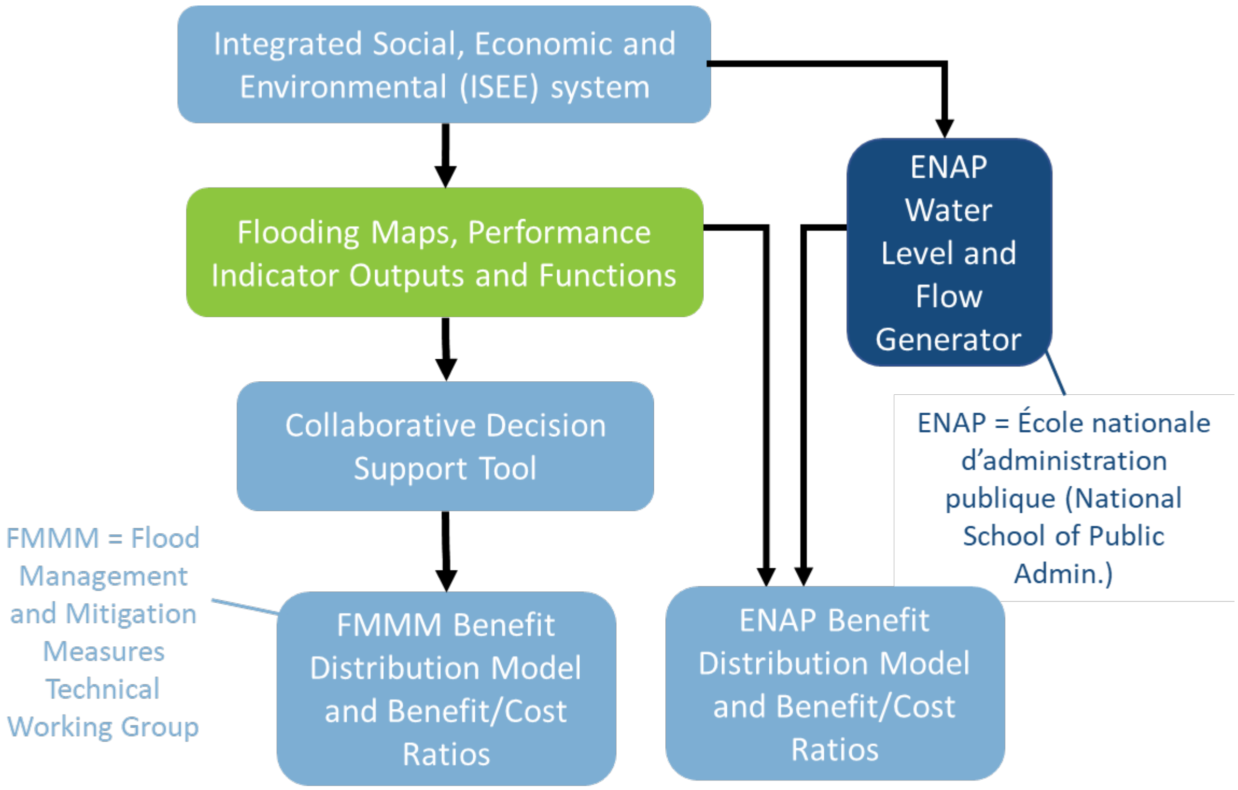


Figure 15. Use of ISEE to assess performance indicators and Benefit /Cost ratios.

Dark blue boxes represent model inputs, light blue boxes represent models or tools, and light green represent intermediate model outputs. Arrows represent the direction of the flow of data or output through the network. Arrow width or length are not intended to convey any sense of the relative magnitudes of data or output moving from box to box.

3.2.7 Performance indicators

Performance indicators (PIs) are quantitative measures that were developed to reflect how society, the economy and the environment are impacted by floods under different mitigation measures. PIs were developed in collaboration with over 40 experts from various fields such as flood damage quantification, social vulnerability, economics, ecology, and members of Indigenous communities. PIs were selected to encompass the expected impacts of diverse types of mitigation measures, and to allow for comparison of these measures.

Selection criteria included:

- Responsive to water level fluctuations
- Representative of sensitive species
- Encompassing lake, river and floodplain in both Canada and the United States
- Including all seasons and associated flow conditions (low flow, spring flood, etc.)
- Data are available for calibration and validation

Economic indicators allow a comparison of the cost of implementing mitigation measures with the economic benefits of these measures. Economic indicators used in the Study included:

- Residential structural damage
- Residential material damage
- Temporary lodging costs
- Clean-up costs
- Commercial, industrial and recreational structural damage
- Commercial, industrial and recreational material damage
- Commercial income loss
- Recreation income loss
- Agriculture yield loss
- Damage to farm buildings
- Crop yield loss
- Structural damage to public buildings
- Material damage to public buildings

Together, these PIs are intended to cover the majority of economic impacts resulting from floods. Damages were modeled for every year of a historical reference period (1925-2017), based on the building stock and building values of 2018. The objective was to describe and quantify conditions throughout the water level regime, which includes well-known past flood events. Validation and calibration processes were performed by adjusting model parameters to maximize concordance with observation datasets. When possible, to maximize model accuracy, calibration was done using local empirical data (Roy et al. 2022). For the structural damage PI, data on property values, home elevations and other home characteristics were used to estimate the cost of damage to homes based on the height of the floodwaters. The income loss PI was used to assess, for example, agricultural yield losses, by overlaying flood maps onto crop maps to delineate flooded crops. Economic damages could then be estimated based on flooded area, product value, and annual yield. Knowing yearly average damage and prevented damages associated with minor, moderate and major flood levels allowed assessment of the potential benefits of mitigation measures over a wide range of hydrological conditions. Maps displaying the spatial distribution of damage across the LCRR basin allowed visualizing where damage and damage prevention would take place.

Environmental indicators represent potential impacts of the change in water level regime on the natural environment, including species of particular concern, habitat, and critical areas such as wetlands. The environmental PIs were selected using literature information, Indigenous knowledge, field data and expert knowledge and were designed to assess the impacts of the variations in the hydrologic regime on specific components of the ecosystem (Roy et al. 2022). An initial list of potential PIs was developed and then refined by Study researchers and experts in the field, using selection criteria chosen to inform the Board’s evaluation of mitigation measures. Selection criteria included sensitivity to water level fluctuations, ecological relevance, threatened or endemic species status, and organism life history (Roy et al. 2022). Environmental performance indicators were specifically designed to weigh the mitigation measures based on the impacts of modifying the water level regime and do not necessarily consider all potential environmental impacts.

The environmental indicators selected for the Study were:

- Muskrat winter lodge viability
- Spiny Softshell Turtle egg survival
- Wetland habitat area
- Least Bittern reproductive potential
- Waterfowl staging habitat during spring migration
- Copper Redhorse suitable habitat for spawning and early larval development
- Northern Pike spawning area and probability of survival of eggs and larvae

The selected species are important to the ecosystem and the economy. For example, the Copper Redhorse is a species found only in a few Québec rivers that spawns in running waters of the Richelieu River; it is designated as endangered in Canada and threatened in Québec. Northern Pike is an important game fish and is considered an "umbrella species" meaning that its spawning habitat is like that of many other fish species. The Spiny Softshell Turtle is endangered in Canada and considered threatened in Québec and Vermont. The Least Bittern is designated as vulnerable in Québec, threatened in Canada and New York and a species of special concern in Vermont. It should be noted that the intent of these PIs was to allow comparison of potential impacts of various mitigation measures; evaluation of these PIs was not intended as a rigorous environmental assessment of each proposed measure. While this list of PIs is not exhaustive, the selected PIs met the criteria described above, including sensitivity to water level fluctuations. Potential flood mitigation measures may affect water quality; however, relationships between water levels and water quality are not well documented at the scale evaluated for this study. The selected species provide a basis for assessing the potential impacts of mitigation measures; a more comprehensive environmental evaluation would be undertaken prior to implementing any structural mitigation measure.

Indigenous interest performance indicators reflect valued components of the environment to Indigenous communities. Indigenous interest PIs, selected for the study in consultation with the communities, were:

- Wild rice survival between the germination and floating stages
- Black ash basket-grade habitat and harvest
- Archeological site vulnerability

Wild rice is an aquatic self-sowing annual grass that is a culturally important staple food for native peoples. While its cultural importance was the primary factor in selecting wild rice as a PI, it also provides secondary ecological benefits, such as cover and brood-rearing habitat for ducks, nursery areas for fish and amphibians, and a food source for herbivores (Roy et al. 2022). Black ash is a hardwood tree often found in wetlands that is of ecological, ethnobotanical and cultural importance. Black ash is central to the identity and culture of the W8banaki and Kanien'kehà:ka (Mohawk) Nations. Indigenous peoples in Canada and the United States have used its wood for centuries for producing baskets and other products (Roy et al. 2022). Archaeological sites represent areas of cultural or spiritual significance[15] that are threatened by anthropization, the industrialization of the banks, and which can be degraded by the phenomena of erosion. The selected PIs incorporated cultural and ethnobotanical features that must be considered to support the exercise of Indigenous rights for current and future generations.

[15] In addition to the three PIs, sweet grass was also discussed as a fourth indicator. Sweet grass is a sacred resource for the W8banaki Nation. However, due to the absence of location data for the species within the Study area and a lack of information providing a direct link between water levels and sweet grass habitat quality, a specific performance indicator for sweet grass was not developed (Roy et al. 2022).

In addition to the three indicators listed above, several of the environmental PIs are also important to the Indigenous peoples in the basin. These include wetland area, Northern Pike spawning habitat, Copper Redhorse spawning habitat, waterfowl migration habitat and muskrat winter survival (Roy et al. 2022).

Social indicators[16] aim to describe the population's vulnerability to flooding. Vulnerability is not restricted solely to exposure to flooding, but also depends on the characteristics of the population, their available resources and the infrastructure. Factors considered included sensitive populations, such as elderly or low-income; adaptive capacity; location of housing, infrastructure, and essential services; and accessibility, including whether roads become impassable, or housing becomes inaccessible to first responders during a flood. Social risk is made up of the flood hazard, which is the probability that a flood may occur at a given location (in the map on the left side of Figure 16, areas shown in red are likely to be flooded); and the total vulnerability, considering the various factors described above (in the center of Figure 16; the deeper the red color, the higher the vulnerability). Combining these two maps results in a flood risk map (on the right side of Figure 16; the red areas indicate locations of vulnerable populations who are most likely to experience flooding).

The selected PIs provided a framework for evaluating the benefits and drawbacks associated with the various flood mitigation measures considered by the Study Board.

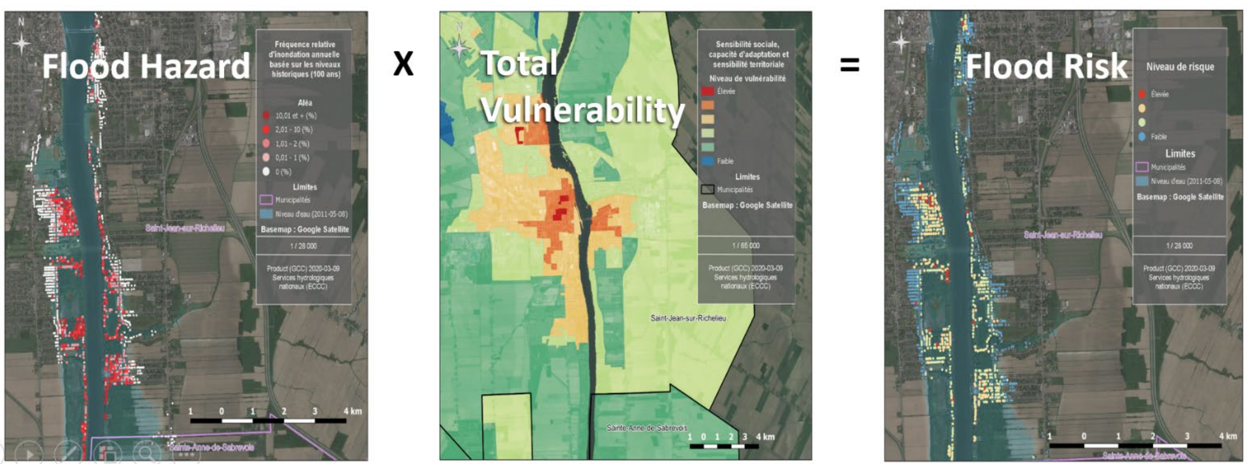


Figure 16. Flood frequency (left), total vulnerability (center) and risk level (right), in the Richelieu Valley; from the ISEE model (Thomas and Gagnon, 2020).

[16] The Study included social considerations in its evaluations, but at the time of this report, social aspects had not been formally assessed in a quantitative way using PIs.

3.2.8 Collaborative Decision Support Tool

The Study developed a Collaborative Decision Support Tool (CDST) to support Board decision-making, specifically related to structural mitigation measures (Theme 1). The CDST is an Excel-based model that assembles and manipulates information produced by the ISEE system. Over the course of the Study, the CDST evolved from a water balance model and visualization tool used to evaluate water level trends, to a tool to provide water level and damage forecasts for first responders. The CDST is primarily a “window” into the ISEE system, capturing and presenting ISEE outputs in a manner that made it easier for the Board to see the outputs and use them in developing findings and recommendations.

Typical ISEE output included several hundred thousand pieces of data. The CDST revealed what was significant in those data, using the data to answer questions that the Board asked. For example, the CDST evaluated whether certain structural measures would increase Lake Champlain levels in dry years, and during which parts of the year such increases would occur. The CDST included structural flood damage reductions from ISEE and showed, for example, how many properties in Canada and the United States would avoid damage if the flood of 2011 were to happen again. These simulations indicated good agreement with actual damage; CDST simulations estimated 3,839 homes would have been damaged under the 2011 conditions; the actual number has been reported as approximately 4,000 homes in Canada and the United States combined (LCBP 2013).

3.2.9 Benefit/cost analyses

One of the key considerations for the Study Board was the economic viability of a potential flood mitigation measure. For this report, the Study adopted the standard principles for benefit/cost (B/C) analysis to evaluate the economic viability of measures under consideration. The B/C analysis results depend on the costs of the infrastructure, the damages evaluation, the period considered, the probability of events in relation to the return period and the interest rates considered. Benefit/cost ratios for structural mitigation measures were computed by dividing the present value of the expected annual benefits of each measure by the corresponding present value of projected total annualized costs. If the expected net benefits were greater than the costs, the B/C ratio was greater than one, a threshold for evaluating the efficacy of a proposed structural solution.

Two B/C ratios were developed. One used the 1925-2017 water levels from ISEE to generate a set of synthetic water levels, to provide a wider range of water levels that represent the long-term distribution of high and low levels (Bouchard St-Amant and Dumais, 2022). The second B/C ratio was developed using the CDST (Moin et al. 2022). The CDST produces a population-based B/C ratio internally, based on the historical flood damages from ISEE. Both approaches provide useful information about benefit/cost ratios. Additional study of benefit-cost approaches and discussion of underlying assumptions may be appropriate before implementation of particular structural measures to reduce flooding risk in the LCRR basin.

3.2.10 Decision criteria

To evaluate potential flood structural mitigation and management measures, the Study Board identified a set of decision criteria (Table 2). These criteria were intended to compare the various potential measures and evaluate whether there would be major negative impacts associated with them, to assist the Study Board in developing recommendations. (Note that comprehensive assessments of the impacts of the recommendations are beyond the scope of this study, and further evaluations will be needed before implementing the recommended measures.)

The Study's decision criteria evolved over time in response to feedback from stakeholders. Considering how stakeholders prioritize decision criteria provides insight into what stakeholders value. Understanding stakeholder values has implications for mitigation recommendations because it suggests what is likely or unlikely to be supported.

Study researchers conducted household risk perception surveys, social network analyses and emergency responder surveys to assess stakeholder priorities (SPE 2022). In general, there was some consistency in prioritizations across Québec, New York and Vermont, with human health and safety, including that of vulnerable residents, as a top priority for most stakeholders. Mid-level priorities generally included environmental protection and preventing structural damage. There was a generally lower prioritization for preventing economic harm, protecting historical and cultural sites, and reducing street closures (SPE 2022).

The decision criteria presented in Table 2 guided the Board in evaluating the potential structural flood mitigation measures described later in this report and developing recommendations. In general, the Board considered these criteria sequentially; for example, the first consideration was whether a potential mitigation measure was within the Study scope and mandate; if not, the measure was removed from consideration and evaluations of the other criteria were not necessary.

3.3 CLIMATE CHANGE STRATEGY

The Study Board was directed to examine the implications of a changing climate on future floods in the basin. To meet this requirement, study scientists adopted the IJC Climate Change Guidance Framework[17], which includes using a broad range of approaches to determine potential future conditions. A key question for the Study Board was how to prepare for the flooding along the shoreline of Lake Champlain and the Richelieu River that will occur in the future. The strategy adopted by the study was designed to support the best possible answer to that question despite the irreducible uncertainty in estimates of the severity and chance of future flooding.

The Study used recent peer-reviewed approaches to factor knowledge on the future of flooding into decisions regarding proposed flood mitigation measures. Scientists know that climate change will amplify weather extremes, but the effects on floods and droughts are uncertain. Higher temperatures can decrease snowfall and increase evapotranspiration in the watershed and may lead to lower summer water levels in the future. However, increased precipitation in the spring may increase the chance of flooding, and lower snowpacks due to higher winter temperature might have the opposite effect. In addition, more winter precipitation in the form of rain can exacerbate flooding. If future floods are much larger than historical ones, development outside the current regulatory floodplain (delineated under existing hydrologic conditions) will start to be flooded. Alternatively, if climate change reduces spring flooding, structural measures designed to reduce water levels

[17] Climate Change Guidance Framework | International Joint Commission (ijc.org); the goal of the framework is to provide guidance to the various IJC boards for addressing climate change using the best available institutional and organizational science and stakeholder input.

might not be a desirable investment. The structural measures proposed by this study have been evaluated using plausible future water supplies to determine their robustness. Given advancing climate science and the evolving climate, these evaluations should continue to be conducted in the future.

To generate a broad perspective on potential future water supplies under a changing climate, a strategy called “decision scaling” was adopted. Decision scaling involves using “climate stress tests” to perturb the system to see how it would respond to increasingly extreme hydrology and then considers the plausibility of the hydrology, the magnitude of the impacts and the mitigation strategies together as the basis for planning. Here, the word “plausible” means there is some evidence that a flood of a certain magnitude could occur. This is analogous to the way engineers test structures, by determining loads that cause failure and then assessing whether those loads will be encountered in the use of the structure. The Study Board’s use of decision scaling improves confidence in its recommendations despite the uncertainty in flood predictions.

Table 2. Study Board decision criteria.

#	Criterion	Context	Evaluation
1	**Within study scope and mandate**	International study focused on solutions that reduce Lake Champlain and Richelieu River flood damages with a transboundary perspective, not local flooding problems.	Based on the reference from governments and the IJC's directive and continuing advice to the study, which stipulated only non-structural and moderate structural solutions would be studied.
2	**Technically viable**	The measure applies sound engineering and is effective in reducing flood damages.	Based on technical and scientific assessment and input by the Study's experts, including estimates of flood level reductions.
3	**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 benefit-cost analyses completed by the study.
4	**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.
5	**Environmentally sound**	Increases environmental benefits, or at a minimum, limits detrimental impacts. Protection and restoration of ecosystem services.	Based on evaluation of the effects on selected indicator species and habitats.
6	**Resilient to Climate Change**	Works 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.
7	**Implementable**	Because governments alone can implement Study recommendations, the Board prefers measures that meet the requirements that governments impose for such measures.	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.

A first approach, presented in Figure 17, used historical weather time series to create stochastic (randomly determined) scenarios of precipitation and temperature using a tool called the stochastic climate/weather generator. These scenarios were then used as input to the HYDROTEL model that simulates inflows (termed "Net Basin Supplies" or NBS) to Lake Champlain. Simulated inflow time series were input to the two-dimensional hydraulic lake model that simulates water levels in Lake Champlain and at Saint-Jean-sur-Richelieu, together with lake outflow and streamflow. The water balance model results were used to create a series of water surface profile scenarios and the two-dimensional hydraulic model calculated water levels for each timestep and each cell in the ISEE system. Functions embedded in ISEE produced impact estimates, including estimates of damages to flooded buildings (Werick 2022).

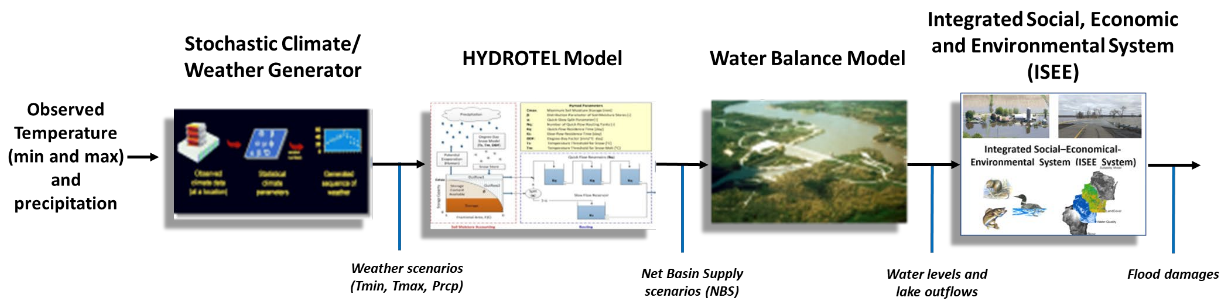


Figure 17. Combination of models used for assessing the LCRR system's vulnerability to warming temperature and increasing precipitation (François and Brown 2022).

In addition to the stochastic inflows presented above, the Study assessed potential impacts of a changing climate using a statistical evaluation of historical climate data to predict the likelihood of future floods. A probable maximum flood scenario was also developed, considering the possibility of heavy snowpack, temperatures conducive to rapid snow melting and large rainfall events leading to floods even greater than the 2011 flood. Global and regional climate model projections were also used to generate potential future scenarios. Taken together, these four approaches resulted in a robust evaluation of the implications of a changing climate.

3.4 SOCIAL, POLITICAL, AND ECONOMIC CONSIDERATIONS

The LCRR basin is a complex, adaptive social-ecological system whose flood hazards result from a combination of natural and anthropogenic factors. Climate change, extreme weather events, and the natural composition of the region's aquatic and terrestrial systems impact and are impacted by a wide range of individual and institutional behaviors. The LCRR Study analyzed the social acceptability, and economic and political feasibility, of proposed flood mitigation measures. Historically, technical and economic analyses have been used to recommend measures (Jordan and Turnpenny, 2015). However, earlier studies from the IJC have demonstrated the need to analyze the social desirability of measures before making recommendations. Four guiding questions provided context to the numerous studies carried out. These questions were intended to clarify the ways that potential flood mitigation measures and recommendations would impact the communities, and the political feasibility and social acceptability of those measures. They included:

1. How is flooding a priority for stakeholders?
2. How do stakeholders prioritize decision criteria?
3. What do we know about social vulnerability?
4. What are stakeholders' reactions and preferences to mitigation measures within each Theme, and what factors hinder and enable the implementation of proposed measures?

Each of these questions was addressed through a combination of research activities, analytical approaches and data collection carried out in Québec, New York, and Vermont throughout this study (SPE 2022). Methods and data collection tools used to answer these questions included economic studies, historical analysis, media analysis, stakeholder focus groups, social vulnerability analysis, household risk perception surveys, social network analysis, emergency responder surveys, hazard mitigation plan analysis, meetings with stakeholders and political entities and expert workshops. The work was multi-disciplinary. Multiple data points, based on quantitative and qualitative data, that supported similar results, were used to improve the validity and accuracy of this analysis.

The inclusion of a team to study, from the onset, the social, political and economic drivers associated with flood mitigation was new for IJC studies and will provide useful insights for other studies in the future.

3.5 COLLABORATION AND ENGAGEMENT WITH INDIGENOUS PEOPLES IN THE BASIN

The Lake Champlain and the Richelieu River basin continues to serve as a resource for food, water, economy and spiritual practices for Indigenous peoples. Hunting, gathering, fishing, boating and recreation are important activities. There are cultural and archeological sites (campsites, villages, meeting sites, burial sites) of traditional and sacred importance to the Indigenous peoples across the basin. The Study reached out to Indigenous groups with interests in the basin to make certain that the Study Board heard their concerns about cultural resources and practices that were impacted by past and present flooding in the basin. New knowledge gathered from this engagement was also incorporated into the performance indicator work, helping to ensure that the various flood mitigation measures considered potential impacts on Indigenous interests in the basin.

As part of the study's outreach to Indigenous groups in the basin, the Board sent a letter to the four state-recognized Tribes in Vermont and to the federally-recognized Stockbridge Munsee Community of Mohican Indians inviting participation in the study. The Board was able to continuously share updates on the study with the Vermont Tribes through the Chief of the Nulhegan Band of the Coosuk Abenaki Nation.

The Study also engaged the Ndakina Office of the Grand Conseil de la Nation Waban-Aki (GCNWA) and the Mohawk Council of Kahnawà:ke (MCK) to produce a report that characterized their interests in the basin. The report has two parts. The first part characterizes the traditional use and occupation of the territory (UOT) of the study area by the W8banakiak and the Kanien'kehà:ka for subsistence, economic, spiritual, or social purposes. The second part assesses the archeological potential, the archeological sediments, and the vulnerability of the archeological sites to impacts from future flooding, erosion and flood management actions.

The GCNWA and the MCK used pre-existing UOT data already at their disposal from previous studies and supplemented this by carrying out semi-directed interviews oriented toward gathering basin-specific data using a protocol developed by the Ndakina Office. In addition, views of the participants were gathered regarding the management of the hydrological dynamics of the Richelieu River. The data resulting from these interviews and from the review of the pre-existing data available at GCNWA were used to identify the presence of places valued for their cultural, historical or heritage interest. These were included in the study of potential areas of archeological interest. The interests identified in the report were also used to help develop the Study's set of performance indicators including species harvested in the study area that could be affected by changes to the hydrological regime of the system. The three indicators that are specific to the Indigenous Nations are listed in Table 3. More information on each of these performance indicators is available in the report, *Evaluation of Structural Flood Mitigation Alternatives Using Performance Indicators* (Roy et al. 2022).

