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Ice jam modelling of the Red River in Winnipeg

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Red River spring floods are often accompanied by ice jams which impact many areas along the river. Since historical times, this has been a regular phenomenon, however analyses of recorded data over the past one hundred years suggests that ice jamming has become more severe and that this state will be maintained or even be exacerbated in the near future.

This paper describes the implementation of the numerical computer model RIVICE by Manitoba Water Stewardship to simulate the behaviour of ice jams along the Red River in Winnipeg. Specific results of the model to support Floodway operations are (i) discharges required along the Red River to reduce or maintain backwater levels upstream of an ice jam in Winnipeg and (ii) changes in discharges if additional inflow of ice occurs which can potentially exacerbate an existing ice jam situation.

Data from two ice jams in Winnipeg in the spring of 2009 and 2010 were used for the calibration and validation of the model. The data includes recorded water levels and flows, bathymetry, satellite imagery and airborne video. Backwater levels and the extent of the ice jam fronts were used as output variables, which showed good agreement with field data. The large spatial scale and prolonged temporal scale provided by remote sensing imagery is an important extension of the knowledge base of ice break-up and ice jam processes along the Red River.

1. Introduction

Spring flooding along the Red River usually begins with the break-up of the river's ice cover. Within and around Winnipeg, ice conditions impose challenges to the operation of the Red River Floodway, a channel circling the east side of Winnipeg to divert floodwaters from the Red River south of the city back into the Red River north of the city (see Figure 1). The start of operation of the Red River Floodway usually occurs when the ice has broken up and a large portion of it has cleared from the Red River south of Winnipeg.

If ice enters the Floodway channel it could jam against bridges and reduce channel capacity, or threaten the integrity of the bridge structures. There is evidence that ice break-up is occurring earlier in the spring. Since the Floodway was constructed in the late sixties, there is a significant trend to earlier start dates during the years of Floodway operation, approximately half a day each year (Lindenschmidt et al., 2010). This implies that break-up is now occurring roughly three weeks earlier than when the Floodway first began operating. Earlier break-up dates along the Red River has also been confirmed by Lacroix et al. (2005). Ice thicknesses have not significantly decreased during this timeframe (data not shown).

Ice jam flooding is often accompanied by the ice break-up along the Red River. Severe ice jamming occurred in the years 1996, 2004 and 2007, especially along the reach downstream of Winnipeg. The year 2009 saw unprecedented ice jam flooding which was exacerbated by unusual ice conditions. The ice was of average thickness but the cold weather conditions and the snow cover on the ice that persisted into the spring flooding season kept river ice from deteriorating before spring runoff. The ice cover consequently maintained its strength, making its break-up most severe when high flows resulting from the March snowmelt in the southern, headwater of the river basin encountered the strong, solid ice in the northern, downstream portion of the basin. River levels along the river both upstream and downstream of Winnipeg were particularly affected by ice. The ice in Winnipeg was also particularly stubborn in moving out of the Winnipeg area and ice jams occurred within the city, raising water levels much above open water conditions. An unprecedented condition occurred when the rising water levels in Winnipeg required the operation of the Floodway, even though most of the river had a substantial ice cover within Winnipeg and upstream of Winnipeg. This made decision-making on the operation of the Floodway in such uncharted territory challenging.

Computer modelling is used to support Floodway operations by simulating flows and water levels in the river system throughout Winnipeg and calculating the height of the gate settings required at the Inlet Control Structure to divert water into the Floodway. The model is also used to forecast operational sequences to divert inflowing flood waters from the Red River and Assiniboine river basins. Due to the increasing persistence of ice floes in the system during the required onset of Floodway operations, the Manitoba Government is committed to extending its modelling capabilities to include the simulation of flows and water levels along the Red River under ice cover and ice jam conditions:
Improvements are planned to the floodway operations computer model to account for the influence of ice cover [and ice jams] on the 2009 experience …" (MB, 2009, p.18).

