CGU HS Committee on River Ice Processes and the Environment
23rd Workshop on the Hydraulics of Ice Covered Rivers
St. John's, Newfoundland and Labrador, Canada, June 9-12, 2025.

Using an operational index to foresee future ice scenarios in the Upper St. Lawrence River

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The upper St. Lawrence River between Kingston, at the mouth of Lake Ontario, and Montreal, about 250 km downstream, is an important river reach, with hundreds of infrastructure assets along its shorelines. Hydroelectric dam facilities regulate the flow along that reach. In the winter, water discharge is carefully managed to promote ice coverage and limit backwater extent, and is guided by an operational ice status index (ISI). This paper describes a study to anticipate ice season length and the number of mid-winter break-ups. The study covers two key sites: Lake St. Lawrence downstream of Kingston, in the international (Canada/USA) section of the river, and Canal Beauharnois, near Montreal. An ice presence prediction method was developed based on air temperature thresholds and validated against historical ISI records. This prediction method was applied, using input data from future climate scenarios, to provide information on the effects of projected climate change on the ice cover at the key sites. The modelling of future ice presence was performed using two sets of air temperature input data (climate scenarios RCP 4.5 and 8.5) over two periods (2040-2060 and 2080-2100). The predictions indicate an ongoing reduction in the ice season length due to progressively later season starts and earlier season ends. A modest increase in the number of freeze-up/break-up cycles is possible for the 2040-2060 period.

1. Introduction

The St. Lawrence River, located in central Canada, south of Ottawa, flows north-easterly from Lake Ontario to the Gulf of St. Lawrence. The reach of interest to the present paper, herein referred to as the "Upper St. Lawrence River", is between Kingston, at the mouth of Lake Ontario, and Montreal, about 250 km downstream (Figure 1). The river width varies from about one to six kilometres, and the difference in water level between these two locations is about 54 m. Within that reach, several dam structures regulate the flow on an ongoing or as-needed basis (Figure 2). The water discharge (or "flow") – which averages about 7000 $m^3/s \pm 3000$ m^3/s in any given winter – is controlled mainly by the Moses-Saunders hydroelectric dam, in Cornwall, which straddles the Canada-USA border. The Long Sault Dam, on the American side, can also be utilized if the capacity of Moses-Saunders is exceeded. Upstream, there is the Iroquois Dam, which is not used for flow management, but can function to suppress high water levels. Near Montreal, there are the Beauharnois and Coteau-Les Cèdres hydroelectric dams, which are run-of-the-river structures that share the discharge from upstream – the releases at these facilities are typically made to match those of the Moses-Saunders Dam (GLAM, 2021). The waterway is managed by the International Joint Commission (IJC - https://www.ijc.org/en) through its various boards and committees. The members of that Board are from Canada and the USA. River flow is controlled according to a regulation plan that considers various interests, such as municipal and industrial water use, hydropower, and commercial navigation (IJC, 2014).

Most of the river freezes every winter. The operators have to regulate flow carefully in the presence of ice, as it can cause issues, namely, floods induced by ice jams and frazil ice. The discharge is reduced at the beginning of the winter to promote the formation of a stable ice cover, after which it may be gradually increased. This is a common procedure used in other regulated rivers. However, a challenge the operators have been encountering in the last decade or so is the occurrence of mid-winter break-up events. This greatly complicates their operations. For example, during the winter of 2016-17, the ice cover along the Upper St. Lawrence River went through a total of five sequences of freezing and melting, resulting in complex adjustments to the outflow of Lake Ontario that winter.

2. IJC's requirements

IJC required projections of future ice scenarios to support mid- to long-term preparedness. This included information on plausible changes in ice season length and mid-winter freeze-up events. NRC made them aware of already existing hydraulic or numerical models (Das and Lindenschmidt, 2021; Rokaya et al., 2022; Barrette et al., 2024). That avenue was not feasible, however, since utilizing these models would have required specialized river ice modeling expertise in-house, which they did not have. IJC expressed interest in a self-contained solution that would allow them to generate their own assessments without external support. An alternative was to use historical ice coverage data from the St. Lawrence River, correlate it with past climatological parameters, and then extend that correlation into the future in conjunction with downscaled climate data. But the lack of sufficient information on ice coverage also made that solution impractical.

3. Objective

To address this impasse, NRC utilized the IJC's record of Ice Status Index (ISI), a three-fold classification system that operators use in the winter as a proxy for ice cover extent and stability. This approach was unconventional, as the ISI was not designed for use in predictive ice modelling, but it was pursued as a practical solution to the problem. The objective of this paper is to describe the ISI system and how it was used to foresee future ice scenarios.