Table 3. Environmental performance indicators (PIs) of interest to W8banaki and Mohawk Nations (left); PIs of particular importance to W8banaki and Mohawk Nations (right).

Environmental Performance Indicators of Interest to Indigenous Groups	Performance Indicators specific to Indigenous Groups
Wetland area	Black ash habitat
Northern pike spawning habitat	Wild rice survival
Copper Redhorse spawning habitat	Vulnerability of archeological sites
Waterfowl migration habitat	
Muskrat survival in the winter	

The results of this study are available in the GCNWA report (GCNWA 2021). The report authors acknowledge the limitations and biases implicated in the study in that the absence of data of reported activity/interests in certain regions of the basin should not be interpreted as an absence of interest in those areas. The information contained in the report also should not be extrapolated or used for any other purposes than the LCRR study.

The archeological component of the GCNWA-MCK study is part of a continuity of management and protection of the archaeological heritage of the W8banakiak and Mohawk on the Richelieu River and Lake Champlain, particularly of Missisquoi Bay. The research identified sites and areas of potential vulnerability to erosion in the study area and made it possible to understand the mechanics of the different soils making up archaeological sites.

Additional research was carried out on Indigenous archeological data in the US portion of the basin. The Study engaged the Vermont State Historic Preservation and New York State Parks, Recreation and Historic Preservation agencies to obtain information on areas of archeological interest in the southern portion of the basin. As the location of the sites is sensitive information, they cannot be made public, and the Study reached an agreement with the agencies to access the data strictly for the purposes of identifying sites that have the potential to be affected by flooding.

This component of the study used data gathered from Vermont and New York agencies on sites of archeological interest, combined with the data on archeological sites provided by the GCNWA and MCK and overlayed them with a map of the extent of flooding in the basin in 2011 (Figure 18). The data in this report were then shared and reviewed by the Indigenous Nations that had shared data as well as the Chief of the Nulhegan Band of the Coosuk Abenaki Nation . Across the entire basin, a total of 330 sites were mapped and 147 would have been affected during the 2011 spring flood.

The Study Board is extremely appreciative of the contributions that the Ndakina Office of the GCNWA, MCK and the Chief of the Nulhegan Band of the Coosuk Abenaki Nation have made to the study. It is important to also acknowledge the different political and organizational structures which shape engagement with Indigenous peoples on either side of the border. In the Canadian portion of the basin, the Study developed a formal relationship with federally-recognized Indigenous Nations; while in the US, the Study often called upon private citizens in their capacities as leaders of state-recognized Tribes. Not having the administrative and financial resources of a federally recognized Tribe, the capacity of this latter group to participate was limited.

In considering performance indicators for the study, it is important to distinguish between the constitutionally protected food, ritual and social activities of First Nations and Native American Tribes, and the sport and recreational fishing, hunting and trapping activities of the non-native population. Traditional Indigenous activities also have cultural, emotional and spiritual values and are important to the overall well-being of individuals and communities. In Canada, these activities are also protected under section 35 of the Constitution Act of 1982, which recognizes and affirms Aboriginal and Treaty rights. Moreover, community fisheries and hunts contribute to the food security and sovereignty of the members of the Nation, particularly the elders and families in precarious socio-economic situations. Finally, the majority of these activities are undertaken by families and are intergenerational. They play an important role in the cultural transmission and the consolidation of intergenerational and socio-community ties.

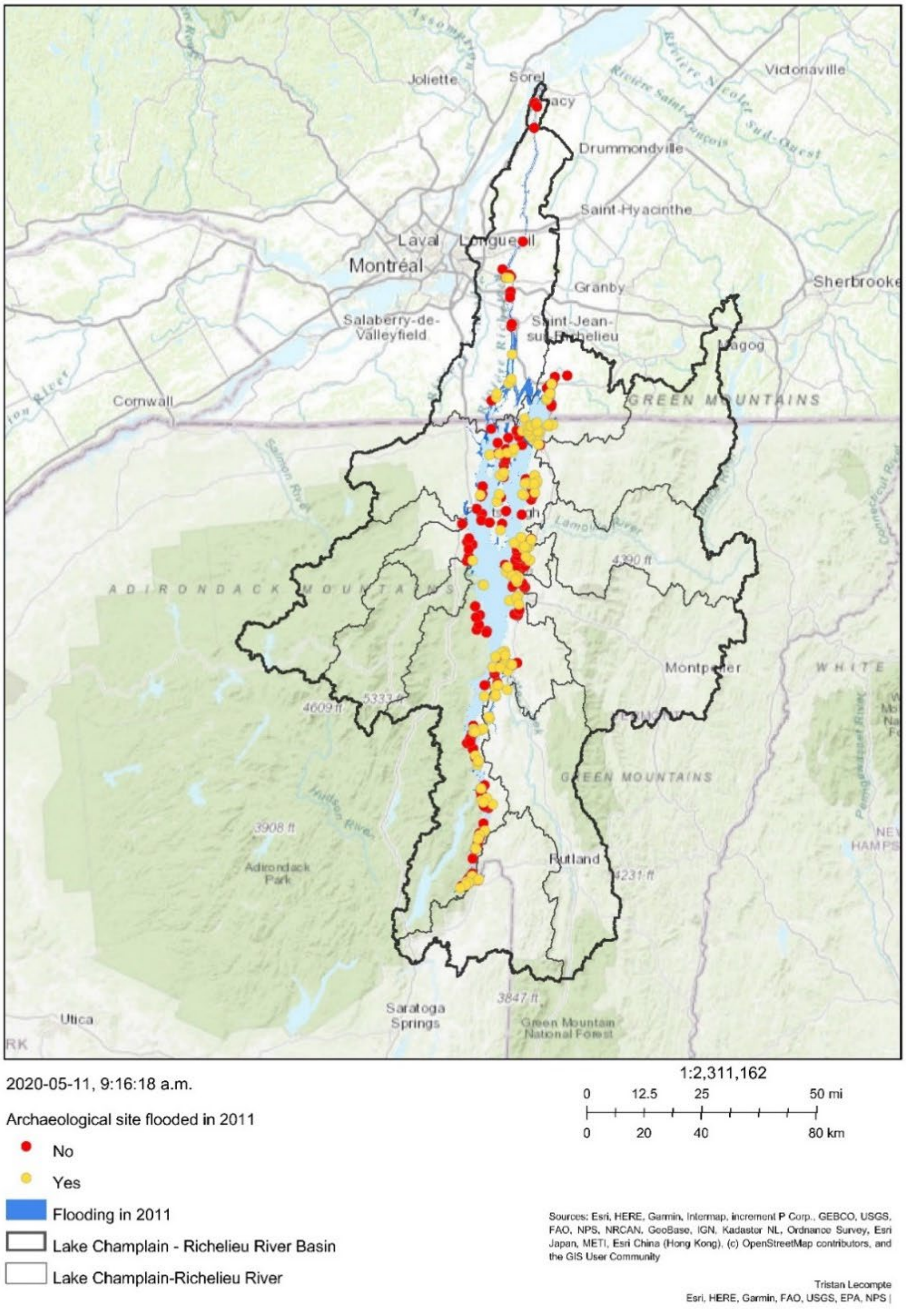


Figure 18. Indigenous archeological sites near lake and river shorelines and associated 2011 flood impacts. Sites flooded in 2011 are shown in yellow. (Lecompte, 2021).

3.6 PUBLIC ADVISORY GROUP AND STAKEHOLDER PERSPECTIVES

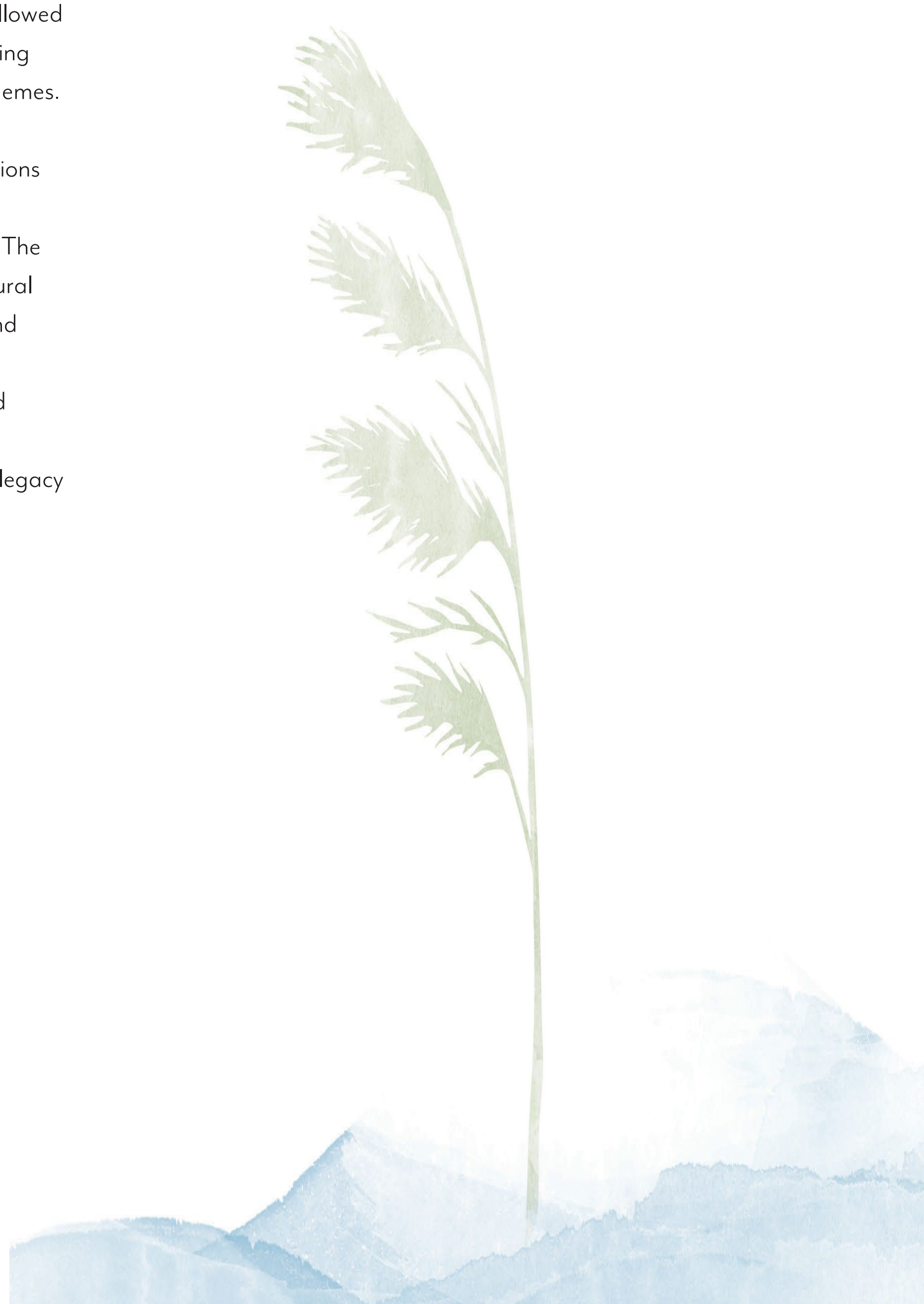
Public and stakeholder engagement was an essential and ongoing component of the LCRR study and included both direct engagement by the Study Board (for example through public meetings or outreach efforts) as well as collaboration with a Public Advisory Group (PAG). The binational PAG represented various areas of interest and included regional representation from across the Lake Champlain-Richelieu River basin. Its members drew on their knowledge, networks, contacts and experience to provide advice to the Study members and to encourage public participation in the study. Since the initiation of the Study, work was executed with the belief that good quality credible scientific data must be combined with public and stakeholder input to foster a shared understanding of the relationship between basin communities and their environment in the context of flooding, ultimately leading to viable flood mitigation measures. The PAG provided valuable input to guide the Board's decision-making; for example, strengthening the Board's recommendation regarding the protection of wetlands in the basin and ensuring that impacts downstream of proposed structural mitigation measures were identified and considered.

Throughout the study, key findings were shared through reports, technical webinars, videos, fact sheets and white papers. These were made available on the study website (www.ijc.org/lcrr) and summarized in a study newsletter, *The Current*, which was distributed on a bimonthly basis. Multiple PAG meetings, target audience and public meetings were held throughout the study to collect input from a variety of perspectives about potential study recommendations. Hundreds of individuals representing public, private, non-profit, government and business interests participated in surveys, focus groups, meetings, and workshops, providing essential information that influenced study research directions and recommendations.

Public outreach meetings in early 2022 presented preliminary recommendations. These meetings were accompanied by a draft summary report for public consultation (ILCRRSB 2022). Using these meetings and the public consultation report, the Study Board solicited comments from the public. The Board's final recommendations incorporate revisions that were based on this input.

4 STUDY ANALYSIS AND FINDINGS

This section provides a review of the flood mitigation measures that the Study Board considered under each of the four Study Themes, the process used to evaluate them, and a discussion of the most promising ones. The analysis demonstrates how structural measures under consideration performed when evaluated against the various social, environmental and economic performance indicators, how robust they were to water supply variability. including climate change, and the expected acceptability of the measures from the social and political perspectives. The Study evaluated the expected impacts of climate change on future water levels. This information is presented in sequence followed by the resulting recommendations for the overarching topic of climate change and for each of the four Themes. That is, a climate change subsection comes first, concluding with its recommendations, and subsections follow for Study Themes 1, 2, 3, and 4, with corresponding recommendations for each Theme. The Theme 1 subsection includes a set of distinct structural measures, with discussion of their relative merits and viability, rather than proposing a single recommendation. Finally, there are discussions and recommendations regarding capacity building to support future flood mitigation efforts, the Study's legacy products to support the implementation of recommendations, flood management, and opportunities for collaboration.



4.1 EXPECTED FUTURE VARIABILITY OF WATER SUPPLIES

The Study Board was directed to consider the effect of climate change on flooding. Two questions were paramount: would flooding get worse or better, and would the measures the Board recommended be more or less justifiable in the future?

The Study used recent peer-reviewed approaches to factor knowledge on the future of flooding into decisions regarding proposed flood mitigation measures. The Board looked at this issue from four perspectives to ensure a robust analysis:

1. The first perspective was represented in peer-reviewed papers (Lucas-Picher et al. 2020) using traditional downscaling of Global Circulation Model results for the high emission scenario representative concentration pathway (RCP) 8.5. Based on a range of climate change perspectives, the average annual net basin supplies (inflows) to Lake Champlain would be expected to decline over time, lowering the frequency of flooding, although natural variability could still produce floods larger than 2011 even as the average lake levels declined.

2. Stochastic analyses demonstrated that the potential range of flooding included floods much larger but also less frequent than the 2011 flood. One of the stochastic analyses found a correlation between annual net basin supplies and the Arctic Oscillation Index; it projected a semi-periodic cycle of high and low mean water levels in the future. Defining "flood" as a peak annual Lake Champlain level of 30.35 m (99.57 ft) or higher, the historical record shows such cycles. There was little flooding in the 1960s, fairly frequent flooding in the 1970s.

3. A study to estimate the probable maximum flood (PMF) focused on the interaction of snowpack, temperature and spring precipitation in causing floods. This evaluation found that there were insufficient data to estimate the PMF as a function of the interaction of those three phenomena. Instead, peer-reviewed methods of estimating the PMF from a stochastic analysis of just water levels or releases were employed. Using those methods, the maximum possible flood flows were estimated at 5,449 m^3/s with a probable maximum Lake Champlain level of 35.74m (compared to actual 2011 releases of about 1,539 m^3/s and a maximum lake level of 31.32 m). The probability of the PMF cannot be estimated using statistical methods, but because it is probably the largest flood possible, the PMF should be considered very unlikely to happen.

4. A decision scaling effort used a weather generator to create a wide range of synthetic net basin supplies (NBS). The NBS values were then processed through the water balance model to predict a range of future lake levels and releases. The dataset created by this effort was used to address the fundamental questions, using the decision scaling results but mindful of the results from the three other processes. This work confirmed the findings of the first perspective, both the decline in future average levels and persistent risk of floods worse than 2011, and the generated floods showed variability similar to that demonstrated in the stochastic analysis. It also suggested that flooding would be expected to become less frequent and severe, as the preponderance of models showed.

4.1.1 Decision-scaling results

The potential impacts on water inflows and lake levels resulting from changing climate are driven by conflicting trends:

- Warming temperatures lead to a reduction in inflows and then lake level. The reduction is explained by larger evapotranspiration over the basin and evaporation over the lake.

- Increasing precipitation leads to an increase in runoff, inflows and lake level.

- If both precipitation and temperature increase, the change in inflows and lake level depends on the relative importance of the change in precipitation and temperature. Based on the HYDROTEL model as calibrated, an increase of 4°C would more than cancel out an increase in precipitation by 10 percent, leading to decreases in inflows and lake levels. On the other hand, an increase in precipitation by 20 percent or more would more than counteract warming by 4°C and would lead to increased inflows and higher lake levels.

The outflow from the lake and the water level at Saint-Jean-sur-Richelieu are generally a function of the lake level (roughness of the channel, affected seasonally by vegetation growth and ice cover, also affects flows and water levels), so similar results are obtained for these variables.

Using decision scaling to relate future flooding to specific changes in temperature and precipitation

Figure 19 provides a depiction of the potential distribution of future maximum lake levels for various combinations of changes in temperature and precipitation (François and Brown, 2022). Figure 19 is complex because it offers a dense array of information. The x-axis is made up of the range of temperature change processed in the Weather Generator. Similarly, the y-axis shows the percentage increases in annual precipitation processed through the Weather Generator.

In the main chart, at the intersection of each temperature and precipitation pair, there are five circles colored white or in shades of blue and red. The key to the colors is shown on the right of the graph. White represents the 2011 flood level. The darker the blue, the higher the peak level modeled, up to about two meters above the 2011 flood. Deeper reds indicate the degree to which the peaks are lower.

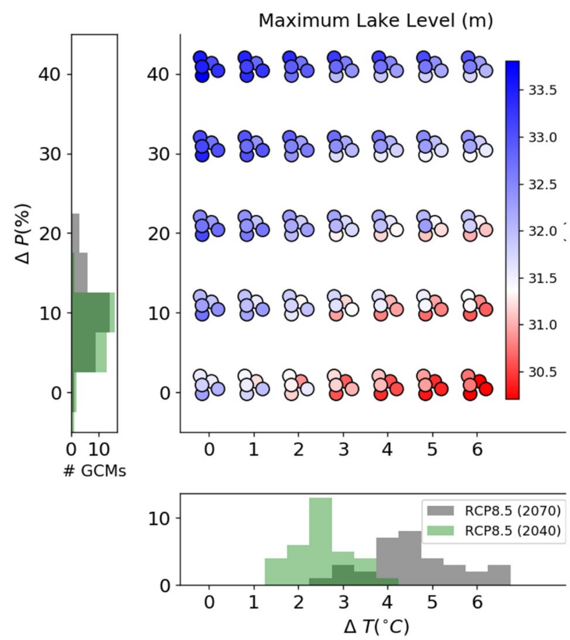


Figure 19. Statistical depictions of future maximum lake levels for all predicted combinations of temperature and precipitation changes (François and Brown 2022).

The five-circle set on the bottom right is colored dark pink and red; that reflects the much lower levels that would occur in a future with 6°C warmer temperatures but with no increase in precipitation. The five circles represent five different "realizations" of weather-generated levels, each representing a different but plausible level of variability. The five dark blue circles in the top left reflect a basin with a 40 percent increase in precipitation but no increase in temperature.

Which of these temperature-precipitation pairs will actually happen in the future? The probability of any pair of red or blue futures cannot be determined, but the figure does show how many models support the projections of each temperature-precipitation pair. This is indicated in the grey and green bar graphs situated to the left and below the main chart. The green bars represent the nearer future, labeled 2040 and spanning years 2026 to 2055. The grey bars represent a more distant future labeled 2070, representing years 2056 to 2085. In the near-term future, for example, the green bars below the chart show models forecasting temperature increases from between +1.5°C and +4°C for the 2040 horizon while it roughly ranges from +2.5°C to +6.5°C for the 2070 horizon. Similarly, the bars to the left show precipitation projections ranging from -3 percent to +22 percent. The analysis does not rule out the possibility of no increase in temperature but a 40 percent increase in precipitation (the dark blue circles in the upper left of Figure 19), but the intersection of predicted temperatures and precipitation shows that current scientific projections are mostly for pinkish levels in the near term with more red levels towards the end of the century (François and Brown 2022).

The plausibility of mega-floods under future conditions was evaluated by comparing the weather and land surface conditions that model simulations indicate would lead to flooding with HYDROTEL simulations of Weather Generator and historical floods. The Study's analysis showed that selecting a hydrologic data series that combined the March 1st snow water equivalent from the simulated 1971 flood and the April-May rainfall in the simulated 2011 flood would produce Lake Champlain water levels higher than 2011. The fact that higher levels could result from the coincidence of snow and rain that have been seen in different years in recent history influences the intuitive sense of the plausibility of floods even larger than 2011.

Figure 20 provides an example of a parallel coordinate plot that explores connections between multiple meteorological drivers and the resultant flows and water levels. This plot is composed of multiple vertical axes arranged left to right; each axis represents the range of either a predictor of flooding at Saint-Jean-sur-Richelieu or a variable that is used to describe the flood at Saint-Jean-sur-Richelieu. In the case presented below, the predictors are the lake level on March 1, the snowpack condition on March 1 (represented by the snow water equivalent variable at this date), and the rainfall during March and April.

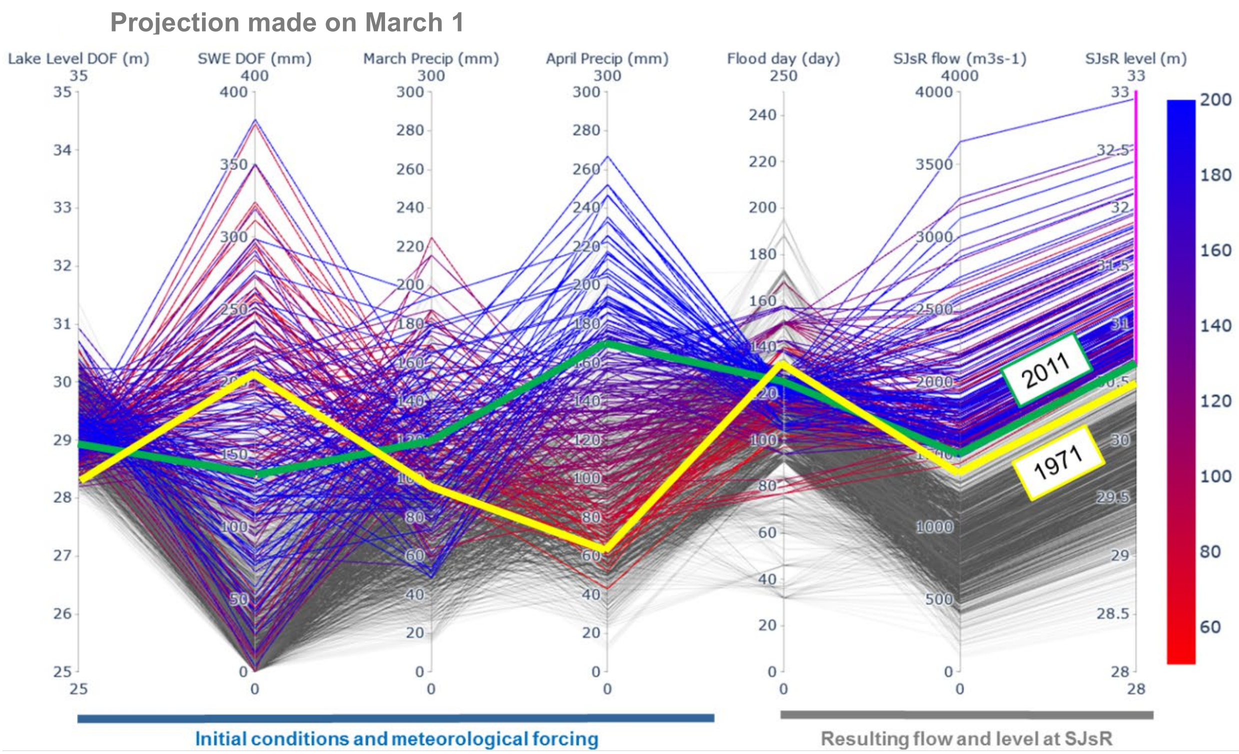


Figure 20. Parallel coordinate plots linking a set of antecedent conditions (i.e., from left to right: lake level, SWE, March rainfall and April rainfall) to variables that describe the flood at SJsR (date, flow and water level) (François and Brown 2022).

The flood date is given as the day of the year (1 is January 1, 92 is April 2, etc.). The two largest historical floods (based on inflows simulated in HYDROTEL), 1971 and 2011, are indicated in yellow and green, respectively. Simulated floods that are larger than the 2011 floods are shown in purple. The color scale on the right indicates the April rainfall (mm).

The variables used to describe the flood events are the flood date (calendar day), and flow and water levels at Saint-Jean-sur-Richelieu. Each line connecting the different vertical axes represents a specific year/flood from the sub-set of simulations used for the analysis. Simulated floods that lead to a water level higher than the one simulated for the 2011 flood are highlighted in color. The color scale from red to blue indicates the total rainfall during April. The historical floods (based on inflows simulated in HYDROTEL) that occurred in 1971 (yellow) and 2011 (green) are also shown on the plot for the sake of comparison with the simulated ensemble (François and Brown 2022).

Figure 20 illustrates that many events from the climate stress test ensemble are greater than the 2011 flood; some are significantly larger (François and Brown 2022). This is no surprise, as the climate stress test ensemble includes scenarios with increases in precipitation that go significantly beyond what the climate projections (i.e., +30 percent and above) show. For such scenarios, a significantly larger snowpack could be accumulated across the catchment, especially if warming is low, which provides ideal land-surface conditions for a mega-flood. In those instances, like the 1971 flood, no significant rainfall in March and/or April is required to generate a mega-flood downstream of the lake. These events could occur if the increase in precipitation compensates for the increase in evaporation. It is also interesting to note that megafloods can occur even when the snowpack is significantly smaller than the conditions observed in 2011, but this would require a very wet spring season.

