Integrated Social, Economic and Environmental System (ISEE)

International Lake Champlain - Richelieu River Study

A REPORT TO THE INTERNATIONAL JOINT COMMISSION

Submitted by

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December 2022

ACKNOWLEDGMENTS

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

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We would like to acknowledge the support from Lake Champlain Richelieu River Study members through the course of this ambitious project. We especially want to thank Bill Werick, Syed Moin and Ted Yuzyk of the Flood Management and Mitigation Measures Technical Work Group for their insights. We also want to thank Perry Thomas and Rose Paul, who successively assumed the role of United States Resource Response Co-lead, and Matthew Kraft for their participation to the selection of performance indicators in the early stage of the Study. We are also grateful to Study managers Serge Villeneuve, Serge Lepage, Maryse Sohier, Robert Flynn and Mae Kate Campbell for their administrative and coordination efforts. Also, we want to thank Study Co-Chairs Deborah Lee and Jean-François Cantin and the LCRR Study Board for their support.

EXECUTIVE SUMMARY

Following the spring 2011 flood in the Lake Champlain Richelieu River (LCRR) basin, the governments of Canada and United States mandated the International Joint Commission (IJC) to examine the causes of flooding and to recommend solutions to attenuate the impacts of future floods. The IJC established the International LCRR Study Board to identify and evaluate solutions to mitigate flooding in the basin.

To evaluate flood mitigation alternatives, the LCRR Study developed the Integrated Social Economic Environmental (ISEE) system, an integrated modelling platform designed to quantify the benefits and drawbacks of alternatives using Performance Indicators (PIs). This report describes the technical features of the ISEE system, with a particular focus on its components and functioning.

An integrated modelling framework allows coupling of models from different disciplines to support a comprehensive assessment of complex natural resource management aspects using a consistent methodology across the social, economic and environmental components. The LCRR ISEE system has its origins in the 2D Integrated Ecosystem Response Model (IERM2D), which has shown its usefulness in evaluating the environmental impacts of water regulation plans in previous IJC studies. In the LCRR study, the ISEE system was used to evaluate the potential impacts of three structural flood mitigation alternatives: a flow diversion through the Chambly Canal, a selective excavation with a submerged weir, and the latter combined with an additional minor diversion through the canal.

The ISEE system uses a geo-referenced database and a collection of open-source Python scripts to model PIs in aquatic and riparian areas to evaluate scenarios over time to account for the long term hydrological variability. ISEE relies solely on free open-source Python libraries facilitating migrations, updates, sharing and collaboration with partners and organizations.

The ISEE system simulates hydraulics and estimates the impacts of water level variations using various PIs developed through a collaboration with experts from several fields. To do so, it incorporates water level time-series at several key locations provided by the LCRR Water Balance Model. These water levels are used as inputs to create hydraulic maps (water level, velocity) by interpolating 2D hydrodynamic data layers (hydrodynamic scenarios). The ISEE interpolation engine is designed to recreate the complex and distinct hydraulics of the different sections of the water body while considering the seasonal variation in plant growth and ice cover, the input of local tributaries, the management of the Saint-Ours dam and a backwater effect of the St. Lawrence River. The ISEE system can simulate hydraulic maps projected on a 10 m resolution grid covering 2,500 km^2, with levels associated to extreme low to extreme high flows (25-2500 m^3/s). Hydraulic maps are in turn cross-referenced to numerous geospatial datasets, (e.g. building elevation, slopes, bed substrate, land use, vegetation class) to calculate performance indicators (PIs).

PIs are based on mathematical response functions estimating the response of social, economic and environmental components to flood mitigation and variations in water level. The ISEE system contains 29 PIs addressing diverse components such as social risk, flood damage and income loss attenuation to the residential, commercial and recreation sectors, agricultural yield loss, wetland class area and habitat area of key species and endangered fish and wildlife species. These PIs are analysed by comparing results obtained under mitigation scenarios to a baseline scenario (state of reference). ISEE provides results as maps illustrating the spatial distribution of impacts or benefits, for specific high or low flow events, or for the average of a long period representative of the natural hydrological variability.

The last section of this report presents a technical description which aims at providing required information to handle and run the ISEE system files.

THE INTERNATIONAL JOINT COMMISSION

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

FIND OUT MORE ABOUT THE STUDY

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

Email lcrr@ijc.org

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

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1 INTRODUCTION

In the spring of 2011, the Lake-Champlain-Richelieu River (LCRR) region suffered extreme flooding directly affecting more than 40 communities and thousands of residents had to be evacuated. This flood prompted the governments of the United States and Canada to mandate the International Joint Commission (IJC) to examine the causes of flooding and recommend solutions that would attenuate the impacts of future floods. The IJC established the International LCRR Study Board to identify and evaluate solutions to mitigate flooding in the basin.

To evaluate flood mitigation alternatives, performance indicators (PIs) are required to quantify the benefits and drawbacks on social, economic and environmental components, as well as elements of interest to indigenous communities. Integrative modelling is an ideal approach, as it is a recognized and effective approach to combine the multiple sources of information required to develop PIs with a homogeneous methodology across the study area.

This report presents in detail the integrative modelling platform developed for the LCRR flood study: the Integrated Social, Economic and Environmental (ISEE) system. This system was designed to simulate floods and water level variations and incorporate PIs providing metrics to evaluate flood mitigation alternatives. This report is focused on a description of the ISEE system, including its main components and functioning. For more information regarding PI methodology, see Bachand et al. (2022) and for PI results comparing flood mitigation alternatives, see Roy et al. (2022).

This technical report is organized into the following chapters:

Chapter 1 introduces the Study and its technical components. It provides an overview of integrated modelling systems developed in previous studies, and presents the concept of PIs and the ISEE system.

Chapter 2 presents the geographic context of the Lake-Champlain-Richelieu River (LCRR) study for which the ISEE system was developed. It covers the physical characteristics of the water bodies and the causes of floods. It also briefly describes the mitigation alternatives developed by the Study and their evaluation using the ISEE system.

Chapter 3 provides a functional description of the ISEE system and its modelling components.

Chapter 4 contains a technical description of the ISEE system, of the computer code, data structure and algorithms.

1.1 LCRR STUDY MANDATE

The catastrophic 2011 flood in the LCRR basin was a call to action. In 2013, at the request of the governments of Canada and the United States, the IJC outlined options for addressing flooding and flood management in the basin (IJC, 2013). In 2016, the two governments formally instructed the IJC to “fully explore the causes, impacts, risks and solutions to flooding in the Lake Champlain-Richelieu River basin.” The IJC established the LCRR Study Board to oversee the Study and provide recommendations. The Study was undertaken through an international collaborative approach involving individuals from federal, state and provincial resource management agencies and academia, with expertise in flood management, planning and mitigation. The Study was led by a Study Board with representation from Canada and the United States.

The main objective of the Study was to recommend structural and non-structural alternatives to mitigate flooding and flooding impacts in the Lake Champlain-Richelieu River basin. Potential alternatives to be considered include moderate structural modifications, such as weirs and channel enhancements, and non-structural approaches, such as land use regulations, building adaptation, floodplain management and protection and/or creation of wetlands. To assist in its decision making, the International LCRR Study board decided to invest in the development of an integrative tool for the assessment of impacts on resources. The integrated modelling system developed by the study was called the ISEE System.

1.2 INTEGRATED MODELLING OVERVIEW

An integrated modelling framework allows coupling of models from different disciplines to support a comprehensive assessment of social, economic and environmental aspects of complex natural resource management (Ratna Reddy et al. 2015). The approach captures the strengths of each model (e.g., integrating a hydrodynamic model developed by hydraulicians, economic damage functions developed by economists and habitat models developed by ecologists) (Jørgensen and Swannack, 2019). An integrative approach provides the advantage to analyse various components using a consistent methodology which facilitates interpretation.

An integrative modelling framework is therefore well suited for a flood mitigation study, in which numerous response models (social, economic and environmental models) are dependent on physical models simulating the effects of mitigation alternatives. In this study, the ISEE system combines a water balance model (WBM) providing water supply time-series, 2D hydrodynamic simulations providing water levels and currents maps across the full range of flow stage, and a precise digital elevation model (DEM). It also gathers numerous geospatial data layers describing the physical, socio-economic and environmental components of the entire Richelieu River and Lake Champlain basin, as well as various response functions. The data and models are stored in a single format in a common directory.

The tool allows the calculation of PI metrics to assess flood mitigation alternatives using available historical water supply time-series at a quarter-monthly time step. Those metrics are calculated for each proposed mitigation alternative and compared to a baseline condition (state of reference).

Integrated modelling accounts for the spatial distribution of phenomena, which is of key importance in a flood study, in order to identify where flood impacts occur, where mitigation alternatives provide flood relief and where environmental impacts occur. The results can be presented in various ways, including as maps displayed in a GIS. However, large scale spatially distributed modelling comes with the challenge of handling large datasets. Furthermore, covering a large study area and a high number of components with integrated models tends to come at the expense of some analytical precision. Therefore, integrated modelling systems are best suited to evaluating and exploring alternative scenarios or policies (Peterson, 2005) such as in this study.

1.3 PREVIOUS INTEGRATED MODELLING SYSTEMS

Integrated modelling systems were developed by ECCC in other IJC studies in several transboundary basins, but also for local water bodies, to address local and regional water resources issues (Figure 1.3.1).

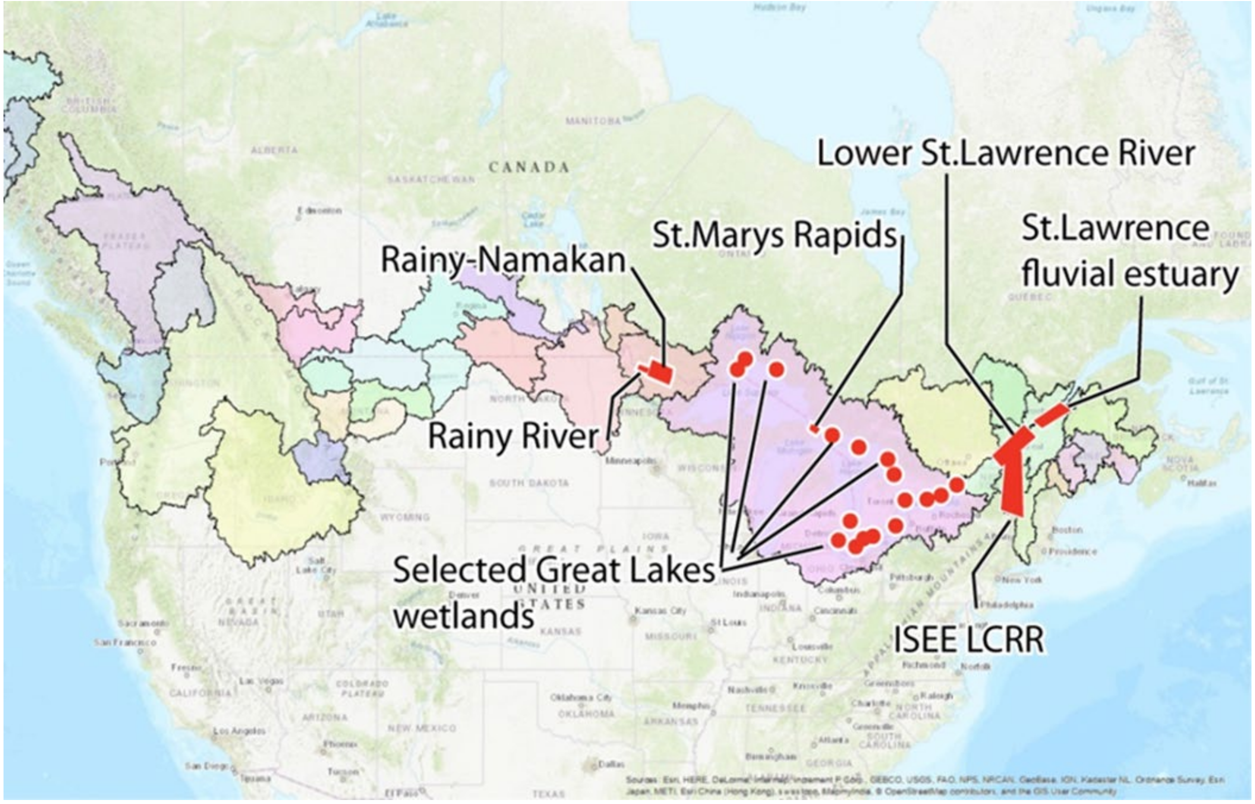

Figure 1.3.1. Red areas denote Integrated modelling systems previously developed in selected watersheds

The ISEE system takes its origin from the 2D Integrated Ecosystem Response Model (IERM2D), developed to evaluate environmental impacts of water regulation plans for the IJC Lake Ontario-St. Lawrence River study (LOSLR) (Morin and Champoux 2006). The IERM2D is a two-dimensional model covering the study area and integrating hydrodynamic data, simulated physical variables and biological models. For the LOSLR study, the IERM2D was the main tool to assess the potential environmental impacts of several regulation plans on the Lower St. Lawrence River and the results played a key role in the formulation of the regulation Plan 2014.

An ISEE system was also developed for the St. Lawrence River estuary for assessing the effect of a new bridge on fish communities. Detailed modelling of the estuary, combined with real-time fish radio tracking allowed the integration of a deep-learning application into fish habitat models (Guénard et al. 2020).

The ISEE system is also based on the 2016 Rainy-Namakan chain of lakes study. The IERM of the Rainy-Namakan lakes and Rainy River was deployed to assess the impacts of water-level changes on key components of the ecosystem. The IERM contributed to the development of new lake level Rule Curves, the 2018 Rule Curves (Morin et al., 2016a, 2016b; Bachand et al 2017b).

The St. Marys Rapids (outlet of Lake Superior) IERM is another building block for the ISEE system. It was developed to assess the impact of the control gate opening scenarios on the quality of spawning habitat of four aquatic species known to use the St. Marys Rapids to spawn (Bachand et al., 2017a). This IERM incorporated hydrodynamic modelling carried out by USACE and high-definition drone imagery of the St. Marys rapids used for substrate mapping by artificial intelligence. Modelling results provided important information for optimizing gate management.

More recently, an ISEE system was built for assessing the long term change in wetland vegetation on the Canadian Great Lakes. This system, called the Coastal Wetland response Model (CWRM), is able to reproduce the historical observed changes in coastal wetlands in term of large wetland classes and the evolution of two invasive plants: Cattail and Phragmites. The main results from this development were the application of climate change time-series and their effect on wetland resilience and vulnerability (ECCC, 2022).

2 LAKE CHAMPLAIN AND RICHELIEU RIVER STUDY CONTEXT

2.1 THE LCRR STUDY AREA

Lake Champlain is a natural freshwater lake with a north-south main orientation, located between the Adirondack Mountains on its western shore (New York) and the Green Mountains on its eastern shore (Vermont), part of the Appalachian Mountains (Figure 2.1.1).

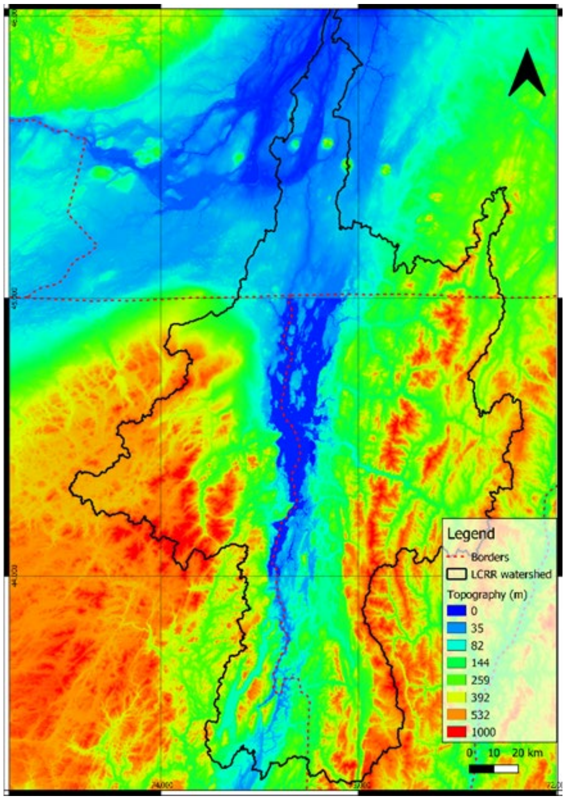

Figure 2.1.1. LCRR Watershed topography.

Like the St. Lawrence Valley, Lake Champlain was part of the Champlain Sea created by the retreat of the glaciers at the end of the last ice age. It is relatively deep in its western portion, with a maximum depth of about 120 m and an average depth of 19.5 m. In contrast, the eastern and northern parts are shallower and contain large islands, connected by artificial causeways, which create various basins whose water levels can vary from the main body of water under particular wind conditions.

The shores of the lake were settled by various Indigenous communities before colonial times, and today the cities of Burlington (Vermont) and Plattsburgh (New York) are the main population centres. Approximately 580,000 people live in the US portion of Lake Champlain, while another 25,000 live in the Quebec portion around Missisquoi Bay.

The lake level usually varies between 29 and 30 m (NAVD88), but high water level events at around 31 m can occur sporadically and cause flooding and damage on both sides of the border.

The Richelieu River is the outlet of Lake Champlain and connects it to the Atlantic Ocean via the St. Lawrence River. It is about 124 km long and its average flow is 330 m³/s. The topography of the area is shown in Figure 2.1.1 and the elevation profile of the river is illustrated in Figure 2.1.2.

