The Causes and Impacts of Past Floods in the Lake Champlain-Richelieu River Basin

Historical Information on Flooding

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

Submitted by the International Lake Champlain-Richelieu River Study Board

December 2019

ACKNOWLEDGEMENTS

The International Lake Champlain-Richelieu River Study Board is pleased to submit its first report to the International Joint Commission, ***The Causes and Impacts of Past Floods in the Lake Champlain-Richelieu River Basin***. The report is the product of a collaborative binational effort involving researchers and organizations in Canada and the United States.

The Study Board wants to express its sincere appreciation to all the individuals who contributed to the preparation of this report. We also acknowledge and thank the Study's Public Advisory Group and the members of the public who have participated in outreach and engagement activities over the course of the Study to date.

Finally, we want to gratefully acknowledge the International Joint Commission for the opportunity to serve on the Study Board. We look forward to continuing to work together on our final report addressing the challenging issue of mitigating the impacts of future flooding in the beautiful Lake Champlain-Richelieu River basin that our two nations share.

INTERNATIONAL LAKE CHAMPLAIN-RICHELIEU RIVER STUDY BOARD

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Kristine Stepenuck

Study co-manager, Canada:
Serge Villeneuve

Study co-manager, United States:
Robert Flynn

NOTE TO READERS

This is the first report of the International Lake Champlain-Richelieu River Study Board (Study Board). It presents the initial phase of work to better understand and recommend responses to the ongoing risks of flooding in the Lake Champlain-Richelieu River basin. The report is based on extensive scientific analysis, however, in terms of its overall language, level of complexity, citations and presentation of data, the report has been prepared for general, non-scientific readers.

In addition, the Study Board has prepared a brief stand-alone report summarizing the highlights of the Causes and Impacts report, available on the Study's website, *lcrr@ijc.org: Lake Champlain-Richelieu River Basin, Understanding Past Floods To Prepare For The Future.*

EXECUTIVE SUMMARY

The Causes and Impacts of Past Floods in the Lake Champlain-Richelieu River Basin is the first report of the International Lake Champlain-Richelieu River Study Board (Study Board) to the International Joint Commission (IJC). It presents the initial phase of work of the Study Board to better understand and recommend responses to the ongoing risks of flooding in the Lake Champlain-Richelieu River (LCRR) basin.

A CALL TO ACTION

The LCRR basin is rich in natural landscapes, history and vibrant communities. It is also a region highly vulnerable to flooding. In the past 90 years, severe floods have occurred several times in the basin. Generally, these floods were the result of a combination of rapidly melting snowpack and heavy rainfall in the late winter and spring months.

In the spring of 2011, the region experienced flooding beyond anything ever seen in the 100 years for which flood data are available. Lake Champlain water levels far exceeded the previous historical maximum level. The Richelieu River rose above flood stage for more than two months. Many farms and homes along the river in Québec and along the shoreline of the Lake Champlain were damaged. More than 40 communities were directly affected, and thousands of residents needed to be evacuated. Damages were estimated at more than $82 million ($2018 US)[1].

The catastrophic 2011 flood was a call to action. In 2013, at the request of the governments of Canada and the United States, the IJC outlined options for addressing flooding and flood management in the basin. In 2016, the two governments formally instructed the IJC to "fully explore the causes, impacts, risks and solutions to flooding in the Lake Champlain-Richelieu River basin." The IJC established the Study Board to oversee the Study and provide recommendations.

This **Causes and Impacts Report** presents the Study Board's findings with respect to evaluating the causes and impacts of past floods, and in particular, the events of 2011. A shared understanding of the causes and impacts of past floods is the starting point for a comprehensive assessment of measures that could be undertaken in the future. The findings of this report, therefore, will inform the work of the Study Board for the remainder of the Study.

OVERVIEW OF THE STUDY

The objective of the Study is *to recommend structural and non-structural measures to mitigate flooding and flooding impacts in the Lake Champlain-Richelieu River basin*.

Possible measures to be considered include moderate *structural modifications*, such as weirs and channel enhancements, and *non-structural approaches*, such as land use regulations, building adaptations, management of floodplains and wetlands, and decision-making tools.

The Study is being undertaken through an international collaborative approach involving individuals from federal, state and provincial resource management agencies and academia with expertise in flood management, planning and mitigation. It is led by a Study Board with representation from Canada and the United States.

[1] **$105 million in Canadian dollars equivalent (CAN 2018).**

The Study Board is supported by binational working groups addressing key analytical, communications and information management tasks. The IJC also established an independent review group and a Public Advisory Group. In addition, the Study Board is engaging with Indigenous peoples in the basin to seek their input.

CAUSES OF PAST FLOODING IN THE BASIN

The factors contributing major floods in the LCRR basin 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.

With the exception of the major flood in 1927 and floods caused by tropical storms typically occurring in the fall, most of the largest flooding events recorded in the last 150 years in the basin have occurred during the spring, with a significant snowpack still present over much of the basin. The high terrain of the Adirondack and Green Mountains of New York and Vermont can accumulate large amounts of snow throughout the winter, persisting into the rainy spring season. A heavy snowpack, coupled with significant warm spring rains, commonly drives the most serious flood conditions on Lake Champlain by rapidly contributing large volumes of water to the lake. Flooding primarily driven by precipitation and snowmelt events can be locally amplified by wind-driven waves and oscillating seiche waves when accompanied by strong winds.

In 2011, the confluence of warm temperatures, record precipitation and rapid melting of a near-record snowpack caused historically high flood levels in the basin tributaries and in Lake Champlain and the Richelieu River. Since the 19th century, anthropogenic modifications, including urbanization and expansion of impervious surfaces, particularly in floodplains, the conversion of wetlands to agriculture, and the establishment of transportation infrastructure in and along rivers have tended to alter the timing and amount of water flowing through the watershed. The cumulative effects of these modifications have not been quantified. The Study will analyze some of these modifications.

IMPACTS OF 2011 FLOODING IN THE BASIN

The 2011 spring flooding event had significant and wide-ranging impacts on the economy and health of the residents of the LCRR basin and on the natural environment of the basin. However, the identification of specific or detailed impacts from the flood is limited by a lack of data and a lack of standardized methodologies for collecting and reporting basin-wide data.

Impacts on the basin's economy

Available data suggest that the 2011 spring flooding event caused more than $67 million[2] damage in Québec, more than $11 million[3] in New York and more than $4 million[4] in Vermont ($2018 US).

Residences were particularly affected by the 2011 spring flood.

Impacts on human health and safety

Primary concerns with respect to human health were focused on: ensuring human safety and conducting any evacuations as needed; supplying clean drinking water; containing spills of toxic substances; providing medical care; restoring electricity; and repairing damage to transportation infrastructure to restore access to communities isolated by washed out roads. In Québec, the eight-week period of inundation led to extensive water damage to residences, with resulting environmental health issues including mold exposure and electrical hazards. In the first few weeks of flooding, an estimated 2,535 homes were flooded and 1,651 residents were forced to evacuate. The flooding also led to psychological health impacts among affected residents in both the immediate term and longer term, though information on the extent of these impacts is limited.

[2] **$86 million in Canadian dollars equivalent (CAN 2018).**
[3] **$14 million in Canadian dollars equivalent (CAN 2018).**
[4] **$4 million in Canadian dollars equivalent (CAN 2018).**

Impacts on infrastructure

During the 2011 spring flood, more than 100 bridges and roads were damaged in the study area in Québec. In New York and Vermont, transportation infrastructure was impacted during the 2011 flood by both high water levels in the lake and tributary flooding. Lakeshore flooding in 2011 led to the inundation of about 79 kilometers (km) (50 miles) of low-lying roads, causing transportation disruption and threatening to isolate some communities.

Impacts on erosion

The record levels on Lake Champlain during the spring flood of 2011 led to inundation and erosion of unconsolidated shoreline sediments along Lake Champlain. The most significant erosion occurred in areas where the largest waves broke onshore, along long zones of uninterrupted fetch. Shorelines with steep banks with little vegetation and with lawns extending to the water's edge or shoreline immediately adjacent to seawalls were particularly vulnerable to erosion.

Impacts on the natural environment

Despite the limited data, direct and indirect impacts on the natural environment can be inferred from a general understanding of flood processes and from an extensive knowledge of the basin's natural environment and wildlife. Key impacts from the 2011 spring flood on the natural environment in the basin included:

- alteration of spawning sites used by the copper redhorse, a designated endangered fish species under the *Species at Risk Act*;
- displacement of fish spawning to developed areas in the floodplain of the Richelieu River that are generally unsuitable for fish, compromising their reproductive success;
- entrapment of fish in flooded pools not connected to the river;
- modification of the fish community's composition and abundance;
- damage and flooding of nesting sites of the eastern spiny softshell turtle, including a highly productive nesting area in Vermont, located near Missisquoi Bay, which was inundated for several weeks;
- the spread, by flood waters, of contaminated sediments and invasive species such as phragmites, purple loosestrife, Japanese knotweed, Eurasian watermilfoil, curly leaf pondweed and water chestnut;
- possible flooding of marsh birds' nests, including those of the black tern and least bittern; and,
- impacts on water quality, including significant sediment and phosphorus loading to Lake Champlain, which, together with additional inputs from runoff caused by extreme precipitation from Tropical Storm Irene, resulted in large blooms of cyanobacteria during the late summer of 2011 at sites not commonly impacted by blooms;

REVIEW OF RESPONSES TO PAST FLOODS

Nearly every major flood in the basin over the last 90 years has led to major investigations on how to prevent or mitigate future flooding events. The governments of Canada and the United States have given three references to the IJC to recommend solutions to mitigate flooding in the basin: in the 1930s; the 1970s; and again with this present study that follows the 2011 spring flood.

Several of these investigations considered the feasibility of regulating the Richelieu River and Lake Champlain by means of a gated structure on the river. However, there were concerns about environmental issues associated with such structures, and no public consensus was reached.

Flood management and risk reduction measures can be organized into four themes:

- *flood control* structures that reduce flood levels;
- *flood retention* measures in the watershed to reduce the flows into Lake Champlain and the Richelieu River;
- *flood response plans*, prepared before but implemented as flood waters rise to reduce flood impacts; and,
- *floodplain management* and land use regulation to reduce the risks to humans and the natural environment in floodplains.

There is currently no major flood control structure for Lake Champlain and the Richelieu River. The existing Fryer Island dam cannot regulate flows and has never been used for flood control.

State, provincial and municipal governments in the basin are undertaking a range of measures in the areas of flood retention, flood response and floodplain management.

LOOKING AHEAD

Looking ahead, the challenge is clear. Forty years after the last major IJC investigation of flooding in LCRR basin, the basin experienced the greatest flood and greatest flood damage on record. The region's vulnerability to flooding remains high. What can be done to better prepare for future flooding in the basin?

The analyses summarized in this report present the Study Board's findings regarding the causes and impacts of past floods in the LCRR basin. These findings will inform the balance of the work of the Study Board as it develops recommendations to reduce the impacts of future flooding.

The Study Board work will provide a variety of opportunities for public engagement to ensure that residents of the basin are aware of the Study's progress and have opportunities to provide input. Over the course of the Study, the Study Board is maintaining a website to serve as the primary tool for posting reports and other materials related to the Study, and for publicizing notices of public meetings in communities throughout the basin (https://ijc.org/en/lcrr).

The Study Board's final report and recommendations will be submitted to the IJC in 2022.

STAY CONNECTED, BE ENGAGED

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

Email the Study at lcrr@ijc.org

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

Follow the Study on social media

- @IJCsharedwaters
- www.facebook.com/internationaljointcommission/
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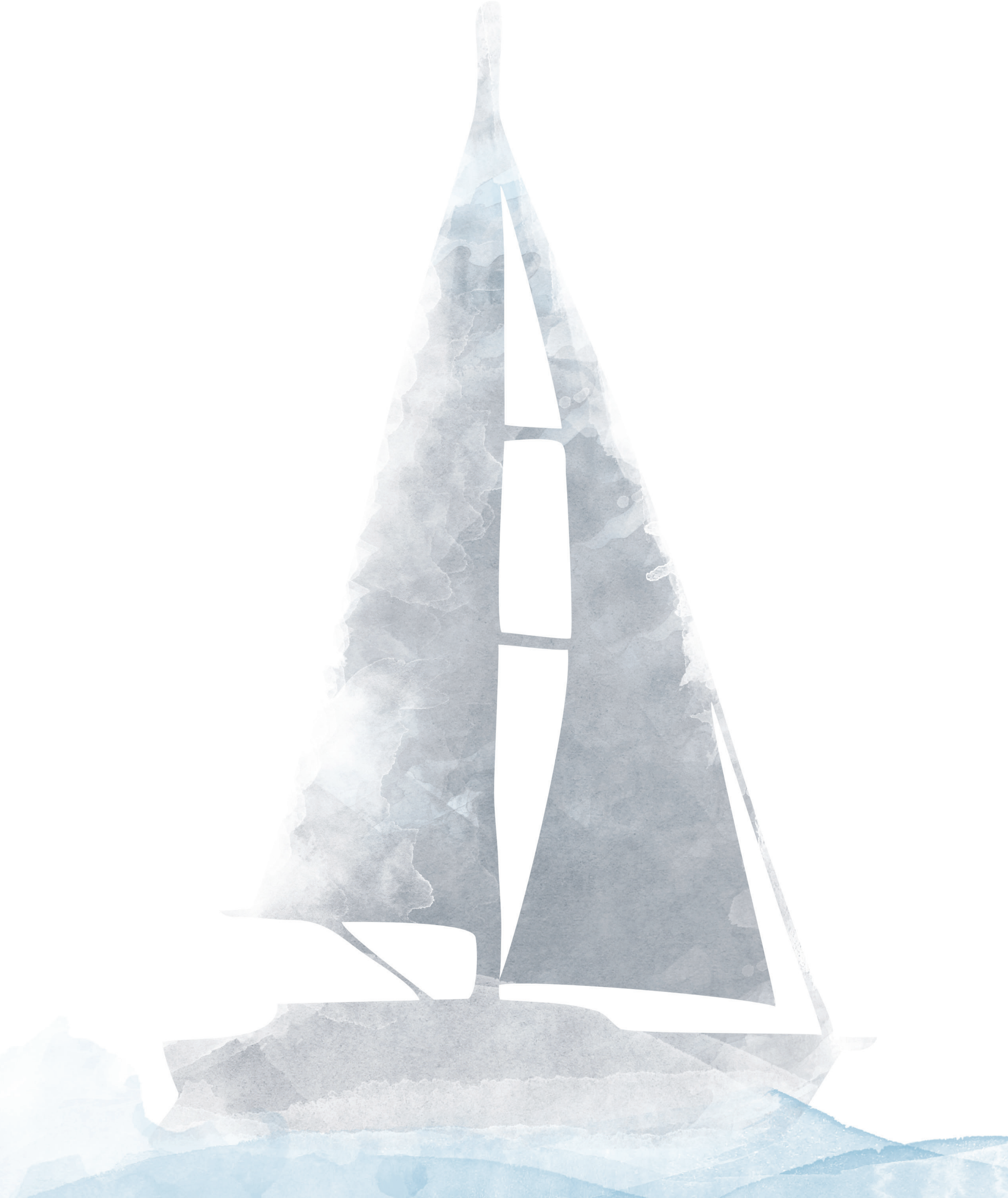
List of Acronyms

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

COVABAR	Comité de concertation et de valorisation du bassin de la rivière Richelieu
DEC	Department of Environmental Conservation
ECCC	Environment and Climate Change Canada
FEMA	Federal Emergency Management Agency
FFWRS	Flood Forecasting, Warning, and Response System
FHARC	Flood Hazard Area and River Corridor
ICRB	International Champlain-Richelieu Board
ICREB	International Champlain-Richelieu Engineering Board
IJC	International Joint Commission
IRG	Independent review group
LCBP	Lake Champlain Basin Program
LCRR	Lake Champlain Richelieu River
MDDELCC	Québec Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (Ministry of Sustainable Development, Environment, and Fight Against Climate Change)
MELCC	Quebec Ministère de l'Environnement et de la Lutte contre les changements climatiques
MFFP	Québec Ministère des Forêts, de la Faune et des Parcs
MSP	Ministere de la Securitie Public du Québec
NAVD	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
NOAA	National Oceanic and Atmospheric Administration
NWS	United States National Weather Service
PAG	Public advisory group
RCM	Regional county municipality
RFC	River forecast center
SBA	Small Business Administration
SIZ	Special intervention zone
TWG	Technical working group
USACE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey



1. INTRODUCTION TO THE REPORT

The Causes and Impacts of Past Floods in the Lake Champlain-Richelieu River Basin is the first report of the International Lake Champlain-Richelieu River Study Board (Study Board) to the International Joint Commission (IJC). It presents the initial phase of work of the Study Board to "fully explore the causes, impacts, risks and solutions to flooding in the Lake Champlain-Richelieu River basin."[5]

The report is organized into the following chapters:

- **Chapter 1** presents an *overview* of the Study and study setting;
- **Chapter 2** analyzes the *causes* of past floods, with particular emphasis on the spring flood event of 2011;
- **Chapter 3** evaluates the *impacts* of past floods in the basin, including impacts on the natural environment, the economy, human health and safety, and infrastructure;
- **Chapter 4** briefly summarizes past *responses* of the IJC regarding flooding in the basin, and reviews past and current *flood management and mitigation measures* in the basin; and,
- **Chapter 5** summarizes the *findings* with respect to the causes and impacts of flooding in the basin and identifies next steps in the Study.

1.1 A CALL TO ACTION

The LCRR basin is a large international watershed in southern Québec and northern New York and Vermont, rich in natural landscapes, history and vibrant communities. It is a region of wide-ranging geography – a deep lake surrounded by the beautiful Adirondacks to the west and the Green Mountains to the east, and to the north, flat, fertile farmland along the river all the way to the St. Lawrence River.

It is also, as recent history suggests, a region highly vulnerable to flooding. Seven of the 10 highest lake stages ever recorded at the Rouses Point gauge on Lake Champlain have occurred in the last 50 years (1976, 1983, 1993 {twice}, 1994, 1998 and 2011). Generally, floods are the result of a combination of rapidly melting snowpack and heavy rainfall in the late winter and spring months. There are also instances of severe summer and fall floods, such as the devastating November 1927 flood and Tropical Storm Irene in August 2011, though these are more likely to be flash floods rather than the long duration floods that occur in the spring.

[5] **From the 2016 Letters of Reference to the IJC from the governments of Canada and the United States. See https://ijc.org/en/lcrr.**

In the spring of 2011, the region experienced flooding far beyond anything ever seen in the 100 years for which flood data are available. Lake Champlain water levels far exceeded the previous historical maximum level. 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 the Lake Champlain were damaged. More than 40 communities were directly affected, and thousands of residents needed to be evacuated. Damages were estimated at more than $82 million ($2018 US)[6].

The catastrophic 2011 flood was a call to action. In 2013, at the request of the governments of Canada and the United States, the International Joint Commission (IJC) outlined options for addressing flooding and flood management in the basin. In 2016, the two governments formally instructed the IJC to undertake a study into the causes, impacts, risks and solutions to flooding in the LCRR basin. The following year, the IJC established the International Lake Champlain-Richelieu River Study Board (the Study Board) to oversee the Study and provide recommendations (For details, see the Study's website: https://ijc.org/en/lcrr).

The **Causes and Impacts Report** is the first major analysis to be issued by the Study Board. The Study Board's final report and recommendations will be submitted to the IJC in 2022.

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.

[6] **$105 million in Canadian dollars equivalent (CAN 2018).**

1.2 OVERVIEW OF THE LAKE CHAMPLAIN-RICHELIEU RIVER STUDY

1.2.1 STUDY OBJECTIVE AND TASKS

STUDY OBJECTIVE

Recommend structural and non-structural measures to mitigate flooding and flooding impacts throughout the Lake Champlain-Richelieu River basin.

Flooding is a natural part of the dynamics of many rivers and lakes, and the LCRR basin is no exception. No measures can completely eliminate the prospects of flooding in these systems. The primary focus of the Study, therefore, is to investigate and recommend measures to reduce the impacts of possible future flooding in the basin.

There is a wide range of possible measures to reduce the impacts of flooding. These include:

- moderate *structural modifications*, such as weirs and channel enhancements; and
- *non-structural approaches*, such as land use regulations, building adaptations, management of floodplains and wetlands, and decision-making tools.

STUDY TASKS

Under the letters of reference from the governments of Canada and the United States to the IJC, the Study Board is undertaking 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 syste**m 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 resources response to water levels fluctuations, so as to support the planning, evaluation and ranking of potential flood mitigation solutions.

1.2.2 PURPOSE OF THE CAUSES AND IMPACTS REPORT

This report presents the Study Board's findings and conclusions with respect to the Study Board's first task: ***evaluating the causes and impacts of past floods, and in particular, the events of spring 2011***.

The report represents the first key building block of the Study as the Study Board works towards developing practical and effective responses to the ongoing risks of flooding in the LCRR basin. An understanding of the causes and impacts of past floods is an essential starting point for a comprehensive assessment of measures that could be undertaken in the future. The findings of the **Causes and Impacts Report**, therefore, will inform the work of the Study Board on the remaining six tasks.

1.2.3
STUDY ORGANIZATION

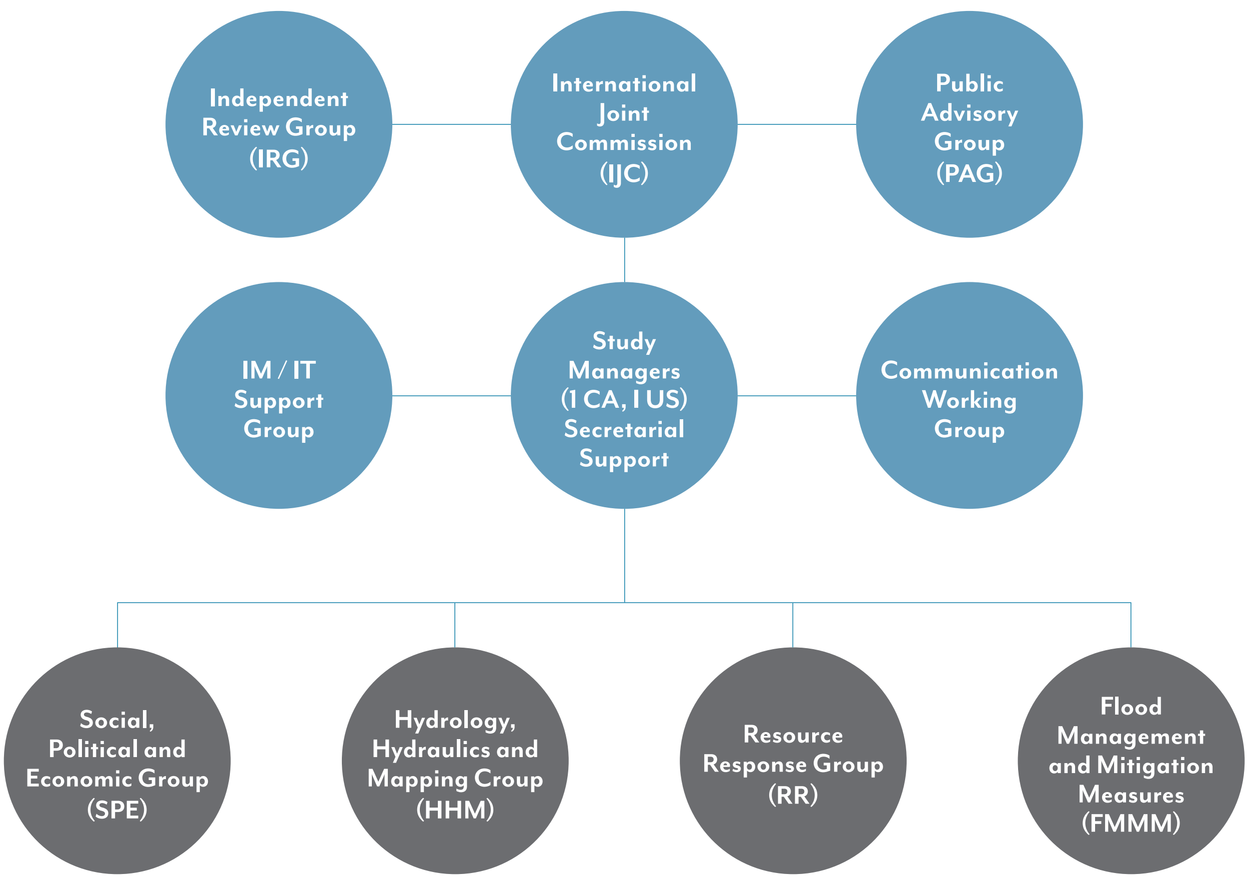
The Study is an international collaborative approach involving individuals from federal, state and provincial resource management agencies and academia with expertise on flood management, planning and mitigation, as well as economics and social sciences. It is led by a Study Board with representation from Canada and the United States.

The Study Board is supported by binational groups addressing key analytical, communications, outreach and information management tasks (Figure 1-1).

These include:

- a *Hydrology, Hydraulics and Mapping Technical Working Group (TWG)* is creating hydraulic models to consider the impacts of future climate change and other factors, and developing several decision-making tools, including flood forecasting and flood mapping models;
- a *Flood Management and Mitigation Measures TWG* is designing and evaluating flood management and mitigation options;
- a *Resource Response TWG* is developing the indicators needed to assess various flood management and mitigation options in terms of impacts on the environment, people and the economy; and,
- a *Social, Political and Economic (SPE) Analysis Group* is advising the Study Board on many of the complex social, political and economic issues that form an important component of the challenge of flood mitigation and management.

Figure 1-1 | Lake Champlain-Richelieu River Study organization



In addition, a binational *public advisory group* (PAG) has been established by the IJC to assist the Study Board with the critical task of engaging the public over the course of the Study. Finally, the IJC established an*independent review group* (IRG) to help ensure that the Study is scientifically credible and transparent.

The Study Board is also directly engaging with Indigenous peoples in the basin to seek their input in the Study. Consultations with the *Nation Abénakise*, Mohawk Council of Kahnawà:ke (representing the Mohawk communities), and Abenaki tribes (represented by the Chief of the Nulhegan Band of the Coosuk Abenaki Nation) have been ongoing since early in the Study. To date, the Canadian section of the IJC has signed a memorandum of understanding with the *Nation Abénakise* to conduct a survey of Indigenous uses of the land and water along the Richelieu River.

This information will be instrumental to the evaluation of flood impacts and potential mitigation measures. The Mohawk Council of Kahnawa:ke continues to provide important input on materials affecting their interests as these arise.

Over the course of the Study, the Study Board is maintaining a website (http://ijc.org/en/lcrr) to serve as the primary tool for posting background materials and Study reports and to provide notices of upcoming meetings and opportunities for review and comment.

For a list of the members of the Study Board and the binational technical and advisory groups, see: https://ijc.org/en/lcrr.