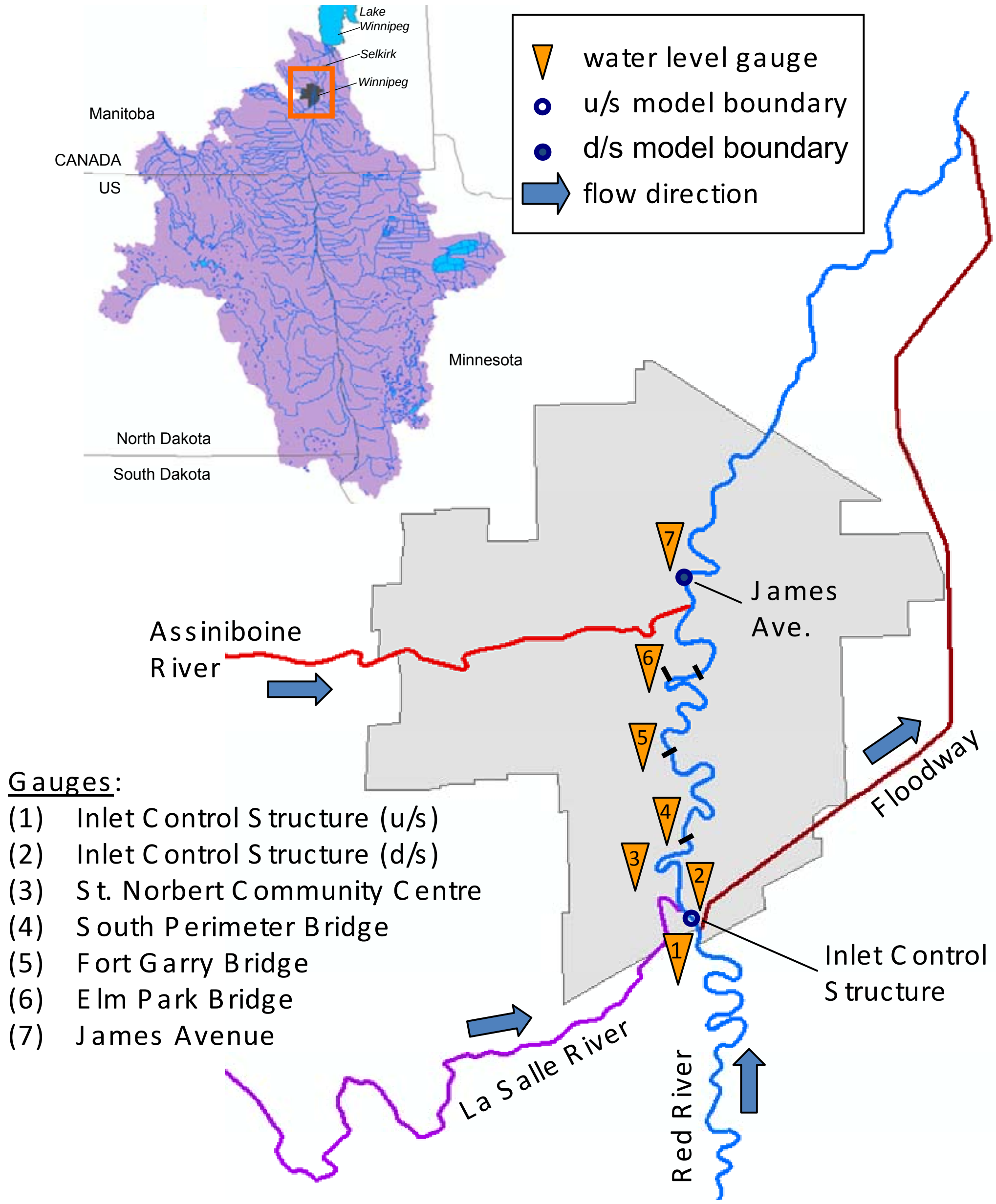

Figure 1. Depiction of: (i) major waterways through the City of Winnipeg, (ii) upstream (u/s) and downstream (d/s) boundaries of the model setup of the Red River and (iii) gauges used for the calibration of the model.

The ice jam model RIVICE was implemented to simulate the hydraulics of the Red River under ice conditions. In regards to supporting the operations of the Floodway, the objectives of the model are to:

- simulate the potential maximum backwater levels occurring from an ice jam along the Red River within Winnipeg;
- determine the discharge distribution between the Red River and the Floodway required to stabilise backwater levels upstream of an ice jam;
- compute the water level drop once the ice has cleared from the city.

2. Study site

2.1 *Red River*

The Red River originates along the North and South Dakota boundaries and flows northward into Manitoba, through the City of Winnipeg and onward to discharge into Lake Winnipeg. The river is approximately 885 km in length with a maximum relief of 70 m. The lower reach of the river is remarkably flat with a gradient of about 1:5000. Its main tributary is the Assiniboine River which flows from the west into the Red River at Winnipeg. The total area of the watershed, excluding the Assiniboine watershed, is 105,500 km2. The average discharge upstream of Winnipeg at Ste. Agathe is 184 cms with maximum and minimum recorded discharges of 3230 (in 1997) and 3 cms (in 1990), respectively (daily flow series between 1958 and 2010). Half of the annual average discharge occurs in the months of April and May, most of which is due to spring melt runoff.

2.2 *Red River ice*

Ice on the Red River is typically present from November to April. The ice cover is generally smooth, and once formed, tends to remain in place through the entire winter and has been measured to be up to 1 m thick in the Winnipeg region. Rains or melting snow on saturated or frozen soil has caused a number of catastrophic floods. Spring flooding is frequently exacerbated by mechanical ice breakup and ice jamming, especially during early and rapid melt events and due to the fact that snowmelt runoff starts in the warmer south and flows northward.

Ice jams do occur along the Red River in Winnipeg. They can hinder the operation of the Floodway, evident in the extreme flood years of 1997 and 2009, when ice remained largely stationary or in large pans much longer than in other years. Floodwater diversion was required before the ice was cleared to protect property in Winnipeg. Large ice pans did move into the Floodway during both events causing ice accumulations at the first bridge, St. Mary’s Road Bridge, crossing the diversion channel. The accumulation persisted for only eight hours during the 1997 event (John Harris, pers. comm.). However, the accumulation at the same bridge during the 2009 event required mechanical removal of the ice floes using 15 extended-reach excavators for a continual period of three days before the ice cleared the channel (see Figure 2).

3. RIVICE model

The fundamental premise of the RIVICE software is that the calculations of ice generation and evolution can be separated from the hydraulic processes (water surface profiles, changes in flow and water level, etc.) if they are done frequently. This is a so-called "loosely-coupled" relationship between the ice and the hydraulics, even though the changed ice conditions are directly introduced into the hydraulic solution at each computation cross-section and every time-step. Under very rapid jamming conditions, the time-step varies from seconds to minutes to best capture these rapidly changing ice events. It does not require a complex simultaneous solution of ice and hydraulic equations. However, the user must make a careful selection of the length of time step that suits the situation at hand.

Figure 2. Ice pileup in the area of the Floodway inlet and the Red River leading into Winnipeg in the spring of 2009.

3.1 *Ice cover setup*

An ice cover is input by the user starting from a certain cross-section extending downstream with a given thickness. The ice extends to the downstream boundary or to an ending cross-section selected by the user. The model then computes how far each parcel of ice will travel during the time step. This is based on the computed flow velocity from the hydraulic subroutines. It is assumed that the ice floes travel at the same velocity as the water.

3.2 *Ice cover shoving due to hydraulic loading*

An ice cover on flowing water is subjected to hydraulic forces which can cause deformation and thickening. The algorithm used in RIVICE involves the incremental summation of computed forces on the ice cover in a step-mode beginning from the leading edge and advancing from cross-section to cross-section in the downstream direction. The forces include (refer to Figure 3):

(i) hydrodynamic thrust F_t on the leading edge;
(ii) hydraulic drag F_d of the flow on the ice under-surface;
(iii) component of weight of the ice cover and the water contained in its voids, acting along the hydraulic gradient F_w;
(iv) force shed to the river banks includes cohesion F_C of the ice cover to the banks which acts as a frictional force of the ice cover against the river banks;
(v) hydraulic forces exerted on the ice cover in the stream-wise direction create stresses in the ice, which are spread laterally towards the riverbanks. The lateral stress results in a reaction of static friction at the bank F_f, which acts as a stabilizing influence on the cover;
(vi) force shedding to the bank or instream bridge pier can be further changed along the river reach. This is done by changing the forces being computed by a "user coefficient" that can vary from below one to well above one by the added number of pier faces that can resist ice

jam forces being generated. Values below one can be described by a resistance loss such as the introduction of warmer sewer outflows that can follow a shoreline for a significant length and thus reduce the capability of the bank to provide a resistive force along the temperature affected length.