The Study's climate change analysis (François and Brown 2022) supported the following findings:

1. Climate change is likely to reduce average Lake Champlain levels and Richelieu River flows during the 21st century, but the region will still be susceptible to floods greater than that of 2011. "Megafloods" greater than the 2011 floods are plausible, if unlikely, in any given year; the best way to deal with them is through floodplain management and emergency response planning, rather than structural measures.

2. Estimates of the relationship between increased temperatures and increased evapotranspiration are important, and the estimates developed by the Study are reasonable, but also uncertain (François and Brown 2022). There is credible research that predicts that Lake Champlain levels will trend downward over the 21st century based on a system of models that suggest carbon emissions will increase temperature and precipitation, but that warmer temperatures will increase evapotranspiration enough to overcome the effects of increased precipitation. The lack of direct evapotranspiration measurements in the basin creates uncertainty. Lower water levels would reduce the flood risk but could also have substantial drawbacks. A program of monitoring to validate and improve the evapotranspiration estimates could help reduce uncertainty about future low water levels.

3. The likelihood of floods around Lake Champlain and along the Richelieu River will change, and there is no consensus on how to consider climate change in flood frequency estimation to support the regulation of development in flood-prone areas. Study evaluations, as well as data from the 2011 flood, have indicated that a substantial portion of the damages from very large floods occurs in areas that are outside designated "floodplains."

4. Model simulations used in the Study can be used to help explain how snowpack and rainfall affect flooding. In particular, visualizations from these simulations can make the plausibility of greater than 2011 floods more palpable and assist in communicating flood risk.

4.1.2 Recommendations

The multiple approaches to climate modeling employed by the Study all indicated major uncertainty in future water regime with a very low (but not null) probability for larger floods than the spring flood of 2011, and the potential for more frequent and extended periods of low water levels in the lake and river. The Study has produced water supply scenarios using a variety of techniques, and that information should be made available to all interested parties. Therefore, the Study Board recommends that the IJC advise the governments to encourage decision-making bodies to consider climate change in their decision making across all aspects of flood risk management and response.

4.2 STRUCTURAL MEASURES REDUCING FLOODING (THEME 1)

Implementing a structural solution to address widespread flooding in this shared basin has been challenging, as history has shown. A structural solution (notably a dam) has been proposed twice previously and was determined to be the most technically effective measure for addressing the flooding issue (IJC 1938, 1981). Implementing this solution has either been incomplete, as in the first case, or met with opposition, as in the second case. The IJC directed the current study to focus on non-structural and only moderate structural solutions, given the history regarding the construction of a significant dam. The study explored a broad range of structural measures that could be employed to find an acceptable structural solution to mitigate the flooding issue.

The Saint-Jean Shoal is the natural control point for water levels in the LCRR system. This means that it acts as a constriction for water flow, influencing water levels upstream (Figure 21). To decrease maximum flood levels on the shoreline of the lake and the river upstream of this point, increasing the volume of water that can be passed through the shoal would be key.

Figure 21. Aerial view of the Richelieu River at Saint-Jean-sur-Richelieu, looking downstream.

The structural measures evaluated for this study were identified from past IJC reports, ideas put forth by residents and organizations in the basin, and a scan of potential innovative structural measures implemented outside of the basin. The different structural measures identified are generally captured under four general categories (FMMM & HHM, 2021):

1. addressing human interventions in the Richelieu River (primarily removal of human artifacts, excavation),
2. application of instream flow modification structures,
3. water diversion schemes, and
4. flood-related engineering modification on the floodplain (mainly dikes and levees).

Many of the solutions that were identified are specific to the existing channel morphology, the hydraulic regime, and basin hydrology. In evaluating impacts of measures, the cumulative impacts of historical modifications on flows were considered, including historical analysis of past modifications and quantitative reconstruction of natural conditions to allow for numerical flow simulations of natural and altered states (for example, Figure 14).

Study scientists initially identified a large number of potential structural measures. Based on preliminary screening, seven potential measures were selected for consideration (FMMM & HHM, 2021).

These potential measures included various combinations of:

- selective removal of human-built structures to increase flow across the Saint-Jean Shoal,
- diverting flow through the Chambly Canal along the side of the shoal,
- installing a fixed weir (submerged flow restriction) upstream of Saint-Jean-sur-Richelieu, and
- installing an inflatable weir or bladder either upstream of Saint-Jean-sur-Richelieu or at the shoal.

For each potential structural measure considered, study scientists conducted an initial assessment of the effectiveness at reducing high water levels during major floods, using the available information and data to determine whether it warranted further evaluation.

The Study was directed by the IJC not to consider major structural works and to focus on “moderate structural works.” This eliminated further consideration of measures that involved the damming of the river. The Study, therefore, focused its attention on measures involving the selective removal of material from the river and diversion of water through the Chambly Canal, as these are considered moderate structural solutions.

Specifically, three structural measures were explored in detail (Moin et al. 2022):

1. Selective excavation of the Saint-Jean-sur-Richelieu Shoal to remove human-made features and other selected areas of higher elevation on the shoal that act as a constriction, with a permanent submerged weir to help moderate flow and avoid low water levels during dry periods.

2. Diversion of significant flow (400 m^3/s) through the Chambly Canal during flood events to increase water flows and thereby decrease upstream river and lake water levels.

3. Diversion of a moderate amount of flow (80 m^3/s) through the Chambly Canal, in conjunction with Measure 1 (selective excavation and submerged weir).

The hydraulic implications of each measure were assessed using the Study's modeling tools and 93 years of flow data, to determine the impacts that these structures could have on water levels on the Richelieu River and Lake Champlain. These evaluations included extreme high water levels (spring 2011) and the historical low water level (1964). The ISEE System was used to evaluate the structural measures against the various performance indicators, for example, the number of residential buildings that would be spared from flooding based on the water level reduction achieved with each measure. Analysis of the measures included assessment of technical feasibility, mapping natural and modified riverbed elevations, simulations of flow impacts and benefits associated with structural measures, development of thorough cost estimates, and exploration of potential operating plans. The analysis of these measures was conducted to provide a proof-of-concept design and it is recognized that additional work (e.g., detailed engineering plans, environmental impact assessment) would be required to implement any of these measures.

Each of the potential structural measures is described below. They were evaluated to determine their potential impacts, and to determine which would likely be the most effective, according to the Study Board's evaluation criteria and performance indicators.

4.2.1 Selective excavation of the Saint-Jean-sur-Richelieu Shoal with submerged weir (Structural Measure 1)

The focus of this measure was the removal of the various human artifacts located on the shoal and excavation of a portion of the shoal to increase the conveyance of the Richelieu River. This option is appealing, as it reverses the impacts of human interventions and moves the system back toward a more natural state, as determined using the reconstructed DEM of the upper Richelieu River described previously that approximates the river's state before anthropogenic changes were made (Thériault et al. 2022). Measure 1 involves the selective removal of unused human structures that remain in the river, to increase the flow volume through this section of the river (Figure 22). The plan would remove submerged dikes and an older, submerged eel trap (the visible eel trap that is a cultural landmark for the local community would not be removed).

Various excavation strategies were explored, but all resulted in the permanent lowering of water levels to varying degrees, which would be good for flood mitigation. However, they also exacerbated water levels during low flow conditions. For this reason, it was recognized that excavating alone would not be a viable solution, so efforts then focused on excavating in combination with the design of a submerged weir to mitigate the low-water impacts. The excavated material would be used to construct the weir. Figure 22 provides an overview of this measure. The excavation combined with the submerged weir would address extreme flows at both ends of the spectrum, lowering water levels during floods and selectively raising water levels at low flows.

This configuration would approximate the natural hydraulic control conditions for the shoal that existed before many of the human interventions. Figure 23 compares Lake Champlain water levels under the historical pristine state, baseline conditions, and Measure 1. The blue line depicting Measure 1 conditions closely follows the red line for the pristine state, affirming that this measure would return the river to a more natural state (Moin et al. 2022). The weir would not only compensate for the decrease in water level caused by the excavation of the shoal, but would also generally raise the water level during the summer and fall seasons, thus minimizing the possible impacts of a decrease in lake level that could also be caused by climate change.

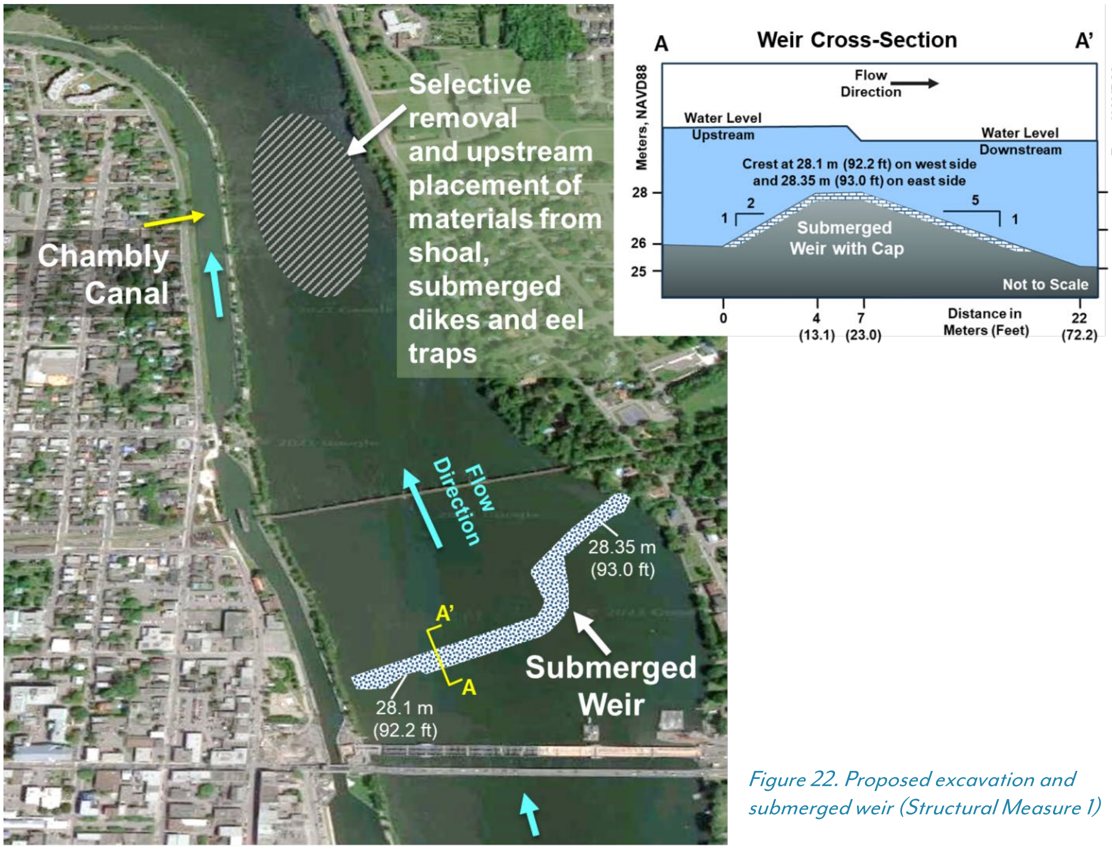


Figure 22. Proposed excavation and submerged weir (Structural Measure 1)

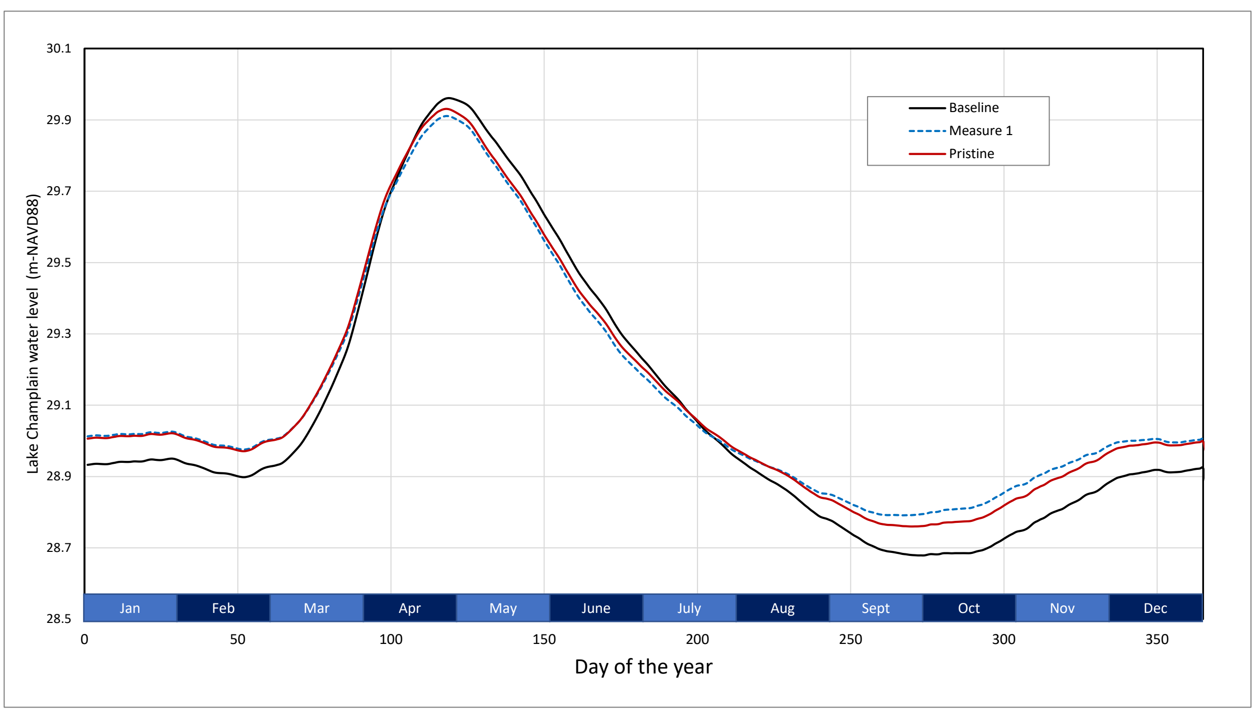


Figure 23. Comparison of Measure 1 water levels with the pristine condition (Moin et al. 2022).

For the proof of concept, the Study simulated an implementation of the measure that would involve the removal of approximately 31,310 m^3 (40,952 yd^3) from the shoal (Moin et al. 2022). The surface impacted by this activity would be about 12 ha. The human artifacts are mostly comprised of loose stone and fill, and the shoal is made up primarily of unconsolidated material that can be easily excavated. Of the 31,310 m^3 (40,952 yd^3) about 25 percent or 7,740 m^3 (10,124 yd^3) would be deposited immediately downstream of the submerged weir where the bed had been extensively dredged and lowered in 1939 (Moin et al. 2022). Approximately 9,000 m^3 (11,770 yd^3) of the material would be removed from artifacts; the remainder, about 22,000 m^3 (22,775 yd^3), would be scraped from the shoal. The average depth of material to be removed would be approximately 30 cm (11.8 in), and the overlying depth of water in this stretch of the river would vary between 1.5 and 4.5 m (5 and 15 ft), depending on the time of year (Moin et al. 2022). Based on the Study's analysis, this measure would cost about CDN$8 million (US$6 million) to implement. The total annualized cost over 50 years, including operation and maintenance, was estimated as CDN$336,000 (US$252,000)[18].

The combination of the selective removal of human artifacts on the shoal with the placement of the submerged weir at the optimal location would achieve two hydraulic conditions. 1) Raising the base water level with a new weir near Saint-Jean-sur-Richelieu will prevent excessively low flow during dry conditions, and 2) Deepening the river just downstream of the weir, where a constriction of flow between narrower riverbanks would otherwise continue to cause LCRR flooding, will increase the rate of water flow through the river, reducing water levels and flooding in the LCRR. The removal of the material on the shoal would improve the current flow constriction and increase the conveyance capacity of the river, thereby allowing more flow through the river and decreasing water levels. This also would result in a lower water level at Rouses Point, as anytime there is an improvement in river channel conveyance, there is a consistent drop in the water levels for the entire reach (in this case, between Rouses Point and the shoal at Saint-Jean-sur-Richelieu) and for all flows. For medium to low flow situations in the Richelieu River, the submerged weir would provide an obstruction, thereby backing up water for all points upstream. The height of the submerged weir was adjusted during the design phase, to determine an optimum level of the weir of 28.10 m (92.2 ft). This weir height would allow for lowering of water levels during floods and selectively raising water levels for medium to low flows. However, to ensure flow in the center of the channel during low discharges and to utilize the existence of higher natural bathymetry, the proposed weir would have two different crests, 28.10 m (92.2 ft) on the west side of the channel, transitioning to 28.35 m (93.0 ft) towards Iberville on the east bank, acting as the new hydraulic control for the system.

The submerged weir would have little effect on upstream or downstream water levels under very high flow conditions, but would maintain water levels in the lake and upstream reaches, increasing levels by approximately 15 to 65 cm during very low flow conditions. Figure 24 shows the effect of Measure 1 on Lake Champlain water levels for the low water conditions observed in 1964-1965 (Moin et al. 2022).

Using hydraulic modeling results for flows below 500 m^3/s (17,657 ft^3/s), a discharge-depth relationship was developed (Figure 25). This evaluation demonstrated that even for the minimum observed flow of 59 m^3/s (2,083 ft^3/s), a depth of 28 cm (11 in) of water would be maintained over the weir (Moin et al. 2022).

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[18] Costs in this section of the report are presented in 2021 dollars, unless otherwise noted. These calculations assume a project life of 50 years and a discount rate of 3 percent.

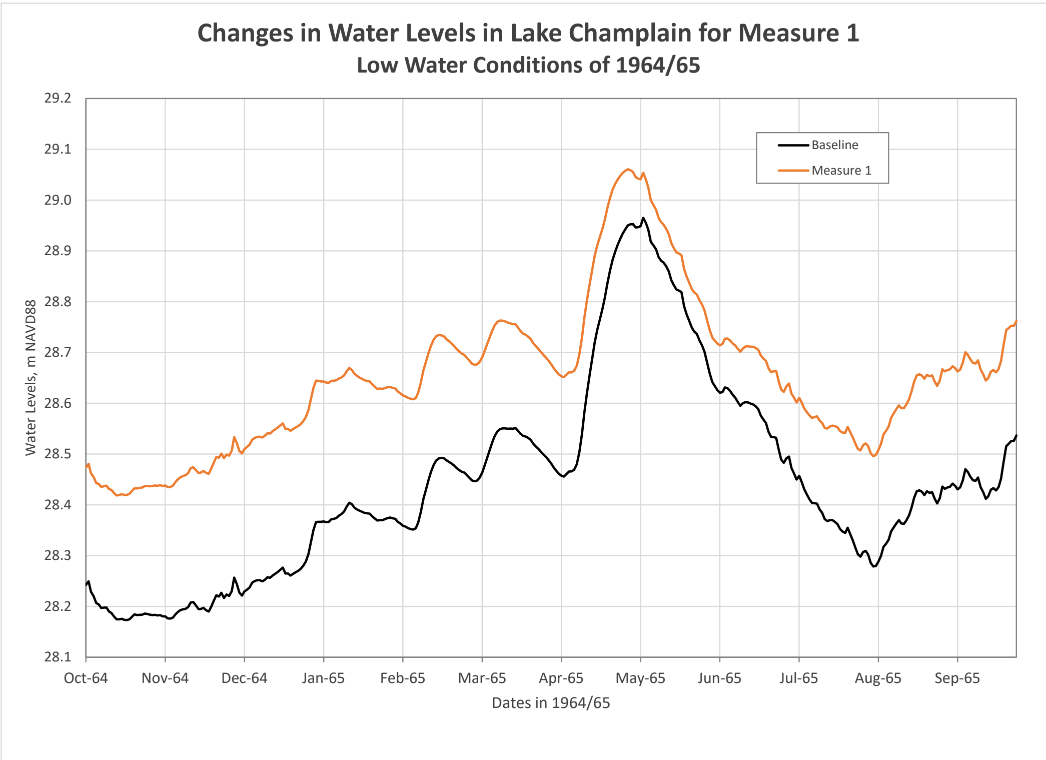


Figure 24. Measure 1 water level impacts during an extreme low-flow period (1964/65).

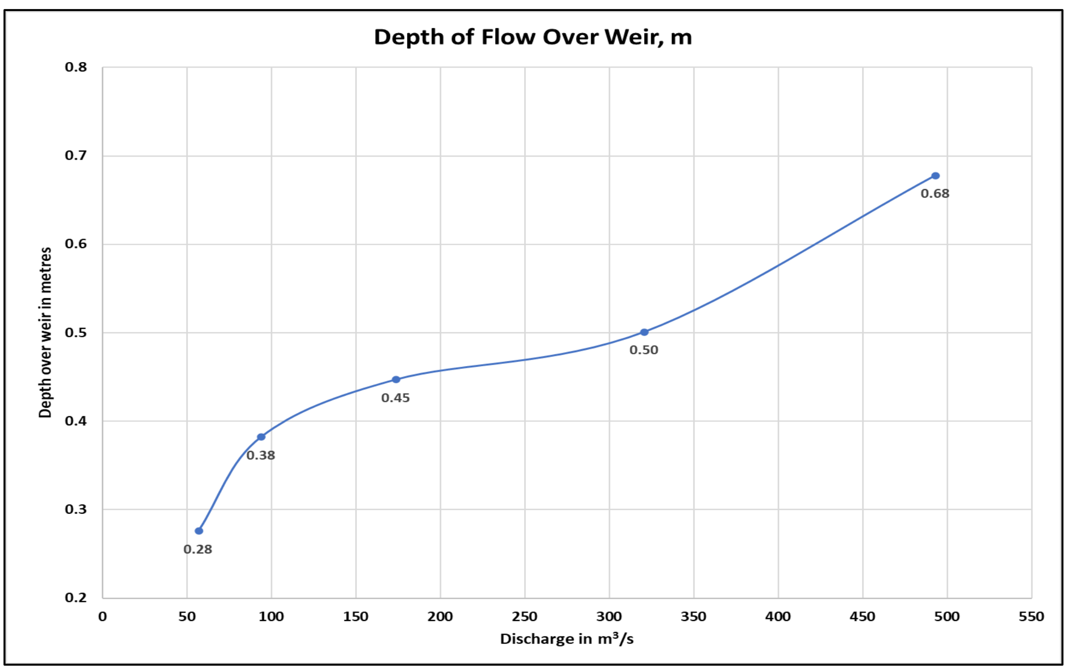


Figure 25. Depth of water over the submerged weir for Measure 1.

Figure 26 shows the water level drop across the submerged weir for different river flows. As expected, for a flow of 59 m³/s (2,083 ft³/s) is 64.7 cm (25.5 in). For a flow of 500 m³/s (17,658 ft³/s), the water level behind the weir would rise and the drop across the weir would decrease to about 20 cm (7.9 in). As the flow rate increased further, the drop across the weir would continue to decline. For example, for a flood of about 1,500 m³/s (52,973 ft³/s), similar to the 2011 event, the depth of flow over the weir would be about 2.4 m (7.87 ft) and the drop across the weir would be only 4.6 cm (1.8 in; Figure 26). For a mega-flood of 2,192 m³/s (77,407 ft³/s), the Study's highest modeled flow, the drop would be reduced further, to about 2.9 cm (1.1 in). The limits of the mesh used to hydraulically model the flow prevented simulations of any higher flows, but the drop over the weir would continue to be less noticeable as flows rose higher.

The Study's assessment determined that for a flood comparable to spring 2011 (peak discharge of 1,477 m³/s and corresponding water level of 31.23 m for Lake Champlain at Rouses Point), this measure could reduce peak water levels by 15.2 cm at Saint-Jean-sur-Richelieu and 10.7 cm (4.2 in) at Rouses Point on Lake Champlain (Moin et al. 2022). During extreme low flow conditions, this measure could increase water levels by up to 28 cm (11 in).

A key advantage of the submerged weir is that it can be constructed using the excavated materials, reducing construction costs. This material would also provide a more natural substrate for aquatic life habitat. The weir would not be visible except at extreme low flows (as noted above, a depth of 28 cm (11 in) of water would be maintained over the weir). The weir could also be easily repaired or modified pending future needs to alter the flow regime.

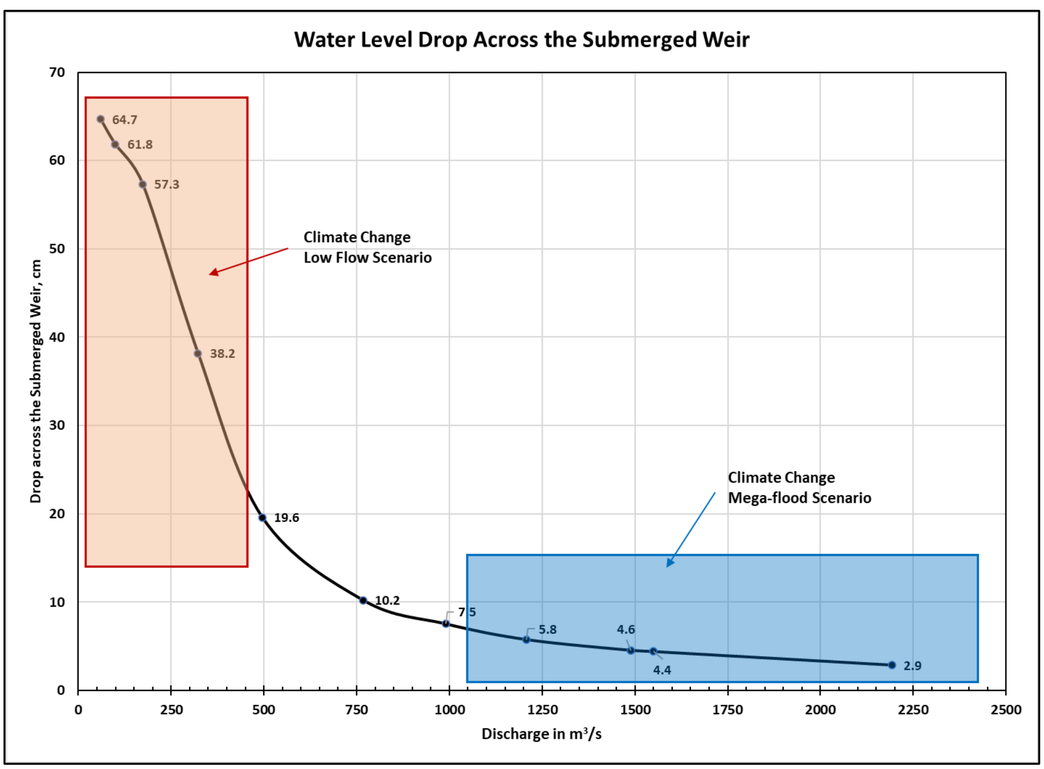


Figure 26. Water level drop across the proposed submerged weir for various river flows (Moin et al. 2022).

