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Overview of water level, discharge and ice in the St. Lawrence Seaway at Montreal

Report No.: NRC-OCRE-2022-TR-036

Paul Barrette and Cédric Gaïqui

April 2023

Ocean, Coastal, and River Engineering
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Summary

Unlike in most other countries, rivers in Canada freeze during the colder months of the year. Hence, in addition to flooding events in open water, which are a challenge on their own, those involving ice introduce an additional set of issues which are also difficult to foresee and prepare against, given the acknowledged complexity of river ice dynamics. The purpose of this report is to examine the influence of surface ice on water levels in the St. Lawrence River, with the premise that an improved understanding of related phenomena would ultimately increase the reliability of the well-known stage-discharge relationships in winter conditions and provide additional insights into floods induced by ice. Fundamental to any endeavor aimed at monitoring water levels are basic principles in hydrology and hydraulics, including the various field methods used to gather these data – these are summarized. The basis for the relationship between stage and discharge is the Manning formulation. When ice is present, however, that relationship is no longer reliable. Instead, the presence of ice can lead to very high-water levels at relatively low discharge, which is caused by channel constriction by ice keels below the water surface.

Lake St. Louis, a river segment along the St. Lawrence Seaway next to Montreal, is the target area for a site-specific analysis presented in this report. Historical stage and discharge data for up to 50 years were downloaded from ECCC's website – these were generated at two hydrological stations: Pointe-Claire and Lasalle. Indirect evidence of the influence of ice on stage is indicated by the difference in daily water level patterns: they fluctuate more in the winter than in the summer. Discharge, which is derived from water levels, is also more stable in the summer than in the winter (bearing in mind it is considered unreliable for icy conditions). A full-ice cover is associated with low water levels, which may be caused by non-uniform flow, leading to a variation of water depths in the flow direction observed between the two stations. This is consistent with observed discrepancies in water levels at the stations. Additional insights could be obtained with more detailed information about the ice cover and its dynamic behavior, as well as about discharge from the Ottawa River and that resulting from dam operations.

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1. Introduction

Amongst all major natural hazards worldwide, flooding, followed by droughts and earthquakes, are those which draws the most attention in the scholarly literature (Watson and Ahn, 2022). Flooding is the most common natural disaster worldwide and poses a significant threat in urban areas (Li et al., 2023). Canada is the country that has the most inland waters, and a large proportion of its population live in cities, towns and other agglomerations that are located along river shorelines. This is particularly the case for southeastern Canada, namely along the St. Lawrence River and its tributaries, which host some of the largest population densities in the country (Figure 1). Amongst weather events in Canada, including hurricanes, floods, 'convective storms' (hail, rain, wind), and winter storms, floods are the most costly (Government of Canada, 2016).

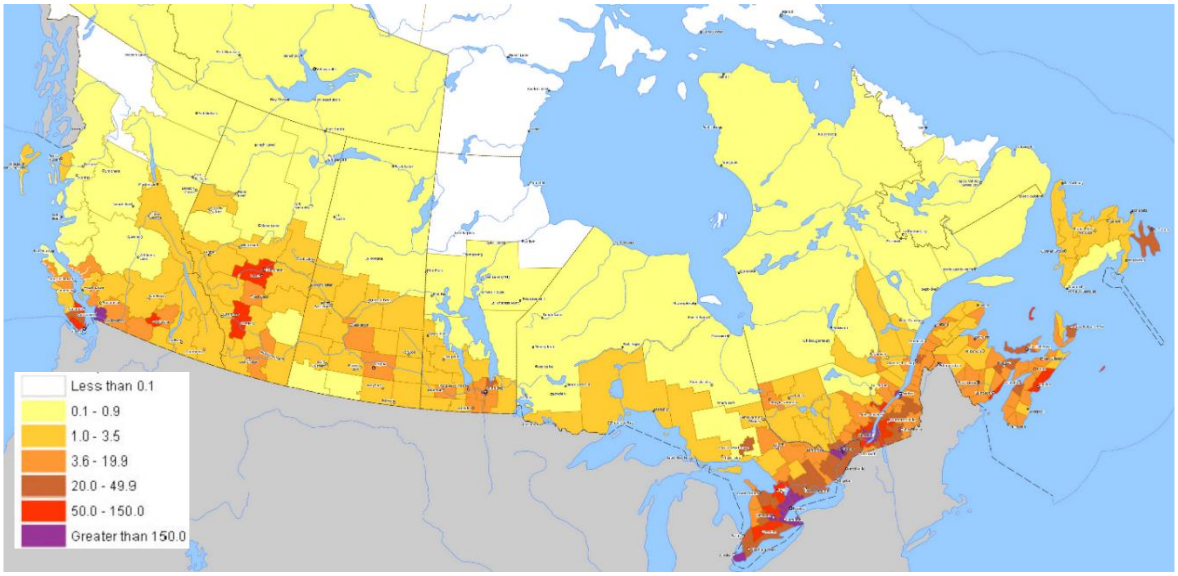

Figure 1: Population density by census zones – the unit in the legend is person(s) per square kilometer.[1]

Unlike in many countries around the world, rivers in Canada freeze during the colder months of the year. While this is expected by Canadians, it presents significant engineering challenges. The reason is that, in addition to flooding events in open water, which are a challenge on their own, those involving ice introduce an additional set of circumstances which are also difficult to foresee and prepare against, given the acknowledged complexity of river ice dynamics (Beltaos, 2021, Lindenschmidt, 2020). Much less research has been conducted on floods under icy conditions compared to those under open-water conditions. What that research shows, however, is that the north-eastern US and south-eastern Canada are particularly prone to these events (Rokaya et al., 2018b).

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[1] https://open.canada.ca/data/en/dataset/e8260251-8893-11e0-994b-6cf049291510. The source of this image is from *Statistics Canada, Population and Dwelling Count Highlight Tables, 2006 Census, Catalogue number 97-550-XWE2006003*.

2. Objectives

The main objective of this report is to provide a general overview of water levels and discharge as well as the salient differences between open-water scenarios and those involving the presence of surface ice. This includes methods, basic notions alongside definition of terms. These notions are then transferred over to Lake St. Louis, which is located along the south shore of Montreal Island. The water levels and discharge at that location are described and the effects of the ice on these parameters are discussed.

3. Flooding and streamflow information

In general, a flood is caused by an increase in the water level due to an increase in the extent of water circulation. From a financial standpoint, when dealing with damages caused by extreme events, floods are divided into two broad categories: sewer backup and overland flooding (Government of Canada, 2016). The latter, overland flooding, is when water flows over a property. In coastal areas, this may include:

- Storm surges, when the flood is due to high winds sweeping water over land, beyond the normal shorelines.
- Tidal waves, typically the consequence of an earthquake or subsea slumping.

From an inland context, which is that relevant to this report:

- Groundwater flooding, when the water table rises above its normal level.
- Pluvial flooding, when rainfall is so heavy that the drainage system is not able to handle the volume.
- Riverine flooding, when a river carries higher than normal water volumes.
- Ice jam flooding, when a river channel gets partly or completely obstructed by ice.

For a river system, ‘water level’ is synonymous of ‘water depth’ or ‘stage’, and ‘discharge’ is synonymous of ‘flow’. These are two important variables, and are part of what is known as ‘streamflow’ data. The interdependency between these variables is central to any endeavor aimed at foreseeing flood risks. Along with other types of streamflow data, they are typically collected on a systematic basis for two distinct purposes (Herschy, 2009):

- To plan and design hydraulic structures and channels, and to modify or adapt existing ones. For instance, what will be the discharge in a channel that has a maximum water depth? How high should a weir be built so it can accommodate a total discharge x?
- To guide operational requirements. For instance, how high will the water get along these shorelines under a given discharge x, either in the short-term (days to weeks) or for the long-term (to account for climate impact)?

In Canada, hydrological records are gathered by Water Survey of Canada (WSC), which is the operational branch within the Department of Environment and Climate Change Canada (ECCC)’s National Hydrological Services (NHS). WSC is responsible for the collection, interpretation and dissemination of standardized hydrometric data and information in Canada. It does so by establishing standard practices for field methods, instrumentation layout and procedures for the operation and monitoring of gauge station (Moore, 2019, Moore et al., 2019).These records are produced by a countrywide network of hydrometric stations – there are currently about 2200 active stations – and are made available at no cost to stakeholders from all provinces and territories by means of bilateral agreements. The Province of Quebec has its own data management system, but also shares that information under similar agreements. Following is some general information on WSC’s system:

- The two main data types discussed earlier are provided: water level and discharge. The former is in meters above a given reference level; the latter is in cubic meters per second. Some stations also collect air and water temperatures.
- Most stations transmit their data in 'real-time'[2] mode, i.e., the measurements are sent to WSC's data center via satellite or telephone lines. Real-time information is used for short-term requirements.
- Historical data over various time spans, depending on the station, are also available.[3] These data also include those generated by 5600 inactive stations.[4] They are routinely used to obtain long-term trends (over decades), to help foresee future trends.
- To view the data, one can do a station search, using the station name or number.[5] A search can also be done from a map.[6]

3.1. Stage

The stage of a river is defined as "the height of the water surface above an established datum plane" (Herschy, 2009, p. 95). Water levels are collected using a 'stage sensor', which is a device designed to generate readings of that level. Three types of stage sensors are reported by Moore (2019): float systems, pressure sensors systems and non-contact systems (Figure 2):

- The float systems are located inside a 'stilling well', connected to the river by intake pipes, whose purpose is to damp any short-term surface fluctuations such as waves. The stage is obtained by recording the position of a cable attached to a float resting on the water surface. Independent water levels inside and outside the shelter are used to validate the sensor data.
- The pressure sensor systems measure the hydrostatic pressure[7] exerted onto the sensor by the water. The sensor can either be of the submersible type or housed in the shelter and connected to an orifice line in the water. Sensor response is converted into water depth where the unit is located. A few options are used to anchor the hardware at the river bed.
- Non-contact sensors rely either on electromagnetic or sound signals that bounce off the water surface and back to the sensor. They can be mounted on a bridge or other structures above the water surface.