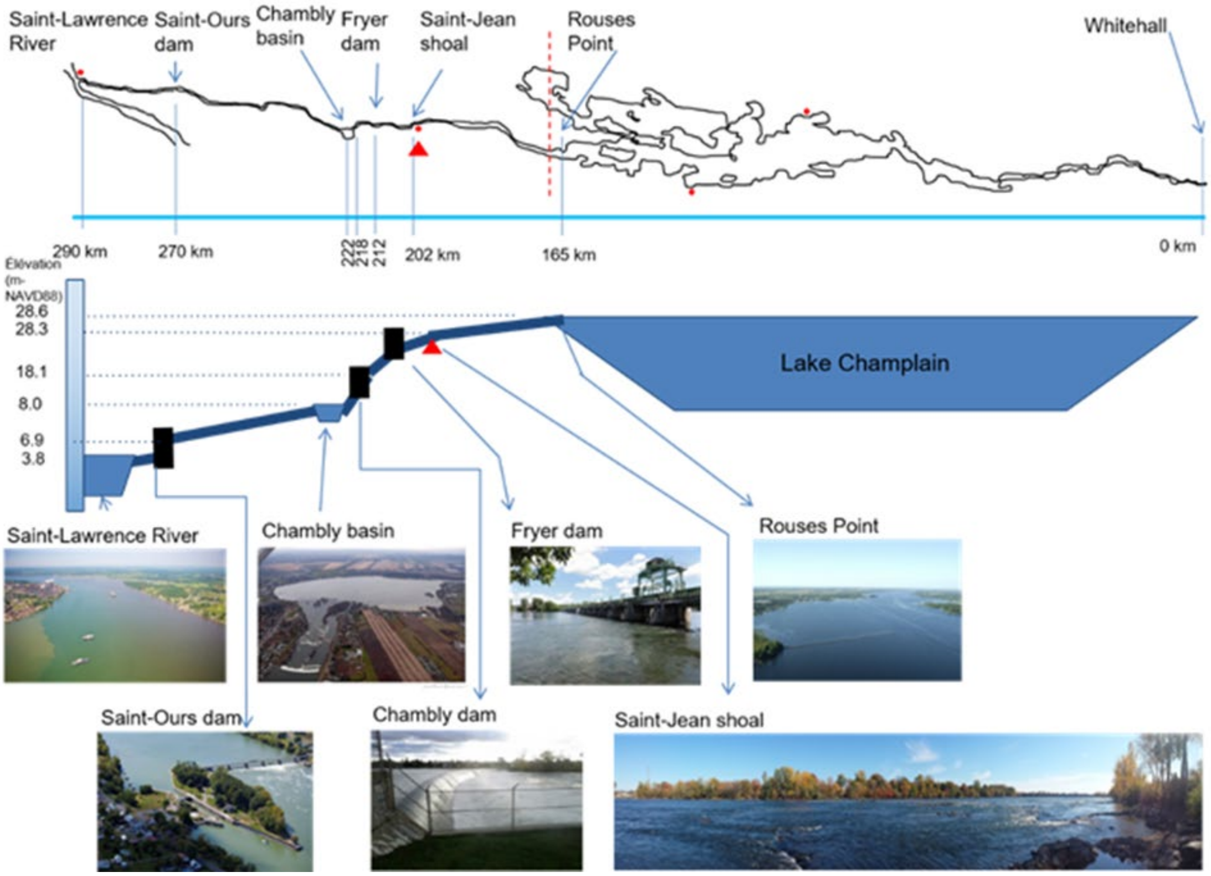

Figure 2.1.2. Schematic altimetry profile with structures and key morphological features. Water flows from Right to left.

The river can be divided into three sections (Figure 2.1.3) with distinct hydrodynamic characteristics. First, the 'Upper Richelieu' sector is located between Lake Champlain and Saint-Jean-sur-Richelieu. This reach is 35 km long, characterized by a very low gradient (0.3 m) and large floodplain, which can occasionally connect to Missisquoi Bay during extremely high water level conditions. This portion of the river is frequently flooded in the spring. To some extent, it can be considered an extension of Lake Champlain due to its very low slope and water levels similar to those observed in the lake under average flow conditions. This area includes several municipalities that were the most severely impacted by flooding in 2011, including Lacolle, Saint-Paul-de-l'Île-aux-Noix, Saint-Blaise-sur-Richelieu, Henryville and Saint-Jean-sur-Richelieu.

The second section, the 'Chambly Canal' sector (12 km long) is located between the cities of Saint-Jean-sur-Richelieu and Chambly. It presents a significant drop in water level, as this section contains the more significant rapids of the river, the Saint-Jean-sur-Richelieu and Fryer Island rapids (Figure 2.1.3). The Saint-Jean rapids is the natural control point for the water level of Lake Champlain, which makes it an area of particular interest. In this area, the Chambly Canal was built to bypass the rapids and allow the navigation of barges between the province of Quebec and the state of New York. This is the most populated area of the river and has undergone multiple channel alterations since the 1800s that have directly influenced the water level observed upstream (Gosselin et al, 2022; Thériault et al., 2021).

The third section is the 77 km long 'Lower Richelieu' reach located between the towns of Chambly and Sorel-Tracy (Figure 2.1.3). Except for a steep slope break at Saint-Ours where a dam is regulating the water level for recreational navigation, the overall slope is relatively low and similar to the one found in the Upper Richelieu. However, in this area, the floodplain is restricted, as the channel is located in a shallow canyon with relatively steep banks. Consequently, this area has a lower vulnerability to flooding. However, the northernmost portion of the river is strongly influenced by the water level of Lake Saint-Pierre and by the flow of the St. Lawrence River. In the most extreme cases, the backwater effect of the St. Lawrence River level on the Richelieu River level can be observed up to the Chambly Rapids.

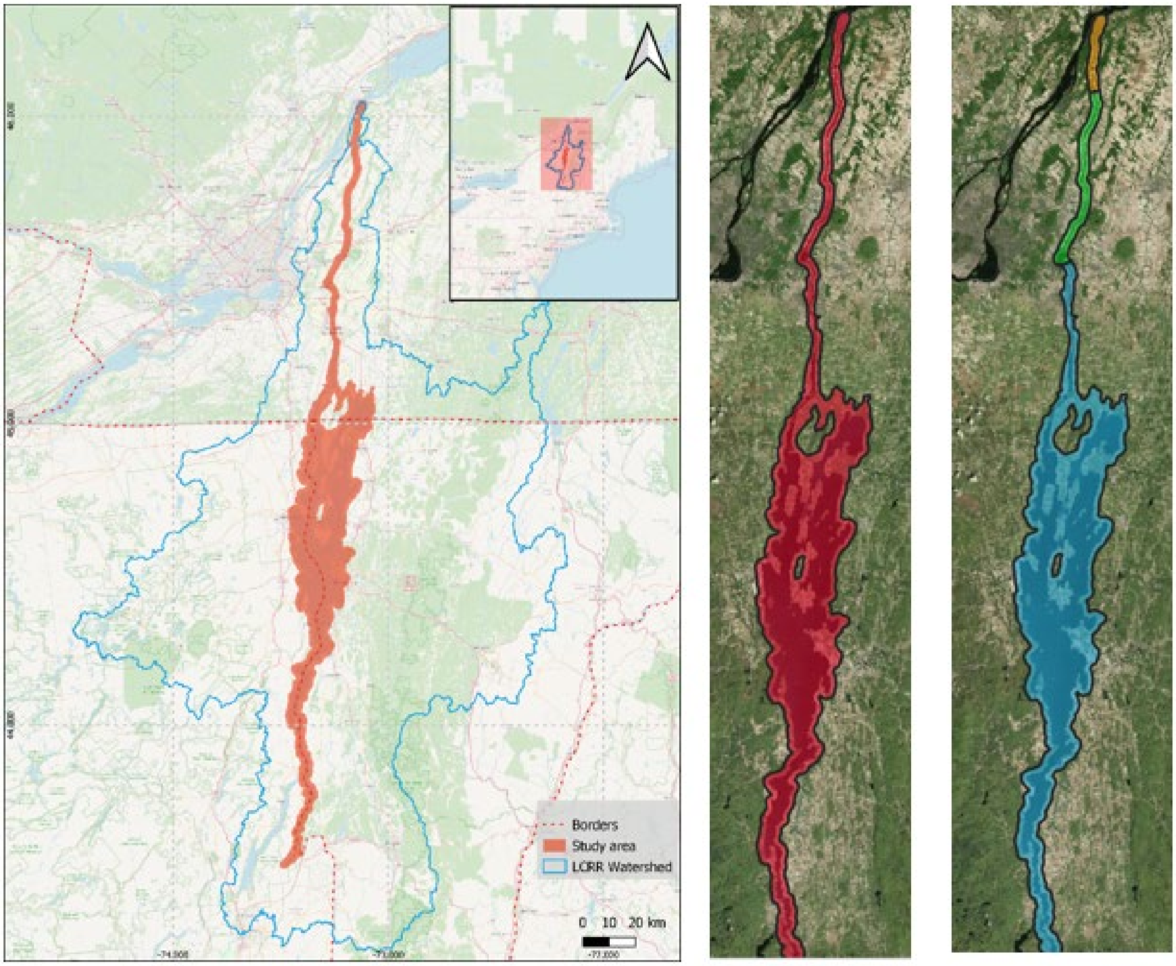

Figure 2.1.3. (Left) Study area in the LCRR Watershed. (Center) Study area in red. (Right) Representation of the LCRR basin sections (Blue: Lake Champlain and Richelieu River upstream of the Chambly Dam, Green: Chambly to Saint-Ours Dam, Orange: Saint-Ours dam to St. Lawrence River).

2.2 CAUSES OF FLOODING IN THE LCRR BASIN

The LCRR basin is vulnerable to flooding. In the past 90 years, severe floods have occurred several times. Generally, these floods were the results of a combination of rapidly melting snowpack and heavy rainfall in the late winter and spring months (ILCRRSB, 2019). In the spring of 2011, the region experienced flooding beyond anything ever seen in the last 100 years for which flood data are available. The Richelieu River rose above flood stage for more than two months. That year, the confluence of warm temperatures, record spring precipitation and rapid melting of a near-record snowpack caused historically high flood levels in the basin tributaries and in Lake Champlain and the Richelieu River (Saad et al., 2016).

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

2.3 FLOOD MITIGATION ALTERNATIVES

The ISEE system was used during the LCRR Study to evaluate and compare mitigation alternatives. In March 2021, the LCRR Study published the results of a preliminary evaluation of a wide range of structural alternatives to reduce extreme water levels in the Lake Champlain - Richelieu River system (FMMM/HHM, 2021). The alternatives that were then evaluated included structural alternatives from the 1973 IJC reference study, as well as potential alternatives identified from the literature. Following this effort, the Study Board decided that the Study would pursue improvements to the most promising alternatives, then conduct a more in-depth analysis of their benefits and drawbacks through the ISEE system.

The three alternatives that were selected involve alterations of the shoal at Saint-Jean-sur-Richelieu or a flow diversion through the Chambly Canal.

- Alternative 1: Selective excavation of the Saint-Jean-sur-Richelieu shoal with submerged weir
- Alternative 2: Major Chambly Canal diversion
- Alternative 3: Selective excavation of the Saint-Jean-sur-Richelieu shoal with submerged weir and minor diversion through the Chambly Canal

More details on the LCRR proposed alternatives can be found in Roy et al. (2022) and Moin et al. (2022).

3 THE INTEGRATED SOCIAL ECONOMIC ENVIRONMENTAL (ISEE) SYSTEM

3.1 INTRODUCTION

The ISEE system uses a geo-referenced database and a collection of Python scripts to model PIs in aquatic and riparian areas to evaluate scenarios over long periods. It was developed to meet the following objectives:

- Simulating water levels, throughout the year, over a reference period (1925-2017) allowing the quantification of the baseline natural variability, including spring floods and summer low flows, anywhere in the LCRR Study area.
- Quantifying the effects of the mitigation alternatives from a hydraulic perspective throughout the year, with a particular focus on flood relief and low flows.
- Covering the entire study area with similar PIs, where applicable, on both sides of the United States-Canada boundary.
- Integrating high resolution geospatial datasets over a large extent (up to 250k hectares), including flow depths, water velocity, slopes, land use and detailed information such as buildings and crops.
- Modelling the benefits or drawbacks of flood mitigation alternatives on population vulnerability and social risk.
- Quantifying the attenuation of economic damage provided by the flood mitigation alternatives using PIs of structural damage and income loss to the residential, commercial, industrial, recreational, agricultural and public sectors.
- Modelling the benefits and impacts on the natural environment of modifications to the water level regime associated to the flood mitigation alternatives using a selection of PIs representing wetlands and fish and wildlife habitats, including key and endangered species.

The ISEE system framework has its origins in previous studies (e.g. Morin et al. 2016b, Bachand et al. 2017b), but the system architecture and script library were vastly improved to increase computation performance. In addition, ISEE relies solely on free open-source Python libraries, facilitating migrations, updates, sharing and collaboration with partners and organizations.

The ISEE system simulates floods and estimates the impacts of water level variations using various PIs (Figure 3.1.1). More specifically, the WBM provides water level time-series at several key locations based on historical water records of water supply (a). For each time step of the series, water levels are used as input to create a hydraulic map based on 2D hydrodynamic simulations and a precise DEM (b). Flood maps are cross-referenced to numerous geospatial datasets, such as physical layers (e.g. slopes, bed substrate), land use, vegetation class, socio-economic data and building information (c). Then, PIs are calculated based on mathematical response functions (d). PI results can be presented as time-series, expressing the variations of a component over time, for floods of contrasting magnitude (e). PI results can also be presented as maps to illustrate the spatial distribution of impacts or benefits, for a specific high or low flow event, or for the average of a reference period (f).

The components and workflow of the ISEE system

The ISEE system combines multiple models and datasets, with linkages between its different components (Figure 3.1.2).

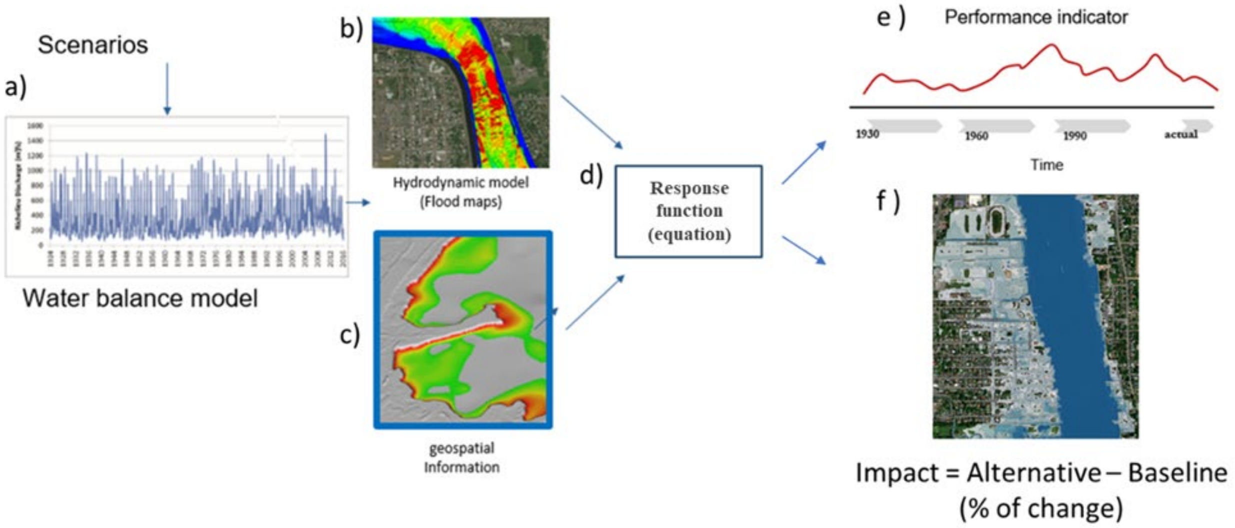

Figure 3.1.1. Overview of ISEE system workflow. a) Water level time-series at several locations for each alternative (water balance model output), b) 2D Hydrodynamic simulations specific to each flood mitigation alternative, c) Geospatial information (physical, biological, land use, social, economic) d) Performance indicators (response functions) estimating flood impacts, e) Output: PI results time-series (aggregated over space) f) Output: PI results Map (aggregated over time). For more detail on each component, see Section 3.2

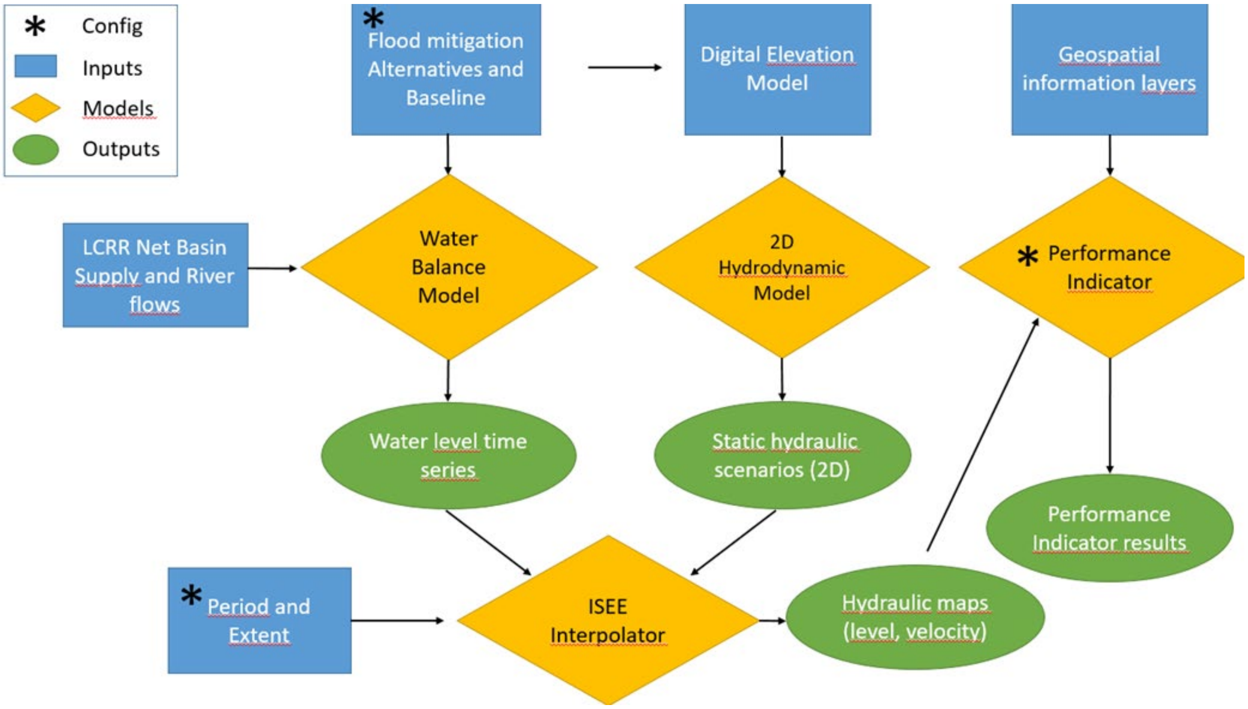

Figure 3.1.2. Conceptual representation of the Integrated Socio Economic Environmental system workflow, including key configuration settings (*), Input data (blue), models (yellow) and outputs (green).

Each run of the ISEE system requires the user to input three key configuration settings (identified as * in Figure 3.1.2):

1. A scenario: baseline or a flood mitigation alternative

   The ISEE system allows a user to select among three flood mitigation alternatives and the baseline scenario. The selected mitigation scenario defines the parametrization for the WBM and for the 2D hydrodynamic model, which together allows creation of hydraulic maps (water depths, velocity) at each time step.

2. A performance indicator

   The ISEE system contains a script library of 32 PIs describing the effect of water level variation on various social, economic and environmental components. Configuring a PI triggers the selection of the required geospatial datasets (e.g. buildings, land use).