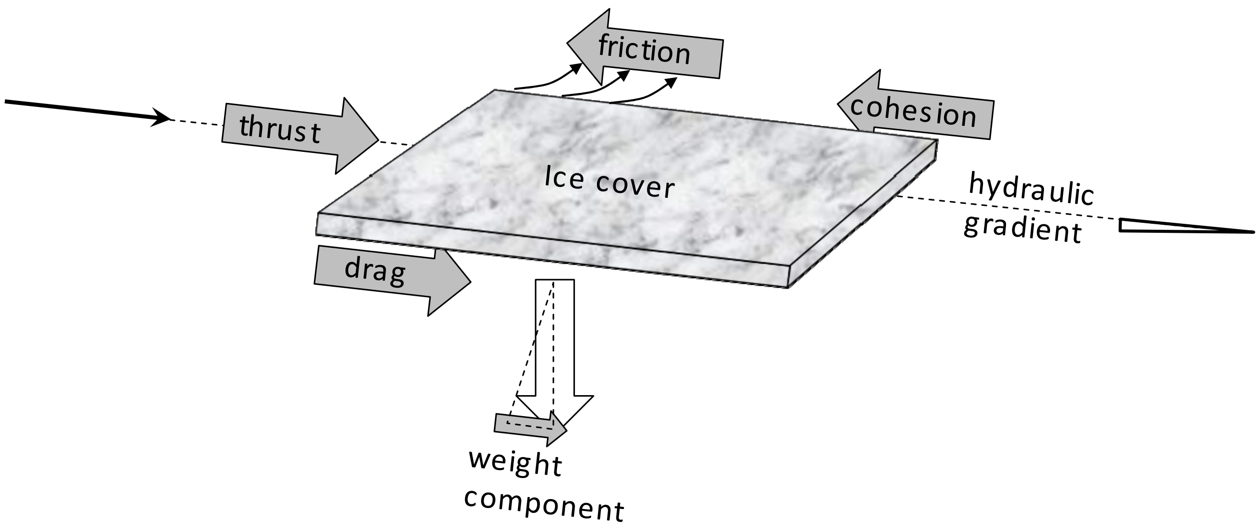

Figure 3. Forces applied on an ice cover.

As the calculation proceeds downstream, the stress in the ice cover f_i is determined from:

$$f_i = \frac{(F_t + F_d + F_w - F_c - F_f)}{t\,B}$$

where *t* is the ice thickness and *B* is the width of the ice cover. If the stress exceeds the maximum resistance of the ice cover, shoving or telescoping of the ice must occur to attain the minimum required thickness. The simulation of a shove is done by:

- thickening of the ice cover at an unstable location (i.e. stress in ice cover exceeds its internal resistance) to achieve a stable thickness; this may be restricted in any given time step by the maximum rate of movement of the ice as described below.
- reduction in ice volume at the leading edge to be equivalent to the volume required to thicken at the unstable location (a downstream "recession" of the leading edge results).

The volume of ice which is supplied to thicken the cover at an unstable location is limited by the maximum rate of movement of the ice cover, estimated to have a maximum speed equal to the average flow velocity. This represents an upper limit to the volume of ice that can move in a shove during a time step.

3.3 *Deposition/Erosion of ice cover*

Deposition of ice on the underside of a stationary ice cover occurs if the average flow velocity of the water is below a computed or specified threshold v_{dep} (default = 1.2 m/s), and there is ice-in-transit under the ice cover at that location. If this velocity is exceed, deposition will be truncated and the ice that is in transit will continue to travel downstream.

If the velocity and shear stresses are large enough, erosion of the established ice cover can occur. Erosion of the ice cover is simulated if the velocity exceeds a computed or specified limit $v_{erosion}$ (default = 1.8 m/s) (Michel, 1971). The ice will be thinned until the velocity reaches the specified limit. If an ice cover reaches a thickness that is less than 0.15 m, the erosion process is truncated at that point.

4. Results and Discussion

Two modelling case studies will be described and the simulation results discussed here:

i) Ice jam at Lord Avenue in Winnipeg on 26. and 27. March 2010 causing a backwater effect of approximately one metre rise upstream of the jam. The Floodway did not have to be operated at the time of the ice jam, hence this case serves to calibrate the RIVICE model to the hydraulic conditions of the Red River in Winnipeg.

ii) Ice jam at St. Vital Bridge in Winnipeg on 8. April 2009 causing a half metre water level rise upstream of the jam. The Floodway was required to be operated during this time and scenarios are run to determine if additional ice floes would have exacerbated the jamming and the resulting backwater effects.

4.1 *Ice jam at Lord Avenue*

The model was first calibrated on an ice jam that occurred within Winnipeg when the Inlet Control gates and the Floodway channel were not yet in operation. This jam occurred in the upstream portion of the model along a residential street called Lord Ave. The condition of the ice cover and the progression of the cover breakup leading to the ice jam can be tracked from the satellite imagery provided in Figure 4. Most of the river indicated in the imagery acquired 21. March still had an intact ice cover, except for some openings around South Perimeter Bridge and the Inlet Control Structure. The ice cover extending immediately downstream of the Inlet Control Structure was thicker than the rest of the stretch, determined from RADARSAT-2 imagery acquired at the beginning of March 2010 (Lindenschmidt et al., 2010). By 23. March, portions of the ice cover had broken up to form open water around the meander at the St. Norbert Community Centre and the most downstream river section indicated in the figure. The image acquired on 26. March shows the ice cover between the Inlet Control Structure and Lord Avenue having cracked into two large ice sheets that had lodged itself in the meander at Lord Avenue. Further crumpling of these ice sheets and additional incoming ice floes lodging at the same location caused the ice jamming at Lord Avenue, which commenced late evening on 26. March and persisted until mid afternoon the following day. The ice at and immediately downstream of the South Perimeter Bridge had already cleared.