This instrumentation is a standard part of a gauging system (Herschy, 2009, Moore, 2019, Moore et al., 2019), the complexity of which is beyond the scope of this report. To provide a brief outlook of what is involved, Figure 3 summarizes some of the main components involved in the determination of stage at a given location.

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[2] https://wateroffice.ec.gc.ca/mainmenu/real_time_data_index_e.html

[3] https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html

[4] https://www.canada.ca/en/environment-climate-change/services/meteorological-service-standards/publications/hydrometric-data-information/chapter-2.html

[5] https://wateroffice.ec.gc.ca/search/real_time_e.html

[6] https://wateroffice.ec.gc.ca/map/index_e.html?type=real_time

[7] Equal to ρgh, where ρ is the water density, g is the gravitational acceleration and h is water height above the sensor.

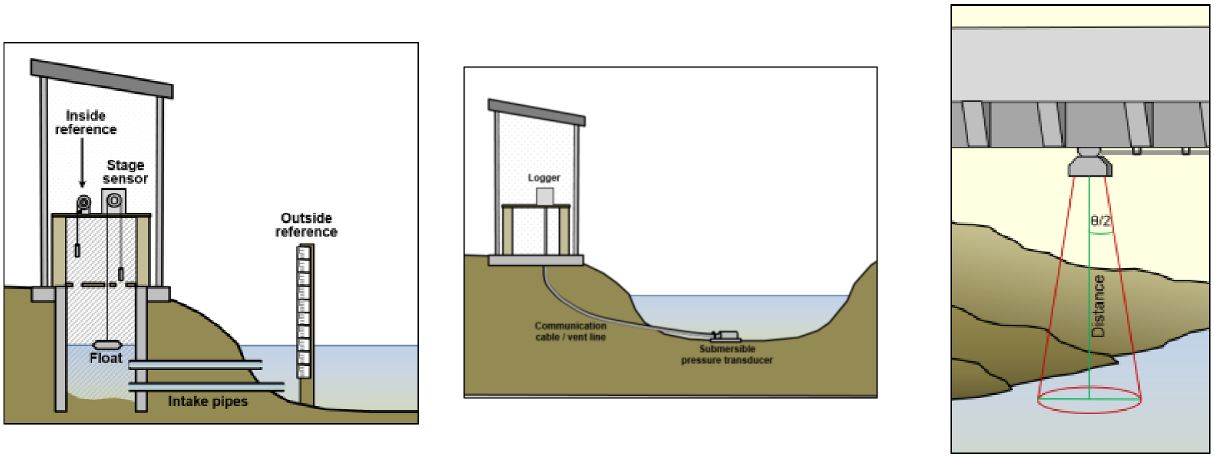

Figure 2: Three types of 'stage sensor', i.e., devices that are designed to monitor stage (Moore, 2019): Left) Float system. Middle) Pressure sensor system. Right) Non-contact sensor system.

3.1.1. Gauge (or chart) datum

The 'gauge datum' is the basis for all measurements, i.e., an arbitrary coordinate system[8]. It is a fixed horizontal surface against which all elevations are expressed, and should be well below what is known as the 'zero flow' ('G' in Figure 3).

3.1.2. Station shelter (or gauge house)

The station shelter ('A' in Figure 3) houses the instrumentation, devices and ancillaries used to record and transmit this information.

3.1.3. The sensor

The sensor shown in ('B' in Figure 3) is of the pressure type. In this case, it incorporates a bubbler system, where gas (air or nitrogen) is ejected by the sensor and the pressure exerted by the water on the escaping gas is used to determine water depth.

3.1.4. Reference gauge

The reference gauge allows to verify sensor readings. A staff gauge is shown in ('C' in Figure 3).

3.1.5. Benchmark

A benchmark is a fixed reference point of known elevation ('D' in Figure 3). WSC benchmarks take the form of a brass plug or cap affixed vertically or horizontally in a rock or concrete surface.

3.1.6. Direct water level reading

For various motives or as part of standard procedures, WSC technologists (E) can measure the water level against a manually-held leveling rod ('F' in Figure 3).

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[8] https://wateroffice.ec.gc.ca/report/datum_faq_e.html

3.1.7. Point of zero flow

As will be seen later, the elevation of zero flow (‘G’ in Figure 3), which is typically along the river bed, is used in conjunction with stage-discharge relationship.

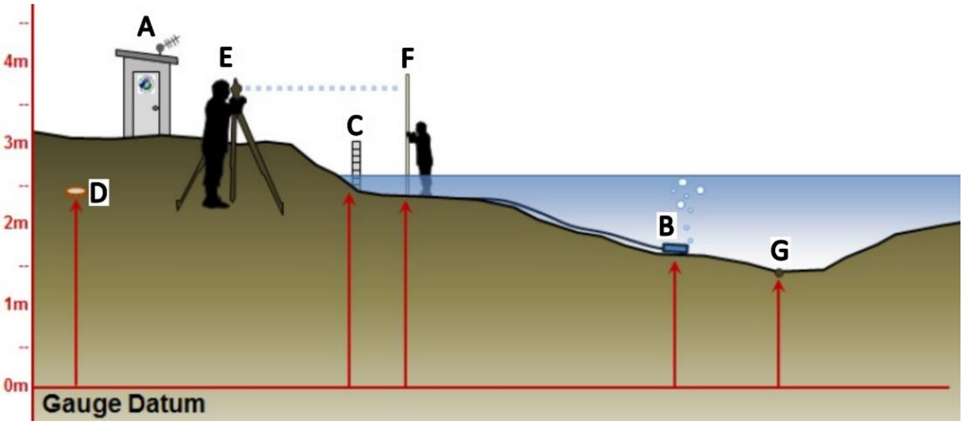

Figure 3: Various components of a gauging system – see text for details (from Moore et al., 2019). Note that all measurements are made with respect to a gauge datum.

WSC’s preferred acquisition rate is one reading every 5 minutes, i.e., high enough to capture peak periods with sufficient accuracy. Each individual datum can either be instantaneous or averaged over a given time span, e.g., 20 seconds (to smooth out minor fluctuations). The target accuracy for WSC’s sensors is +/- 3 mm, or 0.1% of the water depth, whichever is greatest. Each sensor system has its advantages and drawbacks. For instance, the float systems are better protected against flooding events, but the inside of stilling well must be kept at temperatures above the freezing point. The pressure sensor system can be relatively inexpensive but it is exposed to damage by ice. Non-contact sensors are low maintenance and are not exposed to damage, but they require a stable platform and will not be effective under wavy conditions or with floating ice or debris.

3.2. River discharge

River discharge refers to the volume of water per unit time crossing an imaginary vertical plane that is perpendicular to the flow (Figure 4). It is typically measured in cubic meters per second. Various methods can be used to determine discharge (Herschy, 2009). For instance, current velocities can be collected at various intervals across a river channel, and at a few depths (to capture the full envelope), using current meters. The total volume of water per unit time is obtained by adding up the volume enclosed in each interval. In Figure 4, this corresponds to the volume comprised between the measuring section (in red) and the envelope (in black). Another example of a method to determine discharge consists in tracking a float that travels a known distance along the channel at different positions across it. WSO does not measure discharge directly[9]. Instead, it is derived from the water level data using a ‘stage-discharge’ model. This is discussed next.

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[9] https://wateroffice.ec.gc.ca/contactus/faq_e.html#Q6

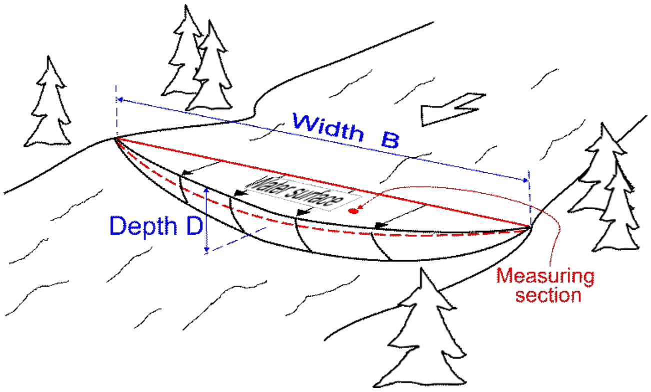

Figure 4: River discharge in a channel of width B and depth D. Note the effects of friction along the river bed and the shoreline. The 'measuring section' is a vertical plane at right angle to the flow direction. Adapted from Herschy (2009).

3.3. Relationship between stage and discharge

Water flows downstream due to the action of gravity, and it would accelerate continuously (i.e., freefall) if it were not for various sources of flow resistance, such as that induced by boundaries (river bed, shorelines), vegetation, debris and human-made structures (e.g. Herschy, 2009, Powell, 2014)(Figure 5). The higher the flow resistance, the lower the flow velocity, the higher the water level. The latter – i.e., water level – can be used to derive discharge. A relationship between stage and discharge is of utmost interest because, once established, that relationship can then be used to derive discharge values by recording stages, bearing in mind it is much easier to monitor stage than it is to monitor discharge. Indeed, most hydrological stations only provide information on water levels, not discharge.

The basis for this relationship between discharge and stage is the Manning formulation:

$$Q = A\left(R^{(2/3)}S^{(1/2)}\right)/n$$

In that equation, Q is the discharge (m^3/s), *R* (m) is the hydraulic radius, *S* (m/m) is the slope of the channel along the bed, and *n* is Manning's roughness coefficient. The hydraulic radius is the cross-sectional area (labeled 'measuring surface' in Figure 4) divided by the 'wetted surface' (the dotted line along the river bed in that figure). Underlying the usage of this formulation, which is unique to any river channel section (it is a site-specific rating curve), are assumptions, namely that the flow is uniform and steady, under open water conditions.

More information on the procedures used by WSC for developing these relationships is provided in Rainville et al. (2016). The influence of various factors on the stage vs. discharge relationship is shown in Figure 5.