3. A period and area of interest

   The ISEE system computes hydraulic maps and PIs over time-series at a quarter-monthly time step, with possible daily time-steps when needed. The user can define computation over a specific period, which can range from a single quarter-month to multiple decades. The default methodology compares alternatives over the reference period (1925-2018), which represents the period for which historical hydrological data was available.

   The area of interest of the computation can also be customized. The extent is primarily defined by the PI being calculated. For instance, the spatial validity of a fish spawning habitat can be restricted to particular areas where conditions are known to be suitable (e.g. rapids). Different PIs can also be applied in Canada and the United States, as they were developed using different methodologies and datasets. For each ISEE run, the area of interest can be defined as a list of grid points belonging to a particular section. Selecting a particular area of interest triggers the appropriate calculations to create hydraulic maps. The ISEE grid is divided into six sections presenting different hydraulic properties. Hydraulic maps are created with either distinct hydrodynamic simulation datasets or interpolation methodologies.

Once the three key configuration inputs are defined, the ISEE system can compute PIs by generating hydraulic maps and combine them to appropriate geospatial data using response functions (e.g. habitat model, damage curve). Figure 3.1.2 presents the workflow of the ISEE system, with its key components, including Inputs, models and outputs.

Technical details on the key components are presented hereafter, including a description of the models, major datasets, and methodology to generate hydraulic maps, performance indicators and output formats.

3.2 WATER BALANCE MODEL

The purpose of the WBM is to provide water level and discharge time-series, based on the net basin supply (NBS) throughout the reference period. The first step to create this model was to produce the historical NBS using the available historical observations of flows and levels in the basin. This NBS represents the historical series of average daily water input to Lake Champlain. It is the main and essential source of input data to reproduce the natural variability in the system. The NBS corresponds to the sum of the variations in lake level (translated into flow values) and the average outflow from the Richelieu River computed on a daily basis, such that:

$$\mathrm{NBS} = \Delta \mathrm{S} + \mathrm{O}$$

where Δ S represents the variation in lake volume and O the outflow from the Richelieu River

The LCRR WBM integrates the effect of the control section at Saint-Jean-sur-Richelieu on Lake Champlain outflows. It allows reproduction of historical water levels at key locations along the water body, namely Saint-Jean-sur-Richelieu, close to the control section, and Rouses Point at the lake outlet, using the NBS as an input. The model is based on the equilibrium of the changes in the volume of the lake and the Richelieu River outflow, and the NBS for the current day. The Richelieu River outflow is based on the stage-discharge relationship presented in Champoux and Morin (2018) and Gosselin et al. (2022) and the WBM was calibrated through an iterative process. For calibration results, see Boudreau et al. (2022).

The WBM was first calibrated and validated using the baseline configuration and historical water level and flow observations from 1973 to 2018. This model was run for the complete reference period (1925-2018) to provide a water level time-series of the baseline scenario. Then, the model configuration was modified to simulate different flood mitigation alternatives. Since the Saint-Jean shoal is controlling the outflow and the water level of Lake Champlain, modifications to the shoal would result in changes in water levels and flows of Lake Champlain and the Richelieu River. Thus, by modifying the stage-discharge relationship to reflect a change in the Saint-Jean-sur-Richelieu control section, it was possible to simulate the change in water levels and flows, based on historical NBS series. The resulting water level and flow time-series obtained for the baseline and for the flood mitigation alternatives later serve as input to the interpolator used to generate 2D hydraulic maps projected on the ISEE grid.

3.3 DIGITAL ELEVATION MODEL

An accurate characterization of land elevation is an essential component of the ISEE system. The hydrodynamic model incorporates elevation information at each node of a finite element grid to calculate accurate water levels and currents. The ISEE system also uses elevation to estimate water depths across the study area at each time step of the reference period. In addition, elevation data are used to derive various terrain attributes such as slope and slope curvature, which are important variables used in several environmental performance indicators.

To obtain coverage of the entire study area, a high-resolution digital elevation model (DEM) was produced from a large set of topographic and bathymetric data sets from several sources in the United States and Canada. Table 3.3.1 lists the main data sources and Figure 3.3.1 illustrates the distribution of datasets used on the study area.

Table 3.3.1. List of bathymetric and topographic data sources used for the LCRR DEM.

Data sources	Acquisition technology	Survey year
BATHYMETRY		
Hydrology and Ecohydraulics Section (HES-ECCC)	Monobeam and RTK survey	2015 - 2019
Canadian Hydrographic Service (CHS)[1]	Multibeam	1981 - 2018
Public Services and Procurement Canada (PSCPC)	Multibeam	2017
Parks Canada (PC)	Survey plan	1966-1971
Various Private Firms	Mono and multibeam	2014, 2019
Manley & *al.*, Middlebury College	Mono and multibeam	2005
Vermont Center for Geographic Information (VCGI)[2] (USA)	Monobeam	1992-2010
National Oceanic and Atmospheric Administration (NOAA)[3] (USA)	Multibeam	2018
TOPOGRAPHY		
Government of Québec[4]	LIDAR	2008, 2013
United States Geological Survey (USGS)[5] (USA)	LIDAR	2012-2017

The floodplain elevation on both sides of the border was characterized with LiDAR (Light Detection and Ranging) data. For all data, the minimum planimetric accuracy was 15 cm. The minimum vertical accuracy was 15 cm on open land and 25 cm on forested terrain, although 80% of the measurement points have a vertical accuracy lower than 6 cm (Géomont, 2011). The density of measurements was higher than 2 points/m^2 in the area north of Saint-Jean-sur-Richelieu, acquired in 2008 (Figure 3.3.1), and higher than 1 point/m^2 in the Haut-Richelieu and Missisquoi Bay region, acquired in 2013.

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[1] The Canadian Hydrographic Service data used and the metadata (survey dates, confidence zone category and measurement techniques) are available on the CHS Digital Data Portal (https://inter-j01.dfo-mpo.gc.ca/registry-registre/).

[2] This data layer includes bathymetric data derived from NOAA nautical charts. The original data released in 1992 did not include information from Mallets Bay north and from the Crown Point Bridge south. VCGI added data for these missing areas in 2003 by taking points from the LCBP data bundle. VCGI also replaced the shoreline points in 2010 using the shoreline as defined in the Vermont Hydrography Dataset (VHD) dataset. https://maps.vcgi.vermont.gov/gisdata/metadata/ElevationDEM_LKCHDEM.htm.

[3] Detailed information about this dataset https://www.ngdc.noaa.gov/nos/D00001-D02000/D00267.html.

[4] The source of the 2008 survey is the ministère des Transports du Québec and the 2013 data was acquired by Géomont (Agence de géomatique montérégienne). This data is made available to the public through the Forêt ouverte service (https://www.foretouverte.gouv.qc.ca/) of the ministère des Forêts, de la Faune et des Parcs. The metadata are available at this link : https://diffusion.mffp.gouv.qc.ca/Diffusion/DonneeGratuite/Foret/IMAGERIE/Produits_derives_LiDAR/metadonnees.zip.

[5] This dataset combines several USGS LIDAR surveys collected between 2011 and 2018. The metadata can be viewed on the USGS website using the 3DEP LidarExplorer (https://prd-tnm.s3.amazonaws.com/LidarExplorer/index.html#/) downloaded using the TNM Download application (https://apps.nationalmap.gov/downloader/#/).

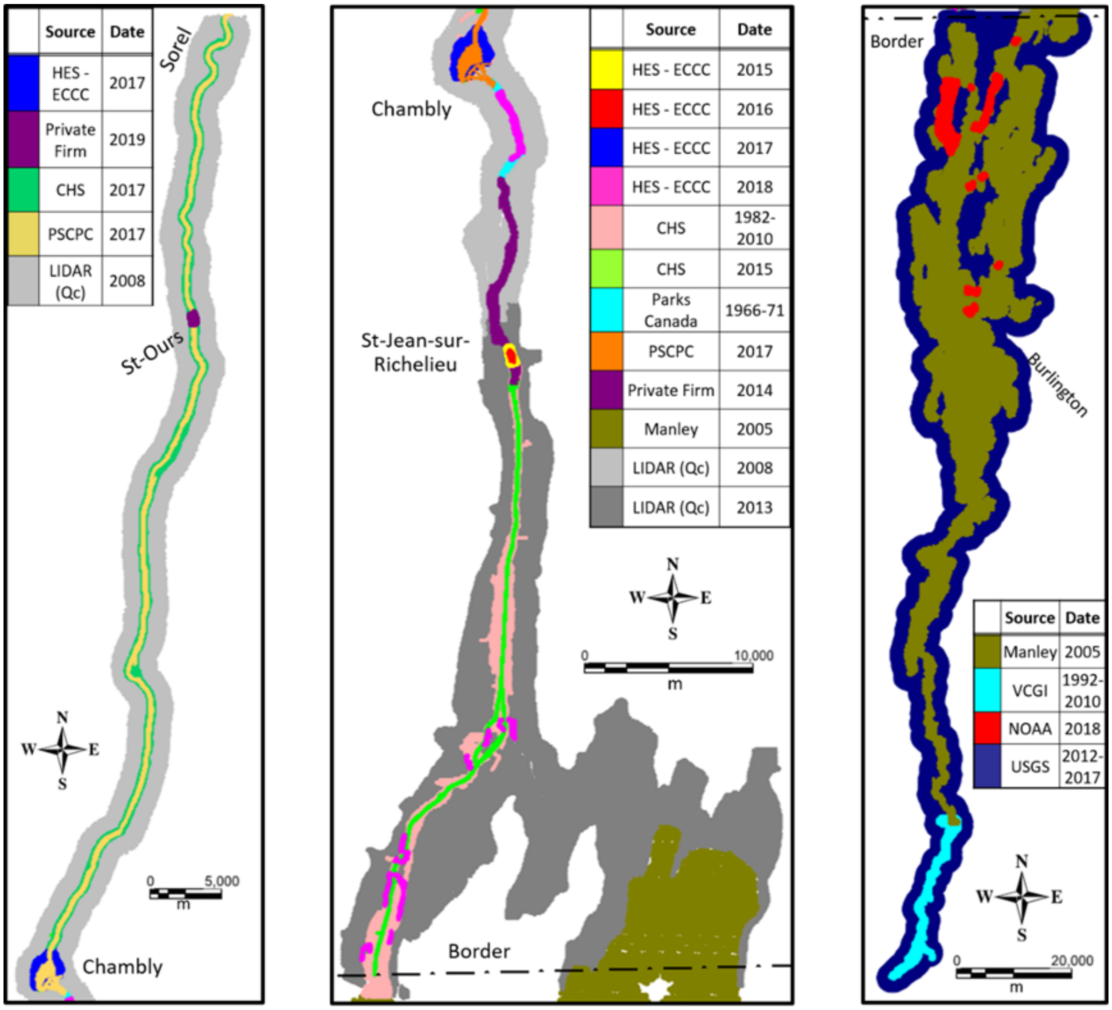


Figure 3.3.1. Spatial distribution of the datasets used for the LCRR DEM. Left panel: Chambly Basin to Sorel. Middle panel: Border to Chambly Basin. Right panel: Lake Champlain. For a description of the data sources, see Table 3.3 1.

On the US side, elevations were assembled by merging Vermont data, acquired between 2008 and 2017, and New York State data, acquired by the USGS in 2014-15, with a vertical accuracy of 9.25 cm (IJC, 2015).

The bathymetric dataset on the Canadian side is made of a mosaic of data sources sampled over a period ranging from 1960 to 2019. The most recent field surveys were sounded in areas critical to hydrodynamic modelling, where accurate elevation data were considered essential. For example, a high-precision bathymetric survey in the St. John Shoal area was completed by ECCC Hydrodynamics and Ecohydraulic Section (HES-ECCC) in the fall of 2016, taking advantage of exceptionally low water levels (Figure 3.3.1). Recent surveys were conducted using Global Navigation Satellite System (GNSS) receivers operating in real-time kinematic (RTK) mode, providing centimetric horizontal and vertical accuracy (± 5 cm error). The GNSS receivers are coupled to mono or multibeam echosounders which generally obtain a vertical accuracy of ± 15 cm. These surveys also provide control points to evaluate the level of concordance of overlapping elevation data sets.

On the U.S. side, bathymetric data were obtained from Middlebury College (Manley et al., 2005), NOAA and the Vermont Center for Geographic Information (VCGI).

The handling and assembly of such a large amount of information, acquired over several decades, is complex, as data collection techniques have progressively improved; the precision, accuracy and density of the data vary considerably from one dataset to another. In the case of overlapping datasets, special care was taken to select the best available information to constitute the LCRR DEM. Also, the datasets use different vertical datums, which implies a conversion in order to obtain a DEM in a unique datum.

This section briefly describes the different processing steps applied to the collection of datasets in order to create a seamless DEM used in the LCRR study.

3.3.1 DEM processing

Integration in a spatial database

Considering all the available datasets, nearly 2 billion point elevation measurements were assembled to constitute the DEM for the Study. In order to facilitate processing, validation, and quality control, and in some cases, correction, these data were integrated into a spatial database. In addition, this type of database facilitates the extraction of subsets of data to work on issues specific to regions of the LCRR basin.

Transformation of the data in a unique vertical reference system

The North American Vertical Datum of 1988 (NAVD88) is the vertical datum used for this study. Since the different datasets were collected over several decades (Table 3.3.1), several vertical datums were used. On the Canadian side, the elevation is generally provided based on the Canadian Geodetic Vertical Datum of 1928 (CGVD28) or 2013 (CGVD2013). On the American side, the two datums used are the National Geodetic Vertical Datum of 1929 (NGVD29) and NAVD88. As for bathymetric data, they are generally sounded relative to the Chart Datum (CD) or at depth relative to the local water level at the time of the sounding.

A transformation of the elevation values of all datasets was therefore performed to convert them to the vertical datum of the Study (NAVD88). The details of these transformations are described in Boudreau et al. (2015).

Inspection and validation of elevation data

A first step in data validation is to compare datasets with each other and, when available, with control points acquired in the field by ECCC HES. To do this, the different datasets are overlaid in a GIS for a point comparison of the elevation values, allowing to quickly identify the datasets whose elevation values differ significantly from the other datasets covering the same area. Then, an automated validation can be performed by comparing the elevation values of a given dataset with a dataset with superior measurement reliability. To do this, each point to be validated is systematically compared to points in the control dataset located within a defined radius (25 cm). This comparison process is automated with scripts written in Python that directly query the spatial database. These comparison techniques allowed, quality control of the vertical datum conversions and confirmation of the reliability of less recent datasets. Following this exercise, some of the less reliable data, often dating back several decades, were removed.

3.3.2 Data selection and resampling for the LCRR DEM

The raw elevation dataset covering the vast extent of the LCRR basin represents a very large volume of data that presents challenges for use and handling. Since the spatial resolution of the data exceeds the needs of the study in many places (10 m resolution, see appendix for details), a procedure was developed to reduce the density of information while preserving an adequate characterization of the terrain.

To do so, two techniques were used, namely the selection of the most reliable data in overlapping areas and the reduction of density of certain data sets.

Selecting the most reliable data in case of overlaps

Once all available elevation data were compiled, overlaps between different datasets remained at several locations throughout the study area. Although these overlaps are useful for data comparison and validation, they create a redundancy of information.

Thus, for each overlapping area, the datasets were visually inspected using a GIS and analyzed with automated scripts to select the dataset whose elevation values appear most reliable. Due to the wide variety of available datasets and the variability in the extent of overlapping areas, data selection was based on a fine analysis of each overlapping area with particular attention to the following criteria:

- Year of survey (favoring the most recent data);
- Homogeneous coverage of the overlapping area (favoring complete and uniform coverage rather than longitudinal transects);
- Data precision (favoring recent, high-resolution data);
- Accuracy of elevation data (compared to elevation data acquired by GNSS).

Once the dataset was selected, the spatial coverage representing the overlap was integrated into the spatial database using a polygon identifying the data to retain for the LCRR DEM for that specific area.

This process allowed discarding of large amounts of elevation measurements. The main advantage of this visual inspection was the ability to precisely select the points to be retained and thus ensure the most reliable information was used throughout the domain. Figure 3.3.2 illustrates a comparison of the raw data and the retained data for the LCRR DEM in the Saint-Ours sector.

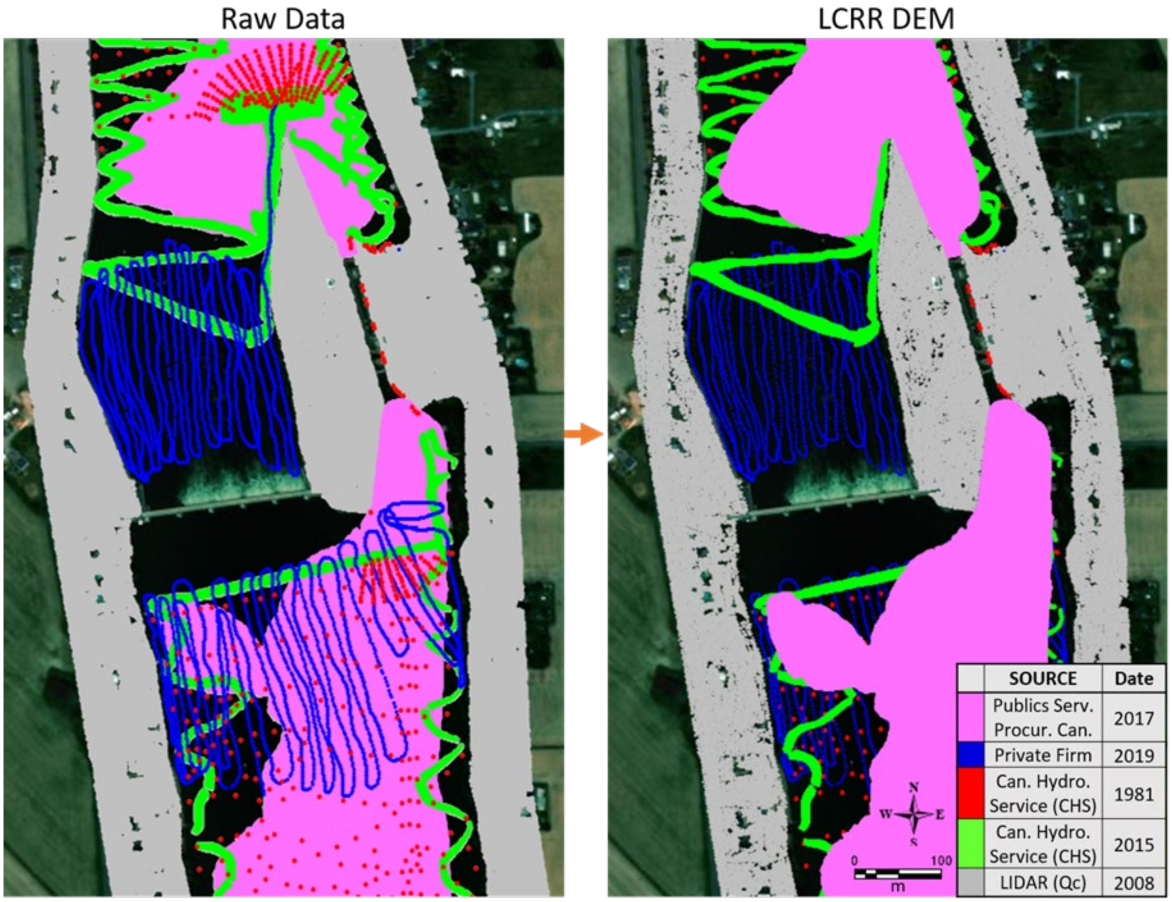


Figure 3.3.2. (Left) All available raw data sets. (Right) Data retained for the production of the LCRR DEM. Richelieu River, Saint-Ours sector.