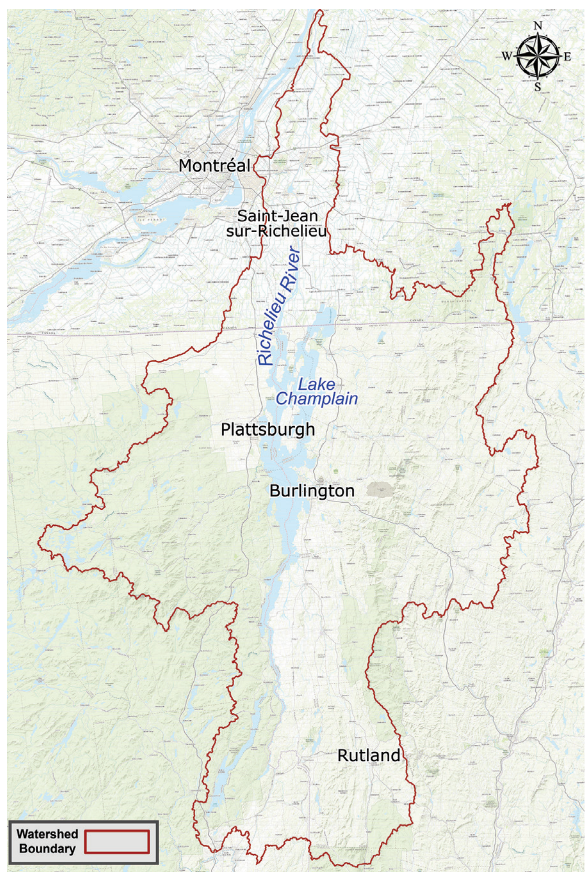
1.3 OVERVIEW OF STUDY SETTING

1.3.1 NATURAL ENVIRONMENT

The LCRR basin (Figure 1-2) covers an area of about 23,900 kilometers^2 (km) (9,277 mi^2). About 84 percent of the basin is in the northeastern New York and northwestern Vermont, and 16 percent is in Québec. The international border crosses the northern outlet of the lake, close to where the river begins, as well as an important bay in the lake, Missisquoi Bay.

While conducting analysis at basin scale, the Study focuses on the reduction of flood impacts on Richelieu River and Lake Champlain, and does not directly address the impact of flooding on their tributaries.

Figure 1-2 | Study area: Lake Champlain-Richelieu River basin



The basin has two distinct types of topography. In the United States, the basin is rugged and mountainous, with peak elevations of more than 1,628 m (5,340 ft) in the Adirondack Mountains of New York and nearly 1,340 m (4,395 ft) in the Green Mountains of Vermont. A large number of streams discharge from these mountains into Lake Champlain.

At the Canada-United States border, the terrain of the basin moderates in a relatively short distance to flat plains. These plains generally continue northward for the full length of the Richelieu River.

LAKE CHAMPLAIN

Lake Champlain has a surface water area of nearly 1,130 km^2 (about 436 mi^2). All but 44 km^2 (about 17 mi^2) are located within the United States. Only the northern half of Missisquoi Bay lies in Québec. The lake is about 193 km (121 mi) long and flows from Whitehall, New York, north to near the US-Canadian border to its outlet at the Richelieu River near Rouses Point, New York. The average depth of the lake is 19.5 m (64 ft), with a maximum depth of 122 m (400 ft). The lake varies from narrow and almost riverine in the far south, to approximately 19 km (12 mi) across near Colchester, Vermont, and Port Kent, New York.

Lake Champlain is divided into five distinct areas, each with different physical and chemical characteristics and water quality: South Lake; Main Lake; Malletts Bay; the Northeast Arm; and Missisquoi Bay (Figure 1-3). The south part, south of Crown Point, New York, is long, narrow and shallow, accounting for 40 percent of the length of the lake but only about one percent of its volume. The main lake section extends to Rouses Point, New York, and accounts for more than 80 percent of the lake's volume. More than 70 islands and numerous inlets and bays add to the complexity of the lake's narrow profile.

The lake has several streams and tributaries with drainage areas greater than 650 km^2 (about 250 mi^2), including Otter Creek, and the Mettawee, Poultney, Winooski, Lamoille and Missisquoi Rivers in Vermont, and the Bouquet, Ausable, Saranac and Great Chazy Rivers in New York.

RICHELIEU RIVER

The Richelieu River extends about 124 km (78 mi) 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 (Figure 1-4). At its maximum, the river's basin is only about 26 km (16 mi) wide.

The section, or reach, of the river from its outlet to below Saint-Jean-sur-Richelieu provides Lake Champlain's primary outlet and control. At Rouses Point, the Richelieu River is only 29 m (about 95.5 ft) above sea level. 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. The gradient of the river is low, with a drop of only 0.3 m (about 1 ft) over the entire reach.Near Saint-Jean-sur-Richelieu, the river becomes much narrower with a steeper gradient, as it meets a long natural barrier formed by rock shoals. These shoals are about 210 m (689 ft) wide and extend for about 3.2 km (2 mi), and have a significant effect on Lake Champlain water levels and outflows.

Figure 1-3 | Lake Champlain
(Note: the 5 distinct areas of the lake are each marked in a separate color)

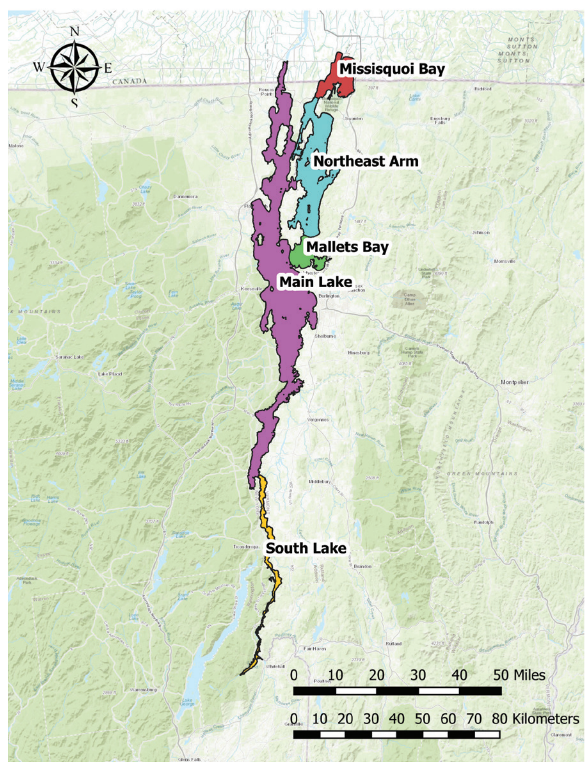
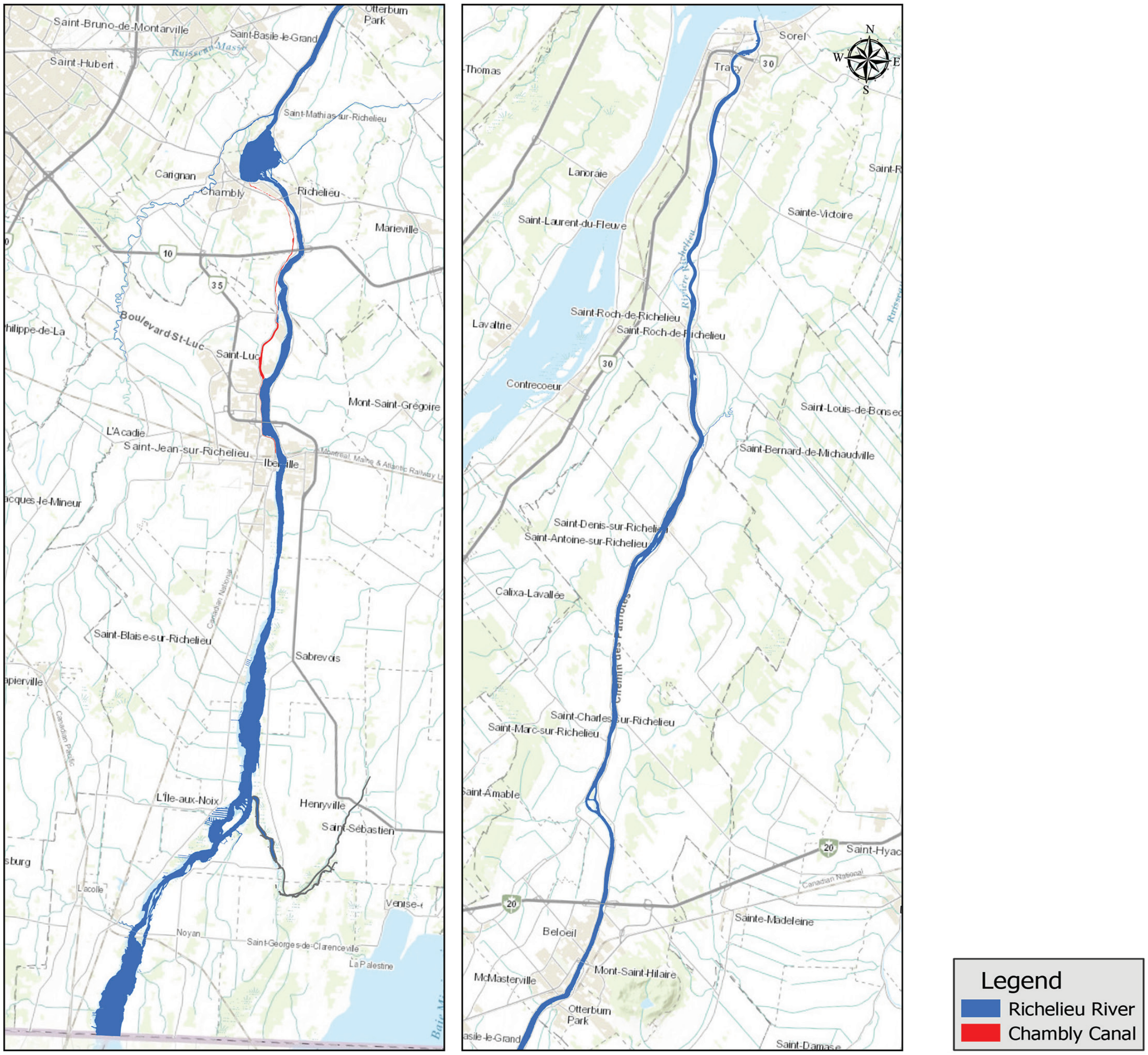


Figure 1-4 | Richelieu River and Chambly Canal

(Note: the left side of the figure illustrates the southern portion of the river, from its outlet on Lake Champlain to the Chambly Basin; the right side illustrates the northern portion, to the river's outlet at Sorel, Quebec.)



In this reach, the river drops about 25 m over 12 km (about 82 ft in 7.5 mi). The Chambly Canal passes along the west side of the river to facilitate navigation past these rapids. The canal consists of nine locks over a length of nearly 19 km (12 mi).

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

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 developed areas (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 Quebec. Of the remaining basin area in Quebec, about 8 percent is urban and other developed land, nearly 16 percent is forest, and about 2.4 percent is wetlands.

REGIONAL HYDROCLIMATOLOGY

The LCRR basin is characterized by a moderate, subhumid continental climate, with four distinct seasons and highly variable weather conditions over the course of the year. Winters are long, cold and snowy while summers are short and moderately warm. Higher elevations of the basin in the Green Mountains of Vermont and the Adirondacks of New York have generally lower temperatures, shorter summers, and more precipitation than the central and lower areas, where temperatures are moderated by elevation influences and to some extent by Lake Champlain itself.

Total average annual precipitation within the basin varies from approximately 71 cm (28 in) for the northwestern shore of Lake Champlain to 152 cm (60 in) along the ridges of the Green and Adirondack Mountains. On average, there is slightly more precipitation in summer (3.5 mm/day, 0.14 in/day) than in winter (2.5 mm/day, 0.1 in/day) (Glisan *et al.* 2019). At higher elevations, annual snowfall regularly exceeds 300 cm (118 in), while the lower portions of the basin receive annual snowfall totals closer to 165 cm (65 in). This variation reflects the combined influence of the prevailing westerly winds, the effects of the lake and the highly variable topography.

A combination of topography and climate make the LCRR basin naturally prone to flooding. The steep mountain slopes of the upper basin, the flow regime of the upper Richelieu River, high winter snowfall amounts and the frequency of heavy spring rainfall are all key drivers of flooding in this basin.

In most of the basin's mountainous areas, a high percentage of the winter precipitation is stored in the snowpack. As a result, 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 period. Since 1908, peak annual lake levels have typically occurred in spring, although most exceptions (2015, 2013, 2004, 2003, 1995, 1991, 1965, 1957, 1927) have occurred over the past three decades primarily due to high lake levels in mid-winter, but also occasionally by high summer levels.

Streamflow in the upper Richelieu River is a direct function of water levels in Lake Champlain and thus, from the outlet of Lake Champlain to Saint-Jean-sur-Richelieu, flooding occurs simultaneously with flood stages on the lake.

ECOSYSTEMS

The LCRR basin supports a diverse range of ecosystems and wildlife. Three major ecosystem types are of particular importance with respect to 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. In modeling and evaluating possible flood mitigation measures in the basin, the Study is focusing on the predicted impacts on and responses of these selected indicators. The Study's indicator species include: the eastern spiny softshell turtle (*Apalone spinifera spinifera*); copper redhorse (*Moxostoma hubbsi*); muskrat (Ondatra zibethicus); northern pike (*Esox lucius*); the hairy-nicked tiger beetle (*Cicindela hirticollis rhodensis*); black tern (*Chlidonias niger*); least bittern (*Ixobrychus exilis*); migratory waterfowl; and wild rice *(Zizania palustris)*. Indicator ecosystems used in the Study include wetlands and small fish communities.

Lake Champlain

Lake Champlain is home to 93 fish species, including northern pike and yellow perch (*Perca flavescens*), sought-after commercial and sport fishing species, and the eastern spiny softshell turtle which is listed as state-threatened in Vermont, a species of special concern in New York and endangered in Québec. The lake is also home to the rare hairy-necked tiger beetle, recognized as a species of concern in the United States. Around 200 bird species frequent the lake, including the black tern, which is endangered in New York and Vermont. At least 17 waterfowl species frequent Lake Champlain and 12 are known to breed there.

Missisquoi Bay, the northern part of Lake Champlain that is located in Canada, is inhabited by 56 species of fish, including a vulnerable fish species, the bridle shiner (*Notropis bifrenatus*). More than 200 bird species frequent the bay, including 26 species of waterfowl (LCBP, 2014). The bay is also home to the eastern spiny softshell turtle.

Richelieu River

The Richelieu River is abundant in aquatic diversity. It is home to about 200 species of birds, including 35 species of waterfowl, and 80 species of fish (MFFP, 2018; eBird, 2018). Eleven species of endangered or threatened fish are found in the river, including American shad (*Alosa sapidissima*), eastern sand darter (*Ammocrypta pellucida*), river redhorse (*Moxostoma carinatum*), and copper redhorse. The copper redhorse is found only in Québec and the health of the species is regarded as an indicator of the impacts of human activity on aquatic ecosystems in southern Québec. The Richelieu River plays a decisive role in the life cycle of the copper redhorse by providing spawning and rearing habitat, and serving as a migration route.

Many species of mammals are known to frequent the LCRR basin, including muskrats, beavers (*Castor canadensis*), and river otters (*Lontra canadensis*).

Riparian and shoreline environments

Riparian and lake shoreline environments constitute the transitional area between terrestrial and aquatic ecosystems, and the structure and biological composition of this environment is largely dictated by changes in water level.

The shoreline of Lake Champlain encompasses highly diverse and productive habitats. Sand dunes, remote islands, forested floodplains and lush wetlands characterize the shoreline ecosystems. In shallow water, emergent plants such as cattail (*Typha spp.*), sedges (*Carex spp.*), and broad-leaved aquatic plants provide shelter and food to many different invertebrates and small fish. They also offer fertile hunting grounds for larger predators such as bass (*Micropterus spp.*), pike, snapping turtles (*Chelydra serpentine*) and wading birds. On the shore, flood-tolerant trees and shrubs such as silver maple (*Acer saccharinum*), green ash (*Fraxinus pennsylvanica*), dogwood (*Cornus spp.*), willow (*Salix spp.*), and buttonbush (*Cephalanthus occidentalis*) provide shelter and nesting places for wildlife. In addition, mammals such as minks (*Neovison vison*) and raccoons (*Procyon lotor*) feed in the shallow water, consuming crustaceans, fish, mollusks, amphibians and plants.

Muskrats are a keystone species of Lake Champlain and the Richelieu River, playing a crucial role in maintaining the structure and integrity of ecosystems. They build houses and burrows in different types of wetlands and agricultural drainage channels, mainly in the shorelines or riparian zone of these habitats. They also play an important role by modifying the vegetation structure, most notably by controlling the abundance of one of their preferred food sources, cattails. Muskrats also alter the topography and create clearings and channels through wetlands, thus shaping a diverse set of vegetation patches. This behavior promotes the development of hemi-marsh, which can benefit many fish and birds (Batzer *et al.*, 2006).

Floodplains and wetlands

Floodplains and wetlands support high levels of biodiversity. They are also valuable economically in terms of the services they provide to society, including water quality benefits and the support of highly productive fisheries. Furthermore, with their capacity to store floodwater and release it slowly, wetlands tend to attenuate the impacts of flooding.

Flooding is an integral part of floodplain and wetland ecosystem dynamics, as they are highly dependent on seasonal water level fluctuations. Seasonal inundation enhances biological productivity and maintains diversity in the system (Bayley, 1995). The plant and animal communities that occupy the floodplains and wetlands are strongly influenced by hydrological variations, including both natural and anthropogenic (human-caused) water-level changes. Fish species such as northern pike have evolved to take advantage of the high water levels that generally takes place over the same weeks every year so that they can rear their offspring in the food-rich, sheltered floodplain habitat. Floodplain and wetland habitats are critical habitats for spawning, and are also used as nursery habitats for juveniles at early stages.

As well, plant communities in floodplains time their seed deposits after the spring floods to best take advantage of the nutrient rich soil generated by flooding (Bayley, 1995).

The Lake Champlain basin has more than 1,214 km^2 (121,400 ha or about 300,000 acres) of wetlands. In the United States portion of the basin, an estimated 50 percent of the original wetlands have been lost to development and landscape modification. Many of the remaining large wetlands on Lake Champlain are located at the mouth of large rivers flowing into the lake or in shallow embayments, such as Missisquoi National Wildlife Refuge, Sandbar National Waterfowl Management Area and Kings Bay Wildlife Management Area.

On the Richelieu River, riparian wetlands are mostly concentrated in the section extending from Missisquoi Bay to Saint-Jean-sur-Richelieu (Canards Illimités Canada, 2013). Riparian wetlands appear relatively fragmented along the margins of the river, though notable large preserved marshes are still found in privately owned ecological reserves located along the South River and at its confluence with the Richelieu River.

1.3.2 SOCIO-ECONOMIC SETTING

POPULATION

The LCRR basin spans parts of seven counties in Vermont, five counties in New York, and five regional county municipalities (RCMs) in Québec (Figure 1-5). Total population within the basin is estimated at about 1,015,000. About 39 percent of this total lives in Vermont, 38 percent in Québec and nearly 23 percent in New York.

The distribution of populations, infrastructure and the built environment, key factors in considering the social and economic impacts of flooding, vary widely in the basin (Figure 1-6). 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, the county that contains Burlington, the largest city in the state.

INDIGENOUS PEOPLES

The Study area is located in the traditional territories of *Haudenosaunee* (Iroquoian) and *Wabanaki* (Algonquin) peoples, who continue to be present and active on the lands and waters of the region. Broadly speaking, the Mohawk (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 Quebec and reservation land

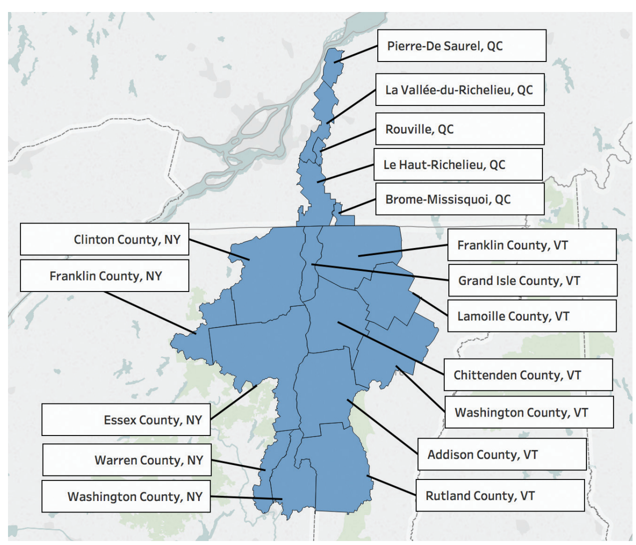
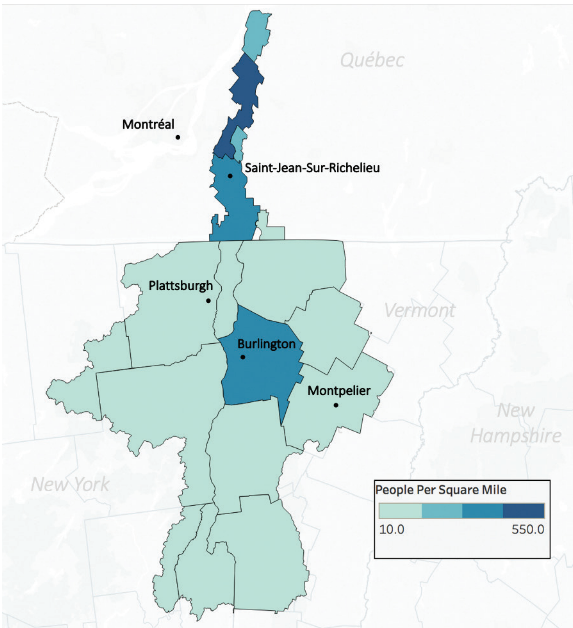


Figure 1-5 | Counties and regional county municipalities within the Lake Champlain-Richelieu River basin
(Note: This map only depicts portions of the counties/RCMs within the basin, not their entire boundaries)

Figure 1-6 | **Population densities within the Lake Champlain-Richelieu River region**



in the State of New York. The Mohawk communities of Kahnawà:ke, Kanesatake, and Akwesasne are located nearest the Study area.

The northeast portion of the Study area is of particular importance to *La Nation Abénakise* (Abenakis Nation), whose reserve lands are in the province of Quebec. Abénakise population centers are located at Odanak and W8linak. Four *Abenaki* tribes recognized by the State of Vermont currently reside on the east side of Lake Champlain but do not have reservation lands. The lands and waters of Lake Champlain and the Richelieu River have central importance to the cultures and livelihoods of all these communities.

ECONOMY

Québec

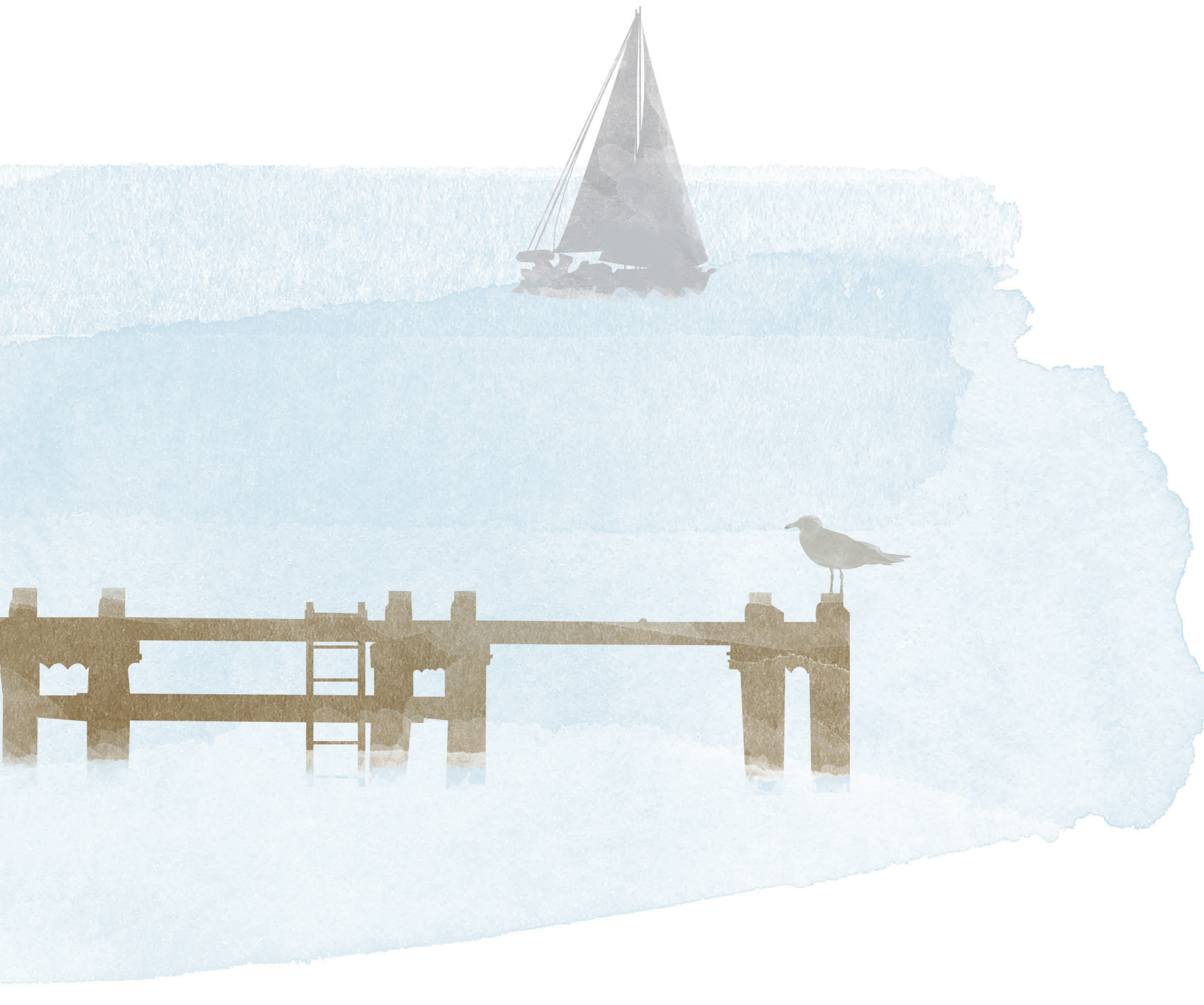
The region of Québec within the LCRR basin is characterized by its diversified economy based on a well-developed commercial sector driven by urban growth from Montreal, high population growth, and industry rooted in agriculture, metal products, machinery, transportation equipment, aerospace and life science sectors. An additional important economic activity in the region is tourism, particularly concentrated around outdoor activities, culture and popular tourism-related villages.

Vermont

The most prominent industry in the state of Vermont is healthcare, where nearly 50,000 residents are employed. Healthcare is closely followed by education and retail. Other prominent industries include manufacturing, construction, hospitality, agriculture, and real estate. Tourism and recreation, particularly centered on Lake Champlain, also represent a substantial economic sector in Vermont, with direct spending by visitors often exceeding $1 billion in a year. Additionally, there are currently nearly 10,100 km^2 (1.01 million ha or 2.47 million acres) of farm and forest (https://vtfuturesproject.org/).

New York

In New York, the region within the LCRR basin is known as the North Country. This area accounts for about two percent of the state's population and is made up primarily of small communities with aging populations. Primary economic contributors to the region include the local universities and military bases, as well as correctional facilities. Agriculture, health care, and outdoor recreation are also important components of the North Country's economy (DiNapoli, 2017).



2. CAUSES OF PAST FLOODING IN THE BASIN

Chapter 2 | reviews the causes of past flooding in the LCRR basin, with a focus on the 2011 spring flooding event. First, the chapter presents an overview of five major floods in the basin. Next, it reviews the role of factors contributing to these floods. These factors include both natural forces, such as geography and weather, and anthropogenic (human-caused) changes in the basin, such as population growth and land use changes, channel modifications and the construction of infrastructure. Note, however, that there are linkages, as in, for example, the role of some anthropogenic activities in affecting the level of Lake Champlain.

2.1 OVERVIEW OF PAST FLOODS

This section presents a brief overview of five major floods in the basin. To allow for comparison between the different gauging stations and events, all elevations are referenced to meters above a common vertical datum, North American Vertical Datum of 1988 (NAVD 88).

THE FLOOD OF 1927

The flood of November 1927 was unusual in that the flood occurred in the fall rather the typical spring flood scenario. In the month preceding the flood, rainfall averaged about 150 percent of normal across the region, with some areas receiving up to three times normal amounts. From November 2 to 5, some areas received rainfall exceeding 228 mm (8.98 in) (Kinnison, 1929). The rain fell consistently throughout the month, saturatingthe soils.