The Lake Champlain-Richelieu River is a transboundary water, and any water level impacts from a structural solution need to be documented for impacts at the International Boundary. The Study used 93 years of hydrologic data to assess such water level impacts. Figure 27 shows the differences between the baseline condition and Measure 1. The figure shows differences in water levels at Rouses Point over 48 quarter-months to indicate water level fluctuations over a calendar year (for example, the first four quarter-months correspond to the month of January), using 93 years of hydrologic data. The zero line means no change; positive values indicate water levels increased at the border and negative values determine the period when the water levels would be decreased, as compared to the baseline condition. The figure also captures other statistics that indicate about 62 percent of the time, water levels would be raised, and 38 percent of the time they would be lowered by various amounts. Most of the decrease would occur in the spring (quarter-month 14 to quarter-month 26), and from late summer to the following spring, the water levels would be increased. Noted exceptions are the wetter (for example, the maximum levels shown by the orange dots) and drier (minimum levels shown by the green dots) periods when the water levels would be either lowered or raised throughout the period (Moin et al. 2022).

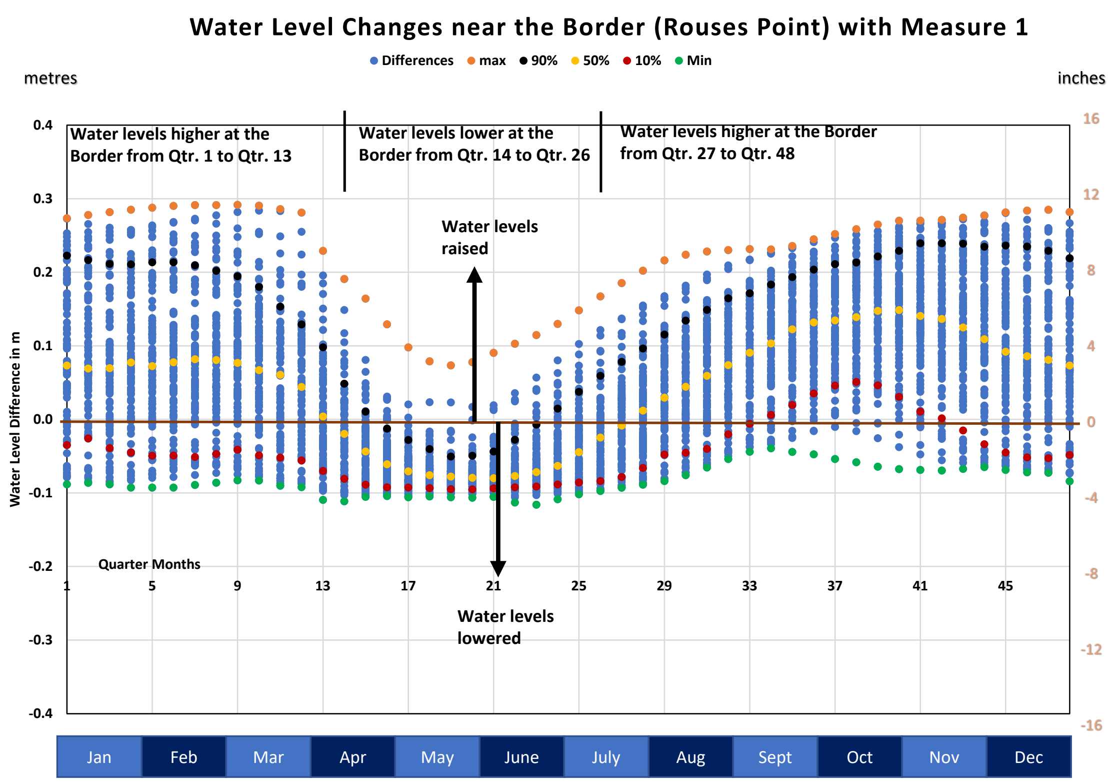


Figure 27. Water level changes near the Unites States-Canada border associated with Measure 1.

4.2.2 Optimized Chambly Canal diversion (Structural Measure 2)

Structural Measure 2 explored modifying the Chambly Canal to maximize the capacity to divert flow, with a design capacity for the canal set at 400 m^3/s (14,125 ft^3/s). This scheme reflects what would be hydraulically possible in terms of a major diversion. The diversion scheme (Figure 28) would require excavation of the river channel, reshaping and reinforcing the canal walls and installing various gates to control the flows. Under this measure, a considerable amount of flow would be diverted through the Chambly Canal during the spring high-flow season.

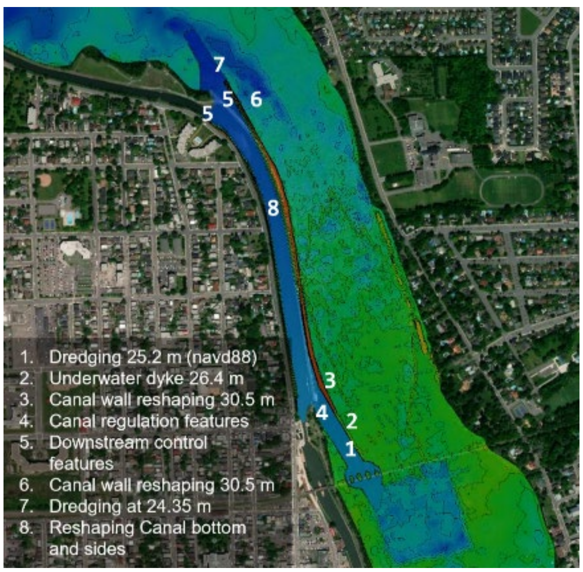


Figure 28. Proposed river diversion under Structural Measure 2.

To sustain flows of this magnitude, the slope of the canal would need to be adjusted by excavating the channel. In total, the Study estimated that 126,516 m^3 (165,477 yd^3) of material would have to be excavated from the river for this measure. The capital cost for this measure was estimated between CDN$83M and CDN$113M (US$62M-$85M). Total annualized costs over 50 years, including operation and maintenance, were estimated at CDN$4.9M (US$3.7M)[19].

Several diversion options were considered for the operation of the gates in developing Measure 2, including:

- **Based on the water level at Rouses Point**: The diversion would be operated when the water level reaches flood stage, 30.5 m (100.06 ft), corresponding to a flow of about 1,130 m^3/s (39,904 ft^3/s).
- **Using a set date**: The diversion would be operated starting on a particular date each year. This date was set to March 15 for the assessment.
- **A theoretical operational design**: Based on the historical record, a "perfect forecast" simulation was conducted to identify the best-case scenario.

To assess the potential benefits of this measure, the "perfect forecast" scenario was used. For the 2011 flood condition, Measure 2 would have provided reductions in peak water levels of 34.3 cm (13.5 in) in Saint-Jean-sur-Richelieu and 22.1 cm (8.7 in) at Rouses Point on Lake Champlain. Because the diversion structure would remain closed except at high flows, there would be no impact at extreme low water levels (other than slight differences due to the changes in bathymetry occurring as a result of channel excavation for the diversion design). At the International Boundary, using 93 years of hydrologic data, this measure was predicted to raise water levels about 60 percent of the time (though by less than 2 cm), and lower levels about 40 percent of the time, usually during the periods when the diversion would be operated.

[19] These calculations assume a design life of 50 years and a discount rate of 3 percent.

However, it would also be much more costly than Structural Measures 1 and 3 and there would be significant technical challenges to implementing this measure. For example, the historical designation of the canal could present design issues that would affect the feasibility of this measure. The high anticipated water velocities associated with the diversion would require reinforcement of the canal or restrictions on the amount of flow that can be diverted. Measure 2 would only lower water levels during periods of high flooding, and would be used infrequently. Measure 2 would also generate temporary increases in water level downstream of Saint-Jean-sur-Richelieu following the opening of the canal gates, leading to a potential increase in flood damage in the downstream river reach (Roy et al. 2022).

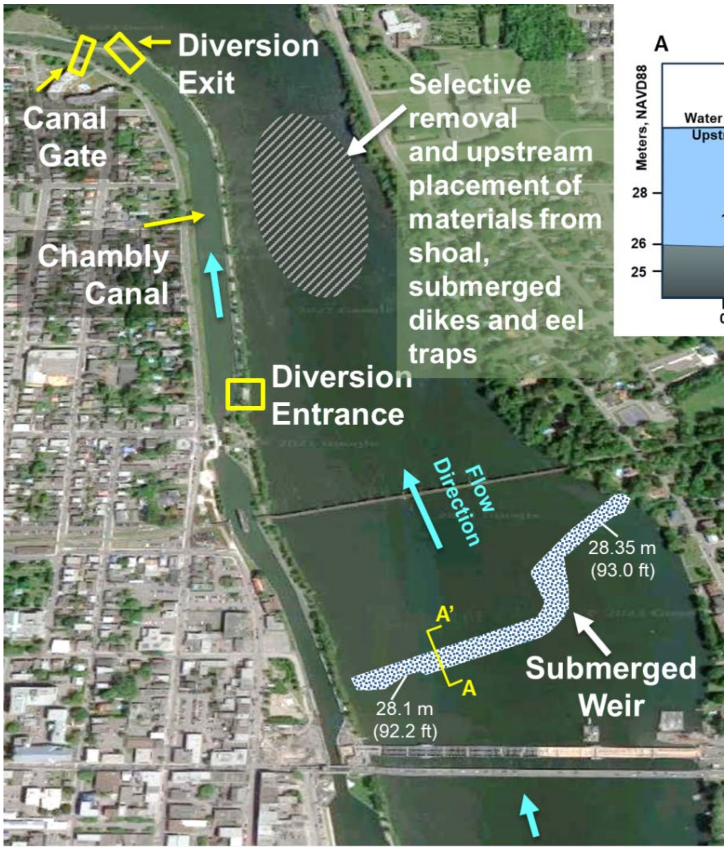
4.2.3 Modest flow diversion through the Chambly Canal and selective excavation on the Saint-Jean-sur-Richelieu Shoal with submerged weir (Structural Measure 3)

This measure builds on Structural Measure 1 and adds a modest diversion through the Chambly Canal north of Lock #9 in Saint-Jean-sur-Richelieu[20]. As for Measure 1, Measure 3 includes the selective removal of unused human structures that remain in the river, to promote faster flow through this section of the river (Figure 29). The plan would remove submerged dikes and an ancient, submerged eel trap (the visible eel trap that is a cultural landmark for the local community will not be removed). In addition, a submerged weir would be installed to mitigate low-water impacts. The excavation combined with the submerged weir would address extreme flows at both ends of the spectrum, lowering water levels during floods and selectively raising water levels at low flows.

Measure 3 would add a moderate diversion, which would consist of two sets of box culverts with gates[21]. These would be placed in the dike system separating the river from the canal. For the proof of concept, it was proposed to divert about 80 m^3/s (2,825 ft^3/s) of flow through the canal during flood conditions. The overall scheme is shown in Figure 29. As noted previously, the analysis of these measures was conducted to provide a proof-of-concept design and it is recognized that additional work (e.g., detailed engineering plans, environmental impact assessment) would be required to implement any of these measures. Gates would open and close based on water levels to divert flows to the canal and route them back to the river. Once the water level near the lock reaches about 29.25 m (95.96 ft), corresponding to about 30 m (98.43 ft) NAVD88 at Rouses Point, the gates would be opened. The gates would be closed once the water level at Rouses Point drops below 29.5 m. The lift gates controlling the flow into the Chambly Canal would be large, fixed-wheel gates or roller gates, which would be raised and lowered with a hoisting mechanism. This could be done manually or could be automated using a float system.

Similar to Measure 1, Measure 3 would bring water levels closer to the historical pristine state (Figure 30), as determined using the reconstructed DEM of the upper Richelieu River described previously that approximates the river's state before anthropogenic changes were made (Thériault et al. 2022). The blue line in Figure 30 depicting Measure 3 conditions closely follows the red line for the pristine state, affirming that this measure would return the river to a more natural state (Moin et al. 2022).

[20] Note that limited consideration was given to diverting the water through Lock# 9. This was based on the results of experiments in 1979 (ICRB 1979), when vibrations were noted with a substantial diversion through the lock, and also in consideration of the historical nature of the lock structure (FMMM/HHM 2022).
[21] Note that the Study did not evaluate a minor flow diversion alone, without the excavation and weir. There may be other diversion possibilities that could be considered in future evaluations.



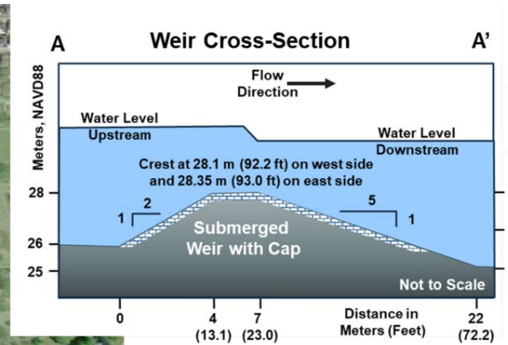


Figure 29. Proposed excavation and submerged weir (Structural Measure 3).

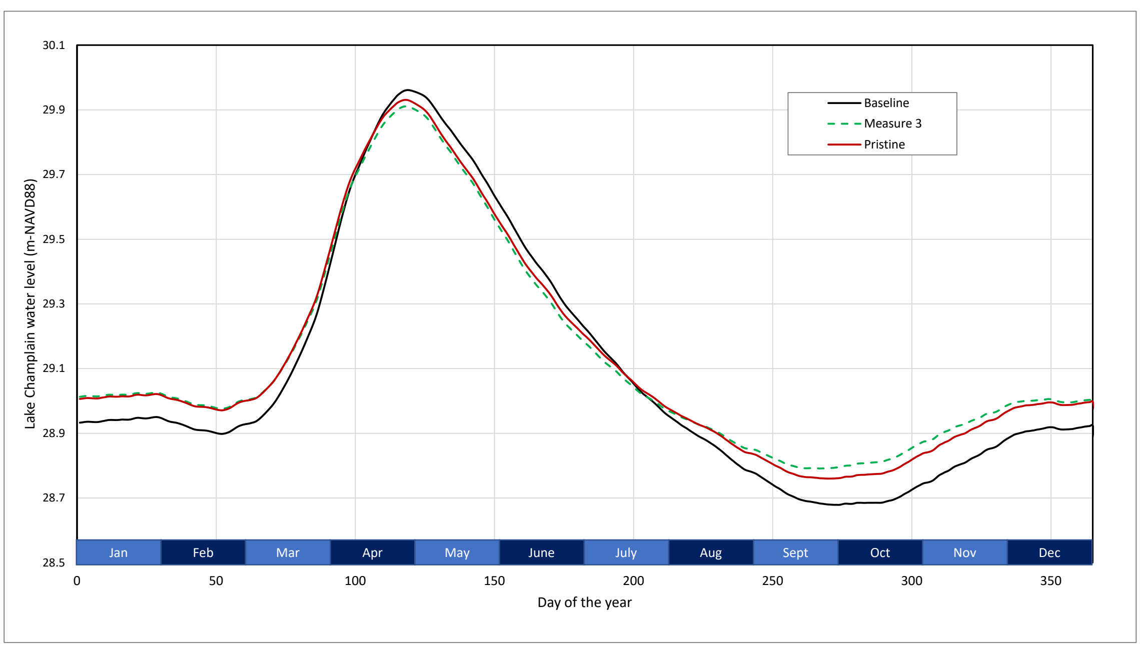


Figure 30. Comparison of Measure 3 water levels with pristine state (Moin et al. 2022).

The weir would not only compensate for the drop in water level caused by the excavation of the shoal, but would also generally raise the water level during the summer and fall seasons, thus minimizing the possible impacts of a reduction in lake level that could also be caused by climate change.

The water level impacts from this measure are generally similar to those of Measure 1, but with some additional flood mitigation during the flood season. This measure was estimated to cost about CDN$21M (US$15.8M) in capital costs. Annualized costs over 50 years, including operation and maintenance, were estimated at approximately CDN$916,000 (US$687,000)[22].

For this measure, the gates would be opened and closed once the water level has reached a predetermined stage. The proposed plan for operations is based on a simple principle that water needs to be diverted when the river is at or approaching flood stage. Once the water level near the lock reached about 29.25 m (95.96 ft), corresponding to about 30 m (98.43 ft) at Rouses Point, the gates would be opened. The gates would be closed once the water level at Rouses Point dropped below 29.5 m. In the model simulations used for the benefit/cost analysis, the diversion was operated in only three years-- 1993, 1998 and 2011. A second simulation tested this measure with the diversion operational in 27 years, for a total of 542 days. In this simulation, the diversion generally stopped before the start of the navigation season for recreational boating in mid-May, except for one or two events with delayed or prolonged flooding, like in 2011. If the governments further investigate the feasibility of this measure, the operating rules for the diversion should be studied in greater detail.

The river works are the same as those described in Measure 1. However, this would need to be augmented with river "training" for the modest diversion through the canal, to route the flows as needed. The bottom of the diversion culvert entrance would be slightly below the normal water level in the river. To place the culvert boxes across the dike, a section of about 40 m (131 ft) would be rendered dry using cofferdams for a period lasting no more than a couple of weeks. Once the culverts were placed and slopes were protected with riprap, the cofferdam could be removed. A similar operation for installing the exit culverts would be required.

As with the other measures, Measure 3 was assessed for its potential water level reductions for the Spring 2011 flood. In addition to the reduction in water levels resulting from Measure 1 activities (removing material from the shoal and installing the submerged weir), Measure 3 would provide additional water level reduction when the canal diversion was open. For 2011 conditions, this would have occurred for a period of two months, from April 14 to June 14, when the water level/flow combination met the threshold for part of the flow to be diverted. The corresponding reductions in peak water levels would have been 22.3 cm (8.8 in) in Saint-Jean-sur-Richelieu and 15.2 cm (6 in) at Rouses Point on Lake Champlain. Throughout the period the diversion was in operation, Measure 3 would have provided better relief than Measure 1 by about 7 cm (3.2 in) in Saint-Jean-sur-Richelieu and 4.5 cm (2 in) on the lake (Moin et al. 2022). This measure would have the same impact on low water levels as Measure 1, increasing water levels by up to 28 cm (11 in) during extreme low flow conditions. Similar to Measure 1, about 62 percent of the time, water levels at the International Boundary would be raised, and 38 percent of the time they would be lowered by various amounts, but more than for Measure 1. Most of the lowering would occur during high flow periods in the spring when the gates would be open, while increased water levels would generally occur beginning in late summer (Moin et al. 2022).

[22] These calculations assume a design life of 50 years and a discount rate of 3 percent.

4.2.4 Assessment of structural measures

The three structural measures were compared based both on their relative effects on water levels, and against performance indicators and decision criteria. Table 4 compares the costs of the three measures, their effects on high water levels and low water levels[23], and their effectiveness in reducing both the number of flooded homes and the overall amount of damages during the spring 2011 flood.

Over the reference period (1925-2017), the number of years when the water level would reach the minor flood threshold at Saint-Jean-sur-Richelieu would be reduced from 19 years to 2 years with Measure 2 and to 11 years with Measures 1 and 3. Similarly, the number of years that Lake Champlain would exceed flood level thresholds would be reduced from 37 to 18 years with Measure 2 and to 30 years with Measures 1 and 3. In most years, the flood mitigation measures would not significantly affect water levels downstream of the Saint-Jean Shoal. However, gate opening of the major diversion through the Chambly Canal (Measure 2) could cause temporary increases in discharge and water levels downstream that would sometimes lead to higher peak levels (Moin et al. 2022).

The three measures were the focus of Theme 1 of the Study because they were moderate structures that would only impact the extremes of the hydrograph and potentially have less impact on the environment. A structural solution that would bring the hydraulic regime closer to the early state-of-nature was appealing from an environmental perspective. Both Measures 1 and 3 would be responsive to that perspective. These measures would also help to mitigate the effects of the widening of the Chambly Canal in the 1970s. Figure 31 provides a comparison of water levels under the baseline condition, the three mitigation measures and the pristine state. Measure 2 (yellow line) closely follows the baseline (black line), while Measures 1 and 3 (dashed blue and green lines) are closer to the pristine state (red line) (Moin et al. 2022).

Table 4 includes benefit/cost ratios for each measure. Two B/C ratios are provided for Measures 1 and 3. The first (lower) ratio used the 1925-2017 water levels from ISEE to generate a set of synthetic water levels (Bouchard St-Amant and Dumais 2022). The second, higher number is based on the historical flood damages from ISEE (Moin et al. 2022). Both approaches provided useful information about benefit/cost ratios. For simplicity, annual cost numbers presented in the following sections used the CDST approach. Additional study of benefit-cost approaches and discussion of underlying assumptions may be appropriate prior to implementation of particular structural measures to reduce flooding risk in the LCRR basin.

The incremental B/C ratios shown for Measure 2 and Measure 3 are the additional benefits obtained for the additional cost considered, compared to Measure 1. An incremental ratio of 0.69 for Measure 3 means that the additional benefits anticipated with the proposed additional measure are less than the additional cost required to implement that measure.

[23] It is important to note that the Study did not develop performance indicators for non-flood periods; however, public outreach activities made it clear that the impacts of low water are also of concern to many stakeholders. Increasing low flow water levels is considered beneficial for recreational boating, as shallow water can restrict access to boats and incur costs for marina owners related to boatlifts and dredging. Higher water levels during droughts and late summer can also help mitigate water warming during the summer, maintain adequate water quality and prevent algal blooms. Given the concerns about low water level impacts, the Board included a qualitative assessment of low water conditions in evaluating potential measures.

Table 4. Assessment of structural measures.

Measure Parameters	Measure 1. Selective removal of shoal material + submerged weir	Measure 2. Large Chambly Canal Diversion	Measure 3. Selective removal of shoal material + submerged weir + moderate Chambly Canal diversion
	Economic assessment		
Capital cost[1]	CDN $8M (US$6.4M)	CDN $100M (US$75M)	CDN$21M (US$16.8M)
Operation & maintenance cost	-	CDN$400,000 (US$300,000)	CDN$20,000 (US$15,000)
Total annualized cost[1]	CDN$336,000 (US$252,000)	CDN$4,887,000 (US$3,665,000)	CDN$916,000 (US$687,000)
Total annual benefits[2]	CDN $3.4M (US$2.5M)	CDN$4.7M (US$3.5M)	CDN$3.6M (US$2.7M)
Benefit/cost ratio[3]	7.98-10.11	0.95	3.33-3.96*
Incremental ratio[4]	N/A	0.45	0.69
	Water level assessment		
Decrease in Richelieu River level for 2011 flood	15.2 cm (6.0 in)	34.3 cm (13.5 in)	22.3 cm (8.8 in)
Decrease in Lake Champlain level, 2011 flood	10.7 cm (4.2 in)	22.1 cm (8.7 in)	15.2 cm (6.0 in)
Increase in Lake Champlain Level, 1964 drought (spring, fall)	7 to 28 cm (2.8 to 10.9 in)	negligible	7 to 28 cm (2.8 to 10.9 in)
	Impact assessment		
Homes saved from flooding, 2011 flood[5]	596 (15.5%)	1,175 (30.6%)	928 (24.2%)

1. Costs as presented in Moin et al. (2022), in 2021 dollars and assuming a design life of 50 years and discount rate of 3 percent.

2. Total annual benefits were determined based on expected annual damages, including residential structural damages, recreational income loss, temporary lodging costs, socio-sanitary costs, commercial income loss, agricultural yield loss, and cleanup costs, assuming a 50-year future and discount rate of 3 percent (Moin et al. 2022).

3. Two economic evaluations were completed for the Study; the first B/C value shown is from Bouchard St-Amant and Dumais (2022); the second is from Moin et al. (2022).

4. The incremental B/C ratios shown for Measures 2 and 3 are the additional benefits obtained for the additional cost considered, compared to Measure 1 (Bouchard St-Amant and Dumais, 2022)

5. Total residences spared from flooding, Canada and United States combined. The percentages shown are compared to the baseline of 3,839 residences flooded in 2011 (Moin et al. 2022).

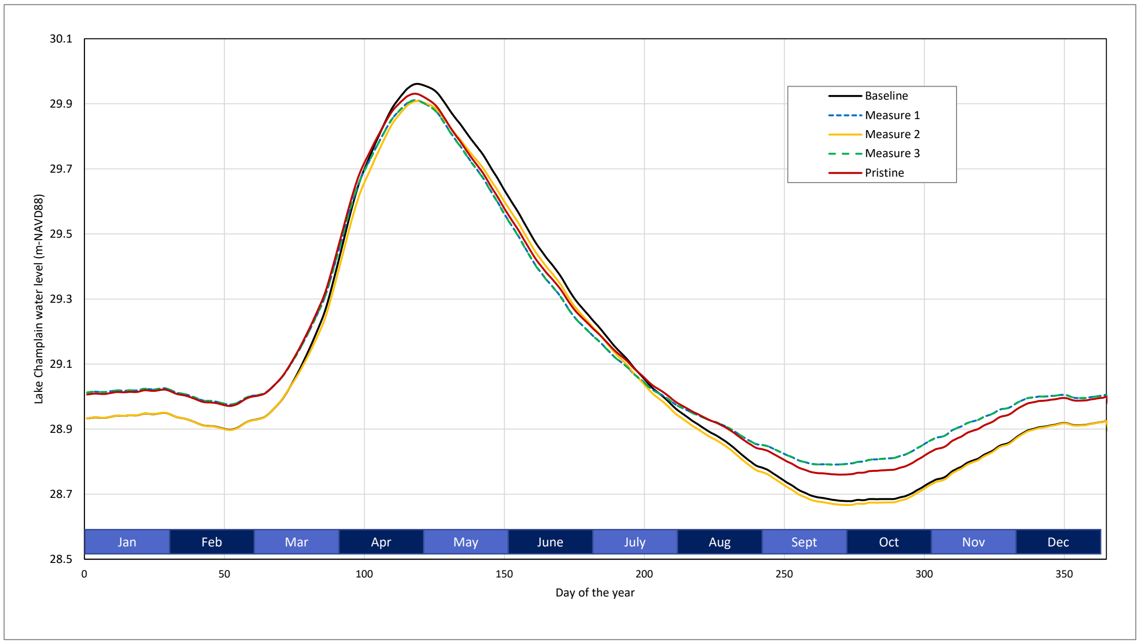


Figure 31. Comparison of Lake Champlain water levels for baseline conditions, the three mitigation measures and the pristine state for the Richelieu River (Moin et al. 2022). Note: Measure 1 and Measure 3 follow similar profiles.

