Evaluation of Potential Structural Solutions in the Richelieu River to Mitigate Extreme Flooding

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

Submitted by

Flood Management and Mitigation Measures
Technical Working Group

AND

Hydrology, Hydraulics, and Mapping
Technical Working Group

October 2022

ACKNOWLEDGMENTS

The authors acknowledge the significant modelling and analytical support received from the Study's Hydrology, Hydraulics and Mapping Technical Working Group. In particular, the authors thank Jean Morin, Olivier Champoux, Remi Gosselin and Mouna Doghri for all their help in the design and assessment of these three structural measures.

The authors also want to acknowledge the Resource Response Technical Working Group for the data they provided from the Integrated Social, Economic and Environmental System, which enabled a comprehensive evaluation of these structural solutions. The authors especially thank Mathieu Roy, Marianne Bachand and Charles Rhodes for their insights on the data and the interpretation of the results.

The authors are particularly grateful for all the technical support and information regarding the Chambly Canal provided by Parks Canada, namely François Ferrer, Eric Filion-Paquette and Rene Bernard. The detailed costing for each measure was made possible based on input from Marcel Thum and Khaled Manai of Public Services and Procurement Canada.

These individuals contributed to specific areas of the report:

Measures design and simulations: Olivier Champoux, Jean Morin, Rémi Gosselin, Mouna Doghri and Syed Moin

Measures environmental and social impact: Mathieu Roy, Gabriel Poirier, Charles Rhodes and Marianne Bachand

Chambly Canal design review and comments: François Ferrer, Eric Filion-Paquette, Rene Bernard, Marcel Thum and Khaled Manai

Benefit/cost analysis and report writing: Syed Moin, Bill Werick and Ted Yuzyk.

This report received valuable review and comments from the Study Board members and study managers.

INTERNATIONAL LAKE CHAMPLAIN-RICHELIEU RIVER STUDY BOARD

Co-chair, Canada

Jean-François Cantin

Co-chair, United States

Deborah H. Lee

Members, Canada

Michel Jean

Daniel Leblanc

Madeleine Papineau

Richard Turcotte

Members, United States

Eric Day

Ann Ruzow Holland

Pete LaFlamme

Kristine Stepenuck

Study co-manager, Canada

Serge Lepage

Study co-manager, United States

Mae Kate Campbell

This report has been a collaborative effort between the Flood Management and Mitigation Measures (FMMM) and Hydrology, Hydraulics and Mapping (HHM) Technical Working Groups (TWGs).

TECHNICAL WORKING GROUPS

FMMM, Canada

Jan Adamowski

Pascal Marceau

Syed Moin

FMMM, United States

Ben Rose

HHM, Canada

Olivier Champoux

Milena Dimitrijevic

Simon Lachance-Cloutier

Dominic Roussel

HHM, United States

Tim Calappi

Chris Gazoorian

Blaine Hasting

Bill Saunders

FMMM study co-lead, Canada

Ted Yuzyk

FMMM study co-lead, United States

Bill Werick

HHM study co-lead, Canada

Jean Morin

HHM study co-lead, United States

Jesse Feyen

EXECUTIVE SUMMARY

The International Lake Champlain-Richelieu River Study looked at a broad range of structural and non-structural solutions to mitigate flooding in the Lake Champlain-Richelieu River basin.

THE MEASURES

Following an earlier scan of seven structural options, the Study Board focused on three measures to undertake a comprehensive evaluation.
The three structural measures were:

Measure 1: Selective Excavation of the Saint-Jean-sur-Richelieu Shoal and Installation of a Submerged Weir.

Measure 2: Major Flow Diversion through the Chambly Canal.

Measure 3: Modest Flow Diversion through the Chambly Canal with Selective Excavation of the Saint-Jean-sur-Richelieu Shoal and Installation of a Submerged Weir.

DECISION CRITERIA

These three measures were evaluated using the extensive data collected by the Study and model outputs and assessed as to whether a measure met the Study Board's seven decision criteria:

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

FINDINGS

A preliminary assessment was undertaken by the Study Board using the existing Study information to determine if a measure met the criteria. This was debated over several sessions to come to a consensus. In some cases, the scientific and technical information was clear; in others, it was less clear or was qualitative in nature, but a judgement was still made. These results were needed to undertake the various consultations and provide direction on where the Study was leaning in terms of proposing a structural solution.

Based on these evaluations, it was determined that Measure 1 is a highly viable solution and Measure 3 is also a viable solution. Measure 2 was not considered a viable solution based on technical and economic grounds. The Study Board therefore drafted an initial recommendation:

"The Study Board recommends the IJC advise governments that it is possible to achieve a modest relief of flood (on the order of 10 cm on the Lake and 15 cm at Saint-Jean-sur-Richelieu for an event like the 2011 flood) and drought water levels by returning the hydraulic regime at the Saint-Jean-sur-Richelieu shoal to a more naturalized hydraulic state. This can be achieved by removing some flow-impeding human artifacts in addition to some selected excavations of the shoal and installing a submerged weir in the area of the Saint-Jean-sur-Richelieu shoal. From the Study's evaluation of the proofs of concept, this moderate structural solution is technically feasible, economically beneficial, and socially acceptable. Also, based on the Study's analysis with environmental performance indicators it appears that the structural solution has positive environmental impacts and no significant negative environmental impacts."

The final recommendation was included in the Study Board report to the International Joint Commission, released in August 2022.

It is important to note that the Study provided a proof-of-concept with regards to the structural solutions. It is not to be considered an implementable project plan as is, without a final design phase. This report provides the governments, stakeholders and the public with a level of information to evaluate the viability of a structural solution. Should the governments decide to pursue a measure, they will have access to all the data and models compiled by the Study. The governments will then proceed to make modifications, such as undertaking a comprehensive environmental assessment, to comply with the various applicable laws and regulations.

THE INTERNATIONAL JOINT COMMISSION

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

FIND OUT MORE ABOUT THE STUDY

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

Email lcrr@ijc.org

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

Follow the IJC on social media

@IJCsharedwaters

www.facebook.com/internationaljointcommission/

www.linkedin.com/company/international-joint-commission/

TABLE OF CONTENTS

Acknowledgments i

Executive Summary iv

Find Out More About The Study ix

1 INTRODUCTION 1

1.1 CONTEXT 1

1.2 GEOGRAPHICAL SETTING 3

2 EVALUATING IMPACTS METHODOLOGY 5

2.1 STUDY MODELLING FRAMEWORK 5

2.2 BENEFIT/COST ANALYSIS 6

2.2.1 Study Approach 6

2.2.2 Steps in Benefit/Cost Analysis 8

2.3 CLIMATE CHANGE DECISION SCALING 9

2.3.1 Study Approach 9

2.3.2 Decision Scaling Paradigm 10

3 SELECTIVE EXCAVATION OF THE SAINT-JEAN-SUR-RICHELIEU SHOAL AND INSTALLATION OF A SUBMERGED WEIR (MEASURE 1) 12

3.1 SELECTIVE EXCAVATION OF THE SHOAL 12

3.2 SELECTIVE EXCAVATION OF THE SHOAL AND INSTALLATION OF A SUBMERGED WEIR 12

3.2.1 Excavation Plan 13

3.2.2 Excavation Quantities for Measure 1 13

3.2.3 Pristine State of the System 14

3.2.4 Submerged Weir Design 15

3.3 COST ESTIMATE 16

3.4 IMPACTS ON WATER LEVELS 17

3.4.1 Extreme High-Water Levels 17
3.4.2 Extreme Low-Water Levels 17
3.4.3 Mean Annual Water Levels 17
3.4.4 Water Level Impacts at the International Boundary 20
3.4.5 Summary of Extreme Water Level Impacts 20
3.4.6 Implications for Flood Response 20

4 MAJOR CHAMBLY CANAL DIVERSION (MEASURE 2) 22

4.1 DESIGN FLOW THROUGH CANAL 22

4.2 DIVERSION DESIGN 23

4.2.1 Canal gates 23
4.2.2 Canal reinforcing 23
4.2.3 Dredging volumes (in the river and canal) 23

4.3 PROJECT COSTS 24

4.3.1 Capital 24
4.3.2 Operating 24

4.4 CANAL OPERATING PLAN 24

4.5 IMPACTS ON WATER LEVELS 26

4.5.1 Extreme High-Water Levels 26
4.5.2 Extreme Low-Water Levels 26
4.5.3 Mean Annual Water Levels 26
4.5.4 Water Level Impacts at the International Boundary 26
4.5.5 Summary of Water Level Impacts 30
4.5.6 Implications for Flood Response 30

5 MODEST FLOW DIVERSION THROUGH THE CHAMBLY CANAL AND SELECTIVE EXCAVATION ON THE SAINT-JEAN-SUR-RICHELIEU SHOAL WITH INSTALLATION OF A SUBMERGED WEIR (MEASURE 3) 32

5.1 SCALED-BACK CANAL DIVERSION SCHEME 32

5.2 PROJECT COSTS 33

5.2.1 Capital 33
5.2.2 Operating 33
5.2.3 River and Canal Works 33
5.2.4 Project Cost Estimate. 33

5.3 CANAL OPERATING PLAN 35

5.4 WATER LEVEL IMPACTS 35

5.4.1 Extreme High-Water Levels 35
5.4.2 Extreme Low-Water Levels 36
5.4.3 Mean Annual Water Levels 36
5.4.4 Water Level Impacts at the International Boundary 36
5.4.5 Summary of Water Level Impacts 39
5.4.6 Implications for Flood Response 39

6 EVALUATION OF IMPACTS 41

6.1 WATER LEVELS 41

6.2 ECONOMIC ASSESSMENTS 44

6.2.1 Expected Annual Damages and Benefits 44
6.2.2 Benefit/Cost Analysis 47

6.3 ENVIRONMENTAL IMPACTS 50

6.4 SOCIETAL IMPACTS 52

6.4.1 Residential Damages Avoided 52
6.4.2 Impacts on Indigenous Communities 54

7 CLIMATE CHANGE 56

7.1 FUTURE CLIMATE 56

7.2 CLIMATE CHANGE IMPACTS ON STRUCTURAL MEASURES 56

7.2.1 Submerged Weir Performance for Mega-Floods 56

7.2.2 Submerged Weir Performance for Climate Change Induced Low-Flows 57

7.2.3 Modest Chambly Canal Diversion Performance for Mega-Floods 59

7.2.4 Modest Chambly Canal Diversion Performance for Climate Change Induced Low-Flows 59

7.3 IMPLICATIONS OF CLIMATE CHANGE ON THE ECONOMIC VIABILITY OF THE STRUCTURAL MEASURES 59

7.3.1 Robustness Testing of the Economic Viability of the Measures 59

7.3.2 Robustness Assessment of the Economic Viability of the Measures 60

8 PRELIMINARY ASSESSMENT OF PROPOSED MEASURES 64

8.1 DECISION MAKING PROCESS 64

8.2 EVALUATION OF MEASURES 65

8.2.1 Measure 1 65

8.2.2 Measure 2 66

8.2.3 Measure 3 67

9 SUMMARY AND PRELIMINARY RECOMMENDATION ON A STRUCTURAL SOLUTION 69

List of Figures

Figure 1-1. Geographical area of interest. 3

Figure 1-2. Human interventions on the Richelieu River Shoal. 3

Figure 1-3. The visible eel trap on the shoal is a landmark at low-water levels. 4

Figure 2-1. Integrated Social, Economic and Environmental (ISEE) modeling framework. 5

Figure 2-2. Four stages of benefit/cost analysis. 7

Figure 2-3. Four perspectives used in the Study’s climate change assessment. 10

Figure 3-1. Selective excavation of the shoal and construction of a submerged weir. 12

Figure 3-2. Excavation and spoil use plan (Measure 1). 13

Figure 3-3. Cross-section across the shoal where selective material will be removed. 13

Figure 3-4. Evolution of the current morphology (left) from the pristine state (right). 14

Figure 3-5. Annual hydrograph of Lake Champlain, current (black) and pristine (red) conditions. 14

Figure 3-6. Isometric and cross-sectional views of the submerged weir. 15

Figure 3-7. Proposed cross-section of the weir.... 15

Figure 3-8. Elevation of submerged weir and river training modifications.... 15

Figure 3-9. Measure 1 water level at Rouses Point compared with 2011 flood. 18

Figure 3-10. Measure 1 water level impacts during an extreme low flow period (1964/65). 18

Figure 3-11. Performance of Measure 1 compared to baseline and pristine state. 19

Figure 3-12. Measure 1 water level changes at the United States - Canada border. 19

Figure 4-1. Canal modifications for Measure 2. 22

Figure 4-2. Measure 2 water levels compared with 2011 flood 28

Figure 4-3. Measure 2 water level impacts during an extreme low flow event (1964/65).....28

Figure 4-4. Performance of Measure 2 compared to baseline and pristine state. 29

Figure 4-5. Measure 2 water level changes at the United States - Canada border. 29

Figure 5-1. Layout of Measure 3.....32

Figure 5-2. Measure 3 water levels compared with 2011 flood. 37

Figure 5-3. Measure 3 water level impacts during an extreme low flow event (1964/65).....37

Figure 5-4. Performance of Measure 3 compared to baseline and pristine state. 38

Figure 5-5. Measure 3 water level changes at the US - Canada border..... 38

Figure 6-1. Comparison of measures to baseline conditions and the pristine state for the Richelieu River..... 43

Figure 6-2. Flood damage (CDN$) in the United States and Canada for the 2011 event for baseline conditions and three mitigation measures. 45

Figure 6-3. Time series of flood damages for all sectors for baseline and measures..... 45

Figure 6-4. Damage frequency curves for baseline and measures. 46

Figure 6-5. Expected annual damages (in Canadian dollars) for the baseline scenario for the United States and Canada. 48

Figure 6-6. Changes in areas of different large wetland classes, Measure. 1 versus baseline. 53

Figure 6-7. Number of residences flooded for each measure, by country. 53

Figure 6-8. River reaches of the Richelieu River as per the ISEE tiles. 54

Figure 7-1. Hydraulic performance of the weir for various mega-floods. 57

Figure 7-2. Flow depth maps for the baseline (left) and Measure 1 (right). 58

Figure 7-3. Depth of water over the submerged weir in Measure 1. 58

Figure 7-4. Baseline damage frequency curves for the current climate and for conditions so dry the B/C of Measures 1 and 3 drop to 1.0. 62

Figure 7-5. CMIP5 temperature and precipitation changes projected over the basin for 2026-2055 (labeled 2040) and 2056-2085 (labeled 2070). 62

Figure 7-6. Plausibility of a reduced 200-year flood peak in Saint-Jean-sur-Richelieu. 63

List of Tables

Table 3-1. Cost estimate for Measure 1. 16

Table 3-2.Total annualized cost for Measure 1. 17

Table 3-3. Summary of the Extreme Water Level Impacts for Measure 1. 20

Table 3-4. Summary of overall water level impacts for Measure 1. 21

Table 4-1. Cost estimate for the major flow diversion. 25

Table 4-2. Total annualized cost for Measure 2. 25

Table 4-3. Summary of the Extreme Water Level Impacts for Measure 2. 30

Table 4-4. Summary of overall water level impacts for Measure 2. 31

Table 5-1. Estimated capital costs for Measure 3. 34

Table 5-2. Total annualized cost for Measure 3. 35

Table 5-3. Summary of extreme water level impacts for Measure 3. 39

Table 5-4. Summary of overall water level impacts for Measure 3. 40

Table 6-1. Water level relief provided by each measure for extreme high and low events. 43

Table 6-2. Residential flood relief from the proposed measures for the upstream/downstream reaches during the 2011 flood. 43

Table 6-3. Ten highest baseline flood damages and residual damages with three Study measures and benefits of the measures. 46

Table 6-4. Expected annual baseline and residual damages and expected annual benefits. 48

Table 6-5. Benefit/Cost analysis for each measure. 49

Table 6-6. B/C ratio sensitivity to interest rates. 51

Table 6-7. Environmental impacts associated with each measure. 51

Table 6-8. Example benefits (CDN$) by river reach. 55

Table 6-9. Impacts on indigenous peoples associated with each measure. 55

Table 8-1. Assessment for Measure 1 Based on decision criteria. 65

Table 8-2. Assessment for Measure 2 based on decision criteria 67

Table 8-3. Assessment for Measure 3 based on decision criteria. 67

List of Acronyms

Acronym	Description
BWT	Boundary Water Treaty
CAWG	Climate Adaptation Working Group
CDST	Collaborative Decision Support Tool
CLIMEX	Climate Extremes
CMIP	Coupled Model Inter-comparison Project
CORDEX	Coordinated Regional Downscaling Experiment
COVABAR	le Comité de concertation et de valorisation du bassin de la rivière Richelieu
CPR	Canadian Pacific Railway
CRCM	Canadian Regional Climate Model
ECCC	Environment and Climate Change Canada
FMMM	Flood Management and Mitigation Measures
GCM	General Circulation Model
GIS	Geographic Information System
GSC	Geodetic Survey of Canada
H2D2	Two-Dimensional Hydraulic and Dispersion Simulation
HHM	Hydrology, Hydraulics and Mapping
ICRB	International Champlain-Richelieu Board
ICREB	International Champlain-Richelieu Engineering Board
IJC	International Joint Commission
ILCRRSB	International Lake Champlain-Richelieu River Study Board
INRS	Institut national de la recherche scientifique
ISEE	Integrated Socio Economic and Environmental
IUGLS	International Upper Great Lakes Study
LCBP	Lake Champlain Basin Program
LCRR	Lake Champlain-Richelieu River
LOSLR	International Lake Ontario - St. Lawrence River Study
NAVD88	North American Vertical Datum of 1988

Acronym	Description
NBS	Net Basin Supplies
NGVD29	National Geodetic Vertical Datum of 1929
NOAA	National Oceanic and Atmospheric Administration
PI	Performance Indicator
PMF	Probable Maximum Flood
QM	Quarter-month
RCM	Regional Climate Model
SJSR	Saint-Jean-sur-Richelieu
SPE	Social, Political, Economics Advisory Group
TWG	Technical Working Group
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey
USWRC	United States Water Resources Council
WBM	Water Balance Model

Measurement Units and Datum Conversion Factors

Metric System – United States Customary Measurement System Units

(With abbreviations)

Length

1 millimetre (mm) = 0.0394 inch (in)

1 in = 25.4 mm

1 centimetre (cm) = 0.3937 in

1 in = 2.54 cm

1 metre (m) = 3.2808 feet (ft)

1 ft = 0.3048 m

1 kilometre (km) = 0.6214 mile (mi)

1 mi = 1.6093 km

Area

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

1 $mile^2$ = 2.59 km^2

1 hectare (ha) = 2.47 acres

1 acre = 0.405 ha

Volume

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

1 ft^3 = 0.02832 m^3

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

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

1 ac-ft = 1.233481 dam^3

Flow rate

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

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

NAVD88 – NGVD29 Datum Conversion Factor at Rouses Point

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

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

NAVD88 (ft) = NGVD29 (ft) – 0.43 (ft)

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

NAVD88 (m) = NGVD29 (m) – 0.131 (m)

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

1 INTRODUCTION

This report documents the comprehensive assessment of these three proposed measures using the substantial data compiled and applying the suite of models developed by the Study.

1.1 CONTEXT

Flooding has been a chronic issue in the Lake Champlain-Richelieu River (LCRR) basin. Periodically there are extreme floods, with the worst over the past 100 years occurring in 2011. This resulted in the Governments of Canada and the United States giving the International Joint Commission (IJC) a reference to determine how the impacts of future flooding can be mitigated. The International Lake Champlain-Richelieu River Study Board (ILCRRSB) was established in 2016 and provided a directive by the IJC to guide the work of the Study (ILCRRSB, 2019).

The Study Board initially explored a broad range of structural and non-structural solutions and identified seven structural measures for consideration (FMMM/HHM, 2021).

The seven measures were:

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

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

These three measures were evaluated using the extensive data collected by the Study and model outputs and assessed as to whether a measure met the Study Board's seven decision criteria:

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

The Study Board debated the utility, effectiveness in reducing floods, potential impact on drought levels on Lake Champlain, number of residential buildings that would be spared from flooding, and some of the economic and environmental implications of implementing each measure. Central to the discussions was the need to adhere to the United States and Canadian governments' request to focus on "moderate structural works" as the Study Board aids the IJC in fulfilling the terms of the reference from the two governments.

The Study Board determined that Measures 4, 5 and 6 were major structural solutions, as they involved the damming of the river with a significant effect on the flow regime and potentially, on the environment. The unsuccessful history of trying to implement a dam further indicated to the Study Board that there may be little political and social appetite to pursue such a flood control structure. The Study Board consequently decided that no further Study resources should be committed to Measures 4-6.

The Study Board therefore turned its attention on Measures 1, 2, and 3, as these would be moderate structural solutions. It was concluded that the diversion of water through the Chambly Canal was a very promising solution. In particular, the Study Board decided that Measure 2b, optimizing the diversion, particularly warranted further attention, as Measure 2a was a less effective utilization of the canal. This measure's potential to provide significant flood relief, negligible impact on low water levels, and potentially limited environmental implications made it appealing to the Study Board.

Measures 1 and 3 were considered less promising at that time to the Study Board, as they would result in permanent water level lowering, which could be problematic if climate change reduces net basin supplies (inflows to the watershed), as some early climate work is predicting. However, the potential benefits in reducing flood damages of these approaches led the Board to further consider them, and to address the shortcomings through subsequent moderate structural design. The initial lowering of the shoal was limited in scope, so the Study Board determined that further analysis regarding the removal of various human artifacts on the shoal was warranted in order to fully explore this measure.

The Study Board tasked the Flood Management and Mitigation Measures Technical Working Group (FMMM TWG) with exploring these three measures in greater detail and conducting a thorough assessment. The Study Board also requested that the FMMM TWG work collaboratively with Parks Canada and Public Services and Procurement Canada on the assessment of the Chambly Canal diversion.

The analysis of these measures was conducted to provide a proof-of-concept design and it is recognized that additional work (e.g., detailed engineering plans, environmental impact assessment, etc.) would be required to implement any of these measures.

This report documents the comprehensive assessment of these three proposed measures using the substantial data compiled and applying the suite of models developed by the Study. This information was then used to assess whether a measure satisfies the Study Board's decision criteria and whether a structural solution should be recommended.

In the report, the term "natural state" for the Richelieu River is used to demonstrate the performance of the measure against such state. Natural state implies the condition of the river in the absences of all human interventions like the eel trap, submerged dikes, Chambly Canal and its widening into the river, several rail and road bridges, etc.; in essence, a pre-settlement hydraulic condition.

1.2 GEOGRAPHICAL SETTING

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. For its first 37 km (23 mi), the river is wide (up to 1.5 km or 0.9 mi) and there is no significant impediment to flow. Near Saint-Jean-sur-Richelieu, the river becomes much narrower with a steeper gradient, as it meets a long natural barrier formed by rock shoals. These shoals are about 210 m (689 ft) wide, extend for about 3.2 km (2 mi), and serve as the primary hydraulic control for the watershed, regulating Lake Champlain water levels and outflows, as well as flows in the Richelieu River (FMMM/HHM 2021).

The Chambly Canal passes along the west side of the river, approximately 48 km (30 mi) north of the Lake Champlain outlet and facilitates navigation past the rapids at Saint-Jean-sur-Richelieu. The Chambly Canal stretches for about 20 km (12 mi) along the Richelieu River. Measures 2 and 3 involve routing additional flow through the canal. The section of Chambly Canal of interest is a small section (~ 1 km or 0.6 mi) in the community of Saint-Jean-sur-Richelieu, immediately downstream of Lock #9 (Figure 1-1).

Figure 1-1. Geographical area of interest.

This section of the canal was previously widened by about 30 m (100 ft) into the river channel in the early 1970s. Based on Study modelling, the widening of the canal resulted in raising high water levels on the Richelieu River by 20 cm (8 in), and by some 10 cm (4 in) on Lake Champlain (FMMM/HHM 2021). The extension of the entrance pier in the 1970s was determined to have raised water levels by an additional 2 cm (0.8 in) on the river and lake.

The shoal, located in the same section of river, naturally controls the water levels upstream on the river and lake. Numerous human interventions have taken place on the shoal: eel traps, submerged dikes, artificial island; that have reduced the conveyance of the river (Figure 1-2).

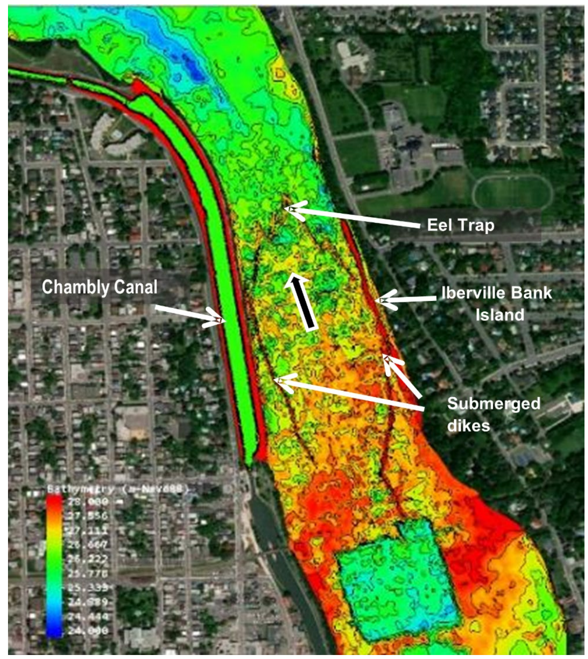

Figure 1-2. Human interventions on the Richelieu River Shoal.

(Red is shallow area at ~28 m and green and blue, deeper zones at ~24 m NAVD88).

The Study has documented the human interventions over the past 200 years in the shoal area (Thériault, et. al., 2020). Study modelling estimates of the cumulative impacts of these interventions have determined the water levels have been raised by about 64 cm (25 in) on the river and about 47 cm (18 in) on Lake Champlain since its pristine state before human interventions. (FMMM/HHM 2021).

Measure 1 focuses on the removal of some of these human artifacts, thereby increasing the flow conveyance and reducing water levels upstream. Measure 3 examines combining selective excavation of the shoal with a modest Chambly Canal diversion. The modest diversion would provide some high-water level relief but would be significantly less costly than the major diversion measure (Measure 2).

Some of the eel traps on the surface of the shoal are a visible cultural landmark for the community at low water levels (Figure 1-3). Concerns were raised through meetings with Parks Canada that the visible eel trap should be protected and excluded from the removal of human interventions on the shoal to maintain this important landmark.

Figure 1-3. The visible eel trap on the shoal is a landmark at low-water levels.

2 EVALUATING IMPACTS METHODOLOGY

2.1 STUDY MODELLING FRAMEWORK

The Study has developed and calibrated hydrodynamic and water balance models to better understand the hydraulics and hydrology. The inputs from these physical models feed into the Integrated Social, Economic and Environmental System (ISEE). ISEE uses a geographical component for display purposes. Figure 2-1 describes how the modelling framework is structured and used in evaluating measures. The physical inputs are shown in the green boxes. Hydrodynamic models simulate baseline conditions and the measures under consideration; the output produces stage-discharge rating curves as a measure of the effectiveness of the flood mitigation measure, as shown in the top left corner of the figure. The water balance model simulates changes to the hydrological regime, namely discharge and water levels at key locations for the baseline and mitigation measures. The other input into the ISEE is socio-economic and environmental data, such as property elevations, damage data, land use, environmental features like wetlands, flora and fauna, etc. Using the property damage data and related water levels, stage-damage curves are developed, shown in the bottom left corner of the figure.