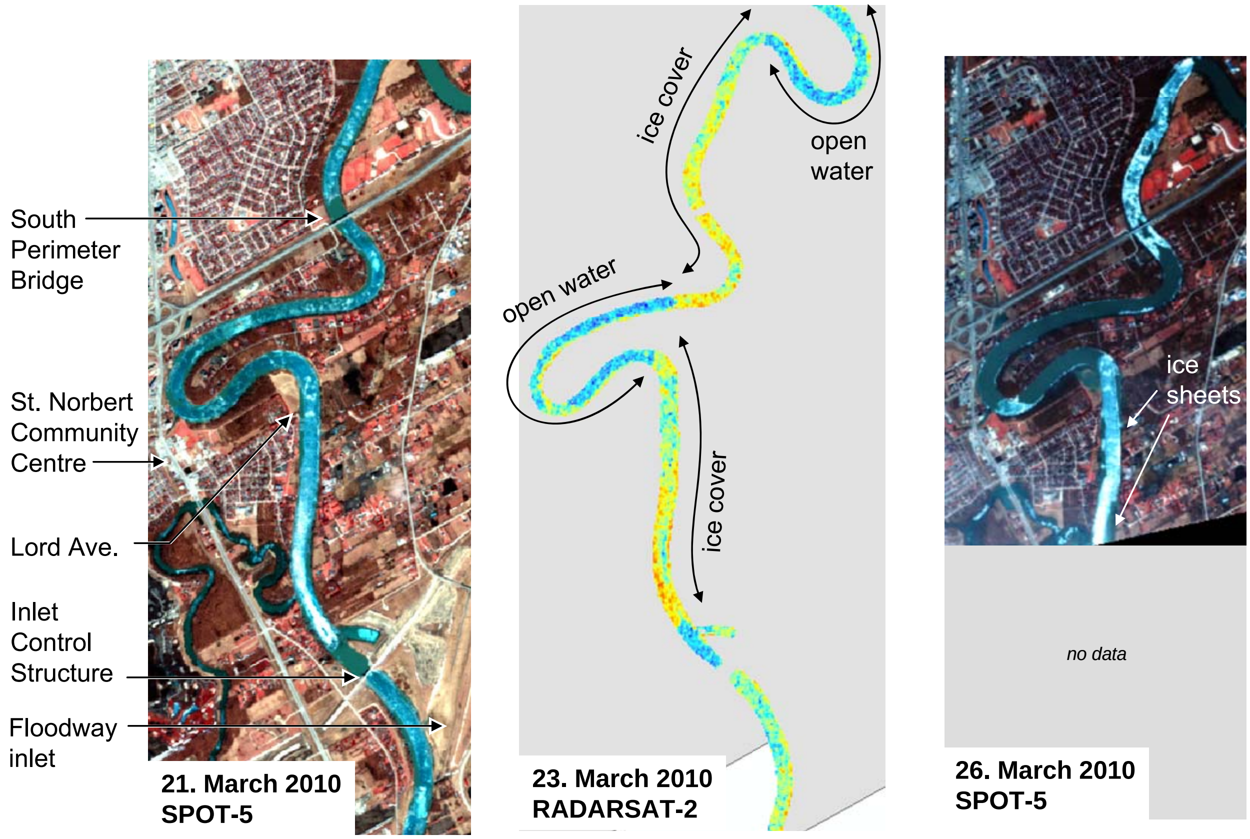

Figure 4. Progression of ice cover breakup leading to ice jamming at Lord Ave., 27. March 2010. SPOT-5 images © 2010 CNES, Licensed by Iunctus Geomatics Corp, www.terraengine.com; RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. 2010 – All Rights Reserved / RADARSAT is an official mark of the Canadian Space Agency

The change in water levels at selected stations along this reach is shown in Figure 5. Discharge into the river channel and water levels at selected gauges along the top stretch of the river are shown in the figure for the time period 24. - 30. March 2011.The discharge increased from 1000 to 1400 cms during this time. The ice jam caused a sharp rise in the water levels upstream of the jam, as indicated by the water level readings from the Inlet Control Structure in Figure 5. The water level rose by 1.3 m within 18 hours of the onset of jamming. The flow constriction dropped the water levels downstream of the jam, which is evident by the drop in water level at James Avenue during that day. Unfortunately, the gauge at South Perimeter Bridge did not function at the time of the ice jam, however readings from a gauge at St. Norbert Community Centre (data not published here) confirm a drop in water levels downstream of the ice jam area. The flow constriction persisted until 27. March when the ice jam was artificially broken up using an Amphibex machine (Topping et al., 2008). Once the ice jam was released, the water levels at the Inlet Control Structure drastically dropped accompanied by a sharp water level rise at the St. Norbert Community Centre and James Avenue gauges. The Floodway was then operated by raising the gates at the Inlet Control Structure, evident by the divergence of the water levels in the upstream and downstream gauges of the Inlet Control Structure from mid-day on 28. March and onward.

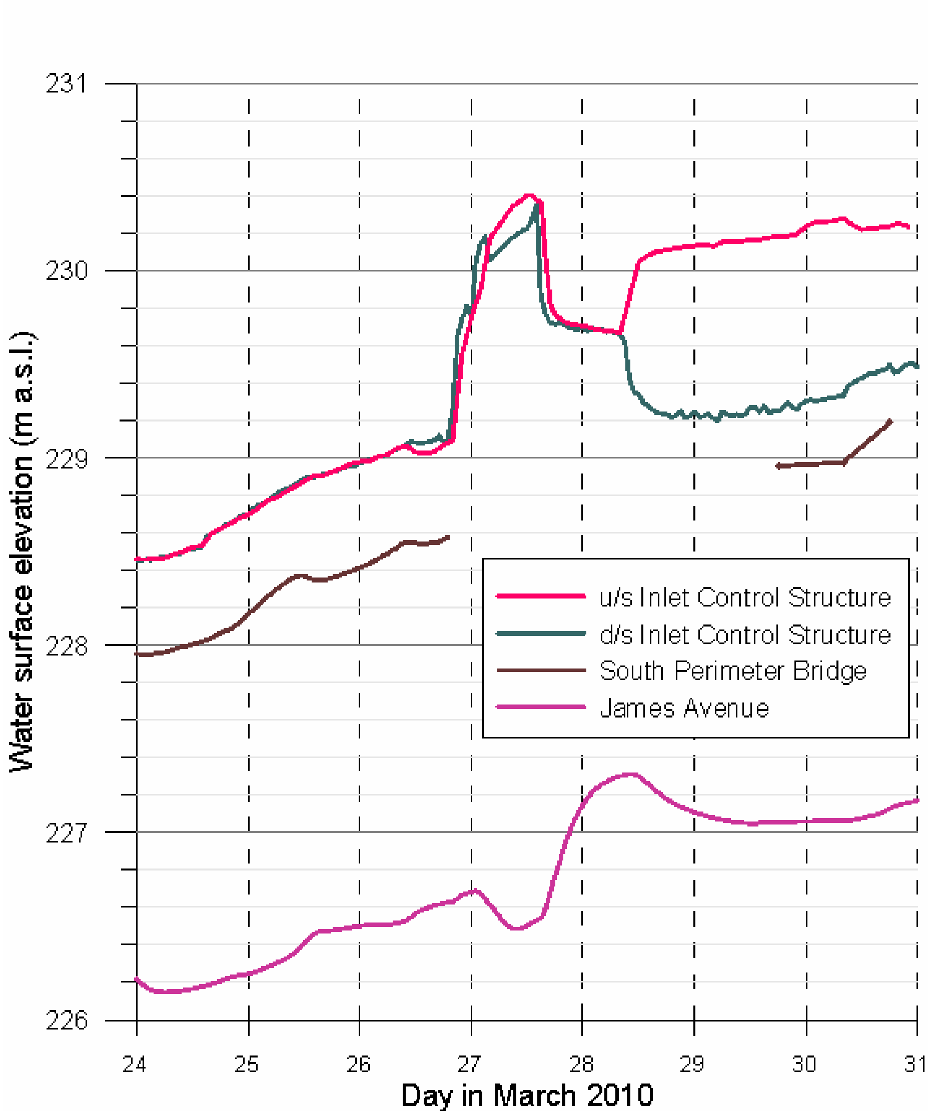

Figure 5. Water levels at selected gauges and flow through the Red River during the Lord Ave. ice jam. Gauge data from Water Survey of Canada (http://www.wsc.ec.gc.ca).