Density reduction

Data acquisition technologies have significantly improved throughout the last few decades. LIDAR topographic surveys and multibeam bathymetric soundings now produce data with a very high level of accuracy, but with a resolution that far exceeds the needs of the large-scale coverage of the ISEE system.

For example, the LIDAR data provided by the Government of Quebec has a minimum density of 1 to 2 pts/m^2 and the CHS multibeam data has an average density of 15 pt/m^2. Since these densities are higher than required for the ISEE grid (1 pt/100 m^2), automated processing was applied to resample the data. To do this, a moving window of 1 m^2 was used to select the point closest to the center of the window. Thus, only one elevation value was retained per m^2 where elevation data was available, significantly reducing the size of the datasets. This process was automated using a script in Python and systematically applied to LIDAR and multibeam datasets. It is important to note that when the most accurate elevation data available was required, such as for the development of some indicators (e.g. building damage), elevations were obtained through precise GNSS field surveys or through analyses distinct from the one described here.

3.3.3 Interpolation on the ISEE grid

The processing restricted the size of the dataset to be interpolated on the ISEE grid to 250 million points. In order to have a continuous coverage over the whole study area, the elevation data were interpolated on the ISEE grid using an Inverse Distance Weighting (IDW) algorithm. For a detailed description of the ISEE grid see Chapter 4. Figure 3.3.3 shows the raw, interpolated and resampled elevation data on the ISEE grid for the St-Jean-sur-Richelieu area.

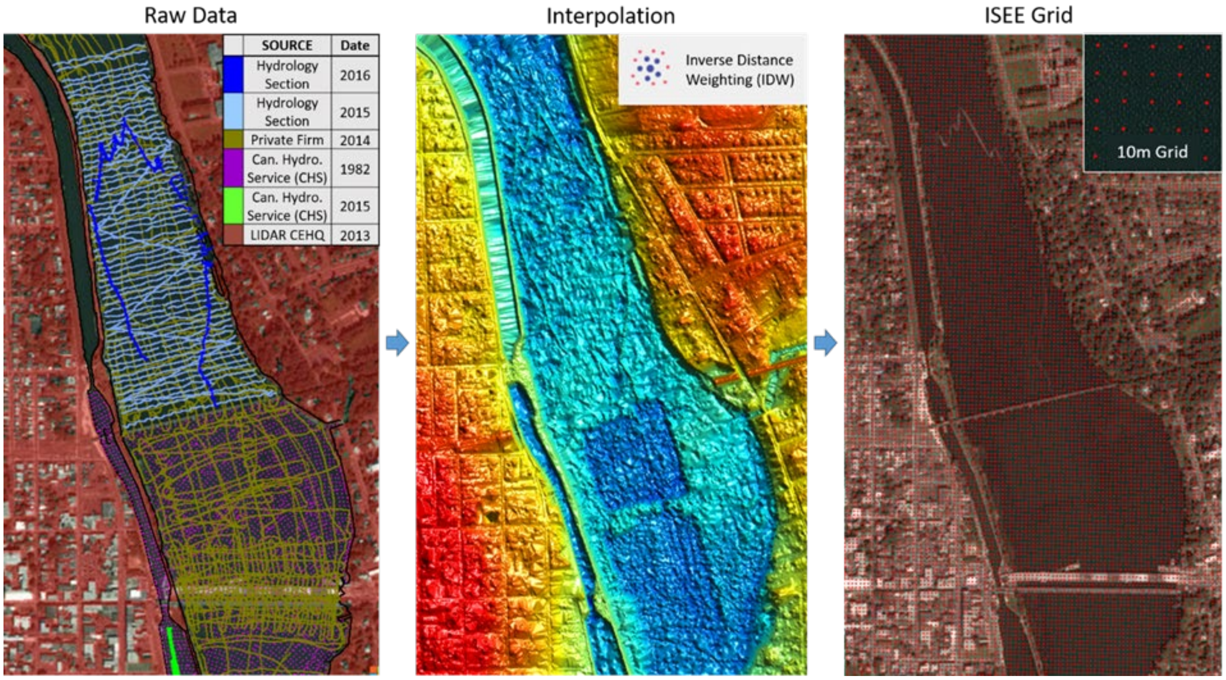


Figure 3.3.3. Process of interpolating raw bathymetric and topographic data into the ISEE grid. (Left) Raw Topographic LIDAR data on the floodplain (red) and instream bathymetric transect (Center) Interpolated elevation data. (Right) Resampled elevation on the 10m- ISEE grid.

3.3.4 DEM alterations to simulate structural mitigation measures

The three flood mitigation alternatives to be evaluated required modifications to the bathymetry of the Saint-Jean-sur-Richelieu shoal area. Therefore, a separate DEM for this area was created for each alternative (Figure 3.3.4). More details on the bathymetric and topographic data used and the treatments applied to generate these modifications can be found in Boudreau et al. (2015) and Gosselin et al. (2022).

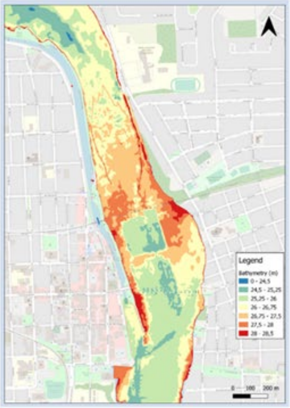
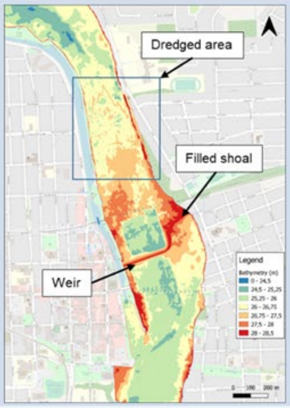
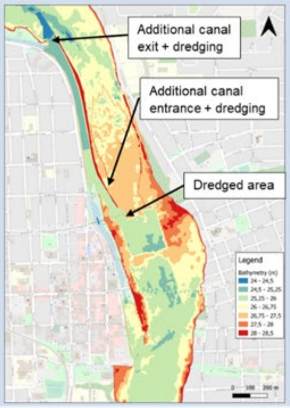
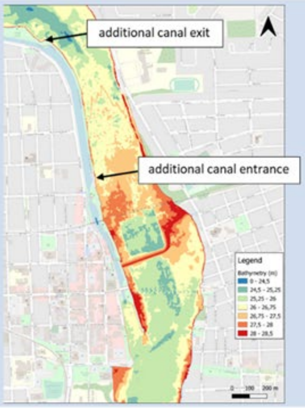
Baseline	**Alternative 1** **Selective excavation of the shoal with submerged weir**	**Alternative 2** **Major Chambly Canal diversion**	**Alternative 3** **Alternative 1 + minor diversion**
			
Current state	• Lowering WLs at high flows • Increasing WLs at low flows • Recreating hydraulic conditions closer to natural/pristine state.	• Lower water levels at high river flows to lessen the impact of floods on LCRR upstream of Saint-Jean-sur-Richelieu	• Decreasing WLs at high flows and very high flows(>1200 m^3/s), with a minor diversion through the Chambly Canal • Increasing WLs during low flows

Figure 3.3.4. Bathymetric alterations associated with each flood mitigation alternatives integrated into the ISEE grid.

3.4 2D HYDRODYNAMIC MODEL

The purpose of the hydrodynamic model is to provide spatially continuous water levels and currents across the study area. For this study, hydrodynamic modelling was performed using the H2D2 software (Matte & Secretan, 2008). H2D2 is a finite element software that solves 2D shallow water equations, also known as the Saint-Venant equations. It was developed at INRS-Eau (now INRS-ETE) with the assistance of ECCC and has been used in several studies in the past decade, including previous IJC studies (Morin et al., 2005; 2016).

The method consists of dividing the study area in quadratic elements forming a finite element grid, with varying dimensions to represent the shape and complexity of the terrain. Where the terrain is more complex, a finer mesh with a greater number of elements is required. For instance, the Saint-Jean shoal accounts for 133,966 of the 741,670 elements of the entire LCRR mesh. The model predicts a two-dimensional water surface elevation and average water velocities of the water column along the water body for a given water supply (discharge or level). Given the presence of dams along the river (Chambly dam and Saint-Ours dams), distinct hydraulic models of the corresponding river reaches were developed to account for the singularities of each section. Thus, the study area is separated in three hydraulic sections, each with their own hydrodynamic model parameters and boundary conditions (Figure 2.1.3).

Steady state simulations, further referred as hydraulic scenarios, for the Baseline scenario were computed over a range of increasing lake levels for each of the three sections (Figure 2.1.3). For the Lake section, a total of 44 hydraulic scenarios were produced, ranging from 27.9 m to 32.2 m at Rouses Point (approximately 0.1 m increments), corresponding to flow discharges ranging from 25 to 2,500 m^3/s at Fryer Island Dam. Those steady state scenarios represent the equilibrium state of the system under these river discharges and cover a wide range of hydrologic conditions, ranging from extreme low to extreme high flow conditions. The resulting set of steady state simulations is further referred as a hydrodynamic simulation dataset. Similar simulations were carried out for each of the three flood mitigation alternatives, with a modified bathymetry and appropriate boundary conditions for each alternative (See Gosselin et al. 2022 for more details).

The two sections downstream of Chambly are more complex due to the Saint-Ours dam management and the influence of the St. Lawrence water levels (Figure 2.1.3; Figure 3.5.1). Therefore, for these sections, four different runs (hereafter called hydrodynamic simulation datasets) were computed over the same range of river discharge, but with four increasing levels of the St. Lawrence River at Sorel (3.1 m, below the historical minimum and 5.00 m, 7.00 m and 8.20 m, above the historical maximum). For the section between Chambly and Saint-Ours dam, the lowest dataset was run with a fixed water level at Saint-Ours dam (6.86 m), corresponding to the water level upstream of the dam when it is actively maintaining levels.

All sets of steady state simulations for the Baseline scenario and the flood mitigation alternatives were interpolated on the 10 m regular grid and integrated in the ISEE system, where they provide water level and flow velocity at each node, hereafter referred to as hydraulic maps.

Table 3.4.1. Hydrodynamic simulation datasets produced for different hydrodynamic sections (Figure 2.1.3), mitigation scenarios (Alternative 1: submerged weir, Alternative 2: major derivation, Alternative 3: submerged weir with minor diversion), over a range of Richelieu River discharge. The simulations covering the sections downstream of Chambly were carried out with a fixed St. Lawrence River water level at Sorel and with the Saint-Ours dam gates open or closed. Each dataset is made of a number of hydrodynamic scenarios representing water level increments of approximately 10 cm.

Hydrodynamic section	Mitigation scenario	Range of river discharge (m^3/s)	St. Lawrence level (m)	St. Ours Dam	Number of hydrodynamic scenarios
Lake Champlain & Upper Richelieu	Baseline	25-2500	NA	NA	44
Chambly to Saint-Ours	Baseline	25-2500	3.10	closed	48
Chambly to Saint-Ours	Baseline	25-2500	5.00	open	48
Chambly to Saint-Ours	Baseline	25-2500	7.00	open	48
Chambly to Saint-Ours	Baseline	25-2500	8.20	open	48
Saint-Ours to Sorel	Baseline	25-2500	3.10	closed	48
Saint-Ours to Sorel	Baseline	25-2500	5.00	open	48
Saint-Ours to Sorel	Baseline	25-2500	7.00	open	48
Saint-Ours to Sorel	Baseline	25-2500	8.20	open	48
Lake Champlain & Upper Richelieu	Alternative 2 (canal open)	27-2530	NA	NA	53
Lake Champlain & Upper Richelieu	Alternative 1	26-2530	NA	NA	43
Lake Champlain & Upper Richelieu	Alternative 3 (diversion)	1012-2515	NA	NA	22

3.5 ISEE SYSTEM HYDRAULIC MAP INTERPOLATOR

One of the key components of the ISEE system is the ability to generate maps simulating on-the-fly hydraulic conditions, conditions that prevailed at any time in the recent past, or future conditions under climate change scenarios. To meet the LCRR study objective, i.e., evaluating flood mitigation alternatives, the ISEE system simulates hydraulic maps at a quarter-monthly (QM) time step throughout the reference period (1925-2017). These long time-series allow consideration of the natural hydrological variability of the system. The ISEE system yields depths and velocity on a 10 m regular grid covering a study area of 250,000 ha and representing 25 million grid nodes (Figure 3.5.1). The ISEE grid is separated in 47 tiles[6] of 100 km^2 and the study zone is separated into six modelling sections[7] , each with its own calculation parameters and boundary conditions (Figure 3.5.1). The six different sections cover the following portions of the study area:

- Section 11: Lake Champlain, US side.
- Section 12: Lake Champlain, Canadian side (Missisquoi Bay).
- Section 20: Richelieu River, from Rouses Point to Saint-Jean-sur-Richelieu
- Section 30: Richelieu River, from Saint-Jean-sur-Richelieu to Chambly dam.
- Section 40: Richelieu River, from Chambly dam to Saint-Ours dam.
- Section 50: Richelieu River, from Saint-Ours dam to the St. Lawrence River.

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[6] Originally, each tile contained 1 million grid nodes for a total of 47 million nodes, but to avoid unnecessary calculations only the grid nodes that correspond to areas that are relevant for the considered performance indicator are kept in the ISEE system.

[7] The study area is separated into three hydraulic sections, each with its own hydrodynamic model parameters and boundary conditions (Figure 2.1.3). However, to incorporate other considerations such as administrative divisions or different interpolation methods and variables, the ISEE system divides the study area into six distinct modelling sections (Figure 3.5.1).

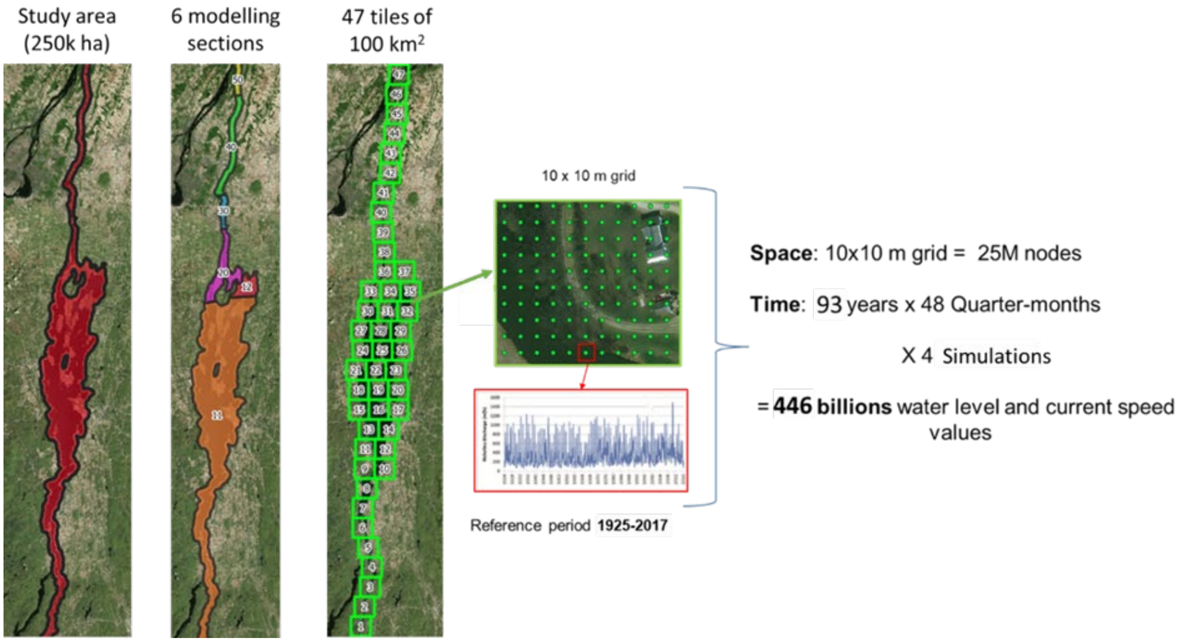
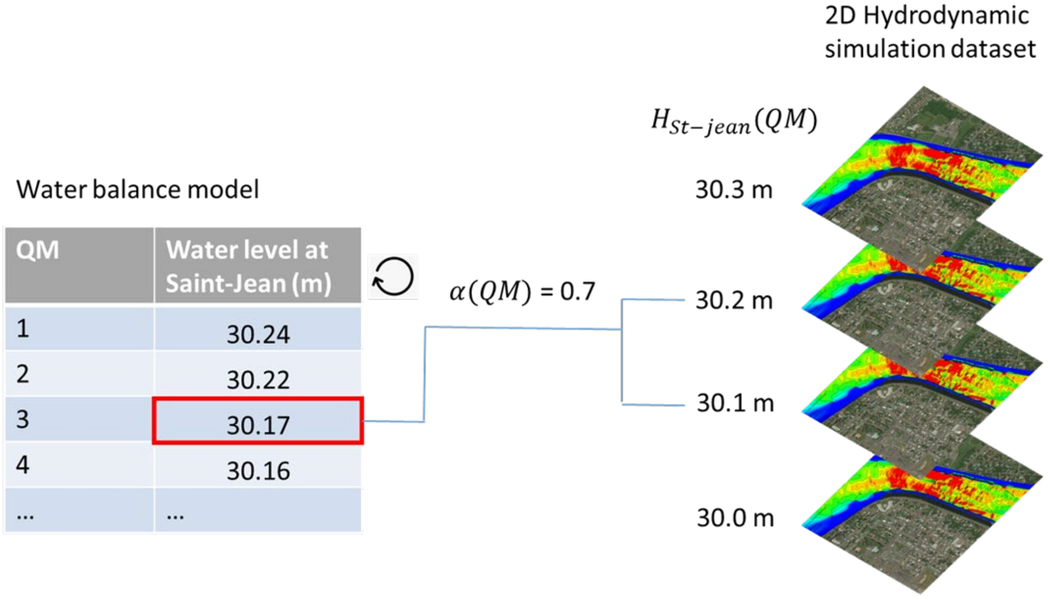


Figure 3.5.1. Extent of the study area, modelling sections, tiles and spatial and temporal resolutions of the LCRR ISEE system

To generate water surface elevation and velocity (hydraulic maps) for any given quarter-month of the reference period, the ISEE system uses stored hydrodynamic simulation datasets (Table 3.4.1). More specifically, for any given quarter-month, water level and velocity maps are produced by linearly interpolating between the two closest hydraulic scenarios relative to the water level output by the WBM for that specific time-step (Figure 3.5.2).