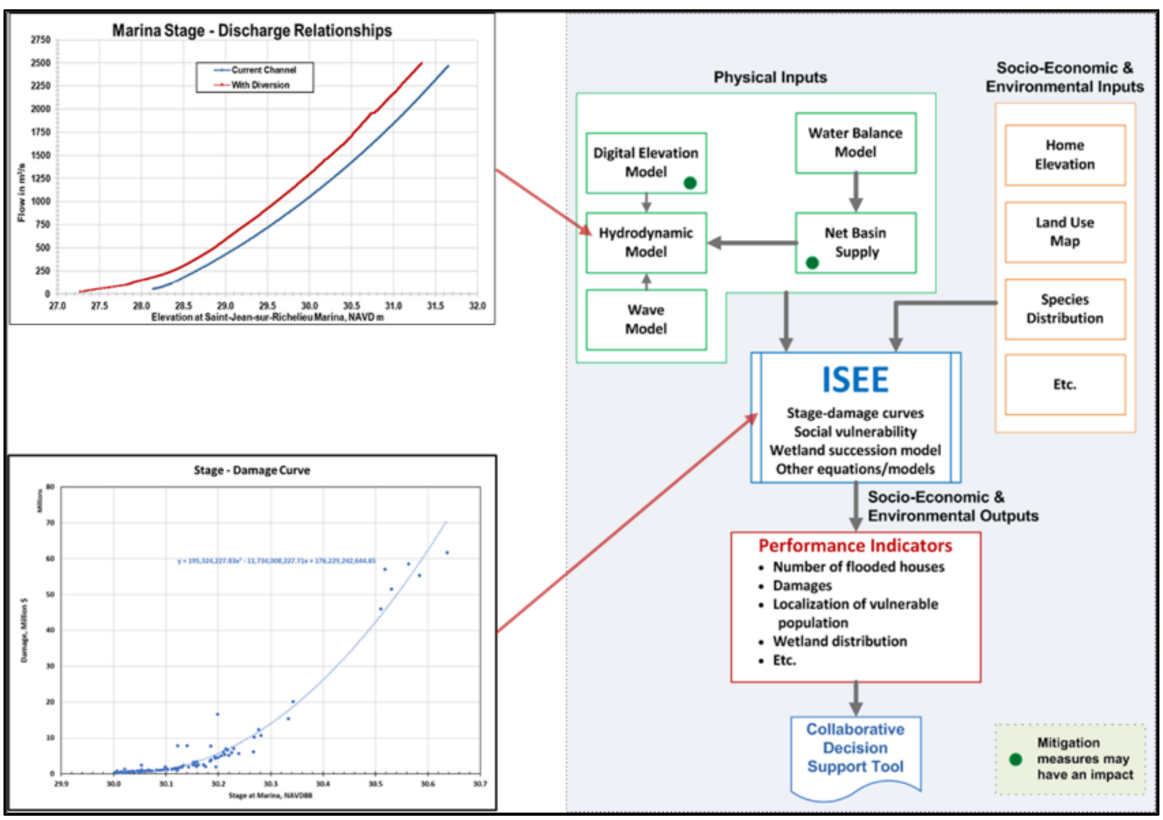

Figure 2-1. Integrated Social, Economic and Environmental (ISEE) modeling framework.

ISEE integrates the various modelling and other data/information inputs to assess impacts. Details on the Study's models and modelling framework can be found in FMMM/HHM (2021). The Collaborative Decision Support Tool (CDST) is an Excel model that holds selected and summarized ISEE output data and combines the results in ways that map into and support the Study's efforts (FMMM, 2022 in preparation). The CDST translates the immense amount of data produced by ISEE into summary results tailored to support the assessment of how well the Study Board's decision criteria have been met by each measure. The version developed for the Study's Benefit/Cost Analysis was used to obtain the results in this report.

The choice of data and the specific mappings were developed over time in several steps and interactions. For example, ISEE produced damages for every parcel at all selected flood elevations. The Richelieu basin total damages, at the Sorel outlet, for different hydrological scenarios were used in the CDST to support the cost-effectiveness evaluation for the measures considered. The CDST produces either aggregated results for the entire period of simulation or alternatively, the user can highlight key periods to examine a measure's performance. For example, measures could be evaluated in 2011, a flood year, or in 1964, a drought condition.

The Social, Political and Economic (SPE) Analysis Group (AG) completed an economic assessment independent from the method used in this report (SPE 2022). The findings of the work will be incorporated into the Study Board's final evaluation and report.

2.2 BENEFIT/COST ANALYSIS

2.2.1 Study Approach

One of the key decision criteria adopted by the Study Board is the economic viability of a measure. For the purposes of this report, the Study adopted the standard principles for benefit/cost analysis to evaluate the economic viabilities of the three measures being considered.

FMMM TWG carried out the Benefit/Cost Analysis using the established and widely used procedures for engineering projects (e.g., Net Benefits Committee Report, 1977; USACE IWR 2003; IBI Group Report, 2015), with some modifications.

A typical Benefit/Cost Analysis of engineering projects for flood mitigation requires three fundamental pieces of information to produce the integrated product, as presented in Figure 2-2:

1. **Discharge-frequency estimates.** These are based on key time series of hydrological variables in the basin. From the Water Balance Model results, recorded and estimated Lake Champlain discharge and water levels at the lake outlet, Richelieu River flow at Saint-Jean-sur-Richelieu and Richelieu River water levels at the marina were available. By conducting a frequency analysis, estimates of the population statistics from a sample of 93 years of recorded flow and water levels (1925 to 2017) were made. This is the standard practice in station flood frequency analysis to estimate more infrequent events like a 500-year return period flood estimate. For more robust estimates, results from stochastic analysis and/or climate change series could also be used; for purposes of this evaluation, frequency analysis was used to provide the necessary information.

2. **Stage – discharge rating curves** are used to translate the statistically estimated discharges to water levels at the location of rating curves. The rating curves were developed through hydrodynamic modelling efforts for the baseline conditions and changes resulting from the proposed measures. With each of the measures, as bathymetric changes are made and features like the submerged weir and diversion are added, the rating curves will change. These changes in the rating curves drive residual damages. The information was captured in the hydrodynamic model runs as provided by HHM TWG.

3. **Stage – damage curves.** These stage-damage surveys are carried out for vulnerable, economically measurable features like primary and secondary residences, apartments, commercial facilities, institutions, services, sectors including agricultural, etc. From the collected information, the stage-damage curves were built for various sections of the geographic areas. The damage information was collected from the payouts during the 2011 floods for a known water surface elevation; the units of measurements are economic, i.e., in 2019 dollars. The damages included both property and content damages and related damages collected by various study groups.

These three pieces are required to produce damage-frequency information. Expected Average Annual Damages (EAAD) were used to calculate the benefits of each measure; EAAD is the area under the damage-frequency curve (Figure 2-2, panel 4). The difference in baseline and measure EAAD is the benefit achieved by that measure. The Benefit/Cost Ratio was computed by dividing the present value of the expected annual benefits by the present value of projected total annualized costs computed for each measure. If the expected net benefits were greater than the costs, the benefit/cost ratio was greater than one, a threshold for evaluating the efficacy of a proposed structural solution.

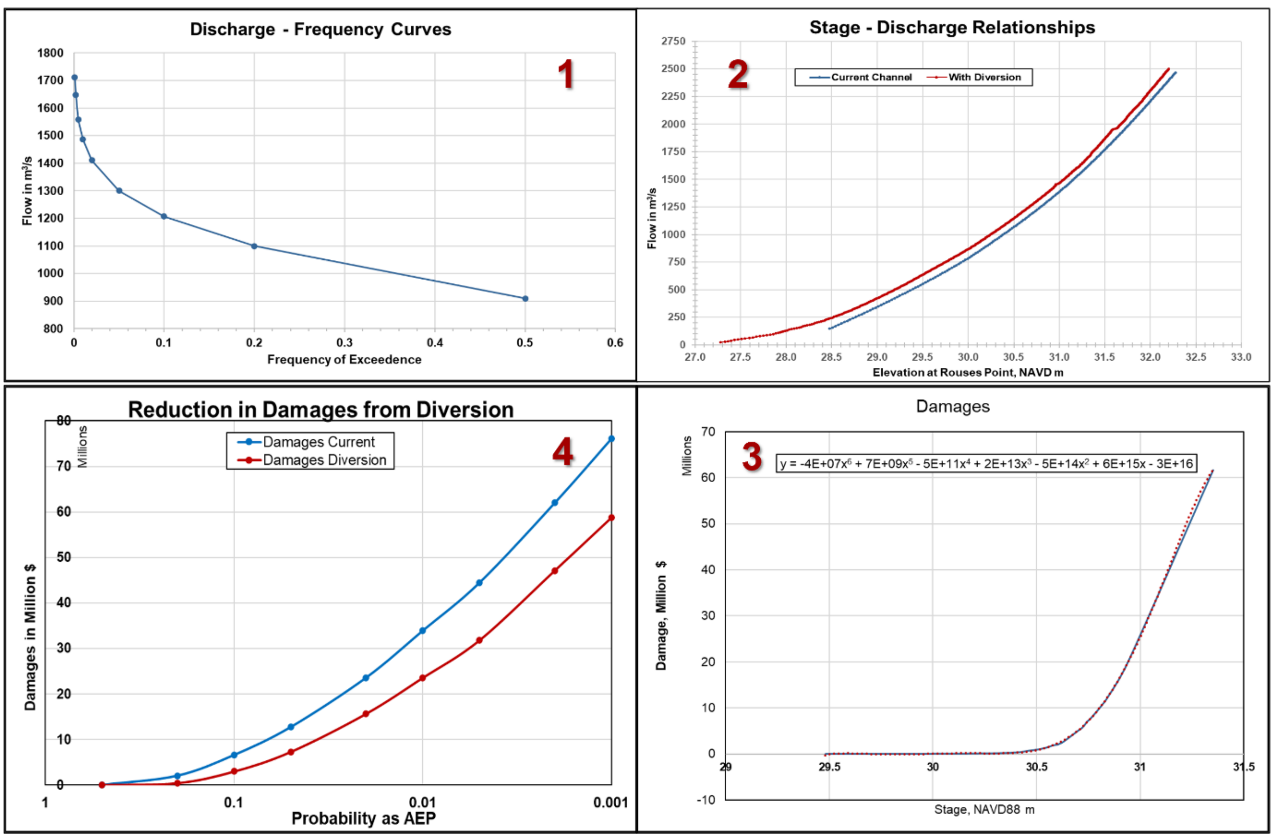

Figure 2-2. Four stages of benefit/cost analysis.

Typically, such relationships are developed for a few reaches, and the four curves in Figure 2-2 can be connected. For example, in graph 1, the 10-year return period flood is 1,200 m^3/s (42,376 ft^3/s). In graph 2, when the discharge is 1,200 m^3/s (42,376 ft^3/s), Lake Champlain (Rouses Point) elevation is about 30.65 m (100.56 ft). In graph 3, the damage when Lake Champlain is at 30.65 m (100.56 ft) is about CDN$6 million (US$4.5 million), which is the 10-year return period damage estimate on graph 4. Benefits can be calculated for each reach. Initially, it was proposed to relate all damage functions to an index location such as Saint-Jean-sur-Richelieu Marina or Rouses Point, the interface of the lake and riverine environments. However, flooding along the Richelieu River can be attributed to two major sources: (1) Lake Champlain outflow and (2) the St. Lawrence River water level in the reaches immediately upstream of Sorel and extending to St. Ours. Local tributaries also influence flood levels. It was observed that the historic flood of 2011 did not produce the same level of damages or impacts at points near the outlet of the Richelieu River as were exhibited farther upstream; evaluating benefits for an index location would have required a complex multimodal analysis. FMMM TWG therefore essentially used the damage-frequencies for each of the surveyed or mapped properties aggregated temporally on an annual basis, rather than a few reaches to calculate EAAD and benefits.

2.2.2 Steps in Benefit/Cost Analysis

One of the key aspects of this analysis is the manipulation of flood damage data; these are the economic indicators obtained through the ISEE model (Roy, et.al., 2022). ISEE assigns a water level at each building for every timestep, using the results from a water balance model and a hydrodynamic model for 93 years of historical data (1925 to 2017) to compute a flood damage time series at each building. This approach is unique to this Study, and it emulates the first three steps described above for use on one or a few reaches. The following steps describe techniques in developing a time series of damages through ISEE and CDST modelling to develop the flood damages versus probability curves.

There were four curves produced, the baseline damages and the residual damages for the three measures under consideration.

Step 1 – The Study carried out multiple steady state hydrodynamic model simulations for the baseline condition and the three measures, producing water levels for all the properties identified through ISEE mapping under different water level scenarios for the 48 quarter-months each year, for 93 years.

Step 2 – The ISEE model used these water levels as the independent variable driving impact functions at each property, including:

1. Structure and material damages
2. Agricultural yield damages
3. Cleanup cost damages
4. Commercial income loss damages
5. Socio-sanitary cost damages
6. Temporary lodging cost damages
7. Recreational income loss damages

ISEE also calculated non-economic impacts on flora and fauna, and indigenous and cultural performance indicators. These informed the Study Board's determinations on other decision criteria. The ISEE system outputs all this information in zipped comma separated variable (CSV) files that can be read in Power Queries into Excel.

Step 3 – The CDST model, an Excel model, imports ISEE output and parses the data into time series of economic and environmental performance indicators. The overall and categorized damage over the historical time series of 93 years was used as a time series of baseline damages and residual damages (the damages that are computed with a measure in place. The basis of this analysis was synthesized as seven-time series; four of damages for the baseline and residual damages that would be incurred in the presence of a measure and three series of benefits for the measures as differences between baseline damage and measure residual damage.

Step 4 – The four Excel-based time series on baseline damages and residual damages provided sample data that can be used in the benefit/cost analysis. The Study then computed the costs of the measures and compared them with benefits derived from reduction in damages.

The evaluation and the information feeding into the benefit/cost analysis are detailed in Chapter 6 of this report.

2.3 CLIMATE CHANGE DECISION SCALING

A key question for the Study Board is how to prepare for the flooding along the coast of Lake Champlain and down the Richelieu River that will occur in the next few decades. The Board adopted a climate change strategy designed to support the best possible answer to that question, despite the irreducible uncertainty in estimates of the severity and chance of future flooding.

2.3.1 Study Approach

This approach draws on data provided from four different perspectives on possible future flooding (Werick 2021):

1. Stochastically generated future Net Basin Supply (NBS) datasets

2. Probable Maximum Flood

3. Stress test NBS developed using a "weather generator"

4. Climate modeling (peer reviewed climate research published in 2020)

The first perspective was statistical. NBS data sets were developed using three different assumptions about the patterns in the historic supplies to help predict patterns in future supplies. The second perspective focused on the design of the Probable Maximum Flood (PMF). Originally, the design intent of the PMF analysis was to consider the joint probabilities of maximum snowfall, optimal spring temperatures for flooding and maximum spring precipitation, but there was not enough data to conduct that analysis. In lieu of that, a PMF ratio developed by Zhou et. al. (2008) was used to estimate the PMF from the 10,000-year event. Maximum possible flood flows were 5,449 m^3/s (192,423 ft^3/s), with a Lake Champlain level of 35.74 m (117.24 ft.). The third perspective applied a "weather generator" that superimposed various temperatures and precipitation patterns to generate flooding sequences that could occur. Finally, the last perspective used the input from global climate models (GCMs) and Regional Climate Models (RCMs) to model future climate and thus, possible future floods.

The inputs from these four perspectives were fed into the water balance model (Figure 2-3) to determine the range of water levels these NBS sets would create. The decision scaling approach described below examined the results from these different perspectives to determine the implications of future climate on a range of decisions, from implementing structural solutions to various policy decisions.

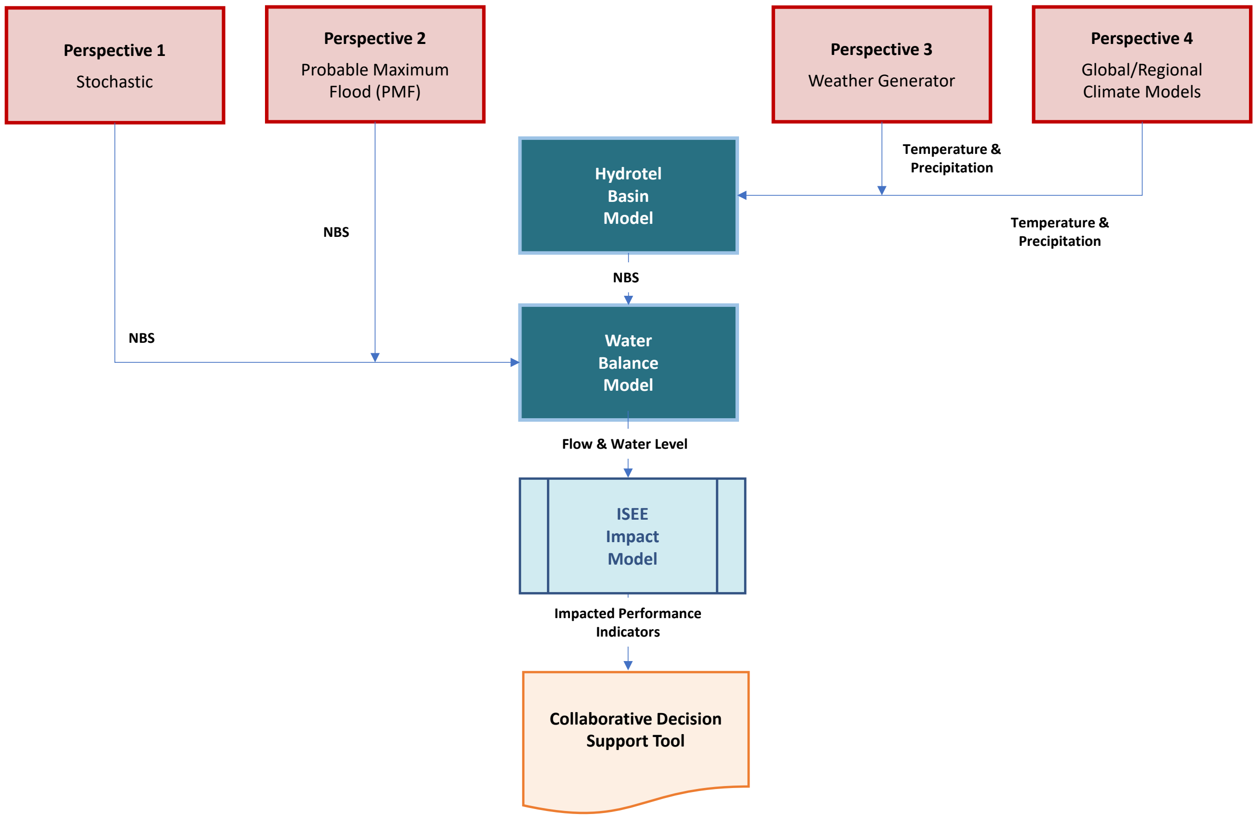

Figure 2-3. Four perspectives used in the Study's climate change assessment.

2.3.2 Decision Scaling Paradigm

Climate change could make flooding more or less of a problem, increasing or decreasing the benefit/cost (B/C) ratios of proposed measures over time. The IJC has developed guidance (2017) for factoring climate change into management decisions; that approach, called decision scaling, was used by the Study Board, and the results are summarized here (François and Brown, 2022).

Decision scaling goes beyond the study of climatology; it explicitly connects plausible changes in climate and the advisability of specific decisions. In this case, the decision before the Study Board is whether or not to recommend further consideration of a particular measure. In this analysis, "advisability" means the degree to which measures are cost-effective. Cost-effectiveness is one of the seven criteria the Study Board considers before making its recommendations, and the one most significantly affected by climate change. If it appeared likely that the costs of any measure would exceed their benefits in the future, the Study Board would at least caveat, if not withdraw, its support for it.

If climate change were to make flooding worse, the B/C ratio for these measures would increase. Greater damages without the project (the baseline condition) would mean that any measure that would reduce flood damage would have increased benefits, while costs would remain the same.

The decision scaling analysis used a "weather generator", a computer model that created precipitation and temperature inputs to the Lake Champlain hydrologic basin model, which in turn simulated NBS (water inflows) into Lake Champlain. In order to define breaking points in system performance, the changes in precipitation and temperature went beyond projections from climate models. The simulations preserved the variability of current net basin supplies, so the NBS may be shifted higher or lower, but would still produce a wide range of floods and droughts, as in the current climate.

This allowed the simulation of a variety of extreme events and provided a robust analysis.

The four perspectives were used together to challenge and refine findings from the individual perspectives about likely Lake Champlain levels in the 21st century, and inform the Board's evaluation of potential structural measures, as described in the following sections of this report.

3 SELECTIVE EXCAVATION OF THE SAINT-JEAN-SUR-RICHELIEU SHOAL AND INSTALLATION OF A SUBMERGED WEIR (MEASURE 1)

3.1 SELECTIVE EXCAVATION OF THE SHOAL

The focus of this measure was on removing various human artifacts and higher elevation portions of the shoal to increase the conveyance in the Richelieu River. The Study Board found this option appealing, as it reverses the impacts of human interventions and moves the system back towards a more natural state. Various excavation strategies were explored, but all resulted in the permanent lowering of water levels, both in the lake and river to varying degrees, and exacerbated low water levels. Because of the impacts on low water levels, it was recognized that excavation alone would not be a viable solution, so efforts then focused on excavating in combination with the design of a submerged weir to mitigate the low-water impacts.

3.2 SELECTIVE EXCAVATION OF THE SHOAL AND INSTALLATION OF A SUBMERGED WEIR

This measure focuses on removal of human artifacts to increase conveyance. The hydraulic gains would be achieved through removal of the submerged dikes, an older, not visible eel trap, and some excavating of the shoal. However, the highly visible eel trap would not be removed, and would remain as a visible cultural landmark for the community at low water levels. It was determined that the removal of this eel trap would not significantly improve the conveyance. This was a positive solution, as it would increase conveyance while protecting the visible landmark for the community, that input from Parks Canada indicated the residents have come to appreciate (Figure 1-3). Figure 3-1 depicts Measure 1. When contrasted to Figure 1-2, the material and features like the submerged dikes, shallower parts of the river are removed in Figure 3-1. Figure 3-1 also shows the proposed dike where the river bottom was already shallow merging with the shallowest region towards Iberville.

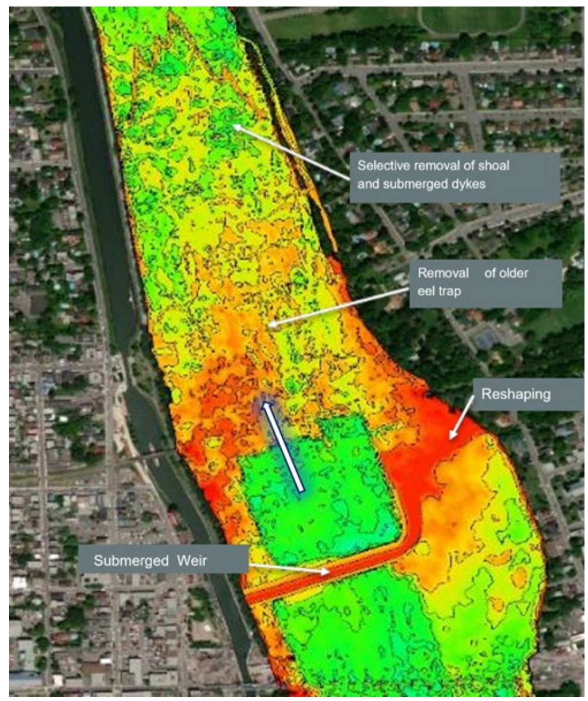

Figure 3-1. Selective excavation of the shoal and construction of a submerged weir.

The bathymetry in red colour are the shallowest regions and transits to deeper zones from yellow to green.

During the initial hydraulic modelling of selective removal of the human artifacts in the river, the study concluded that such action would permanently lower the water levels in the Richelieu River and Lake Champlain. Therefore, a submerged weir was selected to be incorporated into the design to control the lowering of the water levels during low flow periods. The proposal is selective in shaving the extreme highs and lows in Richelieu River and Lake Champlain.

Figure 3-1 depicts the planned excavation and reshaping of the riverbed; deeper areas are shown in green and shallower ones are in red. The two large green “squares” shown in Figure 3-1 were dredged in the 1930s as part of the flood mitigation project associated with the construction of the Fryers Island Dam. (Thériault, et. al., 2020). Some raising of the riverbed was included in the design on the east side, to divert flow towards the centre of the river and avoid erosion of the east bank (Figure 3-1). This configuration approximates the natural hydraulic control conditions for the shoal that existed before many of the human interventions (Thériault, et al. 2020).

3.2.1 Excavation Plan

Figure 3-2 shows the area that would be excavated. The dark red areas reflect removal of ~30 cm (11.8 in) depth of material and the lighter red/orange colors indicate varying lesser amounts to be removed. Based on the excavation plan, some 31,310 m^3 (40,952 yd^3) would need to be removed from the shoal to achieve the desired hydraulic effect.

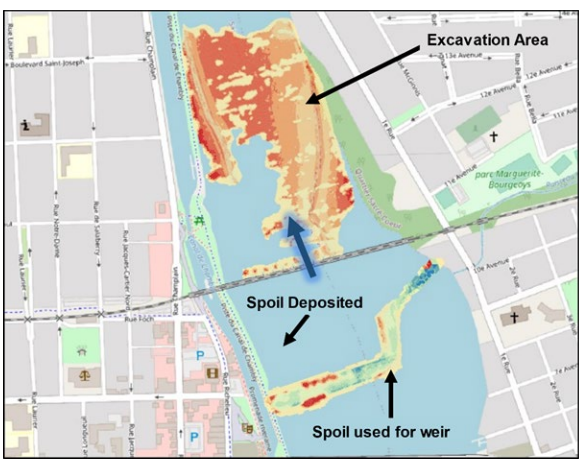

Figure 3-2. Excavation and spoil use plan (Measure 1).

The human artifacts are mostly comprised of loose stone and till, and the shoal is made up primarily of unconsolidated material that can be easily excavated. It is anticipated that blasting would not be required.

Potential structural measures to control water levels were investigated in the 1970s. As noted in the Technical Report of the Physical Aspects Committee (ICRB 1977), the investigators carried out soil analysis at several locations where material was to be removed in the shoal area. Six bore holes were made across the shoal area to a depth of about 8.0 m (26.2 ft.). The cross-section revealed black shale rock with an overburden of silty glacial till, with pockets of silty clay with some sand deposits near the shore at the Chambly Canal. The graphic shown in Figure 3-3 was taken from the 1977 technical report. The material was identified as dense silty till with standard penetration indices varying from a minimum of 50 cm (20 in) the upper layers, to over 1.3 m (50 in) in the lower layers.

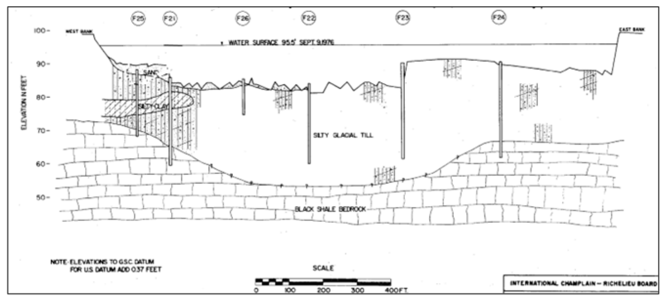

Figure 3-3. Cross-section across the shoal where selective material will be removed.

The material’s gradation varied from silt to silty sand with gravel. The quality of material excavated and identified for reuse in weir construction need to be evaluated for contamination, a step beyond this proof-of-concept stage. Boulders up to 60 cm (24 in) in diameter were also found in the material. The depth of material to be removed by the current proposed measure is, on average, about 30 cm (11.8 in). The overlying depth of water in this stretch of the river would vary depending on the time of year between 1.5 and 4.5 m (5 and 15 ft), with an average of 2.4 m (8 ft). Average flow velocity is on the order of 1.2 m/s (4.0 ft/s).

3.2.2 Excavation Quantities for Measure 1

Of the 31,310 m^3 (40, 952 yd^3) to be removed, about 25 percent or 7,740 m^3 (10,124 yd^3) would be used to construct the submerged weir. The rest of the dredging spoil would be deposited immediately downstream of the submerged weir where the bed was extensively dredged and lowered in 1939. Approximately 9,000 m^3 (11,770 yd^3) of the material would be removed from artifacts like submerged dikes built for diverting water into the mills; the remainder (about 22,000 m^3 (22,775 yd^3)) would be scraped from the shoal. Based on the thalweg profile, the average current elevation on the shoal is 27.15 m (89 ft). As proposed in Measure 1, the elevation would be 26.92 m (88.3 ft). On average, 23.2 cm (9.1 in) of material would be removed (this amount could vary between zero and 30 cm (11.8 in)). The surface area impacted by the measure would be about 12 ha (30 acres). This excavation approach would provide significant cost savings, as no material would need to be transported off-site and the spoil would serve as the construction material for the submerged weir.