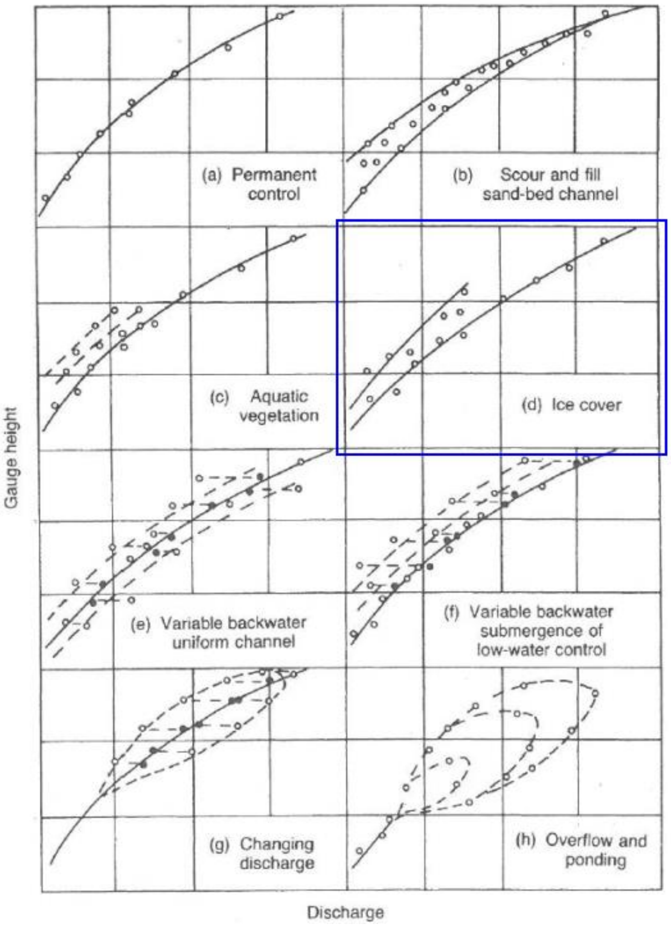

Figure 5: The relationship between stage and discharge can be affected by various factors (Herschy, 2009, Fig. 4.4). In this scheme, (a) is the simplest scenario, representative of about 75% of cases. That shown in (d) is related with ice (see also Figure 6).

These relationships are helpful in anticipating future river dynamics. This is true for operational needs (day-to-day decision-making), for instance when weather forecasts call for a large amount of precipitation, which is one of the most influential factors. Communities can better prepare for impending floods. It also applies to climate impact analyses, i.e., if future precipitation regimes in 30 or 50 years (or more) is foreseen, an appreciation of the corresponding stage can also be obtained. For instance, if a regional climate model predicts that precipitations in a given drainage basin will increase by a given amount within the next 50 years, a hydrological model can then translate that information into an estimate of the resulting (increased) discharge for the river in that basin. This will, in turn, be used to determine the corresponding increase in stage.

3.4. Scenarios involving ice

For scenarios involving ice, as mentioned earlier, the relationship between water discharge and water level can also be described by Manning's formulation (Figure 5d), but only if we assume a uniform ice cover. The trace is shifted upward. This is also shown in Figure 6, i.e., from the green line to the blue field. What this means is that, for a given discharge, the stage is higher with an ice cover than without it. One reason is that the presence of ice occupies 9/10th of its thickness (if it is brought in from upstream). Another reason for this increase in stage is that, contrary to open-water conditions where there is no resistance at the water surface, ice exerts a resistance to flow at the ice-water interface. That resistance is in addition to all other possible sources listed in Figure 5. It increases the hydraulic radius and decreases the area (Herschy, 2009).

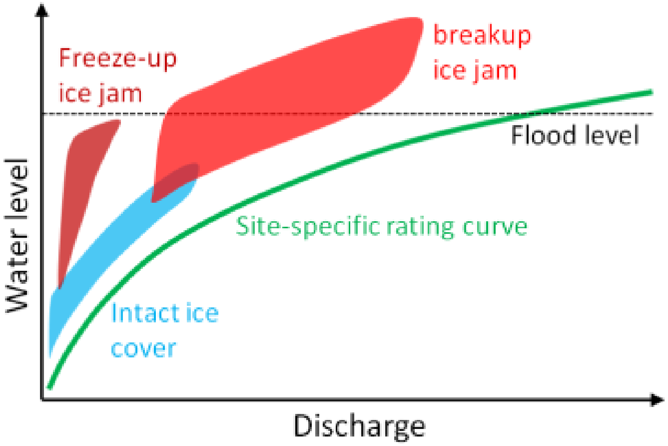

Figure 6: The relationship between discharge and stage along a given river segment, for open-water conditions (green line – 'Site-specific rating curve') and for icy conditions (the three colored areas). The dotted line is where the stage is sufficiently high to cause flooding. From Turcotte et al. (2019).

In reality, ice-covered conditions – e.g., channel configuration, flow velocity, etc. – are far more complex. At many locations along the length of a river, the ice may locally consist of an accumulation of ice fragments (or 'floes'). In other cases, ice cover thickening can result from the accumulation of large amounts of frazil ice[10]. Thicknesses can range from less than a meter to ten meters or more – Gold and Williams (1963) document an ice thickness of up to 90 m in the Ottawa River (although this is seen as an extreme case).

A generic depiction of one such scenario is shown in Figure 7. Ice floes are drifting downstream and eventually stop, typically as the accumulation bridges between shorelines. That then defines an 'ice jam'. For the thicker accumulations, the keel of the ice will constrain water flow, i.e., there is less room for water circulation below the ice. When that happens, the water level upstream will rise, a phenomenon termed 'backwater'. This is the difference between the water level that is affected by the presence of ice, and the water level that would prevail with the same discharge under open water conditions (e.g. Beltaos, 2021). Because the stage is largely controlled by the thickness of the ice jam, which varies unpredictably and substantially, that difference is also unpredictable, and can be in the order of several meters. This leads to flooding upstream of the jam.

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[10] Ice crystals that form below the water surface – massive amounts can be generated under certain conditions.

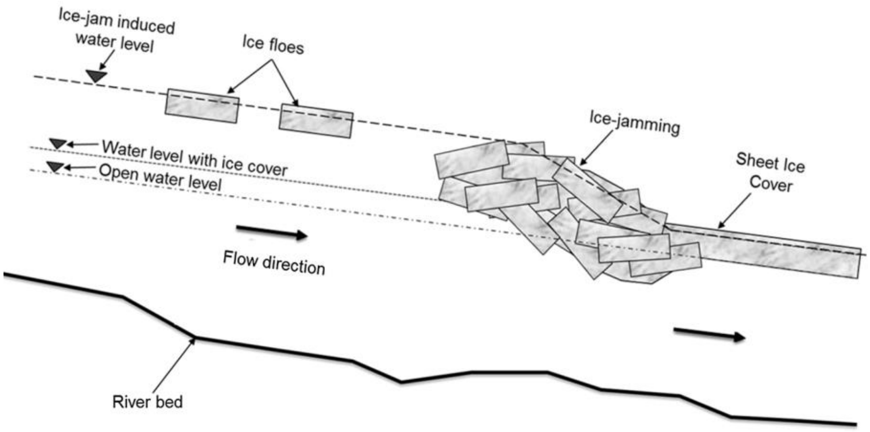

Figure 7: Example of a river ice jam with associated water levels (from Rokaya et al., 2018a) – the slope is exaggerated for the purpose of illustration. In this case, it is an accumulation of ice floes. Three water levels are indicated: open water, with a uniform ice cover and with an ice jam.

Two additional fields are shown in Figure 6, labeled 'freeze-up ice jam' and 'break-up ice jam' (Beltaos, 1995, 1996, 2021). The former refers to jams that form in the autumn, while the latter is for jams that occur in the spring or mid-winter. Those are key periods of the year. Because air temperatures tend to be lower in autumn, freeze-up jams will acquire a certain amount of mechanical strength (as the water in the interstices freezes), and are less inclined to thicken. Also, at that time of the year, the flow is generally less, and ice jam initiation is due to congestion. Break-up jams, on the other hand, form from more open water conditions under high flows; they can be thicker, rougher, and generally induce higher backwater levels than freeze-up jams. These jams can also let go abruptly, thereby producing surges of ice and water that can cause extensive property damage as well as loss of life downstream.

It can be seen from the foregoing that:

- In all cases where ice is present, the site-specific rating curve is no longer reliable, as shown in Figure 6. As pointed out by Beltaos (2021), "[t]he complex hydrometeorological and structural processes that lead to ice jam formation, progression, and release are highly site-specific. Therefore, regional parametric equations, such as those developed for open water flood frequency studies, do not apply."
- High water levels – those that can cause flooding – are linked with ice jams.
- For ice jams, there is a substantial scatter in the stage data, i.e., in Figure 6, they are fields, not lines. The scatter is because the stage depends on a number of factors (other than discharge), such as location, length, ice volume/strength/bottom roughness, and extent of grounding.

Due to the above considerations, deriving stage from discharge is a challenge. Yet, such a relationship is essential, because discharge is a parameter that is much more available than ice jam stage in the perspective of flood risk evaluation.

3.4.1. Stage vs. discharge under icy conditions

One way to address this challenge is by considering the most influential parameters (Table 1) and arranging them into dimensionless parameters, under some assumptions (Beltaos, 2013). This is shown in Figure 8, which is a generalized relationship that is valid for more than one river segment that meet these assumptions and for which values for each variable are known.

B_i	Channel width	*m*
H	Water depth	*m*
g	Gravitational acceleration	m/s^2
q	Discharge per unit channel width	m^2/s
S_w	Water surface slope	*deg.*

Table 1: Some of the most influential parameters (m: meter, s: seconds, deg.: degrees) in characterizing the dynamics of an ice jam.