Economic performance indicators

Based on the economic performance indicator analysis, results suggest that all three measures would provide reductions in flood damage. Overall, economic impacts of floods in the basin were estimated to be CDN$696M (US$522M) for the reference period (1925-2017) without flood mitigation measures (Roy et al. 2022). Over the same reference period, Measure 2 would provide the greatest reduction, with a reduction in damage of CDN$359M (US$262M; 52 percent), followed by Measure 3 with CDN$277M (US$202M; 40 percent) and Measure 1 with CDN$248M (US$181M; 36 percent). Despite providing the greatest decrease in overall damage, Measure 2 would generate temporary increases in water level downstream of Saint-Jean-sur-Richelieu following the opening of the canal gates, leading to an increase in damage of 11 percent (CDN$11M; US$8M) over the reference period (Roy et al. 2022).

Around 90 percent (CDN$630M; US$473M) of total economic impacts occur in the Canadian portion of the basin. Flood mitigation measures are the most effective in the upper Richelieu River area, where most of the damage occurs. In this portion of the basin, Measures 1, 2 and 3 would reduce damages by 43 percent, 64 percent and 47 percent respectively over the reference period (Roy et al. 2022). Measures 1 and 3 would reduce damage between Saint-Jean-sur-Richelieu and Chambly, but generally have no effect downstream of the Chambly Basin. However, on rare occasions, the measures can have a minor adverse effect in downstream reaches where the water level is slightly raised at the same time that the water level of the St. Lawrence River is high.

The residential sector is the most impacted by flooding, with 63 percent of the total damage (CDN$439M; US$329M, from 1925 to 2017). Flood mitigation measures would reduce residential damage by 42 percent (CDN$184M; US$138M), 58 percent (CDN$256M; US$192M) and 45 percent (CDN$197M; US$148M), respectively. The most important part of prevented damage is concentrated in the upper Richelieu

River area in several municipalities along the river. In the US portion of the basin, the measures are also effective, but flood vulnerability of the residential sector is low, as flood events causing substantial damage are not frequent, with 2011 the only year with residential damages exceeding $1M US.

The commercial, industrial and recreational sector ranks second in flood impacts, as it accounts for 34 percent of the total damage (CDN$237M; US$178M, from 1925-2017). Over the study area, Measure 2 reduces combined damage for the sector the most over the reference period (CDN$99M; US$74M; 42 percent), followed by Measure 3 with CDN$74M (US$56M; 31 percent) and Measure 1 with CDN$61M (US$46M; 26 percent).

The agricultural sector accounts for a minor portion of total flood damages (3 percent, CDN$18M; US$14M, from 1925 to 2017). While Measure 2 provides the greatest reduction in damage to farm buildings, Measures 1 and 3 are more effective at attenuating crop yield loss, as they provide water level decreases extending further through the critical period of the year between planting and harvest dates.

Impacts of measures on structural and material damage to public buildings are relatively minor, representing only 0.3 percent of the total damage suffered through the 1925-2017 period (CDN$1.8M; US$1.4M). While all of the measures would provide reductions in damages, the effects of the measures over the reference period were not statistically significant ($p > 0.05$) in most of the study area, except for a small annual increase in damages (less than CDN$1,000; US$750) in the lower Richelieu River.

Environmental performance indicators

Table 5 provides an assessment of the three structural measures against the Board's environmental performance indicators (Moin et al. 2022). The work undertaken by the Study provides a preliminary analysis of environmental impacts. Should the governments decide to implement one of the measures, it would need to undergo a rigorous environmental impact assessment and further data collection. Table 5 groups the assessment results into five categories, based on their percentage deviation from current baseline conditions, for Lake Champlain and the upstream and downstream reaches of the Richelieu River (not all PIs apply to each area of the LCRR, and thus some of the sections of the table are blank). Green shading indicates a positive assessment; red indicates negative; gray represents negligible change. Cells with no shading were not assessed. It should also be noted that the scores in Table 5 are averages and do not reflect natural variability.

Environmental performance indicator analyses suggest that the modification to the water level regime associated with the mitigation measures would create mostly minor positive impacts (Table 5). For instance, by decreasing water levels in the spring in years of high water levels, the measures provide more suitable depths in the upper river for Northern Pike spawning and waterfowl staging habitat during spring migration. Changes are also beneficial to Least Bittern (an endangered heron) optimal nesting habitat and muskrat lodge suitability in the winter. Furthermore, models do not predict important long-term changes in average riverine and lacustrine wetland area. However, Measures 1 and 3 might cause a slight shift in wetland class distribution in the upper Richelieu River, with a decrease in submerged aquatic vegetation and an increase in marsh and swamp areas. Regarding the effect of the measures on the spawning and early larvae development habitat of the Copper Redhorse, an endemic and endangered fish species, it is not possible to quantify the impacts of the measures due to a lack of high-resolution bathymetric data at critical locations, especially in the Chambly Rapids. Measures 1 and 3 have the ecological advantage of bringing the water level regime closer to its natural state, before multiple anthropogenic modifications were made to the Richelieu River (Roy et al. 2022).

Table 5. Assessment of environmental performance indicators for structural measures (Roy et al. 2022).

	Measure 1			Measure 2			Measure 3		
	Lake	RR up	RR down	Lake	RR up	RR down	Lake	RR up	RR down
Wetlands (marshes and swamps)									
Wetlands (all types)									
Submerged vegetation									
Northern pike spawning area									
Copper redhorse spawning area									
Waterfowl migration habitat									
Least bittern nesting habitat									
Muskrat survival									
Spiny softshell turtle nesting									

Legend:

Increase by 5% or more	*Increase between 2% and 5%*	*Between 2% increase and -2% decrease*	*Decrease between -2% and -5%*	*Decrease by -5% or more*

Indigenous performance indicators

The Study worked closely with Indigenous communities in the basin to address their interests and concerns through the selection of performance indicators. Three performance indicators were selected for this purpose: black ash, which has cultural uses such as basket weaving; wild rice, a cultural food source; and archeological/sacred sites, affecting historic cultural preservation. Several of the environmental performance indicators (wetlands, Northern Pike spawning area, Copper Redhorse spawning area, waterfowl migration habitat and muskrat survival) are also of interest to Indigenous groups; Table 5 summarizes the potential impacts of the mitigation measures on these PIs.

Table 6 presents the impacts of each structural measure on the Indigenous community PIs, using the same color-coded system as used in Table 5. None of the three measures produce negative impacts. Although the black ash performance indicator shows positive results based on an increase in desirable habitat available under the measures, it should be noted that black ash establishment, survivability and reproduction are complex, and the ideal physical-mechanical properties for basketry are not yet fully understood from a wood science perspective (Roy et al. 2022).Based on the performance indicator analysis, the following key points can be made concerning the effects of the flood mitigation measures: the submerged weir (Measure 1), the Chambly Canal diversion (Measure 2) and the submerged weir with minor diversion (Measure 3):

- All three measures would increase basket-grade black ash habitat in the Canadian portion of the study area, by reducing the length of the flooded period. However, even if increasing habitat area might be beneficial for the species, it does not mean that the population will increase in a short period of time, since the habitat availability is not considered as the most critical limiting factor preventing black ash colonization.

- All three measures would increase wild rice survival in Lake Champlain, by reducing water levels during the germination period, and reducing the amplitude of water level decreases between the germination and floating stages.

- The effect of all three measures on the vulnerability of excavated and potential archeological sites along the Richelieu River would not be statistically significant, meaning that no adverse impacts are anticipated.

Overall, the suggested measures have minor effects on the performance indicators that are of particular interest to local indigenous communities.

Table 6. Assessment of indigenous performance indicators for the structural measures (Roy et al. 2022).

	Measure 1			Measure 2			Measure 3		
	Lake	RR up	RR down	Lake	RR up	RR down	Lake	RR up	RR down
Black ash suitability									
Wild rice									
Archeological/sacred site vulnerability									

Legend:					
	Increase by 5% or more	*Increase between 2% and 5%*	*Between 2% increase and -2% decrease*	*Decrease between -2% and -5%*	*Decrease by -5% or more*

Climate change implications

The Study Board's decision criteria include economic viability and resilience to a changing climate. As discussed previously, the Study's climate change evaluations found that floods greater than the flood of 2011 are plausible in the future, even if average water levels are reduced. The Study, therefore, assessed the structural measures during both a drier future and rare but plausible mega-floods. This assessment focused on Measures 1 and 3, as Measure 2 was determined not to be viable based on technical and economic considerations. The Study evaluated whether Measure 1 and Measure 3 would reduce flood damages in the study area in a cost-effective manner under potential future climate conditions. Cost-effectiveness is demonstrated when benefits are greater than costs, meaning the benefit to cost (B/C) ratio is greater than one.

Climate change is expected to increase precipitation, which increases the risk of flooding, but also to increase temperature, which could increase evaporation and hence reduce flood risk. This analysis quantifies the countervailing impacts of higher precipitation and temperature to estimate which will be more influential, but there are uncertainties in that analysis. If the flood risk increases, the cost-effectiveness of the measures would increase (there would be a greater need for flood damage reduction). Climate change would undermine the finding that the measures are cost-effective only if flood risk declines in the future (less need to reduce flood damages). For that reason, the question of the robustness of the cost-effectiveness centers on the degree to which the flood risk is expected to decline under climate change.

The evaluation began by determining the reduction in flood frequency needed to reduce the benefit-cost ratios for Measures 1 and 3 to one. Next, climate projections done in the Study were analyzed to determine the percentage of results in which the flood frequencies would be reduced enough to lower the benefit-cost ratios to one or less. For example, the evaluation suggested that a 28.5 percent reduction in the 200-year flood would reduce the benefit/cost ratio to one for Measure 1, and that the chance of such a reduction occurring in the 2056-2085 time period is about 7 percent. The analysis indicated that Measure 3 will probably be cost-effective despite climate change, and Measure 1 will very likely be cost-effective (Werick 2022).

Decision criteria

The three structural measures were compared to the Decision Criteria, as shown in Table 7. Structural Measure 2, the large diversion, was determined to be neither technically nor economically viable, so was not considered further. Measures 1 and 3 met the first six criteria; the degree to which these measures are implementable requires further assessment.

Measure 1 was determined to be a very viable structural solution. It met the Study Board's decision criteria. It is a passive structure that is not very costly and that brings the hydraulic regime closer to a naturalized state while providing significant benefits. It provides water level relief for both high and low water levels. This measure provides benefits that are primarily positive for society, Indigenous peoples and the environment. No substantial negative impacts were identified. The benefit/cost ratio of this measure is close to 10.

Table 7. Economic losses by sector due to the 2011 flood, as a percentage of the total estimated damage.

	Study Board Decision Criteria						
Measure	Within study scope & mandate	Technically viable	Economically viable	Environmentally sound	Equitable and fair	Climate change resilient	Implementable
Selective excavation + submerged weir	✓	✓	✓	✓	✓	✓	Pending further jurisdictional discussions
Large Chambly Canal diversion	✓	✗	✗	Not evaluated	Not evaluated	Not evaluated	Not evaluated
Selective excavation + submerged weir + moderate diversion	✓	✓	✓	✓	✓	✓	Pending further jurisdictional discussions

Measure 3 was also determined to be a viable structural solution. It provides additional high-water relief, about 50 percent more than Measure 1, but at a greater cost and the incremental benefit/cost of adding the diversion is lower than one. This, in turn, lowered the benefit/cost evaluation, but still resulted in a value well above the break-even point (benefit = cost) at about 3 when the measure is considered globally. This measure provides a similar level of benefits as for Measure 1. Additional societal benefits would be achieved as a result of the further decrease of flood water levels.

The Study's early investigations of the political feasibility of the Theme 1 recommendations suggested limited support for large and high-cost structural interventions, and concerns about potential impacts on drought water levels, water quality and the environment (SPE 2022). The Board's evaluations took these considerations into account. Québec's new flood protection plan also restricts the use of structural measures (SPE 2022). This work also noted potential barriers to feasibility in the United States, particularly if the Boundary Waters Treaty would be triggered by implementation of the mitigation measure and if US funding is desired (SPE 2022). However, during the public comment period, the Board received generally positive feedback from stakeholders on structural measures. The structural solutions the Board is recommending were considered by the public to be moderate and realistic. Some members of the public had questions or wanted more information. Commonly, participants wanted to know more about the function, construction, and potential impact of the submerged weir, particularly what its impact on hydrology and the environment would be. Participants also voiced questions about how the diversion in Measure 3 would be managed. Some members of the public expressed concerns that the solutions proposed would not reduce flood damages enough, or that the likelihood of implementation of these solutions is low. In general, however, members of the public were encouraged by the Study's recommendation on structural solutions.

4.2.5 Water levels at the international border

The Study evaluated the impacts of potential structural solutions on water levels at the International Boundary, using 93 years of hydrologic data. Figure 32 summarizes the results for high flows, using the 2011 flood conditions. This figure shows the water level surface profile from the border (shown on the left) to the Saint-Jean Shoal area, shown on the right, during a flood. The baseline water level is shown in black, Measure 1 in red, and Measure 3 in blue. (Note that Measure 1 and Measure 3 would have similar impacts at some locations, and the red and blue lines can be hard to distinguish.)

Figure 33 similarly depicts a water level profile from the border to the Saint-Jean Shoal area during low flow conditions. These profiles show that the proposed structural measures would raise water levels at low flow above the baseline condition. (Note that the two measures have very similar impacts on water levels, and thus, the Measure 1 and Measure 3 lines are indistinguishable.)

The Study's modeling indicates that the proposed mitigation measures would change the water level regime at the border, with water levels raised about 62 percent of the time, and lowered for the other 38 percent. Most of the lowering would occur in the spring, while increased water levels would generally occur beginning in late summer (Moin et al. 2022).

Article IV of the Boundary Waters Treaty 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."

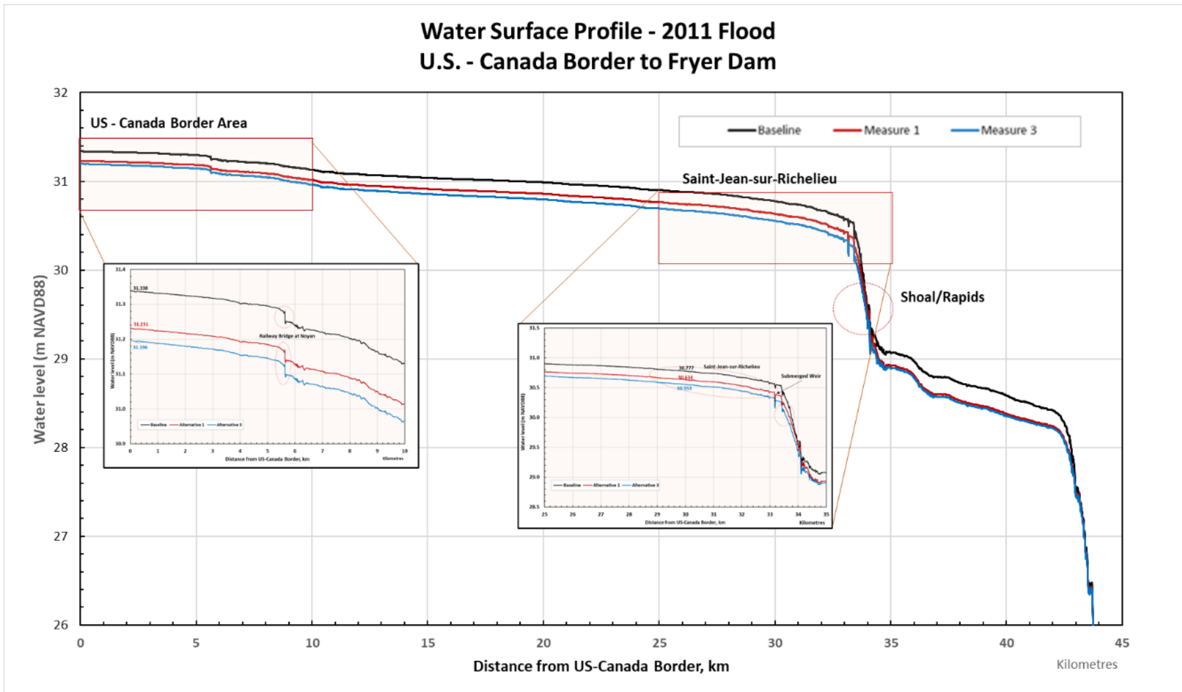


Figure 32. Impacts of Measures 1 and 3 on water levels at the US-Canada border, 2011 flood condition.

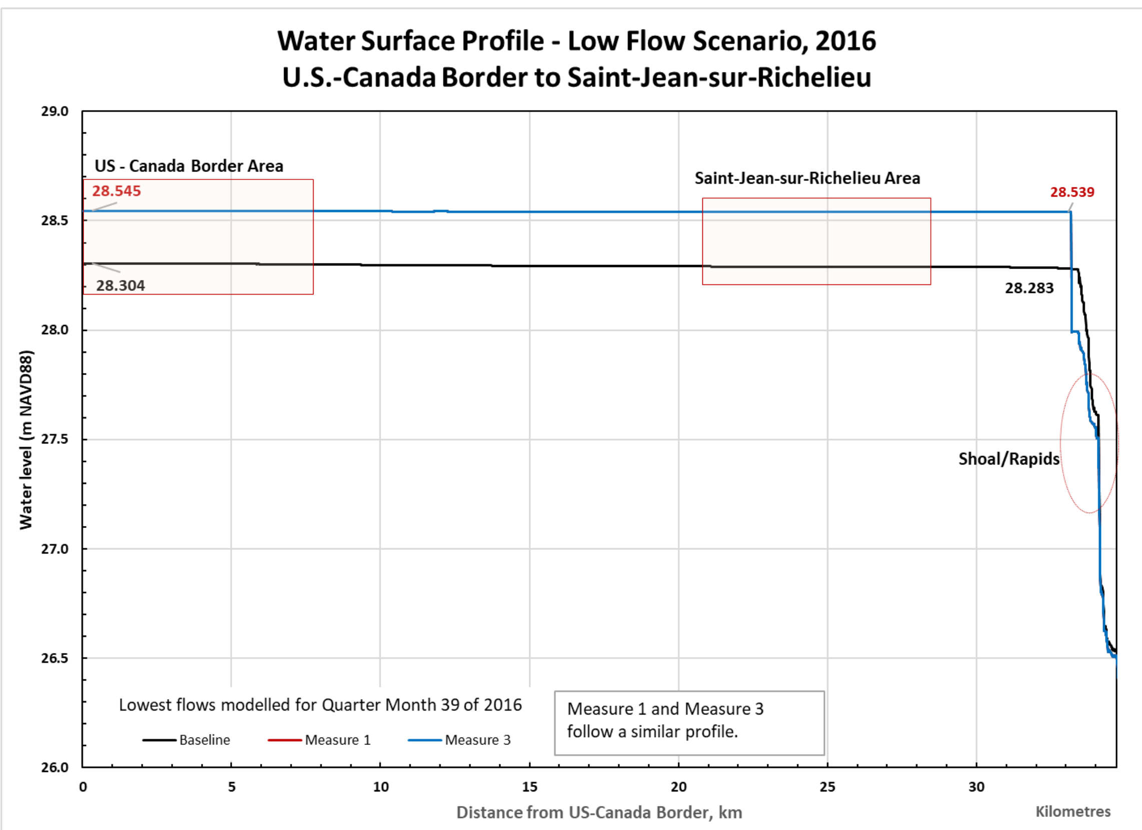


Figure 33. Impacts of Measures 1 and 3 on water levels at the US-Canada border, low flow conditions (2016).

Measures 1 and 3 would both have the potential to raise the natural level of waters at the international boundary. If a proponent (e.g., province of Québec, federal government agency) intends to proceed with Measure 1 or Measure 3, an application to the governments may be required under the Boundary Waters Treaty. The governments may then consider the application and whether approval for the project is needed under the Treaty. If approval is needed, governments may review and approve the effects themselves via special agreement, or they may forward the application to the IJC for review and approval. In either case, the federal governments would consult closely with the Province of Québec and the States of Vermont and New York.

4.2.6 Recommendations

The Study Board recommends the IJC advise governments that it is possible to achieve a modest relief of flood (on the order of 10 cm on the Lake and 15 cm at Saint-Jean-sur-Richelieu for an event like the spring 2011 flood) and drought water levels by returning the hydraulic regime at the Saint-Jean-sur-Richelieu shoal to a more naturalized hydraulic state. This can be achieved by removing some flow-impeding human artifacts in addition to some selected excavations of the shoal and installing a submerged weir in the area, upstream of the Saint-Jean-sur-Richelieu shoal (Measure 1).

If desired, additional flood relief can be gained through combining the removal of the artifacts, selected excavations of the shoal, and the submerged weir with a modest water diversion through the Chambly Canal (for a total peak water level reduction of 15 cm on the lake and 20 cm at Saint-Jean-sur-Richelieu for an event like the spring 2011 flood, Measure 3). While this alternative that includes the Chambly Canal water diversion is less economically performant, this addition brings greater water level relief for larger flood events and should be presented to the governments for their considerations.

From the Study's evaluation of the proofs of concept, the Study Board is of the opinion that these moderate structural solutions are technically feasible, and socially, and economically acceptable. A limited environmental review on both potential structural solutions was conducted that indicated encouraging results.

If the governments decide to implement a structural solution, a process should be put in place to analyze binational social, political, environmental, legal, and economic implications of the final structure design and operation.

The Study Board recommends that the IJC encourage the governments to implement a binational governance mechanism to oversee the implementation and operation of any structural solution the governments may opt to pursue. Functions of a binational governance mechanism for Measures 1 or 3 would include, among others:

- Binationally defining the final design and performance requirements of the submerged weir and removal of shoal material
- Designing and implementing a binational adaptive management (AM) program
- Enabling a binational decision-making process in response to the binational AM program

In addition, the following functions apply to Measure 3:

- Binationally defining the final design and performance requirements of the Chambly Canal diversion
- Implementing a binational water management plan associated with the final design
- Overseeing the application and decisions associated with the operation of the diversion

4.3 UPSTREAM (WATERSHED) STORAGE TO IMPEDE FLOWS AND REDUCE FLOODING (THEME 2)

Located at the interface between terrestrial ecosystems and water resources, such as watercourses and shallow water tables, wetlands are an important part of the drainage network. They affect the routing of overland and subsurface flows through modification of hydrological processes, including increased evapotranspiration, water storage and groundwater recharge. These interactions have led researchers and land planners to link some hydrological services to wetlands, namely flow regulation as highlighted by amplifying low flows and attenuating high flows. For watersheds with recurrent floods, the natural water storage capacity of wetlands becomes an important asset.

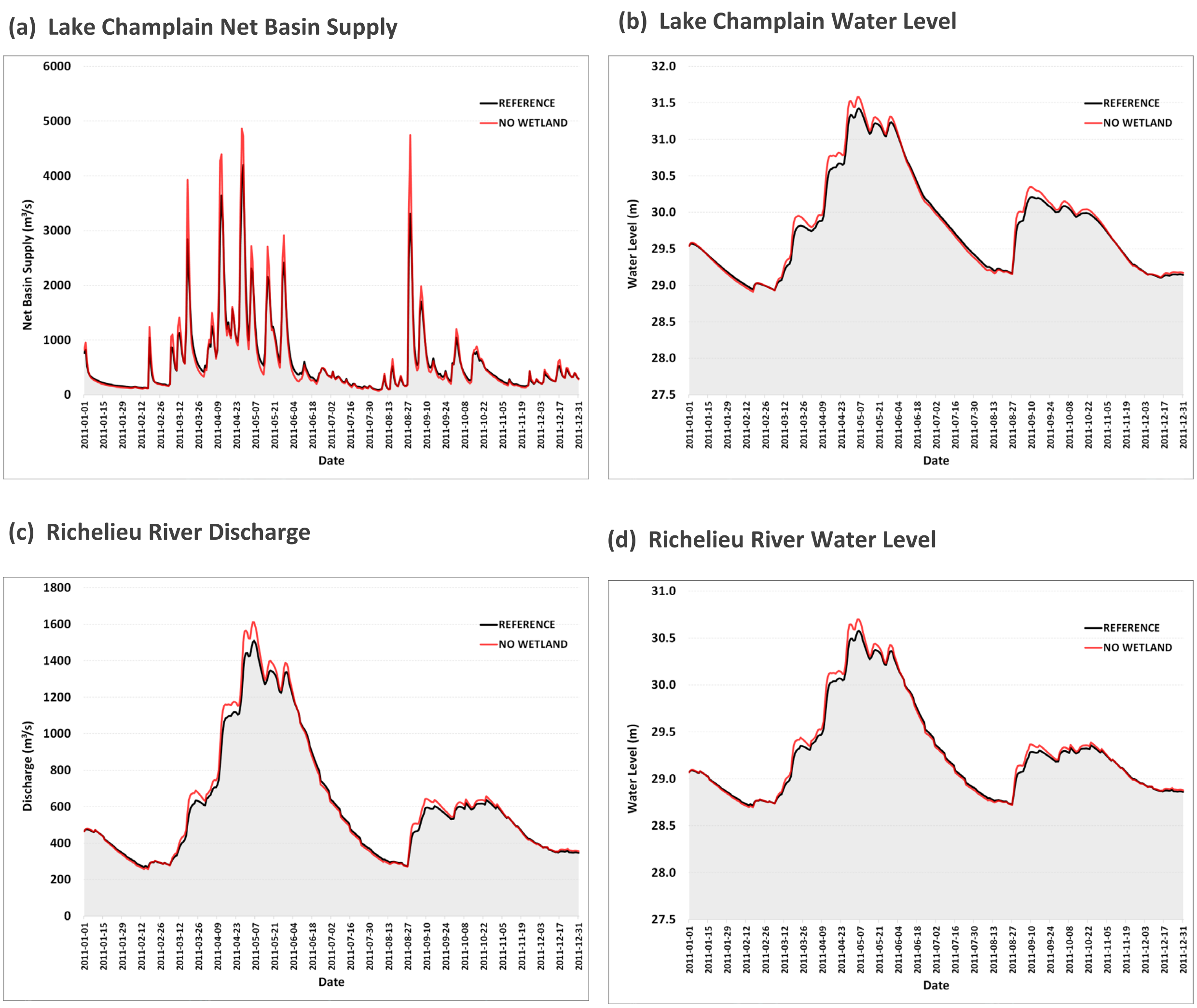
Several approaches could provide flood mitigation for protecting critical areas in the LCRR basin (Rousseau et al. 2021):

- allowing water to naturally be reconnected with the flood plain as stage rises above riverbanks or shorelines (i.e., active-passive storage);
- allowing water to be retained naturally into specific landscapes or water bodies (i.e., passive storage); and
- directing water using gates, dikes, canals and other structures to ensure a pre-determined amount is conveyed to pre-delineated lands and away from areas to be protected (i.e., active storage).