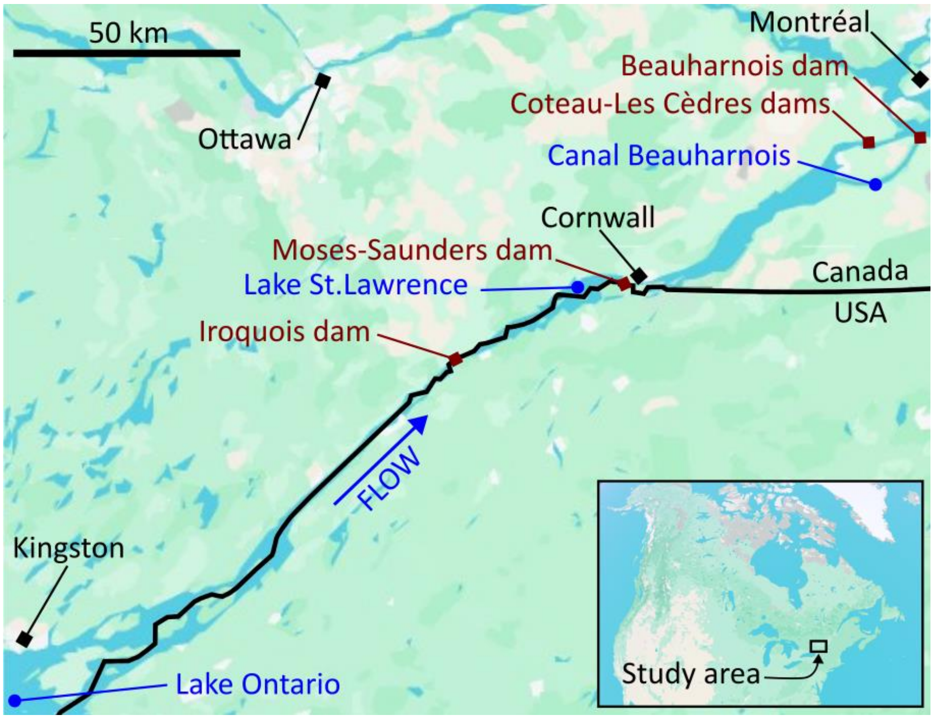

Figure 1. Location of the various elements mentioned in this paper.
Source for the base maps: Google Earth.

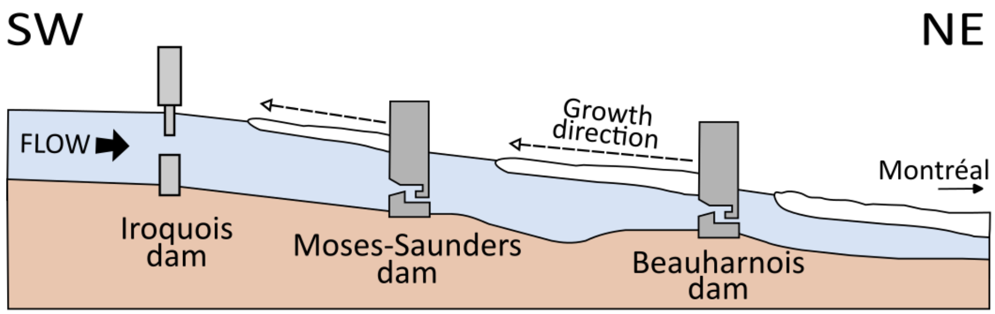

Figure 2. Dam structures on the Upper St. Lawrence River. In the winter, ice typically forms upstream of each dam, starting with the Beauharnois dam. The open water downstream of the dams is due to the turbulence. This is an example of an ISI=2 scenario (stable ice covers). Not to scale. Adapted from International Lake Ontario-St. Lawrence River Board (ILO-SLRB).

4. The ISI

The ultimate aim of winter flow management on the Upper St. Lawrence River is to achieve a stable ice cover, i.e., one that attains sufficient strength and/or thickness to be able to withstand the gravitational load exerted on it by the upstream ice and the frictional forces at the water-ice interface. Without this stability, the cover would fail, potentially leading to rubble pile-ups and consequent floods upstream due to elevated backwater levels. Other considerations also need to be factored in. For instance, the turbines of the Moses-Saunders dam require a minimum net head to function properly (a sufficiently higher water level on the upstream side than on the downstream side), and excessive backwater can reduce that head. Avoiding negative impacts of low water levels on municipal water intakes, including frazil ice risk, is also a factor.

This is where the ISI system comes in. It is a three-fold (0-1-2) classification protocol to identify three stages of ice formation as they relate to decisions on river discharge. A daily ISI value is assigned to each of two areas – Canal Beauharnois and Lake St. Lawrence (Figure 1) – and is mostly based on ice cover extent. This record of ice conditions is used by the IJC in their water regulation and routing modelling to evaluate potential changes to the water regulation plan.

- Under open water conditions in the Fall, ISI is assigned a value of 0.
- As air temperatures drop and the ice cover forms, the ISI is assigned a value of 1, which means the discharge may be lowered to favor the formation of a smooth ice cover.
- When an ice cover is deemed capable of accommodating normal discharge without breaking, it is then referred to as "stable," and the ISI is assigned a value of 2. At that point, the discharge may be increased.

Ice coverage is evaluated by the operators from different sites, including imagery collected during air flights. In many cases, the decision to adjust the ISI value is also based on other parameters, such as water differential (due to ice roughness), a visual appreciation of ice cover strength, and the tension recorded in booms. Operator experience plays a substantial role in these decisions, which are subjected to various 'limits' decreed by the IJC. Ultimately, the judicious flow control at each dam is meant to mitigate flood risk anywhere around Lake Ontario and along the river while ensuring water levels do not drop too much so as not to impact municipal water supply intakes. This is a delicate balancing act. For instance, increasing outflow from Lake Ontario, when a reduction in water levels is required to mitigate floods along its shorelines, increases the risk of floods downstream on parts of the St. Lawrence River shorelines.

The following are two examples of flow management in a given year: a simple scenario (a desirable outcome) in the winter of 2018-19 and a complex one (involving mid-winter break-ups) in the winter of 2016-17. Both are for conditions in Canal Beauharnois.

Example of a simple scenario

On January 11, 2019, ice began to form in Canal Beauharnois at its downstream end, where the dam is, and quickly progressed upstream. On that day, the ISI for that site was raised from 0 to 1, and the discharge reduced from 8540 m^3/s to about 6500 m^3/s in the next four days to further