The lake levels eventually peaked at Rouses Point, New York, on December 10, at 30.28 m (99.34 ft), which is below the NOAA (National Oceanic and Atmospheric Administration) minor flood elevation. The Richelieu River at Saint-Jean reached a maximum daily mean of 1070 m^3/s (37,787 ft^3/s) also on December 10, but quickly returned to below flood levels without a supply of melting snowpack or precipitation adequate to sustain lake levels and flood flows.

This flood was most destructive in Vermont and was driven by remnants of a tropical storm delivering 127 to 254 mm (5 to 10 in) of rain over a wide area (Paulson *et al.*, 1991). The total damage across Vermont was estimated at more than $30 million US[7], with 84 deaths resulting from the flooding, mostly on the lake tributaries in the sub-basins above the lake but not on the lake itself. Devastation occurred across the state, but the Winooski valley was one of the hardest hit areas. The US Army Corps of Engineers built three flood retention reservoirs in the Winooski River basin in response to the 1927 flood to help reduce impacts from future floods (Kinnison, 1929). All three of these reservoirs are still in operation. While they can help reduce the impact of floods on Winooski River, they have no significant impacts on Lake Champlain and Richelieu River floods. (For more information on the impact of reservoirs in the basin, see section 2.2.2)

[7] **$400 million in US dollars equivalent (2018). $520 million in Canadian dollars equivalent (CAN 2018).**

THE FLOOD OF 1976

The flood of 1976 is consistent with the pattern of warm spring rains over late snowpack driving significant floods of the lake and Richelieu River. The combined inflows into Lake Champlain in 1976 exceeded the outflow to the Richelieu River near Rouses Point for about two weeks during a series of moderate rainfall runoff events in late March and early April. Lake Champlain reached major flood stage at Burlington, Vermont for five days, with a peak of 30.8 m (101.1 ft) on April 4 and exceeded minor flood stage for a total of 25 days (March 28 to April 21).[8] The Richelieu River at Fryer Rapids crested at 1,200 m^3/s (42,378ft^3/s), remaining above minor flood stage for 10 days.

THE FLOODS OF 1993 AND 1998

The flood of 1993 produced a peak at Rouses Point, New York, of 30.91 m (101.41 ft) on April 27. This was the highest level since at least 1869 (Shanley and Denner, 1999).

The flood of 1998 was similar in timing and magnitude to that of 1993. On April 5, 1998, Lake Champlain peaked at 30.87 m (101.27 ft) at Rouses Point. The highest recorded stage was 30.882 m (101.30 ft) at Burlington, Vermont.

There is a similarity in timing and magnitude of these events, though the forces driving them and the antecedent conditions are not identical.

In 1993, the flood was preceded by lower lake levels, but a larger snowpack, recharged by a major blizzard in mid-March. This provided for additional water to be continually released into the lake during heavy April rains (Shanley and Denner, 1999). The combined inflows into Lake Champlain exceed the outflow near Rouses Point for almost the entire month of April, though the lake was only above NOAA major flood stage for seven days (April 26 through May 2) and minor flood stage for 27 days (April 18 through May 14). The Richelieu River at Fryer Rapids exceeded MSP minor flood flows of 1,064 m^3/s (37,575 ft^3/s) in 1993 for 20 days, cresting at 1,330 m^3/s (46,969 ft^3/s), slightly below MSP major flood flows of 1,335 m^3/s (47,145 ft^3/s).

By contrast, lake levels leading up to the 1998 flood were significantly greater than in 1993 and the peak lake level was driven primarily by a single, but significant runoff event from rains at the end of March 1998. The combined inflows into Lake Champlain in 1998 exceed the outflow to the Richelieu River near Rouses Point for only about a week, but the lake was still above major flood stage for seven days (April 3 through April 9) and minor flood stage for 24 days (March 31 through April 23), similar durations to 1993. The Richelieu River at Fryer Rapids exceeded MSP minor flood flows of 1,064 m^3/s (37,575 ft^3/s) for 12 days, cresting below at 1,230 m^3/s (43,437 ft^3/s).

Following the 1993 and 1998 floods, lake levels and river flows returned to base levels shortly after precipitation subsided, due to the complete melt of the snowpack.

THE 2011 SPRING FLOOD

In the spring of 2011, the confluence of warm temperatures, record precipitation and rapid melting of a near-record snowpack caused historically high flood levels in the basin tributaries and in Lake Champlain and the Richelieu River (Saad *et al*., 2016). While spring flooding is common along the shores of Lake Champlain, the duration of the 2011 flood period was unprecedented. Lake levels remained above NOAA minor flood stage of 30.35 m (99.57 ft) for 67 days at Rouses Point, from April 13, 2011 to June 19, 2011 (Figure 2-1).

Over the 2010-2011 winter, snowfall in Burlington, Vermont, measured 326.14 cm (128.4 in), the third highest total since 1883 (NOAA, 2011). In addition, no major thaw occurred mid-winter. The mean monthly temperatures from February to June were at or above mean temperatures. Total precipitation in the basin in March was 46 percent above average, while April experienced 174 percent and May 213 percent above average. The three-month total for the meteorological Spring (the months of March, April and May) was also a record, higher than the previous record by 113.8 mm (4.48 in) (NOAA 2011). Table 2-1 shows the precipitation statistics for spring 2011 as recorded in Burlington, Vermont.

8 Flood stages for Lake Champlain are defined for the Rouses Point gauge as minor flood >30.35 m (99.57 ft), major flood >30.81 m (101.07 ft).

The flood resulted in a period of record maximum lake levels recorded at all lake gages on Lake Champlain. The maximum recorded stage at Rouses Point, New York, was 31.32 m (102.77 ft) on May 6, 2011. Before the 2011 flooding, the highest lake level elevation recorded at the Rouses Point, New York, gage was 30.99 m (101.67 ft) on May 4, 1869.

The record flood of 2011 was further exacerbated, at times, by wind set-up, due to persistent winds from the south. Historical observations of Lake Champlain elevations at the Rouses Point gage have shown that water levels there can increase by 15.2 to 30.5 cm (6-12 in) when average south wind speeds over the lake range between 25 to 35 knots for durations of six hours or more. During the spring of 2011, Lake Champlain was in flood status for 67 days.

Over that period, there were eight separate wind set-up events that pushed the nominal lake elevation up by between 7.6 and 21.3 cm (3 to 8.4 in). The most dramatic of these events occurred on April 23, 2011, when the lake was in minor flood status, just below the moderate flood level of 30.65 m (100.5 ft). The ensuing 21.3 cm (8.4 in) rise pushed the Rouses Point elevation into moderate flood and then past the 30.81 m (101.07 ft) major flood threshold. The wind event ended the next day and lake elevations were back down into the minor flood range. The Richelieu River at Fryer Rapids exceeded flood flows of 1,064 m^3/s (37,575 ft^3/s) from April 20 to until June 28, a total of 69 days, including a maximum recorded flow of 1539 m^3/s (54,349 ft^3/s). Increases in the elevation of Lake Champlain during the flood were translated downstream on the river and the same south winds amplified river stages.

Figure 2-1 | **Floods reaching NOAA Major flood level, Lake Champlain (1976-2011)**

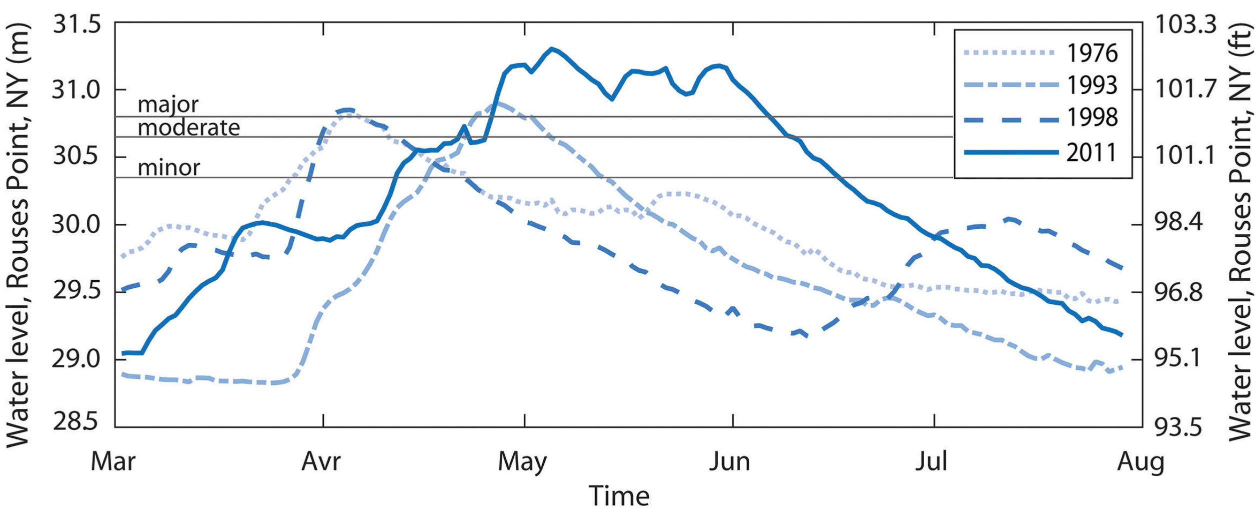


Table 2-1 | **Precipitation in Burlington, Vermont, spring 2011**

MONTH (2011)	AMOUNT		NORMAL		EXCEEDANCE		% ABOVE AVERAGE
	cm	inches	cm	inches	cm	inches	
MARCH	8.59	3.38	5.89	2.32	2.72	1.07	46%
APRIL	20.02	7.88	7.32	2.88	12.70	5.00	174%
MAY	22.02	8.67	7.04	2.77	14.99	5.90	213%
METEOROLOGICAL SPRING	50.65	19.94	20.24	7.97	30.40	11.97	150%

Source: (NOAA 2011)

2.2 NATURAL FORCES AFFECTING FLOODING IN THE BASIN

2.2.1 PHYSICAL GEOGRAPHY

With the exception of a major flood in 1927, the largest flooding events recorded in the last 150 years in the basin have occurred during the spring, with a significant snowpack still present over much of the basin. The high terrain of the Adirondack and Green Mountains of New York and Vermont can accumulate large amounts of snow throughout the winter and into the spring, persisting into the rainy spring season. This results in large snow water equivalent volumes stored across the Lake Champlain region. A heavy snowpack, coupled with significant warm spring rains, commonly drives the most devastating flood conditions on Lake Champlain by rapidly contributing large volumes of meltwater to tributaries and the lake. However, the relative contributions from those influences vary with timing of seasonal freeze and thaw events. Large portions of the watershed lie in high elevations, making snow water equivalent and rate of snowpack melt an important contributor to spring flooding potential.

The exceptions to these spring events are floods caused by tropical storms. For example, in 2011, Tropical Storm Irene caused significant flooding in late August in the tributaries to Lake Champlain. However, while tropical storms drop significant volumes of rain within a few days, which lead to short-duration flooding on Lake Champlain tributaries, the total volume of water entering the lake from individual storms has not often led to large floods along Lake Champlain's shorelines or the floodplain of the Richelieu River.

About 90 percent of the drainage to the Richelieu River comes from Lake Champlain. As such, lake outflows have a dominant impact on the flows in the river downstream. The significant storage capacity of Lake Champlain results in long duration floods in the river (Shanley and Denner, 1999). When the total inflows into the lake are greater than the Richelieu River outflow capacity, Lake Champlain water levels rise and often exceed flood level for weeks, resulting in long, sustained floods along the lake shore and the Richelieu downstream of the lake, long after the flooding had receded in the upper reaches of the Lake Champlain sub-basins.

Water levels within Lake Champlain are also affected by winds and waves. With its north-south orientation and elongated shape, Lake Champlain is especially susceptible to south and north winds, to the extent that a sustained south wind of 25 knots for six hours can setup lake elevations up to 15.2 cm (6 in) at Rouses Point, New York while concurrently dropping lake levels at the Crown Point Bridge by a somewhat similar level. Sustained south winds of more than 35 knots can double those changes in levels. If wind forcing was from the east (or west), the largest setups would be seen on the western (or eastern) shores but with a much smaller change in elevation than the north-south case, due to the shorter distance over which the wind can blow.

For the southerly wind just noted, the enhanced elevations are translated downstream to the Richelieu River as water flows out of the lake. Similarly, the stronger the winds, the larger the waves, which in turn can lead to enhanced shoreline erosion. After the relaxation of the winds, the water surface over the entire lake seeks to go back to its normal undisturbed level, but in doing so sets up a "rocking" of the lake surface. This periodic oscillation of the lake's surface is known as a standing wave or seiche. For the main part of Lake Champlain, this oscillation can last for about four hours, with the height of the wave decreasing quickly over a period of 16 to 20 hours.

These wind and wave conditions can amplify local flooding if lake levels are already high due to a significant volume of inflow to the lake.

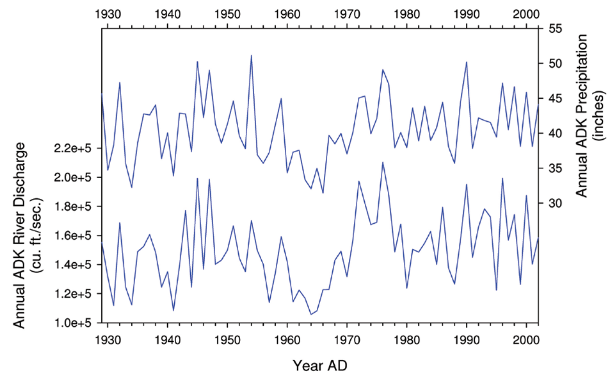
2.2.2
CHANGES IN WEATHER PATTERNS

Climate warming and increases in precipitation and associated changes in snow and hydrologic regimes have been observed over the last century in the study area. Since 1915, the region of the Richelieu River basin has become warmer and wetter (Guilbert *et al.*, 2014) with a temperature increase of 1°C/ 1.8°F (mainly affecting daily minimum temperature) and a precipitation increase of 0.7 mm/.03 in/day. The mean annual discharge at the Richelieu River outlet is around 380 m^3/s (13,420 f^3/s) and it rose significantly by 14 m^3/s (494 f^3/s) per decade during the period 1938-2017.

Many studies have associated this with a change in the North Atlantic Oscillation Index to a generally positive phase beginning around 1970. Trends in specific climatic and hydrologic variables differ in their responses spatially (*e.g.*, coastal versus. inland) and temporally (*e.g.*, spring versus. summer).

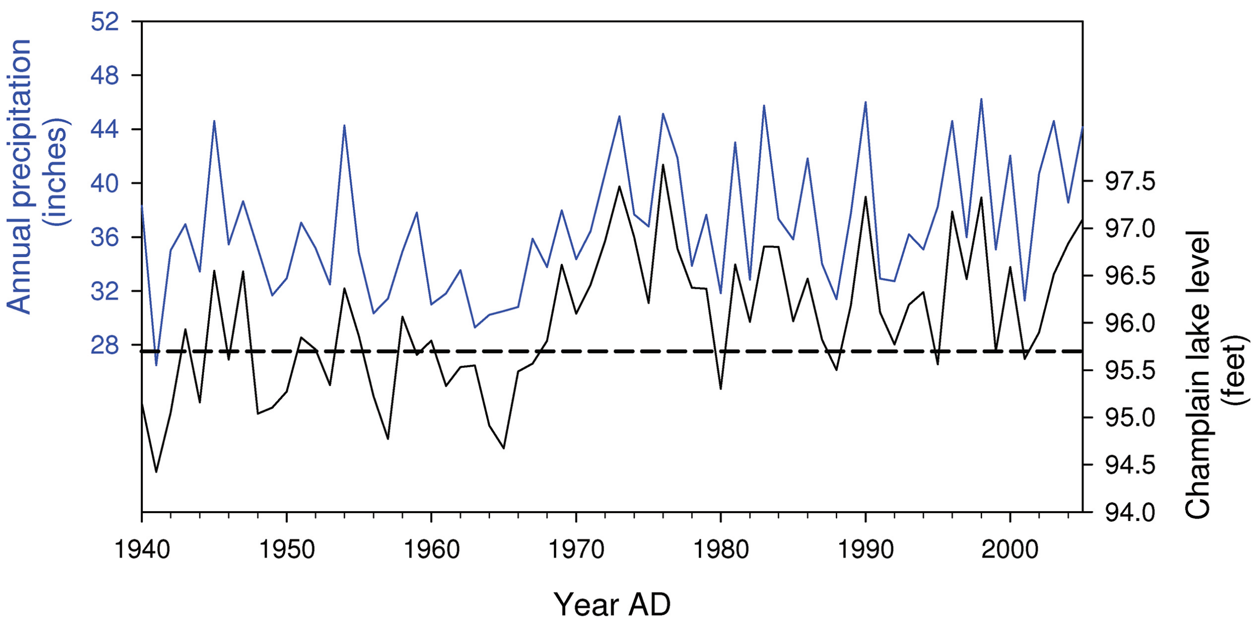
Precipitation is correlated to annual river discharge in Adirondack watersheds as well as to Lake Champlain water levels across the broader Lake Champlain watershed (Figure 2-2 and 2-3).

Figure 2-2 | River discharge and annual precipitation in the Adirondacks, 1929–2002



Annual river discharge in cubic feet per second)
Source: Stager and Thill (2010)

Figure 2-3 | Precipitation and mean lake levels of Lake Champlain since 1940



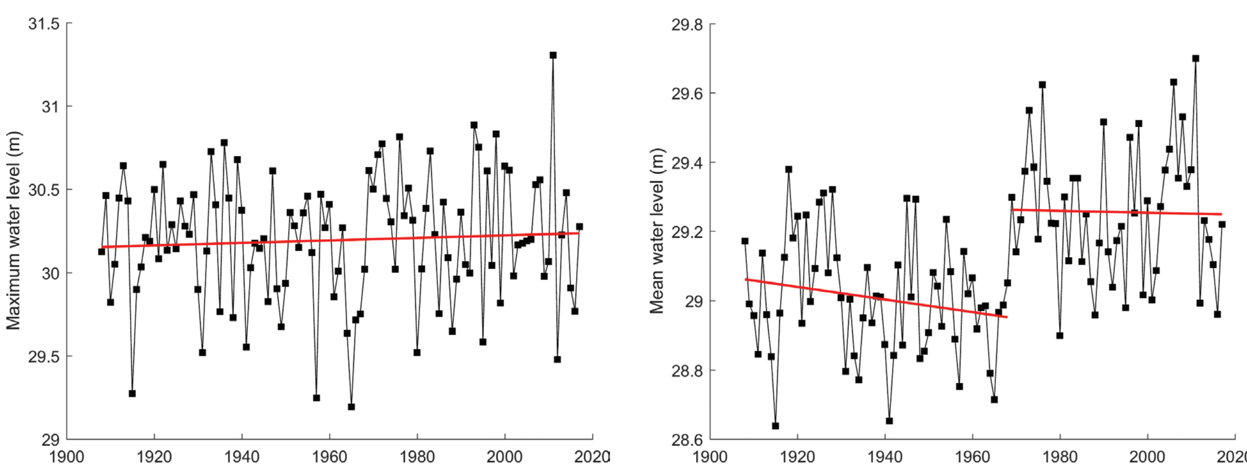
Total annual precipitation averaged from eight USHCN stations in the watershed vs. mean level of Lake Champlain since 1940. Note the prominent jump to higher precipitation and lake levels ca. 1970. The close similarity between these two records shows that precipitation is the dominant source of inter-annual variation in the level of the lake. The dotted line represents the average annual lake level
Source: Stager and Thill (2010)

United States Geological Survey (USGS) discharge data show that many rivers north of the 44th parallel have progressively experienced earlier high flows in winter/spring during the 20th century (Hodgkins and Dudley, 2006). This is consistent with regional warming trends and suggests that a similar change may be expected for Lake Champlain. As winters become warmer and snow is more often replaced by rain, river flow may become more variable and higher during the cold months of the year, thus increasing the magnitudes and frequencies of mid-season floods and ice jams (Stager and Thill, 2010). However, the overall reduction of the snow cover might also reduce the volume of potential meltwater left to be released later on during spring.

2.2.3 TRENDING OF THE BASELINE LAKE LEVEL

A key issue with respect to understanding the recent flooding in the basin is whether the water level of Lake Champlain has risen over time. A recent background study prepared for the IJC shows trends and the presence of change points in the Lake Champlain water levels (Ouarda and Charron, 2019). The analysis identifies two trends in the historical Lake Champlain water levels. The first trend is a decline in mean water levels from 1800 to 1969. The second trend from 1969 to 2018 shows a relatively stable mean annual water level but higher than the previous period (Figure 2-4). However, the analysis concludes that there is an increase in the observed annual maximum (quarter monthly mean) Lake Champlain water level over the 1900-2018 period. It suggests that the point of change in the mean water level in 1969 occurred around the time when anthropogenic modifications took place in the watershed of the Richelieu River. Another study found that after 1971

Figure 2-4 | Trends and point of changes in Lake Champlain water levels



Source: Ouarda and Charron, 2019.

the Lake Champlain water levels increased following the enlargement of the Chambly Canal (WSP, 2017). This latter study suggests that the water level of Lake Champlain rose by 30 cm (1 ft) and from that increase, half of it is because of the enlargement of the Chambly canal and the other half, because of a change in the climate (increase precipitation over the watershed).

2.2.4 EFFECTS OF VEGETATION IN THE RICHELIEU RIVER

Some increase in Lake Champlain water levels during the summer months can be attributed to aquatic plant growth in the channel of the Richelieu River. Aquatic plants increase friction in the river channel, slowing the flow and thereby increasing upstream lake levels. Studies carried out by the International Champlain-Richelieu Board (ICRB) suggest that vegetation in the Richelieu River section between Lake Champlain and Saint-Jean-sur-Richelieu has an impact on lake levels, especially during summer months.

The appearance, existence and growth of aquatic vegetation are greatly influenced by factors related to nutrients entering the LCRR system. However, aquatic plants are also affected by various climatic and flow parameters including temperature, magnitude, duration and timing of peak flows and the subsequent runoff pattern. As a result of these numerous factors, the impact of plant growth on lake levels can vary considerably from year to year and even from month to month. Typically, the impact is greatest in the month of August and lowest in the months of April and November.

In general, vegetation affects the lake levels at the low and medium range of flows and has less impact at high flows. During the period 1951-1975, the average lake level increase due to plant growth has almost doubled compared to the 1925-1950 period. As regional warming continues and reflective ice cover decreases, Lake Champlain is likely to warm as well. With increasing water temperatures, the effect of plant growth on lake levels also will continue to increase.

2.3 ANTHROPOGENIC CHANGES TO THE BASIN

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, as well. However, the degree to which many of these activities have affected flooding in the basin is not certain and remains to be assessed.

2.3.1 POPULATION GROWTH AND LAND USE CHANGES

Population growth can influence land use when the natural land cover in a region is converted to a wide range of new purposes, such as agriculture, housing in urban and suburban areas, 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, and an increase in the area of impervious surfaces, such as asphalt (for example, parking lots and roads).

These changes can influence how water moves through a watershed, particularly during a flood event. When rains falls on natural land cover, the flow of rainwater is slowed by vegetation and soils. Where the natural cover has been removed and replaced by drainage systems and impervious surfaces, the runoff into streams, rivers and lakes will be more rapid (Clithero, 2017). The loss of natural cover also can increase the rate of flow of pesticides, road pollutants, gasoline and fertilizers into the environment. Researchers have concluded that the amount of rainwater runoff nearly doubles when impervious surface area is 10 to 20 percent of the watershed area, and triples at 35 to 50 percent (Arnold and Gibbons, 1996 as cited in Clithero, 2017). In other words, as impervious surface increases in a watershed, stormwater runoff increases drastically.

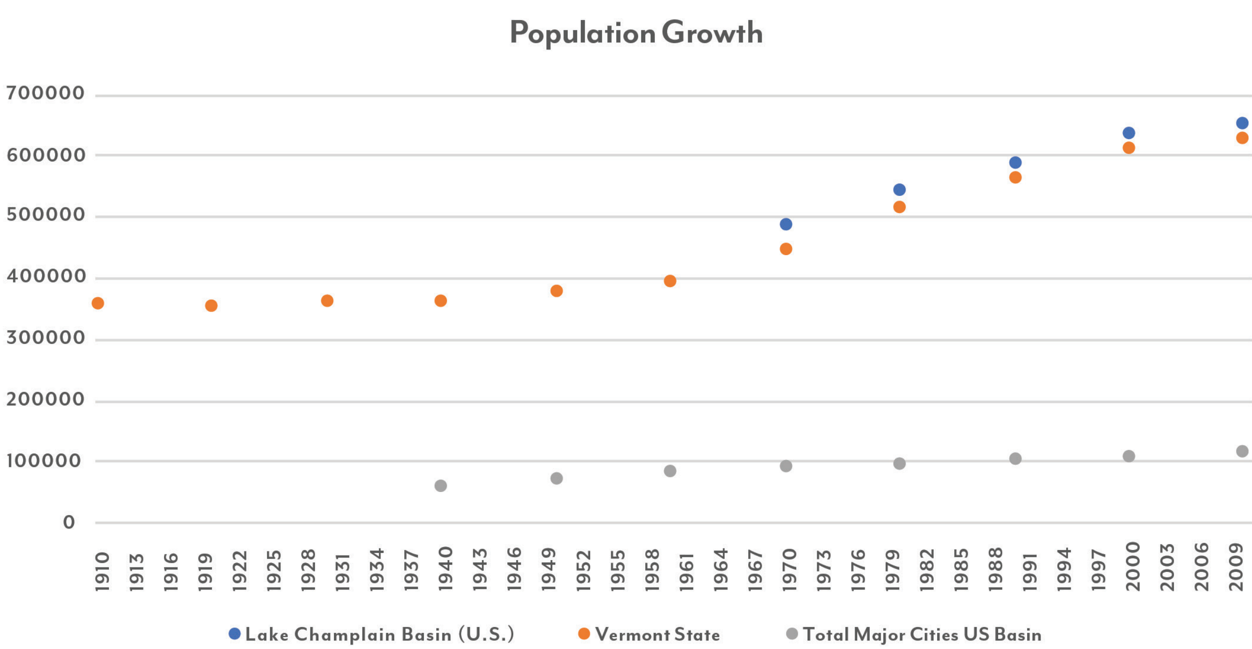
POPULATION GROWTH

Reliable data on the link between population growth and land use changes in the basin are limited. In general, the 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 6 percent (LCBP, 2019) (Figure 2-5). However, growth rates have varied from one area to another. Much of Vermont has seen steady growth over the last decade, while some parts of New York have experienced significant population declines.

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 (Figure 2-6, on page 22). Figure 1-6, in Chapter 1, also illustrates that the population density in the Richelieu River valley is highest in these urban areas.

