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Modelling the Impacts of Dam Rehabilitation on River Ice Jam: A Case Study on the Matane River, QC, Canada

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Dam rehabilitation can be a way to stabilize an aging dam, reduce the associated risks of flooding, optimize its operation and update its utility on a river system. The Mathieu-D'Amours Dam is located on the Matane River, in the downtown area of the City of Matane (Quebec, Canada). It is owned and operated by the Ministère du Développement durable, de l'Environnement et de la Lutte contre les changements climatiques (MDDELCC). The structure is made of 11 gates which are fully opened in winter and spring to let the ice move through and reach the St. Lawrence River 1.6 km downstream of the dam. The MDDELCC is currently planning to modify the existing dam and has mandated WSP to assess the impacts of dam rehabilitation on river ice jam. In a previous study, WSP showed that historical ice jams and floods have occurred both upstream and downstream of the dam and that only a few gates were currently efficient to convey ice during breakup. The impacts on ice regime of a dam modification were modelled using the CRISSP2D software developed at Clarkson University. The dam was first modelled as a boom to initiate ice jam in accordance with the standard method. An alternative technique was also applied by representing the dam pillars as nonmoving parcels and letting the moving ice accumulate against these pillars. That last technique has several advantages over the standard "fixed boom method" since it does not artificially force the ice to accumulate along a specific axis and allows the simulation of multiple dam geometries, including various gates widths. Modified dam geometries were simulated with CRISSP2D to assess the changes in jam conditions at the dam and ice discharge through the gates. Following the simulations, solutions to mitigate the risk associated with dam rehabilitation were analyzed and compared.

1 Introduction

Ice jam events periodically occur on the Matane River, near its outlet to the St. Lawrence River, which cause flooding and damages to the riverine structures. The Ministère du développement durable, de l'environnement et de la lutte contre les changements climatiques (MDDELCC) owns the Mathieu-D'Amours Dam, located on the Matane River in the City of Matane (Figure 1). Over the years, the MDDELCC has gathered information about historical ice jams and has developed methods to mitigate the associated flood risks, including de-icing works.

The MDDELCC is currently planning to modify the existing dam, which will likely change the river ice dynamics in the area. Discussions among the stakeholders have begun, but no decision has yet been made about the future configuration of the dam.

WSP was mandated by the MDDELCC to assess the impacts of Mathieu-D'Amours Dam rehabilitation on river ice jam. Several activities were performed by WSP to conduct this task, including: site visit, historical research, description of existing river ice dynamics, analysis of historical ice jams, documentation of the de-icing works in Matane and numerical modelling of ice jam using the CRISSP2D software.

2 Site Description

The Mathieu-D'Amours Dam is located in the downtown area of the City of Matane (Figures 2 and 3). This dam has 10 radial gates (each 6.1 m wide) and one overflow gate (12.2 m-wide). A fish passage is located on the left bank. In summer, the dam gates are closed to increase the upstream water level and create a pond for municipal recreational activities. Between fall and the end of the spring freshet, the gates are fully open to lower the upstream water levels and maximize the water and ice discharge capacity of the dam.

Downstream of the dam, the Matane River runs through the City of Matane and is surrounded by concrete walls on both sides. A natural obstacle, called "Roche à Camel", is located 350 m downstream of the dam. This obstacle separates Matane River and Harbour in low flow/low tide conditions. Tides do not influence significantly the flow capacity of the dam, as the higher high water large tide (HHWLT) is lower than its sill elevation.