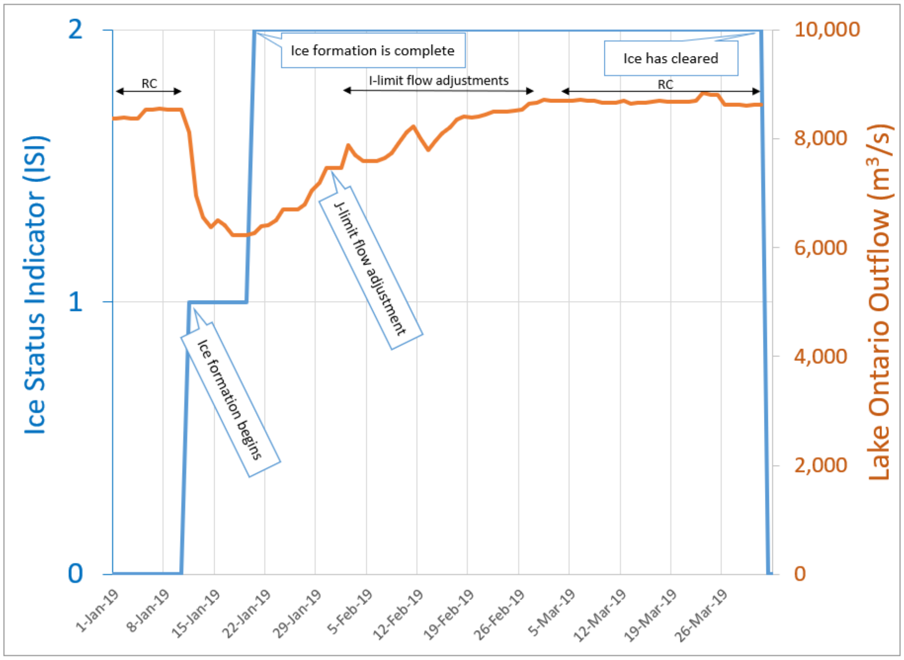

Figure 3. A comparison between the ISI number for Canal Beauharnois (vertical axis on the left) over time of the year (horizontal axis) during the winter 2019 with discharge (vertical axis on the right). RC: Rule Curve.

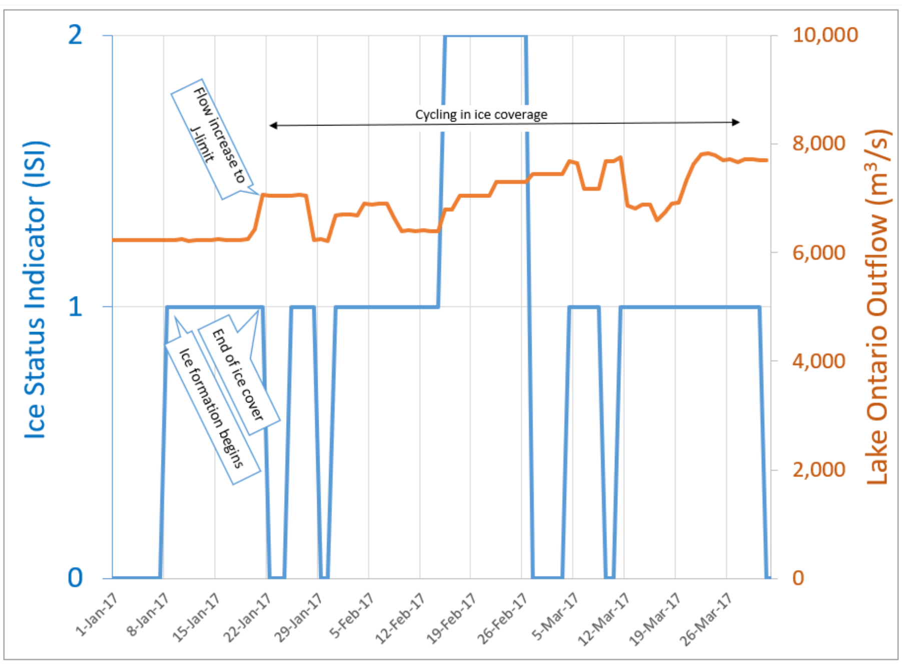

Figure 4. A comparison between ISI number, also for Canal Beauharnois (vertical axis on the left) over time of the year (horizontal axis) during the winter 2017 with discharge (vertical axis on the right).

promote ice cover growth (Figure 3) and also to account for warmer temperatures in the weather forecast. On January 20, the canal was fully covered with ice – the ISI value was thus raised to 2, and the discharge was progressively increased to 7470 m^3/s. That increase is referred to as the J-limit, i.e., the maximum discharge increase in any given week. Another requirement was to keep the water level in Lake St. Lawrence, upstream of the canal, from exceeding a maximum level (the I-limit). To meet that requirement, several adjustments were made to the amount of water allowed through the dams. From March 1st onward, the discharge was mostly governed by the "Rule Curve". This dictates a discharge that only considers water influx to Lake Ontario, i.e., conditions in the river no longer take priority. After the ice had cleared the canal on March 31st, the ISI was reduced from 2 to 0.

Example of a complex scenario

This scenario was similar to the previous one at its initial stage, but with a lower discharge (6230 m^3/s) (Figure 4). Ice began to form in Canal Beauharnois at the dam on January 8, 2017, and quickly progressed upstream. On that basis, the ISI for that site was raised from 0 to 1, and the discharge was not changed. An ice jam occurred at one location but dissipated two days later. The air temperature was higher a week later, and the ice began to melt in place. By January 21, there was no more ice in the canal, so the discharge was raised to 7050 m^3/s, a level consistent with the Rule Curve. Ice started to form again on January 25, and the ISI was increased to 1, but had disappeared by January 29 – the ISI was set to 0 again. This time, the discharge was reduced to 6230 m^3/s, to favor ice growth. On January 31, a third ice cycle began in Canal Beauharnois, with an ISI=1, and the discharge was set to 6700 m^3/s, then to 6900 m^3/s. On February 14, ice coverage was complete, and the ISI was set to 2. But with warmer temperatures, that ice began to break up again. On February 27, the ISI was back to 0, and the procedure had to start over again, with a short cold span permitting ice formation until March 9, with two other cycles later on.

5. Rationale for NRC's ISI-based prediction method

The conception of the prediction method was guided by the following considerations:

- This was a 'proof-of-concept' – could an ISI-based ice prediction method be achieved with a reasonable degree of success? If so, it would open the door to refinements in later editions of the prediction method.
- A 'plug-and-play' approach was adopted, with a transparent procedure ('black box'-style artificial intelligence methods were ruled out).
- Of all climate parameters that play a role in ice cover extent, it was decided to only use air temperature since its influence on ice formation was demonstrated at the locations of interest (Sudom and Barrette, 2023). The inclusion of other parameters, such as water temperature, river flow, and precipitation, could improve prediction, but this was left to later editions.