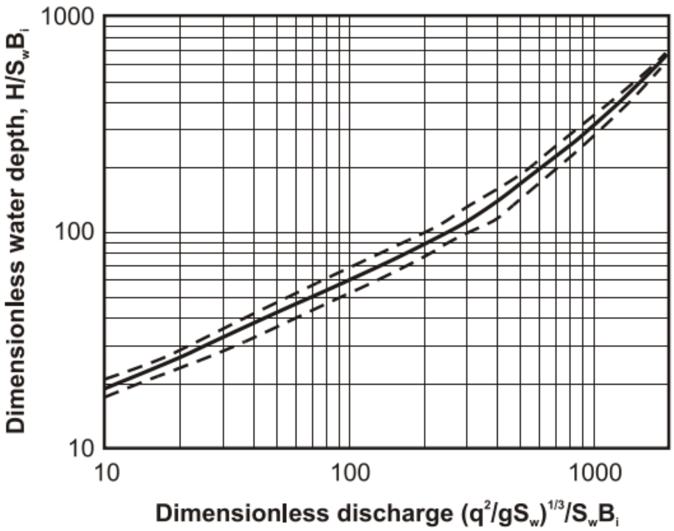

Figure 8: Example of a relationship between discharge and water depth for an ice jam (from Beltaos, 2013, Fig. 7.6). The parameters on both the horizontal and vertical axes are normalized, to take into account the most important parameters (Table 1).

The above is the basis for a ‘stochastic’ approach. Instead of assigning specific (observed, or at least realistic) values to each parameter, as typically done under open water conditions, a number of them are randomly selected and 100’s or 1000’s simulations are run (Lindenschmidt, 2020, Lindenschmidt et al., 2021). The relationship of discharge vs. water level has been approached in several other ways also, as pointed out by Rokaya et al. (2018a) and Lindenschmidt (2020). These include fuzzy logic, artificial neural network, decision-tree models and k-nearest neighbors algorithm.

3.4.2. Summarizing icy scenarios

So far, we have discussed the effects of ice on water levels for an intact ice cover and for ice jams (Figure 6). Three additional circumstances can be envisaged. One is an intact ice cover and a negligible water current, the most extreme example of which is a landlocked lake. In this case, the ice forms from a pre-existing water mass, as a flat or corrugated cover (e.g., due to wind action). It does not occupy additional room and will not induce an increase in water levels.

Another scenario is when ice drifts along with the currents but where there is no jam, i.e., the ice keeps moving downstream. A third scenario, which is irrespective of the others, is where water flow is regulated by dams upstream of the gauge stations.

All five scenarios are summarized in Table 2.

Table 2: River ice scenarios and related changes in water levels.

Scenario	Description	Water level
Negligible currents	Negligible flow below a uniform ice cover. The ice forms in situ.	Remains constant
No ice jam	Drifting ice does not come to a halt – it keeps drifting.	May or may not increase
Intact ice cover	Water flows below a uniform ice cover, for example if it forms as 'border ice' growing out from one or both shorelines until they bridge.	Increases (Figure 6)
Ice jam	Drifting ice comes to a halt and accumulates.	Increases (Figure 6)
Regulated river	Controlled releases of water (e.g., from a hydroelectric dam) upstream of the gauge station(s).	May or may not increase

4. Hydrology in the St. Lawrence River

4.1. Relevance

The Great Lakes - St. Lawrence Seaway is a deep-draft waterway with a total length of 3,700 km between the Atlantic Ocean and the head of Lake Superior (Jenish, 2009). The water conditions in the St. Lawrence Seaway along this seaway have to be rigorously monitored so as to accommodate as best as possible various requirements, namely shipping activities. These are critical to the North American economy and one must ensure there is an adequate draft for navigation purposes. Figure 9 shows the Montreal to Lake Ontario segment, with has a series of locks that lift ships to 75 m above sea level.

Figure 9: The St. Lawrence Seaway between Lake Ontario and Montreal (Jenish, 2009). The name of the seven locks is indicated in red font – in the upstream direction: St. Lambert, Côte Ste Catherine, Lower and Upper Beauharnois, Snell, Eisenhower and Iroquois.

Another requirement is an adequate water level at hydroelectric plants so they can deliver enough energy to the power grids. A third requirement is to avoid shoreline flooding, which can turn into a delicate balance between keeping water levels low enough to preserve the shorelines around Lake Ontario, but without flooding those downstream. Yet another requirement is linked with ice management – water discharge is used to control the formation of stable ice covers and reduce the risks of ice jams. Water management is done using water levels and discharge. As discussed earlier, the former is measured at hydrometric stations; the latter uses the former as input into a standard formulation adapted to each site. The reader is referred to Bouchard and Cantin (2015) for a discussion on how to reconcile these various requirements.

4.2. Lake St. Louis

The target study area for this report is Lake St. Louis, located along the southern shoreline of Montreal Island (Figure 10 and Figure 11). At that location, the river widens to a maximum distance of about 9.5 km – hence its designation as a ‘lake’. The choice of that area was based on the importance of that river segment when assessing water levels as a function of discharge from Lake Ontario. Namely, a balance has to be achieved between adequate water levels in Lake Ontario, Lake St. Louis and in between, so as to avoid flooding in all areas. A number of hydrological stations are used to manage that balance, including the Pointe-Claire station and the Lasalle station. The former only dispenses water level data; the latter dispenses both water level and discharge data. Lasalle is the last station along the St. Lawrence River that dispenses discharge data. Further downstream, the discharge is obtained by adding the discharge from the various tributaries (Bouchard and Cantin, 2015).

4.3. Hydrological stations

Lake St. Louis in Montreal is home to the Pointe-Claire station (Station Number 15330, 02OA039)(Figure 12). It is located immediately downstream of the Beauharnois hydroelectric dam. Its latitude and longitude coordinates are 45.4276ºN, 73.8206ºW (45º25'39" N, 73°49'14" W). Pointe-Claire is a permanent station that measures the daily mean water level – the historical data from this station can be accessed via this webpage. Lasalle station (Station Number 15410, 02OA016) is located about 15 km downstream of Pointe-Claire station, at 45.415ºN, 73.6231ºW (45°24'54" N, 73°37'23" W)(Figure 13). These data can be accessed via this webpage. Figure 14 and Figure 15 show illustrate some of the winter conditions at each site.

4.4. Water levels

4.4.1. Comparison between water levels in winter and summer

In Appendix 1, water height above sea level at the Pointe-Claire station is shown for a 50-year time span (1971-2020 inclusively) for two periods: the winter (January and February – the blue traces) and the summer (July and August – the red traces) of each year. Those are mean daily values, i.e., an average over 24 hours. Following are some general observations:

- The water levels in the winter fluctuate more than those in the summer. These fluctuations are in the order of one meter or less and generally occur over 5 to 10 days. Some noticeable examples of the differences include 1977, 1987 and 1998.
- For any given year, the traces are mostly horizontal along the full 2-month periods, or with slight gradual decreases and increases both the winter and summer traces up to one meter. The years 2002 and 2017 are examples.

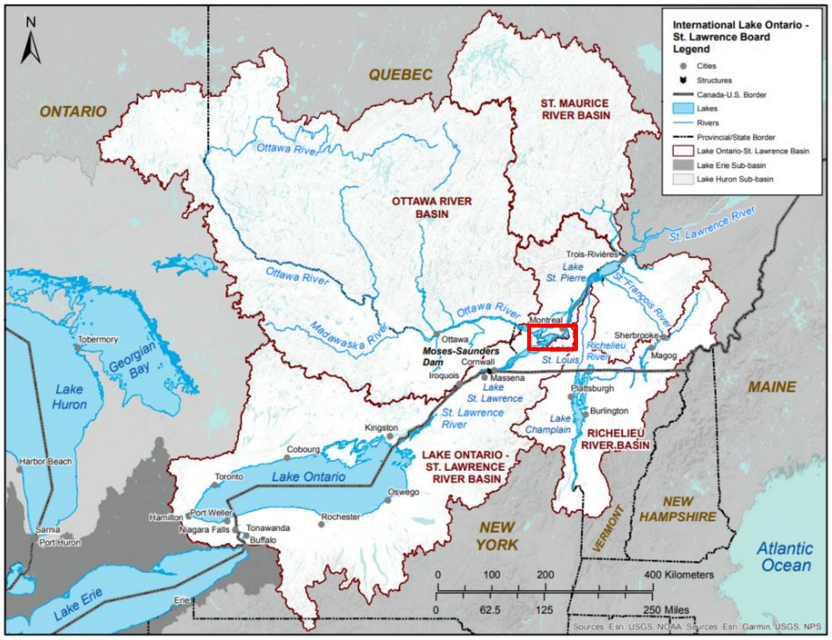

Figure 10: Hydrological context of the St. Lawrence River between Lake Ontario and Montreal. The location of Figure 11 is indicated with a red rectangle. Source*: International Joint Commission (2022). Great Lakes - St. Lawrence River [Static Map].*
Retrieved from: [*https://www.ijc.org/en/watersheds/great-lakes*](https://www.ijc.org/en/watersheds/great-lakes)

Figure 11: Study area (Lake St. Louis) with the location of the Beauharnois hydroelectric dam (yellow marker), Pointe-Claire station (blue marker) and Lasalle station (red marker). Source*: Google Maps. Current direction is from the left.*

Figure 12: The Pointe-Claire station in August 2022. [Photo: P. Barrette, NRC]

Figure 13: The Lasalle station in November 2022. [Photo: J. Lefebvre, ECCC]

Figure 14: At Lasalle station in January 2022. [Photo: J. Lefebvre, ECCC]

Figure 15: At Pointe-Claire Station in March 24 2022. [Photo: J. Lefebvre, ECCC]

- Fluctuations notwithstanding, the overall winter and summer traces of any given year are mostly at the same level with respect to each other during the two-month interval. The largest discrepancy is in 2017, when the January levels exceeded the July levels by about 1.5 m.

4.4.2. Comparison between water levels at the two stations

The Canadian Geodetic Vertical Datum 2013 (CGVD2013) for Pointe-Claire and Lasalle is 20.006 m and 18.298 m, respectively[11], i.e., with a vertical difference of 1.708 m. Assuming an approximate distance of 15 km between the two stations, this gives an average downward slope of 0.007 degrees from Pointe-Claire to Lasalle. In Appendix 2, a comparison is shown between the daily water levels at these two stations for eight years between 2012 and 2020 (for the purpose of this exercise, only those years were examined).

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[11] These are heights above sea level.

Note that, because we are looking at the *difference* in water level, the aforementioned vertical distance between a common datum is irrelevant.