3.2.3 Pristine State of the System

Historical and anthropomorphic changes have taken place within the Richelieu River in the critical shoal area in Saint-Jean-sur-Richelieu. All notable changes in the river's geomorphology have been documented in a report prepared for the Study (Thériault, et. al., 2020). These changes affected the water levels not only locally in the shoal area, but also as far upstream as Lake Champlain. Studying the pristine state of the system provides a frame of reference to evaluate the behavior of the measures pursued to reduce flood damages. Figure 3-4 compares the current morphology of the riverbed to the original conditions, as determined by the Study (Thériault, et. al., 2022). For this evaluation, once a measure was proposed, its potential effect on water levels was tested against the pristine conditions. If a measure would change the morphology (and thus hydraulics) closer to the pristine conditions, it was viewed favorably.

In Figure 3-4, to the left is the current baseline showing the remnants of human artifacts, including the widened Chambly Canal; the river graphic to the right shows the likely bathymetric details that existed prior to the settlement in this area based on archival reconstruction. The proposed submerged weir is designed to follow the pristine bed morphology and recreate the natural hydraulics.

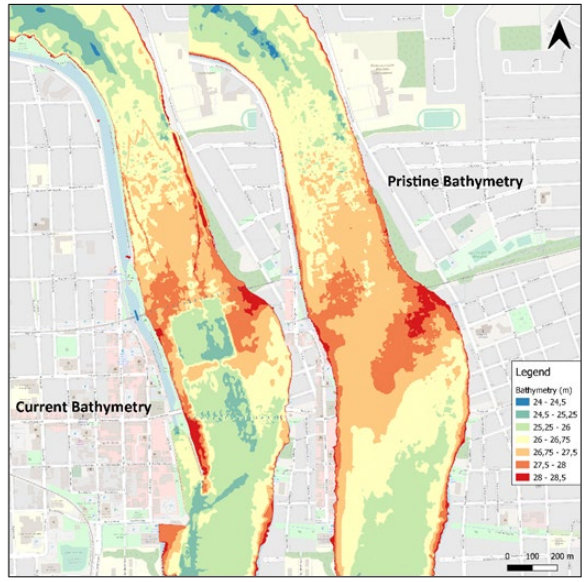

Figure 3-4. Evolution of the current morphology (left) from the pristine state (right).

Figure 3-5 compares the average annual water levels in Lake Champlain for the baseline (current) conditions with the pristine state morphology in the Richelieu River through the critical sections in the Saint-Jean-sur-Richelieu area. It shows that the current (baseline) condition has a higher flood peak than the pristine condition, and baseline water levels are lower from summer to the following spring, as compared to the pristine state.

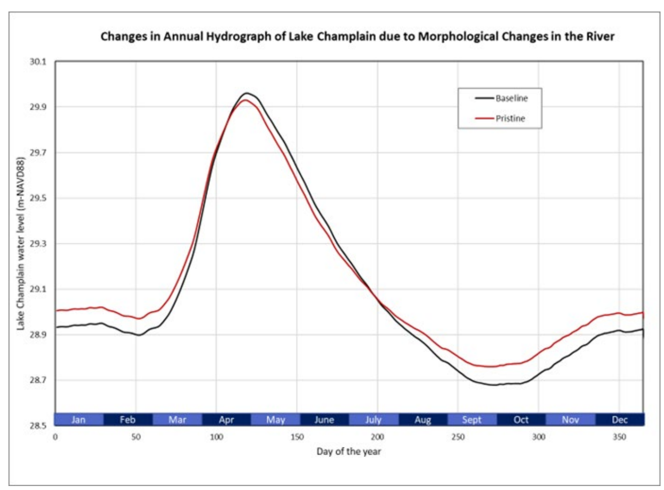

Figure 3-5. Annual hydrograph of Lake Champlain, current (black) and pristine (red) conditions.

3.2.4 Submerged Weir Design

In the first approximation for this proof of concept, the proposed weir design builds on a model that dates to the early 1950s and that has been utilized world-wide (Crump, 1952). The submerged weir model utilized a triangular design with a 1:2 sloping front face and a 1:5 sloping back face. In the design proposed by the Study, the triangular section would be modified to have a ~3.0 m (~ 10 ft) flat top, resulting in a trapezoidal weir, while keeping the front and back slopes to 1:2 and 1:5, respectively. Figure 3-6 shows a three-dimensional perspective for the proposed weir. The final design could incorporate natural looking variations that retain the desired hydraulic characteristics.

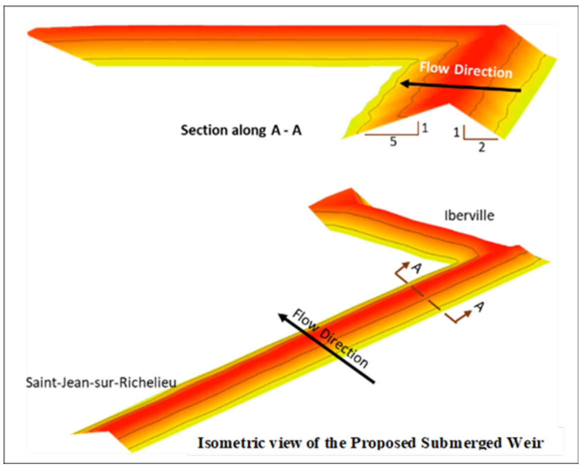

Figure 3-6. Isometric and cross-sectional views of the submerged weir.

The combination of the selective removal of human artifacts on the shoal with the placement of the submerged weir at the optimal location achieves two water management objectives. The removal of the material on the shoal improves the conveyance capacity of the river, thereby requiring a lower water level to deliver the same discharge. This also requires a lower water level at Rouses Point to deliver the same flow, as anytime there is an improvement in channel conveyance, there is a consistent, prismatic drop in the water levels for the entire reach (in this case, between Rouses Point and the shoal at Saint-Jean-sur-Richelieu) and for all flows.

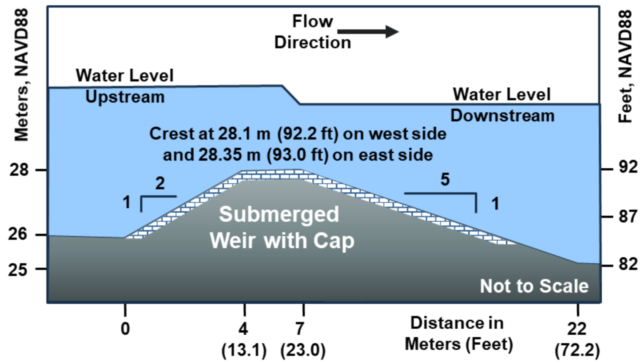

Figure 3-7. Proposed cross-section of the weir.

For medium to low flow situations in the Richelieu River, the submerged weir would provide an obstruction, thereby backing up water for all points upstream. The height of the submerged weir was adjusted during the design phase, to determine an optimum level of the weir of 28.1 m (92.2 ft) NAVD88 (Figure 3-7). This weir height would allow lowering of water levels during floods and selective raising of water levels for medium to low flows. However, to ensure flow in the centre of the channel during low discharges and to utilize the existence of higher natural bathymetry, the proposed weir would have two different crests, 28.1 m (92.2 ft) on the west side of the channel, transitioning to 28.35 m (93.0 ft) towards Iberville on the east bank, acting as the new hydraulic control for the system (Figure 3-8).

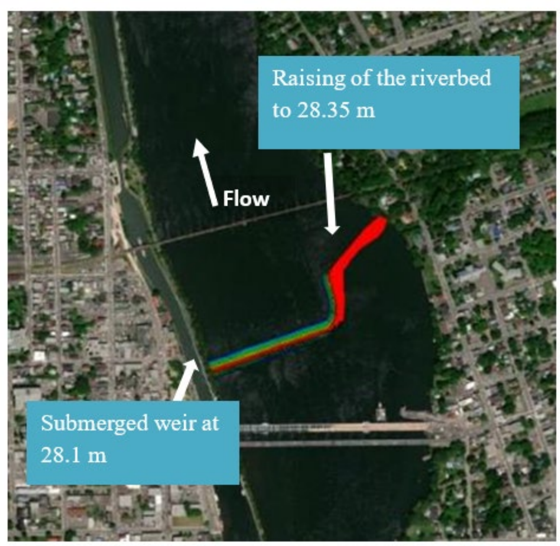

Figure 3-8. Elevation of submerged weir and river training modifications.

A key advantage of the submerged weir is that it could be constructed using the excavated materials, thereby greatly reducing construction costs. This material used for construction of the submerged weir would also provide a more natural substrate for aquatic life. It would not be visible except at extreme low flows, so this would be an added aesthetic benefit. Finally, it could easily be repaired or modified pending future needs to alter the flow regime.

3.3 COST ESTIMATE

Based on the Study's analysis, (Table 3-1) this measure would cost about CDN$8 million (US$6M) to implement.[1] The construction facilities would consist of a fenced area to store river construction equipment and machinery to move material. The costing information was provided by Public Service and Procurement Canada based on other projects. Two other line items were adjusted to accommodate an unknown quality of excavated material from a contamination consideration, and similarly, contingencies were increased to reflect challenges in smaller jobs and instream construction. The material removed from the shoal area is proposed to be used for building the submerged weir, and the remainder deposited in the previously dredged zones immediately downstream of the proposed structures.

Table 3-2 provides other related costs to determine the total annualized cost. The submerged weir is a passive structure that requires minimal funding for operation and maintenance (O & M). A total of CDN$25,000 (US$18,750) was allotted for inspection of the weir and adjustment of the materials, if necessary, after any major flood event. For all flood control structures, a design life of 50 years was assumed to assess annualized costs of the project; the interest rate for the calculations was selected to be 3%, based on current industry practices. The sensitivity of the viability to varying interest rates is discussed in Chapter 6. This resulted in a total annualized cost of about CDN$336,000 (US$252,000).

Table 3-1. Cost estimate for Measure 1.

Item #	Description	Quantity m^3	Unit Rate $\$/m^3$	Item Total
1	Construction Facilities	Lump sum		$ 350,000
2	Lands and Damages	Lump sum		$ 100,000
3	Material removed as per Figure 3-2	31,310	$ 100	$ 3,131,000
4	Fill at the Submerged Weir	7,740	$ 90	$ 696,600
5	Disposal within the river	23,570	$ 90	$ 2,121,300
	Sub-Total			$ 6,398,900
	Contingencies	25%		$ 1,599,725
	Total			$ 7,998,625

[1] All costs are in 2021 dollars.

Table 3-2. Total annualized cost for Measure 1.

Selected Excavation with Submerged Weir	
	Average Estimate
Capital	**$ 8,000,000**
Interest & Amortization*	$ 310,924
O & M	$ 25,000
Total Annual Cost	**$ 335,924**

**$8M amortized over 50 years at 3% annual interest*
Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

3.4 IMPACTS ON WATER LEVELS

The flooding damages in the Lake Champlain - Richelieu River system can be geographically divided into two reaches. The upper reaches of the Richelieu River, upstream of the Fryer Dam/Saint-Jean-sur-Richelieu, and the shores of Lake Champlain constitute the upper reach.

The areas north of the shoal extending to the outlet into the St. Lawrence River at Sorel form the lower reach. From the ISEE analysis, it was determined that hydraulics and factors causing flood damage are different in the two reaches and were treated as such. For example, while the upper reach experienced severe damages during the flood of 2011, impacts were not as severe in the lower reach. Most of the damages in the lower reach occurred during high water level events of the St. Lawrence River, like 2017 and 2019. For the purposes of this report, the impacts are captured for both the upper and lower reaches of the system for all of the measures. The results are presented in Section 6.2

To evaluate the effectiveness of this measure, water level impacts are presented from a number of perspectives.

3.4.1 Extreme High-Water Levels

The 2011 flood, which had a peak discharge of 1,477 m^3/s (52,160 ft^3/s) and corresponding water level of 31.23 m (102.46 ft) NAVD88 in Lake Champlain at Rouses Point, was used as the baseline for comparison purposes for a major flood. The combination of material removed from the shoal and the submerged weir would produce a desirable reduction in water levels through points upstream into Lake Champlain. The reductions in peak water levels would be 15.2 cm (6.0 in) in Saint-Jean-sur-Richelieu and 10.7 cm (4.2 in) at Rouses Point on Lake Champlain (Figure 3-9).

3.4.2 Extreme Low-Water Levels

The performance of the submerged weir was evaluated for extreme low flows. To demonstrate this, the hydrograph for 1964/65, the lowest annual low flow on record, served as the baseline. Figure 3-10 shows how Measure 1 would help to raise the low water levels. The differences between the baseline condition and Measure 1 are less during the spring period and more pronounced from mid-summer to the next spring. The changes in water levels were larger in the fall/winter period by up to 28 cm (11 in) and lower in the spring/summer period. For spring freshet in April/May, Measure 1 would raise water levels about 7 cm (2.8 in).

3.4.3 Mean Annual Water Levels

An important outcome in the design of Measure 1 was to move the hydraulic system back to a more pristine hydrological state, similar to conditions that existed before all of the human interventions modified the river conveyance. Figure 3-11 illustrates Lake Champlain average water levels under current baseline (black line), pristine (red line) and Measure 1 (cyan line) channel conditions.

Measure 1 would closely follow the pristine state for the system, throughout the annual cycle. It would lower the peak freshet and help increase water levels for other times of the year as it mirrors state-of-nature annual hydrograph.

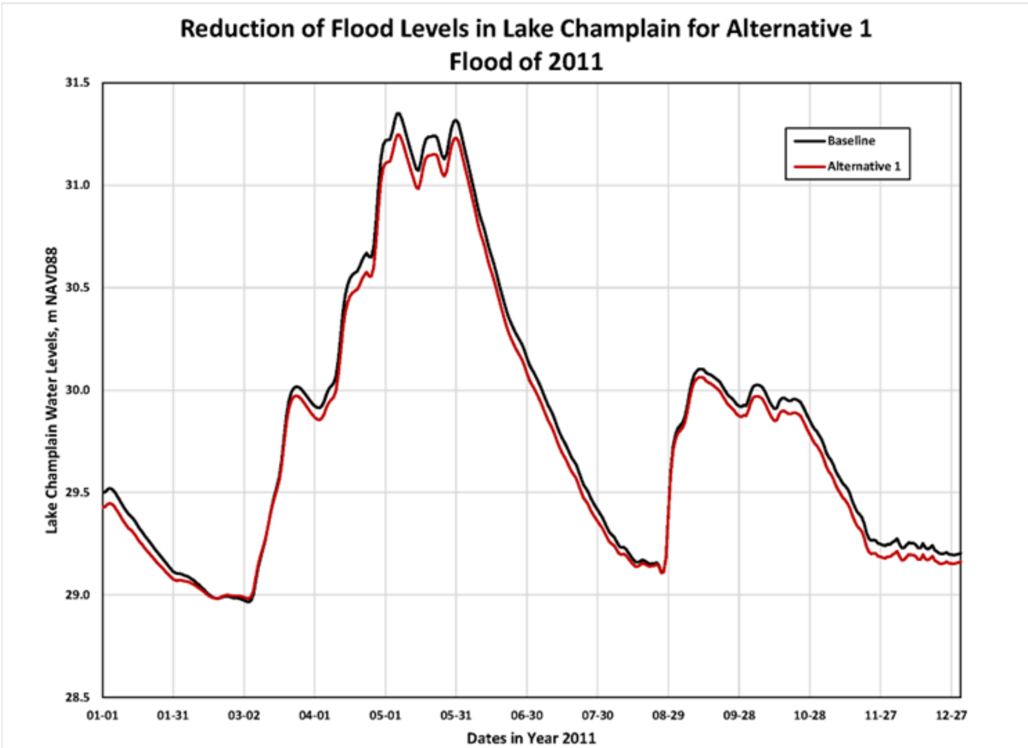

Figure 3-9. Measure 1 water level at Rouses Point compared with 2011 flood.

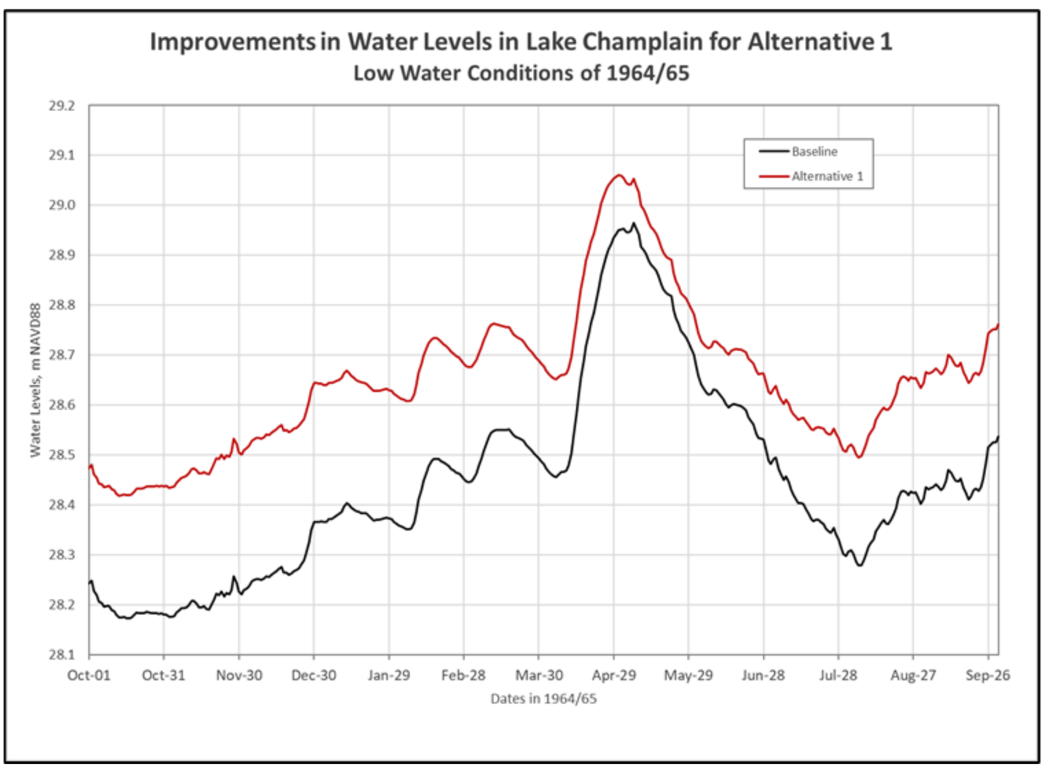

Figure 3-10. Measure 1 water level impacts during an extreme low flow period (1964/65).

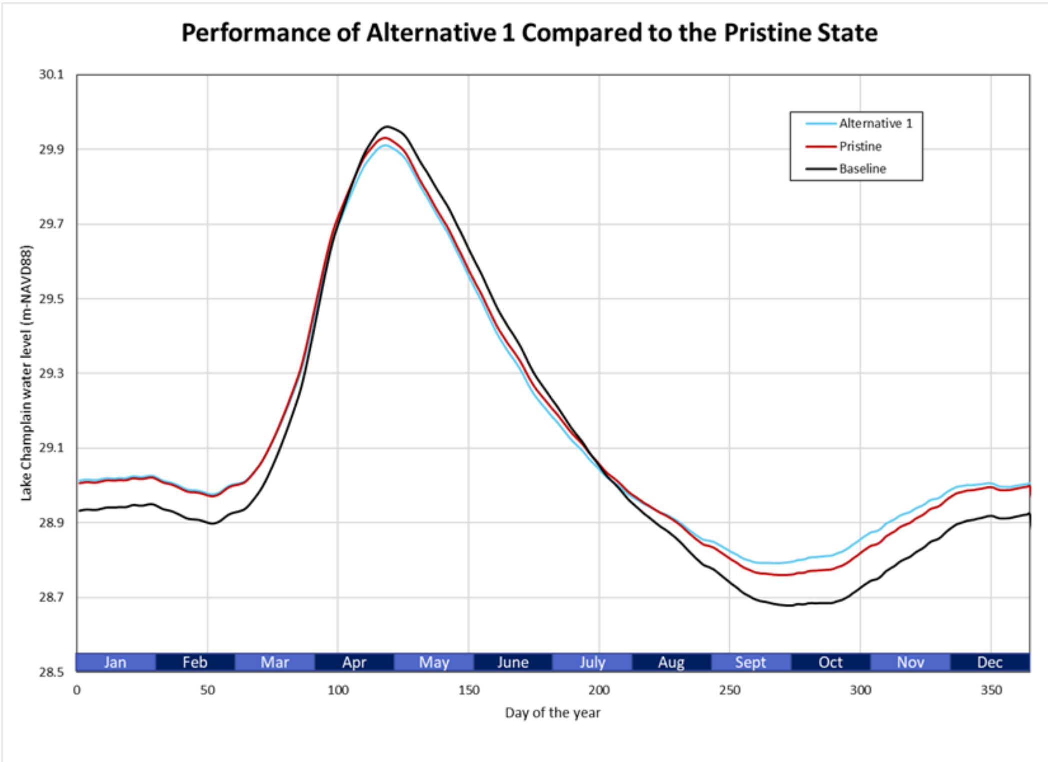

Figure 3-11. Performance of Measure 1 compared to baseline and pristine state.

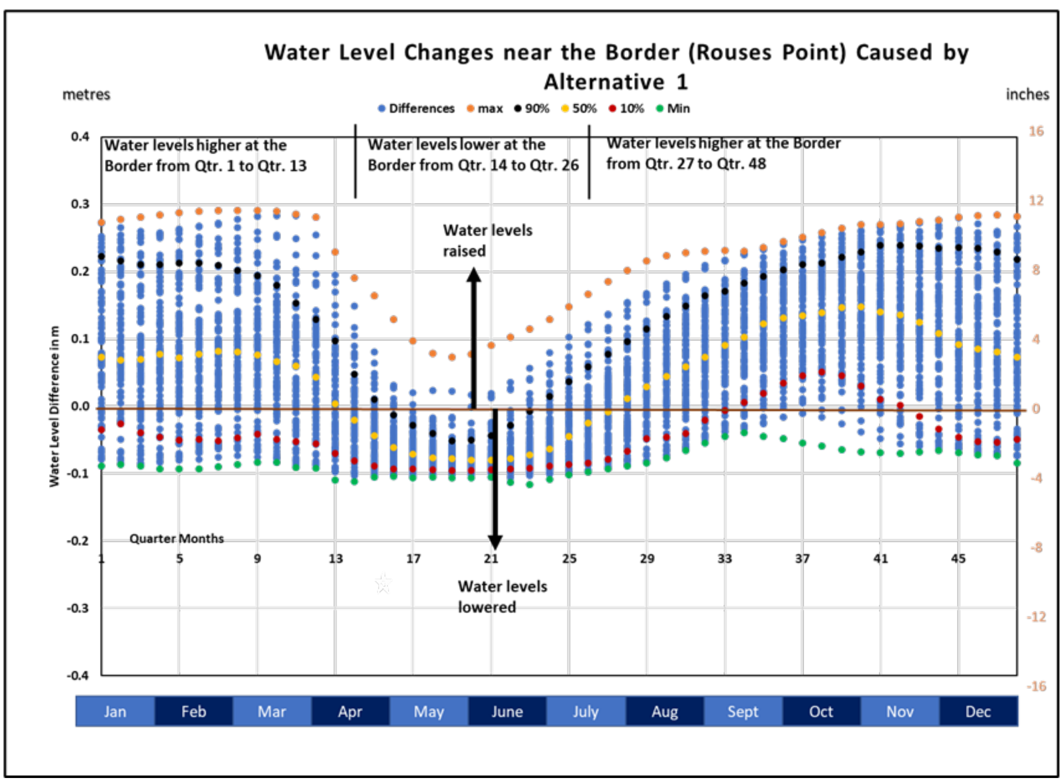

Figure 3-12. Measure 1 water level changes at the United States - Canada border.

3.4.4 Water Level Impacts at the International Boundary

The Lake Champlain-Richelieu River is a transboundary water, and any water level impacts from a structural solution need to be documented for impacts at the International Boundary. The water level impacts at the International Boundary will be critical in determining the binational acceptability of a structural solution. Figure 3-12 captures the differences between the baseline condition and Measure 1.

The figure shows differences in water levels over 48 quarter-months to indicate water level fluctuations over a calendar year (for example, the first four quarter-months correspond to the month of January), using 93 years of hydrologic data. The zero line means no change; positive values indicate water levels raised at the border and negative values determine the period when the water levels would be lowered, as compared to the baseline condition. The graph also captures other statistics that indicate about 62 percent of the time, water levels would be raised, and 38 percent of the time they would be lowered by various amounts. Most of the lowering would occur in the spring (quarter-month 14 to quarter-month 26), and from late summer to the following spring, the water levels would be raised. Noted exceptions are the wetter (for example, the maximum levels shown by the orange dots) and drier (minimum levels shown by the green dots) periods when the water levels would be either lowered or raised throughout the period.

3.4.5 Summary of Extreme Water Level Impacts

The hydraulic performance of the measure is summarized in Table 3-3, showing how much Measure 1 would reduce water levels for an extreme flood (2011), and how much levels would be raised for an extreme low-flow period (1964/65).

Table 3-3. Summary of the Extreme Water Level Impacts for Measure 1.

Measure 1 Relief for 2011 Flood Event	
Water level reduction:	
• Saint-Jean-sur-Richelieu	-15.2 cm (6 in)
• Lake Champlain at Rouses Point	-10.7 cm (4.2 in)
Relief for 1964/65 Low Flow Event	
Raising of low water levels at Rouses Point (seasonal differences)	+7 to +28 cm +2.8 to 11 in

3.4.6 Implications for Flood Response

The overall performance of Measure 1 for the entire period of historical data (1924 to 2017) was evaluated against key hydraulic metrics in terms of the indicators of various thresholds for flooding on Lake Champlain and at Saint-Jean-sur-Richelieu, when compared against the baseline conditions. Only selected flooding thresholds used by agencies in Canada and the United States were captured as a report card of performance. Similarly, the improvements in the water levels against low water level thresholds were also captured and compared against the baseline. These values are presented in Table 3-4. Measure 1 would lower the number of flood events and subsequently would reduce the costs for flood emergency response.

Table 3-4. Summary of overall water level impacts for Measure 1.

Performance during flood events				
	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years above threshold	Measure 1 number of years above threshold
Major flood stage (USGS)	101.50	30.81	4	2
Moderate flood stage (USGS)	101.00	30.65	11	7
Major flood (MSP)	102.30	31.05	1	1
Moderate flood (MSP)	101.74	30.88	2	1
	SJSR marina threshold (ft CGVD28)	SJSR marina threshold (m NAVD88)	Baseline number of years above threshold	Measure 1 number of years above threshold
Major flood (MSP)	99.97	30.45	1	1
Moderate flood (MSP)	99.48	30.30	2	1
Minor flood (MSP)	98.75	30.08	19	11
Performance during low water events				
Number of years below	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years below threshold	Measure 1 number of years below threshold
Low water level events	93.00	28.22	4	0
	93.50	28.37	33	0
	94.00	28.52	65	16
	94.50	28.67	84	67

Notes: United States responsible flood reporting agency- United States Geological Survey, USGS.
Canadian responsible flood reporting agency – Ministère de la Sécurité publique, MSP, Québec.
MSP and USGS thresholds are per their online publications.

4 MAJOR CHAMBLY CANAL DIVERSION (MEASURE 2)

4.1 DESIGN FLOW THROUGH CANAL

Measure 2 explores diverting flow through the Chambly Canal and focuses on the maximum flow that could be accommodated based on the existing canal configuration. After several iterations of flood level reduction, a design capacity for the canal was determined to be about 400 m^3/s (14,125 ft^3/s). This scheme reflects what would be hydraulically possible in terms of a major diversion. The river training would be extensive in order to be able to route this amount of flow into the canal. The Chambly Canal modifications to achieve this major diversion are captured in Figure 4-1.

The key features of the scheme include structures using flap gates to control flow at the entrance close to the North end of the Chambly Canal Lock #9 and two sets of gates at the exit to manage flows exiting the canal. Auxiliary bridges and canal crossings are also required for this measure.