The prediction method was based on thresholds. Examples of similar analyses include those of Newton et al. (2017), Turcotte et al. (2020), Jasek et al. (2021), and De Coste et al. (2022). The advantages of this approach in the case documented in the present paper are ease of design, understanding, and application. There were two input files: historical ISI data and air temperature. Additional information may be found in Sudom et al. (2024).

6. The ISI data

The IJC made daily ISI data available to NRC from two sites: Lake St. Lawrence and Canal Beauharnois. These were in Excel spreadsheets and ranged from December 1960 to March 2023. The data for 1960 – 1999 only indicated dates of initial ice freeze-up and final break-up (i.e., dates of the first and last ISI>0). The data for year 2000 onwards consisted of better-curated, daily records of ice status, including dates of mid-season break-ups and freeze-ups. For the proposed method, the three-fold ISI categorization (0, 1, 2) was converted into a two-fold categorization (ISI=0, ISI>0) as a first approximation. Preliminary trials showed that distinguishing between conditions leading to ISI=1 and those leading to ISI=2 was not feasible at this proof-of-concept stage.

7. The historical air temperature

Historical climate data were obtained from climatedata.ca, which comprises a compendium of data from stations across the country. Data from one station, 4255 at Cornwall, were selected based on the extensive year range and their proximity to the Lake St. Lawrence area. These data were also used for the analyses of the Canal Beauharnois area. Two parameters were derived:

- *Cumulative freezing degree days* (CFDD): the cumulative sum of the daily temperature values (ºC) below the freezing point. By convention, the CFDD is always a positive number.
- *Cumulative melting degree days* (CMDD): an index similar to the CFDD, but where only the temperatures above the melting point are considered.

8. The thresholds

To guide the development of the prediction method, several thresholds were explored during a preliminary analysis phase (Table 1). This was done manually, not programmatically (via computer-controlled iterations), by varying their values and comparing outputs. Other thresholds were also explored but not used, e.g., the slope in temperature over a given number of days and the cumulative daily temperature (irrespective of whether it was above or below 0ºC). The combination of these thresholds and their values, shown in Table 1, was deemed optimum in being able to reproduce the historical ISI (2000-2023). However, there is room for improvement.

9. The procedures

The prediction method was designed to foresee the timing of the first and the last ISI>0 in future seasons – this would determine the length of the winter. It was also to foresee the number of freeze-up/break-up cycles within each season. A season was defined as from October 1 to April 12. Three steps were performed:

STEP 1 – Determine the date of the first ISI>0, i.e., on what day in any given season the first ISI>0 is expected to occur. This represents the beginning of the ice season.
STEP 2 – Determine the number of cycles in a given season.
STEP 3 – Determine the day of the last ISI>0. This represents the end of the ice season.

STEP 1 – Day of the first ISI>0

Procedures:

- This was based on the 2000-2023 historical ISI record. For each of those 23 winters, the day of the first ISI>0 was determined. Using the winter 2000-2001 as an example, December 21 and December 26 were the first days of ISI>0 observed in Canal Beauharnois and Lake St. Lawrence, respectively, for that year. For the winter 2001-2002, these two days were February 2 and February 12, respectively.

- Next, the CFDD from October 1^{st} *to each of these days* was calculated for all years using the historical air temperature. This represents the beginning of the ‘pre-conditioning’ period, when air, water, and land started to cool down. Referring to the winter 2000-2001 as an example again, the mean daily temperature on October 1, 2000, was 18.5^{o}C. All daily temperatures were above 0^{o}C up to November 11 (-0.3^{o}C), which is, therefore, when the CFDD started to accumulate. On December 26, 2000, the CFDD was 217.7 for that winter.
- The CFDD was obtained for every year, with an average of 278^{o}C and 158^{o}C for Lake St. Lawrence and Canal Beauharnois, respectively (Figure 5). A lower CFDD is required for Canal Beauharnois (than for Lake St. Lawrence) because the water has more time to cool down on its way downstream.
- There is a difference in the amount of scatter between the two locations – there is much less of it at Canal Beauharnois. This may have something to do with the difference in channel morphology, i.e., it is simpler in Canal Beauharnois, making it easier to characterize ice conditions (to assign an ISI value to it) on a more consistent year-to-year basis.
- Neither distribution (Lake St. Lawrence and Canal Beauharnois) in Figure 5 shows a statistically significant correlation between the CFDD and the year range.
- Finally, a comparison was made between the observed and predicted number of days after December 1^{st} to the first ISI>0 for the 2000-2022 range to check that the method performed adequately. This was an iterative process – various thresholds were attempted before settling upon those in Table 1.

Table 1. The thresholds used in the ice prediction method used in this study.