In that appendix, the reference point was arbitrarily chosen as the water level on October 1st for all data from that date on (to one year later). For instance, for both stations (Pointe-Claire on the horizontal axis and Lasalle on the vertical axis), the data points in the plot entitled 2012-2013 were obtained by subtracting the water level on October 1st of 2012 from water levels October 1st, 2nd, 3rd, etc. up to September 30 2013. Each plot also includes a 1:1 diagonal – data points on that line are when the difference in water level at the two stations is identical. The following observations can be made from these plots:

- The total span from year-to-year ranges from a minimum of 0.97 meters in 2014-2015 to a maximum of about 1.9 meters in 2016-2017.
- The spread on either side of the zero value (the October 1 reference level) is generally asymmetric, with more data on the negative side. This indicates that the October 1 level is generally lower than that in the rest of the year. This is particularly the case for 2019-2020. The opposite is true for 2014-2015. For the other years, the distribution is somewhere in between those two cases.
- The data from both stations are generally consistent, i.e., a given increase x in water level at Lasalle corresponds to the same increase x at Pointe-Claire. However, that correspondence is not rigorously the same, i.e., at the lower levels, the differences at Pointe-Claire are *higher* than those at Lasalle (by up to about 0.2 m), and vice versa, i.e., at the higher levels, the differences at Pointe-Claire are *lower* than those at Lasalle (by up to about 0.1 m).

4.5. Correlation between water levels and the ice cover

In this section, the ice coverage in Lake St. Louis is correlated with the water level data generated at the Pointe-Claire station. They were extracted from CASRAS[12], a NRC in-house tool, which incorporates ice charts produced by the Canadian Ice Service (CIS) at ECCC (Charlebois et al., 2017, Kubat et al., 2017). Using CASRAS' convenient user interface, one can quickly retrieve the charts at a location and over a time frame of interest – this was done for the Lake St. Louis area (Figure 16 and Figure 17). The standard output for ice coverage is in tenth. The data were exported as a *.csv file and examined in a spreadsheet software (MS Excel). Ice charts in that area were available from 2010 to 2021 – that is the time range for which this analysis was done. MATLAB[13] was used to compile all information and generate plots. The outcome is shown in Figure 18. What can be observed from that figure is that the ice coverage does not appear to affect the water levels. There is, however, a tendency for the levels to be lower at full-ice coverage (10 tenths).

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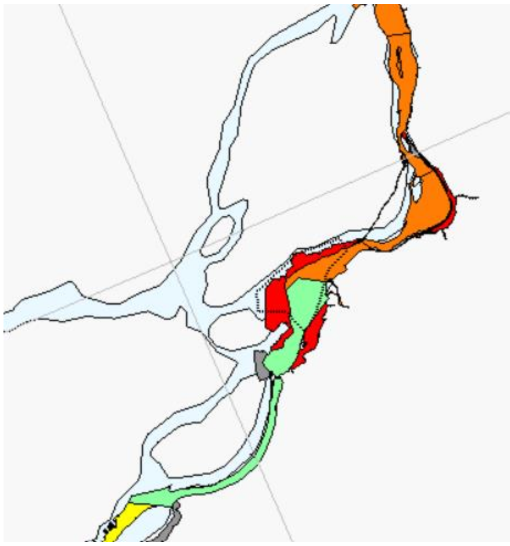
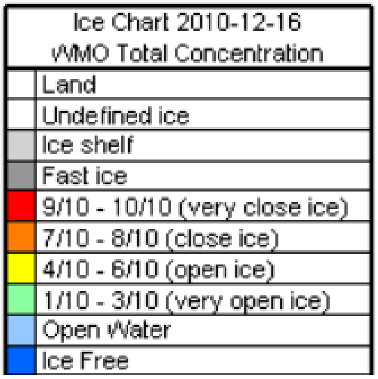
[12] Canadian Arctic Shipping Risk Assessment System

[13] https://www.mathworks.com/products/matlab.html





Ice Chart 2010-12-16 WMO Total Concentration	
⬜	Land
⬜	Undefined ice
▒	Ice shelf
▓	Fast ice
🟥	9/10 - 10/10 (very close ice)
🟧	7/10 - 8/10 (close ice)
🟨	4/10 - 6/10 (open ice)
🟩	1/10 - 3/10 (very open ice)
🟦	Open Water
🟦	Ice Free

Figure 16: Example of ice concentration in the St. Lawrence River along the south and east shorelines of Montreal Island. The various colors represent ice concentrations, as shown by the legend in Figure 17. Note that there is a slight downward shift of the ice overlay over the base map.

Figure 17: Legend for the ice chart in Figure 17 - that chart is dated at December 16 2010. 'WMO' stands for World Meteorological Organizations, a ruling body that oversees standard nomenclatures.

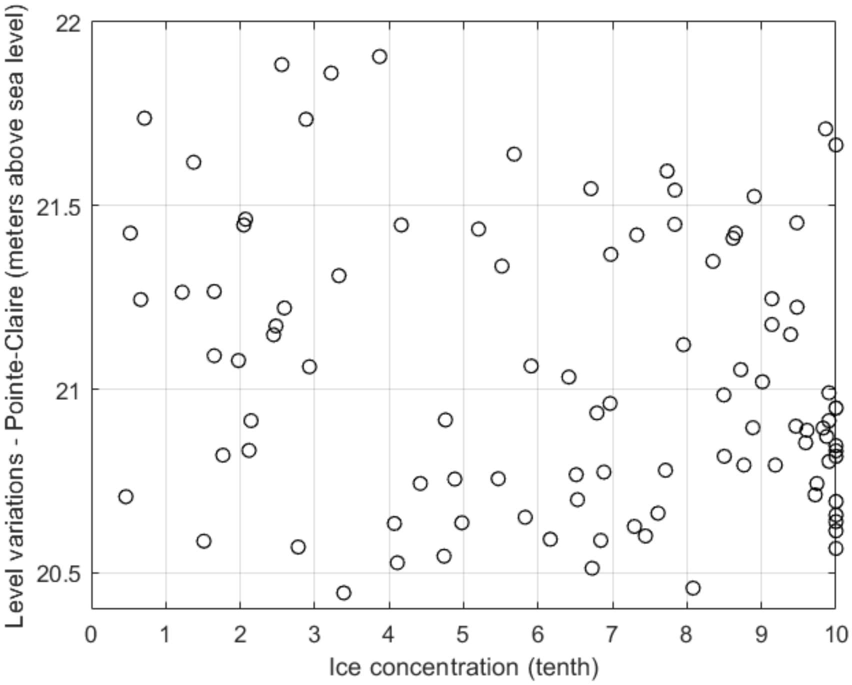


Figure 18: Correlation between the water levels at the Pointe-Claire station and the ice concentration for data collected between 2010 and 2021.

4.6. Discharge

Daily mean discharge data for a 50-year time span (1970-2020) are shown in Appendix 3. The 'winter period' is from January 1st to the last day of February and is bounded by the blue vertical lines; the 'summer period' is from July 1st to August 31st and is bounded by the red vertical lines. As noted earlier, discharge is a function of stage, and it is determined by a formulation that takes into account a number of parameters. Although that relationship is not reliable when ice is present in the river, it may still be instructive to see the outcome of that formulation. The following observations can be made on these plots:

- Discharge during the full 50-year time span varies between about 5,100 to 14,500 m^3 per second.
- The summer discharge is more stable than the winter discharge (likely due to the influence of ice on the latter data, as mentioned earlier).
- The summer discharge is either stable during each time period, or decreases or increases slightly generally by less than 2000 m^2 per second during each time period. Exceptions include the summers of 1972, 1981 and 2003.

5. Discussion

The information provided in this report provides limited evidence of the influence of surface ice on water levels. The fluctuations in water levels in the winter compared to those in the summer (Appendix 1) provide indirect evidence of it. That a full-ice cover is related with low water levels, as shown in Figure 18, is also indicative of such influence.

The slight disagreement between the relative water level differences observed in Appendix 2 is noteworthy. Why would the relative water level not be identical at both locations at all times? This is what would be expected if the flow was uniform – this is shown conceptually in Figure 19. What we are observing instead is that, at high water levels (when the levels are more negative in plots of Appendix 2), that relative level is slightly *higher* than that at the Lasalle station; conversely, at low water levels (when the levels are more positive), water levels at Pointe-Claire is *lower* than that at Lasalle station. This could have to do with a non-uniform flow for that river segment (Figure 20), at conditions where friction is higher than gravity. This is consistent with Figure 18, which shows a full-ice cover tends to occur at low water levels, bearing in mind that the underside of an ice cover contributes to flow resistance. In keeping with that explanation, this would mean that, at higher water levels, the opposite occurs: gravity forces exceed those due to friction.

Even it is understood that the discharge values are unreliable, the difference in discharge behavior between the winter and the summer (Appendix 3) is no doubt indicative of the influence of ice. More detailed information on river dynamics, namely on the nature of the ice cover, would likely help the development of improved stage-discharge relationships.

A proper assessment of river hydraulics under icy conditions would rely on an adequate understanding of which scenario(s) listed in Table 2 could be applicable to Lake St. Louis. For instance, how much of the ice is frozen in situ, or is drifting in from upstream? How much ice jamming occurs in that river segment? How does the outflow from the Ottawa River affect these dynamics, e.g., what if that outflow is reduced when the water level is higher? The St. Lawrence is also a regulated river, i.e., there are hydroelectric dams upstream of the lake. To what extent could that affect ice formation?

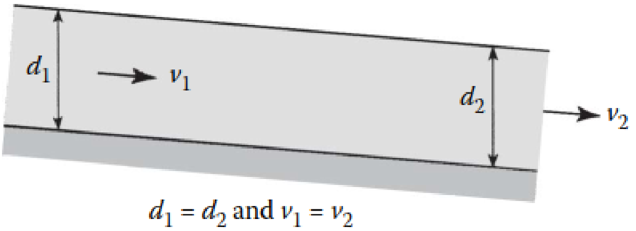


Figure 19: A uniform flow is when the gravity forces acting on the water is equal to the friction forces along the river bed and shorelines, at which point water depth is the same at all locations (from Kay 2017, Fig. 5.7). In this drawing, sites 1 and 2 would represent the location of Pointe-Claire and Lasalle stations, respectively.