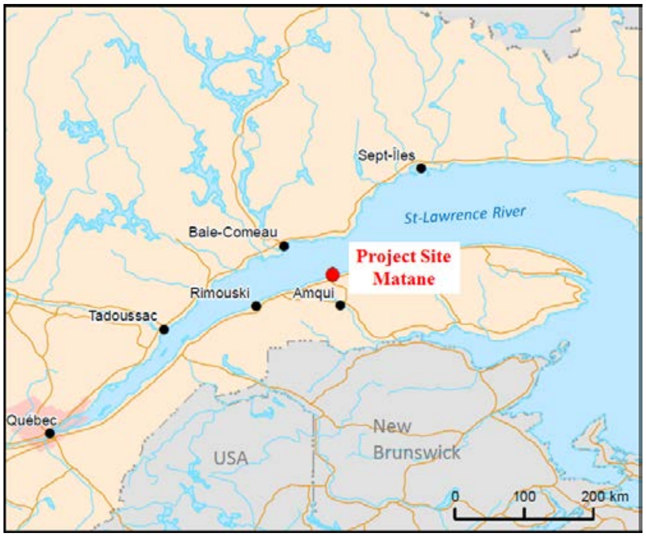

Figure 1. Dam Location in the province of Quebec.

Figure 2. Dam Location in the City of Matane.

Figure 3. Mathieu-D'Amours Dam viewed from downstream (MDDELCC).

3 River Ice Dynamics

The Matane River watershed at the dam has a total area of 1,692 km² (MDDELCC, 2003) and the river runs from south to north. The ice dynamics were analyzed on the reach between the St. Lawrence River and Matane Wildlife Reserve (75 km-long). This analysis allowed to get a better understanding of the freeze-up processes and ice movements during breakup.

Data from Environment Canada weather stations (Matane and St. René-de-Matane) were analyzed to assess the climatic differences between the south and north parts of the watershed. Results showed that the temperature in the north (where the dam is located) is typically warmer in winter and colder in spring and summer. It was also shown that the south part of the watershed receives in average more rain and snow than the north part. These differences help explaining the phenomenon by which the ice breakup starts in the south of the watershed (upstream) and hits less deteriorated ice cover in the north (downstream).

In winter, a complete ice cover typically forms on more than 40 km upstream of the dam. When the ice starts moving, it typically jams first at 3.0 km upstream of Matane in a large meander, directly upstream of a shoal. A second jam site is located at 1.8 km upstream of the dam where the river is divided in two branches around an island (Figure 2). These natural jam sites are beneficial to lower the flood risks in Matane, as they have the capacity to retain significant ice volumes, to delay the ice runs arrival and to break up some large ice floes.

Directly upstream of the dam, the MDDELCC operates an excavator or a crane to break the ice and facilitate its passage through the dam. This operation is typically performed in preparation and during the ice breakup. Observations and witnesses testimonies have shown that the gates on the left-bank side of the dam have poor capacity to convey ice during breakup as they are located behind the island and out of the main current. During breakup, many ice floes are deported toward the left bank where they accumulate against the dam or on the shallow river bed (Figure 4).

The upstream face of the dam pillars have a negative vertical angle, as illustrated on Figure 5. This particularity tends to increase ice accumulation against the structure, as it makes the ice floes flip and dive toward the river bed rather than breaking them into pieces.

Downstream of the dam, the “Roche à Camel” is a natural obstacle where the ice has a tendency to accumulate, which can cause flooding in the downtown area. Every year, in preparation for ice breakup, the City of Matane opens a channel in the ice cover from the Matane Harbour to the dam. This channel is intended to convey the moving ice through the downtown area and let it reach the St. Lawrence River without jamming.

There is no particular frazil issue in Matane since there are no large rapids in upstream river reach that can generate this type of ice.

Figure 4. Ice remains upstream of the dam after breakup on April 6, 2009 (MDDELCC).

Figure 5. Dam pillars on November 24, 2015.

4 Ice Jam Modelling

The longitudinal profile of the aggregate thickness of an ice jam and the variation in water level can be computed for a given jam location when the bathymetry and river discharge are also known (Beltaos, 2015). This work is typically done using a one-dimensional (1D) steady state model such as HEC-RAS. For more detailed simulations, two-dimensional (2D) unsteady state models can also be used.

4.1 Model Description

The hydrodynamic and ice dynamic conditions at the Mathieu-D'Amours Dam are better described by a 2D model because of the river and structure configuration. In this context, ice jam modelling and simulation of dam rehabilitation scenarios were performed using a coupled (water and ice) 2D dynamic model. The software used for the Project is CRISSP2D, version 1.1, developed at Clarkson University (Shen et al., 2000; Shen, 2008).