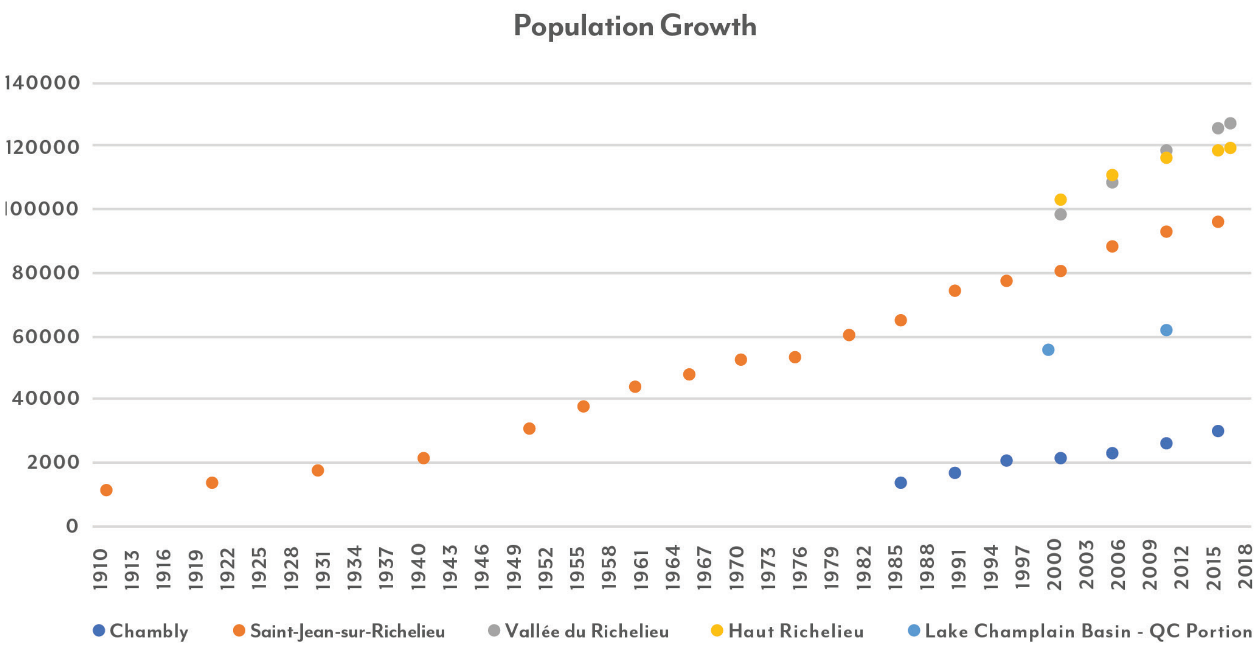
Given that population growth was moderate in the first half of the 20th century, any effects of development in the floodplain on flooding in the basin likely were small or negligible before the 1950s.

Figure 2-5 | Population growth in the United States portion of the basin, 1910-2009



Source: worldpopulationreview.com

Figure 2-6 | **Population growth in the Québec portion of the basin, 1910-2018**



Source: worldpopulationreview.com; Government of Québec (2018), Bulletin statistique régional Montérégie (2017), Statistics Canada (2018)

DEVELOPMENT IN THE FLOODPLAIN

By contrast, 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. As a result, the effects of population growth, such as the development of urban and industrial areas and the increase in the extent of impervious surfaces, might have had a more pronounced effect with regard to flooding conditions and level of impacts.

Population growth in the Richelieu River basin has been paralleled by the growth of buildings in the floodplain. Figure 2-7 shows an increased rate of construction in the area flooded in 2011, starting in the 1940s, with peaks in the 1970s, 1990s and 2000s. As the number of buildings in the floodplain has increased over the years, so too has the value of those buildings and the cost of damages due to flooding (Figure 2-8). The total estimated value of these buildings in 2018 was over $350 million CAN[9].

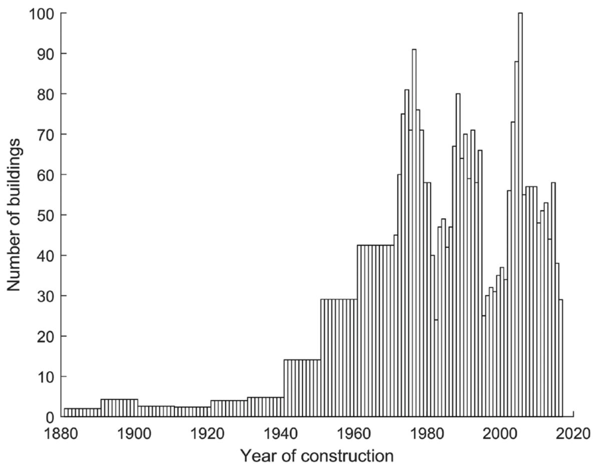
WETLANDS LOSS

As noted, about 50 percent of wetlands in the basin within the United States have been drained and converted to other land uses, usually agriculture and urbanization. Similarly, an estimated 45 percent of the original wetlands of the Richelieu River valley have been converted (Joly *et al.*, 2008).

In some agricultural areas, this conversion is achieved through the installation of tiles to drain former wetlands. For example, about 5 percent of Vermont's cropland (9,500 ha on 525 farms) has tile drainage (LCBP, 2016).

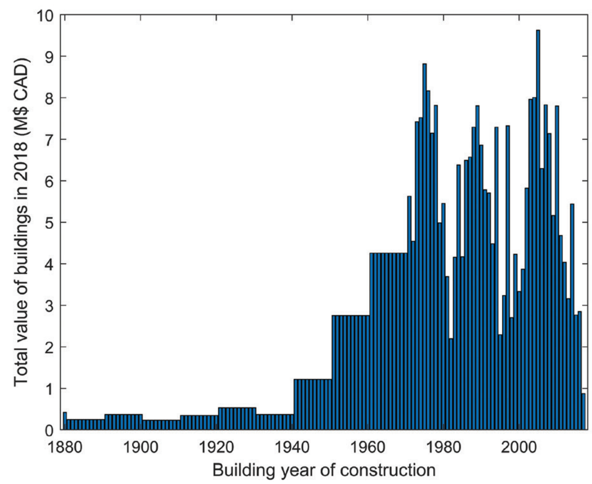
[9] **$271 million in US dollars equivalent (US 2018).**

Figure 2-7 | Buildings (all types) constructed, by year, in the area flooded by the Richelieu River in 2011



Note: Estimates using a 2D hydrodynamic model simulation. Prior to 1970, the number of buildings indicates yearly averages per decade. Data not shown for units for which year of construction is not available (1181 units, or 24% of total number of units). Year of construction after 2011 includes reconstruction of homes damaged in the flood.
Source: Property assessment role, Government of Quebec, 2018.

Figure 2-8 | Estimated 2018 value of buildings (all types) in the area of the Richelieu River flooded in 2011



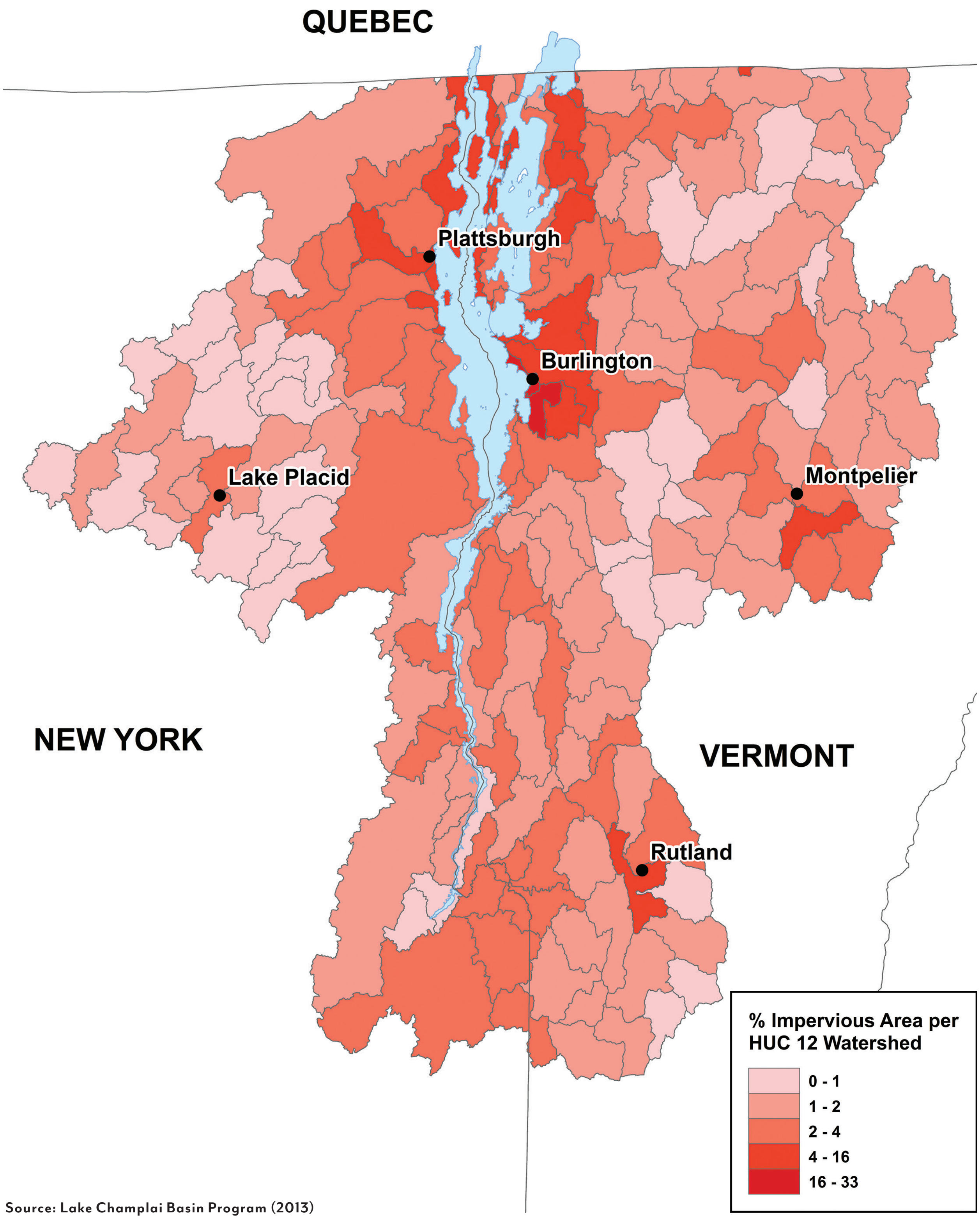
Note: Each column shows the 2018 value (CAN) of buildings constructed in a particular year. The flooded area of 2011 is based on a digital elevation model.
Source: Property assessment role, Government of Quebec, 2018.

IMPERVIOUS SURFACES

In terms of impervious surfaces in the basin, one recent study found that the lakeshore of Lake Champlain has the highest concentrations of developed features in the United States portion of the basin, particularly the Burlington-St. Albans corridor in Vermont and the Plattsburgh area in New York (Figure 2-9) (LCBP, 2013). In a small watershed draining the Burlington waterfront, impervious surfaces constituted 33 percent of the watershed's land area, the highest proportion observed in the basin. There are no comparable data for the Richelieu River portion of the basin.

However, as shown in Figure 2-4, the population growth of major cities in the United States portion of the basin has been relatively modest over the past century. This implies that there has not been a rapid growth in the extent of urban development and related expansion of impervious surfaces since 1950. If that is the case, then the increase in the size of impervious surface areas around Lake Champlain likely has not played a critical in regard to flooding conditions in the basin. However, these effects need to be assessed further before any clear conclusions can be made.

Figure 2-9 | **Percent area of impervious surfaces for Lake Champlain Basin**



Source: Lake Champlai Basin Program (2013)

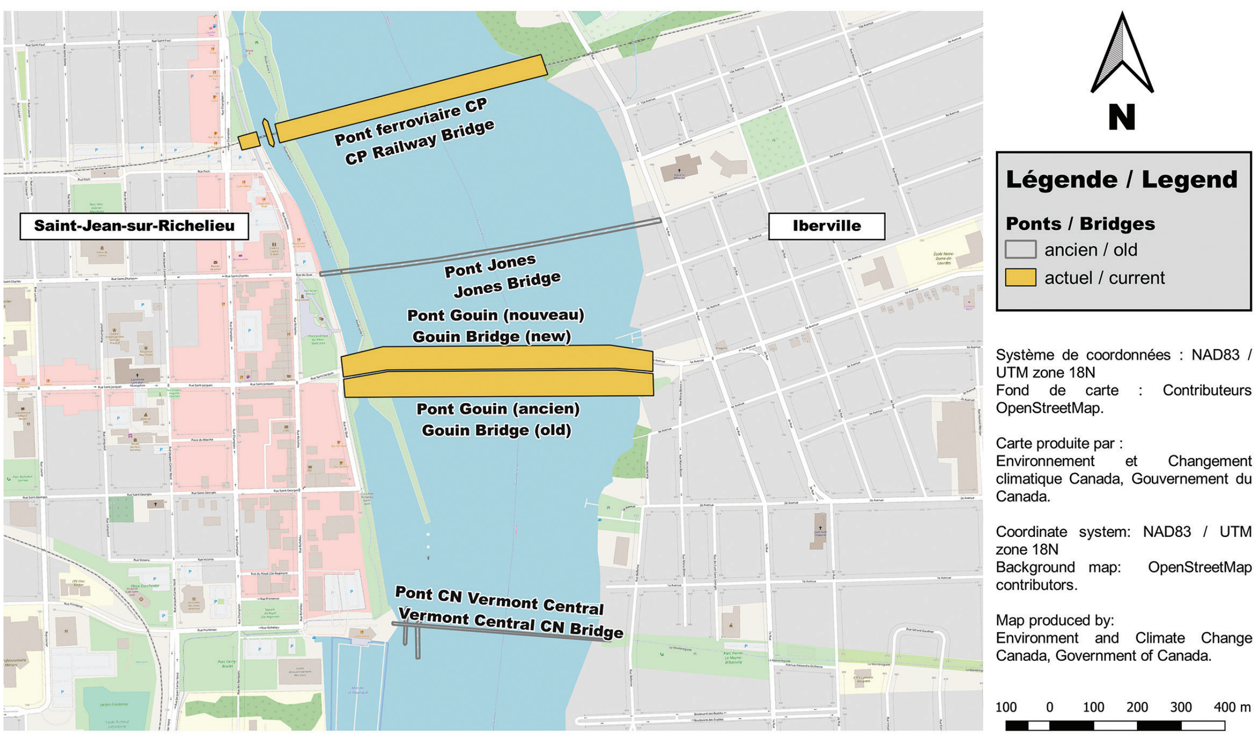
2.3.2
CHANNEL ALTERATIONS AND INSTREAM CONSTRUCTION

Since the 19th century, several channel alterations and instream constructions have been made in the Richelieu River to accommodate human needs (Table 2-2). While some of these constructions had negligible or unknown effects on the hydraulic conditions of the river, others, like the Chambly Canal, have modified the river flows and water levels.

BRIDGES

Over the years, many bridges were constructed in the Richelieu River (Figure 2-10). Some remain today while others have been demolished. The pillars of the remaining bridges and the remnant pillars encroach into the flow section and, as a result, reduce the flow capacity and may cause a variation of the water surface (WSP, 2017). In the Saint-Jean shoal area, several bridges were built. The Jones Bridge was built in 1826 and later demolished following the construction of the Gouin Bridge in 1916. The Gouin bridge of 1916 will be demolished in 2020 as the new Gouin Bridge of 2019 is replacing it. The Canadian Pacific Bridge, built in 1886, is still standing. The Central Vermont Bridge, built in 1864, was demolished in 1967. Many other bridges are located on the Richelieu River. Downstream of Saint-Jean-sur-Richelieu, many remnant and existing bridges were built for railways or roads. Since those civil works are located downstream of the Saint-Jean shoal they have no effect on the water surface profile. However several other bridges are located upstream of Saint-Jean-sur-Richelieu and their effect on the water surface profile are still unknown. However, considering their location, the effect should be less than from those located on the Saint-Jean shoal.

Figure 2-10 | **Location of bridges on the Richelieu River in the vicinity of Saint-Jean-sur-Richelieu.**



(Source: WSP, 2017)

Table 2-2 | **Past anthropogenic modifications in the Richelieu River**

DATES	CONSTRUCTION / MODIFICATION
1826	Construction of Jones Bridge
1831-1843	Construction of the Chambly Canal
Between 1830 and 1886	Construction of Eel trap fisheries and mills with extensive dykes
1864	Construction of the Central Vermont Railway Bridge
1886	Construction of the Canadian Pacific Railway Bridge
1887	Construction of the Atlantic Railway Bridge near Lacolle
1908	Dredging between Jones Bridge and Central Vermont Bridge
Between 1908 and 1911	Extensive large land filling near the Central Vermont Bridge, now the Saint-Jean-sur-Richelieu Marina
1909-1910	Extensive dredging between Jones Bridge and Central Vermont Bridge (spoil left on the Iberville side upstream of the Central Vermont Bridge)
1915-1918	Construction of the Gouin bridge
1916	Demolition of the Jones Bridge
1928-1930	The Canadian government undertakes dredging works. The Richelieu River is dredged to 3.66 m (12 ft) between Sorel and Saint-Ours
1930-1933	A new lock is constructed at the Saint-Ours Canal
1938	Construction of the Fryer Island Dam
1939	Dredging to a depth of 3.66 m (12 ft) between Saint-Jean-sur-Richelieu and Rouses Point (Sévigny 1978)
1967	Demolition of the Central Vermont Bridge
1970	Start of expansion work of the Chambly canal downstream of lock number 9
1973	End of extension work of the Chambly Canal
2017-2019	Construction of the new Gouin Bridge
2020	Projected demolition of the 1918 Gouin bridge structure

CHAMBLY CANAL

The construction of the Chambly Canal, from 1831 to 1843, generally is considered to have an impact on the hydraulic conditions of the Richelieu River (WSP, 2017). Historical photos indicate that the pier at the entrance of the canal was on stilts at the beginning of the canal operation. This structure allowed for a partial flow of water, unlike a river embankment.

In the early 1970s, Transport Canada, then later Parks Canada widened the Chambly canal in the Saint-Jean-sur-Richelieu reach by about 30 m (100 ft) downstream of lock No. 9, into the main river channel. This work was undertaken to address the increased recreational boating traffic and larger recreational vehicles using this waterway. This widening of the canal took place in the narrowest section of the river in the Saint-Jean-sur-Richelieu shoal area, which acts as a natural control affecting lake levels.

The IJC's International Champlain-Richelieu Board (ICRB), which was responsible for regulating water levels in the basin, sought to determine the hydraulic implications associated with the canal widening, using three different scientific approaches. The ICRB found that, in general, the three approaches produced comparable results, ranging from an impact on Lake Champlain water levels of 3-10 cm (1.2- 4 in) (Table 2-3). The stage-discharge relationships methodology produced slightly higher and variable results, which was attributed to increased plant growth impacting the water levels during this period. The fact that the different methods of analysis produced similar results provided the ICRB with a high level of confidence in the assessment of the hydraulic implications of the widening of the canal.

More recent studies have also concluded that the widening of the Chambly Canal in the 1970s likely had an impact on the hydraulic conditions of the upper Richelieu River and the Missisquoi Bay (Murphy, 2014; WSP, 2017). The WSP study, for example, found that of the estimated 30 cm (nearly 1 ft) increase in water levels observed at Lake Champlain since the 1970s, about one-half is explained by the widening of the canal, with the balance explained by a 10 percent increase in water supply (precipitation and water from upstream) in the basin since the early 1970s.

An additional widening of the Chambly Canal was carried out in the 1970s upstream of lock No. 9 in the vicinity of the Canadian Pacific Railway bridge. However, this relatively wide section of the river is upstream of control and hence widening in this small reach has had no effect on lake levels.

Table 2-3 | Estimated water level changes in Lake Champlain after the Chambly Canal widening

METHOD OF ANALYSIS	EFFECT AT HIGH FLOW (CM)	EFFECT AT HIGH FLOW (IN)
MATHEMATICAL MODEL	+9.1	+3.6
PHYSICAL MODEL	+3.0	+1.2
HYDROMETRIC GAUGE STAGE-DISCHARGE RELATIONSHIPS	+4.3 to +10.06	+1.7 to +4.0

(Source: IJC, 1980)

IMPACT OF INSTREAM MODIFICATIONS IN THE RICHELIEU RIVER

Instream modifications, such as the establishment of eel cribs, rail and road transportation piers, and the widening of the Chambly Canal, tend to impede flows and raise lake water levels. In contrast, dredging or removing obstacles tend to accelerate flow passage and decrease water levels. While most of these modifications are minor, their impact is amplified by the fact they were located in the vicinity of the Saint-Jean-sur-Richelieu shoal, which is a critical section that controls Lake Champlain levels.

Many structural remnants are still visible on the Saint-Jean shoal. Among them the most noticeable, especially at low flow conditions, are the old eel-trap installations of the Thuot and Goyette fisheries. Those massive V-shaped stones and wooden board structures were designed to catch eels when they were migrating through the Richelieu River. These remnants reduce the flow capacity of the river.

In the same area, the remnants of two mills races can be found. On the Saint-Jean-sur-Richelieu side of the river, the remnants of the Langelier mill race, built circa 1859, cause another reduction of the flow capacity of the river as well has the more extensive remnants of the McGinnis mill race on the Iberville side of the river. However, while some of these modifications might exacerbate flood impacts in the area, their cumulative impacts during a large flood remain to be quantified. The Study is addressing this question.

CHANNEL MODIFICATIONS OF TRIBUTARIES IN THE BASIN

For many years in Québec, small meandering streams have been straightened and agricultural and municipal ditches have been constructed to improve surface drainage during the spring runoff. In the 20th century, an estimated 30,000 km (about 18,640 mi) of meandering channels were straightened, often with the financial support of governments. These modifications likely have affected the hydrological conditions of several agricultural watersheds, allowing water to flow more swiftly to the Richelieu River. Such channels could experience higher flows of runoff sediments and contaminants, which in turn can impact riparian zones and (in the case of sediments) reduce floodplain availability (that is, the access of flood waters to the floodplain) of small streams (Biron *et al.*, 2014).

In Vermont, about 75 percent of rivers no longer access their floodplains during the annual flood stage due to moderate or severe channel changes caused by historical dredging, the construction of berms and levees, and straightening and armoring of streams. These modifications have led to the loss of floodplain availability and the associated problems of increased stream velocity and erosion, with severe consequences for downstream properties during high flood flows (Kline and Cahoon, 2010).

2.3.3 FLOOD STORAGE RESERVOIRS ON LAKE LEVELS[10]

Reservoirs can reduce flooding by storing water flowing at high rates in the reservoir and releasing water more slowly through the stream channel below the dam. However, reservoirs in the Lake Champlain basin have little effect on Lake Champlain flooding. For one thing, the reservoirs are very small compared to Lake Champlain, so the changes the reservoirs can make to the inflows to Lake Champlain are relatively minor. In addition, lake flooding is less responsive than river flooding to changes in the timing of flows. Table 2-4 and Figure 2-11 (see on page 29-30) show the volume and geographic location of the lakes and reservoirs draining into the Lake Champlain basin . Except for Lake Champlain itself, Bartlett Cary Dam, Waterbury Reservoir and Lake George, the volumes of the other small dams are insignificant.

After the Great Flood of 1927, the Wrightsville Reservoir, on the North Branch Winooski upstream of Montpelier, Vermont, and the East Barre Dam on the Jail Branch upstream of Barre, Vermont, were constructed, along with the Waterbury Reservoir. Wrightsville Reservoir is also used for recreation and is typically maintained

[10] **For more information about reservoirs and their influence on the levels of Lake Champlain, see the Fact Sheet, "Dams and Reservoirs in the Lake Champlain Richelieu River Basin" on the Study's website: https://ijc.org/en/lcrr/fact-sheets**

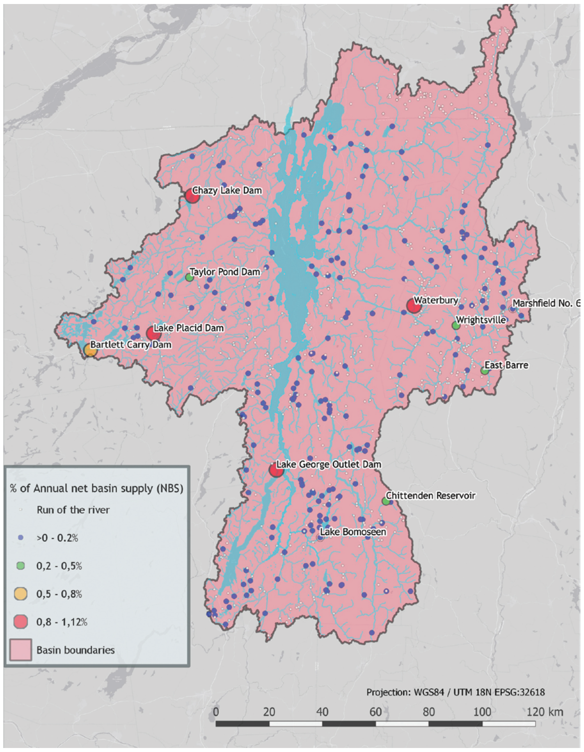
Table 2.4 | Volume of lakes and reservoirs in the Lake Champlain basin

DAM OR RESERVOIR	RECEIVING WATERBODY	STORAGE VOLUM IN CUBIC METERS
Cadys Falls	Lamoille River, VT	863,100
Essex No. 19	Winooski River, VT	2,404,350
Wrightsville	North Branch Winooski River, VT	3,452,400
Peterson	Lamoille River, VT	3,501,720
Lake Dunmore	Leicester River, VT	6,041,700
Clark Falls (Arrowhead Mountain Lake)	Lamoille River, VT	7,398,000
Lake Flower	Saranac River, NY	7,644,600
Lake Bomoseen	Castleton River, VT	8,687,718
Union Falls	Saranac River, VT	10,973,700
Marshfield No. 6	Mollys Brook, VT	11,416,347
Green River Dam	Green River, VT	20,837,700
Chittenden Reservoir	East Creek, VT	21,207,600
East Barre[i]	Jail Branch, VT	29,037,150
Waterbury	Little River, VT	45,621,000
Bartlett Carry Dam	Saranac River, NY	87,449,292
Lake George	La Chute River, NY	2,774,250,000
Lake Champlain[ii]	Richelieu River, QC	28,029,433,896

i. This reservoir is kept dry until needed for flood water retention. The value given is for maximum storage, not normal storage.
ii. Volume at lake elevation 99.587 ft NAVD 88 (30.354 m)

at one-third of the flood storage surface area. The impoundment behind East Barre Dam is commonly kept dry. These reservoirs are intended to protect the municipalities that are immediately downstream. Releases are controlled to minimize downstream flooding. Marshfield Dam on Molly's Brook in Cabot, Vermont, is owned and operated by Green Mountain Power. It is not designated for flood control and is primarily operated for power generation and recreation. The drainage area of Marshfield Dam is fairly small-approximately 57 km^2 (22 mi^2) and, as with Waterbury Reservoir, outflows from the dam have no significant influence on Lake Champlain elevations.

Figure 2-11 | **Map of Champlain basin reservoirs showing their size relative to the net basin supplies of Lake Champlain**



Lake George in New York State is the largest tributary lake draining to Lake Champlain, with approximately 10 times the volume of all the other basin reservoirs put together. It has a dam at its outlet to manage its levels. The lake is used primarily for recreational purposes and any water discharge is used to manage Lake George levels. On the Saranac River, which flows through Plattsburgh, New York, flows are driven by the volume of runoff—not dam operations, since most of the hydroelectric dams were not designed for water storage and flood control. The hydroelectric dams with limited ability to store water include Union Falls, Franklin Falls and the Lake Flower Dam in the village of Saranac Lake. Numerous other dams exist in the basin, such as those in the tributaries of Lamoille River, Otter Creek and Missisquoi River, in Vermont. As is the case on the Saranac River, these are for the most part run-of-river power generation dams, meaning that they have little or no water storage capacity and do not impact flood levels.

2.4 SUMMARY OF KEY FINDINGS

Based on the summary analysis presented, the following key points can be made regarding the causes of past floods in the LCRR basin:

- The 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.
- A heavy snowpack, coupled with significant warm spring rains, commonly drives the most devastating flood conditions on Lake Champlain by rapidly contributing large volumes of meltwater to tributaries and the lake.
- Flooding events can be locally amplified by wind-driven waves and oscillating seiche waves when accompanied by strong winds.
- In 2011, the confluence of warm temperatures, record precipitation and rapid melting of a near-record snowpack caused historically high flood levels in the basin tributaries and in Lake Champlain and the Richelieu River.
- Since the beginning of the 1970s, Lake Champlain has undergone an increase in the average of annual maximum water levels on the order of 0.30 m (0.98 ft).
- 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. In the Richelieu River portion of the basin, population growth and building construction have been concentrated in urban areas along a narrow river corridor, part of the river's natural floodplain. These changes have tended to alter the timing and amount of water flowing through the basin. However, the cumulative impacts of these changes on large flood events need to be studied further.
- Several recent studies have concluded that the widening of the Chambly Canal in the 1970s likely had an impact on the hydraulic conditions of the upper Richelieu River and the Missisquoi Bay of Lake Champlain.