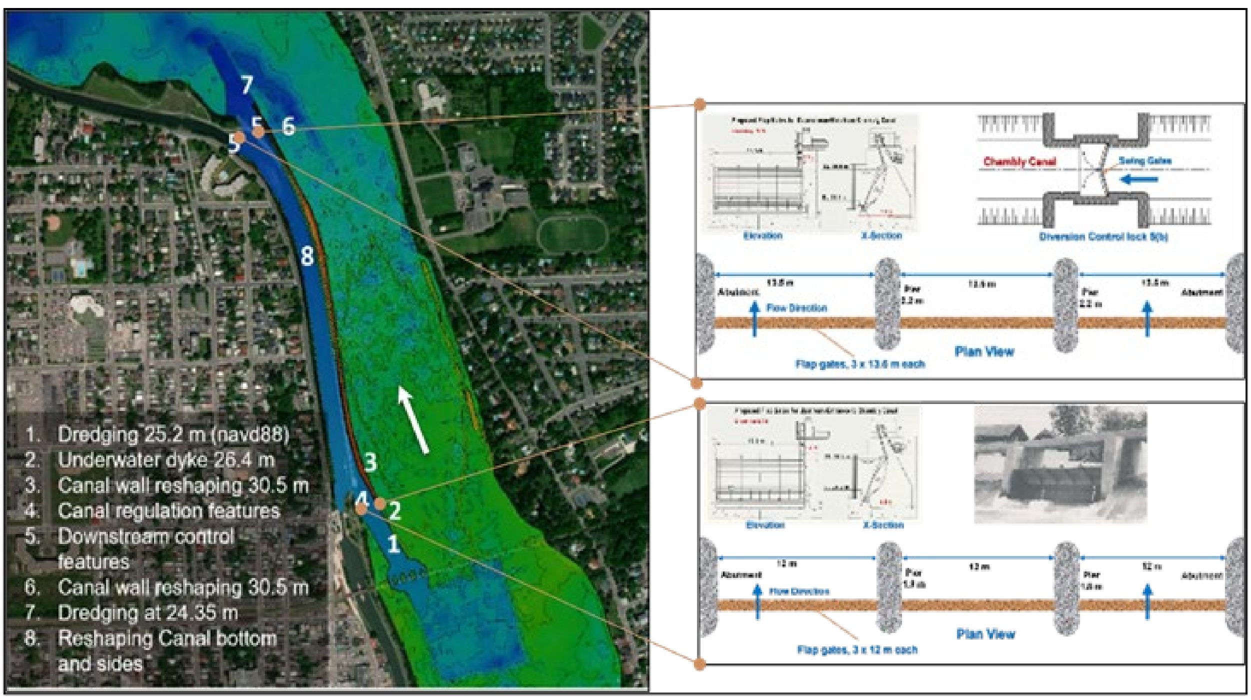

Figure 4-1. Canal modifications for Measure 2.

4.2 DIVERSION DESIGN

The diversion scheme calls for the following work to be undertaken on the canal and in the riverbed (Figure 4-1). Elevations are standardized to NAVD 88 datum:

1. Dredging of riverbed to an elevation of 25.2 m (83.7 ft) to divert flow to the canal entrance
2. Constructing a submerged dike at an elevation of 26.4 m (86.6 ft) for river training
3. Reshaping of the outer canal wall to an elevation of 30.5 m (100.1 ft) at entrance
4. Installing canal entrance gates
5. Adding two gates to control flow exiting the canal: a) gate to close for flow entering the lower canal section, b) exit gate for flow back into the river
6. Reshaping of the outer canal wall to an elevation of 30.5 m (100.1 ft) at exit.
7. Dredging of the riverbed to an elevation of 24.4 m (80.1 ft) to direct flow into the main channel
8. Increasing the longitudinal and lateral slopes in the canal through dredging to convey the design flow

4.2.1 Canal gates

The proposed scheme consists of regulation gates at both the entrance and exit of the Chambly Canal (Figure 4-1). The training of the river would result in an entrance 40 m (131 ft.) wide. It is proposed to employ a simple regulation scheme using flap gates, which are commonly used in diverting and managing water levels. To initiate water flow, the gate would be lowered in the downstream direction; the design is such that the gate becomes part of the spillway. It was proposed to have three flap gates (location 4, Figure 4-1), each 12 m (39.4 ft.) wide by 5.0 m (16.4 ft.) high, anchored at the two abutments and two piers, each 1.8 m (5.9 ft.) wide.

The gates at the downstream end (location 5 riverside) would also be flap gates, and as the total designed width is 45 m (148 ft.), three gates of 13.5 m (44.3 ft.) wide by 5.0 m (16.4 ft.) high would be supported on 2.2 m (7.2 ft.) wide piers and associated abutments. The gates are shown in the Figure 4-1 insert.

Another regulation gate is proposed to manage flow in the canal in the downstream direction (location 5, canal side). The purpose of this gate is to direct all the flow back into the river and prevent flooding along the canal. This gate is proposed to be like the lock gates at Lock #9. This gate would generally be in an open position, except during the diversion.

4.2.2 Canal reinforcing

The Chambly diversion was designed to route a flow of about 400 m^3/s (14,125 ft^3/s). For a flow of this magnitude to be sustained through the canal, the slope would need to be adjusted by reprofiling the bottom through excavation, creating a drop of 1.0 m (3.3 ft). There are other challenges that are associated with the design, such as velocities greater than 2.0 m/s (6.6 ft/s) within several pockets, and greater than 3.0 m/s (9.8 ft/s) in some specific cases. Such velocities would require further reinforcements or restrictions on the amount of flow that can be diverted; the former will increase the cost and the latter would make it less effective.

4.2.3 Dredging volumes (in the river and canal)

It is estimated that 126,516 m^3 (165,477 yd^3) of material would have to be excavated from the main channel for river training; 44,193 m^3 (57,802 yd^3) upstream of the entrance and 82,323 m^3 (107,674 yd^3) downstream of the exit, including canal slope changes. This measure would disturb about 1.37 ha (3.38 acres) of the riverbed for the river training at the diversion entrance, 4.32 ha (10.7 acres) to reshape the Chambly Canal, and 0.94 ha (2.32 acres) for stream training at the diversion exit and the Richelieu River. The total area disturbed for this measure would be 6.62 ha (16.36 acres) in the river.

4.3 PROJECT COSTS

4.3.1 Capital

Based on the quantities estimated, the capital cost was calculated to be between CDN$83M (US$62M) and CDN$113M (US$85M). For benefit/cost analysis purposes, a weighted cost of CDN$100M CAD (US$75M US) was used (Table 4-1). All costs are in 2021 dollars.

4.3.2 Operating

The implementation of Measure 2 is highly dependent on the operation of the canal during periods of high flows. There are several components of the operations, and all of these must be accounted for in developing the cost of the measure. With the operation of the gates, there will be a need for interim replacement of components; additionally, routine Operations and Maintenance (O & M) of a system of this nature is required. As binational waters are being managed, a management board is recommended as part of this proposal. The day-to-day administration of the system will require a budget for this activity. All of these items are reflected in the annualized cost of the measure. Based on Table 4-2, the total annualized cost for Measure 2 is about CDN$4.9M (US$3.7M).

4.4 CANAL OPERATING PLAN

During the optimization phase of the diversion design, various options in diverting the flows were considered.

The following three scenarios were considered for testing purposes:

- Rouses Point water level dependent: Operate the diversion when the water level is at the flood stage, 30.5 m (100.06 ft) NAVD88, corresponding to a flow of about 1,130 m^3/s (39,904 ft^3/s).

- Date dependent: operate the diversion starting each year at a set date; for the Richelieu River, this date was set on March 15 of every year.

- Perfect forecast: This is not a real operating plan, as it is based on the knowledge of how the river will react and therefore removes the uncertainty. From a scan of the flood events, based on a threshold of Lake Champlain water levels in the historical record, 37 events were selected. The water balance model was programmed to open the diversion on March 14 in flood years. This will never happen in a real-world situation.

The perfect forecast was applied to give this measure the best opportunity to be economically viable, given the high implementation costs. Based on the results, there was no need to examine other operation plans which would provide even fewer benefits.

The potential to lower Lake Champlain water levels through early opening of the diversion was not investigated.

Table 4-1. Cost estimate for Measure 2.

Item #	Description	Quantity	Unit Rate	Sub-total
1	Construction Facilities	Lump sum		$ 4,400,000
2	Lands and Damages	Lump sum		$ 3,100,000
3	Dewatering	Lump sum		$ 1,600,000
4	Excavation	45,000 m^3	$ 144	$ 6,500,000
5	Canal slope reshaping	82,000 m^3	$ 113	$ 9,300,000
6	Dredges material disposal	Lump sum		$ 6,000,000
7	Concrete (reinforced) piers & abutments	12,000 m^3	$ 792	$ 9,500,000
8	Upstream gates (12 m x 5 m flaps)	3#	$4,500,000	$ 13,500,000
9	Downstream gates (13.5 m x 5 m flaps)	3#	$ 5,000,000	$ 15,000,000
10	Canal gate (30m by 5 m swing)	1#	$ 8,500,000	$ 8,500,000
11	Canal bed and side armouring	53,000 m^2	$ 166	$ 8,800,000
12	Construction buildings & utilities	Lump sum		$ 760,000
	Sub-Total			**$ 86,960,000**
	Contingencies	15%		$ 13,040,000
Items 7, 8, 9, 10 and 11 include engineering design, drawings and approvals.				
	Total			**$ 100,000,000**

Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

Table 4-2. Total annualized cost for Measure 2.

Measure 2 Expected Annual Cost	
	Average Estimate
Capital	**$ 100,000,000**
Interest & Amortization*	$ 3,886,549
Interim Replacement	$ 100,000
O & M	$ 400,000
Administration & General Expense	$ 100,000
Management Board	**$ 400,000**
Total Annual Cost (C)	**$ 4,886,549**

** $100M amortized over 50 years at 3% annual interest is $3,886,549*

Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

4.5 IMPACTS ON WATER LEVELS

As for the other measures, water level impacts were evaluated from a number of perspectives, as presented below.

4.5.1 Extreme High-Water Levels

For comparing the effectiveness of the proposed diversion during the flood event of 2011, using the perfect foreknowledge of the event, simulation had the diversion gates opened on March 15. The opening of the diversion would allow a flow of up to 398 m^3/s (14,055 ft^3/s) to pass through the Chambly Canal. As the flow in the river would be lowered by a similar amount, the flow could be discharged at a lower water level at the marina and a smaller head difference between the lake and the marina, the key reason for lowered water levels along the reach. The 2011 event had a peak discharge of 1,477 m^3/s (52,160 ft^3/s) and corresponding water level of 31.23 m (102.46 ft) NAVD88 in Lake Champlain at Rouses Point. The combination of the passage of water through the canal (diversion) and the river would increase the flow and thus produce desirable reductions in water levels upstream from the shoal to Lake Champlain. The potential for discharge in the downstream reach being higher than baseline exists, but was not investigated considering the resolution of the water balance model.

As a considerable amount of flow could be diverted through the Chambly Canal, Measure 2 would provide the best overall relief when compared to the other measures. The reductions in peak water levels would be 34.3 cm (13.5 in) in Saint-Jean-sur-Richelieu and 22.1 cm (8.7 in) at Rouses Point on Lake Champlain. This is presented in Figure 4-2.

4.5.2 Extreme Low-Water Levels

The performance of the diversion measure was evaluated for extreme low flows. To demonstrate this, the hydrograph for 1964/65, the lowest annual low flows on record, served as the baseline. The diversion structure would remain closed, as the forecast algorithm would not specify a flood event. Theoretically, all the flow should then pass over the shoal and the two hydrographs should be the same. As shown in Figure 4-3, there are minor differences in the baseline and Measure 2 hydrographs for the water levels in Lake Champlain. These differences originate from the river training changes in bathymetry that would be required for designing the diversion.

4.5.3 Mean Annual Water Levels

The overall performance of the measure was examined for moving the hydraulic system back to a more pristine state, before many of the human interventions modified the river conveyance. This is presented in Figure 4-4. As can be observed, the Measure and the pristine state average hydrographs would be close during the spring freshet; in other periods, Measure 2 would follow the baseline state. Typically, for a spring season period from the end of March to the middle of July, the water levels would be lowered. From mid-July to the following spring, the water levels would be the same as the baseline and have no benefit accrued, such as providing increased levels for recreational boating or environmental indicators.

4.5.4 Water Level Impacts at the International Boundary

The Lake Champlain-Richelieu River is a transboundary water and any water level impacts from a structural solution need to be projected for its impacts at the International Boundary. The water level impacts at the International Boundary will be critical in determining the binational acceptability of a structural solution. Figure 4-5 captures the differences between the baseline condition and Measure 2. The figure shows the differences in water levels over 48 quarter-months to indicate water level fluctuations over a calendar year (for example, the first four quarter-months correspond to the month of January), using 93 years of hydrologic data. The zero line means no change; positive values indicate water levels raised at the border and negative values determine the period when the water levels would be lowered, as compared to the baseline condition. The graph also captures other statistics that indicate about 60 percent of the time water levels would be raised, but by less than 2 cm, while 40 percent of the time, levels would be lowered by various amounts, usually in the periods when the diversion would be operated. One anomaly stands out (in green dots) for 1927, when the peak water level simulated was observed in December; with the perfect forecast algorithm in place for operating the diversion, the decrease in water levels would be traced as the maximums late in the season. This would result in the diversion opening in March of the year and staying open for the rest of the year, resulting in low lake levels in an unprecedented manner.

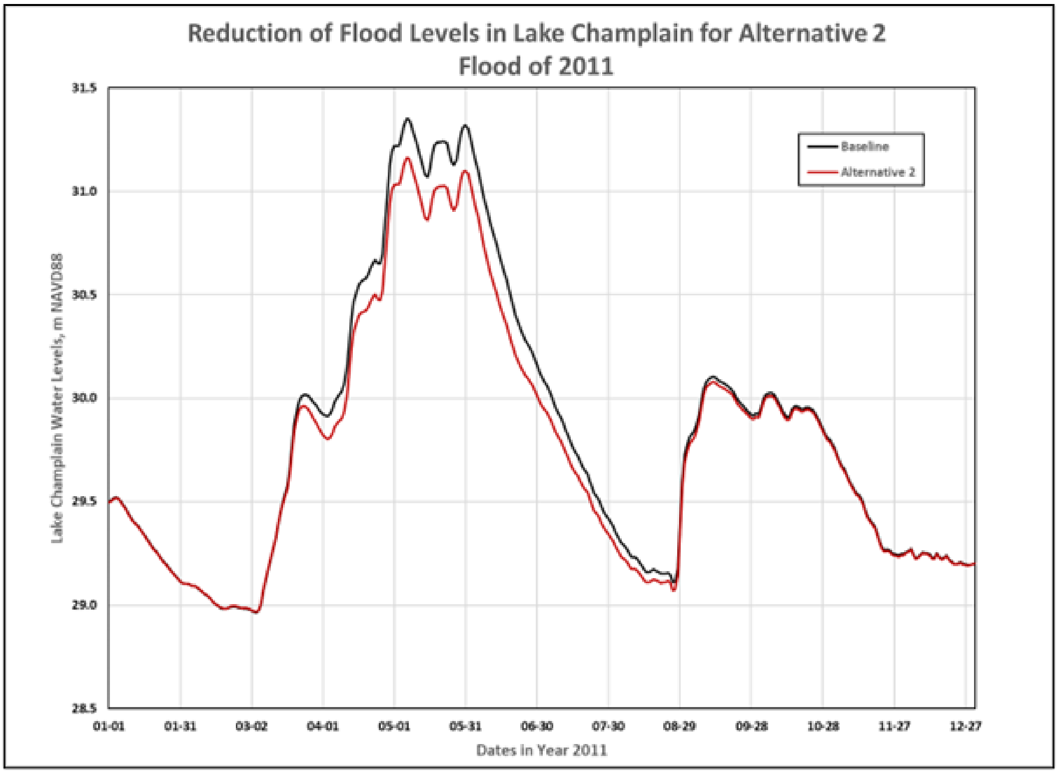

Figure 4-2. Measure 2 water levels compared with 2011 flood

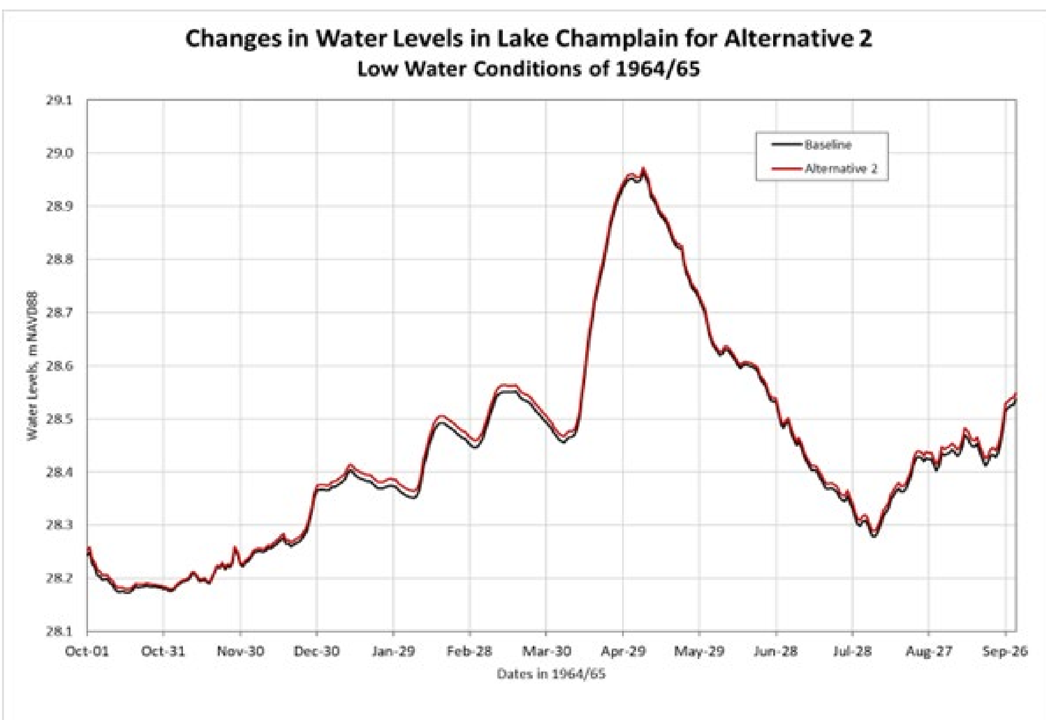

Figure 4-3. Measure 2 water level impacts during an extreme low flow event (1964/65).

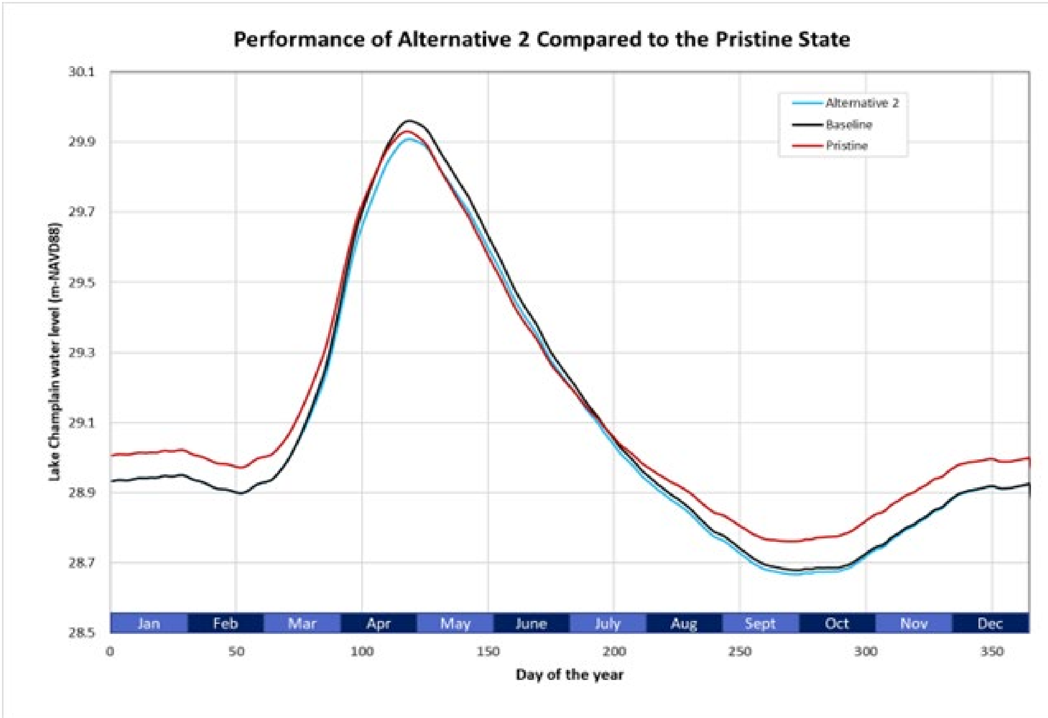

Figure 4-4. Performance of Measure 2 compared to baseline and pristine state.

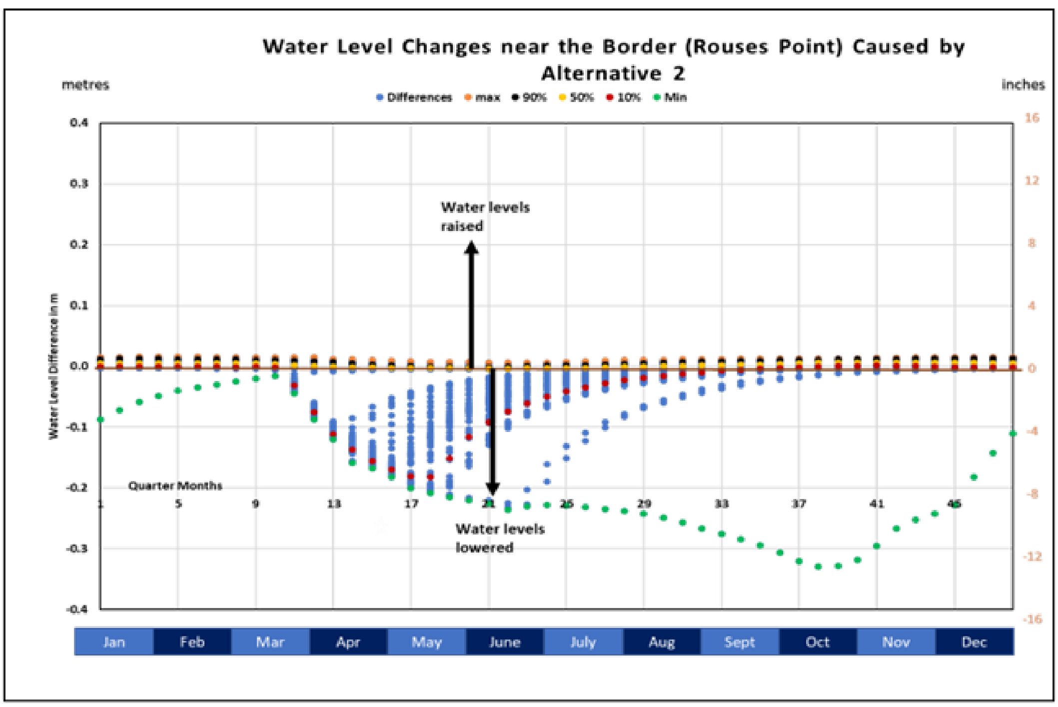

Figure 4-5. Measure 2 water level changes at the United States - Canada border.

4.5.5 Summary of Water Level Impacts

The hydraulic performance of the measure is summarized in Table 4-3. As in Measure 1, two key events were used in most design work and evaluation, the flood of 2011 and the low flows of 1964/65. For the 2011 flood, water level reductions were evaluated at the two index locations of Rouses Point (surrogating Lake Champlain water levels) and the Saint-Jean marina (representing the location of major flooding in Saint-Jean-sur-Richelieu). Measure 2 would provide no low water relief, other than small changes in the water levels in Lake Champlain due to the river training- related bathymetric changes near the diversion entrance.

Table 4-3. Summary of the Extreme Water Level Impacts for Measure 2.

Measure 2 Relief for 2011 Flood Event	
Water level reduction:	
• Saint-Jean-sur-Richelieu	-34.3 cm (11.8 in)
• Lake Champlain at Rouses Point	-22.1 cm (4.7 in)
Relief for 1964/65 Low Flow Event	
Impact on low water levels at Rouses Point	No relief

4.5.6 Implications for Flood Response

The overall performance of Measure 2 over the entire period of historical data (1924 to 2017) was evaluated against key hydraulic metrics in terms of the indicators of various thresholds for flooding on Lake Champlain and at Saint-Jean-sur-Richelieu, when compared against the baseline conditions. Only selected flooding thresholds used by agencies in the United States and Canada were utilized to assess flood performance. Similarly, the increases in the water levels against low water level thresholds were also captured and compared against the baseline. These values are presented in Table 4-4. Measure 2 would lower the number of flood events and subsequently would reduce the costs for flood emergency response.

Table 4-4. Summary of overall water level impacts for Measure 2.

Performance during flood events				
	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years above threshold	Measure 2 number of years above threshold
Major flood stage (USGS)	101.50	30.81	4	2
Moderate flood stage (USGS)	101.00	30.65	11	4
Major flood (MSP)	102.30	31.05	1	1
Moderate flood (MSP)	101.74	30.88	2	1
	SJSR marina threshold (ft CGVD28)	SJSR marina threshold (m NAVD88)	Baseline number of years above threshold	Measure 2 number of years above threshold
Major flood (MSP)	99.97	30.45	1	0
Moderate flood (MSP)	99.48	30.30	2	1
Minor flood (MSP)	98.75	30.08	19	2
Performance during low water events				
Number of years below	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years below threshold	Measure 2 number of years below threshold
Low water level events	93.00	28.22	4	4
	93.50	28.37	33	33
	94.00	28.52	65	65
	94.50	28.67	84	84

5 MODEST FLOW DIVERSION THROUGH THE CHAMBLY CANAL AND SELECTIVE EXCAVATION ON THE SAINT-JEAN-SUR-RICHELIEU SHOAL WITH INSTALLATION OF A SUBMERGED WEIR (MEASURE 3)

5.1 SCALED-BACK CANAL DIVERSION SCHEME

This measure builds on Measure 1, adding a modest diversion through the Chambly Canal. The diversion would consist of two sets of box culverts with gates, one set at the entrance of the canal and the second about 1 km (0.6 mi) downstream (Figure 5-1). These would be placed in the outer wall of the canal. It is proposed to divert about 80 m^3/s (2,825 ft^3/s) of flow through the canal during flood conditions.

As sufficient head is available between the river and the canal at the entrance, only four box culverts, each 4 m (13.1 ft) by 1.5 m (4.9 ft), would be needed. The head at the exit is smaller and therefore five box culverts, each 4 m (13.1 ft) by 2 m (6.6 ft), are proposed. A simple swing gate in the canal would also be required to avoid flooding along the canal.

Limited consideration was given of diverting the water through the Lock# 9. This was based on the results of experiments in 1979 (CAHBICR 1979), when vibrations were noted, and also to protect the historical nature of the lock structure.

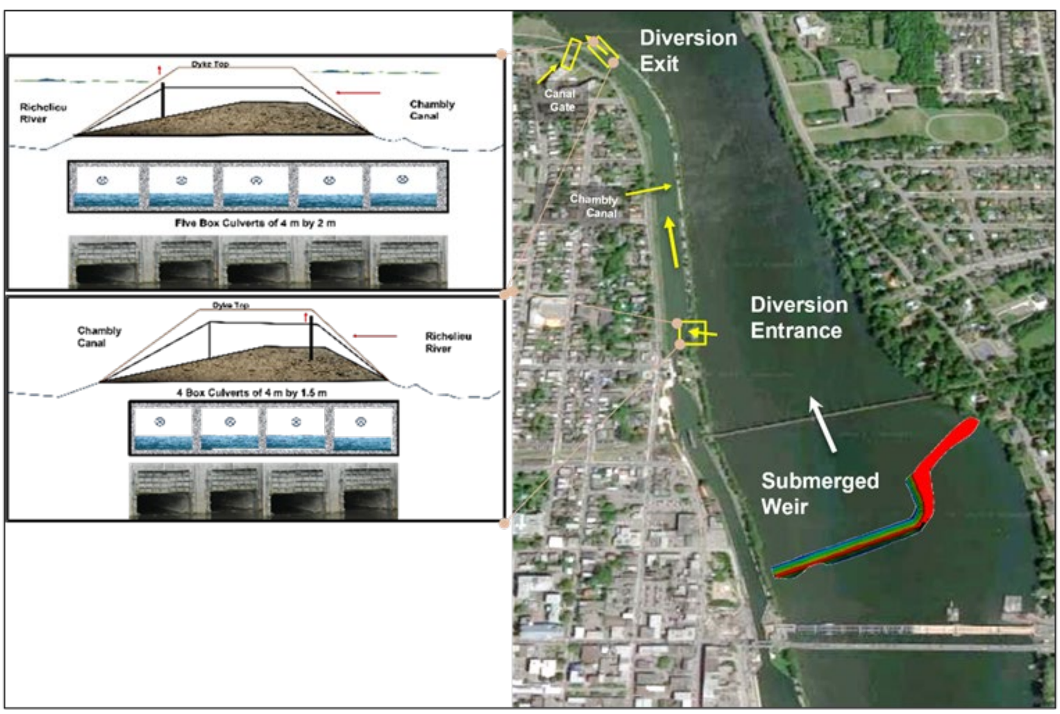

Figure 5-1. Layout of Measure 3.