<table>
<tr><th>Threshold</th><th>Value</th><th>Comment</th></tr>
<tr><td>Beginning of the pre-conditioning period in the Fall</td><td>October 1</td><td>This is when air, water, and land masses start to cool down.</td></tr>
<tr><td>Freezing point for determining the CFDD</td><td>0^{o}C</td><td rowspan="2">The ice’s melting temperature was used for that purpose.</td></tr>
<tr><td>Freezing point for determining the CMDD</td><td>0^{o}C</td></tr>
<tr><td>Period over which the moving CFDD is determined</td><td>10 days</td><td rowspan="2">The moving CFDD or moving CMDD are calculated over that number of previous days, for both the CFDD and the CMDD.</td></tr>
<tr><td>Period over which the moving CMDD is determined</td><td>10 days</td></tr>
<tr><td>Moving CFDD</td><td>10</td><td>The value for the moving CFDD required for a change in ISI.</td></tr>
<tr><td>Moving CMDD</td><td>20</td><td>The value for the moving CMDD required for a change in ISI.</td></tr>
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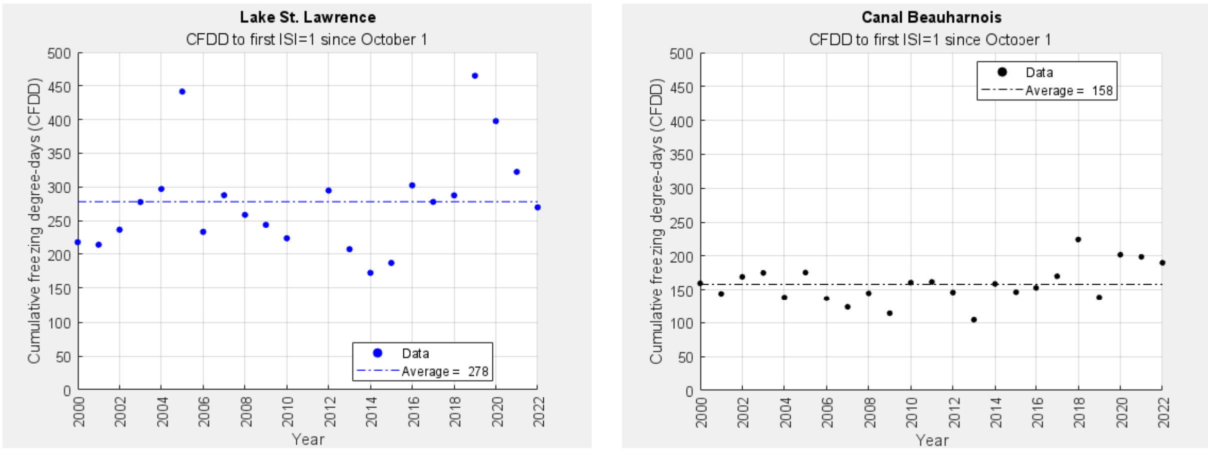

Figure 5. Analysis of the CFDD value required to form first ice each season from 2000 to 2022, for Lake St. Lawrence (left) and Canal Beauharnois (right). An average value of the CFDD required to reach first ice is indicated (278°C and 158°C, respectively).

The procedure to determine the first ISI>0 is then as follows:

- Determine the CFDD required for the first ISI>0. For the present exercise, we use the average CFDD for 2000 to 2023: 278°C and 158°C for Lake St. Lawrence and Canal Beauharnois, respectively.
- Calculate the CFDD from October 1 of a given year, up until the number reaches the average CFDD.
- Take note of the following day – that will be the first ISI>0 for that year, i.e., the first day of the ice season.
- If the CFDD does not achieve that target number, then the prediction is that there will be no ice season that winter.

STEP 2 – The number of cycles

The starting point for this step is the day of the first ISI>0 of any given year, as determined in Step 1. Let us call this 'Day 0'. In the prediction method, the ISI on the next five days, Day 1 to 5, is assumed to remain >0 (to account for data scatter). This means that, for Day 0 to 5, the ISI>0 (ice is present); the method will not capture cycles with a duration of less than 6 days. For Day 6 and all later days, a calculation is performed to determine whether ISI will move back to a zero (no ice) value. For this, the concept of a 'moving CFDD' was used. For Day 6 onward, ISI remains > 0 while both of the following two conditions are fulfilled:

- The moving CFDD (CFDD calculated *only over the 10 previous days*) is ≥ 10, and
- The moving CMDD (CMDD calculated *only over the 10 previous days*) is ≤ 20.

When neither of these two conditions is met, the ISI goes back down to 0. If, at a later day in the season, both of the above conditions are once again fulfilled, the ISI>0. This procedure is repeated for all later days until April 12, the date before which the historical records in all years showed the ice season had ended.

STEP 3 – Day of the last ISI>0

The day of the last ISI>0, as determined from the prediction method, is recorded for each of the 23 years – this corresponds to the end of the ice season.

10. Performance of the prediction method for hindcasting

We first look at how well the prediction method described in this paper can capture past ice scenarios.

Season duration

Method performance was tested against the full 63-year range (Dec. 1959 to Spring 2023). A graphical representation of the ice seasons for Lake St. Lawrence and Canal Beauharnois is shown in Figure 6 and Figure 7, respectively. The ice season starts (first ice freeze-up) when the ISI moves from 0 to >0 for the first time of the year. Conversely, the season ends (last ice) when the ISI moves from >0 to 0 for the last time of the year. On the vertical axis is the number of days from December 1st to start to end for each year. Overall, the correspondence between predicted and observed in this hindcast exercise is very good for the first day of ice at both locations. The last day of ice is also predicted well for Canal Beauharnois, but significant discrepancies can be seen for the predicted last day of ice in many years for Lake St. Lawrence.

Number of cycles

The difference between observed and predicted number of cycles in the hindcast exercise for Lake St. Lawrence and Canal Beauharnois is shown in Figure 8 and Figure 9, respectively. Information on cycling, as mentioned earlier, has only been available since 2000. Our method in its current edition tends to overpredict the number of cycles, especially in Lake St. Lawrence.

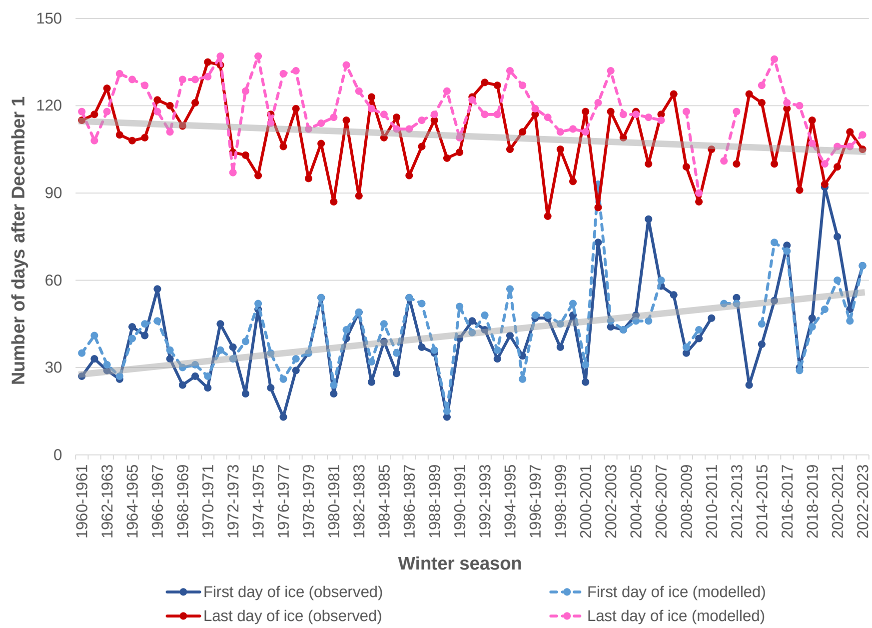

Figure 6. Observed and predicted dates for first ice (freeze-up) and last ice (break-up) on Lake St. Lawrence. The observed ice season duration varies from no ice at all (winter 2011) to 121 days (winter 1970). The grey dashed trendlines for the observed data show that the ice season length has generally decreased over the last 63 years. When extrapolated into the future, they intersect in 2100.