3. IMPACTS OF FLOODING IN THE BASIN

Chapter 3 | reviews the impacts of flooding in the LCRR basin, with a focus on the 2011 flooding event. It considers impacts on people (including the economy, human health and safety, and infrastructure) and impacts on the natural environment.[11]

3.1 PEOPLE AND THE BUILT ENVIRONMENT

3.1.1 THE ECONOMY

Despite their benefits on the natural environment, flooding events are often perceived as natural disasters leading to widespread economic consequences, including damages and lost revenues for people and companies in many economic sectors. While most estimates of economic damages of past floods in Lake Champlain and Richelieu did not evaluate losses of comparable assets or use standardized methodologies, general observations can provide insights on flood economic impacts to residential, commercial and agricultural assets across borders and time.

Economic losses caused by three of the most recent important floods in the LCRR basin present a contrasting portrait (Table 3-1). In 1972 and 2011, the Canadian part of the basin suffered more economic losses than the United States' part, while the opposite occurred in 1976.

QUÉBEC

In spring 2011, the residential sector experienced most of the damage in Québec (Figure 3-1). The agricultural, commercial and industrial sectors were also affected (La Financière agricole du Québec, 2012; Groupe de l'évaluation de l'impact économique, 2011). Following the flood, organizations and municipalities received more than $9 million CAN[12] in financial aid from the province (Ministère de la Sécurité publique du Québec, 2011).

Residential sector

Flooding can result in a wide range of impacts on households, from direct and tangible losses (such as damage to building fabric, household inventory items, and cleanup costs) to indirect and intangibles losses (including increased travel costs, loss of memorabilia, and death of domestic animals). Most of the reports that documented damages suffered during flood events in the basin focused on direct impacts on residential sectors.

In 1972 and 1976, the number of permanent residences impacted by floods around Missisquoi Bay and the Richelieu River was lower than during the 2011 event. The total number of affected residences for the 1972 flood was 1,666, with 78 percent being summer residences. While permanent residences represented only a small portion of the total flooded residential buildings, these

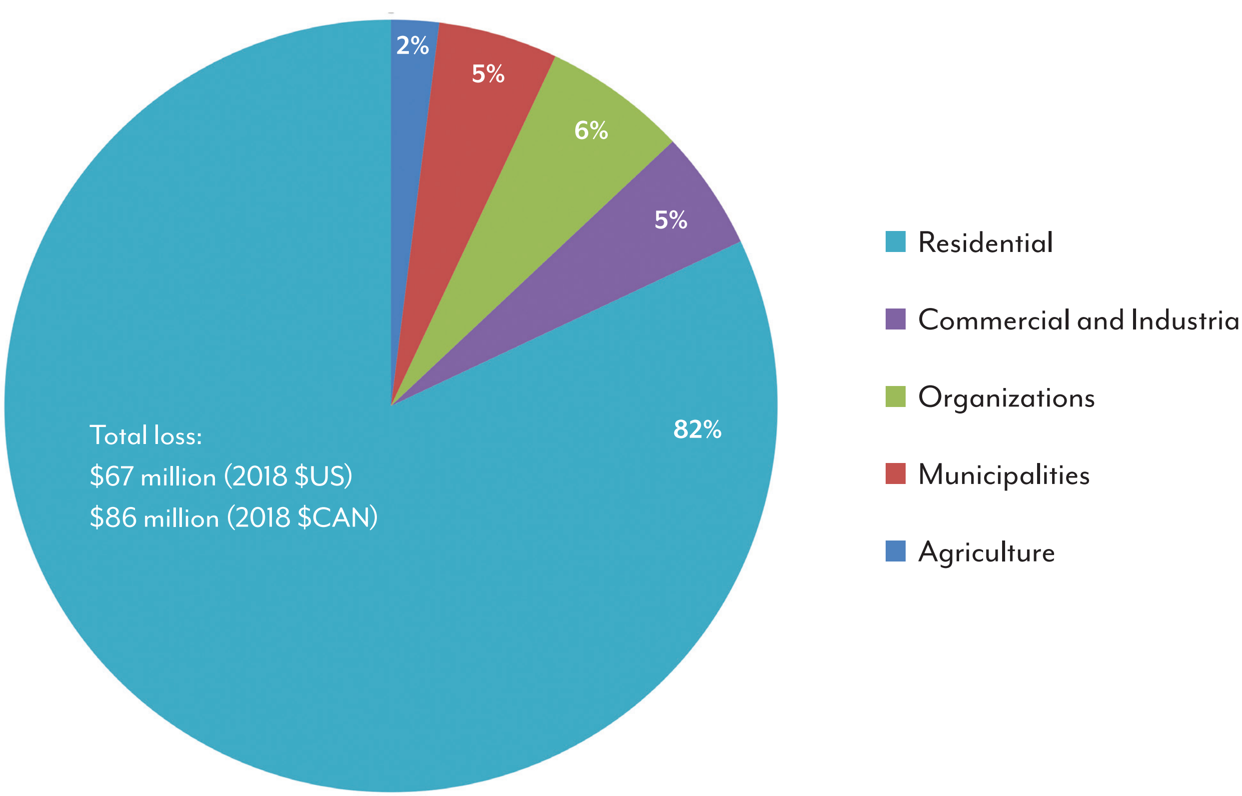
[11] See section 1.3.1 for a brief description of the Study's use of indicator species and ecosystems as an approach to evaluating impacts of flooding on the natural environment in the basin.
[12] $8 million in US dollars equivalent (US 2018). $10 million in Canadian dollars equivalent (CAN 2018).

Table 3-1 | Economic losses of floods in the Lake Champlain-Richelieu River basin ($US 2018)

FLOOD YEAR	VALUE OF LOSSES (US$2018)		
	Québec	United States	Total
1972[i]	$9,188,400	$5,666,300	$14,854,800
1976[ii]	$13,884,669	$17,172,100	$31,745,000
2011[iii]	$67,644,946	Vermont: $3,840,000 New York: $10,650,400	$82,135,346

Sources:
i. ICREB, 1974
ii. The International Champlain-Richelieu Board, 1977
iii. Howland and Mitchell, 2011

Figure 3-1 | Sectoral total losses from 2011 flood in Québec



damages accounted for 38 percent of the total damages to the residential sector. Since the survey was conducted one year after the event, it was difficult in some cases for residents to fully recall the damaged items. This bias could have caused an underestimation of the total damages.

In 1976, the total damages were estimated through a survey and included secondary residences. The total cost was estimated to $1.5 million CAN[13]. Damages to secondary residences represented 61 percent of this amount (Centre de recherche en aménagement régional - Université de Sherbrooke, 1977). Therefore, permanent residences suffered 39 percent of total damage to residential buildings, a proportion similar to the 1972 event.

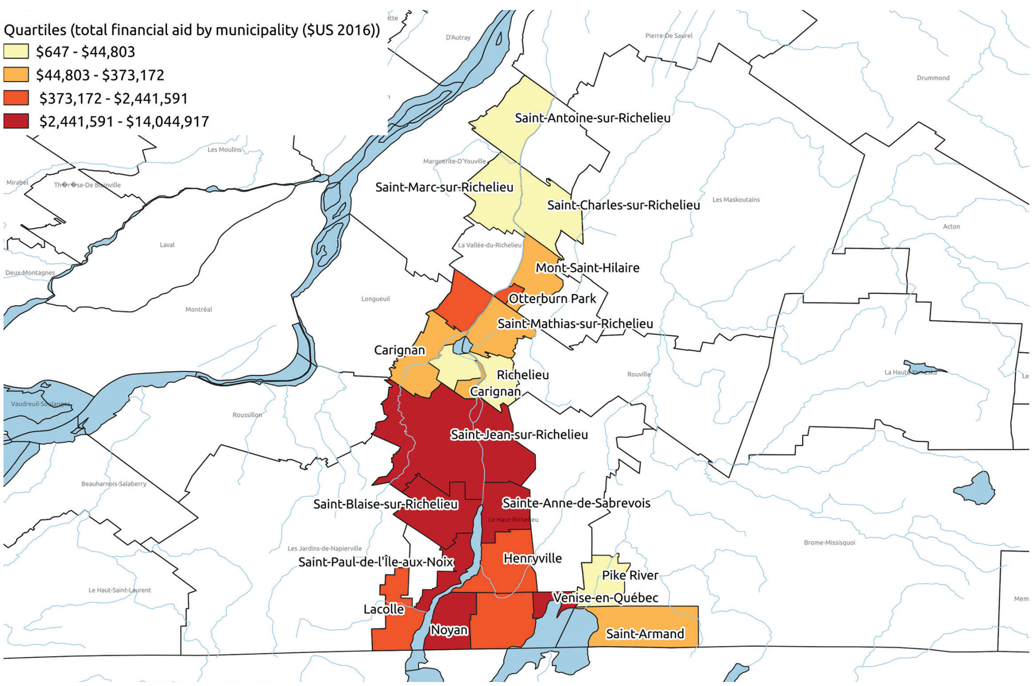
In 2011, a total of 2,535 primary residences were flooded, affecting 3,927 residents. Of these, 1,651 residents needed to be evacuated from their homes (LCBP, 2013). In the Montérégie region of the province (southwestern Quebec), 40 municipalities were affected and 11 municipalities declared emergencies during the flood.

For the Québec government, public spending to evacuate the residents reached $2.4 million CAN[14] in the initial stage of the flood (Programme de mise en valeur du lac Champlain, 2013). The eventual total costs to the Québec government rose to $22 million CAN[15].

Claims to the Ministère de la Sécurité Publique (MSP) were made by individuals, businesses, municipal organizations and building owners. The total amount paid by the MSP exceeded $74 million CAD[16], with 83 percent of this amount paid to individuals.

Municipalities most affected in spring 2011 were located in upstream portion of the river (Saint-Jean-sur-Richelieu, Saint-Paul-de-l'Île-aux-Noix, Sainte-Anne-de-Sabrevois, Saint-Blaise-sur-Richelieu and Noyan). For municipalities in the Missisquoi Bay area, Venise-en-Québec was the most affected municipality (Figure 3-2).

Figure 3-2 | **Financial aid granted to individuals after the 2011 flood events, by municipality**



(Source: Ministère de la Sécurité publique, 2012)

[13] $4.6 million in US dollars equivalent (US 2018). $6.2 million in Canadian dollars equivalent (CAN 2018).
[14] $2.1 million in US dollars equivalent (US 2018). $2.7 million in Canadian dollars equivalent (CAN 2018).
[15] $19 million in US dollars equivalent (US 2018). $24 million in Canadian dollars equivalent (CAN 2018).
[16] $63 million in US dollars equivalent (US 2018). $82 million in Canadian dollars equivalent (CAN 2018).

Of the 1,651 residents evacuated, a large number had to be moved for a long period of time or had to move permanently, including 150 families still housed in hotels as late as June 2012. The provincial government provided funding of about $2.4 million CAN[17] for the evacuation of residents and basic needs, including hotel accommodations (LCBP, 2013). A total of 3,145 people received shelter and emergency feeding services (Organisation de la sécurité civile du Québec, 2011).

Agricultural sector

Agriculture occupies 70 percent of the Richelieu River basin in the province of Québec (COVABAR, 2015). Corn and soybean are the two principal crops grown in the area. Poultry, swine and dairy cattle are the main types of livestock.

Although it is difficult to compare the overall damages to agriculture related to past floods in the basin, several observations can be made.

In general, major flooding can result in direct and indirect losses associated with crop losses, yield reductions, livestock losses, damage to soil and damage to buildings and other infrastructure.

During the 1972 flooding event, agricultural production was impacted in different ways. The total damage was estimated at nearly $350,000 CAN[18] (The International Champlain-Richelieu Engineering Board, 1973). Affected crops on undrained lots yielded 25 to 50 percent lower production than those on the drained lots. The flood lasted one month and this long duration made it impossible for corn to reach maturity. Hay quality was also reduced. Deposits on flooded land of silt, sludge and debris forced clean-up efforts and represented the most important non-crop loss. Additional costs were generated by the need to transport animals to other pastures or to transport food to the affected farms.

During the 1976 flood, agricultural damages represented 37 percent of the total damages (Centre de recherche en aménagement régional - Université de Sherbrooke, 1977). Multiple governmental programs were mobilized in order to compensate producers.

In 2011, flooding affected more than 2,500 ha (6,177 acres) of farmlands in Québec. The inundation lasted 67 days (Environment and Climate Change Canada, 2017). Special programs paid more than $318, 801 CAN[19] in aid in addition to insurance coverage paid by the provincial crop insurance program (LCBP, 2013). There were 3,418 producers insured by the Financière Agricole and 1,373 of them claimed indemnities. Their losses were estimated at $2.5 million CAN[20] (Radio-Canada, 2011). Indemnities covered $0.6 million CAN. Nearly 70 percent of this amount covered losses of vegetable crops, which are particularly sensitive to flooding (La Financière agricole du Québec, 2012).

Commercial and industrial sectors

In 1972, the economic consequences on the commercial and industrial sectors were experienced primarily in camping grounds, marinas, restaurants and hotels/motels/nightclubs. The estimated net revenue losses of about $135,000 CAN[21] were mostly concentrated along the Richelieu River. Much of this damage was caused by business losses rather than physical damages to commercial or industrial assets (International Champlain-Richelieu Engineering Board, 1973).

In 1976, it was estimated that the commercial and industrial sectors suffered more from revenue losses than material losses and damages to assets. In the study area, commercial and industrial losses represented less than 6 percent of the total damages (Centre de recherche en aménagement régional - Université de Sherbrooke, 1977).

[17] $2.1 million in US dollars equivalent (US 2018). $2.6 million in Canadian dollars equivalent (CAN 2018).
[18] $1.6 million in US dollars equivalent (US 2018). $2.1 million in Canadian dollars equivalent (CAN 2018).
[19] $0.27 million in US dollars equivalent (US 2018). $0.35 million in Canadian dollars equivalent (CAN 2018).
[20] $2.1 million in US dollars equivalent (US 2018). $2.7 million in Canadian dollars equivalent (CAN 2018).
[21] $0.6 million in US dollars equivalent (US 2018). $0.8 million in Canadian dollars equivalent (CAN 2018).

Similar to the 1976 flood, the 2011 event led primarily to revenue losses rather than material damages. This situation is not only related to the flood events, but also to the bad weather conditions observed during this period. Indeed, losses of revenues were also reported during this period outside the region affected by the flood event.

According to a local economic intervention committee[22], 74 businesses were directly affected by the flood. Another 202 businesses were indirectly affected by the flood (for example, through decreased attendance, loss of contracts, absenteeism).

The spring 2011 floods also led to the closure of at least two small businesses in the area.

Some businesses affected by the flooding and willing to rebuild reported they had issues obtaining credit from their financial institution for two main reasons:

- they already had contracted considerable debt and did not have enough leverage to obtain more credit; and,
- the flood reduced their credit leverage by decreasing the value of their assets.

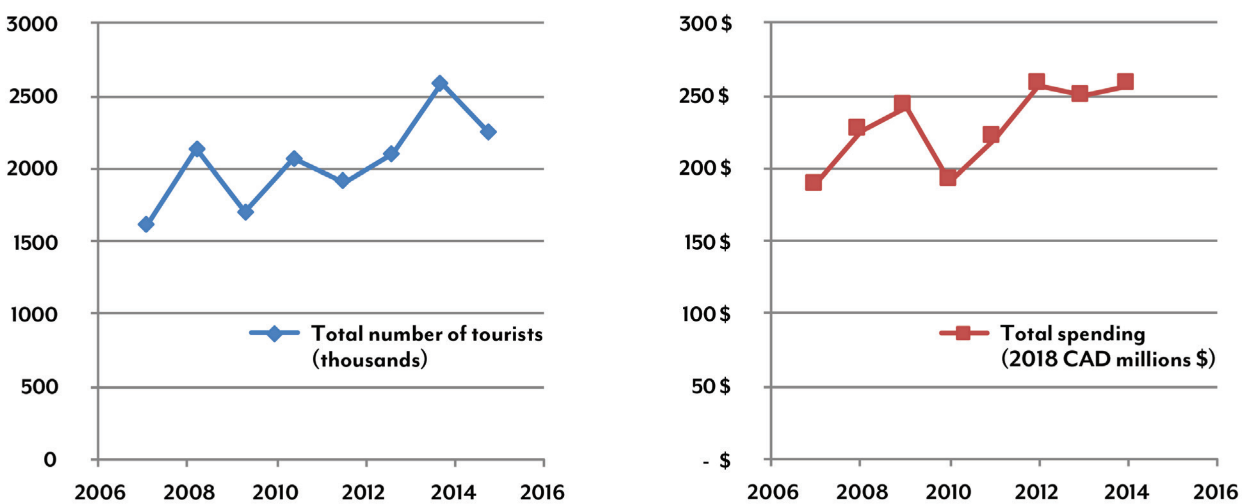
Building contractors were also reluctant to work for affected businesses because of the greater uncertainty of being paid. Uncertainty over the amount to be refunded eventually by the Québec government contributed to this situation.

Tourism and recreational sector

The 1972 flood affected one golf course, twelve campgrounds, four marinas, six restaurants and three hotels/motels/clubs. More than 70 percent of the damages, nearly $90,000 CAN[23], was for net losses of business income. Damage to structure and content accounted for another $25,600 CAN[24]. Additional costs, such as clean-up costs were estimated at about $11,060 CAN. (ICREB, 1973).

In 2011, Montérégie was the fifth most popular region in Québec for tourists (Ministère du Tourisme du Québec, 2011), with 1.9 million tourist visits (though the Montérégie encompasses an area larger than the Richelieu River basin). Figure 3-3 illustrates the pattern of tourist visits in Montérégie between 2007 and 2014. The data suggest that there is no clear evidence that the flood had a significant impact on the tourist industry in the region. This finding is also supported by the data on

Figure 3-3 | Tourists and tourism expenditures in Montérégie, 2007-2014



Sources: Ministère du Tourisme du Québec, 2007 to 2014

[22] Formed by the Conseil Économique du Haut-Richelieu (CLD), the city of Saint-Jean-sur-Richelieu, the Chamber of Commerce du Haut-Richelieu, the Office of Tourism and Congresses du Haut-Richelieu, Rue Principales Vieux-Saint-Jean and the Regroupement des travailleurs autonomes.
[23] $0.4 million in US dollars equivalent (US 2018). $0.5 million in Canadian dollars equivalent (CAN 2018).
[24] $0.12 million in US dollars equivalent (US 2018). $0.15 million in Canadian dollars equivalent (CAN 2018).

tourist expenditures in the region from 2007 and 2014. Nonetheless, reports from government agencies reveal that specific businesses within the tourism sector were highly affected by the floods.

A major study of the impacts on Québec tourism of the 2011 flooding event (Groupe de l'évaluation de l'impact économique, 2011) concluded that marinas and campgrounds were the most affected type of business. Ten of the 18 marinas in the study area (MRC du Haut-Richelieu, MRC Brome-Missisquoi and MRC de la Vallée-du-Richelieu) suffered losses of about $2,6 million CAN[25] in material damages and more than $7,4 million CAN[26] in revenue losses. Five of the ten marinas surveyed experienced losses between 20 and 50 percent of their normal revenues. Only the two biggest marinas were insured against these two kinds of losses.

Table 3-2 | FEMA individual assistance for Vermont and New York following flooding in April 2011 ($ US 2011)

INDIVIDUAL ASSISTANCE	VERMONT	NEW YORK
Residences impacted		
Total	250	1,060
Destroyed	25	14
Major Damage	73	218
Minor Damage	123	342
Affected	29	486
Percentage of insured residences	5%	24.7%
Percentage of low income households	47%	39%
Percentage of elderly households	n/a	n/a
Total Individual Assistance cost estimate	$2,645,322[29]	$5,384,024[30]

Source: Federal Emergency Management Agency. (2018a, 2018b).

[25] $2.2 million in US dollars equivalent (US 2018). $2.9 million in Canadian dollars equivalent (CAN 2018).
[26] $6.4 million in US dollars equivalent (US 2018). $8.2 million in Canadian dollars equivalent (CAN 2018).
[27] $2.2 million in US dollars equivalent (US 2018). $2.9 million in Canadian dollars equivalent (CAN 2018).
[28] $0.11 million in US dollars equivalent (US 2018). $0.14 million in Canadian dollars equivalent (CAN 2018).
[29] $3.0 million in US dollars equivalent (US 2018). $3.8 million in Canadian dollars equivalent (CAN 2018).
[30] $6.0 million in US dollars equivalent (US 2018). $7.8 million in Canadian dollars equivalent (CAN 2018).

Of the 16 campgrounds in the area, 12 suffered material damages of about $2.6 million CAN[27] and revenue losses of about $130,000 CAN[28].

In addition, the opening of the Chambly Canal was postponed by two weeks in 2011 (Programme de mise en valeur du lac Champlain, 2013) and the cycling path along the canal was closed due to high water levels during that period.

NEW YORK AND VERMONT

Residential sector

In the spring of 2011, the basin's prolonged flooding event resulted in widespread damage due to inundation damage from high water levels that resulted in the corrosion, leaking, and disconnection of gas lines and tanks contaminated by floodwaters, creating fire hazards. Septic systems overflowed and many residents were cut off from their communities, requiring row boats to access their properties (LCBP, 2013).

Table 3-3 | FEMA public assistance for Vermont and New York following flooding in April 2011 ($ US 2011)

PUBLIC ASSISTANCE	VERMONT	NEW YORK
Primary impact:	**damage to roads and bridges**	**damage to roads and bridges**
Total Public Assistance cost estimate	$793,753[31]	$38,610,718[32]
Statewide per capita impact	$1.30[33]	$2.03[34]
Countywide per capita impact	Caledonia County ($26.72[35])	-
Countywide per capita impact indicator	$3.27[36]	$3.27[35]

Source: Federal Emergency Management Agency. (2018a, 2018b).

[31] $0.89 million in US dollars equivalent (US 2018). $1.1 million in Canadian dollars equivalent (CAN 2018).
[32] $43 million in US dollars equivalent (US 2018). $56 million in Canadian dollars equivalent (CAN 2018).
[33] $1.45 in US dollars equivalent (US 2018). $1.87 in Canadian dollars equivalent (CAN 2018).
[34] $2.27 in US dollars equivalent (US 2018). $2.92 in Canadian dollars equivalent (CAN 2018).
[35] $29.83 in US dollars equivalent (US 2018). $38.48 in Canadian dollars equivalent (CAN 2018).
[36] $3.65 in US dollars equivalent (US 2018). $4.71 in Canadian dollars equivalent (CAN 2018).

Both wave action and erosion caused damages along the lakeshore and its tributaries. Wave action caused residential damage, including broken windows and structural damage, as well as damage to the causeways linking the Lake Champlain Islands. Fluvial damage and flash flooding caused fast moving water to collide with buildings, cause erosion of streambank supporting structures, and left a thick layer of muddy silt in developed areas (LCBP, 2013).

Public assistance grants from FEMA were dispatched to local, state, and Tribal governments, as well as to certain private and nonprofit organizations, to help communities respond to and recover from major disasters and emergencies. Individual assistance programs provide financial assistance to individuals, households, and businesses for uninsured losses due to a disaster. These funds were primarily used for temporary housing, housing repair, housing replacement, and permanent housing construction.

FEMA data for individual and public assistance are available for the spring 2011 floods in New York and Vermont (Table 3-2 and 3-3). These data represent the costs that households, municipalities and states required coverage for following the spring flooding event of 2011. This also encompasses damage to infrastructure and public services. As indicated in Tables 3-2 and 3-3, the costs and damages from the floods in the United States were higher in New York than Vermont. Infrastructural damage was the primary impact in both Vermont and New York, though the cost was substantially higher in New York.

In the fall of 2011, as a result of Tropical Storm Irene, the Small Business Administration's Office of Disaster Assistance was active in 12 of Vermont's 14 counties, with loan approvals totaling more than $29 million for home and business repair purposes.

Agricultural sector

In 2011, flooded soils in the basin sustained damages from the deposit of unwanted sediments, debris and pollutants. After the flood waters receded, some properties were left with thick layers of silt and rocks (LCBP, 2013). As well, sediment and nutrient losses through hillslope erosion were high where the soil was mostly tilled and fertilized in preparation for planting (LCBP, 2013).

From April-June 2011, counties in New York and Vermont immediately adjacent to Lake Champlain suffered more than $3 million US[37] in crop losses with about 7740 ha (19,000 acres) affected (Table 3-4, see next page) (USDA Risk Management Agency, 2011). Although the direct effects of flooding played a role in these losses, the majority of damages to crops could not directly be attributed to flooding. Rather, a major contributor to crop loss during the spring of 2011 was cold, wet weather and excessive precipitation (USDA Risk Management Agency 2011). For example, the spring of 2011 brought nearly 520 mm (20 in) of rain to Burlington, Vermont, breaking the previous seasonal record by more than 100 mm (4 in).

Damage also occurs when soil moisture levels are too high, after the flood recedes, either at harvesting or during storage, as some feed may become unfit for animal consumption due to toxins produced by unwanted microorganisms. This happened in 2011 in the LCRR Basin, when feed became contaminated by either heavy metals or other undesirable contaminants (LCBP, 2013). Vegetables or crops for human consumption may be subject to complete crop loss due to risk of contamination (Posthumus *et al.*, 2009). This impact was seen in 2011, when the USDA declared some edible crops contaminated and ordered their destruction (LCBP, 2013). The 2011 flood event also decreased the quantity and quality of some feed, forcing farmers to pay extra money for additional feed for their livestock (LCBP, 2013; Posthumus *et al.*, 2009).

[37] $3.3 million in US dollars equivalent (US 2018). $4 million in Canadian dollars equivalent (CAN 2018).

Table 3-4 | **Crop losses in Vermont and New York, April-June 2011**
Note: for Vermont and New York counties immediately bordering Lake Champlain (USDA Risk Management Agency 2011) ($ US 2011)

COUNTY/CROP	DAMAGED AREA IN ACRES	DAMAGED AREA IN HA	INDEMNITY VALUE (USD)
Addison	6,007	2431	$677,397
All Other Crops	66	26,5	$8,697
APPLES	2	1	$2,650
BARLEY	112	45,5	$9,634
CORN	5,508	2229	$633,029
SOYBEANS	319	129	$23,388
Chittenden	892	361	$105,323
CORN	822	332,5	$89,870
SOYBEANS	70	28,5	$15,453
Clinton	782	316,5	$836,654
APPLES	262	106	$815,103
CORN	520	210,5	$21,551
Essex	633	256	$69,785
All Other Crops	633	256	$69,785
Franklin	8,788	3556,5	$1,204,493
All Other Crops	14	5,5	$16,776
CORN	8,669	3508	$1,175,035
OATS	51	20,5	$1,982
SOYBEANS	54	22	$10,700
Grand Isle	419	169,5	$55,508
All Other Crops	419	169,5	$55,508
Rutland	324	131	$84,078
CORN	324	131	$84,078
Washington	1,281	518,5	$233,869
All Other Crops	89	36	$3,756
CORN	1,192	482,5	$230,113
Total	19,126	7740	$3,267,106[38]

[38] $3.6 million in US dollars equivalent (US 2018). $4.7 million in Canadian dollars equivalent (CAN 2018).