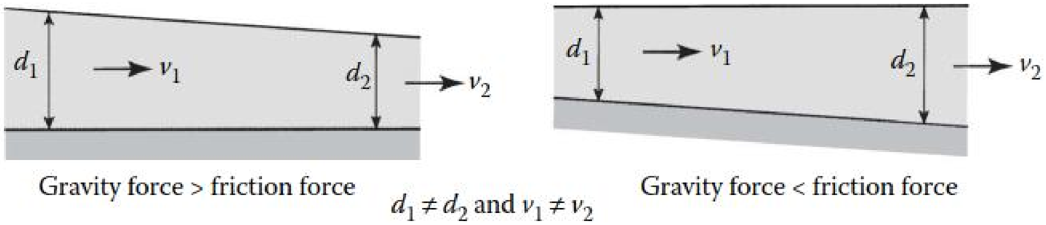


Figure 20: In most natural scenarios, non-homogenous flow prevails, i.e., either the gravity forces are higher or lower than the frictional forces. This leads to a variation in water depth (from Kay 2017, Fig. 5.7). In this drawing, sites 1 and 2 would represent the location of Pointe-Claire and Lasalle stations, respectively.

6. Conclusions

This report's main objective was to examine the influence of surface ice on water levels in the St. Lawrence River. In order to do so, we first briefly summarized basic principles in hydrology and hydraulics, including the various methods to gather these data in the field. This included a generic comparison between the stage-discharge relationship with and without ice. It is shown that the presence of ice can lead to very high water levels at relatively low discharge, caused by channel constriction by ice keels below the water surface.

For the analysis conducted as part of this study, which was meant to be more site-specific, Lake St. Louis next to Montreal was used as a case study. This is a segment of the St. Lawrence Seaway immediately downstream from the Beauharnois dam. The purpose of this analysis was to relate surface ice with water levels, to see if the former had an influence on the latter. Evidence for this influence is not strong. It is found that, under a full-ice cover, water levels tended to be low. This is interpreted in terms of non-uniform flow, leading to a variation of water depths in the flow direction. This is consistent with observed discrepancies in water levels at two hydrological stations in that lake. Also, differences in water level patterns between the winter and the summer is considered indirect evidence of that influence.

In order to gain additional insights to this question, information is required on the details of the ice cover and its dynamic behavior. A better understanding of discharge from the Ottawa River and that resulting from dam operations would also be required. The ultimate aim of this type of endeavor could be to develop more reliable stage-discharge relationships for winter conditions. It is also to gain additional insights into floods induced by ice so as to better anticipate them.

7. Acknowledgements

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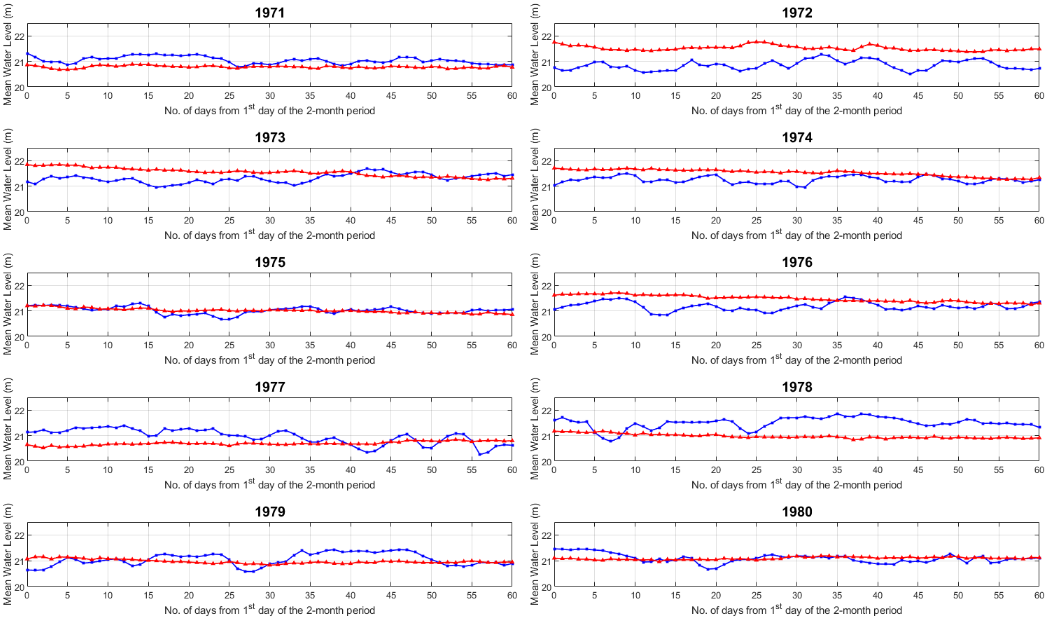
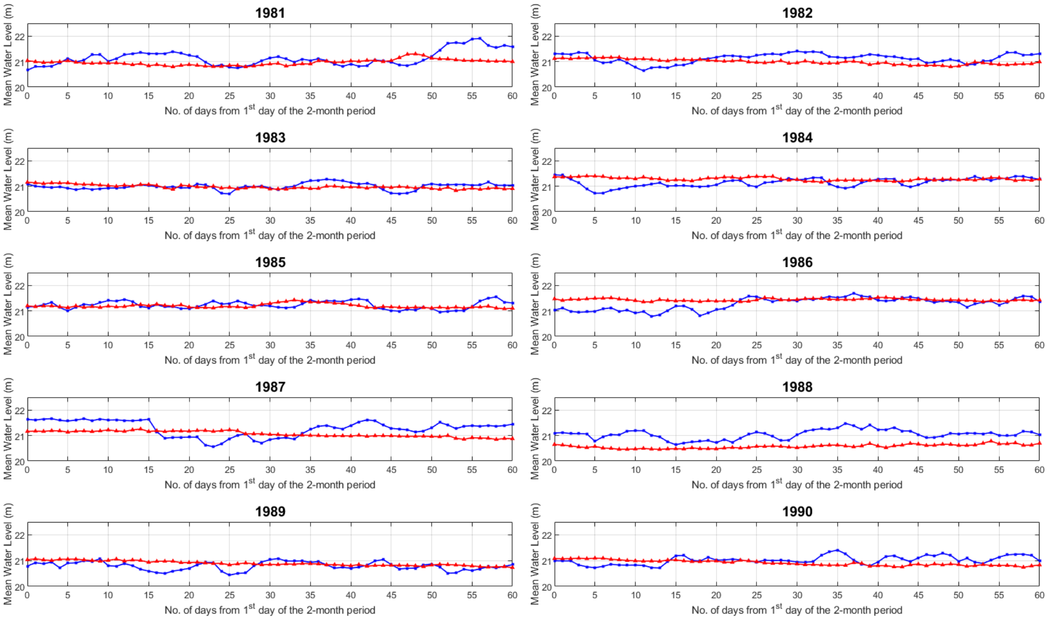
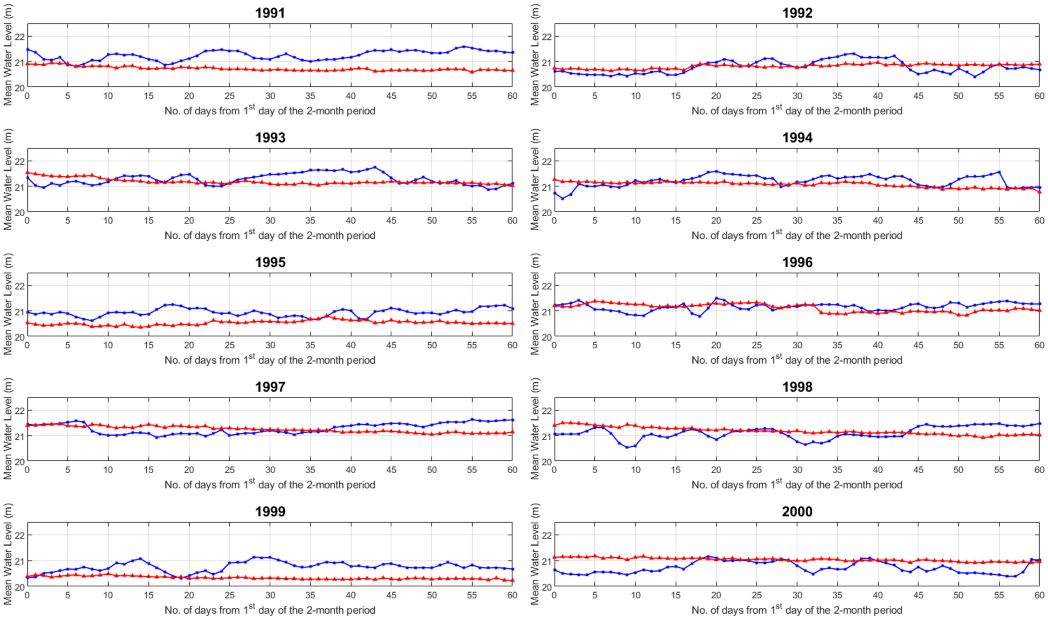
Appendices