Creation/restoration of wetlands on the LCRR landscapes has been discussed as a passive storage approach to reduce both peak flows, and to a lesser extent, runoff volumes. Hydrological modeling studies have shown that wetlands generally reduce flows on the rising limb of a storm hydrograph, dampen the peak flow and slightly increase flows on the recession limb (Rousseau et al. 2021).

The Study investigated the effects of passive and active approaches to flood mitigation in the LCRR basin. Specifically, this investigation assessed the potential of (i) storing floodwater on riparian agricultural landscapes, and (ii) using existing, restored, and constructed wetlands of tributaries in the Vermont and New York sub-watersheds to reduce runoff volumes, peak flows and net basin supplies to Lake Champlain. Note that the Study mandate focused on Lake Champlain and the Richelieu River and did not include addressing local tributary flooding.

The Study's hydrological modeling platform, PHYSITEL/HYDROTEL, was used in these evaluations (Rousseau et al. 2021) to quantify the hydrological services (flow regulation) provided by the 1,551 km^2 of existing wetlands located in the Lake Champlain basin. Existing wetlands play a key role in attenuating high flows and flooding and also augmenting low flows in the LCRR sub-watersheds. Thus, wetlands affect daily Lake Champlain inflows and water levels, and indirectly modify water levels and discharges in the Richelieu River. Model simulations clearly demonstrated that wetlands provide flow and water level attenuation services downstream during high flow events. The Study assessed the potential impacts that might have occurred during the 2011 flood had the wetlands not existed. Figure 34 presents the simulated 2011 hydrographs for both the baseline (existing) condition, and without the presence of wetlands.



**Observations are displayed in black and simulations in red.*

Figure 34. Impact of an absence of wetlands on Lake Champlain inflows (Net Basin Supply) and water levels, and Richelieu River flows and water levels for 2011 conditions.

The Study's results indicated that existing wetlands can reduce, on average, the annual high flow of the 20 Lake Champlain tributaries by 9 to 52 percent (Table 8; Rousseau et al. 2021). These reductions in the tributary flows reduce inflows to Lake Champlain and the Richelieu River, and result in reductions in annual high water levels in Lake Champlain (12 cm; 4.7 in) and the Richelieu River (9 cm; 3.5 in). For the Spring 2011 flood, Lake Champlain peak water levels would have been 15 cm higher and Richelieu River peak levels 12 cm higher without the presence of the existing wetlands, as shown in Table 9 (Rousseau et al. 2021). Existing wetlands also contribute to low flow amplifications. It is therefore very important to preserve and protect existing wetland areas.

Table 8. Attenuation of high flows due to current wetlands (Rousseau et al. 2021).

WATERSHED (% wetland)	ATTENUATION		
	MIN	MAX	AVERAGE
Great Chazy (14%)	16%	51%	36%
Little Chazy (14%)	25%	55%	42%
Dead Creek (24%)	32%	65%	47%
Saranac (12%)	11%	39%	25%
Salmon (8%)	16%	47%	29%
Little Ausable (7%)	12%	47%	30%
Ausable (6%)	3%	32%	17%
Bouquet (6%)	-3%	42%	23%
Putnam Creek (7%)	13%	54%	37%
La Chute (4%)	3%	22%	10%
Poultney (7%)	16%	45%	30%
Otter Creek (9%)	7%	38%	19%
Little Otter Creek (12%)	31%	67%	52%
Lewis Creek (8%)	3%	44%	26%
LaPlatte (7%)	17%	50%	34%
Winooski (3%)	3%	16%	9%
Lamoille (5%)	8%	24%	17%
Missisquoi (7%)	9%	42%	23%
De La Roche (11%)	14%	57%	41%
Aux Brochets (9%)	12%	38%	26%
Reduction in Lake Champlain inflow	***11%***	***34%***	***22%***
Reduction in Richelieu River (Fryers Rapids) flow	***4%***	***11%***	***6%***
Decrease in Lake Champlain water level (RousesPoint), cm (in)	***6 (2.4)***	***26 (10.2)***	***12 (4.7)***
Decrease in Richelieu River water level (Saint-Jean marina), cm (in)	***4 (1.6)***	***21 (8.3)***	***9 (3.5)***

Table 9. Summary of the impact of an absence of wetlands on inflows, water levels, and river discharge for the spring 2011 conditions

Wetlands	Lake Champlain Basin	Richelieu River
Area, km^2 (mi^2)	21,254 (8,206)	22,055 (8,515)
Wetlands Area, km^2 (mi^2)	1,551 (599)	1,616 (624)
Wetlands Drainage Area, km^2 (mi^2)	7,749 (2,992)	7,902 (3,051)
Increase of the highest peak (%)	15.8% (inflow)	6.7% (discharge, at Fryers Rapids)
Increase of the highest water level, cm (in)	15 (5.9)	12 (4.7), at Saint-Jean Marina

In addition to evaluating existing wetlands, the Study evaluated several scenarios involving increasing wetlands of tributaries in Vermont and New York sub-watersheds (Figure 35), as well as temporarily flooding agricultural lands to store floodwaters.

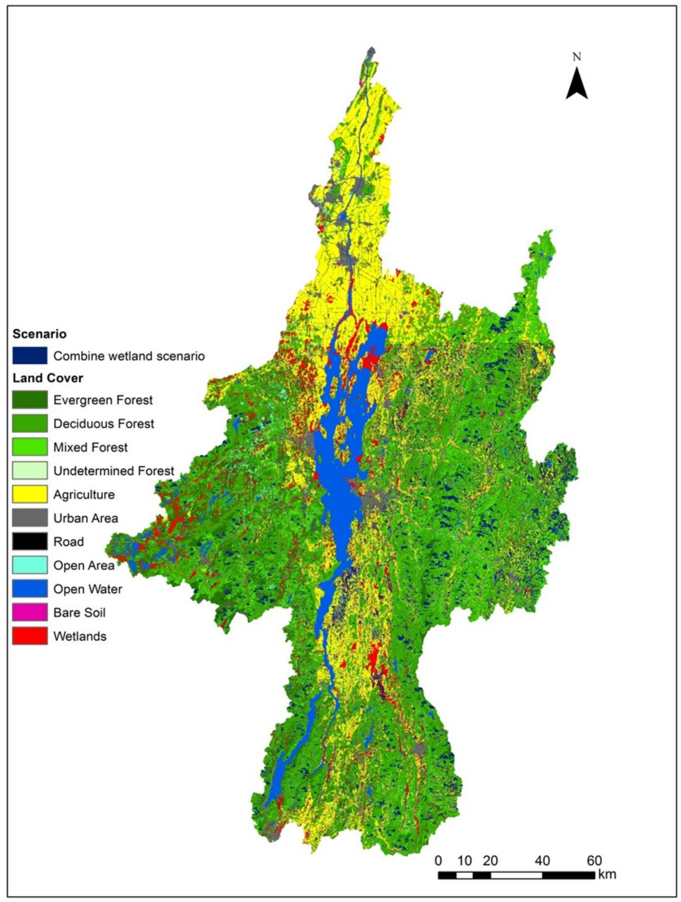


Figure 35. Areas of potential wetland storage (shown in dark blue).

To evaluate the potential effects of additional upland storage, four scenarios were developed:

1. conversion of agricultural land to wetlands within a 1,000-m (3,280 ft) buffer zone along the entire river network of the LCRR basin (cumulative area of 2,471 km^2 (954 mi^2) within the Richelieu River (at Fryers) and 2,256 km^2 (871 mi^2) for the Lake Champlain basin);

2. conversion of local topographical depressions into wetlands (adding 647 km^2 (250 mi^2) of additional wetland in the Lake Champlain basin);

3. addition of wetland areas on land having the potential of naturally accumulating water due to topography and poorly drained soils, using a dataset produced by the US Environmental Protection Agency (additional 865 $km^{2,}$ or 334 mi^2); and

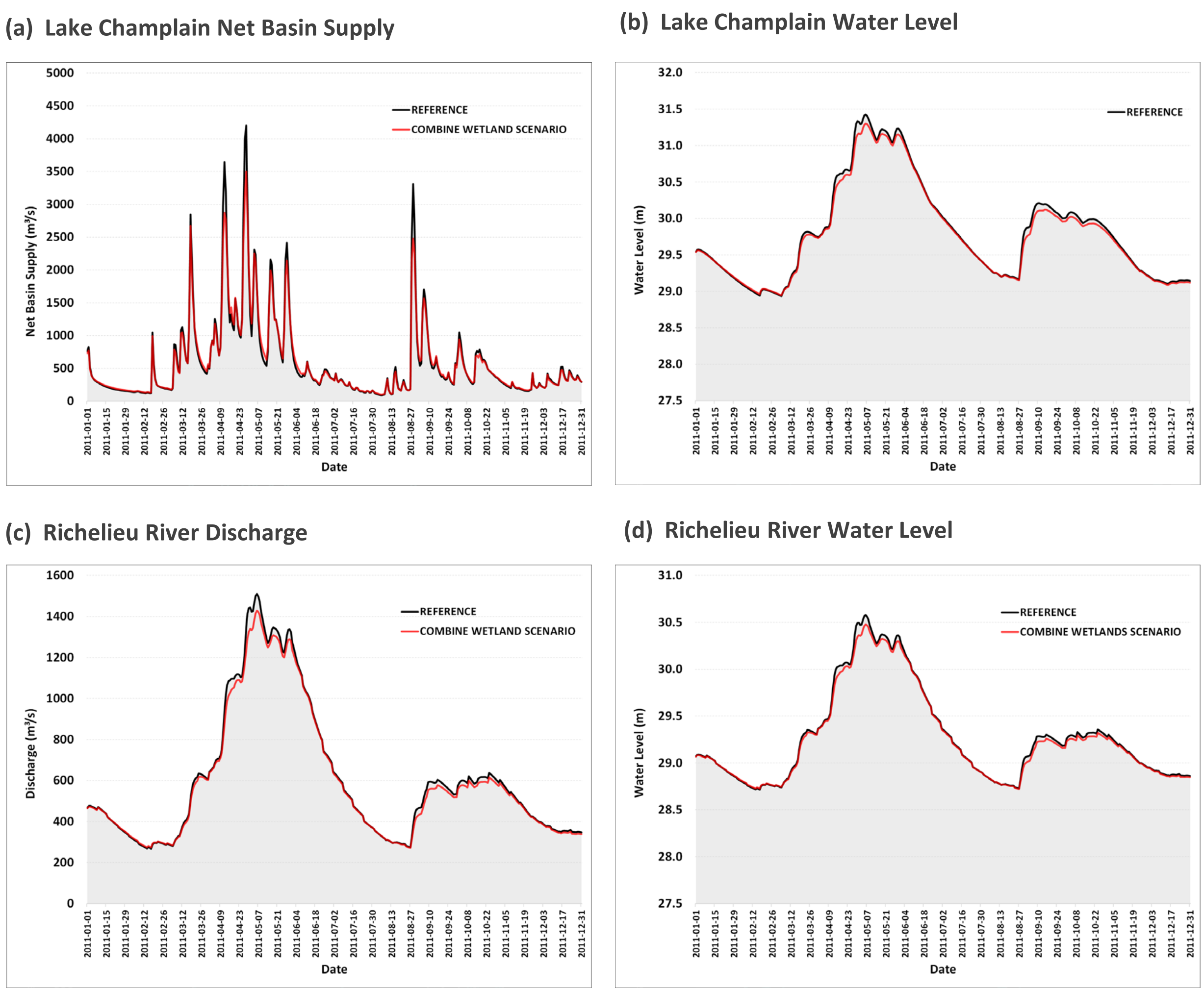
4. combining scenarios (2) and (3) (total addition of 1,493 km^2, or 576 mi^2, of new wetland area).

The four watershed storage scenarios highlighted the potential of achieving additional gains to reduce Lake Champlain inflows and water levels, and to a lesser extent, Richelieu River peak flows and water levels.

4.3.1 Assessment of watershed storage measures

The Study's modeling found that existing wetlands in the LCRR basin have a positive impact on reducing flood levels in the basin. In 2011, wetlands reduced flooding by 15 cm (6 inches) on the lake and 12 cm (4.7 inches) on the river. This means that the preservation of existing wetlands is an important consideration for land use planners in the basin, as existing wetlands are already providing water level relief during floods. The Study also examined the possibility of adding wetland area to further reduce the high water levels.

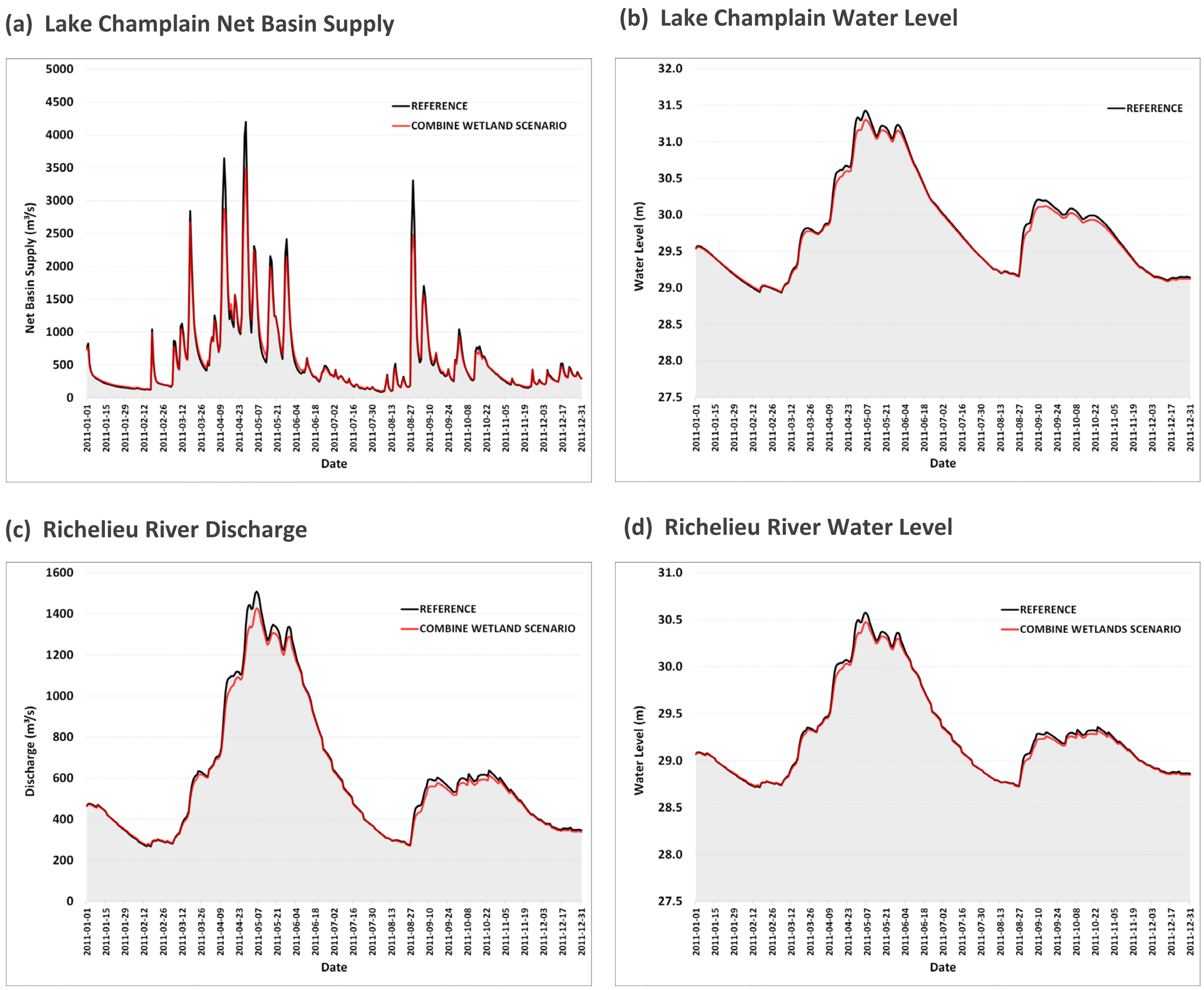
Figure 36 provides an example of the effects of adding wetland areas within the Lake Champlain watershed; specifically, the figure shows the impact of combined wetland scenarios (adding a total additional wetland area of 652 km^2 or 252 mi^2) on the Lake Champlain inflows (Net Basin Supply) (a) and water levels (b), and Richelieu River discharges at Fryers Rapids (c) and water levels at Saint-Jean Marina (d) for the 2011 conditions. Adding this wetland area could have decreased the highest water levels during the spring 2011 flood by 6 cm in Lake Champlain and 5 cm in the Richelieu River (Rousseau et al. 2021).



**Observations are displayed in black and simulations in red.*

Figure 36. Effects of adding 652 km^2 of wetlands on the LCRR basin for the 2011 conditions.

Figure 37 shows the effects of adding wetland areas within the Lake Champlain watershed; specifically, the figure shows the impact of combined wetland scenarios (adding a total additional wetland area of 1,493 km^2 or 576 mi^2) on the Lake Champlain inflows (Net Basin Supply) (a) and water levels (b), and Richelieu River discharges at Fryers Rapids (c) and water levels at Saint-Jean Marina (d) for the 2011 conditions.



**Observations are displayed in black and simulations in red.*

Figure 37. Effects of adding 1,493 km^2 of wetlands on the LCRR basin for the 2011 conditions.

This evaluation indicated that adding 1,493 km^2 (576 mi^2) of wetland area would provide additional flood relief, as shown in Table 10. The addition of this wetland area could have decreased Lake Champlain peak inflows by 16.7 percent and reduced lake water levels by 12 cm (4.7 in) during the 2011 flood. The benefits for the Richelieu River discharges would not have been as large (5.4 percent), but the reduction in water levels would have been similar (10 cm or 3.9 in). While these benefits generally fall within a similar range to the recommended Theme 1 measures, they would require an increase in wetland area larger than the surface area of Lake Champlain (1,130 km^2). The benefits of the additional wetlands would be lower during more typical flow conditions; adding 1,493 km^2 (576 mi^2) of wetlands would, on average, reduce Richelieu River water levels by only 6 cm (2.4 in) (Rousseau et al. 2021). The extensive additional wetland area required to achieve these water level reductions likely renders this measure impractical.

Table 11 summarizes the Study's estimate of additional upland storage that would be needed to provide reduction in peak flows for the 2011 flood. The table shows the additional storage areas that would be required to provide reductions in 2011 peak flows of 5 percent, 10 percent and 20 percent, for two storage depths, 50 cm (19.7 in) and 10 cm (3.9 in). Reducing the 2011 peak flow at Fryers Rapids by 5 percent would require an additional estimated 632 km^2 (244 mi^2) of wetlands with a holding capacity of 50 cm of water; this corresponds to increasing the surface area of wetlands by 39 percent in the watershed upstream of Fryers Rapids (Rousseau et al. 2021).

Further, the Study's analysis indicated that reducing the spring 2011 peak flow at Fryers Rapids by 10 percent would require an additional 1,263 km^2 (488 mi^2) of wetlands with a holding capacity of 50 cm (20 in) of water; this corresponds to increasing the surface area of wetlands by 39 percent in the watershed upstream of Fryers Rapids or by 41 percent in the Lake Champlain watershed. A similar 10 percent reduction in peak flows would require an additional 6,688 km^2 (2,582 mi^2) of wetlands with a holding capacity of 10 cm (4 in) of water (Rousseau et al. 2021). These assessments confirm that reducing the peak flow on the Richelieu River during high flow events such as the 2011 flood would require adding very large areas of wetlands. Although options other than outright purchasing of land for wetland storage exist, such as acquisition of easements, the area required to provide substantial control of flood levels in the LCRR is still quite large and likely impractical for both topographic and financial reasons.

Table 10. Effect of adding 1,493 km^2 of wetland in the Lake Champlain basin on high water levels in Lake Champlain and the Richelieu River.

	Lake Champlain	Richelieu River
Average high-water reduction	8 cm (3.1 in)	6 cm (2.4 in)
Reduction for Spring 2011 flood	12 cm (4.7 in)	10 cm (3.9 in)

Table 11. Estimation of additional wetlands or flooded riparian farmland required to reduce the 2011 peak flow of the Richelieu River at Fryers Rapids.

Assuming additional storage area at 50 cm (holding capacity					
Peak Reduction Scenario	Additional Wetlands, km² (mi²)	Percent Increase Over Existing Area		Percent of Existing Farmland Area Flooded	
		Upstream Fryers	LC Watershed	Upstream Fryers	LC Watershed
5%	632 (244)	39%	41%	17%	20%
10%	1,263 (488)	78%	81%	34%	39%
20%	2,527 (976)	156%	163%	68%	79%
Assuming additional storage area at 10 cm holding capacity					
Peak Reduction Scenario	Additional Wetlands (km²)	Percent Increase Over Existing Area		Percent of Existing Farmland Area Flooded	
		Upstream Fryers	LC Watershed	Upstream Fryers	LC Watershed
5%	3,344 (1,291)	207%	216%	90%	104%
10%	6,688 (2,582)	414%	431%	181%	209%
20%	13,376 (5,165)	828%	862%	361%	418%

The Study also analyzed the water storage capacity of agricultural land in the LCRR basin. Four different analyses were performed using different inputs and assumptions. These analyses are shown in Table 12. Analysis #1 evaluated storage for the spring 2011 flood volume, while #2-4 were applied to the average flood volumes for the LCRR. These results suggest that water storage on agricultural land of the LCRR basin could help reduce future flooding; however, large land areas would be required, particularly if the majority of floodwaters were to be stored. As shown in Table 12, storing the volume of water for an average year could be accomplished on 902 km^2 (348 mi^2) of land, but the wetland water depth would be 1 meter (3.3 ft), which is relatively high. To reduce the water depth, substantially more area would be required. These evaluations suggest that storage of large volumes of floodwaters on agricultural lands would impact substantial farmland areas and be very challenging to implement.

Table 12. Storage capacity of agricultural lands in the LCRR basin.

	Spring 2011 flood, uniform water depth (Analysis #1)	Average year, uniform water depth (Analysis #2)	Average year, uniform water depth (Analysis #3)	Average year, variable water depth (Analysis #4)
Storage volume, 10^8 m^3 (10^8 ft^3)	16.12 (569)	8.915 (315)	8.915 (315)	8.915 (315)
Water depth, m (ft)	0.765 (2.5)	0.423 (1.4)	1 (3.3)	7.58 (24.9)
Storage area, km^2 (mi^2)	2,108 (814)	2,108 (814)	902 (348)	239 (92)

The Study's evaluations indicated that storing water on riparian agricultural landscapes could have provided flood relief in 2011. Table 13 shows the effect that temporary water storage on riparian agricultural lands could have had during the 2011 spring flood conditions. Extending the water storage area to 2,256 km^2 (871 mi^2) of riparian agricultural landscape in the Lake Champlain basin could have reduced peak inflows by 17.9 percent; decreasing the lake water levels accordingly by 5 cm (2 in) and having a similar (4 cm or 1.6 in) effect on the Richelieu River water level (Rousseau et al. 2021). Thus, large-scale storing of water on riparian agricultural landscapes could have provided significant relief in 2011. It remains important to note that this scenario includes considerable additional storage area and would be challenging to implement. Allowing water to be stored on more than 2,250 km^2 of riparian agricultural landscape would require extensive work and take a long time to implement (Rousseau et al. 2021).

Table 13. Summary of the effect of water storage on riparian agricultural landscape on Lake Champlain inflows and water levels, discharges in the Richelieu River at Fryers Rapids and Richelieu River water levels at Saint-Jean Marina for the 2011 conditions.

	Lake Champlain Basin	Richelieu River
Storage Area, km^2 (mi^2)	2,256 (871)	2,371 (915)
Decrease of the highest peak (%)	-17.9% (inflow)	-2.0% (discharge)
Decrease of the highest water level	-5 cm (-2 in)	-4 cm (1.6 in)-

Decision criteria

A comparison of the watershed storage measures to the Study Board Decision Criteria is shown in Table 14 . These measures were within the study's scope and mandate. Expanding wetlands to provide substantial flood relief for Lake Champlain and the Richelieu River, however, was determined to require a very large land area (about the size of Lake Champlain). A rough preliminary benefit/cost estimate suggested about $100 of cost for every $1 of benefit for reducing water levels at the basin scale. This measure is therefore not practical to implement at the scale that would be needed to fully mitigate a large flood, and is not a viable solution to fully alleviate major flooding in Lake Champlain and the Richelieu River. Additional wetlands can, however, provide localized benefits and could have incremental effects.

Engagement with the public and other stakeholders indicated strong public support for the importance of protecting and preserving existing wetlands. Most members of the public also agreed that wetlands alone cannot solve flooding problems, which is congruent with the Study's recommendation. Given the strong support for wetlands and the public's understanding of the other ecological services they provide, it is not surprising that the Board also heard several considerations from the public around this topic. Some members of the public felt that a stronger recommendation around expanding wetland area would be warranted, or expressed the desire for more recognition of the fact that historical wetland area in the LCRR basin has been dramatically reduced due to human land-use changes. A few members of the public expressed that they felt that not recommending expanding wetlands for flood reduction could discourage ongoing wetland restoration efforts, and a few members of the public felt that the Study's analysis undervalued the importance of wetlands, given that the analysis focused on reductions in lake level. The Study Board noted that wetlands provide important benefits, including flow modulation, particularly on a local scale, and encouraged the protection and restoration of wetland areas as part of a comprehensive flood management approach.