Commercial and industrial sectors

The damage experienced by businesses in New York and Vermont following the spring 2011 floods is difficult to quantify, due to substantial gaps in information on the direct and indirect costs of flooding to businesses, as well as their repair needs (LCBP, 2013). However, a review of applications for Small Business Administration (SBA) loans, providing to homes and businesses funds to manage and facilitate repairs and replacements following natural disasters reveals that 54 SBA loans for homes and 20 SBA loans for businesses were filed in Vermont following the 2011 flood. In New York, seven SBA loans were made for homes, and eight for businesses.

Tourism and recreation sectors

The shorelines of Lake Champlain and the upper Richelieu River are highly developed for water-based recreational activities. Additionally, in New York, 75 percent of the Lake Champlain shoreline is within Adirondack State Park, while the rest is used for residences and agriculture.

Following the spring floods in 2011, local businesses reliant on summer tourism and recreation were particularly impacted. As a result of the spring flooding in 2011, total business along the Champlain Canal decreased by 25 percent. In Essex County, New York, the loss of a retaining wall and several docks reduced the typically 21-week tourism season to 15 weeks. Waterfront businesses in Burlington, Vermont, also experienced delayed openings and event cancellations (LCBP, 2013).

3.1.2 HUMAN HEALTH AND SAFETY

Floods can lead to a range of health and safety impacts on populations, ranging from physical injuries and death during the flood to long-term physical and mental health conditions. These impacts may, in turn, have various economic implications on both individuals and the community, such as increased public health spending, loss of income or loss of quality of life.

Following the spring flooding of 2011 in the basin, primary concerns with respect to human health were focused on: ensuring human safety and conducting any evacuations as needed; supplying clean drinking water; containing spills of toxic substances; providing medical care; restoring electricity; and repairing damage to transportation infrastructure to restore access to communities isolated by washed out roads.

Evacuations

Québec

In Québec, the eight-week period of inundation led to extensive water damage to residences, with resulting environmental health issues including mold exposure and electrical hazards. As noted above in 3.1.1, an estimated 2,535 homes were flooded in the first few weeks of flooding, and 1,651 residents were forced to evacuate (LCBP, 2013).

The Canadian Red Cross set up emergency shelters, while some families moved into hotels. Even after the flood waters receded, many families were not able to return to their homes; as of June 2012, nearly 150 families still remained in hotels.

New York and Vermont

No comprehensive data are available on how many evacuations were conducted during the spring 2011 floods in Vermont and New York, because data were combined with the August 2011 Tropical Storm Irene flood in that part of the basin.

At the peak flooding period on Lake Champlain, in early May 2011, the Vermont chapter of the American Red Cross assisted 75 individuals and provided 100 cleanup and comfort kits and 400 meals. The American Red Cross of Northeastern New York supported emergency response efforts in the New York portion of the basin, providing aid to Clinton and Franklin Counties. Temporary shelters were established in Saranac Lake, Ausable Forks, and Plattsburgh. Voluntary evacuations occurred throughout the New York side of the basin to escape the lake flooding and risk of tributary flooding from spring storms and runoff from snowmelt, and to avoid the risk of being caught in landslides.

Drinking water supplies

Québec

In Québec, none of the major municipal drinking water suppliers were impacted during the spring 2011 flood, but many facilities had to increase chlorination and filtration because of increased turbidity.

New York and Vermont

During the spring 2011 Lake flooding, the Vermont Department of Health issued boil-water advisories for thousands of shoreline homes that rely on private wells for water supplies. In New York, Port Henry, Essex, and Willsboro Counties issued boil-water notices, affecting about 3,600 residents during the spring flooding event.

Pathogen and contamination exposure

Flood waters can mix with sewage, gasoline and other pollutants and contaminate homes, basements, furniture, and household contents, public and private drinking water supplies, and food sources. In addition, wet conditions can promote the growth of mold and mildew, impacting respiratory health, particularly for those with asthma or weakened immune systems. Inhalation of mold spores is also a common cause of respiratory irritation, allergic reaction, asthma attacks, chronic sinusitis and other conditions. Mold was cited as a prominent issue for Vermonters and New Yorkers in the basin following the spring 2011 flood.

Flood events typically increase contaminants to Lake Champlain, including E. coli and other pathogens. High nutrient levels in the lake, as observed following the spring flooding event, promote cyanobacteria blooms. If ingested, cyanotoxins released by cyanobacteria can affect humans and animals. While scientists suspect that cyanobacteria blooms and toxin contamination may have been amplified by the 2011 floods, a direct link between the two events has not been confirmed.

Power outages

Power outages presented additional hazards, limiting ability for people to heat their homes or to boil water. For high-risk individuals, loss of power meant spoilage of certain medicines.

Psychological support

Québec

With regards to psychological health effects, between 10 and 20 psychosocial specialists were working full-time during the flood event to assist the affected residents (Organisation de la sécurité civile du Québec, 2011). While there is limited information on the psychological conditions of the affected residents, it is known that nearly 7,000 psychosocial interventions were conducted and that about 350 people were identified as victims of trauma or as having experienced mental health impacts.

New York and Vermont

No comparable information on psychological support in Vermont and New York during the spring 2011 flood is available.

3.1.3
INFRASTRUCTURE

QUÉBEC

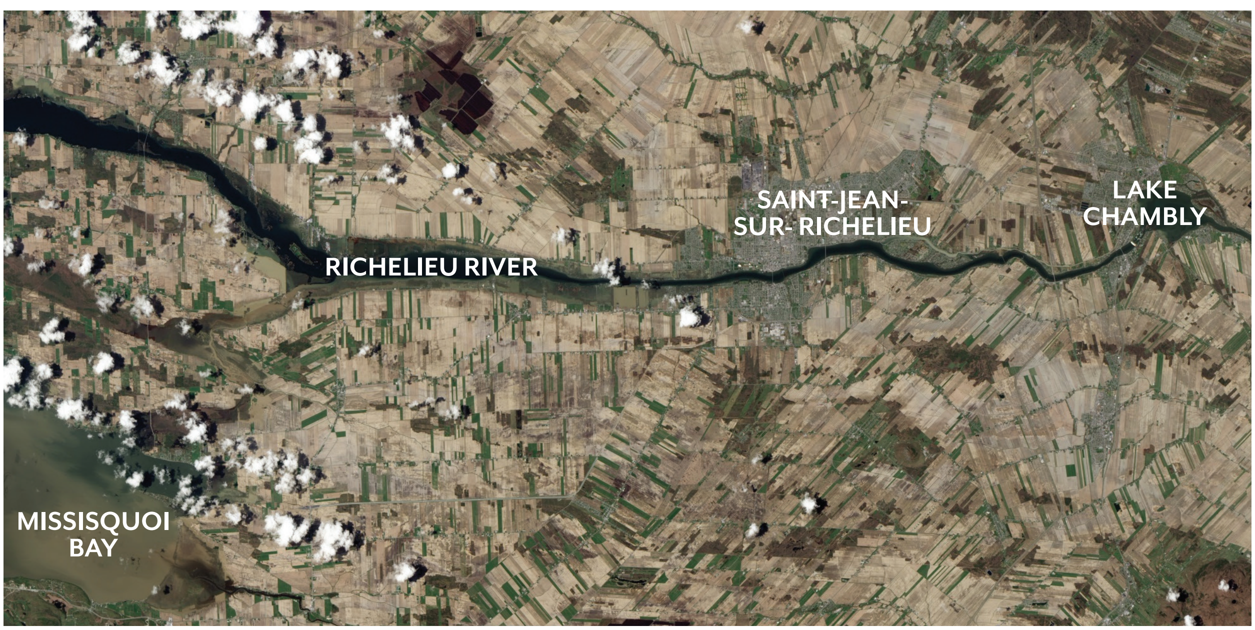
Flood-prone transportation infrastructure within the Richelieu River part of the basin exists all along the river sides. During the floods of 2011, water caused problems in different sectors where the levels reached transportation infrastructure. Deterioration of road shoulders and interruption of transportation were the key impacts on transportation infrastructure. Figure 3- 4 shows the full extension of the inundation limits in 2011 along the river, which extended for more than 1 km (.62 mi) on the river floodplains and 2 km (1.2 mi) inland along Missisquoi Bay.

More than 100 bridges and roads were damaged by the 2011 spring flood (Ministère des Transports de la Mobilité Durable et de l'Éléctrification des Transports du Québec, 2016). An estimated 60 municipal roads were reported partially flooded in different municipalities such as Sainte-Anne-de-Sabrevois and Henryville, generally in the southern area of the river corridor.

Figures 3-5 to 3-7 (next page) illustrate examples of the flooding along the river corridor:

- Figure 3-5 shows a high-resolution aerial photograph taken on May 1, 2011 depicting the flooded roads on the southwest of the Richelieu River, with overflow water appearing in light greenish color.
- Figure 3-6 depicts provincial road 202 at Venise-en-Québec that is partially flooded next to the Missisquoi Bay shoreline and at about 1 km (.62 mi) inland from the shoreline, at the intersection of the road and a Bay tributary.
- Figure 3-7 shows the water levels surrounding the islands and historical site of Île-aux-Noix (Fort Lennox), where affected marinas are shown on the left side of the riverbanks and Roads 223 and 225 appear as partially flooded. Road 225 connects with road 202 to cross the Richelieu River over Île Ash in the municipality of Noyan by a bridge.

Figure 3-4 | Flooding in May 2011, two days after the peak flow of 1,550 m3/s in the Richelieu River – natural color image (Photo taken from NASA Earth Observatory (2011).



(Source: Canadian Coast Guard, 2018)

Figure 3-5 | Flooding, municipality of Lacolle
(Aerial photo taken on May 1, 2011. Floodwaters appear in a light greenish color.)
(Source: Canadian Coast Guard, 2018. United States Department of Agriculture National Agriculture Imagery Program.)

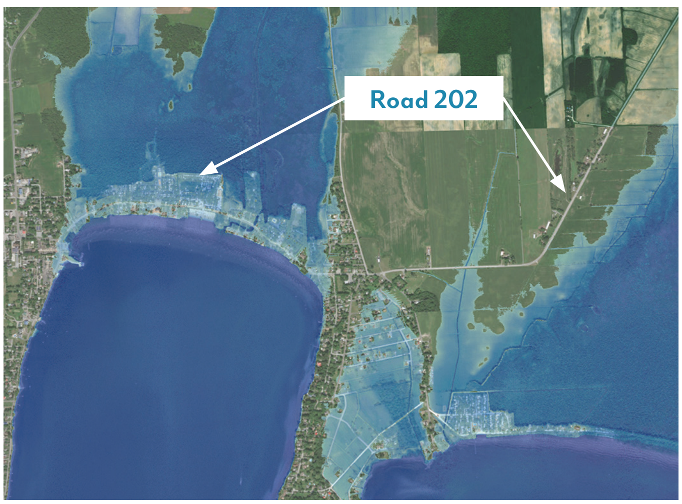


Figure 3-6 | Road 202 in the municipality of Venise-en Québec
(Source: Canadian Coast Guard, 2018)

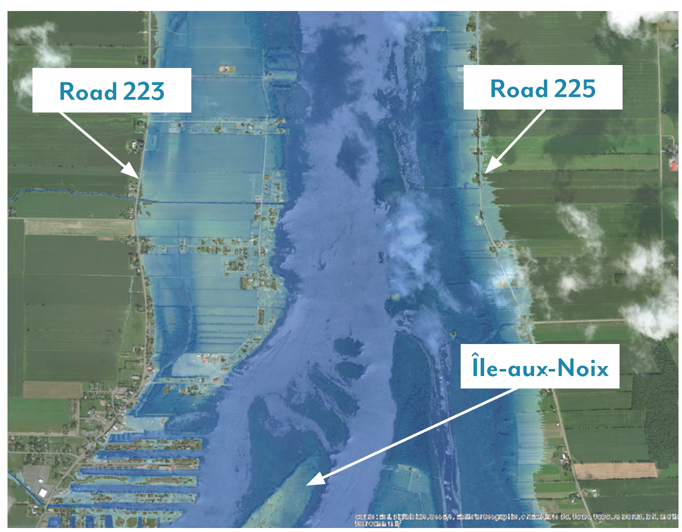


Figure 3-7 | Water levels during 2011 flood, Île-aux-Noix (Fort Lennox)
(Source: Canadian Coast Guard, 2018)

NEW YORK AND VERMONT

During the 2011 spring flood, transportation infrastructure in New York and Vermont was impacted by high water levels and tributary flooding. Lakeshore flooding led to the inundation of low-lying roads, causing transportation disruption and threatening to isolate some communities. During the height of the 2011 flood, about 79 km (50 mi) of roads were flooded (Table 3-5).

Table 3-5 | Summary of road flooding in New York and Vermont, 2011

STATE	LENGTH OF ROAD FLOODED (KM/MILES)
NEW YORK	22.7/14.1
VERMONT	56.2/34.9

(Source: Based on the modeled maximum static flood extent of 2011 and database of road centerlines for Vermont and New York (NYS GIS Program Office, 2018b; Vermont Center for Geographic Information, 2018). Bridge surfaces were mapped as inundated regardless of the actual water-surface elevation in relation to the lowest structural chord of the bridge or the bridge deck.)

In Vermont, the Vermont Agency of Transportation estimated that the spring 2011 flooding resulted in maintenance and repair costs of $15 million US[39]. Fourteen sites across Vermont also reported major slides and slope failures along rivers and streams. At the peak of the flood, the Vermont State Route 2 Causeway between Colchester and South Hero was at risk of total inundation, which would have isolated residents of the Lake Champlain Islands. Sections of nine other major state routes were damaged, closed, or reduced to one lane. The damage to Interstate 89 roads and bridges totaled $6 million US[40] (LCBP, 2013).

In New York[41], spring flooding damage was nearly equivalent to Vermont, and caused $2 million US in damages to bridges and roads in Essex County alone. The spring flooding also caused some minor failures in wastewater treatment infrastructure, and approximately 3,600 people were under boil water advisories (LCBP, 2013).

The transportation disruptions caused by ferry closures and delays was exacerbated by the construction of the new Champlain Bridge, which was delayed due to floating debris dislodged by flood waters (Nearing, 2011). As well, the Champlain Canal, which connects Lake Champlain to the Hudson River, opened a month later than normal due to the high lake level (Nearing, 2013).

Three federal disaster declarations were made in Vermont related to flooding during the spring of 2011. While the direct damages of lake flooding are covered in disaster declaration 1995 (DR1995), flooding in the tributaries to Lake Champlain during the spring of 2011 was another major cause of damages sustained by communities in Vermont. Two other disaster declarations (FEMA-4043-DR and FEMA-4001-DR) were declared in Vermont during the spring of 2011 related to tributary flooding.

[39] $16 million in US dollars equivalent (US 2018). $22 million in Canadian dollars equivalent (CAN 2018).
[40] $7 million in US dollars equivalent (US 2018). $9 million in Canadian dollars equivalent (CAN 2018).
[41] $2.2 million in US dollars equivalent (US 2018). $2.8 million in Canadian dollars equivalent (CAN 2018).

3.1.4
EROSION

QUÉBEC

The Richelieu River is a dynamic fluvial system, driven by forces of erosion and sedimentation occurring at different rates over time. As water flows, it exerts shear stresses over the riverbanks and riverbed, creating erosion. Depending on the type of soil, vegetation, watercourse geometry and flow regime, particular sites along the river can become subject to erosion.

Identifying sites with erosion problems can help prevent loss of shoreline and riverine assets, whether buildings or transportation infrastructure. Although erosion is not a widespread phenomenon along the entire Richelieu River shoreline, the fact that different sites on the riverbanks currently experience erosion and degradation problems should not be overlooked.

The major flooding events of 1993, 1998 and 2011 have all exacerbated the erosion of banks along the river. These can contribute to erosion caused by human actions, such as damage by wave action caused by recreational boats.

NEW YORK AND VERMONT

The record lake level during the spring flood of 2011 led to inundation and erosion of unconsolidated shoreline sediments, which had not been previously exposed to wave action. The spatial distribution of shoreline erosion during the 2011 flood was highly variable (Castle *et al.*, 2013). Some areas experienced little impact, while other areas were greatly impacted. The most significant erosion occurred in areas where the largest waves broke onshore, along long zones of uninterrupted fetch in which wave development was greatest (Castle *et al.*, 2013). The wave-driven flooding reached about 1.5 m (5 ft) above the static lake elevation.

Some shorelines, such as steep banks with little vegetation and lawns extending to the water's edge or shoreline immediately adjacent to seawalls are especially vulnerable to erosion (Castle *et al.*, 2013).

Soil eroded from the shoreline in 2011 resulted in the deposition of organic material in the littoral zone of the lake (Figures 3-8 and 3-9). The deposition of this organic material in the nearshore environment can reduce oxygen levels, leading to the release of legacy phosphorus in the sediments, potentially exacerbating nuisance algal blooms in the lake (Castle *et al.*, 2013). Erosion of shoreline sediment also contributed to lower water clarity in Lake Champlain, which can have significant adverse effects on plant and animal communities that utilize these areas.

Figure 3-8 | Headland erosion along the shoreline of Mooney Bay, New York
(Photo courtesy of LCBP)

Figure 3-9 | Isle La Motte, Vermont, shoreline erosion
(Photo courtesy of LCBP)

At the narrow southern end of the lake in Washington County, New York, chunks of saturated shoreline broke off into the South Bay creating floating islands as large as a half-acre. One of these floating islands threatened a fishing pier and Route 22 where it crosses the lake. Near Dresden, New York, a landslide blocked part of the lake's shipping channel in a remote section of the lake known as "Maple Bend." Army Corps of Engineer workers had to remove trees, boulders and other debris from Lake Champlain to reopen the shipping canal, which leads to the Champlain Canal (Nearing, 2011). Some lakeshore cottages lost land due to prolonged wave action (Figure 3-10). In Colchester, Vermont, high water and waves caused $559,000 US in damage to the Island Line Bicycle Path, a major tourist attraction, where it crosses Lake Champlain along a causeway (Figure 3-11).

Figure 3-10 | Wave damage to a cottage on Lake Champlain shoreline in spring 2011 flood. (Photo courtesy of LCBP)

Figure 3-11 | Spring 2011 flood damage to the Island Line bike path causeway in Colchester, Vermont. (Photo courtesy of LCBP)

3.2 NATURAL ENVIRONMENT

Flooding is a natural process in river and lake environments. Flooding generally has a positive effect on wildlife and their habitats, in particular by maintaining the structure and functions of wetlands and providing necessary habitats for fish and bird reproduction. Therefore, floods provide essential ecological functions and drive biological diversity and productivity within natural systems. However, extreme floods can lead to adverse impacts on the environment. Depending on their timing and magnitude, floods can lead to a decrease in the reproduction success of some species and even threaten the survival of a species.

This section considers the short- and long-term impacts of flooding in the LCRR basin on the natural environment, with particular emphasis on the 2011 flooding event. It focuses on the impacts of flooding on wildlife feeding and reproduction habitats in lake and river aquatic environments, shorelines, and floodplains and wetlands. It also reviews the impacts on water quality.

Quantifying these impacts is challenged by the limited available field data gathered before, during and after the 2011 flood. However, direct and indirect impacts can be inferred from a general understanding of flood processes available in the scientific literature and from an extensive knowledge of the basin's natural environment and wildlife.

3.2.1 LAKE AND RIVER AQUATIC ENVIRONMENTS

In the LCRR basin, there are indications that past floods, particularly extreme events such as the flood of spring 2011, have had an impact on fish spawning grounds in both fast- and slow-flowing water, as well as a direct impact on fish communities.

FISH SPAWNING HABITAT

Severe floods can change the composition of bottom substrates in the littoral (nearshore) zone of the lake, which may adversely affect fish species that spawn in the lake. Large fluctuations in lake levels, along with wave action, can alter the structure of the littoral zone substrate distribution and decrease the quality of spawning substrates (Hofmann *et al.*, 2008). Large water level fluctuations can also increase the rate of shoreline erosion, which transports more organic matter and nutrients into the littoral zone. Higher nutrient intake can result in increased productivity and organic matter decomposition, which may cause oxygen depletion in the nearshore environment, making spawning habitat less suitable for fish (Castle *et al.*, 2013).

If a major flood occurs during the spawning period, increased flow velocity and turbidity in the lake or river can also make conditions unfavorable to fish reproduction or delay it. Flooding can also lead to the destruction of incubating eggs (George *et al.*, 2015), as the accumulation of fine particles may smother them or inhibit groundwater upwelling into spawning beds. Depending on the timing of flooding and breeding, larvae may drift to areas not conducive to their development, which can influence the annual success of juvenile recruitment of a species (Harvey, 1987). Runoff of sediments, nutrients and contaminants can also have an impact on fish survival and reproduction success. For example, eroded sediments irritate gills and can cause respiratory problems in fish, and contribute to siltation of fish spawning sites (COVABAR, 2015). Field observations made in 2011 showed that sturgeon eggs in Saint-Ours on the Richelieu River had almost doubled in diameter when fine particles were attached to the eggs, affecting egg survival.

During the spring 2011 floods, major changes in hydrological conditions led to a reconfiguration of the substrate at several spawning sites located in riffle areas of the Richelieu River. Sandbanks formed in some areas while at other sites, gravel banks appeared. These grounds are used by many species, including the copper redhorse, which is found only in Québec and designated endangered under the *Species at Risk Act*. The species, which the Study is using as an indicator species, is particularly vulnerable to any event that could significantly alter its spawning and rearing habitats, such as extreme low flows or high floods. The only two known spawning grounds for the copper redhorse are in the Richelieu River, one in the Chambly archipelago and the other downstream of the Saint-Ours dam. Furthermore, as seen in 2011, floods can prevent the operation of the Vianney-Legendre fish pass, located at the historic site of the Saint-Ours Canal, which is used to capture spawning individuals as part of an artificial reproduction program.

Figure 3-12 | Releasing carp trapped in agricultural fields, Richelieu River basin
(Source: MFFP, 2011)

FISH COMMUNITIES

The effects of flooding on fish communities can vary depending on the species, life stage and adaptive capacity of the fish. Species that can adapt to a wide range of environmental conditions are better able to withstand the impacts of flooding. Extreme floods can cause a decline in a fish population due to the modification or destruction of habitats necessary for its reproduction, feeding and growth, and to the inaccessibility to those habitats. Extreme floods can also cause the death of fry, juveniles and isolated individuals after the withdrawal of water from the floodplain (George *et al.*, 2015). For example, hundreds of carp were trapped in agricultural fields in Québec when the water receded (Figure 3-12). For these reasons, the Study is using small fish communities as an indicator.

On the other hand, floods are beneficial to some populations. For example, the influx of nutrients can lead to rapid growth of zooplankton and macro-invertebrate populations, which are important food sources for several fish species (Hickey and Salas, 1995). The impacts of flooding on fish populations tend to be more negative in headwater streams, where higher gradients result in greater streambed mobilization during floods and habitat alteration (Carline and McCullough, 2003). Fish population recovery period depends on the frequency and magnitude of flood events, as well as the availability of sediment and woody debris necessary for the reconstruction of complex habitats (Kirn, 2012).

Extreme floods also have the potential to accelerate the spread of invasive species. The dispersion and abundance of the tench (*Tinca tinca*), an invasive fish species, has increased rapidly since 2011. This is of concern, given this species' fertility rate, its ability to survive in flood-induced nutrient-enriched, less oxygenated environments, and its potential to compete for food with the copper redhorse and other fish species (COVABAR, 2014; Masson *et al.*, 2013).

Lake Champlain

In Lake Champlain, fish inventories were conducted from 2009 to 2016 in the USA, and in Missisquoi Bay, data were collected in 2003, 2012 and 2018. In the United States, data show an increase in the abundance of the invasive species alewife in the year following the 2011 flood. In Canada, the alewife was almost absent from Missisquoi Bay in 2003 and 2018, but composed almost 50 percent of the fish community in 2012. While the reason for this increase is unknown, it is possible that flooding led to greater dispersal of the species around the lake. As alewives are not resistant to low temperatures in winter and spring, massive periodic alewife mortality occurs, which can be a public health nuisance in terms of odor and the possible need to remove the dead fish.

The flooding that occurred during the spring of 2011 also disrupted the efforts to control the sea lamprey (*Petromyzon marinus*), population in Lake Champlain (Lake Champlain Fish and Wildlife Management Cooperative, 2011). Flooding of rivers around the lake also resulted in the erosion and transport of large volumes of fine-grained sediment, which was deposited in the deltas and lower reaches of rivers in the basin, in turn making these habitats more suitable for sea lamprey, because these substrates provide ideal habitat for the larval life stages.

In Lake Champlain tributaries, after the flood caused by Tropical Storm Irene in 2011, the population of juvenile brook trout (*Salvelinus fontinalis*) over one year of age decreased to the lowest level observed in 12 years. In addition, though the fry population (young-of-the-year) peaked in spring 2012, this did not result in a significant increase in the juvenile population in 2013, suggesting high mortality, possibly associated with alteration in the amount of favorable habitat (Kirn, 2017) and reduced food availability due to the impacts of flooding on invertebrate populations (Nislow *et al*., 2002). However, long-term monitoring of brook trout populations also highlights their high natural variability, and population declines can be observed even in the absence of major floods (Kirn, 2017).

Richelieu River

Inventories of fish communities in the Richelieu River were undertaken only in 2012 and 2018. Therefore, no direct comparisons can be made with the situation before the extreme flood event of 2011. However, seine fishing data showed a significant increase in species richness (that is, the number of species present) between 2012 and 2018. With respect to aquatic invasive species, the white perch population is low in the river, but tench seems to be more prevalent than in Missisquoi Bay.

3.2.2 SHORELINE HABITATS

Flooding can play a positive role in structuring and maintaining shoreline and riparian vegetation diversity, as plant seeds are transported by rising and falling water levels that contribute to replenish the soil seed bank (Zhang *et al*., 2017). The magnitude, duration, frequency and timing of the floods determine the arrival, establishment and survival of plant species (Garssen *et al.*, 2017).

In the riparian zone, increased water level, flow velocity and shear stress along the side of the river channel during a flood can cause bank erosion and loss of vegetation, as reported during the 2011 flood (Castle *et al.*, 2013). Extreme floods also can cause the removal of topsoil, alter and degrade the soil seed bank that can affect the long-term trend of future vegetation development (Zhang *et al*., 2017). During the 2011 spring floods, shoreline and riparian vegetation likely were impacted by the deposition of contaminated sediments containing fertilizers (nitrogen and phosphorus), pesticides and other pollutants. Such deposition of sediments and fertilizers can also contribute to blooms of cyanobacteria and to the eutrophication of water bodies.

MUSKRATS

Wildlife habitats on the shoreline are impacted by floods and variations in water level. Among them, muskrat is a keystone species that typically build lodges at the water's edge in the fall before the ice begins to form. Winter flooding can make the lodges uninhabitable and cause mortality. Similarly, decreases in water levels may expose muskrat living in the lodges to freezing temperatures. Unpublished data suggested that the muskrat population around Lake Champlain was severely affected following the 2011 spring flood, and that it took at least two years for the population to recover (Danielle Garneau, personal communication).

Studies have concluded that wetlands with stable water levels support a higher muskrat population density than marshes with seasonally variable water levels (Morin and Ouellet, 2006), provided that abundant food sources are available (Messier *et al.*, 1990).