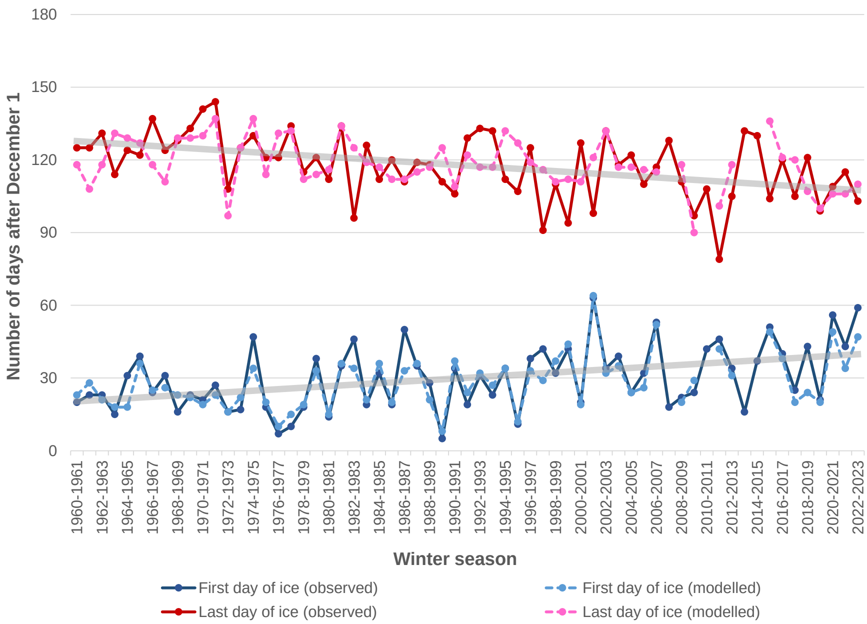

Figure 7. Observed and predicted dates for first ice (freeze-up) and last ice (break-up) Canal Beauharnois. The observed ice season duration varies from 34 days (winter 2001) and 124 days (winter 1977). The grey dashed trendlines for the observed data show that the ice season length has generally decreased over the last 63 years. When extrapolated into the future, they intersect in 2130.

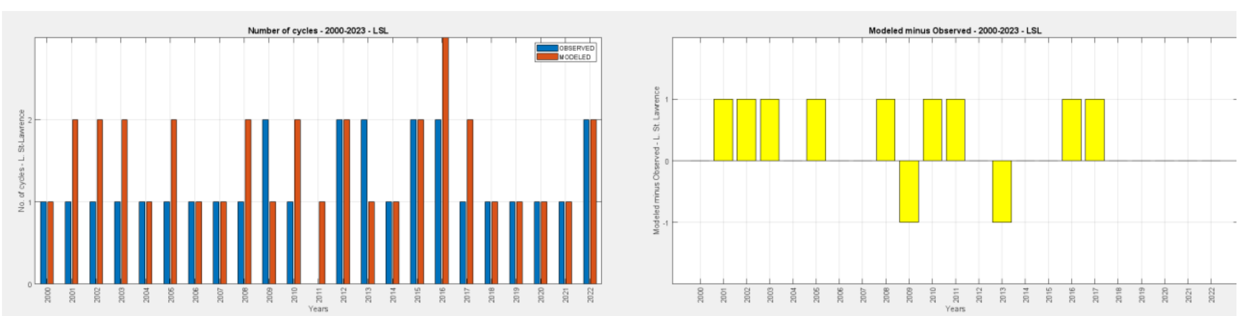

Figure 8. Lake St. Lawrence - number of freeze-up/break-up cycles (2000-2022). Left) observed and predicted. Right) Modeled minus predicted number of cycles.

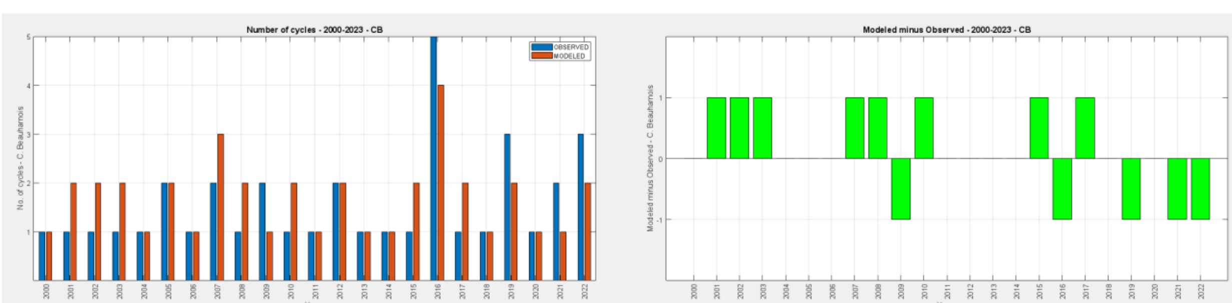

Figure 9. Canal Beauharnois - number of freeze-up/break-up cycles (2000-2022). Left) observed and predicted. Right) Modeled minus predicted number of cycles.