QM	Water level at Saint-Jean (m)
1	30.24
2	30.22
3	30.17
4	30.16
…	…

Figure 3.5.2. Conceptual example of a simple interpolation of two hydrodynamic scenarios of a simulation dataset in the ISEE system, based on an 'interpolation variable' (i.e. water level and discharge at a key location (Rouses Point, Saint-Jean-sur-Richelieu, Chambly, Saint-Ours and Sorel) provided by the WBM to produce a hydraulic map for a given quarter month (QM).

The hydraulics of each section of the water body are interpolated based on water level or discharge at specific locations (Rouses Point, Saint-Jean-sur-Richelieu, Chambly, Saint-Ours and Sorel) output by the WBM, referred to as 'interpolation variables'. Given their distinct hydraulics, each section is interpolated as described below:

Section 11 and 12 (Lake Champlain on the US and Canadian side, respectively) are computed based on the water level at Rouses Point (HRP), and on the linear interpolation between the two closest hydrodynamic scenarios, such that

$$\alpha(QM) = \frac{H_{RP}(QM) - H_{RP}(scenario\ below)}{H_{RP}(scenario\ above) - H_{RP}(scenario\ below)}$$

where α (QM) expresses the interpolation ratio at a given quarter-month and for each variable (var), (water level (x)- and velocity(y) at a given quarter month, maps are interpolated as:

$$var(x, y, QM) = var(x, y, sc_{below}) + \alpha \times (var(x, y, sc_{above}) - var(x, y, sc_{below}))$$

Section 20 (Upper Richelieu River, between Rouses Point and Saint-Jean-sur-Richelieu) is interpolated using the water levels at both Rouses Point and Saint-Jean-sur-Richelieu, to capture the seasonal variation in roughness associated to aquatic plant growth and the effect of ice cover taken into account in the WBM. More specifically, hydrodynamic scenarios are linearly interpolated, but the interpolation factor varies along the river depending on the distance to Rouses Point and Saint-Jean-sur-Richelieu as follows.

$$\alpha_{corrected}(x, y) = \alpha(RP) \times \left(1 - \frac{distance_{RP}(x, y)}{distance_{SJSR-RP}}\right) + \alpha(SJSR) \times \frac{distance_{RP}(x, y)}{distance_{SJSR-RP}}$$

$$var(x, y, QM) = var(x, y, sc_{below}) + \alpha_{corrected}(x, y, QM) \times \left(var(x, y, sc_{above}) - var(x, y, sc_{below})\right)$$

Section 30 (Upper Richelieu, between Saint-Jean-sur-Richelieu and the Chambly dam), is computed using a linear interpolation, similar to section 11 and 12, by using the water level at Saint-Jean-sur-Richelieu from the WBM. This avoids any unrealistic water level jump at the boundary between sections 20 and 30.

Section 40 (Lower Richelieu, between Chambly and the Saint-Ours dam), hydraulic maps are produced by considering the Richelieu River discharge including an additional discharge from the two tributaries of the Chambly basin and a backwater effect of the water level of the St. Lawrence River at Sorel. Multiple hydrodynamic simulation datasets are involved in the interpolation corresponding to the appropriate combinations of river discharge and St. Lawrence water level and operation of the Saint-Ours dam (opened or closed to control upstream water levels) (Table 3.4.1, Figure 3.5.3 and Figure 3.5.4).

When the dam is in a control operation mode, this section is interpolated using the river discharge with a fixed water level at Saint-Ours (6.86 m) such that

$$\alpha(QM) = \frac{Q_{Richelieu}(QM) - Q_{Richelieu}(scenario\ below)}{Q_{Richelieu}(scenario\ above) - Q_{Richelieu}(scenario\ below)}$$

In contrast, when the dam gate is open, i.e. when the river discharge is above 1,000 m^3/s or when the downstream level is high enough that the water flows over the dam (> 6.86 m), the interpolation is bi-linear, using both the river discharge and the water level downstream of the dam, obtained from the section 50 interpolation. A first linear interpolation is performed with the downstream water level, then a second linear interpolation is done on the resulting dataset using the river discharge (Figure 3.5.3 and Figure 3.5.4), such that

$$\alpha_H(QM) = \frac{H_{downstream}(QM) - H_{downstream}(sc_{below}(H))}{H_{downstream}(sc_{above}(H)) - H_{downstream}(sc_{below}(H))}$$

$$\alpha_Q(QM) = \frac{Q(QM) - Q(sc_{below}(Q))}{Q(sc_{above}(Q)) - Q(sc_{below}(Q))}$$

where α_{WL} and α_{Q} express the ratios based on water level downstream ($H_{downstream}$) of the dam (influenced by the level of the St. Lawrence River) and on discharge respectively.

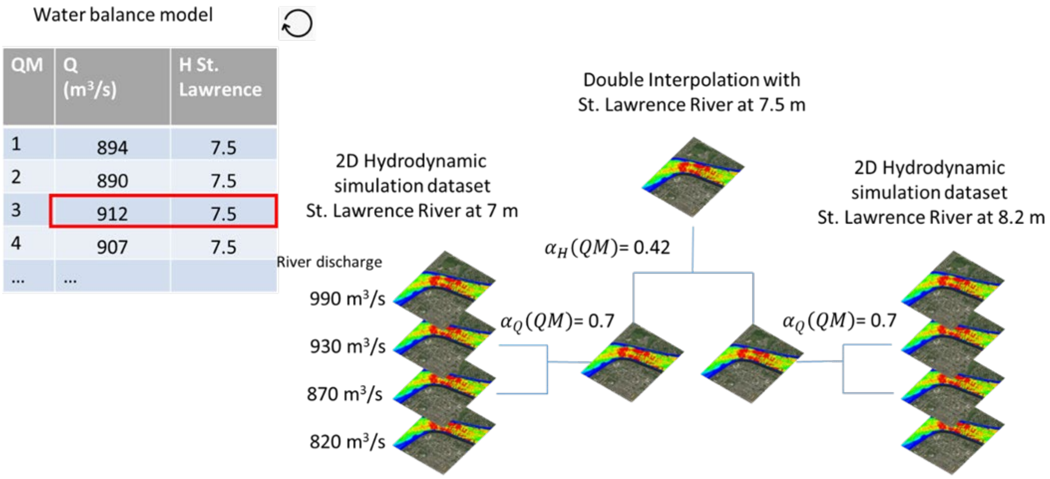
Then the ratios are used to compute each hydrodynamic variable such that

$$var(x,y,QM) = var(x,y,sc_{below}(Q)) + \alpha_Q(QM) \times (var(x,y,sc_{above}(Q)) - var(x,y,sc_{below}(Q)))$$

where:

$$var(x,y,sc_{below}(Q)) = var(x,y,sc_{below}(H)) + \alpha_H(QM) \times (var(x,y,sc_{above}(H)) - var(x,y,sc_{below}(H)))$$

Section 50 (Lower Richelieu, between Saint-Ours dam and the St. Lawrence River), uses hydrodynamic simulation datasets of the full range of discharge over four levels of St. Lawrence River (Table 3.4.1). The same bilinear interpolation as the “open dam” configuration of section 40 is used at all times, using the St. Lawrence River water level and the Richelieu River discharge as interpolation variables.



QM	Q (m^3/s)	H St. Lawrence
1	894	7.5
2	890	7.5
3	912	7.5
4	907	7.5
...	...	

Figure 3.5.3. Conceptual example of a double interpolation used to create hydraulic maps based on river discharge and the backwater effect of the St. Lawrence River. Interpolation is carried out between two hydrodynamic scenarios of two hydrodynamic simulation datasets for a St. Lawrence River water level of 7.50 m at Sorel and a Richelieu River discharge of 912 m³/s.

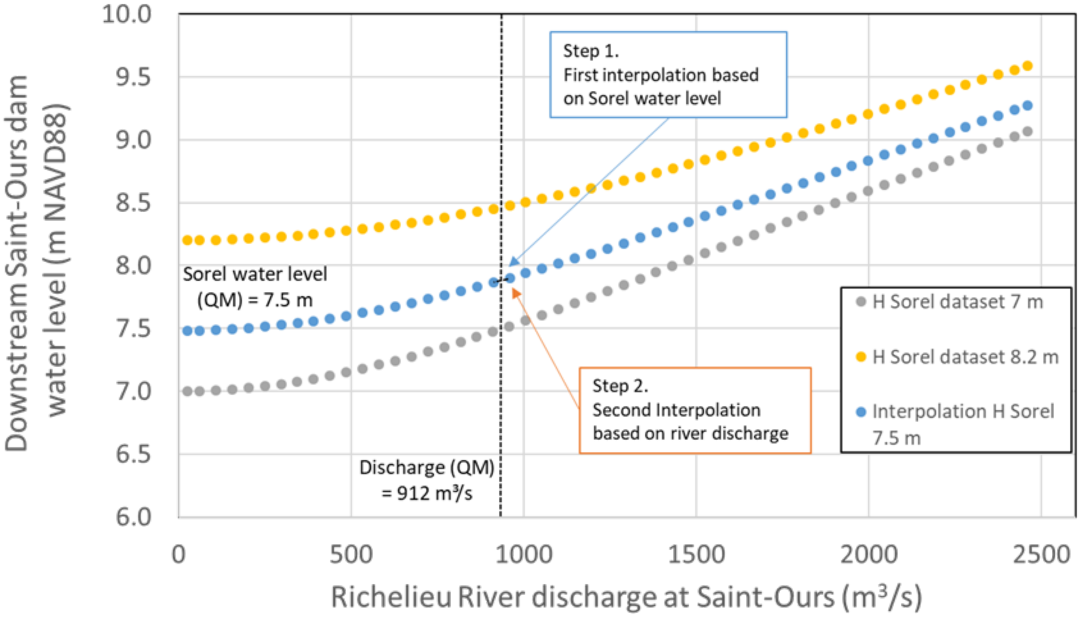


Figure 3.5.4. Water level downstream Saint-Ours dam and Richelieu River discharge of two hydrodynamic simulation datasets of 48 steady-state scenarios with fixed St. Lawrence River water level (7.00 m and 8.20 m in yellow and grey). Example of a double interpolation to create a hydraulic map for a quarter-month (QM) with a St. Lawrence River water level of 7.50 m at Sorel and a Richelieu river discharge of 912 m³/s.

Note that section 20 (Upper River) has its distinct hydrodynamic dataset for each flood mitigation alternative to reflect changes in water surface elevations, whereas for the other sections (lake and downstream from Saint-Jean-sur-Richelieu), the river hydraulics (water level at a given discharge) are unaffected by the mitigation alternatives and therefore the baseline simulations can be used in all cases.

More details and examples of the interpolation of the different sections are provided in Chapter 4.

3.6 GEOSPATIAL DATA LAYERS

A key feature of the ISEE system is the large number of georeferenced layers of information integrated on the same grid. In addition to the hydraulic maps, each grid node is associated with a large dataset with information such as land use, wetland vegetation, and building characteristics required to compute performance indicators. Primary information mostly comes from official governmental sources (e.g. building values, socio-economic census, land elevation data, crop coverage), whereas some data were specifically collected for the Study (e.g. first floor elevations, wetland vegetation transects).

With few exceptions, geospatial information layers are kept constant in time and space for each alternative. However, in the most complex cases, outputs from one PI can be used as georeferenced layer input for the calculations of another PI. For instance, modelled wetland classes are used as input to the waterfowl migration habitat, Northern Pike spawning habitat and Least Bittern nesting habitat PIs. In such cases, the input georeferenced layer is different for each alternative.

3.7 PERFORMANCE INDICATORS

PIs provide measurable values expressing the link between water level or discharge and a given interest or resource. Through carefully elaborated response functions, these metrics quantify the impacts on social, economic, environmental and indigenous interests of each flood mitigation alternative. The PIs are one of the fundamental tools for the Study Board recommendations regarding structural flood mitigation alternatives, especially to evaluate how they are economically viable, equitable and environmentally sound. Selected indicators have to be sensitive to water level variations and representative of the broad interests of LCRR stakeholders. Experts from various fields participated in the selection and development of the different PIs, including economists, ecologists and flood damage and resilience experts (Table 3.7.1).

Details about the complete PI selection and development processes are available in Bachand et al. (2022) and analysis of PI results is available in Roy et al.(2022

3.7.1 PI dimensionality

PIs developed in the LCRR study are either one-dimensional (1D) or two-dimensional (2D). The 1D PIs represent the relationship between the water level variations and particular components of the LCRR basin. The 1D PIs reflect the variation in time but are not spatially distributed. This implies that for a specific time-step, 1D PIs provide a unique value for the entire area where the PI is valid. In this study, examples of 1D PIs include the probability of muskrat winter lodge viability, the probability of spiny softshell turtle egg survival and the probability of wild rice survival between germination and floating stage.

In contrast, 2D PIs are spatially distributed. They combine geospatial datasets and hydraulic maps (i.e. water level and velocity) obtained from hydrodynamic modelling, to produce results at each node of the ISEE grid for any given time-step. The 2D PI results can be aggregated spatially over portions of the study area, yielding temporal series. They can also be aggregated over time, for particular years, or averaged over the entire reference period (1925-2017), yielding a map that can be imported into a GIS software for visualization or further analyses. Results can also be aggregated in both space and time, yielding an average value for the study area for the reference period.

3.7.2 Response function

PIs are quantified using response functions, which are mathematical equations used to link hydraulic variables (e.g. water level, water depth during a specific period, velocity) and a resource or interest. For instance, structural damage is based on a relatively simple equation that predicts flood damage to buildings based on a submersion height (depth relative to first floor elevation) and building characteristics (basement type, number of stories, valuation). In contrast, some PIs include more complex functions such as the wetland class area PI, which involves the combination of deep learning and wetland succession algorithms. In most cases, to estimate the potential impact of a flood mitigation alternative, the change in the water level during a period of interest is combined to other explanatory variables. For example, Northern Pike spawning habitat PI is calculated using water depths and currents during the spawning period, which is dependent on degree-days calculated with maximum daily temperatures (Figure 3.7.1). In addition, the PI also includes vegetation type based on crop coverage data and the wetland class PI outputs.

For more details on each PI response function, see Bachand et al. (2022).

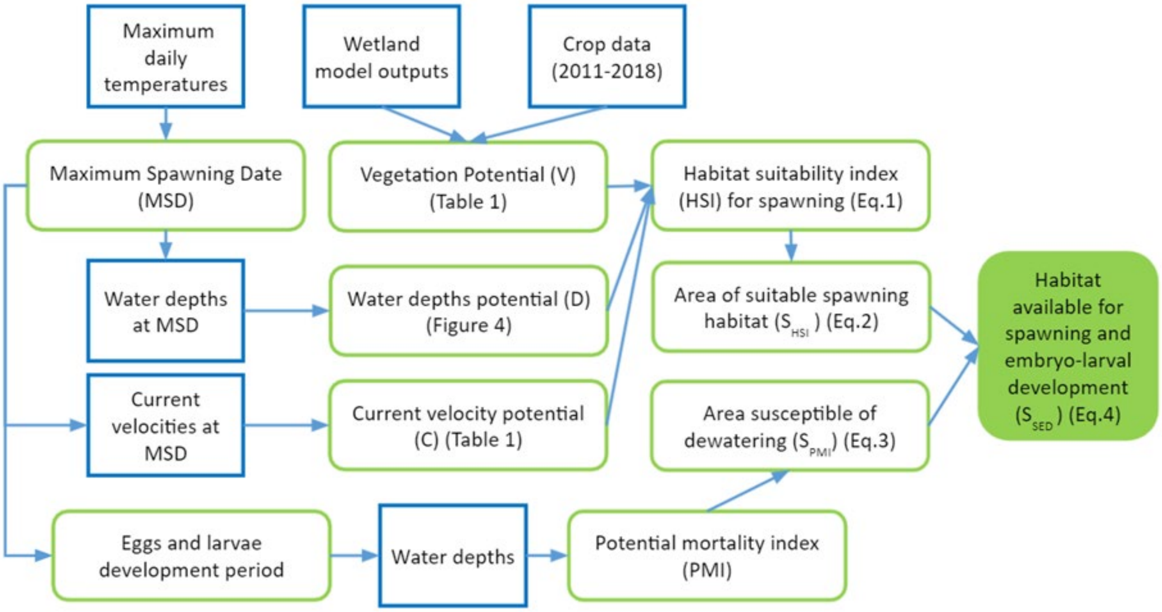


Figure 3.7.1. Example of a Performance indicator response function (Northern Pike spawning habitat area).

3.7.3 Performance indicator outputs

For each simulation, PIs provide a quantitative value at each grid node (for 2D PIs) for each one of the 93 years of the reference period. Those values consist of both tangible and comparable units such as dollars (for structural damage and income loss), hectares (habitat area), or in relative values such as social risk.

PI results can be spatially aggregated over portions of the study area per year, yielding different temporal series for each alternative and the baseline scenario (Figure 3.7.2). They can also be aggregated over time, for particular years, or averaged over the entire reference period (1925-2017), yielding a map, again for every scenario, that can be imported into any GIS software for visualization or further analyses. Results can also be aggregated in both space and time, yielding an average value for the study area over the entire reference period for each alternative. To analyse the effect of flood mitigation alternatives, results simulated with an alternative can be compared with the baseline, by comparing either the temporal variation or the spatial distribution (Figure 3.7.2). For PI results, see Roy et al (2022).