SPINY SOFTSHELL TURTLE

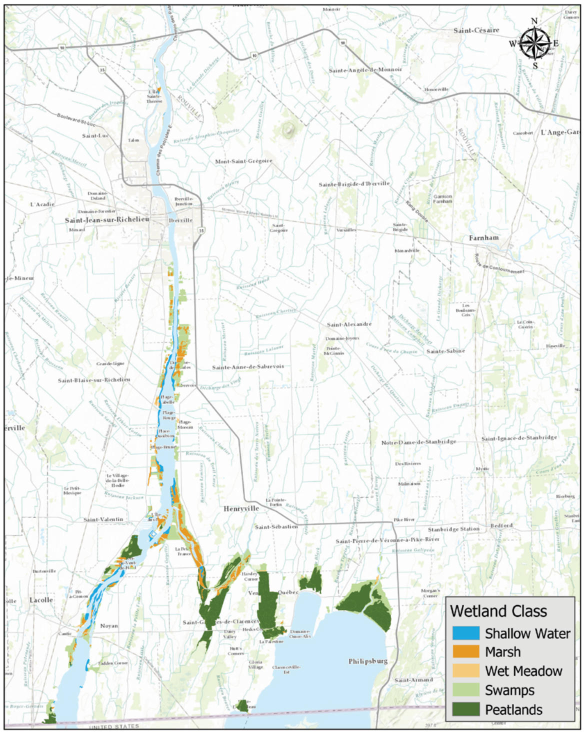
The eastern spiny softshell turtle is another species impacted by flooding. Due to development along the shoreline of Lake Champlain, there remain few areas suitable for nesting or foraging for the eastern spiny softshell turtle, forcing individuals to travel long distances between habitats. In Québec, the continuing decline of this species is also attributed to low reproductive success that has resulted from loss of nesting habitat, altered water regimes caused by dams, floods, invasion of nesting habitats by non-native plants and nest predation by raccoon and other animals.

Some spring flooding is necessary to keep beaches clear of encroaching terrestrial vegetation and suitable for nesting between early June and mid-July (Vermont Fish and Wildlife, 2009). However, when flooding occurs in late-spring and early-summer, turtles may lose access to the rare areas of remaining nesting habitat, since they are flooded when water levels increase. However, turtles can sometimes delay nesting to avoid flood impacts. For instance, in 2011, the first nest in Québec was observed on June 14, whereas turtles usually lay eggs earlier, in early June (Patrick Paré, personal communication).

During the 2011 spring flood, many nest sites of the turtle were impacted. The most productive nesting area in Vermont, located near Missisquoi Bay, was inundated for weeks. Flooding at this site also eroded much of the shale pebble beach used for nesting. This degradation of the nesting habitat might explain the stagnation of Vermont's population from 2011 to 2013.

HAIRY-NECKED TIGER BEETLE

The hairy-necked tiger beetle is another shoreline-dwelling species impacted by flooding on Lake Champlain. It is a species of concern in the United States and is listed as Threatened in Vermont (Schlesinger, 2017). This species is known to inhabit three relatively small areas along the shoreline of Lake Champlain, one location in Vermont and two in New York. *C. hirticollis* is declining in much of its range due to beach front development, overuse of beach habitat, and water level modification. During the spring flood of 2011, the few remaining areas inhabited by *C. hirticollis* were inundated, which likely reduced the suitable area for adult foraging and breeding habitat, and possibly inundated larval burrows.



3.2.3
FLOODPLAINS AND WETLANDS

VEGETATION

Although regular seasonal flooding is generally beneficial to the sustainability of wetlands, extreme flooding can have negative impacts. During the 2011 spring flood, a total of approximately 22 km² (2,200 ha or 5,436 acres) of riparian wetlands and 113 km² (11,300 ha or 27,923 acres) of Lake Champlain's wetlands were flooded (Figures 3-13 to 3-15).

Figure 3-13 (left) | Flooded wetland areas in the Richelieu River and northern Missisquoi Bay, 2011
(Data from: Canards Illimités Canada, 2013, ECCC and MDDELCC)

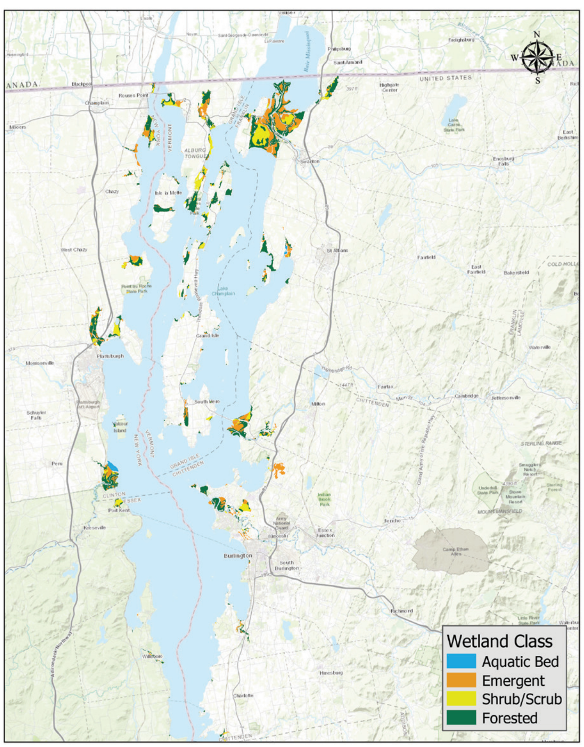


Figure 3-14 | Wetland areas flooded in northern Lake Champlain, 2011
Source: National Wetlands Inventory (U.S. Fish and Wildlife Service, 2016)

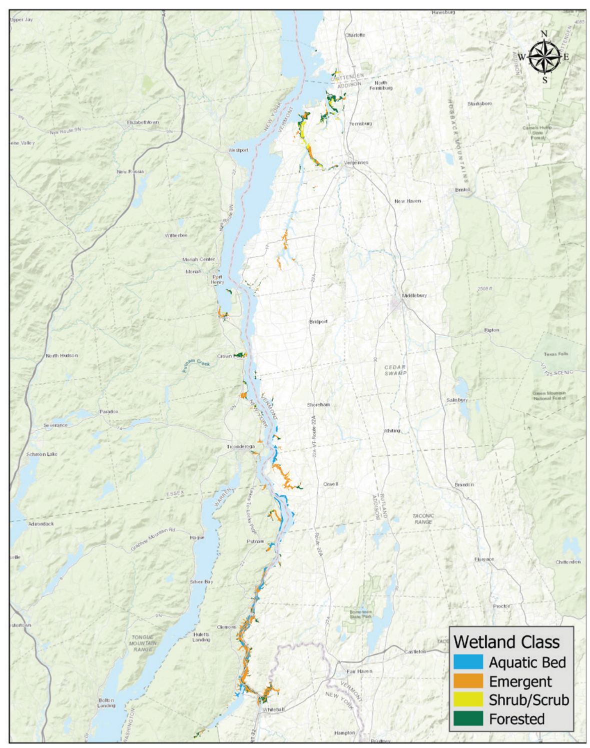


Figure 3-15 | Wetland areas flooded in southern Lake Champlain, 2011
Source: National Wetlands Inventory (U. S. Fish and Wildlife Service, 2016)

Few studies have examined the impacts of floods and water level fluctuations on the wetlands in the LCRR system. However, multiple studies have shown elsewhere the effects of flood frequency and magnitude on wetland type distribution and how plant communities tend to change following a prolonged period of flooding or drought (Grabas and Rokitnicki-Wojcik, 2015; Turgeon, 2005). Submerged vegetation is thought to be the least affected by a rise in water level, but flood events are often associated with an increased turbidity that can suppress plants by restricting access to light. For emergent marshes, it generally takes up to two consecutive years of unsuitable high flows to convert to rooted and floating vegetation, and up to three years to convert back to its original state as the water level lowers (Seabloom *et al*., 2001).

INVASIVE PLANT SPECIES

Most invasive species are rapid colonizers, meaning that they can proliferate quickly in areas that have been denuded of vegetation or where the soil has been disturbed either by natural or human actions. At the Missisquoi National Wildlife Refuge in Swanton, Vermont, the flooding in spring 2011 resulted in the spread of Japanese knotweed (*Reynoutria japonica*), common reed (*Phragmites australis*.), and water chestnut (*Trapa natans*) to areas of the refuge not previously infested (Sefchick-Edwards, 2018). Controlling the spread of invasive species is a major cost to state and provincial governments. In Vermont, approximately $500,000 US dollars[42] is spent every year to control the population of water chestnut in the lake.

The spring floods of 2011, as well as Tropical Storm Irene later that summer, caused extensive erosion of sediment and denudation of vegetation, which left floodplains vulnerable to colonization by invasive species. Perhaps the most troublesome species to colonize floodplains post-2011 was Japanese knotweed. This species is particularly difficult to eradicate, has significant negative impacts on riparian plant and invertebrate diversity, and may accelerate erosion.

NORTHERN PIKE

One species of native fish in the Lake Champlain and Richelieu River basin that particularly depends on flooding to complete its life cycle is northern pike. It can reach considerable size (50-150 cm) and is a top predator, playing an important role in the fish community and ecosystem balance (Casselman and Lewis, 1996). It is also considered an umbrella species, as protecting the integrity of its habitat also protects the habitat of a large number of aquatic species, such as yellow perch and muskellunge (*Esox masquinongy*).

The availability of suitable spawning and nursery habitat often limits the presence and abundance of northern pike in water bodies. Highly successful years of northern pike reproduction often occur in years when exceptionally high spring water levels reach rarely flooded terrestrial vegetation of lakes and rivers floodplains (Rogers and Bergersen, 1995).

However, extremely high spring floods can give them access to higher areas in the floodplains, which are often already developed by humans and unsuitable for spawning. Higher spring floods are therefore not always beneficial. Conversely, poor years of northern pike reproduction in impoundments and natural environments are associated with low or rapidly fluctuating water levels (Rogers and Bergersen, 1995).

MARSH BIRDS

Black tern and least bittern, two marsh bird species inhabiting the wetlands of Lake Champlain and Richelieu River, are highly impacted by flooding. The emergent marsh habitat utilized by black tern is directly linked to long-term variations in lake water levels. The percentage of marsh habitat flooded or stranded and the rate of water level change are important annual hydrologic factors controlling the amount of suitable habitat and the reproductive success of these species. During the nesting period, water level increases can drown eggs and chicks,

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[42] $645,000 in Canadian dollars equivalent (CAN 2018).

and decreases can strand nests making them more susceptible to ground predators. However, these birds have developed adaptations to overcome these issues. For example, black tern can sometimes move the chicks to an auxiliary nest site if the nest is flooded (Heath *et al.*, 2009). In addition, they can nest until late July if a nest attempt is unsuccessful, but not necessarily at the same nesting site (Heath *et al.*, 2009), and their eggshells can resist wet conditions. Least bittern can somewhat elevate nests during the nesting period, but sudden water level increases can down eggs and chicks.

Monitoring at the Missisquoi National Wildlife Refuge suggests that the extreme high water level observed in spring 2011 had impacts on black tern breeding in the refuge, as the number of observed breeding pairs was about 50 percent lower than the previous year. This is also reflected by the low number of fledglings observed in 2011.

In 2011, at the beginning of the nesting period for least bittern in late May, a substantial area of potential habitats, typically located at low elevations, was completely submerged and inaccessible for reproduction. Furthermore, the water level sharply declined in June, which could have further decreased potential nesting success because of nest stranding and increased ground predator access to nests. Moreover, turbidity and siltation associated with extreme floods can have detrimental effects on foraging (COSEWIC, 2009). During and after a flood, there is commonly a decrease in water quality, which may affect the ability of least bittern to see their prey and forage efficiently.

WATERFOWL

Water level fluctuations are one of the main factors influencing the reproduction, molting and migration of waterfowl (Markham, 1982). Fluctuations in water levels influence the composition and abundance of emergent and submerged vegetation (Baschuk *et al.*, 2012), which in turn determines the amount of food available and the shelters needed for nesting. Flash flooding can inundate, destroy, or isolate nests or kill nestlings (Markham, 1982).

Due to the dynamic conditions of wetlands, waterfowl have developed various strategies to breed successfully under adverse conditions. For example, when water levels increase, breeding birds can protect eggs by adding material to the nest to keep it above the water. Some species that usually nest on the ground, such as mallard (*Anas platyrhynchos*) and black duck (*Anas rubripes*), can nest in trees when they are subject to repeated high floods. Waterfowl sometimes can also breed a second time if the first fails (Markham, 1982). However, if this situation occurs late in the breeding season, the birds will not be able to nest again. Waterfowl populations may also relocate to habitats more suitable for nesting.

In 2011, the late arrival of spring delayed the start of the nesting period (Canards Illimités Canada, 2011). It is even possible that nesting conditions were positive for several aquatic bird species, due to the abundance of breeding and nesting habitats provided by large areas of flooded shrubs and hardwoods.

3.2.4 WATER QUALITY

Flooding and precipitation intensity, along with agricultural and forestry practices and other development, can affect sediment, nutrient, and contaminant loads in surface waters found in ecosystems and used by downstream water users, in the basin.

Following a winter of above normal snowfall in the basin, the spring of 2011 broke rainfall records across the region. In Burlington, Vermont, more than 500 mm (20 in) of rain fell from March through May, which represents nearly half of the mean annual precipitation. Excessive rainfall coupled with snowpack melt resulted in extremely high flows in many of the basin's rivers throughout the spring of 2011. This resulted in significant sediment and nutrient loading to Lake Champlain. From April to June, nearly every monitored tributary of Lake Champlain recorded the highest average loads of phosphorus and total suspended solids since monitoring began.

These high nutrient concentrations, together with additional runoff caused by extreme precipitation from Tropical Storm Irene, resulted in large blooms of cyano-bacteria during the summer of 2011 at sites not commonly impacted by blooms. Excess phosphorus contributes to the aesthetic degradation of watercourses and can affect human activities such as swimming, fisheries and recreational boating.

Many areas of Lake Champlain also experienced substantially decreased water clarity during the spring of 2011, likely due to tributary sediment loads and the mobilization of eroded shoreline sediment. The sediment deposition can decrease the amount of dissolved oxygen in the water available for aquatic organisms. Decreased water clarity and high water levels can delay the growth of aquatic vegetation, as aquatic plants need light to penetrate to the bottom for them to germinate and grow (Lake Champlain Committee, 2011). The delay in the growth of aquatic vegetation can also impact wildlife species that utilize this habitat.

In the Richelieu River, sedimentation and siltation due to erosion are common phenomena. The Chambly basin is subject to a rapid siltation process, which causes a decrease in the current and causes suspended solids to settle from the areas upstream of the Richelieu River. The average phosphorus load in the Richelieu River increased between 2009 and 2012. It is possible that the floods temporarily contributed to the increase in this burden. In addition, the proportion of agricultural land and the dominance of annual crops in the basin still exert a strong pressure on aquatic environments (Simoneau, 2007; Simoneau and Thibault, 2009).

3.3 SUMMARY OF KEY FINDINGS

Based on the summary analysis presented in this chapter, the following key findings can be made with respect to the impacts of the 2011 flooding event in the LCRR basin:

- The 2011 flooding events had significant and wide-ranging impacts on the health and economy of the residents of the LCRR basin and on the natural environment of the basin. However, the identification of specific or detailed impacts from the 2011 flood is limited by a lack of data and a lack of standardized methodologies for collecting and reporting basin-wide data.

THE ECONOMY

- Flooding events can have widespread economic consequences, including damages and lost revenues in many economic sectors. Available data suggest that the 2011 flooding event caused more than $67 million damage in Québec, more than $11 million in New York and more than $4 million in Vermont (US 2018).

- The residential sector was particularly affected by the 2011 flood. In Québec, more than 2,500 primary residences were flooded, affecting 3,927 residents. More than 1,650 residents needed to be evacuated from their homes. Municipalities most affected in spring 2011 were located in upstream portion of the river.

- Major flooding can result in direct and indirect losses in the agricultural sector associated with crop losses, yield reductions, livestock losses, damage to soil and damage to buildings and other infrastructure. More than 2,500 ha (6,175 acres) were flooded in Québec, and about 7,740 ha (19,000 acres) affected in Vermont and New York.

HUMAN HEALTH AND SAFETY

- Floods can lead to serious health and safety impacts on populations, ranging from physical injuries or even death during the flood to longer term mental health challenges. These impacts may, in turn, have various economic implications, such as increased public health spending, loss of income or loss of quality of life.
- Following the spring flooding of 2011 in the basin, primary concerns with respect to human health were focused on: ensuring human safety and conducting any evacuations as needed; supplying clean drinking water; containing spills of toxic substances; providing medical care; restoring electricity; and repairing damage to transportation infrastructure to restore access to communities isolated by washed out roads.
- More than 1,650 Québec residents needed to be evacuated from their homes.

INFRASTRUCTURE

- Flooding events can cause significant damage to civil infrastructure, such as roads, railways, and communications technology.
- There is a lack of information regarding the impact of the 2011 spring flood on transport infrastructure in Québec. More than a hundred bridges and roads were damaged.
- In New York and Vermont, transportation infrastructure was impacted during the 2011 spring flood by high water levels and tributary flooding. Lakeshore flooding in 2011 led to the inundation of low-lying roads, causing transportation disruption and threatening to isolate some communities. During the height of the 2011 spring flood, about 79 km (50 mi) of roads were flooded.
- The Vermont Agency of Transportation estimated that the spring 2011 flooding resulted in maintenance and repair costs of $15 million. Fourteen sites across Vermont also reported major slides and slope failures along rivers and streams. Sections of nine major state routes were damaged, closed, or reduced to one lane. The damage to Interstate 89 roads and bridges totaled $6 million.
- In New York, spring flooding damage was nearly equivalent to Vermont, and caused $2 million in damages to bridges and roads in Essex County alone. The spring flooding also caused some minor failures in wastewater treatment infrastructure, and approximately 3,600 people were under boil water advisories.

EROSION

- Erosion is not a widespread phenomenon along the entire Richelieu River shoreline, though specific sites on the riverbanks did experience erosion and degradation problems in 2011.
- The record levels on Lake Champlain during the spring flood of 2011 led to inundation and erosion of unconsolidated shoreline sediments. The most significant erosion occurred in areas where the largest waves broke onshore, along long zones of uninterrupted fetch. The wave-driven flooding reached about 1.5 m (5 ft) above the static lake elevation.
- Shorelines with steep banks with little vegetation and with lawns extending to the water's edge or shoreline immediately adjacent to seawalls were particularly vulnerable to erosion.

NATURAL ENVIRONMENT

- Flooding is a natural process in river and lake environments. Floods can benefit numerous wildlife species that use floodplains as habitat and are critical to the sustainability of riparian and wetland plant communities. However, extreme floods are also associated with adverse impacts on the environment. Depending on their timing and magnitude, floods can lead to a decrease in the reproduction success or even survival of a variety of species.
- Key impacts from the 2011 flood on the natural environment in the basin included:
  - alteration of spawning sites in the Chambly Basin used by the copper redhorse, a designated endangered fish species under the Canadian Species at Risk Act;

- displacement of fish spawning habitats higher up in the floodplain of the Richelieu River during high floods, in areas developed for human needs and unsuitable for fish, compromising their reproductive success;
- entrapment of fish in flooded pools that are not connected to the river;
- modification of the fish community's composition and abundance;
- damage and flooding of nesting sites of the eastern spiny softshell turtle, including a highly productive nesting area in Vermont, located near Missisquoi Bay, which was inundated for several weeks;
- the spread, by flood waters, of contaminated sediments and invasive species such as phragmites, purple loosestrife, Japanese knotweed, Eurasian watermilfoil, curly leaf pondweed and water chestnut;
- possible flooding of marsh bird's nests such as the black tern and least bittern; and,
- impacts on water quality, including significant sediment and phosphorus loading in Lake Champlain, which, together with additional inputs from runoff caused by extreme precipitation from Tropical Storm Irene, resulted in large blooms of cyanobacteria during the summer of 2011 at sites not commonly impacted by blooms.

4. RESPONSES TO PAST FLOODS

Chapter 4 | Since the early 1900s, nearly every major flood in the LCRR basin has led to investigations on how to prevent or mitigate future flooding events. Chapter 4 presents a review of these investigations.

First, it considers the two major studies undertaken by the International Joint Commission (IJC) in response to floods in the basin. It then reviews the extent to which various flood management and risk reduction measures have been adopted in the basin.

4.1 PAST INITIATIVES OF THE INTERNATIONAL JOINT COMMISSION

The governments of Canada and the United States have given three references to the IJC to recommend solutions to mitigate flooding in the basin: in the 1930s; the 1970s; and again, with this present study that follows the disastrous 2011 spring flood.

4.1.1 FIRST IJC REFERENCE

Following severe flooding in 1930s, the IJC received its first reference in 1937 from the governments to address the flooding problem in the basin. The IJC determined flood control structures would be the most effective means of addressing flooding. At that time, the primary focus was on socio-economic benefits. However, it is interesting to note that both the Province of Québec and the State of Vermont raised the issue of possible environmental impacts, but this received little consideration (Brande and Lapping, 1979).

The governments agreed with the proposed course of action and the Canadian government submitted an application (*i.e.*, formal request to undertake specific engineering work in a boundary water) to the IJC. In 1938, the IJC approved the application and construction of the dam began, on what is today known as the Fryer Island dam, located about 8 km (5 mi) downstream of Saint-Jean-sur-Richelieu, Québec (IJC, 1938).

Construction of the Fryer Island dam was completed in 1939. But with the outbreak of World War II, the remedial works and removal of the shoal in the river near Saint-Jean-sur-Richelieu were put on hold, and even after the war ended the project was never completed (Figure 4-1). Eventually, the project was abandoned, though it is unclear why. In 2016, the pathway across Fryer Island Dam was closed off and further work is being done from a safety perspective.

Figure 4-1 | **Fryer Island dam**

4.1.2 SECOND IJC REFERENCE

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

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

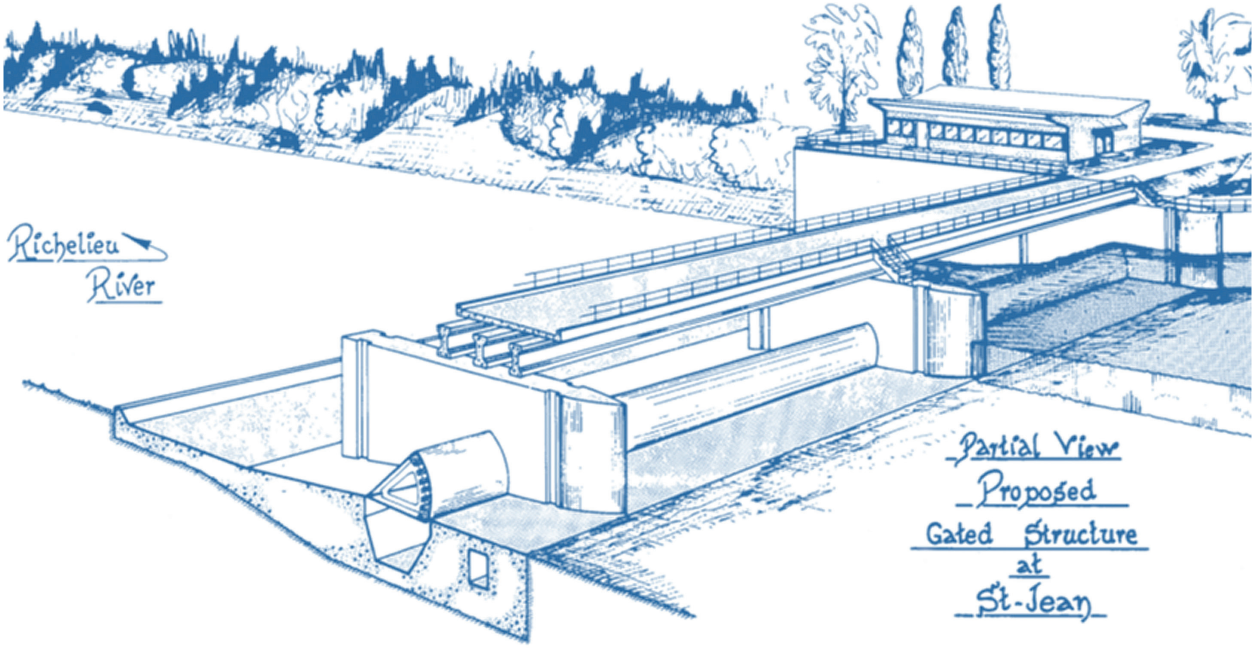
Given the severity of flooding, the governments requested the IJC produce its report within one year of receipt of the reference, an extremely ambitious timeline.

The International Champlain-Richelieu Engineering Board (ICREB) submitted its report to the IJC in March 1974. The report concluded that a regulatory structure could effectively address flooding and was cost-effective. It recommended that it be located in the shoal reach at Saint-Jean-sur-Richelieu (ICREB, 1974). Figure 4-2 (next page) provides a schematic of what was envisioned. The ICREB did its assessment utilizing the existing Fryer Island dam but concluded that it would be significantly more costly to fully implement this option and might not achieve all the desired results.

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

- that the environmental consequences of water regulation needed to be fully assessed; and,
- that there were challenges regarding the economic evaluation and the projected net benefits that would be achieved through water regulation.

Figure 4-2 | **Schematic of proposed regulatory structure, 1974** (Source: ICREB, 1974)



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

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

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

In January 1976, the Government of Canada, with the concurrence the government of Québec, submitted an application to the IJC to dredge the Saint-Jean-sur-Richelieu shoal and construct a fixed crest weir. In February 1976, the IJC responded that it would be deferring its decision until after the ICRB had completed its assessment. After further study, the IJC determined that the fixed crest weir was not an acceptable solution because it was not capable of regulating water levels on Lake Champlain and it could not meet the environmental criteria it had established for evaluation purposes.

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

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

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

The 1977 report recommended that:

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

In addition, the ICRB concluded that while some flood control actions would be compatible with maintaining environmental quality, additional environmental studies and monitoring were necessary for the initial 10 years of operation to evaluate and refine environmental and downstream criteria. It further recommended that any Board of Control established by the IJC include representatives of environmental management agencies on the lake and river.

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

CHAMBLY CANAL

As noted in section 2.2, Transport Canada and later Parks Canada widened the Chambly canal in the Saint-Jean-sur-Richelieu reach by about 30 m (100 ft) into the main river channel in the early 1970s. An investigation by the ICRB concluded that Lake Champlain water levels increased by 3 to 10 cm (1.2 to 4 in) after the canal widening (IJC, 1980).

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

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

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

IJC PERSPECTIVE ON REGULATION AND ADVICE TO THE GOVERNMENTS

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

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

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

RESPONSE TO THE IJC REPORT

Media releases following the release of the report indicate support for the proposed regulatory structure in Québec. The fact that the IJC did not recommend proceeding with implementation suggests there was a lack of support for a structural solution by Vermont and New York constituents. In Québec, on the other hand, regulation was seen to be a viable solution to address the flooding issue.

The governments of Canada and the United States never officially provided a response to the IJC's report. This may have been because there was little desire by Vermont or New York for pursuing the proposed regulatory structure.

4.2 FLOOD MANAGEMENT AND RISK REDUCTION MEASURES

Flood management and risk reduction measures can be organized under four broad categories:

- *flood control structures* that reduce flood levels;
- *flood retention measures* in the watershed to reduce the flows into Lake Champlain and the Richelieu River;
- *flood response plans*, prepared before but implemented as flood waters rise to provide protection and reduce impacts during the flood; and,
- *floodplain management* and land use regulation to reduce the risks to humans and the natural environment in floodplains.

4.2.1
FLOOD CONTROL STRUCTURES

Beginning in the 19th century, the response to major flooding in North America was characterized by large-scale construction projects to control water levels and overbank flows. At the end of the 19th century, the introduction of hydropower for generating electricity created an interest in multi-purpose dams (for example, for electricity, flood control, navigation and water supply.). Dams were managed through operational rules, such as lowering the water behind the dam in the fall and winter, then refilling the reservoir in the spring to provide water for multiple purposes such as navigation and water supply through the dry summer.

In 1941, an architect writing about American dams concluded: "No other achievement of peaceful civilization during the last two decades on this war-torn earth has contributed more to the welfare of future generations than the building of dams in this country" (Zucker,1941). About 40 years later, an international movement against dam-building practices emerged, comprised of environmental, human rights, and social activist groups from a variety of local, regional, national, and international anti-dam campaigns. These groups criticized dams for flooding valleys, displacing farmers, blocking fish migration, reducing water quality and changing natural riverine flow patterns. They argued that dams were short-sighted structures that drew funds away from other potentially sounder approaches. As a result, interest began to grow in non-structural methods to reduce flood risk.