11. Future ISI

The future air temperatures used as input for this analysis are from Teufel et al. (2022). In that study, climate simulations spanning the 2041–2060 and 2081–2100 periods, for Representative Concentration Pathway (RCP) 4.5 and RCP 8.5 climate scenarios, were produced. That work generated, amongst other variables, downscaled air temperatures at 2 m from the surface. Since our ISI prediction method was calibrated using data from the weather station in Cornwall, ON, that same grid cell was chosen for the future climate data. More information on that front is provided in Sudom and Barrette (2023) and Sudom et al. (2024). The latter reference used a slightly different version of the ice prediction model; the version used in the present paper was refined after testing against additional historical data.

The predicted first and last ice for Lake St. Lawrence and Canal Beauharnois are shown in Figure 10 and Figure 11, respectively, for the two RCP climate scenarios. Three main observations can be made from those figures:

- A shortening of the ice season over time (due mainly to later dates for first ice)
- The gradual disappearance of ice conditions that can be described as first ice freeze-up (as defined in section 10 for the season duration), particularly for the RCP 8.5 climate scenario
- More pronounced ice decline trends for Lake St. Lawrence than for Canal Beauharnois.

It is important to note that these are predictions of future ISI, not of actual ice coverage. Although the ISI is predicted to stay at zero in some future years, this does not mean that no ice will be present. The analysis by Sudom and Barrette (2023) predicted that border ice would continue to form at both sites up to year 2100, but with reduced maximum thicknesses. Recent analysis of satellite imagery by Sudom et al. (2025) quantified ice coverage for 10 years of ISI data. In the early part of some seasons, ice coverage of Lake St. Lawrence or Canal Beauharnois was up to about 40% or 10%, respectively, before the ice cover was deemed sufficient to move the ISI above 0.

In addition to future dates of first ice and the ice season lengths, the model was used to predict the future ISI cycles (Figure 12). This may be compared with the historical data in Figure 8 and Figure 9. For RCP 4.5, a modest increase in the number of annual ISI cycles is possible for the 2040-2060 range, but that number is reduced for the 2080-2100 range (for years where there is ice). Under RCP 8.5, the number of annual ISI cycles predicted for 2040-2060 is similar to recent historical years, but ice cover is almost non-existent for year 2080 onward.

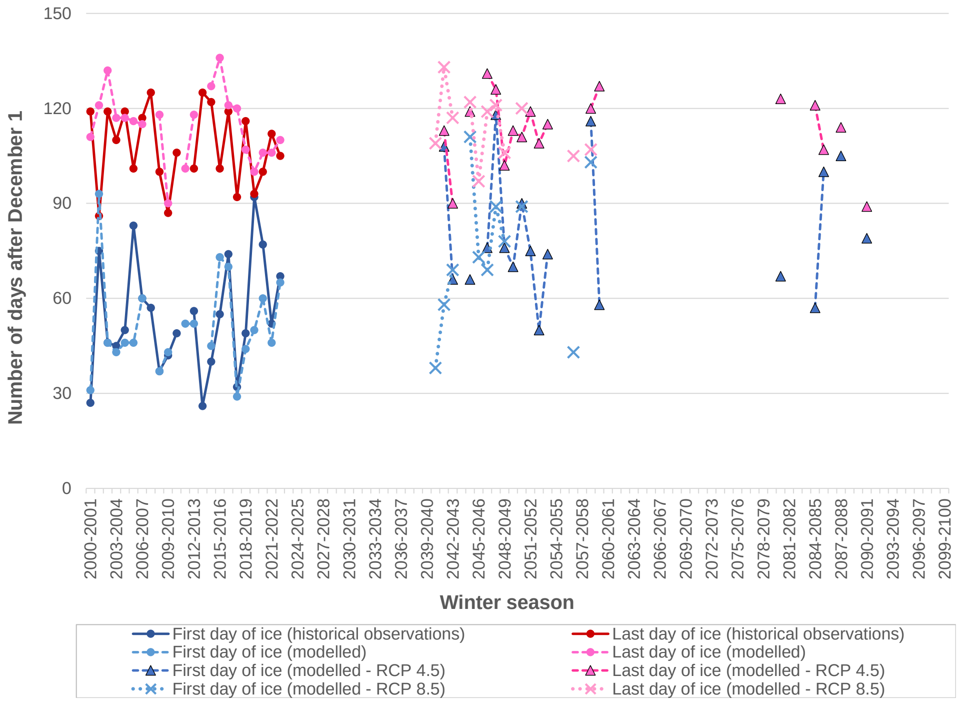

Figure 10. Predicted first and last ice dates (days after Dec. 1) for Lake St. Lawrence. The historical observed values are included for comparison.