5.2 PROJECT COSTS

5.2.1 Capital

Costing of construction materials was coordinated with Public Service and Procurement Canada (PSPC). Based on the proposed design and estimated materials quantities, the capital cost was estimated to be about CDN$21M (US$15.8M) (Table 5-1). Costs for most of the lump sum items were drawn from projects of similar scope in a riverine setting. The culvert sizing was dictated by the hydraulics and the constraint of a discharge of 80 m^3/s (2,825 ft^3/s). The entrance and exit culvert sizes and lengths were obtained using bathymetry data and topographic details of the dike between the canal and the river, adjusting the locations accordingly. The unit rates were first estimated by the Study and then verified/improved by PSPC. The volume of shoal removal and filling requirements would be the same as in Measure 1. The costing in Table 5-1 is the full cost of this measure and not an incremental cost above Measure 1, as all quantities shown include excavation and submerged weir costs at slightly lower rates to take advantage of the larger project.

5.2.2 Operating

A simple operating scheme was proposed that relies on the water level at the gates. Once a level of 29.25 m (95.96 ft) NAVD88 is reached, the gate in the canal would be closed, and the doors at the entrance opened; when the water level in the canal is at 29.25 m (95.96 ft) NAVD88, the downstream gates would be opened to discharge the water back into the river. The gates would be opened and closed once the water level reached a predetermined stage. Since the diversion would not begin until the river level is high enough, it would not result in any undesirable lowering of water levels in Lake Champlain.

The possibility of different operation rules for the canal diversion beyond the proof of concept was briefly explored. Such plans could potentially serve as guidance on next steps, should governments choose to implement this measure. There are other viable options both in design and operations, but these were outside the resources and time constraints of the Study.

The lift gates controlling the flow into the Chambly Canal are large, fixed-wheel gates or roller gates, which are raised and lowered with a hoisting mechanism. This can be done manually or automated using a float system. If a floating mechanism were to be adopted, it could relay a signal to the control office to winch the gates up or down. This is just a consideration at this stage.

5.2.3 River and Canal Works

The river works would be those described in Measure 1. However, this work would need to be augmented with river training for the modest diversion through the canal. The bottom of the diversion culvert entrance is slightly below the normal water level in the river. To place the culvert boxes across the dike, a section of about 40 m (131 ft) would be rendered dry using cofferdams for a period lasting not more than couple of weeks. Once the culverts are placed and slopes are protected with riprap, the cofferdam could be removed. A similar operation for installing the exit culverts would be required.

5.2.4 Project Cost Estimate.

Based on the Study's analysis, this measure would cost about CDN$21M (US$15.8M) to implement and the annual operating costs are captured in Table 5-2.

Table 5-1. Estimated capital costs for Measure 3.

Item #	Description	Quantity	Unit Rate	Sub-total
1	Construction Facilities	LS		$ 1,704,636
2	Lands and Damages	LS		$ 643,222
3	Dewatering	LS		$ 324,656
4	Dredging river side at sluices	LS		$ 166,765
5	Coffer dam U/S & D/S	LS		$ 384,000
6	Entrance culverts	70 m	$ 8,000	$ 560,000
7	Exit culverts	200 m	$ 8,080	$ 1,616,000
8	Earthworks entrance	70 m	$ 4,370	$ 305,900
9	Earthworks exit	200 m	$ 4,160	$ 832,000
10	Sluice gates entrance	4	$ 150,000	$ 600,000
11	Sluice gates exit	5	$ 150,000	$ 750,000
12	Canal gate	1	$ 1,200,000	$ 1,200,000
13	Canal gate abutments	2	$ 150,000	$ 300,000
14	Dredging canal side	LS		$ 166,376
15	Grates	18	$ 10,000	$ 180,000
16	Engineering design and construction	LS		**$ 3,406,744**
17	Shoal removal	31,310	100	$ 3,131,000
18	Fill at the submerged weir	7,740	90	$ 696,600
19	Disposal within the river	23,570	50	$ 1,178,500
	Sub-Total			**$ 18,146,399**
	Contingencies	15%		$ 2,721,960
	Total			**$ 20,868,358**

Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

Table 5-2. Total annualized cost for Measure 3.

Measure 3 Expected Annual Cost	
	Average Estimate
Capital	**$ 21,000,000**
Interest & Amortization*	$ 816,175
Interim Replacement	$ 15,000
O & M	$ 20,000
Administration & General Expense	$ 15,000
Management Board	$ 50,000
Total Annual Cost (C)	**$ 916,175**

** $21M amortized over 50 years at 3% annual interest is $916,175*
Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

Annual funding would be required for operation and maintenance of the sluice gates and upkeep of the structures. All costs are in 2021 dollars. The construction facilities would consist of a fenced area to store river construction equipment, machinery to move material and placement of river excavated material. The costs are from the estimates made by PSPC experts for Measure 1, described in Section 3 of this report. Two other line items were adjusted to accommodate an unknown quality of removed material, and contingencies were increased to reflect challenges in smaller jobs and instream construction. The material removed from the shoal area is proposed to be used for building the submerged weir, depositing the remainder in the previously dredged zones immediately downstream of the proposed structures.

5.3 CANAL OPERATING PLAN

The proposed plan for operations is based on a simple principle that water needs to be diverted when the river is in flood conditions. Once the water level near the lock reaches about 29.25 m (95.96 ft), corresponding to about 30 m (98.43 ft) NAVD88 at Rouses Point, the gates would be opened. The gates would be closed once the water level at Rouses Point drops below 29.5 m (96.78 ft). In the simulations used for the Benefit/Cost Analysis (Section 6.2), the diversion in Measure 3 was operated in only three years, 1993, 1998 and 2011.

A second simulation tested Measure 3 with the diversion operational in 27 years, for a total of 542 days. This would raise the Benefit/Cost Ratio by about ten percent. Other than one or two events with delayed or prolonged flooding like 2011, the diversion would stop before the start of the navigation season for recreational boating in mid-May. If the governments further investigate the feasibility of Measure 3, the operating rules for the diversion would be studied in greater depth.

5.4 WATER LEVEL IMPACTS

To evaluate the effectiveness of this measure and as noted in Section 3.4, water level impacts are presented from several perspectives.

5.4.1 Extreme High-Water Levels

The 2011 flood, which had a peak discharge of 1,477 m^3/s (52,160 ft^3/s) and corresponding water level of 31.23 m (102.46 ft.) NAVD88 in Lake Champlain at Rouses Point, was used as the baseline for a large flood for comparison purposes. In addition to the reduction in water levels through points upstream into Lake Champlain resulting from Measure 1 activities (removing material from the shoal and installing the submerged weir), this scenario would provide additional water level reduction when the canal diversion was open. In the 2011 simulation, this occurred for a period of two months, from April 14 to June 14, when the water level/flow combination met the threshold for part of the flow to be diverted. The reductions in peak water levels would be 22.3 cm (8.8 in) in Saint-Jean-sur-Richelieu and 15.2 cm (6 in) at Rouses Point on Lake Champlain. Throughout the period the diversion was in operation, Measure 3 would provide better relief than Measure 1 by about 7 cm (3.2 in) in Saint- Jean-sur-Richelieu and 4.5 cm (2 in) on the lake. The performance of Measure 3 is captured in Figure 5-2.

5.4.2 Extreme Low-Water Levels

The performance of the submerged weir was evaluated for extreme low flows. To demonstrate this, the hydrograph for 1964/65, the lowest annual low flows on record, served as the baseline. Figure 5-3 shows how Measure 3 would help to raise the low water levels; as the diversion would not be operational during low flow events, Measure 3 would behave no differently than Measure 1. As shown in Figure 3-10, the diversion amounts would be less pronounced during the spring period and more pronounced from mid-summer to the following spring. Variations in water levels would be most pronounced in the fall and winter. During a spring flood in April/May, Measure 3 would result in a water level rise of about 7 cm (2.8 in).

5.4.3 Mean Annual Water Levels

An important outcome in the design of Measure 3, like that of Measure 1, would be to return the hydraulic system back to a status closer to hydrologically pristine or a more naturalized state, similar to conditions that existed before many of the human interventions modified the river conveyance. Figure 5-4 illustrates Lake Champlain average water levels under current baseline (black line), pristine (red line) and Measure 3 (cyan line) channel conditions.

Measure 3 would closely follow the early state-of-nature (pristine condition) for the system, throughout the annual cycle. It would lower the peak freshet and help increase water levels for other times of the year as it would mirror the state-of-nature annual hydrograph. This would be the same as Measure 1, as the flows and water level chosen for comparison were below the threshold of the diversion to be in operation.

The objective of studying this measure was to obtain flood damage reduction, along with improved water levels in the upper river and the lake during periods of low flow. This combination would result in an average hydrological regime remarkably like what existed prior to any changes that influenced the conveyance capacity of the river.

5.4.4 Water Level Impacts at the International Boundary

The Richelieu River being a transboundary water, it is important to consider the performance of the measure with respect to the changes in the water level across the Canada-United States boundary. This measure makes changes in the water level regime from the excavation and submerged weir in a way that affects the water level regime. Figure 5-5 captures the differences between the baseline condition and one with the measure. The figure shows differences in water levels over 48 quarter-months to indicate water level fluctuations over a calendar year (for example, the first four quarter-months correspond to the month of January), using 93 years of hydrologic data.

The zero line means no change; positive values indicate water levels raised at the border and negative values determine the period when the water levels would be lowered, as compared to the baseline condition. The graph also captures other statistics that indicate about 62 percent of the time, water levels would be raised and 38 percent of the time they would be lowered by various amounts. This lowering, however, would be more enhanced than for Measure 1. Most of the lowering would occur in the spring (quarter-month 14 to quarter-month 26), and from late summer to the following spring, generally the water levels would be raised. Noted exceptions are the drier periods (for example, the maximum differences from baseline shown by the orange dots) and wetter conditions (minimum levels shown by the green dots) when the water levels would either be lowered or raised throughout the period.

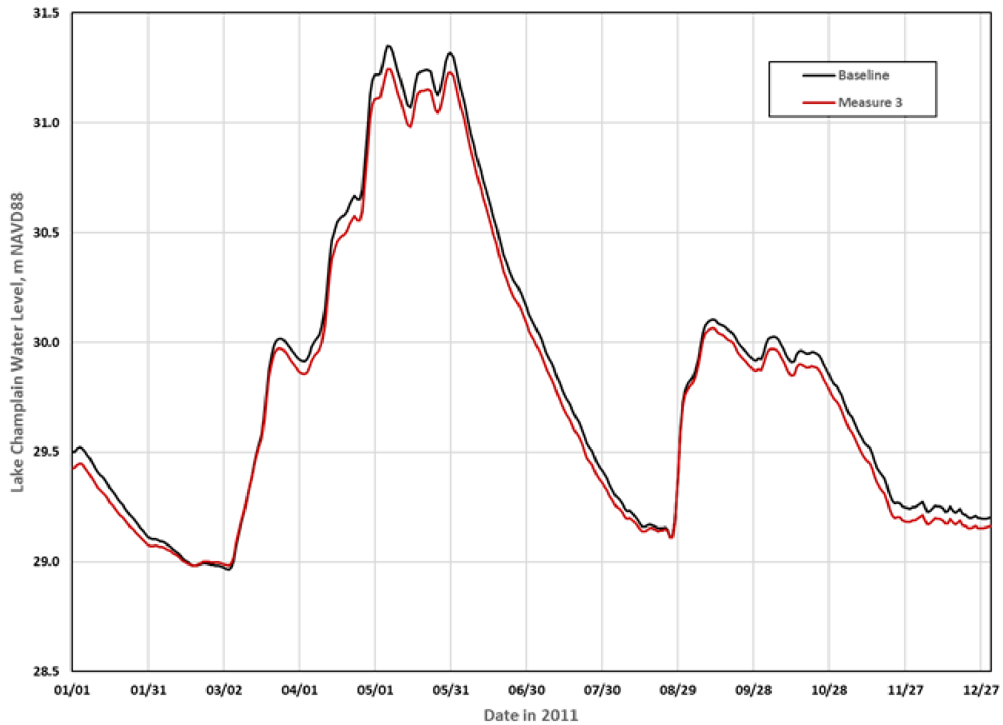

Figure 5-2. Measure 3 water levels compared with 2011 flood.

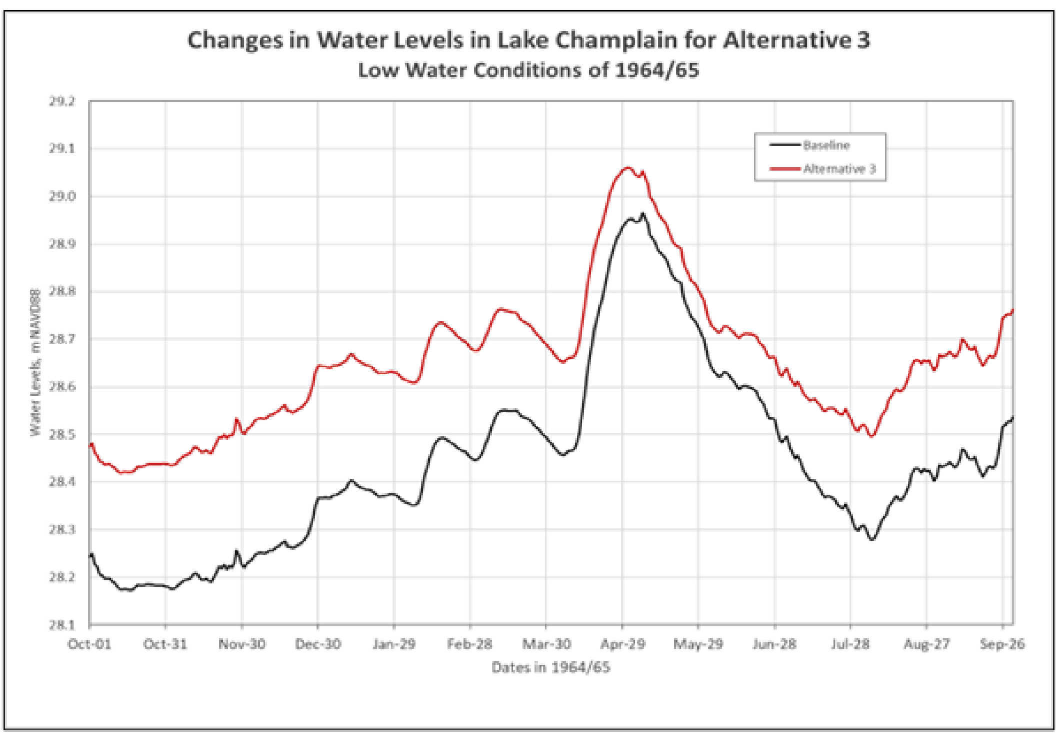

Figure 5-3. Measure 3 water level impacts during an extreme low flow event (1964/65).

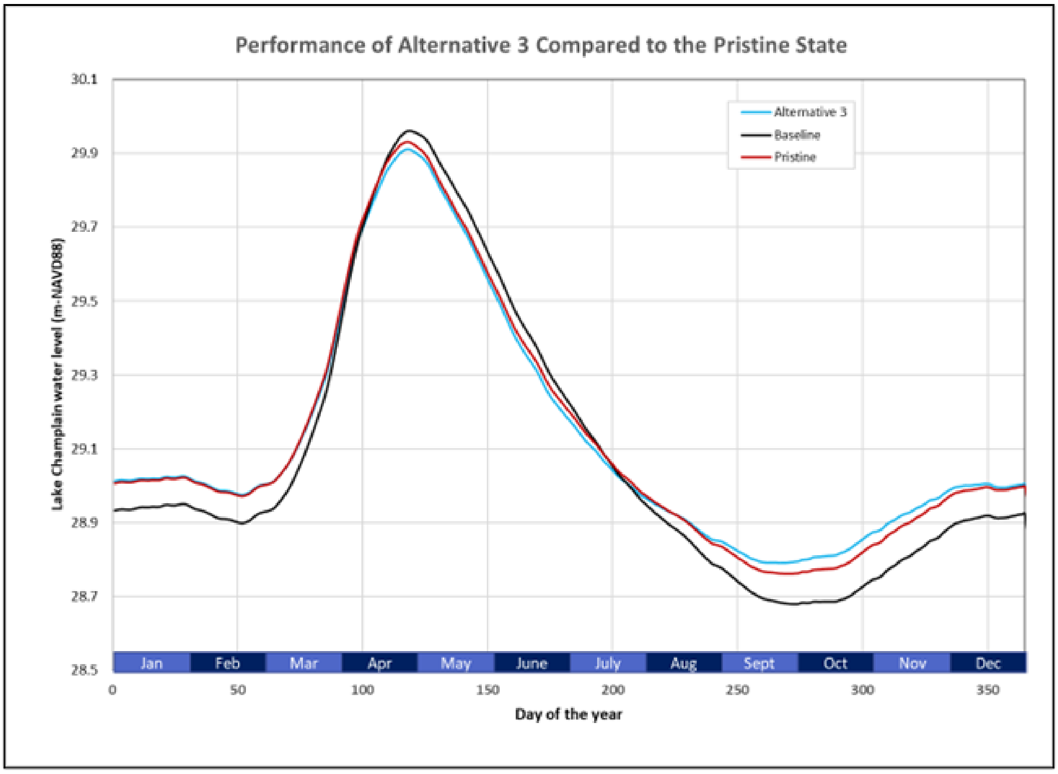

Figure 5-4. Performance of Measure 3 compared to baseline and pristine state.

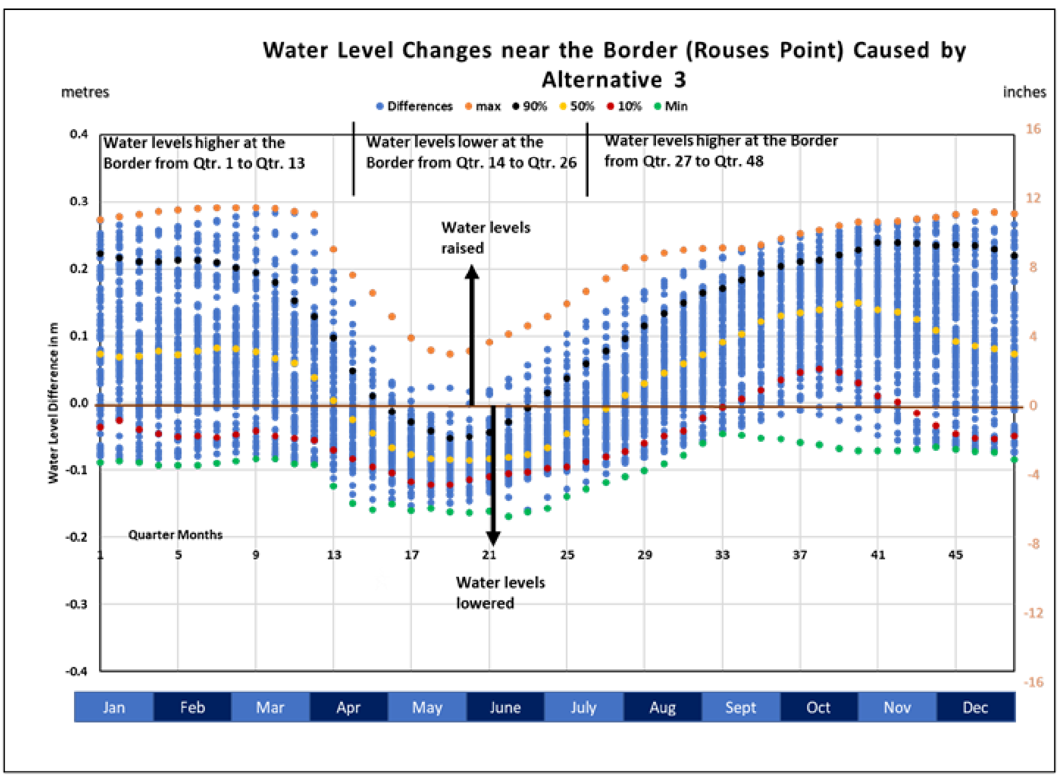

Figure 5-5. Measure 3 water level changes at the US - Canada border.

5.4.5 Summary of Water Level Impacts

The hydraulic performance of Measure 3 is summarized in Table 5-3, showing how much Measure 3 would reduce water levels for an extreme flood (2011), and how much levels would be raised for an extreme low-flow period (1964/65). For the 2011 flood, water level reductions were evaluated at the two index locations of Rouses Point (surrogating Lake Champlain water levels) and the location of major flooding in Saint-Jean-sur-Richelieu. Like Measure 1, this measure would provide low water relief; the 1964/65 low flow event was also evaluated, showing improved water levels throughout this period, with higher relief noted in the late summer to the following springtime and lesser values in the spring period.

Table 5-3. Summary of extreme water level impacts for Measure 3.

Measure 3 Relief for 2011 Flood Event	
Water level reduction:	
• Saint-Jean-sur-Richelieu	-22.3 cm (8.8 in)
• Lake Champlain at Rouses Point	-15.2 cm (6.0 in)
Relief for 1964/65 Low Flow Event	
Raising of low water levels at Rouses Point (seasonal differences)	+7 to +28 cm +2.8 to 11 in

5.4.6 Implications for Flood Response

The overall performance of Measure 3 over the entire period of historical data (1924 to 2017) was evaluated against key hydraulic metrics in terms of the indicators of various thresholds for flooding on Lake Champlain and at Saint-Jean-sur-Richelieu when compared against the baseline conditions. Only selected flooding thresholds used by agencies in the United States and Canada were captured as a report card of performance. Similarly, the improvements in the water levels against low water level thresholds were also captured and compared against the baseline. These values are presented in Table 5-4. Measure 3 would lower the number of flood events and subsequently would reduce the costs for flood emergency response.

Table 5-4. Summary of overall water level impacts for Measure 3.

Performance during flood events				
	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years above threshold	Measure 3 number of years above threshold
Major flood stage (USGS)	101.50	30.81	4	2
Moderate flood stage (USGS)	101.00	30.65	11	7
Major flood (MSP)	102.30	31.05	1	1
Moderate flood (MSP)	101.74	30.88	2	1
	SJSR marina threshold (ft CGVD28)	SJSR marina threshold (m NAVD88)	Baseline number of years above threshold	Measure 3 number of years above threshold
Major flood (MSP)	99.97	30.45	1	1
Moderate flood (MSP)	99.48	30.30	2	1
Minor flood (MSP)	98.75	30.08	19	11
Performance during low water events				
Number of years below	Lake level threshold (ft NGVD29)	Lake level threshold (m NAVD88)	Baseline number of years below threshold	Measure 3 number of years below threshold
Low water level events	93.00	28.22	4	0
	93.50	28.37	33	0
	94.00	28.52	65	16
	94.50	28.67	84	67

6 EVALUATION OF IMPACTS

6.1 WATER LEVELS

As was noted in earlier chapters, the three measures provide varying levels of water level relief on the upper Richelieu River and Lake Champlain. Table 6-1 shows the water level relief that would be provided by each measure for the flood of record (2011) and for the lowest drought event (1964/65).

Measure 2 would provide the greatest amount of flood relief for both the river and lake, followed by Measure 3 and then Measure 1.

In terms of low water level impacts at the Canada-United States border (Rouses Point), some level of relief would be provided only by Measures 1 and 3. Measure 2, which is a major flow diversion, would only impact the flood peak. The impacts for Measures 1 and 3 would vary seasonally, with spring and fall differences being greater and the summer less so. For these measures, the water level changes during the low flow event of 1964/65 were demonstrated in Chapters 3 and 5. If low water relief is factored into selecting a structural solution, Measure 3 is most appealing, followed by Measure 1.

The three measures were the focus of the Study's attention because they were moderate structures that would primarily impact the extremes of the hydrograph and would likely have less impact on the environment than would other structural measures considered. One desirable outcome of the structural solutions was to bring the hydraulic regime closer to the pristine state, which would likely be more appealing from an environmental perspective. Both Measures 1 and 3 would provide that benefit, as demonstrated in Figure 6-1.

In the figure, the baseline (black line) reflects current channel conditions that were used to produce the average annual hydrograph. The pristine state is represented by the red line. This is based on modelled channel conditions after removing all the human interventions in the river that have taken place over time. Measures 1 and 3 would follow the pristine state fairly closely for most of the year, but increase water levels slightly in the fall.

Another important implication of these measures is that they would help to mitigate the effects of the widening of the Chambly Canal in the 1970s. This was and continues to be raised as an issue on both sides of the border. The widening of the canal has been determined to have permanently raised the water levels on the upper Richelieu River by about 20 cm (7.9 in) and on Lake Champlain by 10 cm (3.9 in); the associated impact at the Canada-United States border (Lake Champlain at Rouses Point) would be mitigated if any of the three measures were implemented. However, only Measures 2 and 3 would fully mitigate the impacts of the widening on the upper Richelieu River.

Another consideration in reducing the flood damages across the binational basin is the performance of the measures upstream and downstream of the proposed measures. The ISEE model provides insight into the performance of the proposed measures for the 2011 flood. Table 6-2 presents the reduction in number of homes flooded and the associated percentage reductions for the three measures. A total of 3,839 properties were damaged during the 2011 flood; of these, 366 properties (9.5 percent) were located downstream of the shoal. These downstream properties would fare much better with Measures 1 and 3, while upstream residential properties would experience substantially better reduction in the number of properties removed from flooding in Measure 2, for two reasons. First, the objective of Measure 2 was to reduce damages upstream of the diversion at Saint-Jean-sur-Richelieu; second, the opening of the diversion on March 14 of the 2011 event would increase the flow for the downstream points. Two aspects of flood reduction stand out in Table 6-2 (noted on bold font). First, on a percentage basis, the downstream properties would fare better than the upstream (upstream Richelieu River and Canadian portion of Lake Champlain) locations; and second, in the United States, significant reduction was observed for the Lake Champlain properties in a flood of the size of the 2011 event.

Table 6-1. Water level relief provided by each measure for extreme high and low events.

Relief for 2011 Flood Event	Measure 1	Measure 2	Measure 3
Water level reduction:			
• Saint-Jean-sur-Richelieu	-15.2 cm (6.0 in)	-34.3 cm (13.5 in)	-22.3 cm (8.8 in)
• Lake Champlain at Rouses Point	-10.7 cm (4.2 in)	-22.1 cm (8.7 in)	-15.2 cm (6.0 in)
Relief for 1964/65 Low Flow Event	**Measure 1**	**Measure 2**	**Measure 3**
Raising of low water levels at Rouses Point (seasonal differences)	+7.0 to +28.0 cm +2.8 to +11.0 in	No relief	+7.0 to +28.0 cm +2.8 to +11.0 in

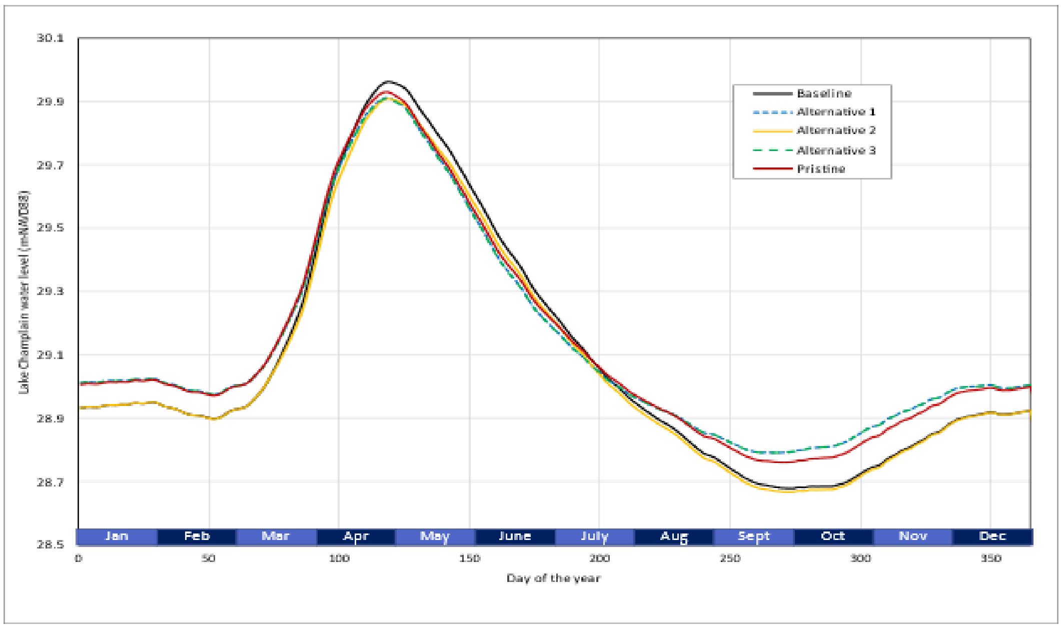

Figure 6-1. Comparison of measures to baseline conditions and the pristine state for the Richelieu River.