There is currently no significant flood control structure for Lake Champlain and the Richelieu River. As noted above, a 1937 IJC reference led to the recommendation to build the Fryer Island dam. However, the excavation required at Saint-Jean-sur-Richelieu, about 10 km (6 mi) upstream of the dam was never undertaken, so the dam cannot regulate flows and has never been used for flood control. In fact, using the dam now would require the construction of levees to protect from flooding adjacent lands.

4.2.2
FLOOD RETENTION MEASURES

Flood retention measures are designed to increase storage in the basin to reduce the flow of water into tributaries. These measures include restoration of wetlands, the construction of retention ponds to offset the impact of new developments, and the use of agricultural lands to store flood water temporarily. They are referred to as "nature-based solutions," because they attempt to restore natural water retention ecological function to address a societal challenge.

Lake Champlain drains more than 21,000 km^2 (8,000 mi^2). Over the years, much of this land has been modified by human development in ways that can affect flooding along tributaries and potentially around the lake and down the Richelieu River. Farmers have drained wetlands to convert them to farmland. Urban development has displaced absorbent forests and wild plains with impervious surfaces, allowing more water to run into tributaries more quickly. Culverts and ditches have been installed to keep highways clear of water. Meandering streams have been straightened, increasing the speed of water flows.

NEW YORK AND VERMONT

The State of Vermont has enacted a series of policies, enforced by the Vermont Department of Environmental Conservation (DEC), aimed at enhancing natural channel management to allow rivers to regain their equilibrium condition over time. These policies include banning gravel mining from streams, requiring stream alteration permits, requiring optimal sizing of replacement bridges and culverts, promoting floodplain restoration, and protecting floodplains from additional encroachment. The Vermont DEC also has coordinated the extensive assessment of Vermont rivers and streams for their geomorphic condition and developed model zoning bylaws to manage for inundation and erosion hazards. Vermont DEC also awards grant funding to purchase river corridor easements on private land that give channel management rights to the state to prevent fluvial erosion hazards and to restrict development in river corridors. The landowner transferring these rights may be paid or earn federal and real estate tax reductions.

In addition, Vermont and New York (as well as several federal granting programs) provide technical help and funding for wetland restoration. Wetlands are largely protected from conversion in the two states, though there are exceptions.

Several non-governmental organizations (NGOs) are working with private landowners in Vermont, most often farmers, to restore wetlands with assistance from federal and state agencies. NGOs work with landowners to purchase the right to manage river channels on private land, and serve as agents to buy out damaged properties in the flood zones of rivers and hold conservation easements that prevent any future development on these sites.

QUÉBEC

In 2012, the Québec government committed to passing an act on the conservation and sustainable management of wetlands and bodies of water. Regional wetlands plans must be developed by regional county municipalities and included in land use plans. The legislation also provides for increased accountability through progress reports based on a "no net loss" objective.

In June 2017, Québec passed a new wetlands protection act founded on the principle of no net-loss of wetlands. The legislation amended important laws relating to land use planning, water management, natural heritage conservation and environment quality.

4.2.3 FLOOD RESPONSE PLANS

Flood response plans are prepared in advance of any major flooding event. A primary goal of such plans is to provide early warnings to emergency response teams so they may take actions that reduce flood impacts. A number of major population centers in the United States and Europe currently have flood forecasting and warning systems, including: south-west Netherlands; London, UK; Venice, Italy; St. Petersburg, FL; New Orleans, LA; and Providence, RI. Typically, these systems provide thresholds for triggering the closing of large-scale flood barriers.

Flood forecasting by itself does not reduce flood risk. Rather, benefits are realized from the response actions communities take, presumably enhanced by knowing sooner and more accurately where flood waters will go. Because flood forecasts are not perfect, evaluations have to consider the costs of preparing for floods that do not occur, or the damages caused by floods that were not forecasted. A review of the current forecasting capacity and effectiveness will be undertaken as part of this Study.

Hydrometeorological forecasting links numerical meteorological, hydrological, and hydraulic models (*i.e.*, flood routing) to forecast the peak levels that a flood is expected to reach. For example, in the LCRR basin, the forecast would produce estimates of near future static Lake Champlain levels, levels affected by wind-generated seiche and waves, discharges from the lake into the Richelieu River, water levels down the Richelieu, flooded areas and depths in the floodplain. These, in turn, could be used in the model to generate expected impacts. Response measures also can be simulated. For example, assuming the placement of sandbags would remove vulnerable property from the data base used in the model, thus reducing the flood damage estimates.

Flood forecasts are already available in the LCRR basin.

In the United States, forecasting systems providing predictions of water discharge are operated by the National Oceanic and Atmospheric Administration's National Weather Service (NOAA NWS). In Quebec, flood forecasting is the responsibility of the Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC). It is recognized that there is the potential to improve the forecasting products by adding flood mapping tools on the top of discharge and water level forecasts and by increasing the forecast lead time.

NEW YORK AND VERMONT

Between 1946 and 1979, the NOAA NWS established 13 River Forecast Centers (RFCs) across the country to centralize hydrological expertise and provide more focused flood and water supply information to the public. The Northeast RFC provides forecasts for all of New England and most of New York, including the United States portion of the basin. It was originally located in Hartford, Connecticut. It was moved in 1994 to Taunton, Massachusetts, and again in 2018 to Norton, Massachusetts.

Over the years, flood forecasting has improved through the application of more powerful computers and more advanced modeling. (https://www.nws.noaa.gov/oh/rfc/docs/Creation.pdf).

In the near future, the watershed approach used by the NOAA NWS's current models will be augmented with a distributed hydrologic model approach for forecasts. Rather than limiting model output to discreet watershed outlet points, the new model will simulate all stream reaches within a drainage area, using an underlying digital elevation model to define the reaches and route runoff through them. This approach will allow for flood response forecasts at all simulated reaches in the national network, from headwater streams to main outlets downstream. Based on the underlying elevation data, the new model will also allow for the expedited identification of areas likely to be inundated during flood events.

QUÉBEC

Québec requires flood response plans and provides a website where people can obtain accurate flood status reports, instructions and recommendations, and find out what programs and services are available (https://www.urgencequebec.gouv.qc.ca).

Québec's *Civil Protection Act* also places ultimate responsibility on the floodplain resident: "Any person who settles on a site where occupation of the land is commonly known to be subject to special restrictions by reason of a major or minor disaster risk without abiding by such restrictions is presumed to accept the risk involved."

During its consultations in the basin in 2018, the Study Board heard a range of concerns from residents regarding flood response. Residents' concerns and suggestions included:

- limited resources in small communities and the possibility of relying on larger nearby communities for flood protection;
- a system of tiered flood danger levels, and suggestions for actions for each level of danger;
- educating students in Vermont and New York about flood preparedness, so they can educate their families;
- adding wind and ice-out conditions to flood forecasting models; and,
- the need to consider the lack of reliable phone and internet access in rural areas when planning emergency flood responses.

4.2.4
FLOODPLAIN MANAGEMENT

Floodplain management focuses on incorporating flood risk reduction practices into floodplain development through laws, land use regulations, and building codes rather than by measures to control flood waters. Measures include identification of flood zones, elevating/flood-proofing buildings, the establishment of buffer zones and best management practices to avoid or limit adverse impacts.

NEW YORK AND VERMONT

The United States *National Flood Insurance Act* was passed in 1968. It allowed property owners in participating communities to purchase flood insurance underwritten by the United States government. Flood insurance had previously been largely unavailable because premiums through the private insurance market that supported the risk of future payoffs were too high for prospective customers.

To participate, a community has to regulate development in the floodplain (the Special Flood Hazard Area) to reduce future flood risks. The program has been modified several times to address cost and effectiveness problems. In 1973, the purchase of flood insurance was required for a mortgage approval on a home in the floodplain. The *Coastal Barrier Resources Act* (CBRA) of 1982 and subsequent amendments denied flood insurance for new structures in designated coastal barrier systems along the Atlantic, Gulf of Mexico, Great Lakes, US Virgin Islands, and Puerto Rico coasts. This law applies to certain points along the Lake Erie and Lake Ontario shores, but not to any place along Lake Champlain shores.

Community Rating System program, New York and Vermont

In 1994, the National Flood Insurance Reform Act created the Community Rating System Program to encourage communities to enhance their local floodplain management programs in exchange for flood insurance premium discounts for their flood insurance policy holders. Currently, Colchester, Vermont is the only community along Lake Champlain participating in the Community Rating System.

As of September 2018, the National Flood Insurance Fund was more than $20 billion in debt to the United States Treasury (after $16 billion had been forgiven), most of it due to catastrophic flooding along the southeast and Gulf Coast states. In 2012, the United States Congress passed a flood insurance reform, the Biggert-Waters Act, which sets premiums at actuarial rates that would generate insurance premium revenue equal to flood damage insurance payouts. Nationally, about 20 percent of the homes covered by insurance are considered to have subsidized rates, which apply to homes already in the floodplain when insurance was first offered. In the northeast, the percentage of subsidized structures is closer to 40 percent, due to the age of building stock.

The Homeowner Flood Insurance Affordability Act of 2014 slowed the implementation of the realistic policy rates imposed by Biggert-Waters.

Emergency Relief and Assistance Fund – Vermont

The Emergency Relief and Assistance Fund provides state funding to match federal public assistance grants to aid in recovery after federally-declared disasters. Federal public assistance funding is made available to communities to repair or replace public buildings and infrastructure. Eligible public costs are reimbursed by federal taxpayers at 75 percent. In 2012, the State of Vermont amended the Fund's rule to create a sliding scale cost share to provide incentives for flood risk preparedness and mitigation efforts by municipalities.

For disasters after October 23, 2014, the State of Vermont will contribute an additional 7.5 percent toward the costs. For communities that take specific steps to reduce flood damage the State will contribute 12.5 percent or 17.5 percent of the total cost, depending on actions taken by the community. For example, to be eligible for a state match of 12.5 percent funding, communities must participate in or adopt the National Flood Insurance Program, state standards for roads and bridges, a local emergency management plan, and a FEMA- approved local hazard mitigation plan.

Vermont Flood Hazard Area and River Corridor (FHARC) Rule

Flood events are Vermont's most frequent and costly type of natural disaster. Historical floodplain encroachments and flood mitigation approaches have either maintained or increased the state's flood vulnerability over time.

In 2015, Vermont adopted rules applying to development that is exempt from regulations under the municipal flood hazard bylaw or ordinance. It also applies to state owned or operated institutions, regardless of whether or not the municipality has adopted a flood hazard bylaw or ordinance. The requirements under this rule are significantly higher than those required by the National Flood Insurance Program. In addition to higher flood inundation standards, the rule manages new development within state-mapped river corridors in consideration of flood related erosion associated with river dynamics.

The purpose of the FHARC rule is to:

- clarify how the state of Vermont will regulate development exempt from municipal regulation in flood hazard areas and river corridors to ensure compliance with National Flood Insurance Program (NFIP) criteria and enhance flood resilience;
- avoid and minimize the loss of life and property, the disruption of commerce, the impairment of the tax base, and the extraordinary public expenditures and demands on public services that result from flooding; and,
- ensure that the selection, design, creation, and use of development exempt from municipal regulation and located in flood hazard areas and river corridors is safe and accomplished in a manner that is consistent with the public health, safety, and welfare, and does not impair stream equilibrium, floodplain services, or the river corridor.

The Vermont Agency of Natural Resources is also responsible for publishing the Vermont Stormwater Management Manual Rule and Design Guidance document in 2017, which details measures to better manage the modified hydrology associated with stormwater and thus decrease flood risk.

QUÉBEC

Background

Following the major floods that occurred in 1974 and 1976 in several regions of Québec, the Québec and federal governments signed the first Canada-Quebec agreement on floodplain mapping and protection. Under the 1976 agreement, in force until 2001, the province identified and mapped floodplains in nearly 250 municipalities and developed standards for the building of structures in these areas. More than 500 floodplain maps were produced for 0-20 year and 20-100 year recurrence flood zones.

In 1987, the Québec government mandated the Ministère de l'Environnement to develop, propose, implement, and coordinate the application of a *Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains*. The 1979 *Act respecting land use planning and development* was used to ensure compliance with standards and restrictions under both the agreement and *Protection Policy*. Under the policy, the provisions of the agreement were required to be incorporated into municipal land use bylaws and development plans.

The *Protection Policy* initially set out protective measures for the urban, tourism, forestry, and agricultural sectors. In 1996, the sector-based approach was ended (except for the forestry sector) to reduce conflicting measures and goals that had developed.

In July 1996, after Québec experienced heavy rains that caused extensive flooding in several regions of the province, the provincial government established the Programme de détermination des cotes de crues (Program to Determine Flood Benchmark Levels) (PDCC) in August 1998. The PDCC, which covered 155 new lake and river zones, ended in March 2004.

The *Protection Policy* was amended in 2005 to limit development in 0-20 year recurrence floodplain zones to public utility or public safety projects. The amendments also allowed municipalities to update maps produced under the agreement on floodplain mapping and protection and helped ensure that maps or benchmarks produced by municipalities got the same recognition as flood zone boundaries determined under the PDCC.

The current *Protection Policy* sets minimum standards for protecting banks, shorelines, and floodplains for all Québec lakes and watercourses. It seeks to help water bodies remain sustainable, prevent degradation and erosion of these areas, preserve and maintain the quality of biodiversity, ensure the safety of people and property on floodplains, protect flora and fauna in these habitats, and promote the restoration of degraded riparian environments. It requires that a 10- or 15-m strip (about 33 to 49 ft) of shoreline vegetation be preserved and protected at all times (3 m, or about 10 ft, for soil cultivation in farming areas) and prohibits, in principle, construction on banks, shorelines, and floodplains. However, construction is allowed under certain conditions subject to prior municipal approval and, in some cases, authorization under the *Environment Quality Act*.

Following spring flooding in 2017, the province initiated a project to develop and consolidate knowledge about the evolution of flood risk areas for decision making (http://www.cehq.gouv.qc.ca/zones-inond/info-crue/index.htm).

Floodplain protection along the Richelieu River

Under the 1976 Canada- Québec agreement on the protection of floodplains, the first Richelieu River floodplain maps for both 0-20 year and 20-100 year flood zones, from Sorel to Lake Champlain, were produced in 1980. In 1983, the RCM du Haut-Richelieu passed an interim control by-law banning new construction in 0-20 year flood zones. Construction and infilling were still allowed in 20-100 year zones. It was not until May 1991 that infilling in 0-20 year flood zones was banned under urban planning bylaws in the RCM municipalities.

After the federal-provincial agreement ended in 2001, flood zone maps could be updated through mechanisms set out in the *Act respecting land use planning and development* to help develop, update, or amend land use and development plans. The RCM du Haut-Richelieu asked that its flood zone maps be updated. As a result, flood zones between Saint-Jean-sur-Richelieu and the Canada-United States border, including Missisquoi Bay, were remapped using airborne LIDAR surveys. The new maps were completed in 2004.

The importance of the updated maps was reflected in the findings of a review by the provincial environment ministry of development along the river. The review found that prior to the updated maps being prepared in 2004, more than 100 new buildings had been constructed in the 0-20 year flood zone. Similarly, it found that between 1978 and 2001 (when the aerial photos used to make the new maps were taken) about 1,100 backfills had been undertaken in the 0-20 year flood zone, most of them on property under provincial ownership.

In September 2006, the RCM du Haut-Richelieu added the new flood zone maps and the amended protection policy to its land use and development plan. Municipalities along the river changed their zoning by-laws to include the new 2004 mapping data and the land use and development plan. The city of Saint-Jean-sur-Richelieu added the changes to its urban planning by-laws in 2007.

After the 2011 floods, and at the request of regional and local municipalities fearing serious land revenue loss and adverse effects on their citizens, the government decreed that a special intervention zone (SIZ) be established for all municipalities along the Richelieu River. Under the measure, all new construction in the 0-20 year flood zone was banned, making it impossible to submit flood zone management plans for new construction. However, the provision did allow for home expansions in the 0-20 year flood zone under certain conditions and reconstruction of buildings in that zone whose repair costs were less than 50 percent of their value.

After major floods in spring 2019, the Québec government extended the application of the SIZ measure to include land that had experienced flooding in 2017 or 2019. Under the revised provision, repairs can be made to existing buildings in the designated zones, but there is a moratorium on the construction of new buildings or the reconstruction of buildings destroyed by flooding in the zones. The measures also imposed additional flood-proofing standards for buildings in the zones repaired after flooding.

4.3 SUMMARY OF KEY FINDINGS

Based on the analysis presented in this chapter, the following conclusions can be made with respect to past and current flood management and mitigation measures implemented in the LCRR basin:

- The governments of Canada and the United States have given three references to the IJC to recommend solutions to mitigate flooding in the basin: in the 1930s; the 1970s; and again with this present study that follows the 2011 floods. Several of these investigations considered the feasibility of regulating the Richelieu River and Lake Champlain by means of a gated structure on the river. However, lack of public consensus and concerns about environmental issues, such as loss of wetlands, were overriding concerns in the United States and resulted in little support for installing water regulation structures. In Québec, the views were mixed but in general there was support for regulation.
- In 1981, the IJC reported to the governments of Canada and the United States that it was:

  "unable to determine the desirability of the gated structure and therefore is unable to make recommendations regarding the regulation of Lake Champlain and the Richelieu River. However, the Commission does recommend that a flood forecasting and warning system be instituted as soon as practicable and that flood plain regulation be implemented by the appropriate jurisdictions as a matter of urgency."

- Flood management and risk reduction measures can be organized under four broad categories:
  - *flood control structures* that reduce flood levels;
  - *flood retention measures* in the watershed to reduce the flows into Lake Champlain and the Richelieu River;
  - *flood response plans*, prepared before but implemented as flood waters rise to provide protection and reduce impacts during the flood; and,
  - *floodplain management* and land use regulation to reduce the risks to humans and the natural environment in floodplains.
- There is currently no major flood control structure for Lake Champlain and the Richelieu River. The existing Fryer Island dam cannot regulate flows and has never been used for flood control.
- The governments of Vermont, New York and Québec are undertaking "nature-based" initiatives to restore natural water retention in watersheds and offset the impacts of new developments. A focus of these efforts is the restoration of wetlands.
- Flood forecasting systems providing predictions of water discharge are operated by the NOAA NWS and MELCC. It is recognized that there is the potential to improve the forecasting products by adding flood mapping tools on the top of discharge forecast and by increasing the forecast lead time.
- Governments in Vermont, New York and Québec are implementing several floodplain management measures, including encouraging community floodplain management activities, adopting municipal regulations to reduce flood damage in residences, and incorporating flood level maps into municipal planning documents and bylaws.

5. SUMMARY AND NEXT STEPS

Chapter 5 | presents a summary of the Study Board's key findings with respect to the causes and impacts of flooding in the LCRR basin and to the responses of governments to this flooding in the past. It also looks ahead to the next phase of the Study.

5.1 THE CHALLENGE

The natural setting of the LCRR basin makes the region vulnerable to long-lasting flooding. In addition, over the years, anthropogenic activities have resulted in the loss of wetlands and other natural land cover, altering the timing and amount of water flowing through the basin.

Severe floods have occurred several times in Lake Champlain or the Richelieu River over the last 90 years, including major flood events in 1927, 1972, 1976, 1993 and 1998. In the spring of 2011, the LCRR basin experienced its worst flooding ever recorded – far beyond anything ever seen in the 100 years for which flood data are available. Lake Champlain water levels shattered the previous historical maximum level. More than 40 communities were directly affected, and thousands of residents needed to be evacuated. Damages were estimated at more than $82 million[43] ($US 2018).

Looking ahead, the challenge is clear. The region's vulnerability to flooding remains high. What can be done to better prepare for and reduce the impacts of future flooding in the basin?

5.2 KEY FINDINGS

On the basis of the analysis summarized in this report, the Study Board makes the following conclusions with respect to the major causes and impacts of flooding in the Lake Champlain-Richelieu basin, and to the responses to this flooding.

5.2.1 CAUSES OF FLOODING IN THE BASIN

The Study Board finds that with respect to the causes of flooding in the basin:

1. Past floods in historical data have shown that severe floods occurred multiple times in Lake Champlain and the Richelieu River, including the extreme spring flood of 2011.
2. The 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 within a relatively short time period. Additional factors contributing to flooding in Lake Champlain include wind intensity and direction, and associated lake seiche waves.

[43] $105 million in Canadian dollars equivalent (CAN 2018).

4. Since the beginning of the 1970s, Lake Champlain has experienced an increase in the average of annual maximum water levels of approximately 0.30 m (0.98 ft).

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. These changes have tended to alter the timing and amount of water flowing through the basin. However, the cumulative impacts of these changes on large flood events need to be studied further.

5.2.2 IMPACTS OF FLOODING IN THE BASIN

The Study Board finds that with respect to the impacts of flooding in the basin:

1. The 2011 flooding events had significant and wide-ranging impacts on homes, infrastructure and the natural environment of the LCRR basin as well as on the health of residents and economy of the basin. However, the identification of specific or detailed impacts from the 2011 flood is limited by a lack of data and a lack of standardized methodologies for collecting and reporting basin-wide data.

2. Available data suggest that the 2011 spring flooding event caused more than $67 million damage in Québec, more than $11 million in New York and more than $4 million in Vermont ($2018 US).

3. The residential sector was particularly affected by the 2011 flood. In Québec, more than 2,500 primary residences were flooded, affecting 3,927 residents. More than 1,650 residents needed to be evacuated from their homes. Municipalities most affected in spring 2011 were located in upstream portion of the river.

4. Flooding also led to direct and indirect economic impacts in the agricultural sector, including crop losses, yield reductions, livestock losses, damage to soil and damage to buildings and other infrastructure.

5. Following the spring flooding of 2011 in the basin, primary concerns with respect to human health were focused on: ensuring human safety and conducting any evacuations as needed; supplying clean drinking water; containing spills of toxic substances; providing medical care; restoring electricity; and repairing damage to transportation infrastructure to restore access to communities isolated by washed out roads.

6. Flooding events can cause significant damage to civil infrastructure, such as roads, railways and communications technology. It is estimated that more than 100 bridges and roads were damaged in Québec. In New York and Vermont, lakeshore flooding led to the inundation of low-lying roads, causing transportation disruption and threatening to isolate some communities.

7. The record levels on Lake Champlain during the spring flood of 2011 also led to inundation and erosion of unconsolidated shoreline sediments. The most significant erosion occurred in areas where the largest waves broke onshore along long zones of uninterrupted fetch. Shorelines with steep banks with little vegetation and with lawns extending to the water's edge or shoreline immediately adjacent to seawalls were particularly vulnerable to erosion.

8. Flooding is a natural process in river and lake environments, supporting wildlife species and a range of riparian and wetland plant communities. However, extreme floods are also associated with adverse impacts on the environment. Key impacts from the 2011 flood on the natural environment in the basin included:

   - during high floods in the portion of the Richelieu River, fish that naturally use the floodplain to spawn were forced to reproduce higher up in the floodplain in habitats that have been developed, compromising their reproductive success;

   - several spawning sites were altered such as those located in the running waters of the Chambly Basin, used by the copper redhorse, a designated endangered fish species under the Species at Risk Act;

- fish community's composition and abundance were modified;
- nesting sites of the eastern spiny softshell turtle were damaged;
- breeding and nesting habitat of marsh birds, such as the black tern and least bittern, were inundated; and,
- water quality was impacted, including significant sediment and phosphorus loading in Lake Champlain; with additional inputs from runoff caused by extreme precipitation from Tropical Storm Irene, large blooms of cyanobacteria appeared during the summer of 2011 at sites not commonly impacted by blooms.

5.2.3
RESPONSES TO FLOODING IN THE BASIN

The Study Board finds that with respect to the responses of governments to flooding in the basin:

1. Nearly every major flood in the basin over the last 90 years has led to major investigations on how to prevent or mitigate future flooding events. The governments of Canada and the United States have given three references to the IJC to recommend solutions to mitigate flooding in the basin: in the 1930s; the 1970s; and again with this present study that follows the 2011 spring floods.
2. Several of the past IJC investigations considered the feasibility of regulating the Richelieu River and Lake Champlain by means of a gated structure on the river. In the mid-1970s and again in the early 1980s, the IJC conducted extensive public consultations regarding such a regulatory structure. However, there was no public consensus on the issue.
3. Responses to floods can be grouped into four broad categories or themes of flood management and risk reduction measures:
   - *flood control* structures that reduce flood levels;
   - *flood retention* measures in the watershed to reduce the flows into Lake Champlain and the Richelieu River;
   - *flood response plans*, prepared before but implemented as flood waters rise to reduce flood impacts; and,
   - *floodplain management* and land use regulation to reduce the risks to humans and the natural environment in floodplains.
4. There is currently no major flood control structure for Lake Champlain and the Richelieu River. The existing Fryer Island dam cannot regulate flows and has never been used for flood control.
5. The governments of Vermont, New York and Québec are undertaking "nature-based" initiatives to restore natural water retention in watersheds and offset the impacts of new developments. A focus of these efforts is the restoration of wetlands.
6. Flood forecasting systems providing predictions of water discharge are operated by the National Oceanic and Atmospheric Administration's National Weather Service (NOAA NWS) and the Québec Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC). It is recognized that there is the potential to improve the forecasting products by adding flood mapping tools on the top of discharge forecast and by increasing the forecast lead time.
7. State, provincial and municipal governments in Vermont, New York and Québec are implementing several floodplain management measures, including encouraging community floodplain management activities, adopting municipal regulations to reduce flood damage in residences, and incorporating flood level maps into municipal planning documents and bylaws.

5.3 LOOKING AHEAD

The analysis summarized in this report presents the Study Board's findings regarding the causes and impacts of past floods in the LCRR basin. This analysis and understanding will inform the balance of the work of the Study Board as it addresses its primary objective of investigating and recommending measures to *reduce* the impacts of possible future flooding in the basin.

Moving forward, the Study Board will be working on the following six remaining tasks in support of this objective:

- assessing the possibilities offered by **floodplain best management practices**;
- evaluating possible **adaptation strategies** to address expected future variability in water supplies;
- developing and making recommendations for implementing a **real-time flood forecasting and flood inundation mapping system** for the basin;
- 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;
- 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,
- developing **resource response models** that include basic indicators for water resources response to water levels fluctuations, so as to support the planning, evaluation and ranking of potential flood mitigation solutions.

Over the course of this work, the Study Board is providing a variety of opportunities for public engagement, such as public meetings and workshops, to ensure that residents of the basin are aware of the Study's progress and have opportunities to provide input. These public engagement activities will be developed and undertaken with the guidance and support of the Study's Public Advisory Group and the Outreach coordinators.

In addition, over the course of the Study, the Study Board is maintaining a website (https://ijc.org/en/lcrr) to serve as the primary tool for posting reports and other materials related to the Study, and for publicizing notices of public meetings in communities throughout the basin.

The Study Board's final report and recommendations will be submitted to the IJC in 2022.

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CHAPTER 4
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MEASUREMENT UNITS CONVERSION FACTORS

METRIC SYSTEM – UNITED STATES CUSTOMARY SYSTEM UNITS
(WITH ABBREVIATIONS)

Length

1millimeter (mm) = 0.0394 inch (in)
1 in = 25.4 mm
1 centimeter (cm) = .3937 in
1 in = 2.54 cm
1 meter (m) = 3.2808 feet (ft)
1 ft = 0.3048 m
1 kilometer (km) = 0.6214 mile (mi)
1 mi = 1.6093 km

Area

1 square kilometer (km^2) = 0.3861 square mile ($mile^2$)
1 $mile^2$ = 2.59 km^2
1 hectare (ha) = 2.47 acres
1 acre = 0.405 ha

Flow rate

1 cubic meter a second (m^3s) = 35.315 cubic ft a second (ft^3/s)
1 ft^3/s = 0.02832 m^3/s

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE

1909


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