Figure 6 shows the longitudinal profile of the water surface along the modelled reach from the Inlet Control Structure to the South Perimeter Bridge. With a steady flow of 1300 cms, the model was first run under open water conditions, until a steady state was achieved (blue line). An ice bridge was then inserted in the model at Lord Avenue (distance = 1770 m). Inflowing ice from the upstream boundary lodged at the bridge forming a jam. The simulation was allowed to continue until the ice jam front juxtaposed upstream to the Inlet Control Structure (upper black line) and a second steady state was achieved. The ice jam is thickest at its toe at Lord Avenue and tapers off to its front at the Inlet Control Structure (black infill). The resulting water level profile matches well with maximum gauge readings at the Inlet Control Structure, St. Norbert Community Centre and South Perimeter Bridge.

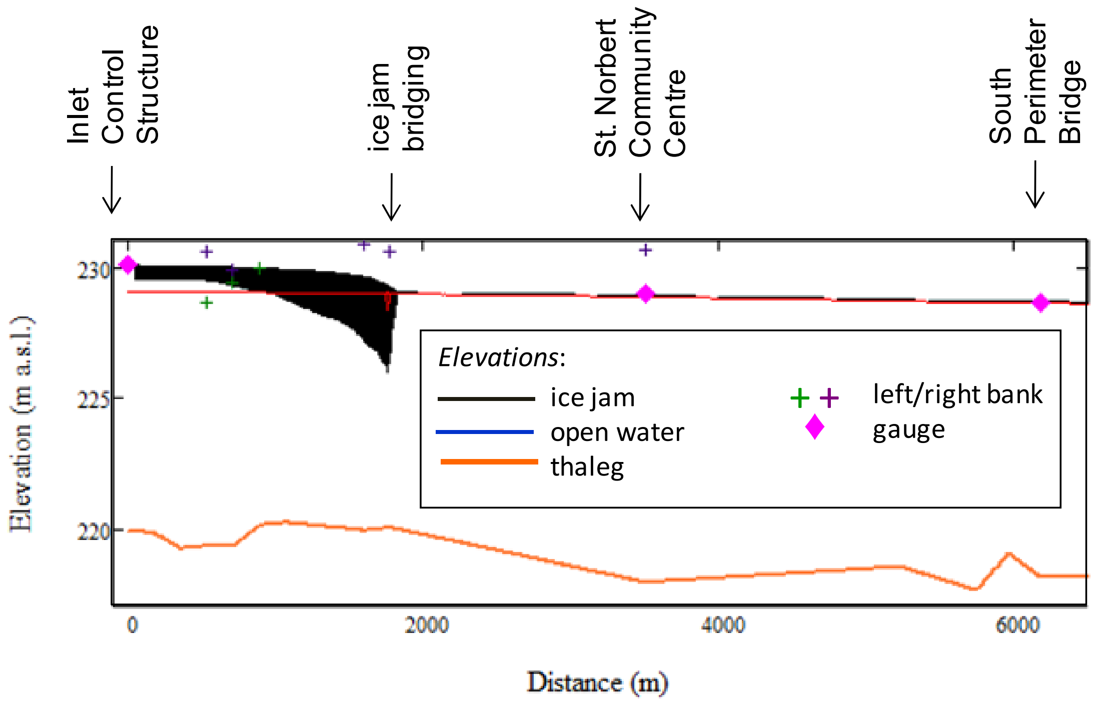

Figure 6. Longitudinal profiles of Lord Avenue ice jam between the Inlet Control Structure and South Perimeter Bridge. Gauge data from Water Survey of Canada (http://www.wsc.ec.gc.ca) and the City of Winnipeg (http://www.winnipeg.ca/publicworks/pwddata/riverlevels/).

4.2 *St. Vital Bridge ice jam*

Traditionally, the floodway should only be operated when the ice cover is gone from the river system. However, in 2009, the ice was very strong and quite intact still as the flood progressed. The strong ice cover was due to the prolonged cold temperatures and intact snow cover well through the month of March.

Operation of the Floodway was difficult because ice at the Floodway inlet did not move freely until several days after levels in the city had exceeded flood stage. A limited operation of the Floodway was required which posed a risk of river ice going into the Floodway channel and forming an ice jam (see Figure 7). Tracked excavators with extended reaches were used to remove ice and help it move between the Floodway inlet and St. Mary's Road Bridge. Minor ice jamming did develop in the floodway channel near St. Mary's Road Bridge but serious jams were avoided when the ice run from upstream of the Red River was able to break through the bridge ice several days later (MB, 2009).

A minor ice jam did occur at the St. Vital Bridge in Winnipeg (see Figure 8) during the operation of the Floodway. The backwater caused by the jam did threaten to overtop some of the upstream lying dikes and volunteers were called to help with sandbagging efforts to raise those dikes (WFP 2009a, 2009b).

Figure 7. River ice entering the Floodway channel during a necessary operation of the Floodway during the onset of spring flooding in 2009.

RADARSAT-2 satellite imagery of the Red River in Winnipeg in Figure 9 shows the extent and conditions of the ice cover along the river a few days before the ice jam occurred at the St. Vital Bridge. A solid ice cover was in place between the Inlet Control Structure and the wastewater treatment plant (WWTP) outfall. An open water stretch extends downstream from this ice cover to the Fort Garry Bridge. Between this bridge and Harris Park, the ice cover had intermittent open water sections. Downstream from Harris Park to the downstream model boundary at the James Avenue gauge, a solid ice cover prevailed.

Figure 8. Ice jam at the St. Vital Bridge

The ice between the Fort Garry Bridge and St. Vital Bridge had progressively broken up and lodged at the St. Vital Bridge to form an ice jam on 8. April 2009. The RADARSAT-2 imagery indicates that the ice within the first meander downstream from the bridge is thicker (yellow shading) which may have contributed to its resistance to the incoming flow of ice.