Table 6-2. Residential flood relief from the proposed measures for the upstream/downstream reaches during the 2011 flood.

Location	Baseline Homes Flooded	Measure 1		Measure 2		Measure 3	
		Relief*	% reduction	Relief	% reduction	Relief	% reduction
Downstream Richelieu River	**366**	**110**	**30.1%**	**54**	**14.8%**	**124**	**33.9%**
Upstream Richelieu River	2346	242	10.3%	601	25.6%	430	18.3%
Canada Lake Champlain	405	30	7.4%	76	18.8%	36	8.9%
US Lake Champlain	**722**	**214**	**29.6%**	**444**	**61.5%**	**338**	**46.8%**
Total	**3839**	**596**	**15.5%**	**1175**	**30.6%**	**928**	**24.2%**

**Relief refers to the number of homes not flooded, compared to the baseline*

6.2 ECONOMIC ASSESSMENTS

Damage reductions developed by ISEE and cost estimates presented in earlier sections of this report were used to assess the economic viability of the measures. Using ISEE results in combination with the CDST enabled the compilation of the damages that would be reduced by each of the measures. The assessment of benefits, expressed as reduction in damages, represents a more thorough evaluation of overall impacts associated with flooding.

Previous assessments of damages for the 2011 flood, in the Study's Causes and Impacts Report, were estimated at CDN$110M (US$86M); these estimates included primarily recorded residential damages, and not a broader set of impacts (ILCRRSB, 2019). The ISEE estimate for structure and content damages, including residential, commercial, recreational, farms and public buildings, is about CDN$136M (US$102M). ISEE also estimated 2011 commercial income loss in Quebec as CDN$23M, with CDN$26M million in socio-sanitary impacts, CDN$3M in temporary lodging costs and CDN$11M loss in recreational income. The total ISEE impacts for 2011 are about CDN$201M (US$151M), about 83% higher than the damages reported in the Study's Causes and Impacts report (ILCRRSB 2019). The damage reduction performance of the three measures is presented in Figure 6-2.

The time series of estimated damages for the baseline conditions and the residual damages for the three measures were assessed and are presented in Figure 6-3. The graph shows the potential for flood damages beyond the recognized flood events like 1933, 1976, 1993, 1998 and 2011, and the performance of the three flood damage reduction measures. The ten highest flood damages, residual damages and benefits are presented Table 6-3 for the baseline and three measures[2].

6.2.1 Expected Annual Damages and Benefits

To further evaluate the benefits of the three measures, expected annual damages (EAD) and benefits were computed. The ninety-three years of the time series of estimated damages described above can be considered a statistical sample from the population of flood damages in the basin. The statistics of the sample were computed at the initial step. The series was tested to determine whether the 2011 event was an outlier, and the computed sample properties indicated the event to be below the threshold (i.e., the 2011 event cannot be considered an outlier).

The first step in the evaluation of benefits was to fit the data to one of several probability distributions for estimating population damage frequencies. The population statistics from the estimated data were used to compute frequencies and return periods of baseline damages and residual damages for the three measures. The historical flow data analyzed indicated the best fit was Generalized Extreme Value Distribution (GEVD) (Ouarda and Charron, 2019); the frequency analysis of flood damages time series also employed GEVD for analysis. using the baseline condition and the three measures. Incidentally, the SPE AG also considered GEVD in its economic analysis.

The expected damages were established for the four (baseline and three measures) series of the key return periods associated with the Annual Exceedance Probability (AEP) of 0.5, 0.2, 0.1, 0.05, 0.01, 0.002 and 0.001. The total damages are plotted against the probability for the four series in Figure 6-4.

[2] All supporting data are captured in the Study's Collaborative Decision Support Tool, described in other Study reports (FMMM/HHM 2021).

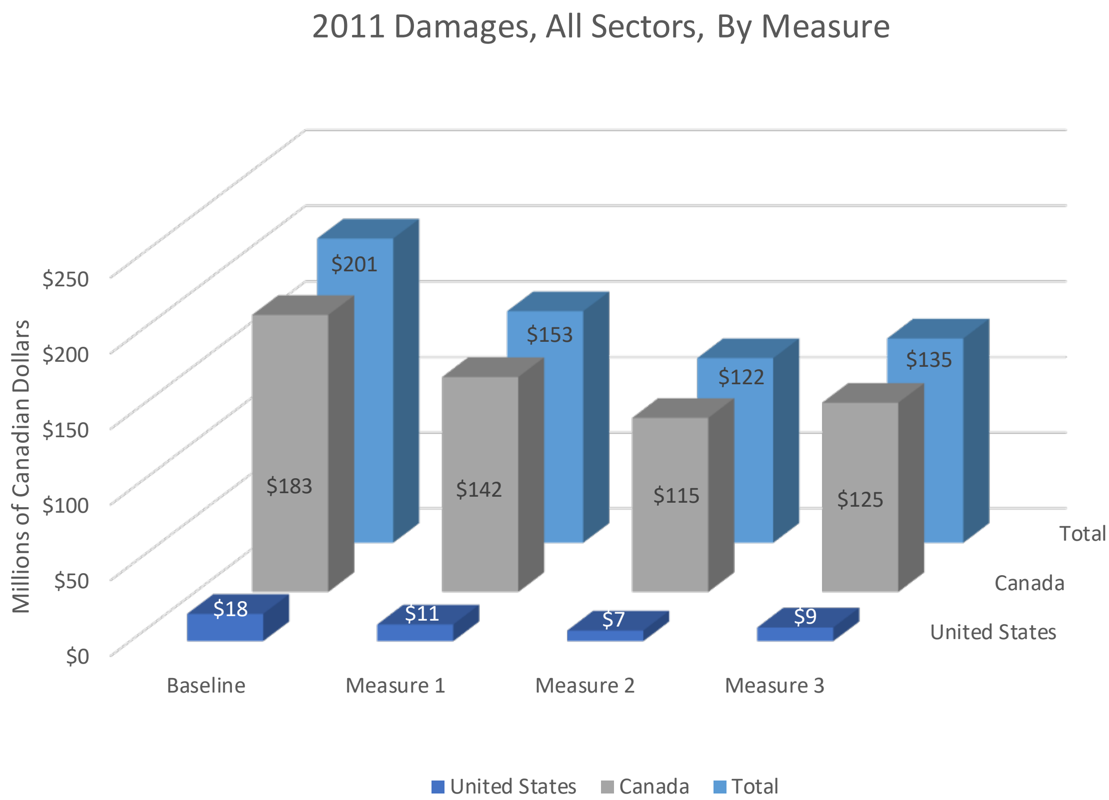

Figure 6-2. Flood damage (CDN$) in the United States and Canada for the 2011 event for baseline conditions and three mitigation measures.

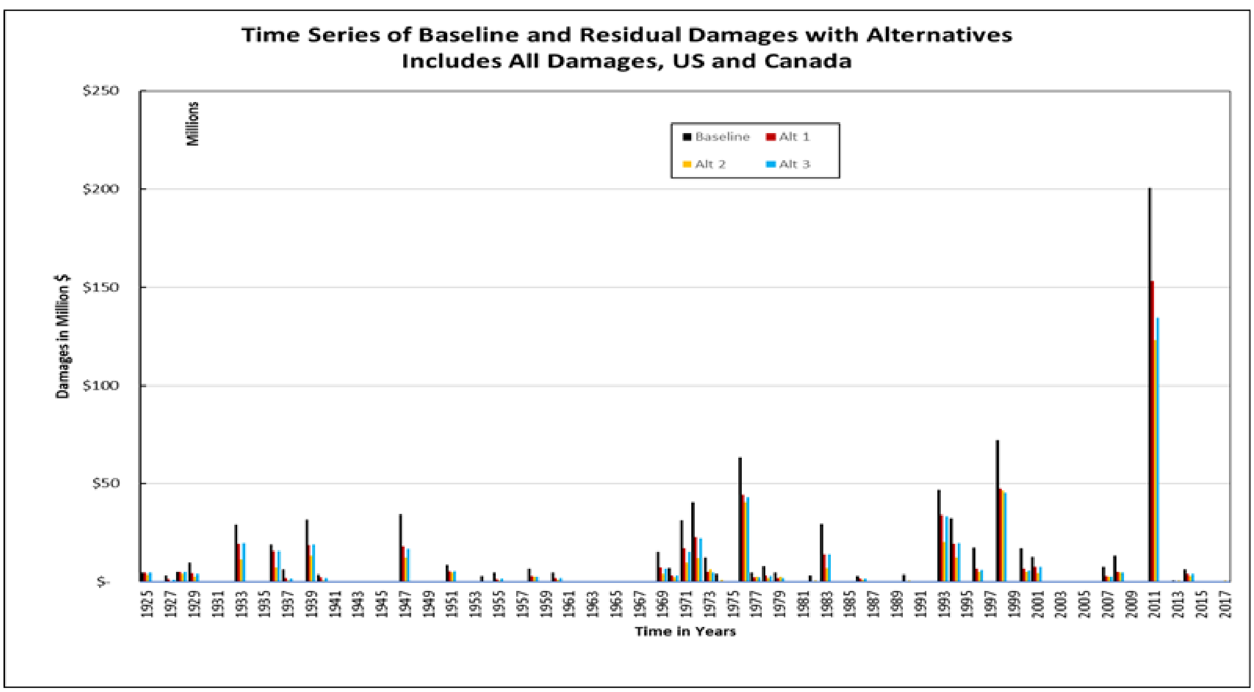

Figure 6-3. Time series of flood damages for all sectors for baseline and measures.

Table 6-3. Ten highest baseline flood damages and residual damages with three Study measures and benefits of the measures.

Year	Damages, Millions (CDN)				Benefits, Millions (CDN)		
	Baseline	Meas 1	Meas 2	Meas 3	Meas 1	Meas 2	Meas 3
2011	$200.84	$153.1	$123.1	$134.6	$47.71	$77.72	$66.21
1998	$72.00	$47.46	$46.27	$45.35	$24.54	$25.74	$26.66
1976	$63.54	$44.42	$40.45	$43.07	$19.12	$23.10	$20.48
1993	$46.75	$34.14	$20.36	$33.34	$12.62	$26.40	$13.41
1972	$40.38	$22.84	$12.07	$22.11	$17.54	$28.31	$18.27
1947	$34.57	$17.97	$12.46	$16.64	$16.60	$22.12	$17.93
1994	$32.38	$19.30	$12.37	$19.62	$13.08	$20.01	$12.75
1939	$31.72	$18.72	$13.54	$19.04	$13.00	$18.18	$12.68
1971	$31.45	$17.00	$9.73	$15.49	$14.45	$21.72	$15.96
1983	$29.31	$14.09	$6.97	$14.06	$15.21	$22.34	$15.25

Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

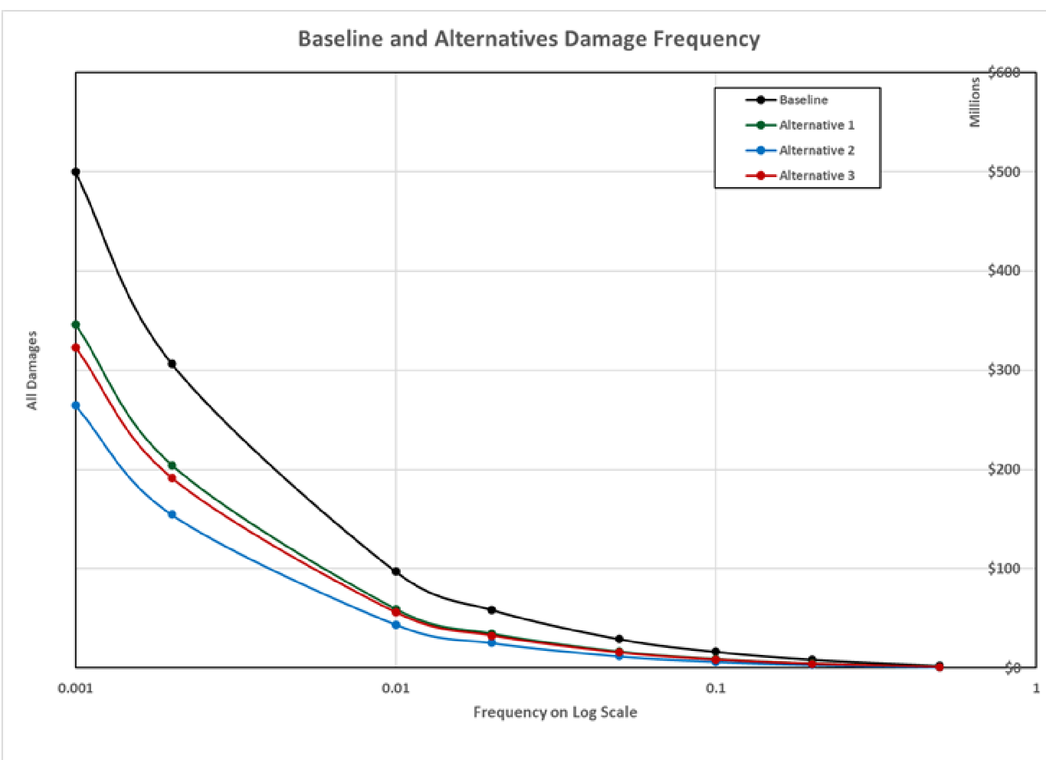

Figure 6-4. Damage frequency curves for baseline and measures.

The graph provides a visual measure of the effectiveness of each measure against the baseline damages. The areas under the curves are the expected annual damages. The differences between the baseline EADs and the measure EADs provide the Expected Annual Benefits (EAB) of the proposed measures. Table 6-4 presents the estimated expected annual damages and resulting expected annual benefits for the three measures.

The EAB over a 50-year future is brought forward to a present value that can be compared with the present value of the projected capital costs, using a discount rate of 3 percent annually. These costs are discussed in Chapters 3, 4 and 5 for the three measures. Here, the expected annual costs and benefits are compared to establish the benefit/cost ratios for the measures. To account for economic uncertainty, sensitivity of the interest rates at 5% and 8% was conducted and reported as part of the evaluation.

Figure 6-5 shows the expected average annual damages from the historical floods; these will be used to represent the baseline. There are seven categories that capture the damages, with residential structural damages being by far the greatest category and accounting for 61 percent of the overall damages (ISEE, 2022 and CDST, 2022). Note that the baseline damages reported in Table 6-4 from all data, CDN$8.1 M (US$6.1 M), are slightly higher than the sample-based EAD of CDN$7.96 M (US$5.97 M).

6.2.2 Benefit/Cost Analysis

A detailed costing for each of the measures was produced in Chapters 3, 4 and 5. The capital cost for each measure is as follows:

- Measure 1: CDN$8M (US$6.4M)
- Measure 2: CDN$100M (US$80M
- Measure 3: CDN$21M (US$16.8M)

Measure 2 is the costliest structural solution, followed by Measure 3 and Measure 1. The measure costs represent the facility construction cost only. Additional costs are added in; these include interim replacement costs, ongoing operational and management expenses, administration and general expenses and a management board to oversee the regulation plan. Information related to costs/expenses are captured in earlier chapters. Total annualized costs are used in the benefit/cost assessment. Table 6-5 contains the costs and benefits for each of the three measures. Note that the benefits were calculated based only on flood reduction, and do not reflect any additional benefits provided by improving the low water regime of the system.

This information was used to compute the Benefit/Cost Ratio for each of the measures and determine the economic viability. A Benefit/Cost (B/C) Ratio of one indicates equal benefits and costs; a ratio greater than one means the benefits outweigh the costs, while a ratio less than one means that costs are greater than the associated benefits.

Table 6-4. Expected annual baseline and residual damages and expected annual benefits.

Damages, Millions (CDN)				Benefits, Millions (CDN)		
	Residual			Baseline EAD less Residual EAD		
Baseline	Meas 1	Meas 2	Meas 3	Meas 1	Meas 2	Meas 3
$200.84	$153.1	$123.1	$134.6	$47.71	$77.72	$66.21

Note: Costs are provided in Canadian currency; a conversion rate of 0.75 can be used to obtain US$

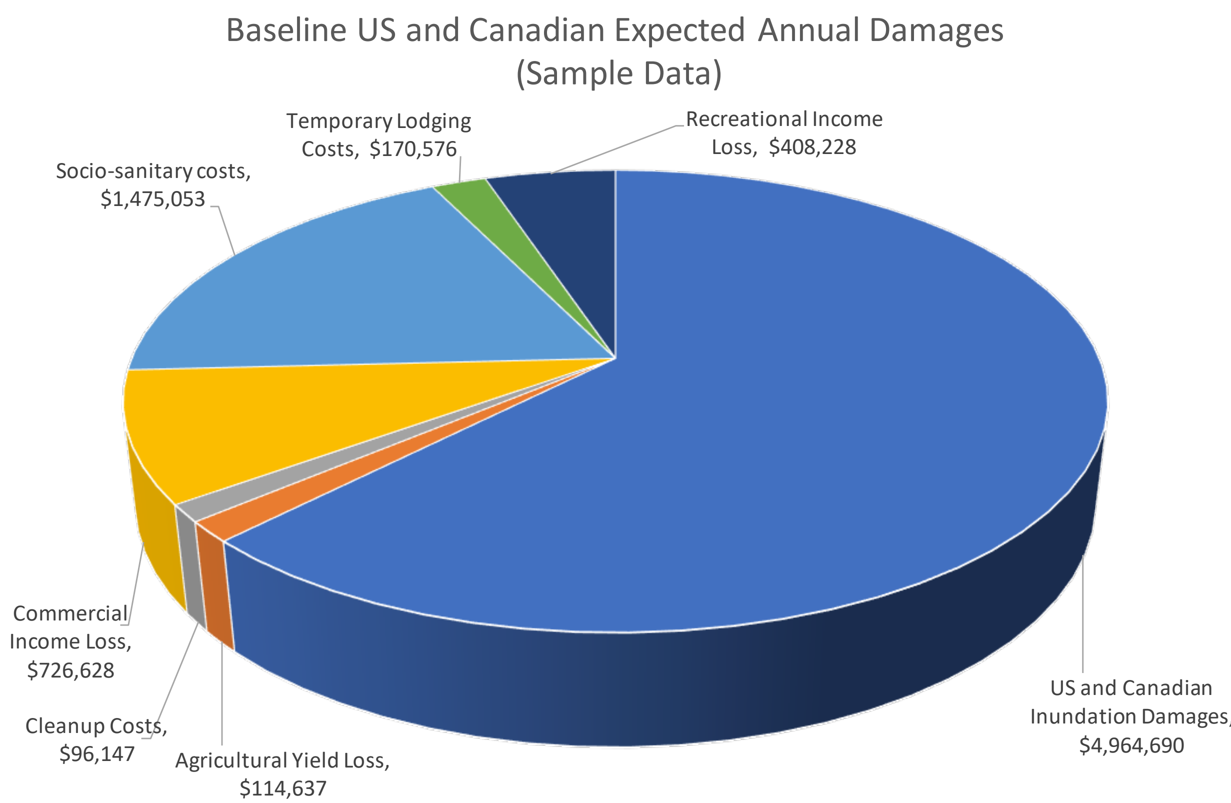

Figure 6-5. Expected annual damages (in Canadian dollars) for the baseline scenario for the United States and Canada.

Table 6-5. Benefit/Cost analysis for each measure.

Measures → Descriptive Breakdown ↓	Measure 1	Measure 2 Average Estimate	Measure 3
Capital	**$ 8,000,000**	**$ 100,000,000**	**$ 21,000,000**
Interest & Amortization*	$ 310,924	$ 3,886,549	$ 816,175
Interim Replacement	$ 25,000	$ 100,000	$ 15,000
O & M	$ -	$ 400,000	$ 20,000
Administration & General Expense	$ -	$ 100,000	$ 15,000
Management Board	$ -	$ 400,000	$ 50,000
Total Annual Cost (C)	**$ 335,924**	**$ 4,886,549**	**$ 916,175**
*** Based on 50 years project life amortized at 3.0% interest rate.**			
Baseline Annual Damages	**$ 8,101,750**	**$ 8,101,750**	**$ 8,101,750**
Annual Damages with Diversion	**$ 4,706,550**	**$ 3,445,050**	**$ 4,469,600**
Total Annual Benefits (B)	**$ 3,395,200**	**$ 4,656,700**	**$ 3,632,150**
B/C Ratio	**10.11**	**0.95**	**3.96**

Based on this Benefit/Cost analysis, Measure 1 is the most cost-effective, followed by Measure 3; both measures have B/C ratios well above 1, which reflects a break-even investment. Measure 2 is not cost-effective, with a B/C below 1. It is important to note that Measure 2 provides more high-water relief, but this comes at a significantly higher cost. Measure 1 is clearly the most cost-effective structural solution.

The diversion component of Measure 3 was an integral part of the proposal and was never viewed as an increment over Measure 1. The incremental benefits of Measure 3 over Measure 1 are much less than the incremental costs of adding the diversion to Measure 1 to yield Measure 3. Measure 3 with the proposed regulation plan described in Chapter 5 would be operational for 27 seasons if the historical supplies are realized. The modest diversion will protect 50 percent more properties from flooding when compared to Measure 1 and increase the flood level reduction by an extra 7.1 cm (2.8 in). This improvement in flood reduction is also evident from the damage probability curves, as shown in Figure 6-4, for return periods greater than the 50-year flood when Measure 3 would start to provide benefits greater than Measure 1. Additionally, the B/C ratio stayed above one even when a sensitivity analysis was carried out with higher interest rates.

The Study selected an interest rate of 3 percent, in line with the current economic setting. It also looked at the impacts that higher interest rates would have on the economic viability of these measures. Table 6-6 shows the B/C ratios for interest rates of 3 percent, 5 percent and 8 percent; B/C ratios are reduced at higher interest rates, but the viability of the measures does not change from the above assessment.

6.3 ENVIRONMENTAL IMPACTS

Extensive work has been undertaken by the Study to evaluate the environmental impacts associated with each measure. This section provides a synthesis of the environmental impacts based on the analysis of key environmental performance indicators (PIs). A more complete understanding of these indicators and analyses undertaken can be found in Roy et al. (2022).

It is important to note that the work undertaken by the Study provides a preliminary analysis of environmental impacts. However, should the governments decide to implement a measure, it would need to undergo a rigorous environmental impact assessment and further data collection.

Table 6-7 provides an assessment of PIs for three large wetland classes and six more PIs associated with critical fauna. The results are grouped under five score categories, based on a percentage deviation from current conditions (baseline). In some areas where the PIs are not applicable, the information in the table is blank. The color-coded results show the percent change in the PIs for each of the three measures for Lake Champlain and the upstream and downstream reaches of the Richelieu River.

Table 6-6. B/C ratio sensitivity to interest rates.

Interest Rates	Measure 1	Measure 2*	Measure 3
3%	10.11	0.95	3.96
5%	7.33	0.72	2.91
8%	5.00	0.51	2.00

** With the perfect forecast these numbers are inflated and will be reduced based on any practical operating plan that would be developed. Measure 2 is < 1, which is the break-even point for an investment.*

Table 6-7. Environmental impacts associated with each measure.

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

Legend:

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

The changes are typically small and can be negligible (2 to -2 percent). There are eight indicators with a greater than 5 percent increase in the average PI score and for two an increase between 2 and 5 percent. No indicators are reduced by more than 5percent, however, five indicators drop by between 2 and 5 percent.

Measures 1 and 3 would produce a more natural hydraulic regime, which is commonly expected to be better, as more natural water levels promote biodiversity. The analysis of PIs shows that there would be minor changes in the average scores, but further analysis would be required to show that these differences are meaningful.

In the case of the PI for the area of suitable habitat for Copper Redhorse spawning, there could be an issue. Due to the absence of precise bathymetric data in one of the known spawning zones (i.e., Chambly Basin) of this endemic and endangered species, it is not possible to completely exclude the potential for negative impacts from Measures 1 and 3.

In addition, the average scores for the PIs do not reflect the shifts from year to year due to natural variability. Figure 6-6 shows the change in areas of four different wetland classes over time under Measure 1, as compared to the baseline. These changes would need to be studied in more detail, including effects on species life span and life cycles, to fully assess the PIs. None of the measures were determined to produce any significant negative effects that would result in the measure being rejected on an environmental basis at this stage (Roy et al., 2022).

6.4 SOCIETAL IMPACTS

Damage assessments developed by ISEE were used to assess the societal impacts of the measures, including residential damages avoided and impacts on indigenous communities.

6.4.1 Residential Damages Avoided

Figure 6-7 shows the number of residences that would be spared from flooding for each structural measure. Results from household risk perception surveys, social network analysis and emergency responder surveys conducted by the SPE group showed that residences spared was considered a high priority for flood management, and this is reflected in the calculation of socio-sanitary performance indicators. The Study's report on social, political and economic analyses (SPE, 2022) looks at the impacts of this in detail.

The Study collected information on over 5,000 residences in the basin to assess flooding impacts; of these, 3,839 were impacted by the 2011 flood. About 81 percent of these residences are in the Canadian portion of the basin and the other 19 percent are in the United States.

Measure 2 would provide the greatest relief for both the Canadian (731 residences spared from flooding) and US (441 residences spared) residents in the basin. This is followed by Measure 3, with 590 and 338, respectively. Measure 1 would provide the least relief, at 382 and 214 residences spared. This analysis shows that there is significant relief to be gained in both countries, and proportionally more on the US side. Another way to look at Figure 6-7 is that out of 3,117 properties, Measure 1 would remove 382 properties from future flooding; there would still be 2,735 properties facing future flood damages.

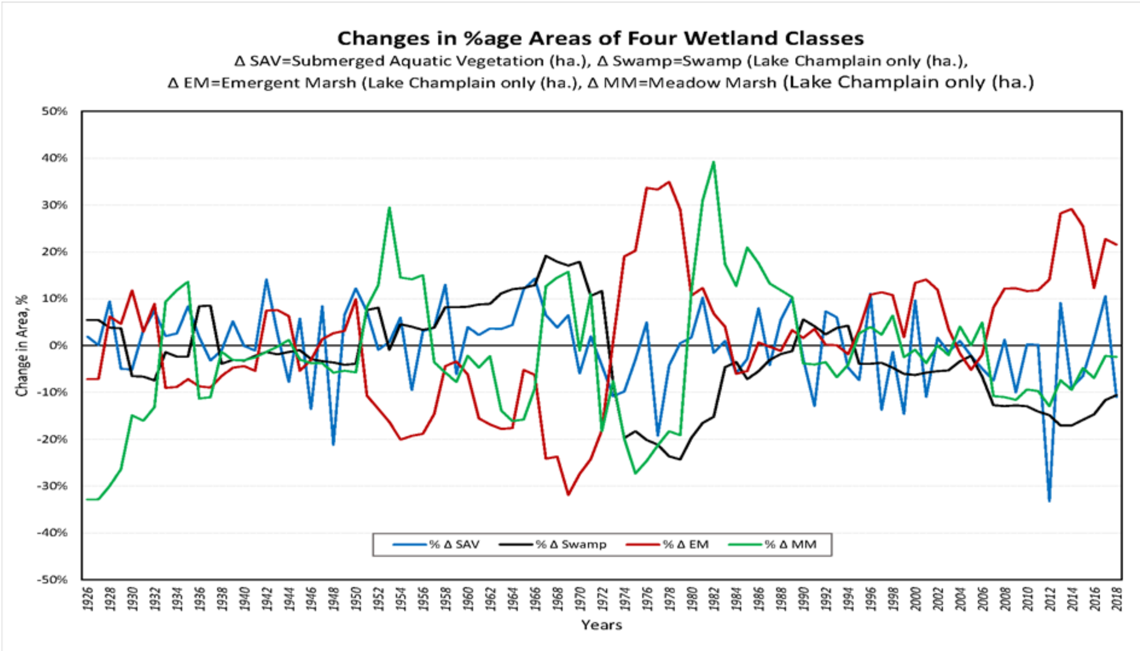

Figure 6-6. Changes in areas of different large wetland classes, Measure. 1 versus baseline.