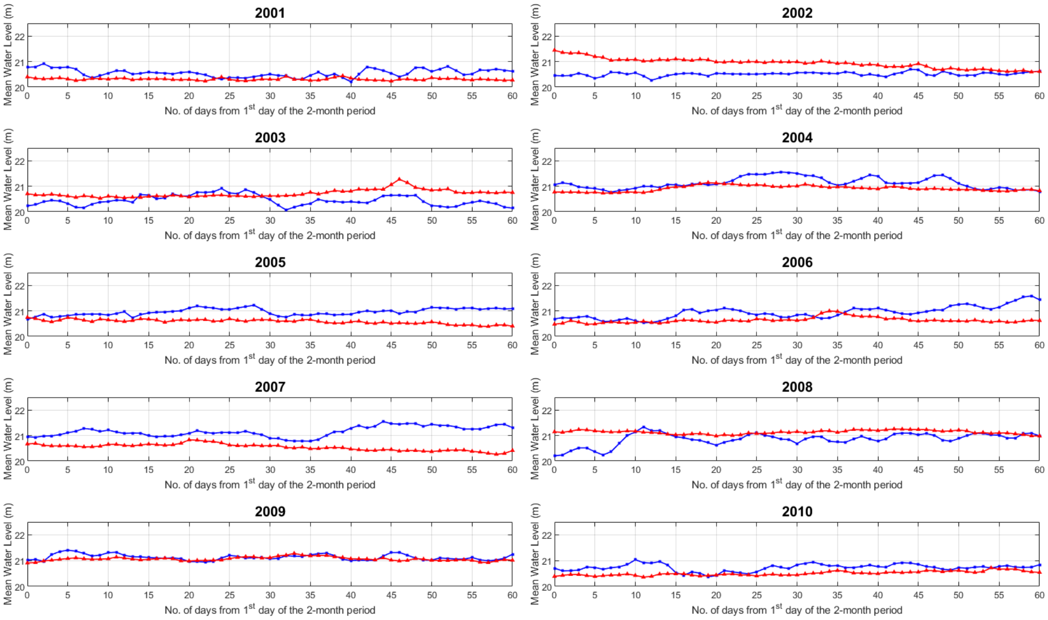
Appendix 1: Water levels

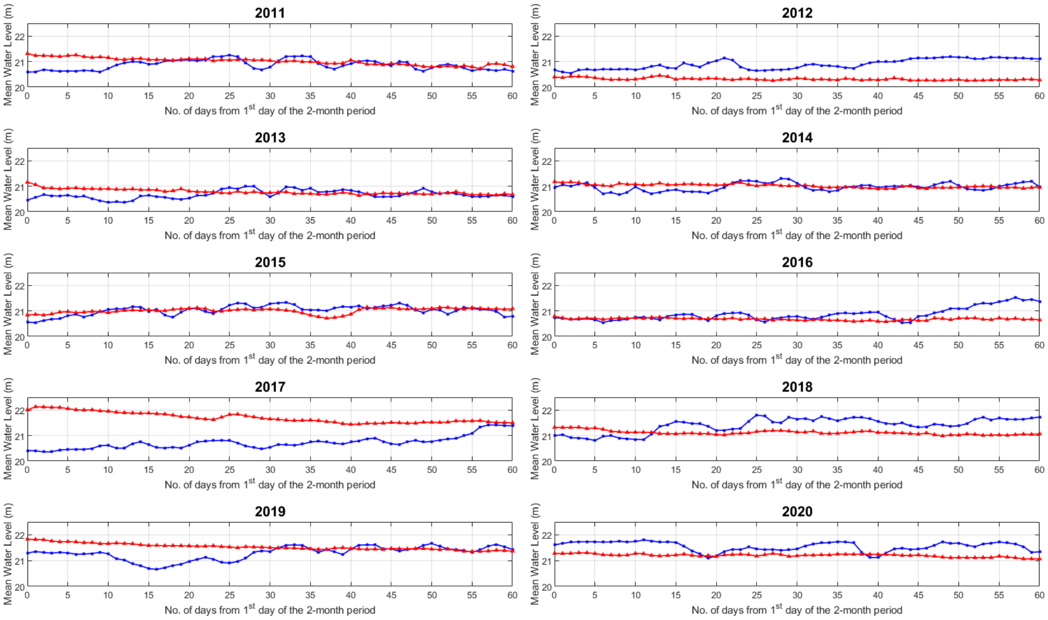
The plots in this appendix are for a 50-year time span (1971-2020 inclusively), based on data generated at the Pointe-Claire station. They compare the mean daily water level between the winter (January-February – the blue traces) and summer (July-August – the red traces) time periods of the same year. On the horizontal axis, the 1st of the month refers to January for the winter data, and to July for the summer data. All heights are based on CGVD2013.



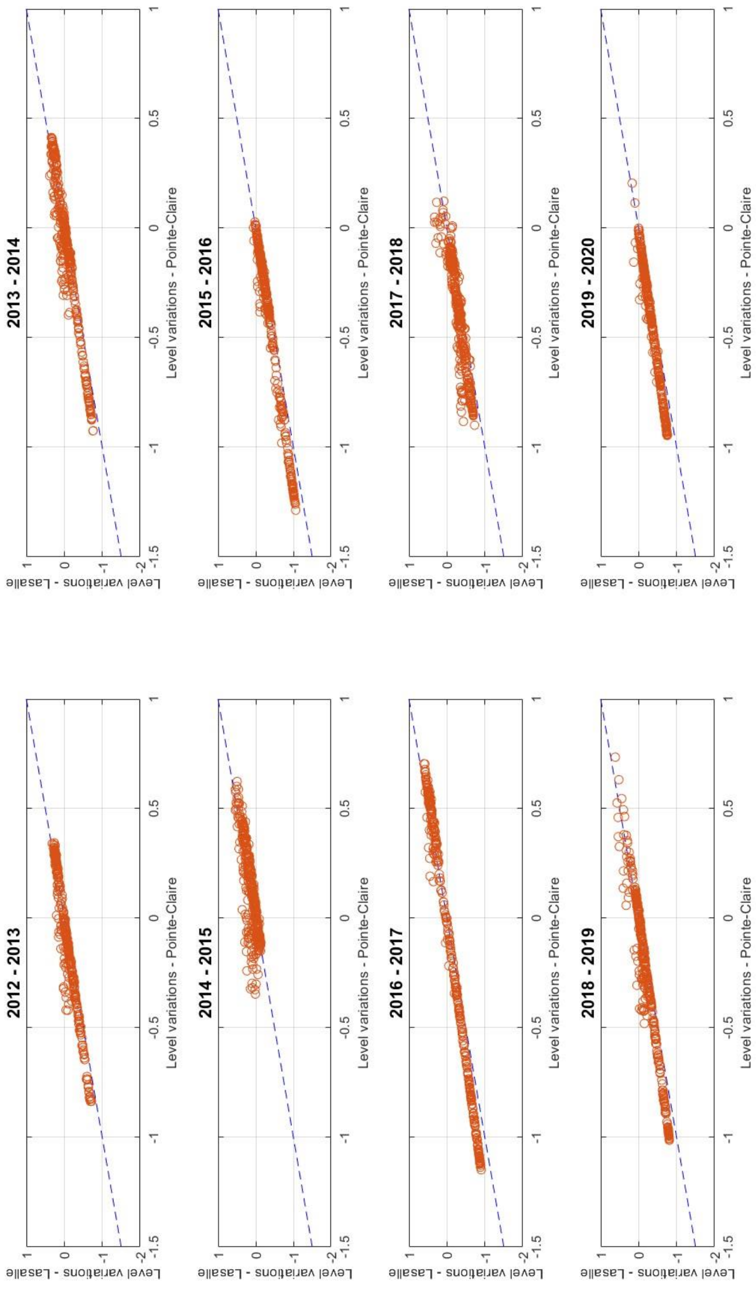

1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
Mean Water Level (m)
20
21
22
0
5
10
15
20
25
30
35
40
45
50
55
60
No. of days from 1st day of the 2-month period


1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
Mean Water Level (m)
20
21
22
0
5
10
15
20
25
30
35
40
45
50
55
60
No. of days from 1st day of the 2-month period


2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
Mean Water Level (m)
22
21
20
0
5
10
15
20
25
30
35
40
45
50
55
60
No. of days from 1st day of the 2-month period


2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
Mean Water Level (m)
22
21
20
0
5
10
15
20
25
30
35
40
45
50
55
60
No. of days from 1st day of the 2-month period

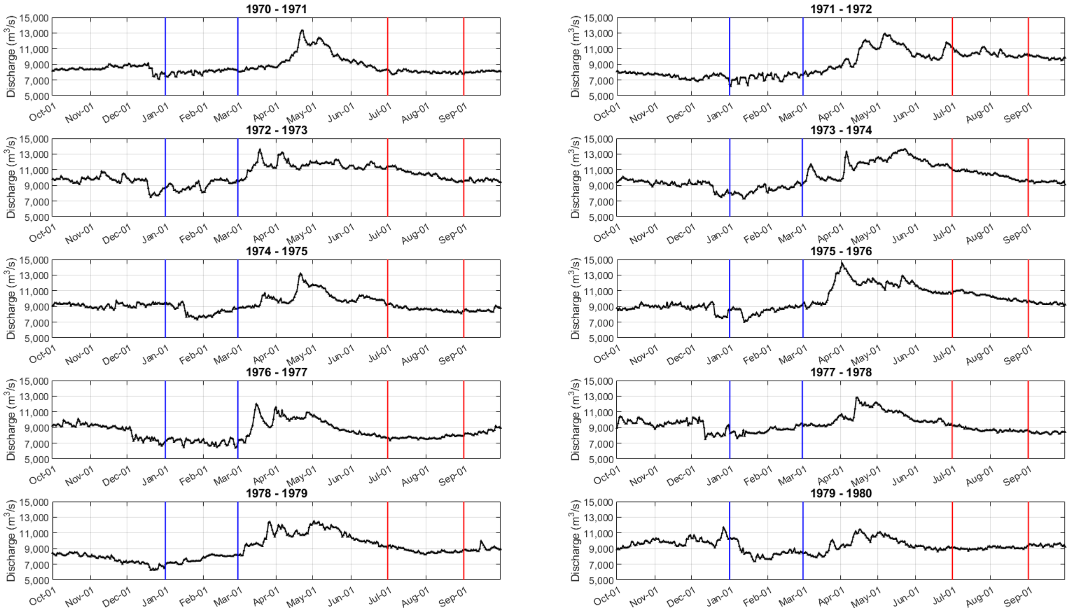
Appendix 2: Water level comparison – Pointe-Claire and Lasalle