Due to their large land requirements and high costs, these measures were determined to be neither technically nor economically viable, so they were not considered to be a reasonable standalone solution. Because these measures were determined to be neither technically nor economically viable for large-scale flood reduction, the remaining decision criteria in Table 14 were not assessed. This does not imply that these measures would not provide, for example, environmental benefit or climate change resiliency.

Nonetheless, it is important to note that the Study demonstrated that existing wetlands provide significant flood relief, and the spring 2011 floods would have been much worse in the absence of these wetlands. For this reason, existing wetlands must be preserved and protected. From a strictly technical perspective, additional wetlands could contribute to flood attenuation by passive water storage. However, adding wetlands and flooding farmland would require extensive land alteration and acquisition. Fostering restoration and construction of wetlands instead of planning for flooding of farmland would provide a socially acceptable framework to build resilience over time in the basin, at least at the local sub-watershed scale (Rousseau et al. 2021).

One of the legacies of the project is a new tool, available in PHYSITEL, to identify potential water storage areas given a pre-estimated runoff volume to be stored. It is readily available and specific to this study and can be applied on any LCRR sub-watershed. Implementation of any large-scale water storage scenario would require long-term field work, but would certainly provide hydrological benefits (Rousseau et al. 2021).

Table 14. Assessment of Study Board decision criteria for watershed storage measures.

Measure	Study Board Decision Criteria						
	Within study scope & mandate	Tech-nically viable	Econom-ically viable	Environ-mentally sound	Equitable and fair	Climate change resilient	Implementable
Agricultural Storage: 2,256 km² (871 mi²)	✓	✗	✗				
Wetland Storage: 647 km² (250 mi²)	✓	✗	✗				
Wetland Storage: 865 km² (334 mi²)	✓	✗	✗				
Wetland Storage: 1,493 km² (576 mi²)	✓	✗	✗				

Green shading indicates a positive assessment; red indicates negative. Cells with no shading were not assessed.

The LCRR Study also recognizes the incremental benefits of multiple strategies for overall flooding reduction in the LCRR system. Optimizing water storage within the watershed through the cumulative effects of many smaller detention storage practices will help to better naturalize the watershed functions, and while difficult to quantify individually, will have a cumulative and positive impact on watershed storage, and will therefore contribute to incremental reductions in lake flooding. The LCRR Study encourages the governments to continue to pursue the implementation of practices such as these to benefit both local tributary flooding issues and the overall effort to reduce flood impacts in the LCRR system.

4.3.2 Recommendations

The Study Board recommends that the IJC encourage the governments to continue protection of existing wetlands as they provide flood relief (reduction of the peak water level by 15 cm in Lake Champlain and 12 cm in the Richelieu River during a spring 2011-scale flood) at the scale of lakeshore and Richelieu riverfront communities.

The Study Board has determined that without the creation of a very large area (650 km² or greater) of new wetlands, there cannot be significant flood mitigation at the scale of lakeshore and Richelieu riverfront communities during major flood events. Therefore, the Study Board does not recommend pursuing a strategy for acquiring land and creating new wetlands as a singularly effective flood management policy for lakeshore and Richelieu riverfront communities.

However, the Study Board recognizes that wetlands reduce local tributary flooding, support biodiversity, and have important environmental co-benefits. Consequently, the Study Board encourages the governments to not only continue to protect these existing wetlands but where possible, to restore wetlands and create new ones. The Study Board recognizes the incremental and cumulative benefits of multiple strategies for overall flood reductions in the Lake Champlain-Richelieu River system. The Study Board encourages the governments to continue to pursue the implementation of practices that have a net positive impact on watershed storage to benefit both local tributary flooding issues and the overall effort to reduce flood impacts in the LCRR system.

4.4 IMPROVING FLOOD RESPONSE (THEME 3)

The goal of the Theme 3 and Theme 4 non-structural solutions is to reduce vulnerability to high water and build flood resiliency through better preparedness, response and recovery strategies. Vulnerability is the combination of exposure and sensitivity. Exposure to flooding is considered through the mapping of flood zones and flooded areas. It is important to note that the elements exposed to a hazard can be both tangible (e.g., people, buildings, ecosystems, etc.) and intangible (e.g., social cohesion, attractiveness, sense of security) (Morin 2008).

Theme 3 focuses on mitigation and adaptation strategies and measures related to emergency preparedness and response. Several potential measures were put forward in the Study, including improving flood forecasting tools to improve response time, preparing for emergencies using actions such as sandbagging and floodwalls, reducing risk through effective mobilization and prompt evacuation, protecting vulnerable populations and maintaining essential services.

The Study's strategies for addressing these topics created several products to achieve these goals. Among these are a new set of models that can be used to produce five-day flood forecasts, ISEE's social vulnerability tool, and new models for projecting flood regimes under climate change scenarios.

4.4.1 Flood forecasting

Flooding around Lake Champlain and the Richelieu River has had devastating impacts on homes, roads, buildings and farmlands. Accurate forecasts can help communities to better plan for potential threats and reduce damages before the flood waters arrive. The Study has supported agencies in both Canada and the United States in developing improved flood forecast models to help create a clearer picture of the timing and impact of future floods, improving flood response.

The term Flood Forecasting System is quite general, covering a range of technologies and activities used in forecasting. To simplify, a Flood Forecasting System provides, on a regular basis, forecasting products about flood conditions (particularly streamflow, water level and the resulting flood depth and extent). These products can range from simple short-term forecast water levels at specific locations to more complex products such as a map of water depth with a probability of occurrence (for example, 75 percent chance of non-exceedance). These forecasts can then be correlated to flood impacts such as number of buildings flooded, critical facilities affected, projected losses, and similar issues; however, these impacts are typically beyond the scope of the forecast itself and so are excluded from the analysis presented here. To provide these products, a Flood Forecasting System needs to continually run simulations of various models (mainly hydrological and hydrodynamic) to convert weather forecasts and conditions on the watershed to flood forecasts. Hydrological forecasters monitor the results and interact with the Flood Forecasting System to produce an official government-issued forecast that can then be disseminated to the users.

The Study evaluated flood forecasting systems in Québec and the United States (HHM 2022). Flood forecasting relies heavily on the evolution in space and time of meteorological conditions such as temperature, liquid and frozen precipitation and solar radiation. In this context, the National Oceanic and Atmospheric Administration (NOAA) in the United States and Environment and Climate Change Canada (ECCC) in Canada operate numerical weather prediction systems that rank among the best in the world; this information is made available through an open data portal to the respective agencies responsible for the production and dissemination of flood forecasts, guidance and warnings.

In the United States, NOAA is the sole federal authority providing flood forecasts, guidance and warnings. In Canada, the provision of flood forecasts, guidance and warnings is a provincial responsibility. For the northern portion of the LCRR watershed, located in the Province of Québec, the responsible authority is the Ministère de l'Environnement et de la Lutte contre les Changements climatiques[24] (MELCC). Each agency is responsible for issuing official flood forecasts for its respective territories and producing coherent binational forecasts for the LCRR (Figure 38); there is no single binational official flood forecast. Experts have reviewed the programs and indicated that independent flood forecasts will continue to be used in the recommended flood forecasting systems in the future. However, the various scientific components (i.e., models) should continue to be improved and deployed collaboratively within ECCC, NOAA and MELCC.

Improvements in many components have occurred during the LCRR Study. In the United States, improved hydrologic models have been created for the LCRR basin; these modeling improvements increase the ability to produce flooding forecasts for the tributaries to Lake Champlain. A new experimental forecast system (Figure 39) produces forecasts of spatially variable lake level, circulation and wind waves in Lake Champlain and the Richelieu River system to provide a proof of concept of what advance warning of floods in the region can look like. In Canada, some requirements are already completed or will be shortly. Notably, the production of long-term hydrological forecasts using ensemble weather forecasts is operational at ECCC (NSRPS ensemble forecast with a 32-day horizon).

This system has been improved with data assimilation from various gauges (ECCC, USGS and MELCC). In addition, MELCC has been working on the post-processing requirement by implementing the wind effect using the ETS model (Loiselle et al. 2021). Flood forecast map applications are also going well, with MELCC already starting to implement results from the study, namely the H2D2 hydrodynamic mode within their Info-Crue project.

[24] Ministry of the Environment and the Fight Against Climate Change

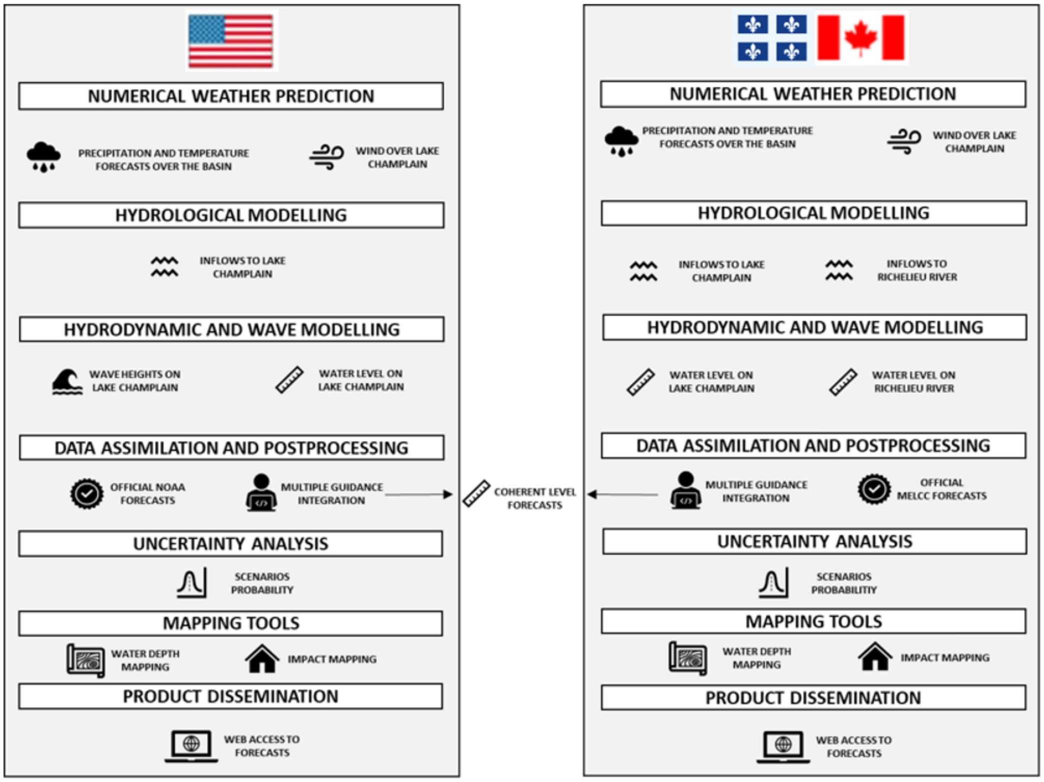


Figure 38. Schematic diagram of the current structure and links between the United States and Québec/Canada flood forecasting systems.

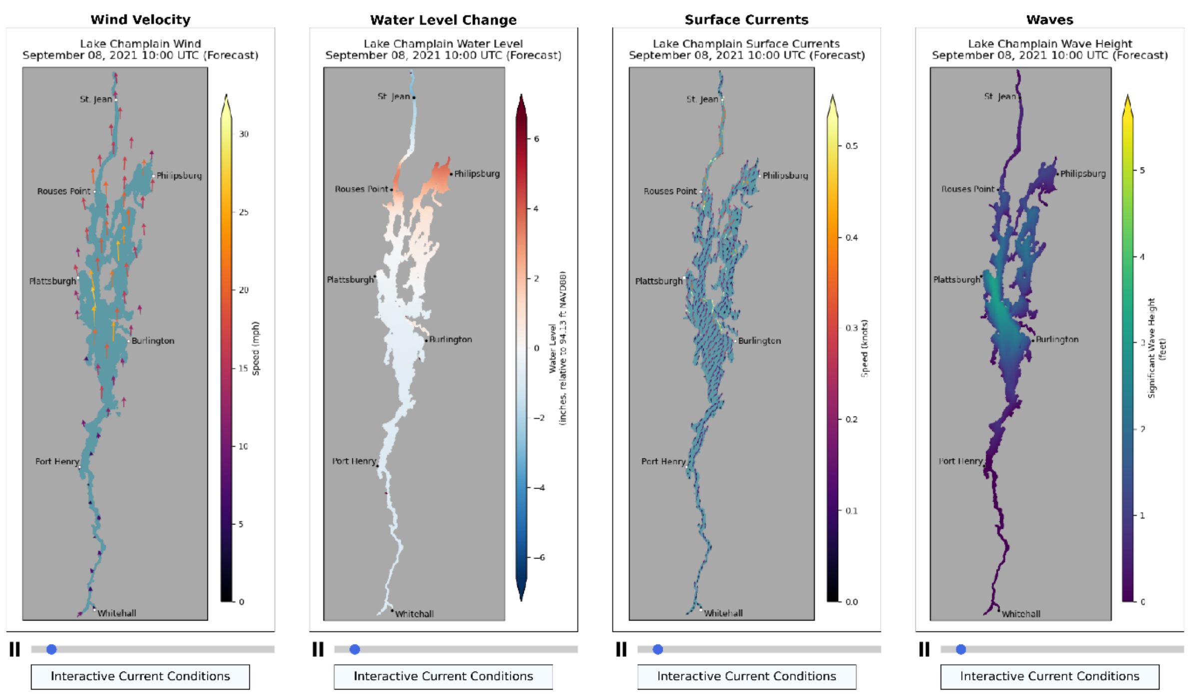


Figure 39. Example of flood forecasting improvements undertaken for Lake Champlain.

An assessment of user needs (Moin et al. 2022) highlighted that desired forecasting products include short-term inundation maps with associated probabilities of occurrence or exceedance of flooding limits, as well as long-term water level and flow graphs assessing the flood risk with ranges of probabilities. The recommended flood forecasting system would use the models (or similar ones) developed or improved during the LCRR Study that can capture the processes relevant to forecasting on the LCRR, such as winter snow accumulation and projected timing and volume of snowmelt, inflows to Lake Champlain, discharge through the Richelieu River, and effects of wind and waves on the system. These individual models and the coordinated use of groups of models in forecasting (ensemble forecasting) would support uncertainty assessment and inundation mapping with forecasts, as desired by users.

Gap analysis between the current situation and the recommended systems highlighted the fact that the required models are mature and have a high level of readiness. Some research is still required to find a proper integration methodology (possibly based on artificial intelligence approaches) for multiple forecast integration, but a hands-on approach by the forecasters can be leveraged in the meantime. While no major technical barriers exist, it is important to point out that the various agencies (NOAA, ECCC, and MELCC) have different institutional settings and operational procedures and systems and will not be able to move at the same pace towards the fulfillment of all recommendations. Because forecasting services are already available today, and have a built-in continuous improvement mechanism, no completion deadline needs to be recommended at this point.

The current independent agency operation framework is also suited for the recommended system. There is no technical incentive justifying a change to more formal joint operation structures, as no limitations were identified with the current operations. The various agencies (ECCC, MELCC, and NOAA) need to provide the required data to each other to maintain the forecasting coordination. If a structural mitigation measure(s) is deployed, the flood forecasting system will need to include the management rules and diversion effects, if applicable, in the hydraulic models. Forecasts will also need to be readily provided to the manager of the diversion.

The IJC LCRR Study allowed the relevant tools to be developed and made available to complete the deployment of the recommended flood forecasting systems. Some work for implementing those tools in operational environments is still required but can be taken over by the various agencies without any major technical barriers.

4.4.2 Social vulnerability

The vulnerability analysis method[25] evaluates, calculates and maps this aspect of sensitivity using four thematic indices: social, territorial, adaptive capacity and infrastructure accessibility. This notion of sensitivity is defined as "the proportion in which an exposed element, community or organization is likely to be affected by the occurrence of a hazard" (Morin 2008). The analysis of the vulnerability, combined with an analysis of the flood hazard, allows the risk to be characterized (hazard x vulnerability = risk) (Figure 40). Knowledge of the risk is an essential element of progress towards the choice of appropriate and robust mitigation and adaptation strategies and measures, and better resilience of communities.

[25] A social vulnerability analysis was performed in Canada and in the United States in 2018 and 2019. First developed by the Canadian team of SPE, the methodology was then replicated in the United States (SPE 2022).

In addition to improvements to existing forecasting systems in Québec and the United States, the Study looked at tools that could go beyond providing information on flood hazards (extent of flood and depth of water) to help local emergency responders prepare for upcoming flooding. The Study developed an approach to assessing flood risk through a model that uses data such as water levels under a given flood scenario and expected damages based on an area's vulnerability. The Integrated Social, Economic and Environmental system (ISEE) is based on extensive high-precision data and can be used to calculate flood damages building by building, as well as estimate the economic, social and environmental impacts of changes to the water level regime. ISEE (Figure 41) incorporates social risks such as vulnerability and can generate maps and information, such as the extent of flood, depth of water, road access and location of people at risk, that can improve emergency responses to floods. One of the key features is that it provides information at a very high level of specificity (for example, for a given building, road or property), which can be very helpful for both emergency response and also for planning over a longer period.

The Study performed an analysis of social and community vulnerability in the LCRR basin. This element of the study focused on the exposure, social sensitivity, territorial sensitivity, adaptive capacity and accessibility of communities in lake and river flood zones. This analysis produced sensitivity maps that cover the basin, as well as recommendations for local actions (SPE 2022).

Figure 40. Vulnerability analysis framework (adapted from SPE 2022).

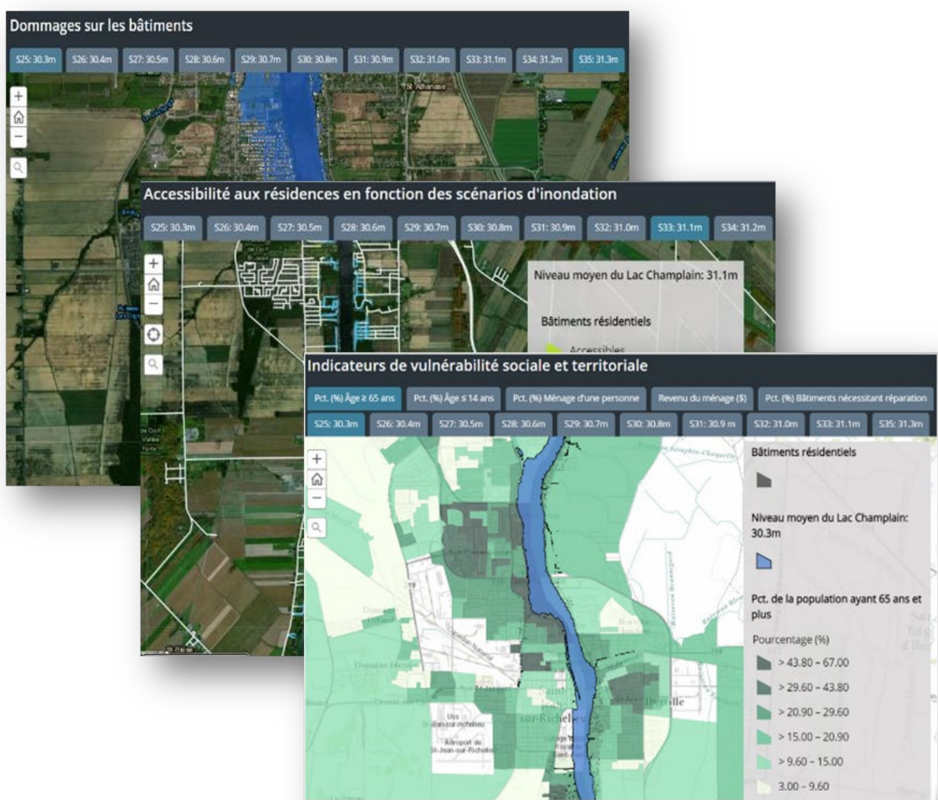


Figure 41. Integrated Social, Economic and Environmental (ISEE) mapping tool (French only).

4.4.3 Assessment of flood response measures

Observations during the Study's *Municipal Needs Assessment Workshops*[26] also showed support from municipal stakeholders for Theme 3 measures, and, more particularly, a need for early forecast and practical map products. Participants underlined the relevance of a flood forecast five days in advance to better prepare the population, especially the vulnerable population. A need for a longer-term forecast (three weeks – based on snowpack and long-term weather forecast) even emerged as a way to make inexpensive preparations and to communicate the potential risk to the population so that they are engaged in preparedness activities. It should be noted that longer-term forecasts of highly variable meteorological and hydrologic conditions will be useful only if they are combined with successive updates to reduce uncertainty in the projections. Mapping products were found to be useful for such things as better distribution of sandbags, determining which evacuation routes to mark, communicating risk in a personalized way by neighborhood, and determining when to evacuate. Municipal stakeholders perceived that they were generally well prepared. Since 2011, the situation in the region has changed: some roads have been raised and buildings have been modified. These data are not always present in the tools provided and it is therefore important to update them systematically to reflect the reality on the ground (SPE 2022).

The Theme 3 recommendations garnered a great deal of interest from stakeholders (SPE 2022). However, updating the data regularly will be important. Feasibility would require building capacity for use, maintenance and upgrading of these tools among federal, state, provincial and local organizations and agencies (SPE 2022). Stakeholders raised questions about funding and coordination among the agencies responsible for hosting new forecasting and modeling tools. Further questions were raised about the degree of coordination required among agencies, and how modeling outputs would be communicated to other agencies, local authorities and public users. Finally, political personnel recognized the need to strengthen floodplain policies and enforcement. This is a component of Theme 4, but it intersects with Theme 3. A deliberate program of capacity building can assist in raising the political feasibility of Theme 3 recommendations (SPE 2022).

A central reaction to presentations of the Study's key findings and conclusions has been a great deal of interest from the public, emergency responders, and municipal officials in the improvements to flood forecasting that the Study has facilitated. The public expressed a high level of support for the Study's recommendation to maintain coordination between the jurisdictions and ensure consistency in forecasts. One reaction some members of the public and planners expressed was a desire for even longer-term forecasts, if possible.

Finally, municipalities and other groups voiced interest in using static mapping products developed by the Study for a wide spectrum of potential flood water levels, to support contingency planning and flood preparedness.

[26] The *Municipal Needs Assessment Workshop* consisted of four working sessions between December 2020 and March 2021, with municipal and regional actors, as well as the ministry of public safety (MSP) (SPE 2022).

4.4.4 Recommendations

The Study Board recommends that all of the weather and hydrological information generated by the National Oceanic and Atmospheric Administration (NOAA, in the United States) and Environment and Climate Change Canada (ECCC) and the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC, in Canada) be made available to and used by the respective agencies responsible for the production and dissemination of flood forecasts, guidance and warnings.

- Continuation and enhancement of the collaboration between the various agencies, namely NOAA, ECCC and MELCC, must be encouraged to ensure all available forecast data and their interpretations are shared in real time with the ultimate goal that the official forecasts on each side of the border are of the highest possible quality and are accompanied by a concerted and consistent cross-border interpretation.

- Improved modeling and forecasting tools developed for the Lake Champlain-Richelieu River basin can greatly aid flood response planning and should be maintained. They showed the possibility of extending the forecasting horizon and providing new operational products relevant to the basin's stakeholders such as water set-up, wave heights, flood extent and depth, and their consequences on the shore, for example: roads cut off, social vulnerabilities, and monetary impacts.

On that basis, the governments are encouraged to operationalize the improved modeling and forecasting tools and coherent risk assessment systems and support/maintain them after the Study. The LCRR tools, supporting data and documentation should be transferred to appropriate agencies in Canada and the US by no later than March 2023.

To support flood preparedness, simulations of flooding of various magnitudes and the related maps produced by the Study Board should be made available to all interested parties by no later than March 2023.

4.5 FLOODPLAIN MANAGEMENT PRACTICES (THEME 4)

Flood Risk Management (FRM) is a strategic approach that aims to increase community resilience to floods. It involves implementing a range of policy tools that prevent and reduce flood hazards, limit flood exposure, and mitigate social vulnerability to flood impacts. Because floods even greater than that of 2011 remain possible in the LCRR basin, there is a need for FRM strategies to reduce and manage flood risk by mitigating the exposure and vulnerability of people, property, and infrastructure assets. Strategies should be guided by overarching principles and implemented through a mix of complementary policy tools.

Strategies for reducing and managing flood risk should target: (1) the flood hazard, meaning inundation of land that is usually dry; (2) the exposure of people, property, infrastructure, and economic activity in or near the flood hazard zone; and (3) the vulnerability of people and assets to harm from flooding. These strategies have to be integrated at scales that are linked to the physical properties of the water system.

4.5.1 Policy tools

Four tools have been identified for inclusion in an integrated FRM strategy.

1. **Flood risk maps** are a valuable resource for FRM, but they should be designed to target specific audiences to achieve their full potential, and should incorporate more detail and advanced technologies (Alberti-Dufort 2022a).

2. **Flood risk communication campaigns** can increase insurance take-up, encourage local emergency management, and inform potential buyers of at-risk properties, but messages should be designed using best practices (Henstra & McIlroy-Young 2022).

3. **Floodplain occupancy** can direct use of flood-prone lands in anticipation of changes in future risk. However, there is a flood risk to existing development, so investments to reduce this flood risk should be implemented whenever justified (Alberti-Dufort 2022b).

4. **Flood insurance** can be an effective tool to speed post-flood recovery but securing widespread coverage will require sharing risk and responsibility between government and the private sector (Shabman 2022).

There are no transboundary issues if, as is currently the case, these tools are considered and applied differently in both countries or in the two states and the province. Each of these tools has varying levels of political feasibility and levels of applicability depending on local contexts.