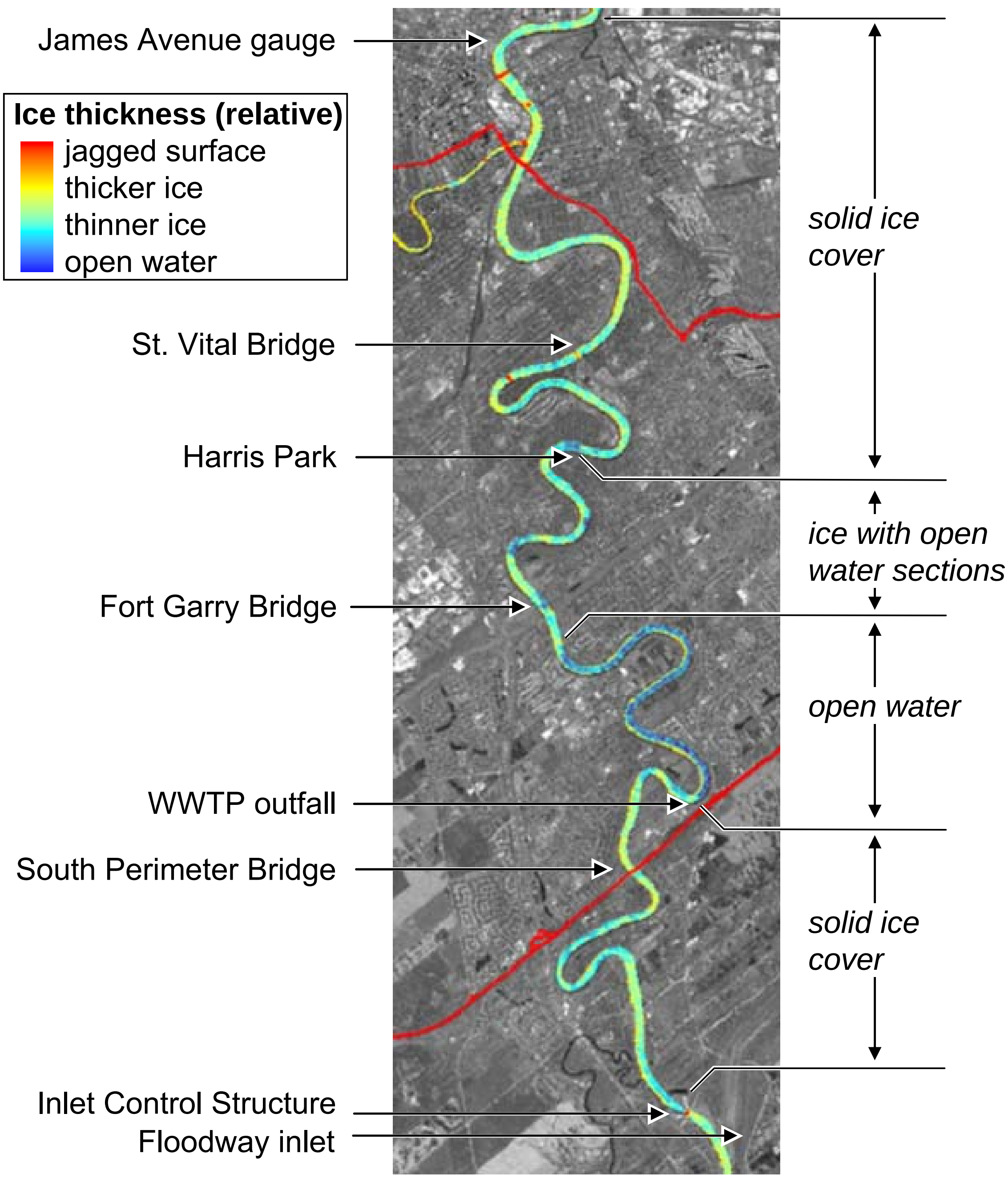

Figure 9. Extent and condition of ice cover on the Red River in Winnipeg on 4. April 2009, some days before the ice jam at the St. Vital Bridge. RADARSAT-2 Data and Products © MacDonald, Dettwiler and Associates Ltd. 2009 - All Rights Reserved / RADARSAT is an official mark of the Canadian Space Agency

Figure 10 shows, for a given discharge of 1300 cms, the longitudinal water level profiles along the modeled river stretch for three cases: open water, ice cover both upstream and downstream portions of the course and an ice jam at the cross-section just downstream of the St. Vital Bridge. The model was first run under open water conditions without any ice on the river stretch, until a steady state was achieved (blue line). Two ice covers were then inserted in the model during the simulation (red infills): (i) an upstream ice cover between the Inlet Control Structure and the WWTP outfall and (ii) a downstream ice cover extending from the jam site to James Avenue. The model was then allowed to continue to run until a second steady state condition was attained resulting in an increased water level profile due to the backwater effects caused by the flow under ice (red line). An ice volume is then inserted that lodged and formed an ice jam just downstream of the St. Vital Bridge. The volume of ice corresponds to the amount of ice that broke up between the Fort Garry Bridge and the St. Vital Bridge. The simulation was allowed to persist until another steady state was achieved. The resulting profile of the backwater levels (black line) and the thicknesses of the ice covers and ice jam (black infills) are included in the figure.

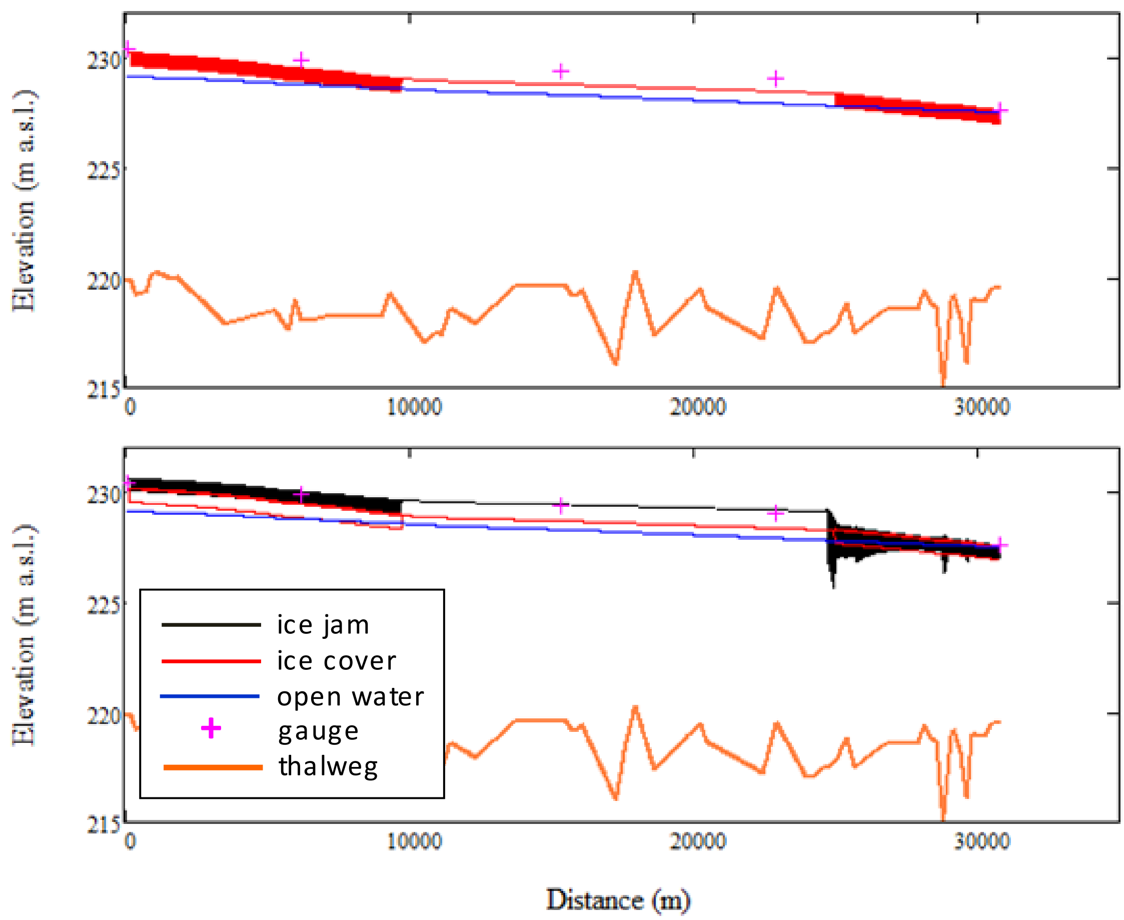

Figure 10. Simulated longitudinal profiles for ice cover only (top panel) and ice cover with ice jam at St. Vital Bridge on 8. April 2009. Gauge data from Water Survey of Canada (http://www.wsc.ec.gc.ca) and the City of Winnipeg (http://www.winnipeg.ca/publicworks/pwddata/riverlevels/).