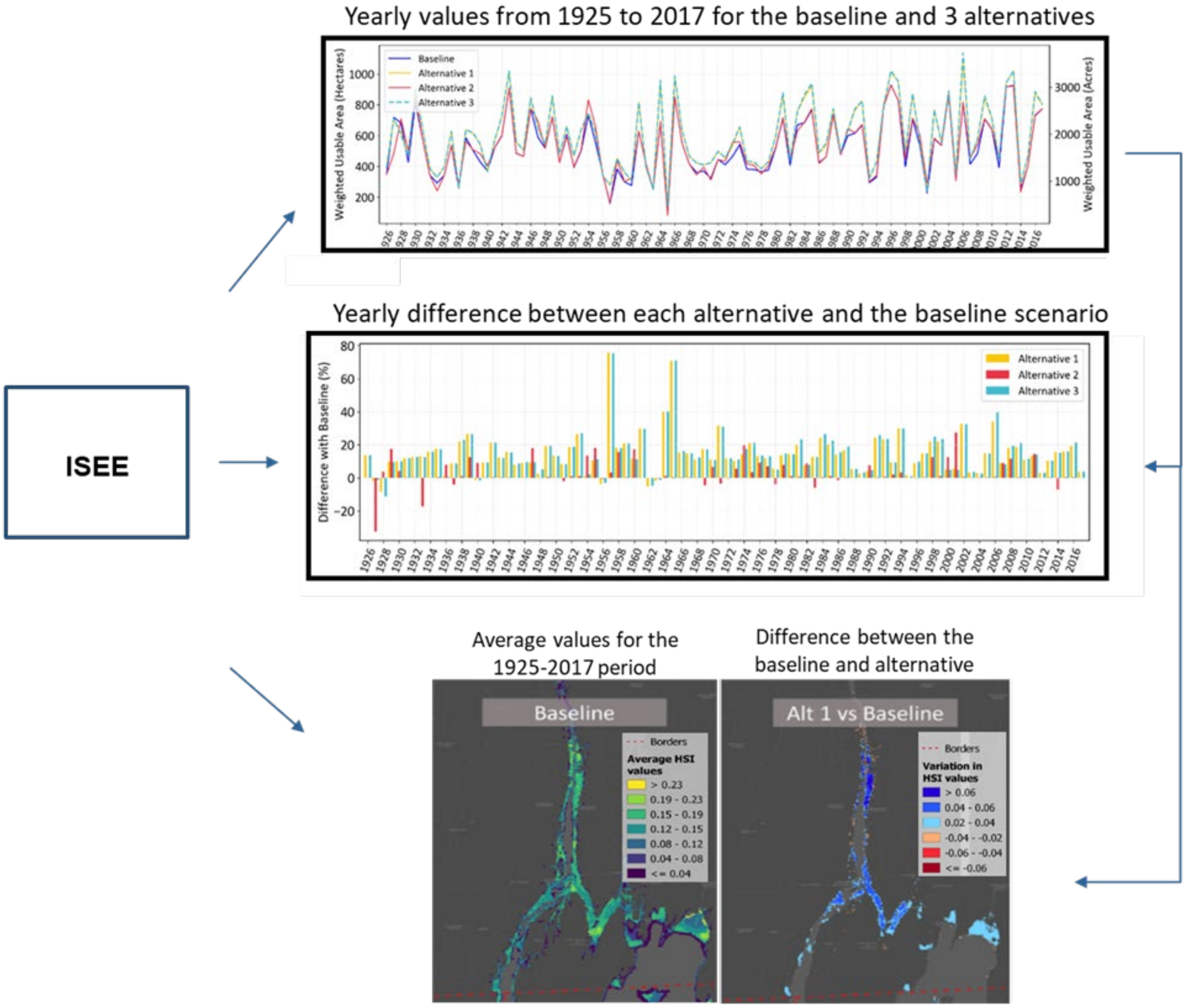


Figure 3.7.2. Example of a PI output. (Top) Time-series of yearly PI values (1925-2017) for the baseline and three different flood mitigation alternatives, (Center) Time-series of yearly difference between baseline and alternative (Bottom), Map of average PI value for the baseline (Left) and difference between the baseline and a flood mitigation scenario (Right).

3.7.4 List of PIs

The following table presents the exhaustive list of PIs that were selected and used to assess the impacts of the flood mitigation alternatives in the LCRR study. The methodology associated to the development of each selected PI is presented in Bachand et al. (2022).

Table 3.7.1. List of performance indicators of the LCRR Study.

#	Performance Indicators	Acronym	Units	Experts
	Economic			
1	Structural damage to residential buildings CAN	RSD	Dollars	CCG[1]
2	Material damage to residential buildings CAN	RMD	Dollars	Ouranos[2]
3	Temporary lodging costs of residential sector CAN	RLC	Dollars	Ouranos[2]
4	Clean-up costs of residential sector CAN	RCC	Dollars	Ouranos[2]
5	Structural/Material damage to residential buildings US	RSMD	Dollars	UVM[3]/IJC[4]
6	Structural damage to industrial, commercial and recreational buildings CAN	CIRSD	Dollars	ENAP[5]
7	Material damage to commercial, industrial and recreational buildings CAN	CIRMD	Dollars	ENAP[5]
8	Commercial income loss CAN	CIL	Dollars	ENAP[5]
9	Recreational income loss CAN	RIL	Dollars	ENAP[5]
10	Structural/Material damage to industrial, commercial and recreational buildings US	CIRSMD	Dollars	UVM[3]
11	Agriculture yield loss CAN	AYL	Dollars	INRS[6]
12	Structural/Material damages to farms buildings CAN	ASMD	Dollars	INRS[6]
13	Agriculture yield loss US	AYL	Dollars	ECCC[8]
14	Structural/Material damages to farms buildings US	ASMD	Dollars	UVM[3]
15	Structural damage to public infrastructures CAN	PSD	Dollars	ENAP[5]
16	Material damage to public infrastuctures CAN	PMD	Dollars	ENAP[5]
17	Structural/Material damage to public infrastuctures US	PSMD	Dollars	UVM[3]
	Social			
18	Social sensitivity index	SSI	Index	UdeM[17]
19	Territorial sensitivity index	TSI	Index	UdeM[17]
	Environmental			
20	Muskrat winter lodge viability	PLV	Survival index	SUNY[7]/ECCC[8]
21	Spiny Softshell turtle egg survival	ESP	Survival index	GZ[9]/MFFP [10]
22	Wetland classes succession	WETL	Habitat area	ECCC [8]
23	Least Bittern reproductive potential	RPI	Habitat area	ECCC [11]
24	Waterfowl staging habitat during spring migration	SHSI	Habitat area	ECCC [12]
25	Copper Redhorse suitable habitat for spawning and early larval development	WUA	Habitat area	MFFP[13]
26	Northern pike spawning and embryo-larval development habitat	SSED	Habitat area	MFFP[14]
	Indigenous Interests			
27	Wild rice survival between the germination and floating stages	PRS	Survival index	ECCC[8]/GCNWA[15]
28	Black ash basket-grade habitat	PFXNI	Habitat area	GCNWA[15]
29	Archeological sites vulnerability CAN	ASV	Vulnerability index	INRS[16]/GCNWA[15]

1 Doyon, B. and Jean, M., Canadian Coast Guard, (2022)
2 Gosselin, C.A., Ouranos (2020)
3 Safavi, N. and O'Neil Dunne, J., University of Vermont (2021)
4 Werick, B., IJC (2021)
5 Bouchard St-Amand, P.A., and Dumais, G., École Nationale d'Administration Publique (2022)
6 Rousseau, A., and Savary, S., Institut National de la Recherche Scientifique (2021)
7 Garneau, D., State University of New York at Plattsburgh (2020)
8 Morin, J., and Bachand, M., National Hydrological Service, Environment and Climate Change Canada (2021)
9 Lazure, L., Paré, P., Zoo de Granby (2020)
10 Bouthillier, L., Ministère des Forêts, de la Faune et des Parcs (2021)
11 Jobin, B., Tardif, J., Canadian Wildlife Service, Environment and Climate Change Canada (2021)
12 Lepage, C., Canadian Wildlife Service, Environment and Climate Change Canada (2021)
13 Vachon, N., Mingelbier, M., Hatin, D., Ministère des Forêts, de la Faune et des Parcs (2021)
14 Mingelbier, M., Ministère des Forêts, de la Faune et des Parcs (2021)
15 Treyvaud, G., Blanchet, E. Grand Conseil de la Nation Waban-Aki (2021)
16 Chokmani, K., Oubennaceur, K., Institut National de la Recherche Scientifique (2021)
17 Thomas, I., Gagnon, A, Université de Montréal (2021)

4 TECHNICAL DESCRIPTION

4.1 INTRODUCTION

ISEE-LCRR was developed in Python, a cross-platform programming language that can be run on Windows, Linux and any other operating system. It is an object-oriented programming language that is stable, open-source, well-documented, and in constant evolution. The ISEE system does not have a graphical interface and works by command line to which various parameters are sent (command line interface).

Python version 3.7 was used to develop the LCRR ISEE system in a virtual environment. A file to reproduce this environment is provided with the ISEE code.

In addition to core modules, the ISEE code makes extensive use of numpy (https://numpy.org/), scipy (https://scipy.org/) and pandas (https://pandas.pydata.org), which are modules to read, process, manipulate, and write data.

The LCRR ISEE system can be run from a startup script ("batch file") under Windows (see Figure 4.4.1) or directly using a Python command line. In order to run, the code needs two environment variables:

- ISEE_ROOT which points to the root directory of the Python code. (Ex: C:\prog\python\isee\src). See Code Structure section for details

- ISEE_DATA which points to the root directory of the input data. (Ex.: D:\data\isee\lcrr). See the Data Structure section for details.

Environment variables must be changed directly in the start-up script provided with the ISEE code or configured in the environment variables of the operating system where ISEE will run. With Anaconda (https://anaconda.org/anaconda/python), the activation of the virtual environment and the initialization of the modules is done using either one of these commands ():

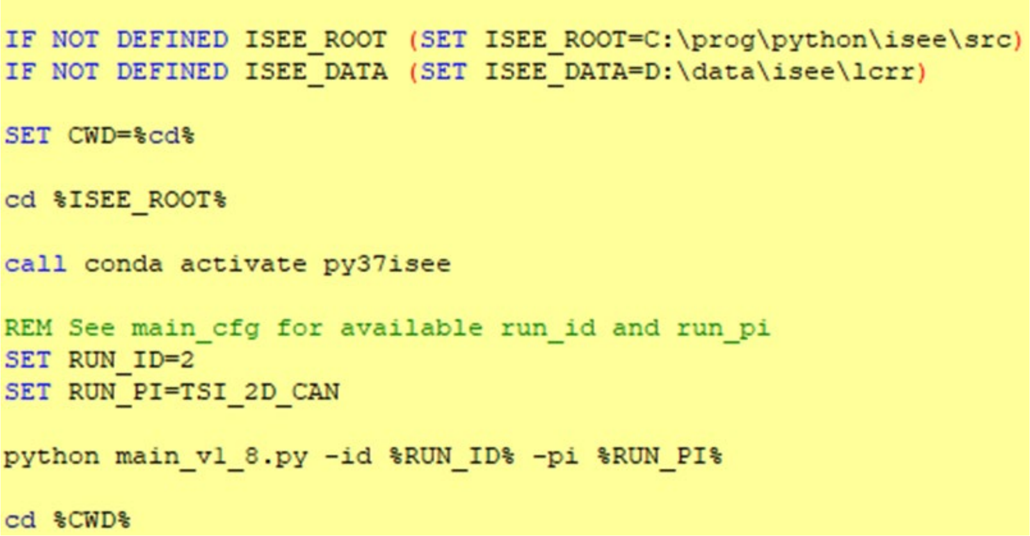
- `call conda activate py37isee`

- `conda activate py37isee`

The ISEE starter module is run using the following Python command:

- `python main_v1_8.py –id %RUN_ID% -pi %RUN_PI%`

The RUN_ID and RUN_PI variables are defined by the user and configure the flood mitigation scenario and the desired performance indicator. *main_v1_8.py* is the main script of ISEE-LCRR (see next section).



```
IF NOT DEFINED ISEE_ROOT (SET ISEE_ROOT=C:\prog\python\isee\src)
IF NOT DEFINED ISEE_DATA (SET ISEE_DATA=D:\data\isee\lcrr)

SET CWD=%cd%

cd %ISEE_ROOT%

call conda activate py37isee

REM See main_cfg for available run_id and run_pi
SET RUN_ID=2
SET RUN_PI=TSI_2D_CAN

python main_v1_8.py -id %RUN_ID% -pi %RUN_PI%

cd %CWD%
```

Figure 4.1.1. Example of startup script on Windows run_isee.bat

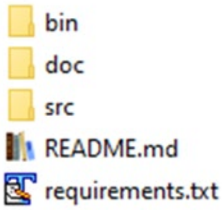
This section presents technical characteristics of the ISEE system such as code and data structure, configuration files, flood mitigation scenarios, how the calculation engine works, the process of interpolation and simplified algorithm for 1D and 2D indicators.

4.2 CODE STRUCTURE

The LCRR ISEE system follows a simple code hierarchy, with the code root defined in the start-up script or in the ISEE_ROOT environment variable.

The root directories are as follows:

- *bin* : Contains the start-up file(s) (.bat or .sh)
- *doc* : Contains the ISEE documentation.
- *src* : The main code is found in this directory while the code specific to PIs is found in the *pi* sub-folder. PI configuration files are in the *cfg* subfolder. An *utils* subfolder contains utility code that can be used on demand or even standalone.



bin
doc
src
README.md
requirements.txt

Figure 4.2.1. Content of ISEE_ROOT

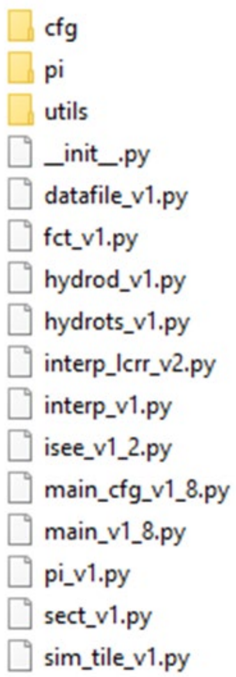

cfg
pi
utils
__init__.py
datafile_v1.py
fct_v1.py
hydrod_v1.py
hydrots_v1.py
interp_lcrr_v2.py
interp_v1.py
isee_v1_2.py
main_cfg_v1_8.py
main_v1_8.py
pi_v1.py
sect_v1.py
sim_tile_v1.py

Figure 4.2.2. Content of src folder

The main start-up module to control the execution of the ISEE system is main_v1_8.py. This is the only module that should be called directly by the python interpreter, except for scripts in the utils directory. The code is modular and each module is specialized in a particular function or task; a generic module to manage PIs, one for tiles, one for time-series, etc. There is also a module specific to each PI.

A free open-source version control system, git (https://git-scm.com/), was used for managing and sharing code between developers. A private management server on github (https://github.com/) was also used for decentralized management and ease of sharing. It contains the latest version of the source code: https://github.com/ECCC-SHE/isee_2

4.3 CONFIGURATION FILES

The ISEE system uses configuration files to modify runtime settings.

There are two types of configuration files:

- the main *main_cfg_v1_8.py* which contain the general settings
- those for each PI (*cfg* directory) which contain parameters that are specific to particular PIs.

The main configuration file contains all the important runtime variables, including some PI parameters such as the class or the PI configuration file to use. It is in this file that the variables chosen by the user, the RUN_ID and RUN_PI variables are defined.

The PI configuration file contains all PI-specific variables. Its content is different from one PI to another and is only used in the PI code.

4.4 DATA STRUCTURE

The ISEE system needs basic input data to ensure its operation: hydrometric time-series (i.e. outputs from the Water Balance Model for each flood mitigation alternative), the ISEE grid, sections and hydrodynamic simulation datasets. Depending on the performance indicator to be calculated, it also needs specific input data of this particular indicator.

Before any ISEE run, all input data is required to be preprocessed and formatted in CSV (comma separated values) files and the land elevation and water level variables converted into a common vertical datum, The North American Vertical Datum of 1988 (NAVD 88).

The data root is set in the start-up script or in the ISEE_DATA environment variable (Figure 4.4.1). All the data that the ISEE needs must be put in this directory. The names of the subfolders and their contents are defined in the main configuration file *main_config_v1_8.py*. They can therefore be modified (Figure 4.4.2).

The essential folders are:

- *dev* : Contains useful development data and execution logs.
- *prod* : Contains ISEE input data.
- *result* : Contains ISEE output data.

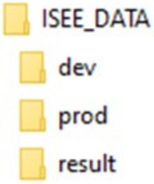


Figure 4.4.1. Content of ISEE_DATA folder .

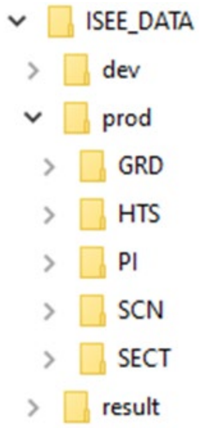
```
fldr_dev = 'dev'
fldr_prd = 'prod'
fldr_out = 'result'
```

Figure 4.4.2. Folder names as defined in the configuration file.

In production mode, the dev folder must contain at least the logs subfolder, where the ISEE output logs are written.

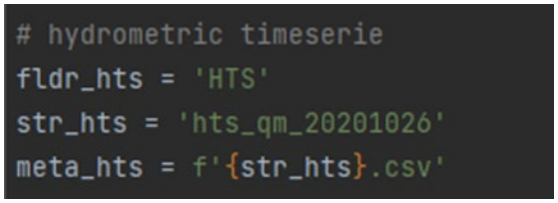
The prod folder contains a folder for each type of input data (Figure 4.4.3). By default, the following folders should be there. Their name can however be modified in the main configuration file (Figure 4.2.2):

- *GRD* : Data from the ISEE grid
- *HTS* : Time-series data
- *PI* : Data specific to each PI
- *SECT* : Section data
- *SCN* : Data from hydrodynamic model scenarios interpolated on the ISEE grid



- ISEE_DATA
  - dev
  - prod
    - GRD
    - HTS
    - PI
    - SCN
    - SECT
  - result

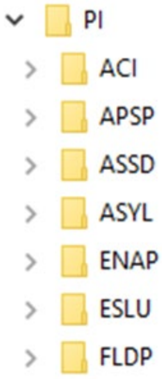
Figure 4.4.3. Content of the prod folder



```
# hydrometric timeserie
fldr_hts = 'HTS'
str_hts = 'hts_qm_20201026'
meta_hts = f'{str_hts}.csv'
```

Figure 4.4.4. Name of the time-series folder as defined in the configuration file

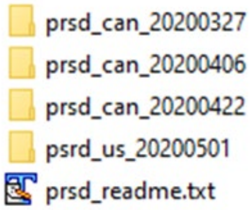
The PI folder has a subfolder for each PI, containing the specific input data for that PI (Figure 4.4.5). Their name is defined in the main configuration file.



PI
- ACI
- APSP
- ASSD
- ASYL
- ENAP
- ESLU
- FLDP

Figure 4.4.5. Example of the content of the PI folder

For each of these data directories, there can be several versions of the data. The subdirectory containing the data used is also defined in the main configuration file (for basic data) or in the PI configuration file (for PI data). A readme file contains a description of each of the folders. By default, the folder also contains the date of its creation (Figure 4.4.6).