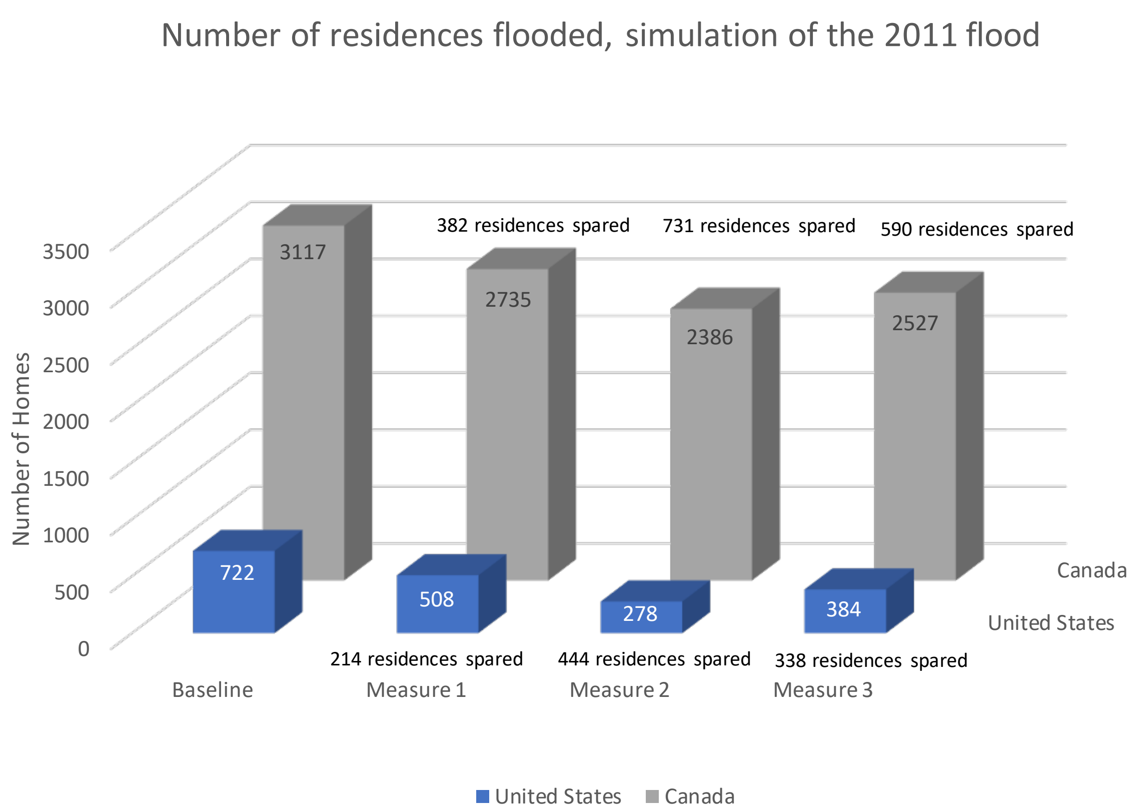

Figure 6-7. Number of residences flooded for each measure, by country.

The distribution of benefits by river reach (identified as ISEE tiles) provides another perspective, particularly for the Canadian portion of the basin. The ISEE evaluation of damages (Figure 6-8) is divided into geographic sections, with Sections 12 and 20 closest to Lake Champlain, and Section 50 closest to the St. Lawrence River. Venice-en-Quebec is in Section 12; Noyan is in Section 20. Saint-Jean-sur-Richelieu above the control point is in Section 20, and below the control point is in Section 30, along with Chambly and Carignan. Section 40 includes Beloeil and Saint-Charles-sur-Richelieu. Section 50 includes Saint-Ours and Sorel-Tracy.

Figure 6-8. River reaches of the Richelieu River as per the ISEE tiles.

Table 6-8 summarizes the benefits in the Canadian portion of the basin in each of these sections for the three measures. The benefits shown are the reduction in simulated 2011 baseline damages attributed to each measure. Measure 2 would produce the greatest residential flood relief, followed by Measure 3 and Measure 1. Both Measure 2 and Measure 3 include diversions, which would increase downstream flows and could occasionally increase downstream flood damages by lesser amounts. Further design improvements or an operational rule to avoid diversions when the Lower Richelieu is in flood stage could reduce this problem. For the economic analysis, residential structural damages were included for both US and Canadian portions; while the commercial, industrial, recreational structural information was captured only for the Canadian part of the basin.

6.4.2 Impacts on Indigenous Communities

The Study worked closely with the indigenous communities in the basin to evaluate the potential impacts resulting from a structural solution. Three performance indicators were selected for this purpose: black ash, which has cultural uses such as basket weaving; wild rice, a cultural food source; and archeological/sacred sites, affecting historic cultural preservation. These indicators are discussed in detail in the Study's performance indicator evaluation report (Roy et al., 2022). Table 6-9 presents the impacts of each measure on these PIs, using the same color-coded system described previously. Measure 3 would produce more positive impacts than the other two measures, and none of the measures would produce negative impacts. Therefore, from an indigenous perspective, any of the measures would appear to be acceptable. Consultations are being conducted with the indigenous communities to confirm this assessment.

Table 6-8. Example benefits (CDN$) by river reach.

Residential Structural 2011 Benefits			
	2011 Measure 1	**2011 Measure 2**	**2011 Measure 3**
Section 12	$1,388,169	$2,734,228	$1,713,601
Section 20	$48,942,978	$23,572,866	$19,018,803
Section 30	$2,414,054	$1,056,530	$2,657,545
Section 40	$241,511	-$38,013	$88,435
Section 50	$938	-$386	$314
	$52,987,651	**$27,325,224**	**$23,478,698**

Commercial, Industrial, Recreational Structural 2011 Benefits			
	2011 Measure 1	**2011 Measure 2**	**2011 Measure 3**
Section 12	$908,815	$1,154,512	$1,108,541
Section 20	$2,068,033	$2,008,346	$1,917,227
Section 30	$89,530	$1,695,984	$1,866,176
Section 40	$2,678,690	-$45,077	$35,406
Section 50	-$2,180,852	$0	$0
	$3,564,216	**$4,813,766**	**$4,927,350**

Figures in red indicate increased damages in the sections from the measures.

Table 6-9. Impacts on indigenous peoples associated with each measure.

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

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

7 CLIMATE CHANGE

7.1 FUTURE CLIMATE

Two separate research groups, one at École de technologie supérieure (ETS) working on traditional climate downscaling and the other at the University of Massachusetts (UM), conducting weather generator analysis, concluded that climate change will reduce average Lake Champlain levels and Richelieu River flows during the 21st Century (François and Brown, 2022). They each also found that floods greater than 2011 were still plausible, even if average water levels are reduced. Accordingly, the performance of the measures during a drier future and during rare but plausible mega-floods must be assessed. The analysis focuses on the two viable measures, Measure 1 and Measure 3, as per Chapter 6. For the purposes of the report and the analysis carried out in this section, terms employed include return period floods, extreme floods and mega-floods. The return period floods are those where a probability of occurrence can be ascribed, while both extreme floods and mega-floods refer to floods greater than 2011. No one can estimate with any useful accuracy the recurrence interval of such floods, especially because of climate change, but there is no evidence to suggest they are anything but rare (more than 200-year recurrence interval). Extreme floods and mega-floods are interchangeable in their context.

7.2 CLIMATE CHANGE IMPACTS ON STRUCTURAL MEASURES

The Study Board's decision criteria include economic viability and resilience to a changing climate. Sections 7.2.1 through 7.2.4 analyze the hydraulic performance of Measure 1 and Measure 3 under extremely high and extremely low flows. Section 7.3 analyzes the economic viability of the two measures in a future with reduced risk of flooding, to determine whether they are resilient to the changing climate.

7.2.1 Submerged Weir Performance for Mega-Floods

Figure 7-1 shows the water level drop across the submerged weir for a variety of flow conditions. For a flow of 500 m^3/s (17,658 ft^3/s), the drop across the weir would be appreciable, at about 20 cm (7.9 in) as the water level behind the weir developed a head to discharge desired flow over the weir. As the flow rate increased, the drop across the weir would be reduced. For example, for a flood of about 1,500 m^3/s (52,973 ft^3/s), similar to the 2011 event, the depth of flow over the weir would be about 2.4 m (7.87 ft) and the drop across the weir would be only 4.6 cm (1.8 in).

For a mega-flood such as 2,192 m^3/s (77,407 ft^3/s), the Study's highest modeled flow, the drop would be reduced further to about 2.9 cm (1.1 in). The limits of the model mesh used to hydraulically model the flow precluded the modeling of any higher flows, but the drop over the weir would continue to be less noticeable as flows rose higher. Figure 7-1 indicates that the weir, while designed and optimized to reduce the flood of 2011, would continue to provide some flood relief that would diminish with increased flows. The weir, which would normally be an impediment to water circulation, has few negative impacts on water circulation during high flows; these impacts continue to decrease with increased flows and the weir is no longer a hindrance during flooding

With respect to the structural integrity of the weir under mega-floods, the velocity fields in the vicinity of the proposed structure were investigated to determine if they would dislocate the large loose stones used to build the weir. The initial assessment was that the structural integrity of the weir would not be compromised during a mega-flood.

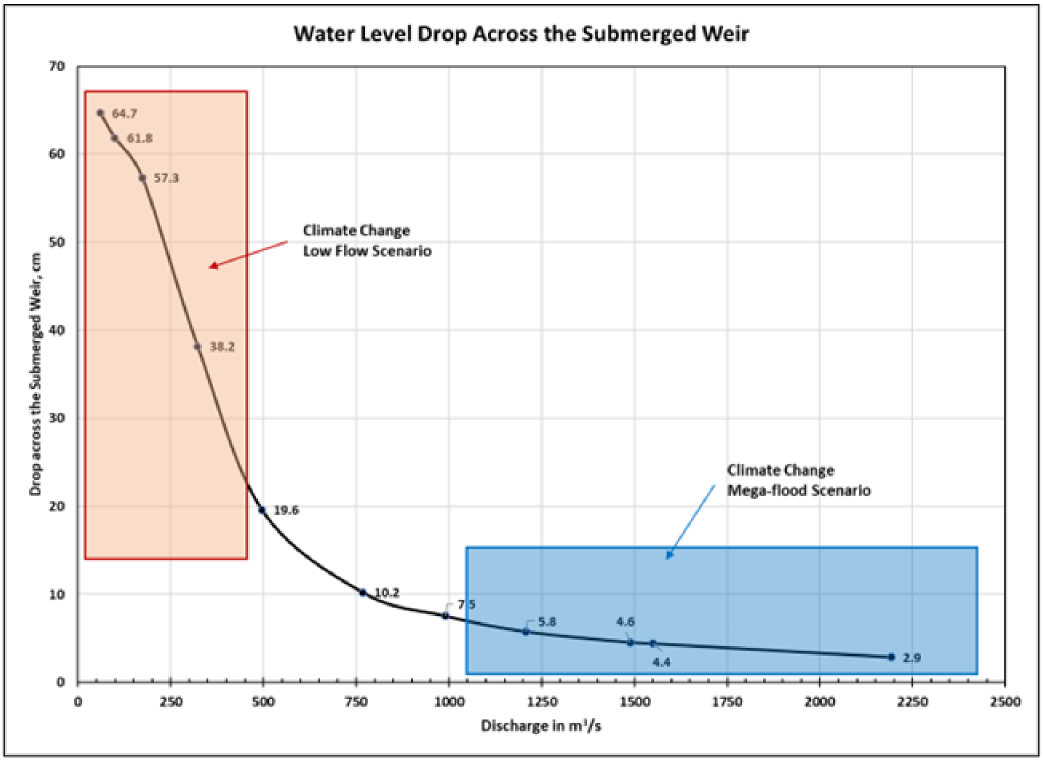

Figure 7-1. Hydraulic performance of the weir for various mega-floods.

7.2.2 Submerged Weir Performance for Climate Change Induced Low-Flows

The Study's analysis indicates that climate change will generally reduce Lake Champlain levels and Richelieu River flows, because increased evaporation and evapotranspiration from higher temperatures will more than compensate for higher precipitation. The submerged weir will be beneficial because it raises low water levels. The hydraulic model results for low-flow conditions were tested for a discharge of 29 m^3/s (1,024 ft^3/s), computed as the 99 percent exceedance probability (i.e., 99 percent of all daily quarter-month flows will exceed 29 m^3/s).

Two other aspects were also studied for the flow regime at the submerged weir location. The first was to investigate the impact of low flows with respect to the spread of water across the weir. For this purpose, the Water Balance Model simulated lowest flow of about 59 m^3/s (2,083 ft^3/s) for the current (baseline) conditions was compared with the lowest flow for the same quarter month for Measure 1. Figure 7-2 presents the two scenarios, the baseline in the graphic on the left and Measure 1 in the graphic on the right. The figure shows depths of water with and without the Measure. The black areas are exposed bed, shallow areas are in blues and higher water depths in red. The graphic shows little difference in the spread of the water, it is still exhibiting water shore to shore. The key difference observed is in Measure 1; as expected, the water is deeper upstream of the submerged weir and shallower downstream, as the conveyance below has increased with excavation.

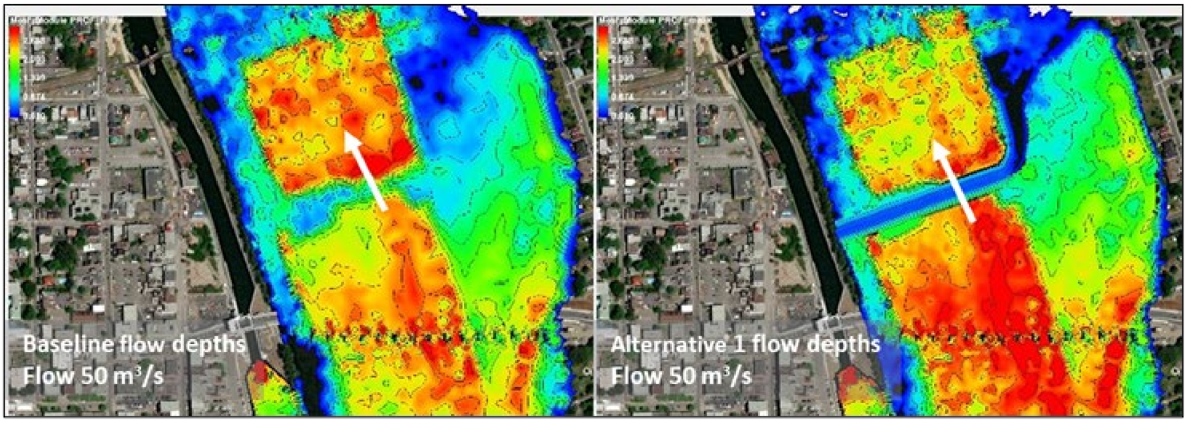

Figure 7-2. Flow depth maps for the baseline (left) and Measure 1 (right).

The second aspect was to investigate the depth of water at the weir at all times. Using hydraulic modelling results for flows below 500 m^3/s (17,657 ft^3/s), a relationship was developed (Figure 7-3). It demonstrated that even for the minimum simulated flow of 59 m^3/s (2,083 ft^3/s), a depth of 28 cm (11 in) of water would be maintained. A downstream weir slope of 1-in-5 will facilitate fish migration.

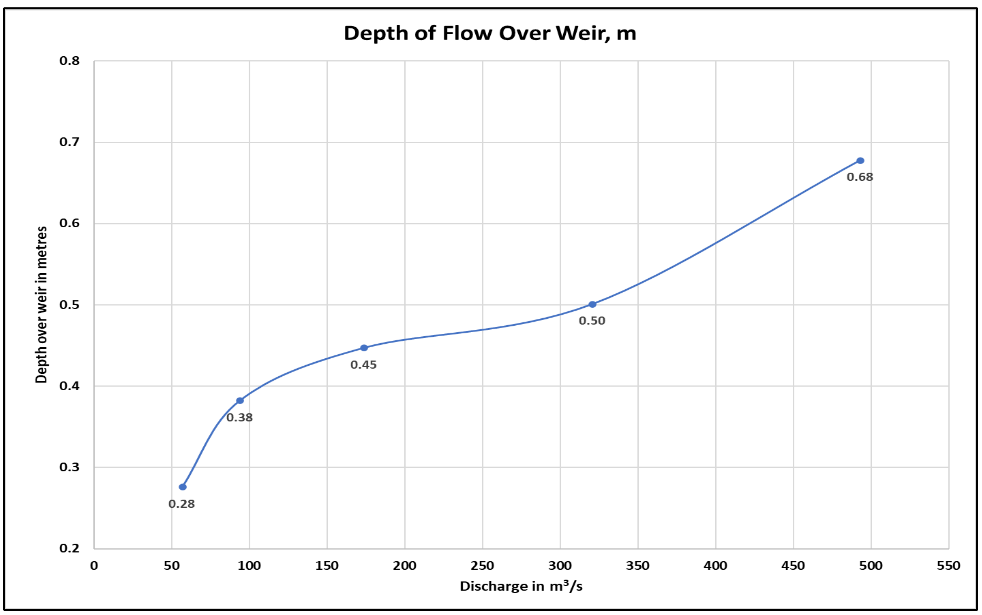

Figure 7-3. Depth of water over the submerged weir in Measure 1.

7.2.3 Modest Chambly Canal Diversion Performance for Mega-Floods

The operational policy selected for this proof of concept would open the gates when the discharge in Saint-Jean-sur-Richelieu reaches 1,000 m^3/s (35,315 ft^3/s) and close the gates when the discharge peak has passed, and flow has returned to 1,000 m^3/s (35,313 ft^3/s). Originally, the operation criterion was to begin diverting water into the Canal when the flow reached 1,000 m^3/s (35,313 ft^3/s), which translates to a level of about 29.8 m (97.8 ft.); the actual level would vary with channel roughness and vegetation. Based on historic hydrology, the diversion would have been used in only three years: 1993, 1998 and 2011. A second operating plan was proposed, this time based on water level, that would open the diversion at an elevation about 0.5 m (almost two feet) lower, 29.25 m or 96 ft. The diversion would have opened in 27 years under this policy based on historic hydrology. Using the diversion more often would increase benefits, and this policy increased the benefit-cost ratio of Measure 3 by about 0.1. However, the lower the trigger elevation, the more likely it is that the diversion would cause a disbenefit by aggravating summer droughts. If the governments investigate the feasibility of the diversion, the operating policy will be a key part of the design.

During a mega-flood, the water levels would rise higher than the 2011 levels of about 30.3 m (99.4 ft.). Once water levels at the point of the proposed diversion exceed 30.5 m (100 ft.), water would overtop the entire stretch of the canal dike (with or without Measures 1 and 3) and the safety of the canal system would be compromised. If the dike could be protected by sandbags or Aqua Dams©, then the diversion would continue to discharge the design flows. This would allow an additional reduction in water levels in the communities both upstream and downstream of the structure.

Under a mega-flood, there is a possibility of the dike breaching through overtopping and/or in the presence of erosion. If the water levels around the diversion features were high enough to overtop the dike, it would be preferable to fill the canal and close the diversion to prevent piping damage in the dike.

7.2.4 Modest Chambly Canal Diversion Performance for Climate Change Induced Low-Flows

The diversion would not be used in low or even normal flows. Water levels would be raised by the submerged weir, but the addition of the diversion would have no impacts on low flows.

7.3 IMPLICATIONS OF CLIMATE CHANGE ON THE ECONOMIC VIABILITY OF THE STRUCTURAL MEASURES

The decision scaling analysis shows that while climate change will probably reduce the current Benefit/Cost ratios of Measures 1 and 3, Measure 1 would remain cost-effective throughout the 21st century and Measure 3 would remain cost-effective for decades. The process used to arrive at that conclusion is described in detail in the Decision Scaling report (François and Brown, 2022) and is briefly summarized here.

7.3.1 Robustness Testing of the Economic Viability of the Measures

Based on current climate conditions, Measure 1 has a Benefit/Cost Ratio of 10.11 and Measure 3, 3.96 (see Chapter 6). This is based on a generalized extreme value (GEVD) distribution fitted to a sample comprised of the 1925-2017 annual damage estimates. The benefits are the differences in areas under the damage-frequency curves for each of the two measures, as described in the section above on benefit/cost analysis.

There are two important caveats that must be considered in this analysis. First, the procedure used provides a qualified judgment about the robustness of the Benefit/Cost Ratios, but not a true statistical assessment. This is discussed in the second step of the robustness assessment described below. Second, it could be argued that the projections chosen, based on the Representative Concentration Pathway, RCP 8.5 (a greenhouse gas concentration trajectory adopted by the Intergovernmental Panel on Climate Change), bias the analysis towards less flooding. To the degree that is true, the assessment is more conservative, attesting to the cost-effectiveness of the measures even based on the driest projections.

7.3.2 Robustness Assessment of the Economic Viability of the Measures

The decision scaling analysis uses a "weather generator" (François and Brown, 2022), a stochastic model that simulates precipitation and temperature inputs (based on the statistical distribution of these variables) to the Lake Champlain Hydrotel basin model, which in turn generates net basin supplies (inflows) into Lake Champlain. To define breaking points in system performance, the changes in precipitation and temperature go beyond projections from climate models. The simulations preserve the variability of current net basin supplies (NBS), so the net basin supplies may be shifted higher or lower but still produce a wide range of floods and droughts, as in the current climate.

The robustness test of the Benefit/Cost Ratios was conducted in two steps:

1. The current condition damage-frequency curves were modified for the baseline and each of the two measures to represent a future with a reduced flood risk, by lowering the curves until the benefits barely justified the measures (B/C = 1)). The current and shifted damage-frequency curves are shown in Figure 7-2. The curves are lower because any level of damage will happen significantly less often. For example, the "200-year" discharge - the discharge from Lake Champlain at Saint-Jean-sur-Richelieu that has a one-half-percent chance of occurring in any year - is now 1,550 m^3/s (54,738 ft^3/s). If the damage-frequency curve were lowered so that the half-percent chance discharge was only 1,250 m^3/s (44,144 ft^3/s), the benefits for Measure 3 would equal Measure 3 costs. The curve would have to be lowered even further to make Measure 1 marginally justified, and that half-percent discharge would be only 1,107 m^3/s (39,094 ft^3/s). The corresponding flow reductions are 19.3 percent and 28.5 percent, respectively.

2. The next step was to quantify the chance that climate change will reduce flooding so that the 200-year discharge is reduced by 19.3 percent or 28.5 percent. True statistical estimates cannot be made without sample data from the future, but the Weather Generator can be used to generate NBS sequences reflective of the range of Climate Model Intercomparison Project Phase 5 (CMIP5) projections, and the likelihood of sequences that dry based on these synthetic simulations can provide a qualified estimate of the discharge reductions. The qualification is that the projections of robustness are based on synthetically generated data that have similar variability to historical data but are also consistent with the ensemble of sixty-three CMIP5 temperature and precipitation projections, weighting each projection equally (the selection and use of these projections is documented in the LCRR report "An analysis of the impacts of climate change on flooding and flood management decisions for the shores of Lake Champlain and shorelines of the Richelieu River," François and Brown, 2022). Using the CMIP5 projections implies that the ensemble represents the best estimate of changes in precipitation and temperature. The CMIP5 projections are shown in Figure 7-3 for two time periods. The x-axis presents projected changes in temperature, compared to the baseline 1970-1999 period, while the y-axis shows projected changes in precipitation, expressed as a percent change, compared to the same baseline period.

The period labeled 2040 covers the timespan from 2026 to 2055 and the projections are shown as yellow circles.

The second period is labeled 2070 and it represents the years 2056 to 2085; the projections are turquoise circles. The 2070 projections are a little wetter and a lot hotter, and subsequent analysis shows they produce lower discharge-frequency curves. The bar plot underneath and on the left side of the scatterplot shows the distribution of change in temperature (x-axis) and precipitation (y-axis) (François and Brown, 2022).

Figure 7-6 includes two graphs that illustrate how the lower discharge-frequency curves can be generated. The graph on the left shows the full range of changes in precipitation and temperature (ΔP is the percent increase in annual precipitation and ΔT is the increase in average annual temperature, in degrees Celsius). for which the Weather Generator was run. Each cell is a combination of the percent precipitation change on the y-axis and the temperature change (degrees Celsius) on the x-axis. The color scheme shows whether the simulation produced historical flows (white), drier than historical (red) or wetter than historical (blue), with the deepness of the color indicating the percentage of simulations with the indicated tendency. For example, a 40 percent increase in precipitation and a zero increase in temperature, shown in the top left cell, is shaded dark blue, indicating a 60 percent increase in flow, whereas the top right cell (also a 40 percent increase in precipitation but with a 6°C increase in temperature), shows only a slight (10 percent) increase in flow. The green (2040) and the slightly larger black (2070) ellipses to the right show the ΔP and ΔT projected in CMIP5. The simulations from these two eras are completely in the pink range, meaning flows are reduced, sometimes slightly (light pink in the 0% ΔP and 1°C ΔT) and sometimes more (red in the 0% ΔP and 5°C ΔT).

The graph on the right side of Figure 7-6 shows the non-exceedance probability of different reductions in the 200-year discharge two periods, labeled 2040 (covering the span from 2026-2055) and 2070 (2056 to 2085). The earlier period (green curve) is further to the right, indicating a smaller decrease in flows (x-axis) for any recurrence interval (y-axis). The red crosshairs superimposed on the graph show the probability of the 19.3 percent or 28.5 percent reductions for both eras. On the lower left, about 8percent of the simulations from the 2070 era (black curve) show a decrease that large or larger. No simulations from the earlier era (green curve) produce reductions that large, but about 7 percent in the 2040 era show reductions of 19.3 percent or more. Looking upward to the middle of the graph, about 57percent of the simulations from the 2070 era show a reduction of 19.3 percent or more. These are the qualified probabilities based on climate model projections that the measures will not be cost-effective. The qualification is important; the fact that all climate models predict something does not mean that something will certainly happen, only that every model in CMIP5 predicts it will happen. Based on CMIP5 projections, there is no chance that Measure 1 will not be cost-effective in the 2040 era and an 8 percent chance that Measure 3 will not be cost-effective. In the 2070 era, there is a 7 percent chance that Measure 1 would not be cost-effective and a 57 percent chance that Measure 3 would not be cost-effective. Hence, the cost-effectiveness of both measures, but especially Measure 1, can be judged robust based on the range of projected CMIP5 projections.

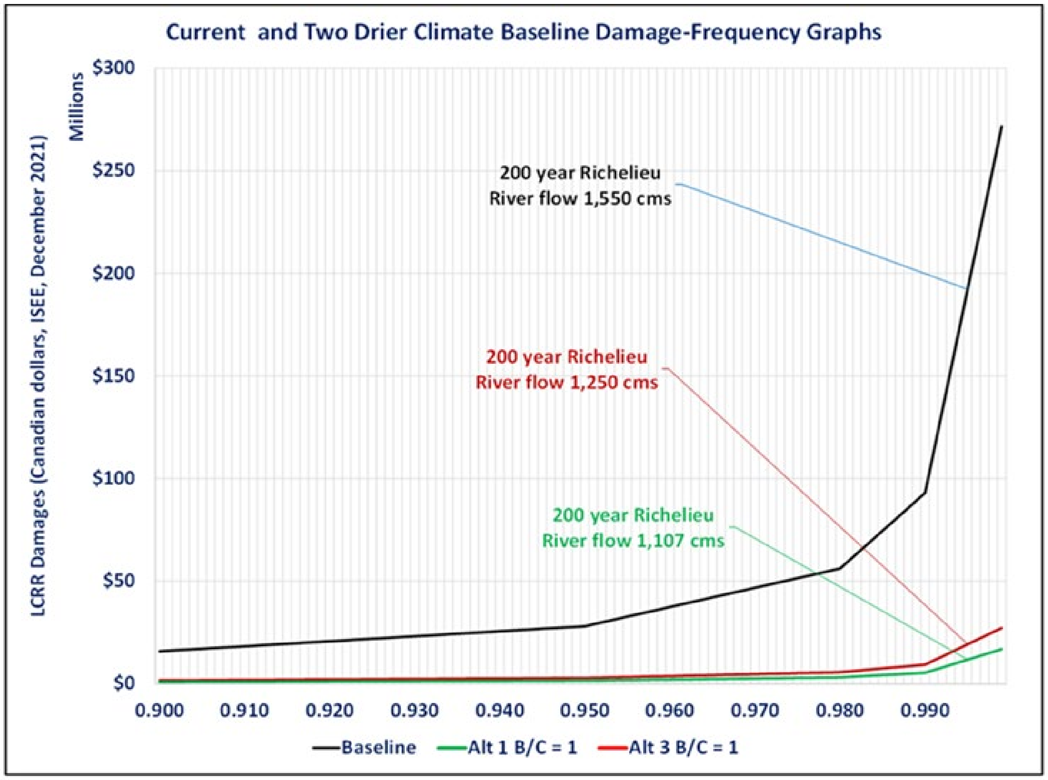

Figure 7-4. Baseline damage frequency curves for the current climate and for conditions so dry the B/C of Measures 1 and 3 drop to 1.0.