4.3 *Scenario: varying water discharge*

For the model configuration of the ice jam at St. Vital Bridge on 8. April 2009, the inflow discharge at the upstream model boundary was varied to study its effects on ice jam juxtaposition and backwater effects. The discharge becomes a very sensitive parameter as the cross-sectional averaged flow velocity v_{mean} of the water underneath the thickening ice jam toe approaches the threshold velocity for erosion $v_{erosion}$. At that time, ice from the ice jam is pulled under and travels downstream. It will deposit under the ice cover when it reaches a cross-section with an average flow velocity less that v_{dep} or float downstream until it reaches another ice bridge. Discharges between 1200 and 1300 cms appear to be at this transition. Figure 11 shows the longitudinal water level profiles for the two simulations, as well as their longitudinal profiles of the average flow velocities. At discharges less than 1200 cms, v_{mean} at the ice jam does not attain $v_{erosion}$ and all the ice volume is juxtaposed on the ice jam front. At a discharge of 1200 cms or more, v_{mean} at the ice jam does exceed $v_{erosion}$ and ice is eroded from the ice jam toe and deposited downstream under the ice cover.

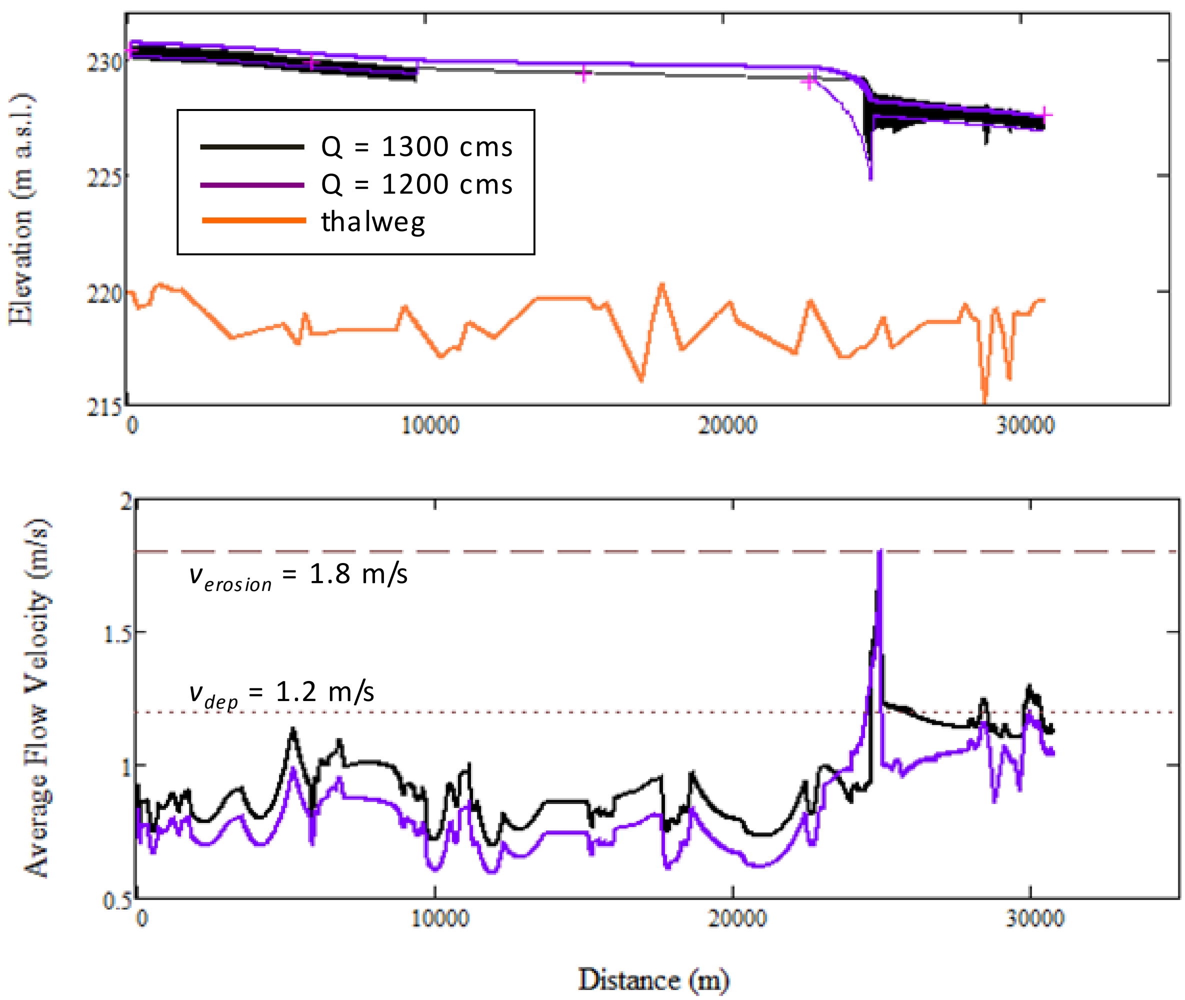

Figure 11: Comparison of longitudinal profiles of water levels (top panel) and average flow velocities (bottom panel) of the ice jam simulation for a river flow of 1200 and 1300 cms.

The highest backwater levels for an ice jam at this location are attained at a discharge of 1200 cms, as is summarised in Figure 12. Hence, to reduce the potential for increased backwater levels from an ice jam, the discharge of the Red River should be control in such a manner as to avoid cross-sectional velocities close to the value of 1.8 m/s.