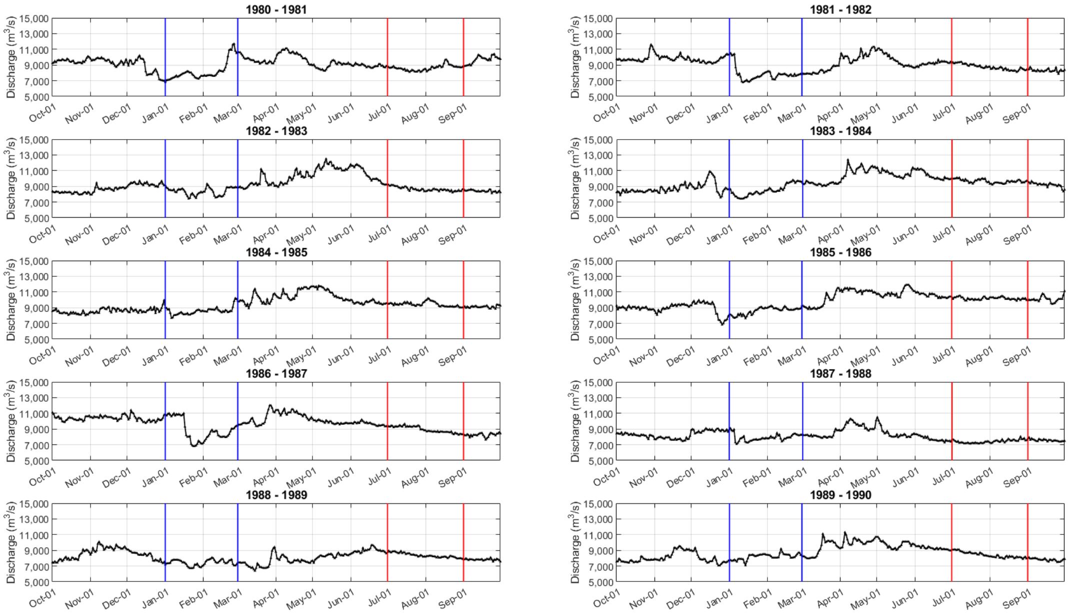


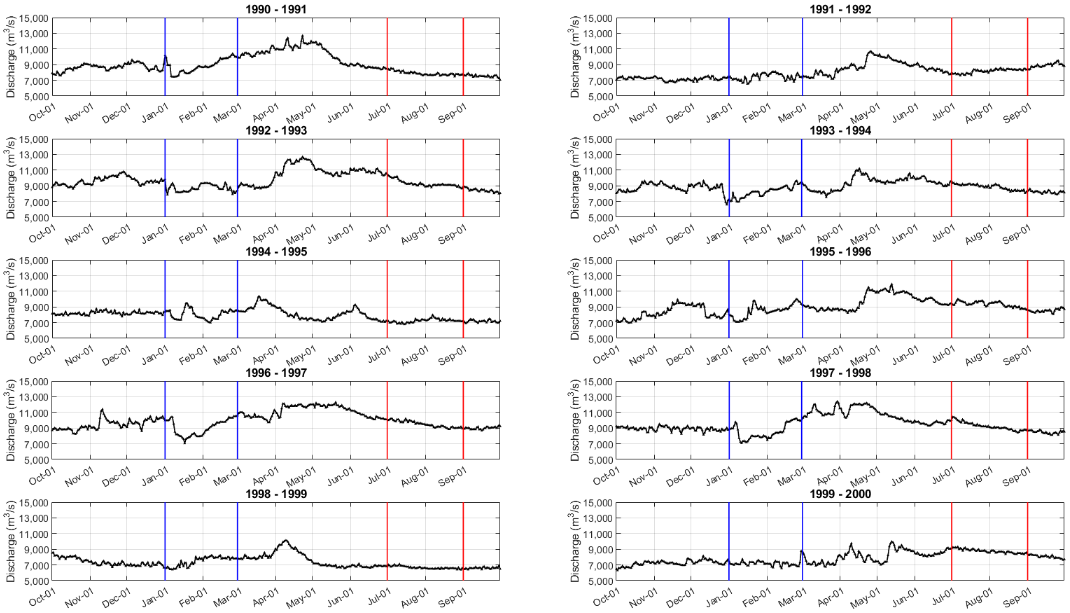
The above plots compare the water levels at two stations: Pointe-Claire (horizontal axis) and Lasalle (vertical axis). For each day of the year, the daily water level is subtracted from that on the previous Oct. 1st.

Appendix 3: Discharge

Variation of daily mean discharge for a 50-year time span (1970-2020 inclusively, divided into five decades). Each year starts on October 1. The two sets of lines (blue on the left and red on the right) correspond to the two-month time periods shown in Appendix 1 for winter and summer periods, respectively. Note: As discussed in the text, the discharge data in the winter are considered unreliable because of the presence of ice.




1980 - 1981
1981 - 1982
1982 - 1983
1983 - 1984
1984 - 1985
1985 - 1986
1986 - 1987
1987 - 1988
1988 - 1989
1989 - 1990
Discharge (m^3/s)
15,000
13,000
11,000
9,000
7,000
5,000
Oct-01
Nov-01
Dec-01
Jan-01
Feb-01
Mar-01
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01


1990 - 1991
1991 - 1992
1992 - 1993
1993 - 1994
1994 - 1995
1995 - 1996
1996 - 1997
1997 - 1998
1998 - 1999
1999 - 2000
Discharge (m^3/s)
15,000
13,000
11,000
9,000
7,000
5,000
Oct-01
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Jan-01
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Mar-01
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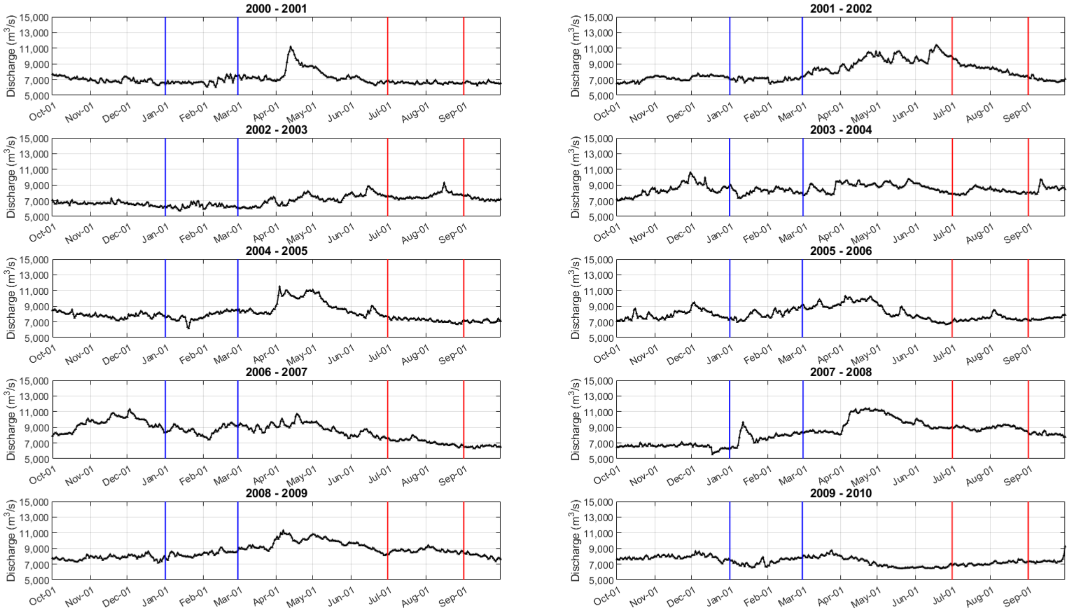
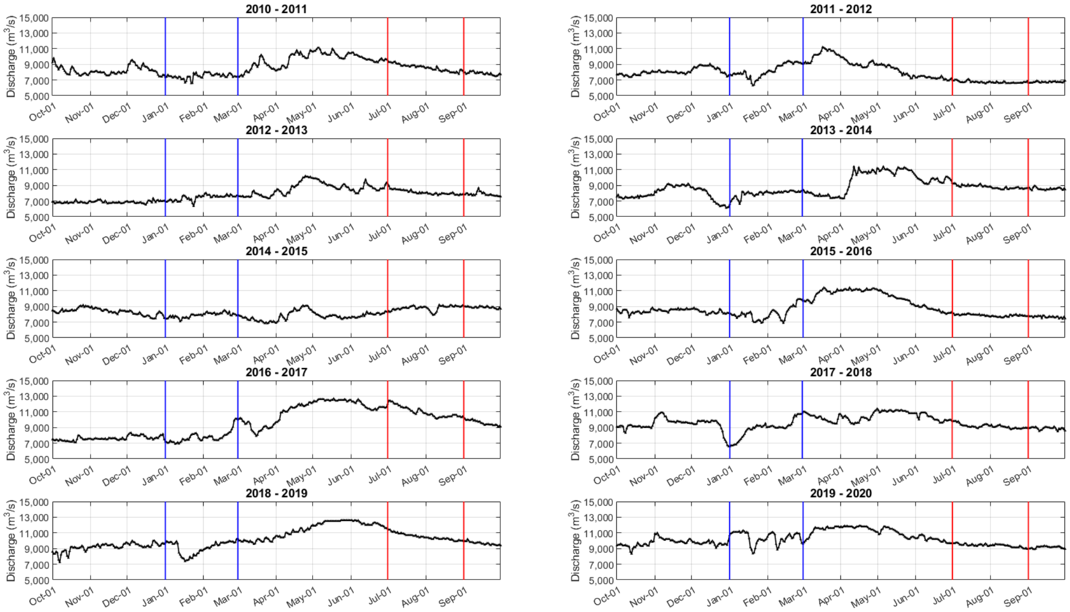
Jun-01
Jul-01
Aug-01
Sep-01


2000 - 2001
2001 - 2002
2002 - 2003
2003 - 2004
2004 - 2005
2005 - 2006
2006 - 2007
2007 - 2008
2008 - 2009
2009 - 2010
Discharge (m^3/s)
15,000
13,000
11,000
9,000
7,000
5,000
Oct-01
Nov-01
Dec-01
Jan-01
Feb-01
Mar-01
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01


2010 - 2011
2011 - 2012
2012 - 2013
2013 - 2014
2014 - 2015
2015 - 2016
2016 - 2017
2017 - 2018
2018 - 2019
2019 - 2020
Discharge (m^3/s)
15,000
13,000
11,000
9,000
7,000
5,000
Oct-01
Nov-01
Dec-01
Jan-01
Feb-01
Mar-01
Apr-01
May-01
Jun-01
Jul-01
Aug-01
Sep-01