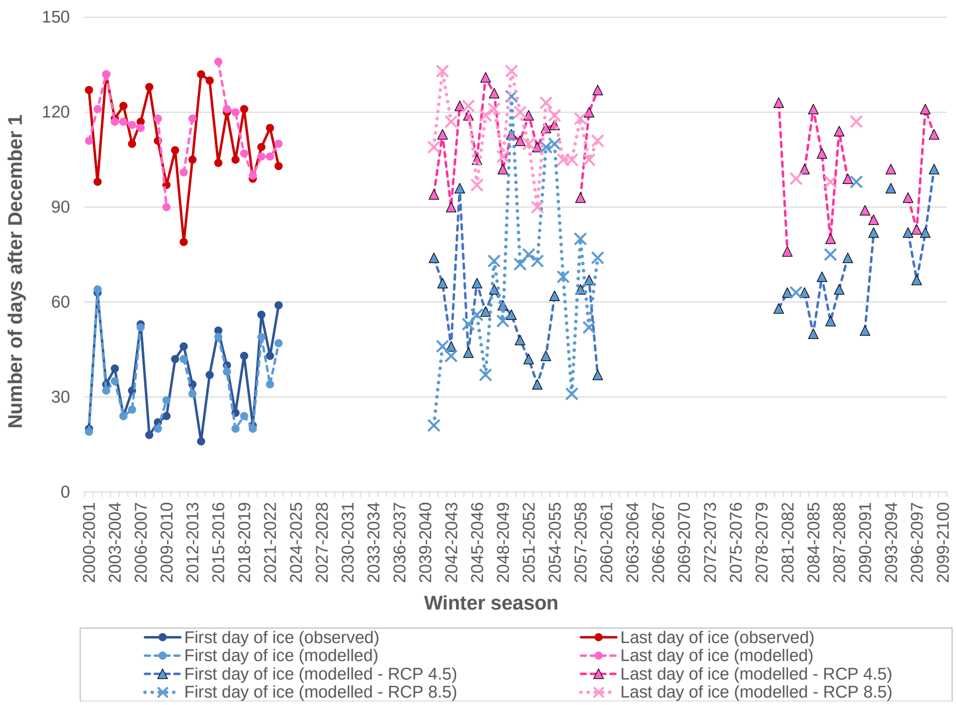

Figure 11. Predicted first and last ice dates (days after Dec. 1) for Canal Beauharnois. The historical observed values are included for comparison.

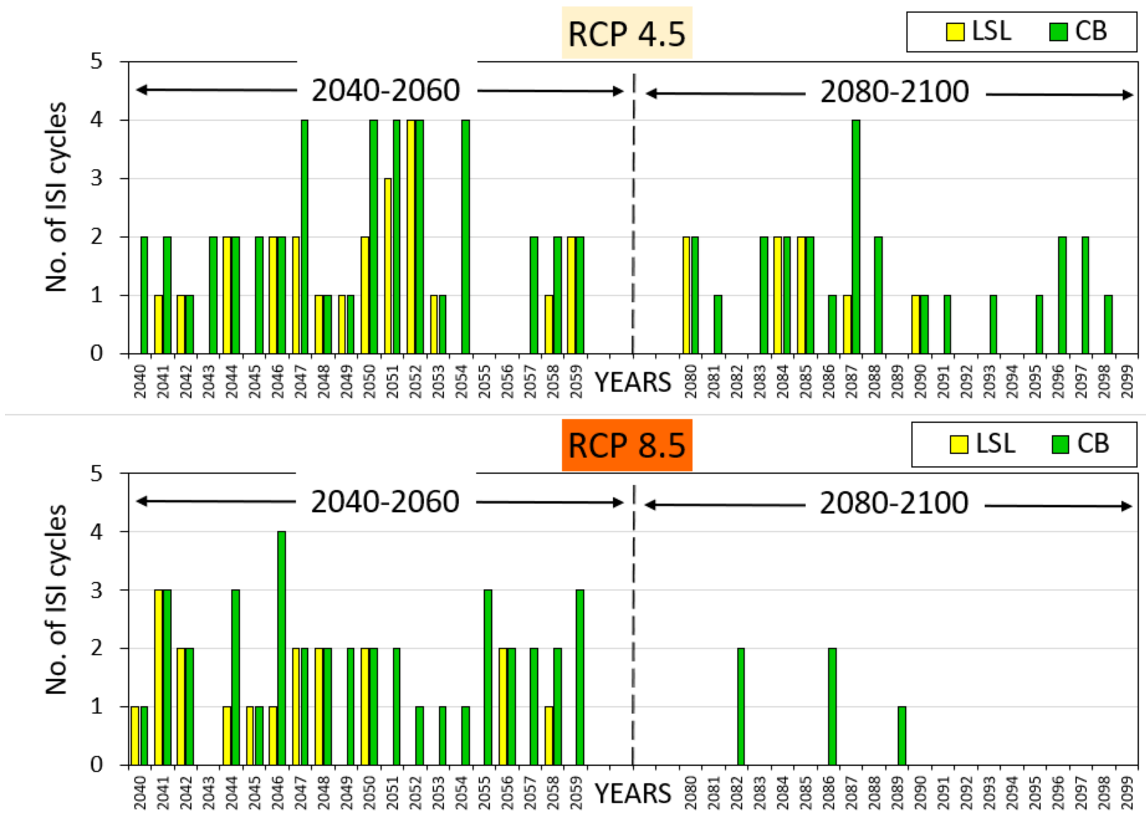

Figure 12. The number of future ice cycles under the two RCP scenarios considered in the present study, the two time ranges, and for both the Lake St. Lawrence (LSL) and Canal Beauharnois areas (CB).

12. Conclusion

In this study, the ISI system used by IJC to guide water management decisions in the upper St. Lawrence River was found to be a reliable proxy for ice cover evolution (season length and number of freeze-up cycles) in the Lake St. Lawrence and Canal Beauharnois areas. The ice prediction method was used to foresee plausible scenarios of future ice presence, using two sets of air temperature input data (climate scenarios RCP 4.5 and 8.5) over two periods (2040-2060 and 2080-2100). The results show an ongoing reduction in the ice season length, due to progressively later season starts and earlier season ends. A modest increase in the number of freeze-up cycles is predicted for the 2040-2060 period, but this is then expected to drop in later years (if there is any ice cover).

The ice prediction method could be improved with a more systematic validation exercise, such as the use of machine-learning algorithms to optimize thresholds or incorporate other relevant input data. Ultimately, it could conceivably be applied to other rivers where indices similar to the ISI are available, such as ice-on / ice-off dates. Moreover, because of its long-standing record, the ISI can be used to supplement satellite imagery (Sudom et al. 2025).

Acknowledgments

This research was supported by the NRC's Climate Resilient Built Environment Initiative, in support of delivering the Government of Canada's Adaptation Action Plan, and towards achieving commitments under the National Adaptation Strategy. The initial work on this topic was supported by the International Joint Commission (IJC), as part of a project carried out by the NRC. The IJC's International Lake Ontario - St. Lawrence River Board provided data and observations from river management operations, including the ISI record. Historical air temperature weather station data were obtained from Environment and Climate Change Canada (ECCC). McGill University provided the modelled data on air temperature for future periods. The authors would like to thank our colleague Richard Burcher for assisting with the environmental inputs and handling the Python coding. Comments provided by Jamie Ferguson and Saber Ansari on the manuscript are gratefully acknowledged.

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