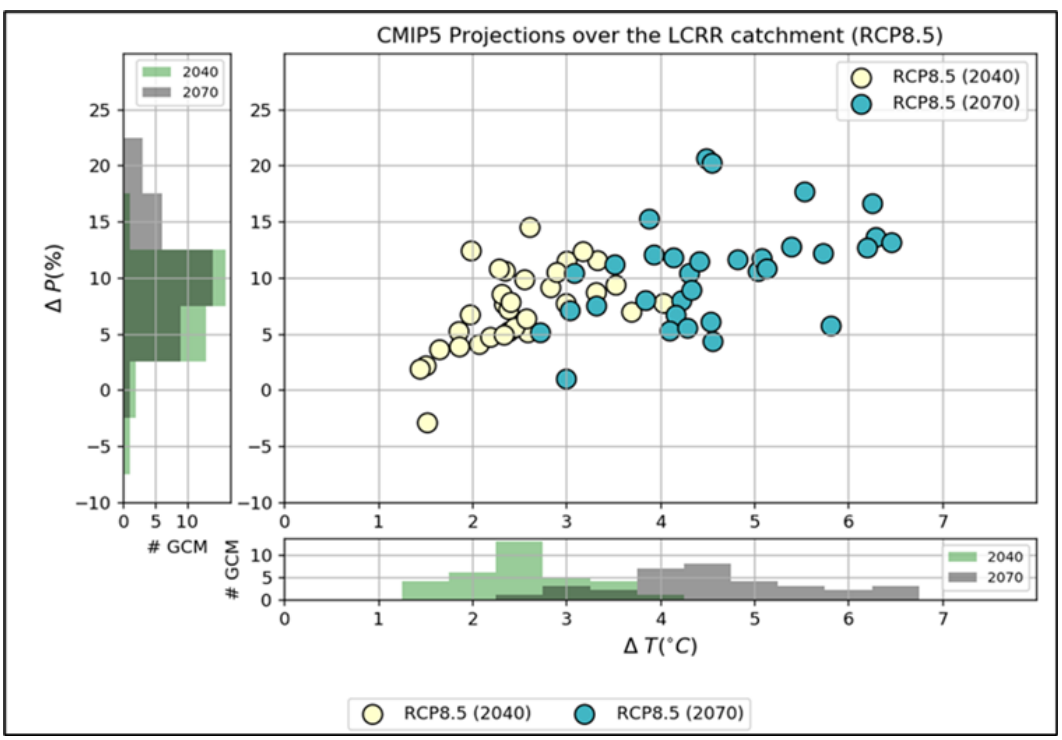

Figure 7-5. CMIP5 temperature and precipitation changes projected over the basin for 2026-2055 (labeled 2040) and 2056-2085 (labeled 2070).

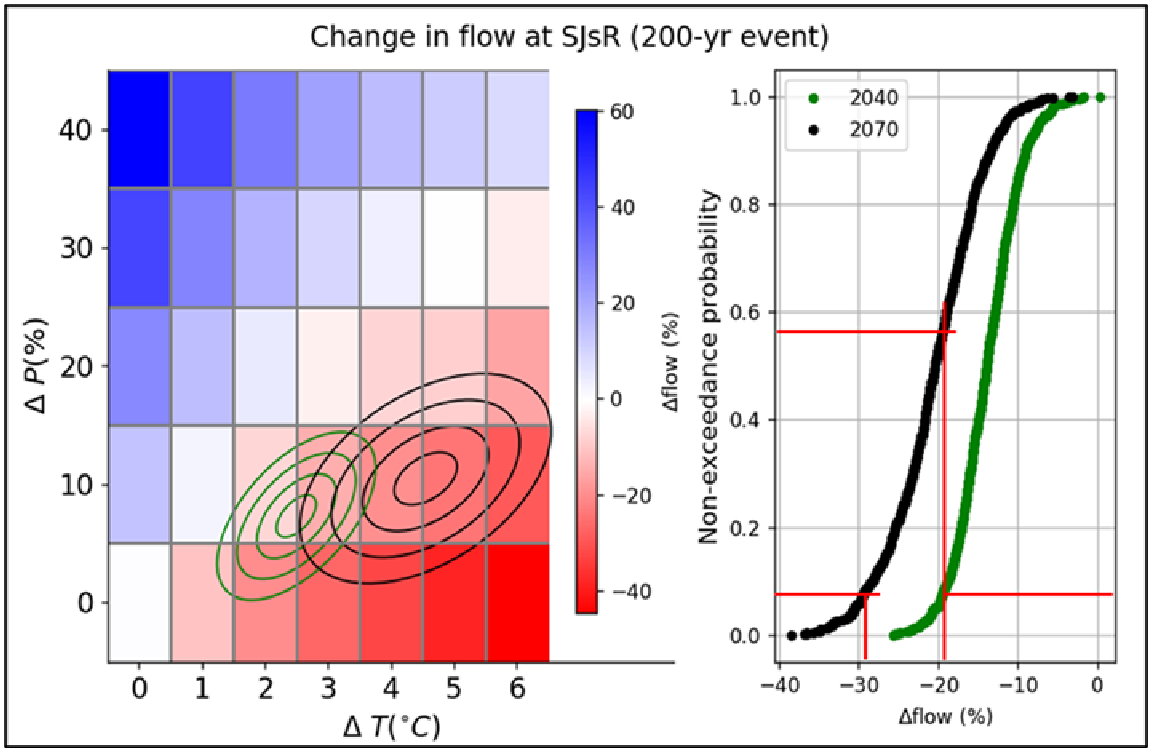

Figure 7-6. Plausibility of a reduced 200-year flood peak in Saint-Jean-sur-Richelieu.

8 PRELIMINARY ASSESSMENT OF PROPOSED MEASURES

8.1 DECISION MAKING PROCESS

The Study Board developed seven decision criteria to evaluate the proposed measures. The decision criteria applied were:

1. **Within study scope and mandate**: Must be a moderate structure, not an instream dam that regulates the full flow range of flows, which has not been implementable in previous IJC references. This criterion is based on the IJC directive and guidance as to what qualifies as a moderate structure.

2. **Technically viable**: The design must be technically sound and apply proven engineering practices and methodologies. It must provide water level relief that is commensurate with the level of investment.

3. **Economically viable**: This is primarily based on the results of a Benefit/Cost analysis, with a ratio of greater than one to be considered an economically viable investment.

4. **Environmentally sound**: The measure increases environmental benefits, or as a minimum, limits detrimental impacts. It protects or restores ecosystem services. This assessment is based on a suite of environmental performance indicators, where results are based on the deviation from the current baseline conditions.

5. **Equitable and fair**: The solution broadly benefits society and not just a particular group or interest (e.g., urban vs rural). It does not result in transferring any disproportionate negative impacts to another interest. The evaluation is based on a suite of social, indigenous and other performance indicators.

6. **Resilient to climate change**: The measure works about as well as or better than other structural solutions across a wide range of possible future climatic scenarios. Decision scaling analysis results based on input from four different methodologies on future climate are used to determine climate change resilience.

7. **Implementable**: This assessment is based on the documented support for a structural solution, metrics from surveys and interviews, feedback on study presentations and discussions with key stakeholders and government representatives. This criterion is incomplete at this stage of report writing and will be assessed after all consultations have been completed.

A preliminary assessment was undertaken by the Study Board using the existing Study information to determine if a measure met the criteria. This was debated over a number of sessions in order to come to an understanding. In some cases, the scientific and technical information was clear; in others, it was less clear or qualitative in nature, but a judgement was still made. These results were needed to undertake the various consultations and provide direction on where the Study was leaning in terms of proposing a structural solution. Based on the feedback received, the Study Board will revisit the decision framework results and revise accordingly in the final Study report. The outstanding criterion, implementable, still needs be assessed based on these consultations and will determine the Study Board's final recommendation.

8.2 EVALUATION OF MEASURES

The Study Board evaluated the three measures and completed its assessment based on the first six decision criteria.

8.2.1 Measure 1

Table 8-1 synthesizes the assessment for Measure 1, selective excavation of the shoal and installation of a submerged weir. The Study Board determined that Measure 1 should be recommended to the IJC as a structural solution that merits consideration by the governments.

Table 8-1. Assessment for Measure 1 Based on decision criteria.

Criteria #	1	2	3	4	5	6	7
Study Board Decision Criteria	Within study scope & mandate	Technically viable	Economically viable	Environmentally sound	Equitable and fair	Climate change resilient	Implementable
	✓	✓	✓	✓	✓	✓	Pending further jurisdictional discussions

The Study Board determined that this measure is clearly within its scope and mandate based on IJC's guidance. It is a moderate solution both in cost and damage reduction (~ CDN$8M/US$6.4M) that focuses on mitigating extreme high and low water levels, with negligible impacts on the rest of the hydraulic regime. As it is a passive structure, it requires no ongoing operational and maintenance costs. This structure was not given consideration in previous references and therefore is a new structural solution being put forward for consideration.

This low technological solution applies basic engineering design, with the excavation of the shoal and using that material to construct a submerged weir to control extreme high and low water levels. It provides a reasonable water level relief of 15.2 cm (6 in) on the river and 10.7 cm (4.2 in) on the lake. This measure has the benefit of raising extreme low water levels on the lake between 7 and 28 cm (2.8-11 in) for the lowest recorded water level year. The engineering design was extensively reviewed by internal and external engineers as being a sound design. The Study Board therefore concluded this to be a technically viable measure.

Based on computed benefits and costing of the solution from this Study, the B/C Ratio for this measure is 10.11; this B/C is very high, making this an attractive solution from an economic perspective. Even if interest rates increase significantly, from 3 to 8 percent, this measure would still be economically viable. The Study Board concluded that this measure is economically viable from this evaluation.

The fact that this measure will return the hydraulic conditions to a more naturalized or hydrologically pristine state was viewed as being positive from an environmental perspective. The environmental PIs indicated the impacts to be primarily negligible; in a couple cases there would be a minor negative impact (submerged vegetation in the upper river and Northern Pike spawning habitat in the lower river). For four of the PIs (Least Bittern nesting and Muskrat habitat in the lake; Northern Pike spawning and waterfowl migration habitat in the upper river), it was determined to be a significant positive impact. There were no cases where a PI produced a significant negative impact. The Study Board recognizes that this is just a preliminary analysis and not a thorough environmental impact assessment, but the Study Board concluded that Measure 1 would appear to be environmentally acceptable.

In terms of being equitable and fair, the Study Board looked at this from a number of perspectives. The benefits accrued by this measure were distributed across the upper reach of the river and lake as indicated by the PI for the number of residences spared. No particular sector, such as agriculture, was negatively impacted. There would be no transfer of any negative impacts to the downstream reach of river.

From an indigenous perspective, this measure is positive in terms of increasing basket-grade black ash habitat in the lake. It also was determined that indigenous archaeological sites would not be impacted with the proposed water level modifications, nor would wild rice production be affected. Based on these evaluations the Study Board determined that Measure 1 is considered to be an equitable and fair solution.

The Study's finding is that a changing climate is expected to result in a general reduction of water levels in Lake Champlain over the 21st century, but mega-floods, similar to or greater than the flood of 2011, are still plausible in the future. It was determined that this measure would be resilient from an operational and structural perspective based on this scenario. The Decision Scaling Report (in preparation) considers how the expected reductions in flood risk would impact the benefit-cost ratios of Measures 1 and 3 and concludes that climate change may reduce the current benefit-cost ratios. However, Measure 1 is still certainly cost-effective.

The last Study Board decision criterion, support for implementation, is the most challenging from the Study Board's perspective. Interviews, surveys, and other feedback suggest that Measure 1 may be socially and politically acceptable. The Study Board will be conducting public, special interests, and governmental meetings to make its final assessment.

8.2.2 Measure 2

Table 8-2 synthesizes the Study Board assessment for Measure 2, a major diversion through the Chambly Canal. The Study Board determined that it is not a viable structural solution, as it did not meet two of its decision criteria, vis-à-vis technical and economic viability.

This measure was determined to be within the Study scope and mandate, as it also focussed on reducing extreme high-water levels and not the full hydraulic regime. This structural solution is the most expensive at around CDN$100M (US$80M), as it focused on maximizing the amount of flow that could be diverted through the canal during the spring freshet. The Study Board determined that this measure can be considered to have met this criterion even though it may be questionable based on the excessive cost. This may also be considered a new structural proposal as the 1970s IJC reference did not fully explore this structural solution until late in their work and only a modest field test was conducted in 1979, when a flow of ~65 m^3/s (2,295 ft^3/s) was routed through the canal for a brief period.

Table 8-2. Assessment for Measure 2 based on decision criteria .

Criteria #	1	2	3	4	5	6	7
Study Board Decision Criteria	Within study scope & mandate	Technically viable	Economically viable	Environmentally sound	Equitable and fair	Climate change resilient	Implementable
	✓	✗	✗	Not evaluated	Not evaluated	Not evaluated	Not evaluated

The Study worked closely with Parks Canada in the design of a significant diversion through the canal. A design flow of ~ 400 m^3/s (~14,000 ft^3/s) was calculated to be the upper limit of flow, and the supporting modifications to the canal built upon this flow. This measure provides a higher water level relief than the other two measures, with a flood level reduction of 34.3 cm (13.5 in) on the river and 22.1 cm (8.7 in) on the lake. The hydraulic modeling determined that the diversion would create extremely high velocities, about 3 m/s (9.8 ft/s), in the canal that would require extensive armouring of the canal bed and reinforcing of the walls. Parks Canada raised concerns that this level of modification would impact the historical and cultural perspectives of the canal. Based on these issues, the Study Board did not feel Measure 2 met its criterion for being a technically viable solution.

It became clear that given the high costs associated with this measure, the benefits would need to be large in order to make this measure cost effective. Rather than spend time and resources on optimizing an operating plan, the benefits were computed based on a perfect forecast that produces the theoretical maximum benefits. This resulted in a B/C Ratio of 0.97. However, that number is inflated, as any realistic operating plan would result in a lower B/C, thus making this measure not economically viable.

Since the Study Board determined that Measure 2 did not meet two key criteria (technically and economically viable), the Board did not feel it was necessary to continue to evaluate the remaining criteria.

8.2.3 Measure 3

Table 8-3 synthesizes the assessment for Measure 3, a modest flow diversion through the Chambly Canal and selective excavation of the shoal with installation of a submerged weir. The Study Board decided that Measure 3 should be recommended to the IJC as a structural solution that merits consideration by the governments.

Table 8-3. Assessment for Measure 3 based on decision criteria.

Criteria #	1	2	3	4	5	6	7
Study Board Decision Criteria	Within study scope & mandate	Technically viable	Economically viable	Environmentally sound	Equitable and fair	Climate change resilient	Implementable
	✓	✓	✓	✓	✓	✓	Pending further jurisdictional discussions

The Study Board determined Measure 3 to be within the Study scope and mandate, as it also focused on mitigating only extreme high and low water levels, and not the full hydraulic regime. This solution combines hydraulic benefits from Measure 1 with a modest flow diversion of ~ 80 m^3/s (~2,800 ft^3/s) to provide additional limited high-water relief. The cost of Measure 3 is about CDN$21M (US$16.8M). The separate cost for the modest flow diversion was about CDN$13M (US$10.4M). This is considered a new solution that has not been explored before.

This solution provides a higher water level relief than Measure 1, with water level reductions of 22.3 cm (8.8 in) on the river and 15.2 cm (6.0 in) on the lake. The relief to low water levels is the same as Measure 1. Measure 3 was determined to be technically viable by the Study Board. This was because the modest flow diversion would require fewer major structural modifications to the canal and the heritage aspects of the canal would not be compromised. Measure 1, which is incorporated in this measure, was determined to be technically viable.

A simple operating plan that is triggered at a specific water level on the river to open and close the canal was used to determine the hydraulic relief that would be obtained. This, in turn, was used to compute the benefits that would be achieved. The B/C Ratio for Measure 3 was computed to be 3.96 and is still economically viable if interest rates increase from 3 to 8 percent. The Study Board determined the economic viability criterion was met. The Study Board recognized that much of the benefit would be achieved from building on Measure 1, and the cost of the additional relief is greater. Measure 3 does, however, provide additional flood relief, making it an appealing measure.

The environmental impacts are like that of Measure 1, as the flow diversion through the canal is small. Therefore, the Study Board determined that Measure 3 is also environmentally viable.

Again, Measure 3 produced comparable results as Measure 1 and therefore also is considered to meet the equitable and fair criterion.

The Study's finding is that a changing climate may result in a general reduction of water levels in Lake Champlain, but mega-floods are still plausible in the future. It was determined that this measure would be resilient from an operational and structural perspective based on this scenario. A Benefit/Cost analysis based on this scenario suggested that this measure will continue to be economically viable, but less so. As noted, Measure 1 was determined to be climate change resilient. The structural integrity of the canal diversion portion of Measure 3 would not be compromised with larger floods, as it is offset to the main channel. Any major floods would be further mitigated accordingly and further justify the capital outlay.

The last Study Board decision criterion, support for implementation, is the most challenging from the Study Board's perspective. Interviews, surveys, and other feedback suggest that this Measure 3 may be socially and politically acceptable. The Study Board will be conducting public, special interests, and governmental meetings to make its final assessment.

9 SUMMARY AND PRELIMINARY RECOMMENDATION ON A STRUCTURAL SOLUTION

A broad range of potential structural and non-structural solutions were identified in the Study's initial evaluation, which were then narrowed down to focus on three measures not previously explored in past IJC references. These three measures were evaluated using extensive data, models and innovative tools developed by the Study to assess their performance and associated impacts. The three measures are:

- Measure 1: Selective Excavation of the Saint-Jean-sur-Richelieu Shoal and Installation of a Submerged Weir.
- Measure 2: Major Flow Diversion through the Chambly Canal.
- Measure 3: Modest Flow Diversion through the Chambly Canal and Selective Excavation of the Saint-Jean-sur-Richelieu Shoal with Installation of a Submerged Weir.

The Study Board evaluated each measure as to whether it passed the Study Board's decision criteria:

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

The last decision criterion (implementability) remains to be assessed. The outcome of consultations underway with the jurisdictions, stakeholders and public will be used to determine the political and social acceptability of a proposed structural solution.

Measure 1, selective excavation of the Saint-Jean-sur-Richelieu shoal with installation of a submerged weir was determined to be a very viable structural solution. It met all the Study Board's decision criteria that were evaluated. It is a passive structure that is not very costly (~ CDN$8M or US$6.4M) and it brings the hydraulic regime closer to a more natural or pristine state, while providing significant benefits. It is an extremely cost-effective structural solution with a Benefit/Cost ratio of 10.11. This measure provides water level relief for both high and low water levels, on the order of 15.2 cm (6 in) on the river and 10.7 cm (4.2 in) on the lake for high water levels using the 2011 flood as a reference. It would raise extreme low water levels on the lake between 7 and 28 cm (2.8-11 in), based on the lowest water year on record (1964/65).

Measure 2, a major flow diversion through the Chambly Canal, was determined not to be a viable structural solution. It did not pass two of the Study Board's decision criteria. It was determined to not be technically viable, as the modifications required would impact the heritage and physical integrity of the canal. To address the high-water velocities associated with the diversion would also add to the already high cost of the project (~CDN$100M or US$80M). It was determined not to be economically viable, with a Benefit/Cost Ratio of < 1, even when applying a perfect forecast to determine the benefits. This structural solution would provide more high-water relief than the other two measures at 22.3 cm (8.8 in) on the river and 15.2 cm (6.0 in) on the lake. However, it would not provide any low-water relief, which is an important feature of the other two measures.

Measure 3, modest flow diversion through the Chambly Canal and selective excavation of the Saint- Jean-sur-Richelieu shoal with installation of a submerged weir, was also determined to be a viable structural solution. As for Measure 1, it met all the Study Board criteria. The cost of this measure is higher, CDN$21M (US $16.8M), but it provides additional benefits. It also was determined to be cost-effective with a Benefit/Cost ratio of 3.96. It would provide a higher water level relief of 22.3 cm (8.8 in) on the river and 15.2 cm (6.0 in) on the lake, and provide the same low-water relief as Measure 1. This measure has the advantage that flood relief can be provided through two approaches, providing additional flexibility to manage floods.

It is important to note that this Study provides a proof-of-concept with regards to a structural solution. If the governments do decide on further studies, then these two measures would be the starting point for more detailed analysis in which both the formulation and evaluation would continue. Formulation options could include the investigation of different weir configurations, excavation quantities and locations, materials for construction, and different rules for opening and closing the diversion. The rules for Measure 3 could be modified, taking some risks by opening the diversion more often while developing hedging strategies to limit undesirable impacts from low water levels if actual net basin supplies are less than forecast. Evaluations would be broadened to include legal requirements by the implementing government, additional physical investigations such as geotechnical borings, and a formal environmental analysis and public review.

The Study Board's role is to provide its recommendations to the International Joint Commission (IJC), in this case regarding potential structural and non-structural solutions to mitigate flooding in the basin. The IJC may take the Study Board's recommendations and may further contribute own observations through hearings and advise the federal governments as to their findings. The Canadian and United States governments determine whether to proceed with the implementation of a structural solution in this binational basin. This decision will involve the federal governments consulting with province of Quebec, and the states of Vermont and New York.

The Study Board drafted a recommendation that supports Measure 1 and Measure 3 as both viable structural solutions for consideration and used it to focus its consultations with the jurisdictions, stakeholders and public. The preliminary recommendation is:

"The Study Board recommends the IJC advise governments that it is possible to achieve a modest relief of flood (on the order of 10 cm on the Lake and 15 cm at Saint-Jean-sur-Richelieu for an event like the 2011 flood) and drought water levels by returning the hydraulic regime at the Saint-Jean-sur-Richelieu shoal to a more naturalized hydraulic state. This can be achieved by removing some flow-impeding human artifacts in addition to some selected excavations of the shoal and installing a submerged weir in the area of the Saint-Jean-sur-Richelieu shoal. From the Study's evaluation of the proofs of concept, this moderate structural solution is technically feasible, economically beneficial, and socially acceptable. Also, based on the Study's analysis with environmental performance indicators it appears that the structural solution has positive environmental impacts and no significant negative environmental impacts."

The preliminary recommendation was refined, and the final recommendation was included in the Study Board report to the International Joint Commission, released in August 2022.

REFERENCES

Brown, G. L., 2012. Decision Scaling: Linking Bottom-up Vulnerability Analysis with Climate Projections in the Water Sector. Water Resources Research, vol 48.

Comité Ad Hoc Bureau International Champlain-Richelieu (CAHBICR), 1979. Chambly Canal Flow Diversion Trial, April 1979. Transmitted by the Canadian section to Environment Canada, Planning and Water Management Branch on November 8, 1979.

Crump, E.S., 1952. "A new method of gauging stream flow with little afflux by means of a submerged weir of triangular profile". Proc Institution of Civil Engineers. 1: 749–767.

Flood Management and Mitigation Measures Technical Working Group (FMMM), 2022. Flood Management and Mitigation Measures Technical Working Group (FMMM), 2022. Documentation of the LCRR Collaborative Decision Support Tool, prepared for the Study Board of the International Joint Commission Lake Champlain and the Richelieu River Flood Study, 42 pp.

Flood Management and Mitigation Measures Technical Working Group and Hydrology, Hydraulics, and Mapping Technical Working Group (FMMM/HHM), 2021. Potential Structural Solutions to Mitigate Flooding in the Lake Champlain-Richelieu River Basin. International Lake Champlain – Richelieu River Study. A report to the International Joint Commission. https://ijc.org/en/lcrr/potential-structural-solutions-mitigate-flooding-lake-champlain-richelieu-river-basin.

François, B. and C. Brown, 2022. An analysis of the impacts of climate change on flooding and flood management decisions for the shores of Lake Champlain and shorelines of the Richelieu River, Report prepared for International Lake Champlain-Richelieu River Study Board, 66 pp.

IBI Group, 2015. Benefit/Cost Analysis for Flood Mitigation Projects for the City of Calgary: Springbank Off-Stream Flood Storage, report submitted to the Government of Alberta, 61 pp.

International Champlain-Richelieu Board, 1977, Technical Report of the Physical Aspects Committee, Regulation of Lake Champlain and the Upper Richelieu River, Report prepared for the International Joint Commission, 117 pp.

International Champlain-Richelieu Board, Ad Hoc Committee 1979, Chambly Canal Flow Diversion Test, Report prepared for the International Joint Commission, 44 pp.

International Joint Commission, 1981, Regulation of the Richelieu River and Lake Champlain, Report by the IJC to the Governments of the US and Canada, 40 pp.

International Joint Commission, 2017, A Climate Change Guidance Framework for IJC Boards; https://ijc.org/sites/default/files/IWI_CAWG_2017_02.pdf.

International Joint Commission, 2017, Final Work Plan of the International Lake Champlain-Richelieu River Study Board, IJC Letter to the Governments of the US and Canada, 144 pp. Final Workplan of the International Lake Champlain-Richelieu River Study Board (Work Plan) | International Joint Commission (ijc.org).

International Lake Champlain-Richelieu River Study Board, 2019. The Causes and Impacts of Past Floods in the Lake Champlain-Richelieu River Basin, Report to the International Joint Commission.

Net Benefits Committee, 1977. Regulation of Lake Champlain and the Upper Richelieu River, Technical Report to the International Champlain - Richelieu Board, 130 pp.

Ouarda, T.B.M.J. and Charron, C., 2019. Frequency analysis of Richelieu River flood flows, Lake Champlain flood level and NBS to the Richelieu River basin. Report prepared by Institut national de la recherche scientifique (INRS), Centre – Eau Terre Environnement for the Lake Champlain – Richelieu River Study.

Roy, M., Bachand, M., Maranda, A., Gosselin, R., Thériault, D., Poirier, G., Champoux, O., Fortin, N., Hennebert, A., Marcotte, C., Oubennaceur K., Blanchet, E., Treyvaud, G., Gagnon, A., Thomas, I., Morin, J. 2022. Evaluation of Structural Flood Mitigation Measures Using Performance Indicators: Lake Champlain Richelieu River Study. Hydrodynamic and Ecohydraulic Section, Environment and Climate Change Canada, Québec City.

Social, Political and Economic (SPE) Analysis Group, 2022. Social, Political and Economic group – Integrative Report, Report prepared for International Lake Champlain-Richelieu River Study Board, 102 pp. (in preparation).

Social Political and Economic (SPE) Analysis Group, 2022. Economic Analysis of Structural Measures in the Chambly Canal, Report prepared for International Lake Champlain-Richelieu River Study Board, 164 pp (in preparation).

Thériault, D., Champoux, O, and Morin, J., 2022. 200 Years of Anthropogenic Changes in the Upper Richelieu River, Technical report prepared by the Hydrodynamics and Ecohydraulic Section, National Hydrological Service, Environment and Climate Change Canada. Prepared for the International Lake Champlain – Richelieu River Technical Working Group, 74 p. https://ijc.org/en/lcrr/200-years-anthropogenic-changes-upper-richelieu-river.

Werick, B., 2022. A Strategy for Addressing Climate Uncertainty Affecting Lake Champlain-Richelieu River Flooding. International Lake Champlain-Richelieu River Study. A Report to the International Joint Commission. https://ijc.org/en/lcrr/strategy-addressing-climate-uncertainty-affecting-lake-champlain-richelieu-river-flooding.

U.S. Army Corps of Engineers, 1996. Risk-Based Analysis for Flood Damage Reduction Studies, Engineering and Design, EM 1110-2-1619, 63 pp.

Zhou, R.D., Donnelly, C.R. and Judge, D.G., 2008. On the Relationship Between the 10,000 Year Flood and Probable Maximum Flood, Paper presented at the HydroVision Conference 2008, Paper No. 131. 16 pp.

INTERNATIONAL JOINT COMMISSION • COMMISSION MIXTE INTERNATIONALE
1909