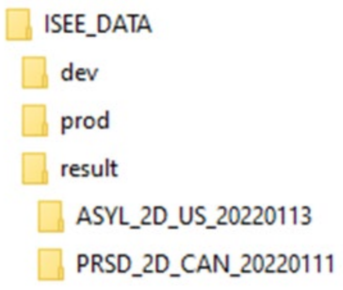


prsd_can_20200327
prsd_can_20200406
prsd_can_20200422
psrd_us_20200501
prsd_readme.txt

Figure 4.4.6. Example of subdirectories for the PRSD performance indicator

The ISEE system creates a detailed log file of all the calculations and associated configurations. This file is found in the *dev/logs* directory. This file can contain a lot of default information and the level of detail in the main configuration file can be modified. The file name is in the following form: *log_isee_lcrr_[PI name]_[version of ISEE]_[date]_[hms].log*

The ISEE system writes the results in a folder it creates under result during execution. The name of this folder is of the following format PI_[alternative]_[date]_[hms] (Figure 4.4.7). The log file is also copied in the folder.



ISEE_DATA
dev
prod
result
ASYL_2D_US_20220113
PRSD_2D_CAN_20220111

Figure 4.4.7. PI results folder examples

4.5 HYDROMETRIC TIME-SERIES (HTS)

The ISEE system time-series are outputs from the Water Balance Model (WBM) and consist of series of average daily water levels simulated using historical net basin supply under the baseline and flood mitigation scenarios (see section 3.2). The WBM time-series are one of the primary and essential sources of input data for ISEE to be able to calculate the historical levels and velocity throughout the system. Time-series contain level and flow data at various key locations in the study area (Rouses Point, Saint-Jean-sur-Richelieu, Chambly, Saint-Ours and Sorel). For the LCRR study, the time-series ranging from 1924 to 2018 were converted to quarter-months (QM) for a total of 4,476 time steps. For each of the WBM locations, the minimum, maximum and average values reached within QM were estimated.

The time-series identifiers in the code are as follows:

Table 4.5.1. Identifiers associated to the baseline and flood mitigation scenarios hydrological time-series.

HTS_ID	Alternative
0	Actual state (Baseline)
1	Alternative 2 (Major diversion through the Chambly Canal)
2	Alternative 1 (Selective excavation of the St-Jean-sur-Richelieu shoal with submerged weir.)
3	Alternative 3 (Selective excavation of the St-Jean-sur-Richelieu shoal with submerged weir and minor diversion through the Chambly Canal)

4.6 ISEE GRID (GRD)

To limit memory use, the ISEE system divides data and calculations into planimetric square tiles of 10 km by 10 km. Forty-seven tiles were created to cover an area delimited by a polygon representing the flood extent matching a lake level of 32.18 m and a discharge of 2,204 m^3/s (hydrodynamic scenario 11E, Boudreau et al. 2015). This flood level represents the highest level integrated in the ISEE system. Unique points were generated every 10 m, which represents up to 1 million points per tile for a total of 25 million points.

As ISEE loops each tile at run time, most data are stored by tile for more I/O efficiency.

Grid points are the basic data unit; each dataset (DEM, water level, depth, etc.) being resampled or interpolated on this grid using an inverse distance weighting (IDW) algorithm.

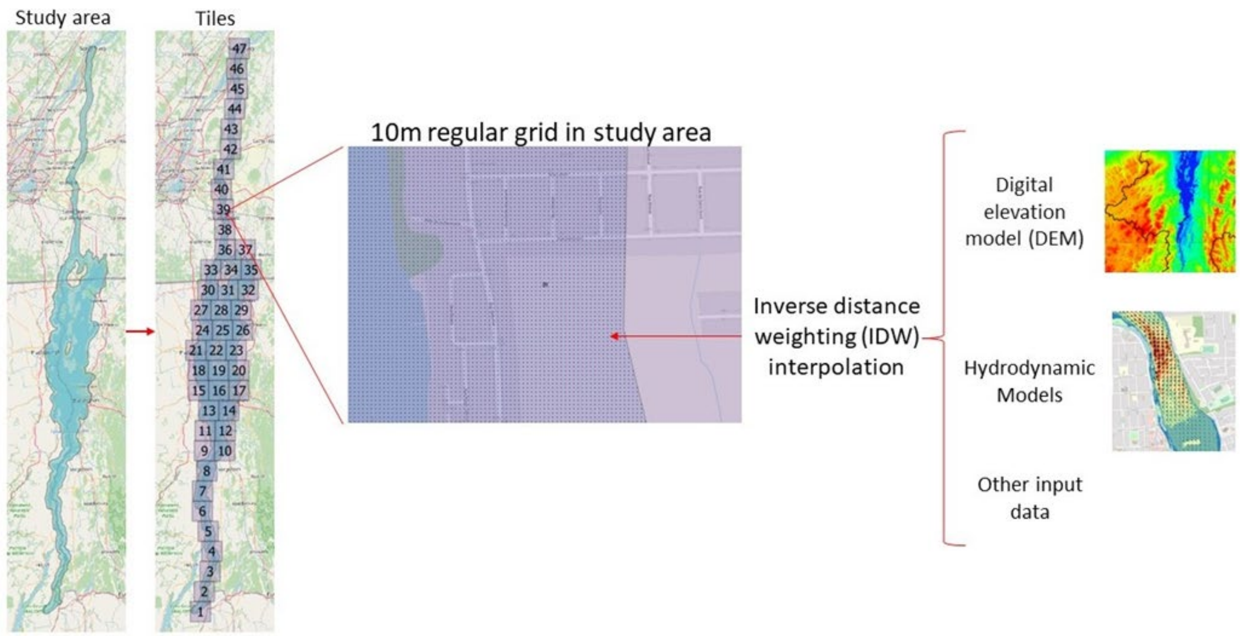


Figure 4.6.1. Data integration on the ISEE grid and data tile structure.

The ISEE system also separates the study area into six distinct sections. This separation is necessary to account for differences in the physical properties of each section and the distinct performance indicators developed on each side of the border. The sections are modelled with different parameters to cover as many scenarios as possible (see section 3.4 2D Hydrodynamic Model).

The tiles are numbered from 1 to 47 and the sections are identified this way:

Table 4.6.1. Section identifiers associated to tiles and specific locations.

SECT_ID	Locations	Tiles
10*	Lake Champlain	1 à 32, 34, 35, 37
11	Lake Champlain, US side	1 à 32, 34
12	Lake Champlain, CAN side	34, 35, 37
20	Rouses Point to Saint-Jean-sur-Richelieu	30, 33, 34, 36 à 39
30	Saint-Jean-sur-Richelieu to Chambly	39, 40
40	Chambly to Saint-Ours Dam	40 à 45
50	Saint-Ours to Sorel	45 à 47

* Section 10 is the combination of sections 11 (US) and 12 (CAN).
Tiles 30, 34 and 37 overlap sections 10 and 20.
Tile 39 overlaps sections 20 and 30.
Tile 40 overlaps sections 30 and 40.
Tile 45 overlaps sections 40 and 50.

4.7 HYDRODYNAMIC SIMULATION DATASETS

Twelve different hydrodynamic simulation datasets, each with over 22 different scenarios (discharge or lake level increments), are needed to cover the range of flow stage in all sections (see section 3.4 2D Hydrodynamic Model). These data are interpolated on the ISEE grid and stored by tile.

The existing model datasets and their identifier in the code are:

Table 4.7.1. Hydrodynamic simulations datasets associated to their respective folder and description.

HYD_ID	Folder	Description
1	base	Sections 10-20-30; Baseline (44 scenarios)
2	2_3p10	Section 40 – Sorel at 3.10m (SO closed) (48 scenarios)
3	2_5p00	Section 40 – Sorel at 5m (SO opened) (48 scenarios)
4	2_7p00	Section 40 – Sorel at 7m (SO opened) (48 scenarios)
5	2_8p20	Section 40 – Sorel at 8.2m (SO opened) (48 scenarios)
6	3_3p10	Section 50 – Sorel at 3.1m (48 scenarios)
7	3_5p00	Section 50 – Sorel at 5m (48 scenarios)
8	3_7p00	Section 50 – Sorel at 7m (48 scenarios)
9	3_8p20	Section 50 – Sorel at 8.2m (48 scenarios)
10	chan_open	Sections 20-30; Big Diversion (derivation) (53 scenarios)
12	renat_shoal	Sections 20-30; Crump Weir (shift-control) (43 scenarios)
13	renat_shoal_div	Sections 20-30; Crump weir with diversion (shift-control) (22 scenarios)

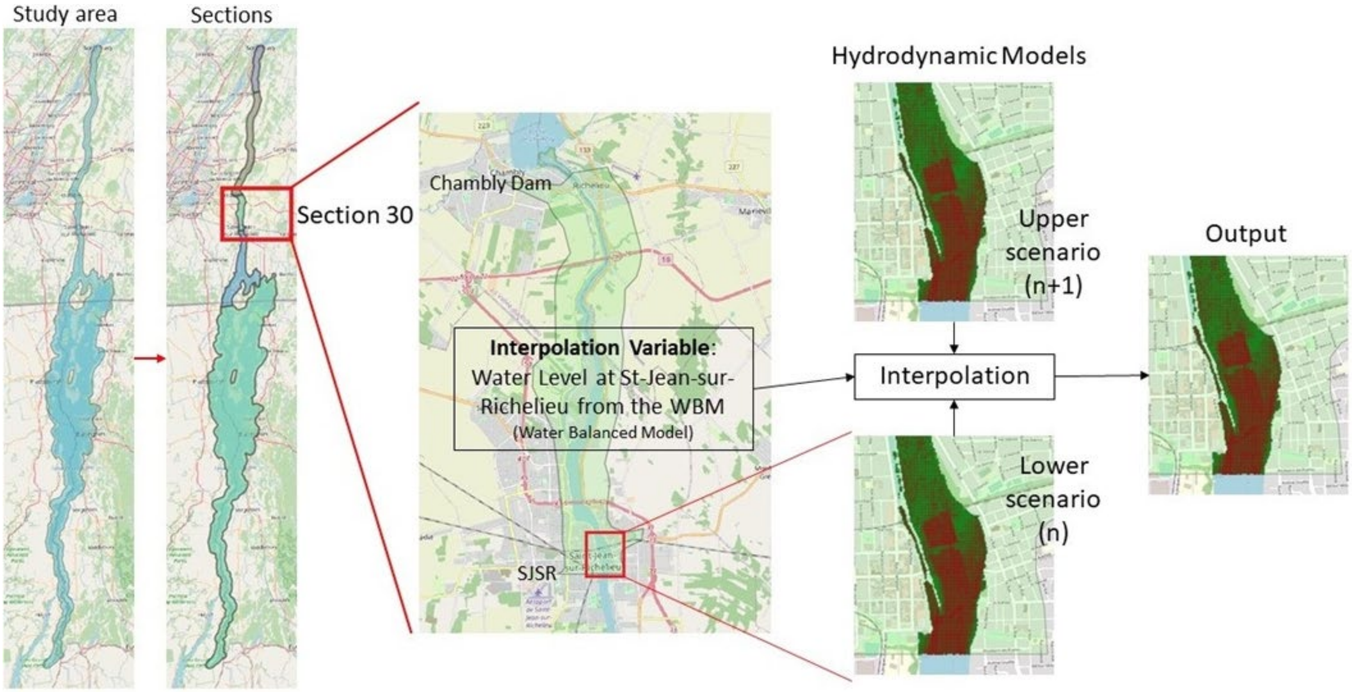


Figure 4.7.1. ISEE Example of the hydraulic map interpolation process in a section.

4.8 MAIN ENGINE

The following tables summarize, for each alternative and section, the parameters, data and type of interpolation used to generate hydraulic maps at a particular time step. For sections 10, 40 and 50 the same conditions and models are used.

WL_RP = Water level at Rouses Point (Lake Champlain)
WL_SJ = Water level at Saint-Jean-sur-Richelieu
Q_CHA = Discharge at Chambly
WL_SO = Water level downstream of Saint-Ours
WL_S = Water level at Sorel

Table 4.8.1. Sections, data and interpolation type used for all alternatives by conditions for sections 10, 40 and 50

Section ID	Section	Condition1*	Condition2*	Interpolation variable(s)	Hydro 2D datasets	Interpolation
10	Lake Champlain			WL_RP	HYD 1	Simple
40	Chambly to Saint-Ours	Saint-Ours Dam closed Q_CHA>1050		WL_S Q_CHA	HYD 3-4-5	Double
40	Chambly to Saint-Ours	Saint-Ours Dam closed Q_CHA<1050	WL_SO>6.80	WL_S Q_CHA	HYD 3-4-5	Double
40	Chambly to Saint-Ours	Saint-Ours Dam closed Q_CHA<1050	WL_SO<6.80	Q_CHA	HYD 2	Simple
40	Chambly to Saint-Ours	Saint-Ours Dam opened Q_CHA>950		WL_S Q_CHA	HYD 3-4-5	Double
40	Chambly to Saint-Ours	Saint-Ours Dam opened Q_CHA<950	WL_SO>6.76	WL_S Q_CHA	HYD 3-4-5	Double
40	Chambly to Saint-Ours	Saint-Ours Dam opened Q_CHA<950	WL_SO<6.76	Q_CHA	HYD 2	Simple
50	Saint-Ours to Sorel			WL_S Q_CHA	HYD 6-7-8-9	Double

**The conditions for opening and closing the Saint-Ours dam are different depending on its current state. If the dam is closed, it will open if the flow is greater than 1050 m³/s or if the level downstream of Saint-Ours is greater than 6.80 m due to the effect of a high level of the St. Lawrence River. If the dam is open, it will close only if the flow is lower than 950 m³/s and if the level downstream of Saint-Ours is lower than 6.76 m.*

Table 4.8.2. Sections, data and interpolation type used for the Baseline scenario for sections 20 and 30.

Section ID	Section	Interpolation variable	Hydro 2D datasets	Interpolation	Note
20	Rouses Point to St-Jean-sur-Richelieu	WL_RP	HYD 1	Simple	Slope correction
30	St-Jean-sur-Richelieu to Chambly	W_SJ	HYD 1	Simple	

Table 4.8.3. Sections, data and interpolation type used for Alternative 1 for sections 20 and 30

Section ID	Section	Interpolation variable	Hydro 2D datasets	Interpolation	Note
20	Rouses Point to St-Jean-sur-Richelieu	WL_RP	HYD 12	Simple	Slope correction
30	St-Jean-sur-Richelieu to Chambly	WL_SJ	HYD 12	Simple	

Table 4.8.4. Sections, data and interpolation type used for Alternative 1 for sections 20 and 30.

Section ID	Section	Condition1	Interpolation variable	Hydro 2D datasets	Interpolation	Note
20	Rouses Point to St-Jean-sur-Richelieu	Channel closed = baseline	WL_RP	HYD 1	Simple	Slope correction
20	Rouses Point to St-Jean-sur-Richelieu	Channel opened	WL_RP	HYD 10	Simple	Slope correction
30	St-Jean-sur-Richelieu to Chambly	Channel opened = baseline	WL_SJ	HYD 1	Simple	
30	St-Jean-sur-Richelieu to Chambly	Channel opened	WL_SJ	HYD 10	Simple	

Table 4.8.5. Sections, data and interpolation type used for Alternative 3 by conditions for sections 20 and 30.

Section ID	Section	Condition1	Interpolation variable	Hydro 2D datasets	Interpolation	Note
20	Rouses Point to St-Jean-sur-Richelieu	Diversion closed = Alt 1	WL_RP	HYD 12	Simple	Slope correction
20	Rouses Point to St-Jean-sur-Richelieu	Diversion opened	WL_RP	HYD 13	Simple	Slope correction
30	St-Jean-sur-Richelieu to Chambly	Diversion closed = Alt 1	WL_SJ	HYD 12	Simple	
30	St-Jean-sur-Richelieu to Chambly	Diversion opened	WL_SJ	HYD 13	Simple	

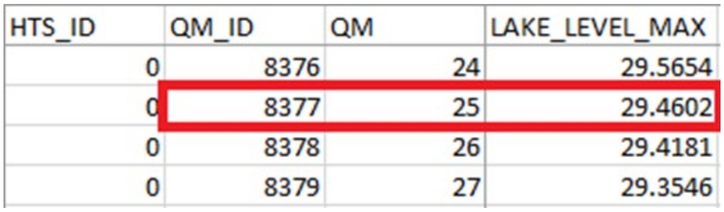
For section 20 (Rouses Point to St-Jean-sur-Richelieu), ISEE performs a water surface slope correction to incorporate the variations in roughness due to plant growth and ice cover accounted for in the Water balance model.

In order to accelerate the processing, the points of each tile are filtered to only keep the necessary grid points for PI calculations.

4.8.1 Simple interpolation

This method consists of creating a hydraulic map (water level, velocity at each grid point) by interpolating between two hydrodynamic scenarios (i.e. two hydraulic maps separated by an 10 cm water level increment). An 'interpolation variable' in the time-series is used to calculate the ratio between the lower and upper scenario values in the metadata. This ratio between the two bounds is used to determine the weighting of each of the two hydrodynamic scenarios at each grid node.

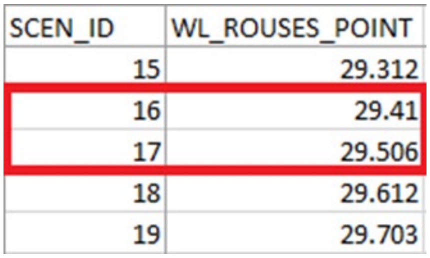
For example, for section 10, the 'interpolation variable is WL_RP (i.e. the water level at Rouses Point, identified as LAKE_LEVEL in the Water balance model output (HTS). Let the lake level be 29.4602 at QM_ID 8377



HTS_ID	QM_ID	QM	LAKE_LEVEL_MAX
0	8376	24	29.5654
0	8377	25	29.4602
0	8378	26	29.4181
0	8379	27	29.3546

Figure 4.8.1. Part of content of the baseline timeseries that shows the water level of the Lake Champlain for the QM_ID 8377.

ISEE finds the hydrodynamic scenarios that are closest to this level (upper and lower) and calculates the interpolation ratio. In this particular case, ISEE finds the upper and lower bounds to be hydrodynamics scenarios (SCEN_ID) 16 and 17 for the lake.



SCEN_ID	WL_ROUSES_POINT
15	29.312
16	29.41
17	29.506
18	29.612
19	29.703

Figure 4.8.2. Part of content of the hydrometric model metadata that shows the water level at Rouses Point for the scenarios 16 and 17.