The first policy tool is flood risk mapping. Mapping is a key tool for the engagement and accountability of all parties involved in flood risk management. Historically, mapping for floodplain management has mainly represented flood hazards. However, there is increasing attention to the issue of vulnerability in flood-prone areas, emphasizing the importance of better understanding the elements exposed to flooding, such as citizens, housing stock, economic activities, essential infrastructure, natural heritage, etc., to make better planning decisions. Flood risk mapping provides an understanding of risk, assists land-use planning, supports decision-making, and assists in disaster response preparation, in addition to being an outreach and information tool for all stakeholders concerned with flood risks (decision makers, citizens, planners, insurers, etc.) (Alberti-Dufort, 2022a). It is technically feasible to develop more accurate inundation maps, including elements such as first-floor elevations of structures in floodplains. Pilot projects are underway in Québec. Mapping advancements are also politically feasible, as there appears to be little resistance to these technologies. However, mapping improvements can be expensive and time-consuming, and flood mitigation professionals must be trained to use these tools.

The second policy tool is the development of an improved and targeted risk communications program. Flood risk communication can achieve numerous goals related to floodplain management, including: fulfilling the government's responsibility to inform and engage citizens in flood risk management, encouraging individuals to take action to reduce their flood risk, equipping people with a better understanding of the potential social and economic impacts of flooding, strengthening public and political support for regulating development on floodplain lands, and making residents aware of the need for flood insurance coverage. (Henstra 2022). The application of best practices for flood risk communication can lead to enhanced public understanding and wiser management of flood risk in the Lake Champlain-Richelieu River basin (Henstra & McIlroy-Young 2022). This recommendation appears technically feasible. At the national level, improvements in flood risk communication are occurring. These developments include FEMA's Risk Mapping 2.0 in the United States, and real estate flood ratings on national real estate websites. Within the LCRR basin, there may be some challenges to feasibility. However, stakeholders think that flood communications programs are an important tool in the watershed. For example, knowing a home's flood risk can lead to making changes to protect a family's well-being and property (SPE 2022). Targeted communications would also allow citizens to better understand the decisions of the authorities on land use planning and possibly collective flood protection measures.

The third policy tool is strengthening the management of floodplain occupancy and developing adaptation solutions that are sustainable and aim to reduce exposure and vulnerability to flooding. Ideally, this would be achieved by reducing the number of people, built elements and services located in floodplains. Floodplain occupancy management may involve several land use planning strategies, including avoidance, relocation, accommodation and protection (Alberti-Dufort 2022b). Planning choices should be based on several factors, such as risk level, risk tolerance or cost, sustainability, other development constraints (e.g., urban sprawl, historical heritage) and benefits associated with a particular solution (Alberti-Dufort 2022b). This proposal is technically feasible, as local jurisdictions commonly manage floodplains through zoning and building codes and consider the development and use of these areas in comprehensive and land-use planning. Furthermore, governance mechanisms exist for amending and updating these policy and planning instruments. Local governments in the LCRR basin appear to support the need for flood planning and resilience, but fear hurdles to the implementation and enforcement of policy tools to achieve these goals; for example, exceptions are often granted to zoning and building code requirements, and comprehensive plans and land use plans are guidance documents only and provide little support for enforcement efforts. To enhance the political feasibility of these tools, significant capacity building and outreach to local elected officials, planning and zoning board members, and local property developers would be helpful. (SPE 2022).

The final policy tool is the development of more robust insurance programming. The US National Flood Insurance Program provides flood insurance to property owners, renters and businesses that helps protect them financially from flood risks. Flood insurance in the United States is not usually included in normal homeowners' insurance policies, but can be purchased separately. Participation in the program is optional, but may be required by lenders for mortgages on properties that are located in high-risk flood areas (https://www.fema.gov/flood-insurance , accessed May 4, 2022). In the United States, FEMA recently promulgated Risk Mapping 2.0. The Study assessed the political feasibility of this program to be high, as it improves on several historical problems with FEMA's prior insurance program. In Québec and Canada, there is movement towards the development of a flood insurance program, though technical and political feasibility are less certain, as the program is in proposal phases (SPE 2022). Of particular interest to some stakeholders are the Study's analyses of the potential benefits of flood insurance. The Study, in consultation with Public Safety Canada, developed a framework for a three-layered insurance model that could be applied across the LCRR basin (Shabman 2022). The framework of the insurance program proposed builds upon insurance option ideas that have been promoted within both Canada (via recent reports from the Insurance Bureau of Canada and Public Safety Canada) and the United States.

Table 15 summarizes the three layers of the insurance program (Shabman 2022). In the United States, where a more established flood insurance program already exists, this concept could be applied using the current flood insurance program as Layer 2.

Table 15. Three-layer insurance framework.

Layer 1	Layer 2	Layer 3
Provincial government leads in creating and offering limited payout coverage Parametric triggered payout All property in community covered A fee might be paid to a "community flood disaster relief fund" All property owners can opt out of coverage, subject to certain conditions	Private insurers offer capped payout indemnity-based coverage to insurable properties in areas now deemed high risk Coverage offered from a pool of private insurers Means-tested premium discounts with revenue equalization payments Included in homeowner all peril policy, with an opt out	Eligibility for post-flood aid begins when damages exceed the Layer 2 cap. Post-flood aid is available to those who opt out of Layers 1 and 2 Post-flood aid can be means-tested based on market value of property, income, non-real property assets

4.5.2 Implementation

Effective implementation of an FRM strategy requires an understanding of the policies and programs in place, an evaluation of their current effectiveness, and then the deployment of complementary policy tools that increase the resilience of communities in the LCRR Study area. Implementation can be enhanced through consultation, engagement, and collaboration; by clarifying and sharing FRM responsibilities; and by monitoring and evaluating outcomes. An effective flood risk management strategy will be particularly important in concert with mitigation measures identified through the Study's other Themes. For example, the benefits of flood water level reductions should be maintained with adaptive land-use planning and floodplain management, particularly constraining land use in areas protected by structural solutions. Equity in the effects of Theme 4 policy measures is a key concern among residential property owners, and flood resilience should be a policy priority that is integrated into comprehensive plans, land use plans, regulations, zoning by-laws, and other instruments that guide local decision-making.

4.5.3 Assessment of floodplain management practices

In Canada, early interviews and questionnaires conducted in 2018 and 2019 as part of risk perception analysis showed that Theme 4 (floodplain management) was the most popular of the four themes (SPE 2022). In 2019, discussion groups with local actors from four municipalities found that participants generally felt that they already have a set of ground rules for floodplain management, but they would like more adaptation options. They would like to see changes in construction techniques, more resilient renovation, and clearer regulations. In the United States, floodplain occupancy also appears as an important theme. In household risk perception surveys, respondents showed strong support for requiring flood insurance, and for keeping development out of the floodplain (SPE 2022).

Reactions from stakeholders and the public related to Theme 4 measures and draft recommendations during the consultation period centered around agreement that improvement to flood risk communication would be greatly beneficial to communities. The Board also heard interest in the Study's work on insurance. Many stakeholders expressed that they felt expanding flood insurance would be the only way to ensure a sufficient compensation fund when floods do occur; others, particularly public participants from Canada who are less familiar with the way a flood insurance program could work, had questions or concerns about how a flood insurance program could be established and carried out in an equitable and affordable manner.

4.5.4 Climate change

As discussed previously, although climate change is likely to reduce average Lake Champlain levels and Richelieu River flows during the 21st century, the region will still be susceptible to "megafloods" greater than the 2011 floods. The best way to deal with them is through emergency response planning and floodplain management practices, rather than expensive structural measures.

The potential impact of climate change is also an important consideration for Flood Risk Management. Perceptions and knowledge about climate change may impact how authorities, organizations and citizens look at the problem definition by focusing not only on past events but also on the future, as the perception of climate change and its impact on water levels may alter how stakeholders bound and scope the problem.

In the Study's household risk perception surveys, citizens were asked how they thought climate change would impact flooding in their region. Results showed that most respondents from the United States and Canada are concerned about climate change. A majority of respondents in both countries think that flooding will become more frequent because of climate change. A majority of respondents in the United States also think that flooding will become more severe. In Québec, 42.8 percent of the population of the region thinks flooding will become more severe. Fewer respondents believe that flooding in the region will become less frequent and severe because of climate change. A key message from stakeholders was to focus on improved communication, stakeholder engagement, and floodplain regulation (SPE 2022).

4.5.5 Recommendations

The Study Board recommends that the IJC encourage the governments to make the best use, in relation to their own context, of the LCRR Study's analysis of best practices related to risk mapping, risk communication, floodplain management, and flood insurance, which include:

- Enhance flood risk mapping for targeted audiences. This includes updating and adding more details to existing flood risk maps;
- Develop flood risk communication campaigns designed for specific target audiences within the LCRR basin;
- Consider floodplain occupancy through the lens of resiliency. This includes land use strategies that avoid, accommodate and retreat from flooded areas, updating and strengthening the enforcement of land use regulations based on flood risk, and shielding development in high-risk flood zones; and
- Explore and/or expand flood insurance. This includes further investigation of the state of flood insurance in the watershed and promoting an insurance arrangement that shares financial liability for flood damages.

Moreover, the Study Board recommends that the IJC advise the governments that the benefits of flood water level reductions should be maintained with adaptive land use planning and floodplain management, particularly constraining land use in areas protected by structural solutions.

4.6 CAPACITY BUILDING

As the environment is continuously changing, authorities need to provide the space for all stakeholders to share experiences and contribute to the evolution of adaptative strategies. Capacity-building is the process of developing and strengthening the skills, instincts, abilities, processes and resources that organizations and communities need to survive, adapt, and thrive in a fast-changing world. Because capacity building connects people, organizations, and information, the Board recommends that the respective governments encourage collaborative communication and capacity building at various scales and through various networks in order to prevent or prepare for flooding impacts on both Lake Champlain and the Richelieu River. Capacity building may include:

- the development of enhanced communication and collaboration pathways among the governments of the basin and other interested parties;
- professional development for personnel in positions that intersect with flooding and flood mitigation; and
- other initiatives to support communities in preparing for flooding, including making planning tools available, and assisting communities with preparing for more frequent floods and the potential for floods larger than 2011.

Capacity building could be accomplished through a transboundary network of professionals from relevant federal, state, regional and local levels. This would include representatives from public, private and nongovernment sectors.

4.6.1 Recommendations

The Study Board acknowledges that the various stakeholders involved in water issues in the Lake Champlain and the Richelieu River basin regularly have different and sometimes divergent understandings of the causes and impacts of flooding in the basin. As such, the Study Board recommends that the IJC encourage governments to create spaces where all the stakeholders involved in watershed issues can address various aspects of the flooding problem in Lake Champlain and the Richelieu River basin with a goal of achieving a better understanding and collaboration among all stakeholders.

The Study Board also recommends the IJC encourage the governments to continue to engage in capacity building for improved flood mitigation, including initiatives to support communities in preventing or preparing for flooding impacts and making planning tools available.

4.7 STUDY LEGACY PRODUCTS TO SUPPORT FLOOD MANAGEMENT IN THE LCRR BASIN AND ELSEWHERE

The Study Board has produced a wealth of data and tools that can be used by others after this Study's completion and are part of the Study's legacy:

- High precision LiDAR Data assembled
- Water Supply Scenarios (Historical, Stochastic, Future Climate)
- Harmonized Vertical Datums and Data Sets
- Water Balance Model
- Digital Elevation Model
- ISEE (Integrated Social-Economical Environmental System)
- Hydrological Model of the entire watershed
- Performance Indicators
- Improved Flood Forecasting
- Improved Flood Risk Communication
- New Flood Insurance Model
- Sophisticated Mapping Tools
- Offline Maps
- Information generated by the SPE evaluation, including survey results

Several tools may be of particular interest:

- The sophisticated LCRR flood forecasting models can produce real-time forecasts that predict Lake Champlain levels and wave heights and water levels in the Richelieu River. These models can be integrated in forecasting systems and the data can be used by regional and local emergency managers to plan for preparedness and response.
- A new set of static floodplain maps was created, covering the entire LCRR from Whitehall, New York to Sorel-Tracy, Québec. These maps represented 11 static scenarios covering the range of water levels for Lake Champlain at Rouses Point from 30.35 m (99.57 ft) NAVD 88 to 32.18 m (105.57 ft); these will be accessible online on the LCRR Study website beginning in early 2023 for a period of five years.
- The IJC's Climate Change Guidance Framework and decision scaling approach offer an innovative way to support decision-making in the face of uncertainty around future climate change.
- The Study's Integrated Social, Economic, and Environmental (ISEE) modeling system provides more granular estimates of flood damages to the built environment than have been available to date.

- The ISEE system can evaluate the costs and benefits of risk reduction investments in the LCRR basin, such as the effects of a flood insurance design on the flood resilience of households and projected impacts on future disaster assistance payments.

- The Study's work on political feasibility and social acceptability of policy tools can serve as a model for future studies.

A Data Products Committee has been developed to manage some of these legacy products and has provided advice on how to properly archive and make these products available (Data Products Committee 2022).

4.7.1 Recommendations

The Study Board recommends to the IJC that the LCRR tools, models, and supporting data required to implement the recommendations of the Study Board should be made available to appropriate agencies in Canada and the US by March 2023.

4.8 OPPORTUNITIES TO COMBINE MEASURES

The Study recognized that dividing the approaches to improving the resilience of the LCRR basin communities to flooding into four themes ran the risk of developing disconnected recommendations and approaches, so efforts were made throughout to maintain and enhance linkages across disciplines, geographies, and cultures. Many diverse communities of experts and impacted residents contributed to the products of the Study, and its success will rely on continued engagement and relationship building. An essential component of success will be combining structural and non-structural measures to deal with high flows directly, as well as allowing at-risk individuals and assets to be moved out of harm's way or protected under emergency conditions and over the longer term.

Structural measures alone cannot keep the waters of Lake Champlain and the Richelieu River within their shorelines under all conditions, but they can provide some relief under the worst flood events. To be most effective, however, they need to be used in combination with approaches that reduce exposure to floods, such as adjustment over time in the locations and construction details of buildings and other structures located at or near the shore, preservation of current wetland areas, and improvements in the ways that human and financial risks are communicated, understood and distributed among communities and individuals. This means that there is not a single solution to the problem of flooding in the LCRR basin, but rather a complementary suite of approaches that can collectively help LCRR communities become better prepared for future floods.

4.9 BINATIONAL COLLABORATION TO ADDRESS FLOODING IN THE BASIN

The Boundary Waters Treaty of 1909 between Canada and the United States set forth a commitment between the Parties to jointly "prevent disputes regarding the use of boundary waters and to settle all questions." The question of how best to manage flows and levels in the transboundary LCRR basin has been addressed by this Study, including collaboration with Indigenous governments and communities. The approach included accessing technical experts in water science, engineering and policy, as well as community experts in emergency response and municipal planning. No single individual, community, agency or institution can effectively implement the recommendations of the Study alone. Innovations that can improve management of the LCRR system can arise from unexpected sources. Lessons can be learned over time at many scales about what works well and what does not. Investments of time, energy and resources will be required to continue to improve and maintain flood mitigation measures that will make the region a safer and more resilient place to live.

5 CONCLUSION

In response to the severe flooding that impacted Lake Champlain and Richelieu River communities in spring 2011, the IJC-convened the LCRR Study Board. The Board examined the factors leading to the high water conditions and worked to develop potential measures to reduce the damage from future high-water events. The Study's experts examined scientific, engineering, environmental and socio-economic components of the flooding problem over six years. They produced recommendations that will create tangible and measurable positive changes over the long term by reducing the frequency, intensity, and damage from flooding along lake and river shorelines.

The Study sought input throughout its investigation from those who live and work in the communities of the region and know it best--residents, community leaders, first responders, realtors, community groups, environmentalists, and Indigenous peoples. The Study also reached out to federal, state, and provincial governments to understand what their programs can offer and what help they need. These essential social, political and economic considerations were incorporated into the design and application of new scientific models to evaluate flood reduction measures, improve flood forecasting, optimize floodplain management, and determine the value of new approaches to flood insurance. Climate change was considered throughout the Study to increase the resiliency of proposed measures under conditions that are likely to change over time, including both potential wetter and drier average and extreme states of the system.

The Study's resulting set of recommendations, as described above and collected in Appendix A, reflect the concerns of basin communities in both countries. The Study Board believes that these recommendations are reasonable and practical approaches to reduce future flooding and its impacts on property and people, without causing harm to ecosystems. The Lake Champlain and Richelieu River watershed will always experience the impacts of storms, snowmelt, and drought, especially in light of a future that includes a changing climate. Thoughtful structural and non-structural approaches, however, can be implemented over time to improve the resilience of communities and individuals, and to reduce risks to safety, buildings, and infrastructure.

The Study has assembled valuable datasets and created tools that can prove useful for future efforts to improve understanding and management of the LCRR system. The interdisciplinary expertise and relationships built during the Study will also persist and bear fruit as recommendations are considered, adapted, and implemented in the years ahead.

APPENDIX A - Study Recommendations to the IJC

Climate Change

The multiple approaches to climate modeling employed by the Study all indicated major uncertainty in future water regime with a very low (but not null) probability for larger floods than the spring flood of 2011, and the potential for more frequent and extended periods of low water levels in the Lake and River. The Study has produced water supply scenarios using a variety of techniques, and that information should be made available to all interested parties. Therefore, the Study Board recommends that the IJC advise the governments to encourage decision-making bodies to consider climate change in their decision making across all aspects of flood risk management and response.

Reduce Water Levels - Structural Solutions and Governance

The Study Board recommends the IJC advise governments that it is possible to achieve a modest relief of flood (on the order of 10 cm on the Lake and 15 cm at Saint-Jean-sur-Richelieu for an event like the spring 2011 flood) and drought water levels by returning the hydraulic regime at the Saint-Jean-sur-Richelieu shoal to a more naturalized hydraulic state. This can be achieved by removing some flow-impeding human artifacts in addition to some selected excavations of the shoal and installing a submerged weir in the area of the Saint-Jean-sur-Richelieu shoal (Measure 1).

If desired, additional flood relief can be gained through combining the removal of the artifacts, selected excavations of the shoal, and the submerged weir with a modest water diversion through the Chambly Canal (for a total peak water level reduction of 15 cm on the Lake and 20 cm at Saint-Jean-sur-Richelieu for an event like the spring 2011 flood, Measure 3). While this measure that includes the Chambly Canal water diversion is less economically performant, this addition brings greater water level relief for larger flood events and should be presented to the governments for their considerations.

From the Study's evaluation of the proofs of concept, the Study Board is of the opinion that these moderate structural solutions are technically feasible, socially and economically acceptable. A limited environmental review on both potential structural solutions was conducted that indicated encouraging results.

If the governments decide to implement a structural solution, a process should be put in place to analyze binational social, political, environmental, legal, and economic implications of the final structure design and operation.

The Study Board recommends that the IJC encourage the governments to implement a bi-national governance mechanism to oversee the implementation and operation of any structural solution the governments may opt to pursue. Functions of a bi-national governance mechanism for Measures 1 or 3 would include, among others:

- Binationally defining the final design and performance requirements of the submerged weir and removal of shoal material
- Designing and implementing a bi-national adaptive management (AM) program
- Enabling a binational decision-making in response to the binational AM program

In addition, the following functions apply to Measure 3:

- Binationally defining the final design and performance requirements of the Chambly Canal diversion
- Implementing a binational water management plan associated with the final design
- Overseeing the application and decisions associated with the operation of the diversion

Impede Flows - Watershed Storage

The Study Board recommends that the IJC encourage the governments to continue protection of existing wetlands as they provide flood relief (reduction of the peak water level by 15 cm in Lake Champlain and 12 cm in the Richelieu River during a spring 2011-scale flood) at the scale of lakeshore and Richelieu riverfront communities.

The LCRR Study has determined that without the creation of a very large area (650 km^2 or greater) of new wetlands, there cannot be significant flood mitigation at the scale of lakeshore and Richelieu riverfront communities during major flood events. Therefore, the Study Board does not recommend pursuing a strategy for acquiring land and creating new wetlands as a singularly effective flood management policy for lakeshore and Richelieu riverfront communities.

However, the Study Board recognizes that wetlands reduce local tributary flooding, support biodiversity, and have important environmental co-benefits. Consequently, the Study Board encourages the governments to not only continue to protect these existing wetlands but where possible, to restore wetlands and create new ones. The LCRR Study recognizes the incremental and cumulative benefits of multiple strategies for overall flood reductions in the LCRR system. The LCRR Study encourages the governments to continue to pursue the implementation of practices that have a net positive impact on watershed storage to benefit both local tributary flooding issues and the overall effort to reduce flood impacts in the LCRR system.

Improve Flood Response

The Study Board recommends that all of the weather and hydrological information generated by the National Oceanic and Atmospheric Administration (NOAA, in the US) and Environment and Climate Change Canada (ECCC) and the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC, in Canada) be made available to and used by the respective agencies responsible for the production and dissemination of flood forecast, guidance and warnings.

- Continuation and enhancement of the collaboration between the various Agencies, namely NOAA, ECCC and MELCC, must be encouraged to ensure all available forecast data and their interpretations are shared in real time with the ultimate goal that the official forecasts on each side of the border are of the highest possible quality and are accompanied by a concerted and consistent cross-border interpretation.

- Improved modeling and forecasting tools developed for the Lake Champlain-Richelieu River basin can greatly aid flood response planning and should be maintained. They showed the possibility of extending the forecasting horizon and providing new operational products relevant to basin's stakeholders such as water set-up, wave, flood extent and depth, and their consequences on the shore, for example: roads cut off, social vulnerabilities, and monetary impacts.

On that basis, the governments are encouraged to operationalize the improved modeling and forecasting tools and coherent risk assessment systems and support/maintain them after the Study. The LCRR tools, supporting data and documentation should be transferred to appropriate agencies in Canada and the US by no later than March 2023.

To support flood preparedness, simulations of flooding of various magnitudes and the related maps produced by the Study should be made available to all interested parties by no later than March 2023.

Floodplain Management

The Study Board recommends that the IJC encourage the governments to make the best use, in relation to their own context, of the LCRR Study's analysis of best practices related to risk mapping, risk communication, floodplain management, and flood insurance, which include:

- Enhance flood risk mapping for targeted audiences. This includes updating and adding more details to existing flood risk maps.
- Develop flood risk communication campaigns designed for specific target audiences within the LCRR basin.
- Consider floodplain occupancy through the lens of resiliency. This includes land use strategies that avoid, accommodate and retreat from flooded areas, updating and strengthening the enforcement of land use regulations based on flood risk, and shielding development in high-risk flood zones.
- Explore and/or expand flood insurance. This includes further investigation of the state of flood insurance in the watershed and promoting an insurance arrangement that shares financial liability for flood damages.

Moreover, the Study Board recommends that the IJC advise the governments that the benefits of flood water level reductions should be maintained with adaptive land use planning and floodplain management, particularly constraining land use in areas protected by structural solutions.

Capacity Building

The Study Board acknowledges that the various stakeholders involved in water issues in the Lake Champlain – Richelieu River Basin regularly have different and sometimes divergent understandings of the causes and impacts of flooding in the basin. As such, the Study Board recommends that the IJC encourage governments to create spaces where all the stakeholders involved in watershed issues can address various aspects of the flooding problem in Lake Champlain and the Richelieu River basin with a goal of achieving a better understanding and collaboration among all stakeholders.

The Study Board also recommends the IJC encourage the governments to continue to engage in capacity building for improved flood mitigation, including initiatives to support communities in preventing or preparing for flooding impacts and making planning tools available.

Data Products

The Study Board recommends to the IJC that the LCRR tools, models, and supporting data required to implement the recommendations of the Study Board should be made available to appropriate agencies in Canada and the US by March 2023.

APPENDIX B - References

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APPENDIX C - Study Participants

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Group Name	United States Co-Lead and Membership	Canadian Co-Lead and Membership
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**Indicates former members*

APPENDIX D – List of Acronyms

AM	Adaptive Management
BWT	Boundary Water Treaty
CDST	Collaborative Decision Support Tool
CDN$	Canadian Dollars
DEM	Digital Elevation Model
ECCC	Environment and Climate Change Canada
ENAP	École nationale d'administration publique (National School of Public Admin.)
ETS	École de technologie supérieure
FEMA	US Federal Emergency Management Agency
FMMM	Flood Management and Mitigation Measures
FRM	Flood Risk Management
GCNWA	Grand Conseil de la Nation Waban-Aki
GCM	General Circulation Model
GIS	Geographic Information System
H2D2	Two-Dimensional Hydraulic and Dispersion Simulation
HHM	Hydrology, Hydraulics and Mapping
ICRB	International Champlain-Richelieu Board
IFRM	Integrated Flood Resiliency Model
IJC	International Joint Commission
ILCRRSB	International Lake Champlain-Richelieu River Study Board
IM/IT	Information Management/Information Technology
INRS	Institut national de la recherche scientifique

IRG	Independent Review Group
ISEE	Integrated Social, Economic and Environmental
LCBP	Lake Champlain Basin Program
LCRR	Lake Champlain-Richelieu River
MCK	Mohawk Council of Kahnawà:ke
MELCC	Ministère de l'Environnement et de la Lutte contre les Changements climatiques
NAVD88	North American Vertical Datum of 1988
NBS	Net Basin Supplies
NGVD29	National Geodetic Vertical Datum of 1929
NFIP	US National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NWS	US National Weather Service
PMF	Probable Maximum Flood
RCP	Representative concentration pathway
RR	Resource Response Technical Working Group
SIZ	Special intervention zone
SJsR	Saint-Jean-sur-Richelieu
SPE	Social, Political, and Economic Analysis Group
SWE	Snow water equivalent
TWG	Technical Working Group
UOT	Use and occupation of territory
US$	US Dollars
WBM	Water Balance Model

APPENDIX E - Conversion Factors

Multiply	By	To Obtain
Length		
centimeter (cm)	0.3937	inch (in)
millimeter (mm)	0.03937	inch (in)
micron (µm)	0.0003937	inch (in)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Area		
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (ft^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)

Volume		
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
Flow Rate		
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
Mass		
gram (g)	0.03527	ounce (oz)

SI Prefixes:

centi = 10^{-2} milli = 10^{-3} micro = 10^{-6} nano = 10^{-9} pico = 10^{-12}

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 × °C) + 32

Vertical coordinate information is referenced to the **North American Vertical Datum of 1988 (NAVD 88)**.

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)

Horizontal coordinate information is referenced to the **North American Datum of 1983 (NAD 83).**

Altitude, as used in this report, refers to distance above the vertical datum.

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