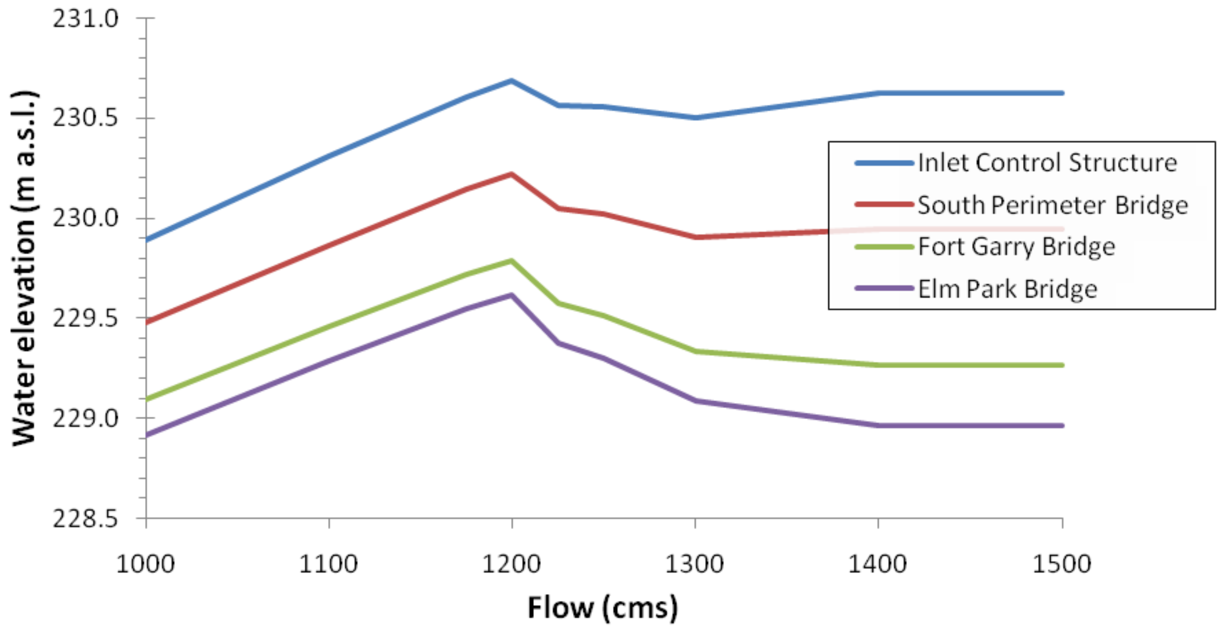

Figure 12. Change in water level elevation (y-axis) for various river flows (x-axis) at selected stations along the river.

4.4 *Scenario: varying volume of inflowing ice*

The ice jam at St. Vital Bridge released before the upstream ice cover between the Inlet Control Structure and South Perimeter Bridge broke up and released. However, the sequence could have occurred otherwise, with the ice from the upstream ice cover breaking up and running into the existing ice jam at the St. Vital Bridge. This scenario was simulated to see the effects on backwater levels from additional ice flowing into the ice jam (see Figure 13). Simulations were carried out with different increments of additional ice volume, up to approximately one million m^3, which represents the total volume of ice of the upstream ice cover. The flow remained 1200 cms for all the simulations, the discharge with the highest backwater levels determined in the previous scenario. The simulation shows that any additional ice volume would decrease backwater levels. The additional ice on the ice jam front would have caused ice thickening at the jam toe. This in turn would increase the average flow velocity under the toe to reach values higher than $v_{erosion}$ causing the model to erode ice from the jam and transport it downstream.

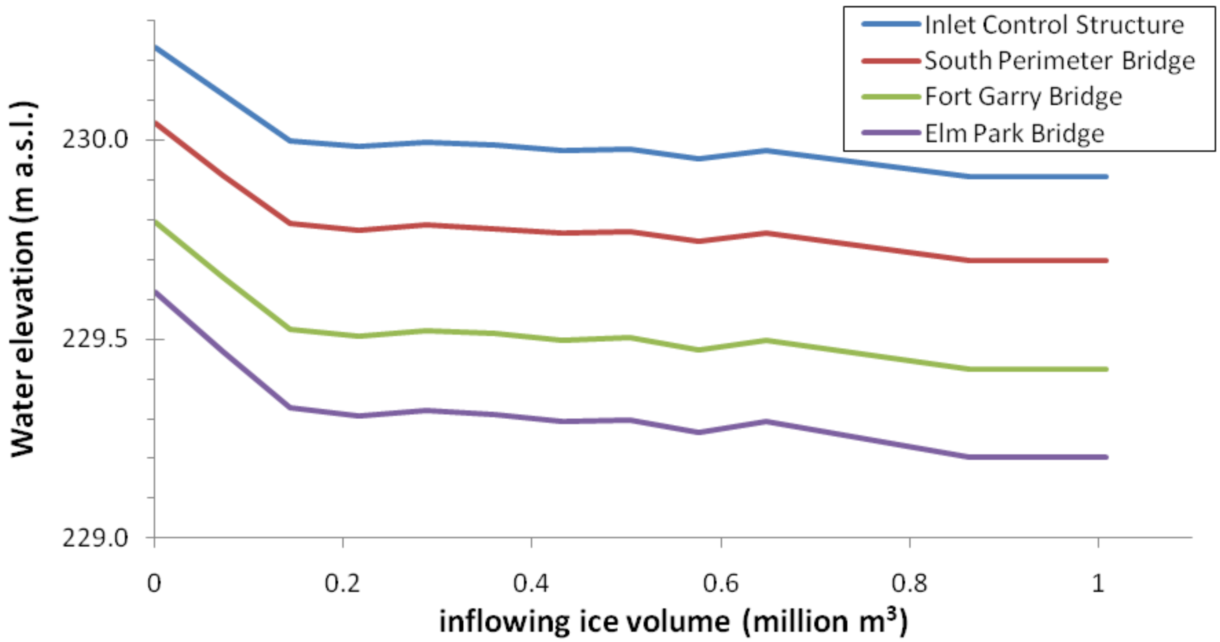

Figure 13: Change in water level elevation (y-axis) for various inflowing ice volumes (x-axis) at selected stations along the river.

4. Conclusions

RIVICE was successful in simulating ice jams that have occurred along the Red River in the city of Winnipeg, both with and without the operation of the Floodway. Both changes in water flow and changes in incoming ice volume are equally sensitive to simulated backwater effects.

If operation of the Floodway with stationary ice covers still intact is imperative and there is a high potential for ice jamming along on the Red River in Winnipeg, the following is recommended for operating the gates at the Inlet Control Structure:

(i) control the discharge through the Red River so as not to cause average flow velocities to hover just below the mean ice erosion velocity along any section with high ice jam potential;

(ii) monitor closely the break-up of an ice cover upstream of an ice jam; take into consideration that the release of this ice may exacerbate an ice jam, if the average flow velocity under the ice jam toe approaches 1.8 m/s which increases backwater levels. If this occurs, a higher discharge may alleviate the rising backwater levels by eroding the ice from the ice jam toe.

It must be note that the parameter set used for these simulations is specific to the location and boundary conditions of these test cases. Further simulations of ice jams at other locations along this river stretch using data from several years need to be calibrated to determine the range of values these parameters can fluctuate within, in particular sensitive parameters such as the ice erosion velocity. A Monte Carlo analysis, in the framework of uncertainty analyses, can be implemented to determine a probabilistic risk of attaining specific backwater levels. This is a topic of future work.

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