The interpolation ratio is calculated such that:

```
Ratio = (29,4602 – 29,41) / (29,506 – 29,41) = 0.5229
```

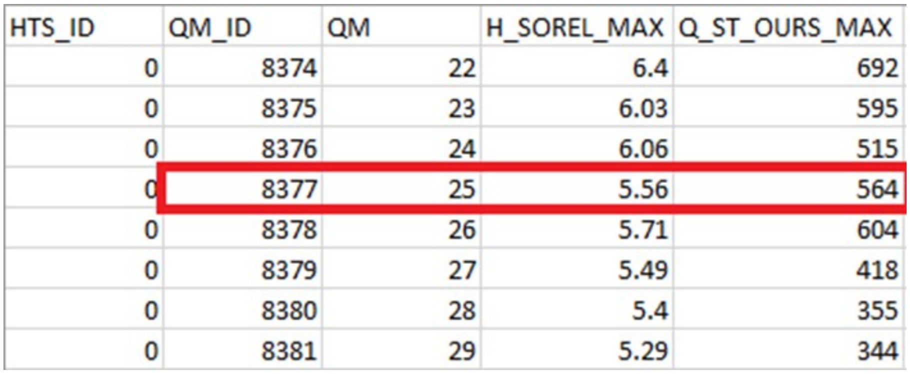
This value is then used to generate hydraulic maps (water level and velocity) at each grid point using hydrodynamic scenarios 16 and 17, such that

```
WL = WL_Scen_16 + Ratio * (WL_Scen_17 – WL_Scen_16)
```

4.8.2 Double interpolation

The double interpolation process is used to create hydraulic maps in the section downstream of Chambly using two conditions: discharge and the water level of the St-Lawrence River. The double interpolation process is similar to single interpolation, but it is applied twice, using two hydraulic simulation datasets. ISEE starts by the two hydrodynamic scenarios bounds according to each of the two interpolation variables, calculates ratios and interpolate values. Then, the values are combined.

For example, for section 50, the 'interpolation variables' are the water level at Sorel (H_SOREL) and the discharge (Q_ST_OURS). Let H_SOREL be 5.56 m and WL_S and 564 m^3/s at QM_ID 8377

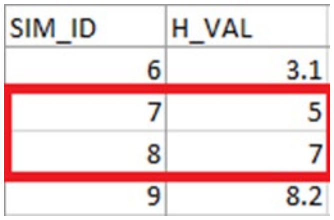


HTS_ID	QM_ID	QM	H_SOREL_MAX	Q_ST_OURS_MAX
0	8374	22	6.4	692
0	8375	23	6.03	595
0	8376	24	6.06	515
0	8377	25	5.56	564
0	8378	26	5.71	604
0	8379	27	5.49	418
0	8380	28	5.4	355
0	8381	29	5.29	344

Figure 4.8.3. Part of content of the baseline time-series that shows the water level of the St-Lawrence River at Sorel and the discharge at Saint-Ours for the QM_ID 8377.

The water level at Sorel is 5.56 m. The two hydrodynamic simulation datasets with the closest values are S 5 m and 7 m. We will therefore interpolate between SIM_ID 7 and 8, with a ratio of 0.28, such that

```
SIM_RATIO = (5.56 – 5.00) / (7.00 – 5.00) = 0.28
```

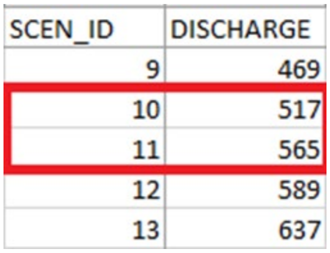


SIM_ID	H_VAL
6	3.1
7	5
8	7
9	8.2

Figure 4.8.4. Part of content of the hydrometric model metadata that shows SIM_ID equivalent for the water level of the St-Lawrence River at Sorel.

Within these hydrodynamic simulation datasets, we then find the lower and upper hydrodynamic scenarios closer to the discharge of 564 m^3/s, which are SCEN_ID 10 and 11. A ratio of 0.979 is obtained, such that

```
SCEN_RATIO = (564 – 517) / (565 – 517) = 0.979
```



SCEN_ID	DISCHARGE
9	469
10	517
11	565
12	589
13	637

Figure 4.8.5. Extract of hydrodynamic simulation dataset metadata that shows the discharge at Saint-Ours for the scenarios 10 and 11.

The ratios are then used to calculate water level and velocity at each grid point using the model results from scenarios 10 and 11 of the hydrodynamic simulation datasets SIM_ID 7 and 8:

```
WL_SIM_7 = WL_SIM_7_Scen_10 + SCEN_RATIO * (WL_Scen_SIM_7_11 –
WL_Scen_SIM_7_10)
```

```
WL_SIM_8 = WL_SIM_8_Scen_10 + SCEN_RATIO * (WL_Scen_SIM_8_11 –
WL_Scen_SIM_8_10)
```

We will then use the values of the two grids and the ratio between SIM_ID 7 and 8 to obtain the resulting hydraulic maps over the whole grid.

```
WL = WL_SIM_7 + SIM_RATIO * (WL_SIM_8 - WL_SIM_7)
```

4.9 SIMPLIFIED ALGORITHM

4.9.1 Algorithm for 1D PIs

```
Loading PI parameters
Time series filtering
Filtering sections to roll
Filtering Rolling Tiles
For each section:
      For each tile in the section:
            For each qm of the time series:
                  PI response function
            Concatenation of results
Aggregation of results
Preparation of results
Writing results
```

4.9.2 Algorithm for 2D PIs

```
Loading PI parameters
Time series filtering
Filtering sections to roll
Filtering Rolling Tiles
For each section to roll:
      Pre-calculation of time series parameters
      For each rolling tile in the section:
            Filtering the points of the tile according to the PI
            Filtering the points of the tile in the section (partial tile)
            For each qm to roll in the time series:
                  Calculation of physical variables on all points of the tile
                  PI response function
                  Concatenation of results
Aggregation of results
Preparation of results
Writing results
```

4.10 PERFORMANCE OF THE LCRR ISEE SYSTEM

The following statistics are based on a run with a time-series of 4,476 time steps in QM.

4.10.1 Size of data

The ISEE system uses and produces a considerable amount of data. To analyse the baseline and three mitigation alternatives with all available PIs in the LCRR, 132 GB are used as input data, 32 GB for the basic input and 100 GB for the PI input. The size of the output depends on the PI, ranging from as low as 1 MB for simple 1D PI to up to 5000 MB for complex 2D PI with many different kinds of results. On average, the size varies between 20 MB and 50 MB.

4.10.2 Processing time

The processing time of the ISEE system depends greatly on the PI, from a few seconds for a simple 1D PI to up to 40 hours for very complex 2D PI that uses the wetlands prediction results. This time is also dependent of the workstation where ISEE runs.

4.10.3 Portability

All the code, date and python interpreter can fit on a 256 GB USB drive, and can be setup up and ready to run on any system.

4.10.4 Improvements and future of ISEE

The implementation of the following features could be considered in future versions of ISEE:

- Adding PI dependency.
- Add a simple graphical interface (GUI) to improve usability.
- Adding multithreading and/or parallel computing.
- Adding GPU processing to improve performance.

5 CONCLUSION

In response to the devastating floods of 2011, the governments of Canada and the United States mandated the IJC to study options for mitigating the impact of flooding. To evaluate the benefits and impacts of different mitigation alternatives, the LCRR Study developed the Integrated Social Economic Environmental (ISEE) system.

The ISEE system is an integrated modelling platform combining physical, socio-economic and environmental models to quantify the effects of mitigation measures using PIs. The ISEE system allows the simulation of water levels in the study area, their variation over time, and the socio-economic and environmental impacts associated with flooding and changes in the water level regime.

The integrated modelling approach allows for the analysis of various water management issues using a consistent methodology. For the LCRR study, the ISEE system integrates three structural flood mitigation scenarios: a flow diversion through the Chambly canal, a selective excavation with a submerged weir, and the latter with an additional minor diversion through the canal.

The developed open-source tool coded in Python includes the following components:

- A Water Balance Model integrating the effect of the natural shoal at Saint-Jean-sur-Richelieu that controls Lake Champlain outflows and levels. The model is able to reproduce historical water levels and outflows at key locations along the water body based on the daily volume changes in the lake and variation in net basin supply.

- A Digital Elevation Model (DEM) built with a collection of the most accurate available topographic LiDAR and bathymetric data. Data processing obtained a seamless 10 m resolution DEM containing around 250 M points.

- 2D Hydrodynamic simulation datasets for the different sections of the water body, for the different flood mitigation alternatives. Steady state simulations produced at increments of 10 cm, ranging from extreme low to extreme high flows (25-2,500 m^3/s) in the Lower Richelieu River.

- An interpolation engine recreating hydraulic maps based on the conditions defined by the water balance model for a particular time step. The complex and distinct hydraulics of the different sections of the water body are produced while considering the seasonal variation in plant growth and ice cover, the input of local tributaries, the management of the Saint-Ours dam and a backwater effect of the St. Lawrence River.

- A collection of geospatial datasets describing the various components of the LCRR basin, including physical (e.g. slopes, bed substrate), social (e.g. population vulnerability), economic (e.g. crops, buildings) and environmental (e.g. wetlands, land use).

- Performance indicators (PIs) reflecting how society, economy and environment are affected by a change in water level due to the proposed alternatives. PIs are based on a response function predicting impacts based on hydraulic data (water level, velocity). Twenty-nine PIs describe various social, economic and environmental impacts, as well as impacts on sensitive indigenous interests.

The LCRR ISEE grid consists of one point every 10 m and it is the base unit of ISEE calculation. Due to the size of the study area and to decrease computational time, the ISEE grid was divided into 10 km^2 tiles. At each node, all necessary physical variables used by PI functions for each time-step (quarter-month) of a water-level time-series are calculated and all input data are interpolated on the grid. Examples of physical variables used include bottom slope, water depth, and hydroperiods (number of dry-wet cycles, number of dry quarter-months, mean water depth during a specific period, etc).

The ultimate outputs of the ISEE system are the various PI results. The 1D PIs provide the impact on a resource/interest based on a single value per time step for the entire study area, whereas 2D PI results are distributed on the grid, showing where benefits or drawbacks are found. ISEE results allow evaluation of flood mitigation alternatives by comparing simulations to a baseline scenario, for a specific high or low flow event or on average over a long period.

In addition to providing a representation of the potential impacts of various mitigation alternatives, the ISEE system represents an innovative method for modelling the variations in both space and time of the hydraulics (water levels and velocities), social impacts (social and territorial sensitivity), economics (damage to buildings, income loss etc.) and ecosystem components (succession of wetland classes, spawning or nesting habitat for certain species, etc.) over a large scale. A substantial number of results and products developed during this project will be made available to the public. These include hydrodynamic simulations, building elevation, floristic surveys, and projected spatiotemporal distributions of wetland classes and habitat maps of species of interest.

In the future, ISEE could be used and possibly expanded as part of further studies (e.g. conceptual phase, environmental impact assessment) by adding lake and river tributaries, revised alternative scenarios, or additional PIs (e.g., marina accessibility, erosion, etc.). The ISEE system is a flexible tool and in other contexts, such as climate change studies or in the context of extreme flood or drought events, the ISEE system could generate steady-state series simulating more extreme hydrological conditions. It could also be used to evaluate the benefits of wetland conservation, restoration or creation programs aiming at reducing flooding impacts and protecting biodiversity. As ISEE can predict the distribution of broad wetland classes, it can also be used to develop specific measures dedicated to a given vegetation class. In this sense, it can provide information to evaluate conservation efforts of key ecosystem services, such as nesting habitat of endangered birds. Finally, the ISEE system has the potential to be adapted and applied in other basins to evaluate water level management plans and the implementation of water level and flow control structures, to assess the resilience of human populations and ecosystems to climate change, and to evaluate riparian or wetland restoration projects.

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Appendix A

Comparison of water levels simulated in ISEE and measured at hydrometric stations at four locations in the LCRR basin.

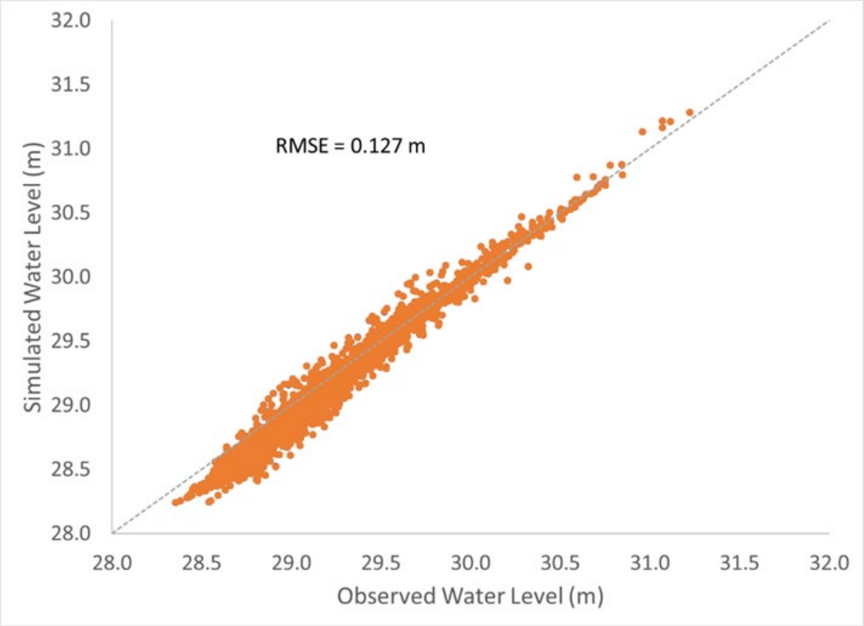

Figure A-1: Comparison of simulated water levels in ISEE with average observed water level for every quarter-month between 1924 and 2017 at Rouses Point.

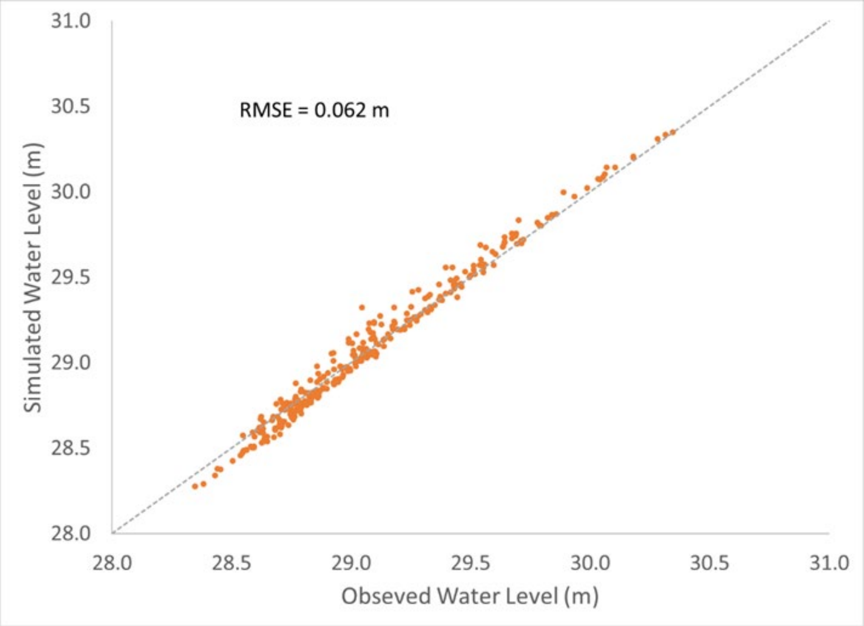

Figure A-2: Comparison of simulated water levels in ISEE with average observed water level for every quarter-month between 2011 and 2017 at Saint-Paul-de-l'île-aux-Noix.

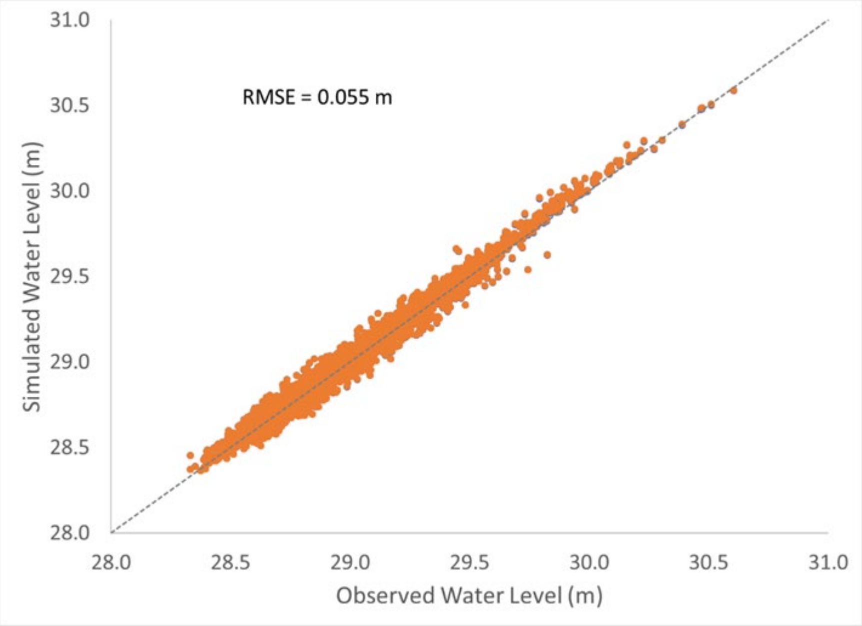

Figure A-3: Comparison of simulated water levels in ISEE with average observed water level for every quarter-month between 1972 and 2017 at Saint-Jean-sur-Richelieu.

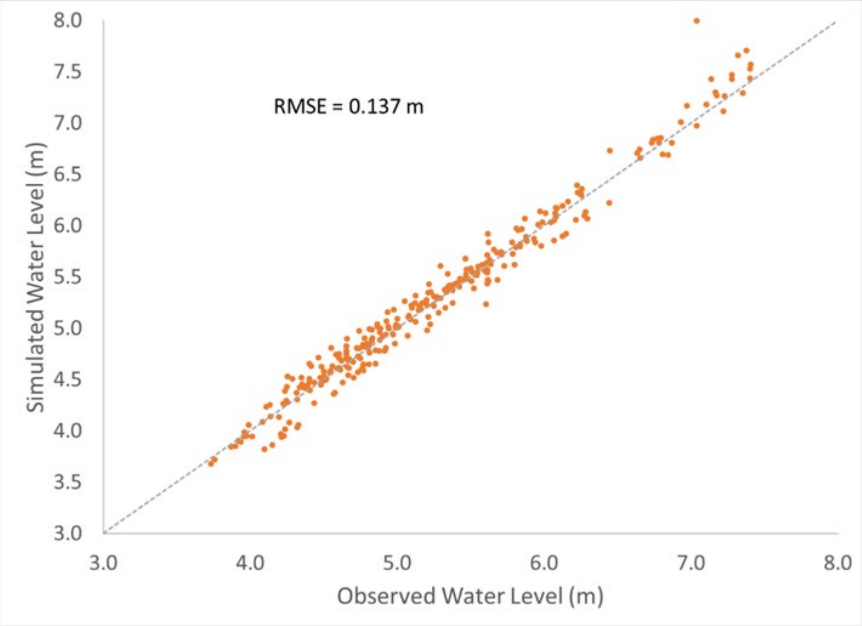

Figure A-4: Comparison of simulated water levels in ISEE with average observed water level for every quarter-month without ice between 2005 and 2017 at Saint-Ours (downstream of the dam).

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