The recommended software to generate the CRISSP2D finite element mesh is SMS (Surface Water Modelling System), which requires the purchase of a licence. For this project, WSP preferred using the Blue Kenue software, developed by the National Research Council of Canada (NRC). Blue Kenue has a free use licence and is widely used in Canada to prepare, analyze and visualize hydraulic data, including 2D triangular mesh. A simple tool was developed by WSP to convert Blue Kenue mesh into CRISSP2D mesh. This tool eases the addition of ice processes to an existing hydraulic model, including TELEMAC-2D models, which are quite common in the province of Quebec.

Figure 6 presents the simulation mesh which is made of 3,522 nodes and 6,489 elements. The mesh size varies between 2 and 10 m, and equals 3 m near the dam. The model's upstream boundary is located 860 m upstream of the dam and its downstream boundary is located 580 m downstream of the dam, in the Harbour. The central pile of the St-Jerome Bridge is represented as an “island” (unmeshed zone) inside the domain. The secondary branch of the Matane River directly upstream of the dam was not included in the model as it is only flooded in summer time, and its capacity to convey ice is very limited due to its narrow inlet.

In all the simulations, the gates were considered fully open, which is the case in spring during breakup. The model geometry includes the sill elevation of all gates as shown on Figure 7.

The Matane River discharge is set as upstream boundary conditions. Discharges were obtained from the MDDELCC hydrometric station #021601, at 9.5 km upstream of the dam. The St. Lawrence water level was set as downstream boundary conditions in the Matane Harbour. Since no data was available for Matane, the level was estimated from Fisheries and Oceans Canada measurements at nearest stations on the St. Lawrence River: stations Rimouski (#2985) and Rivière-au-Renard (#2330).

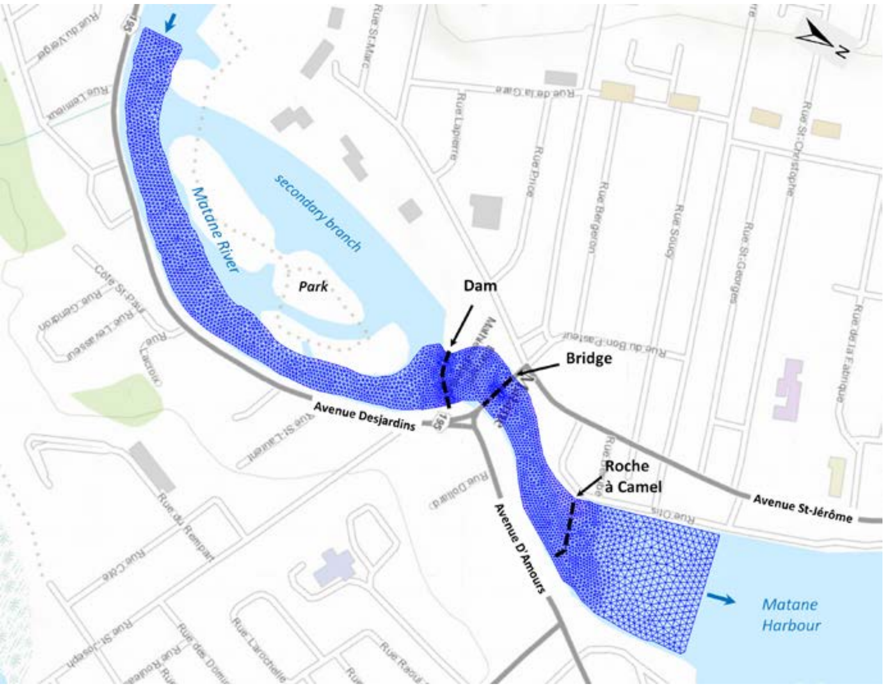

Figure 6. Plan view of the CRISSP2D simulation mesh.

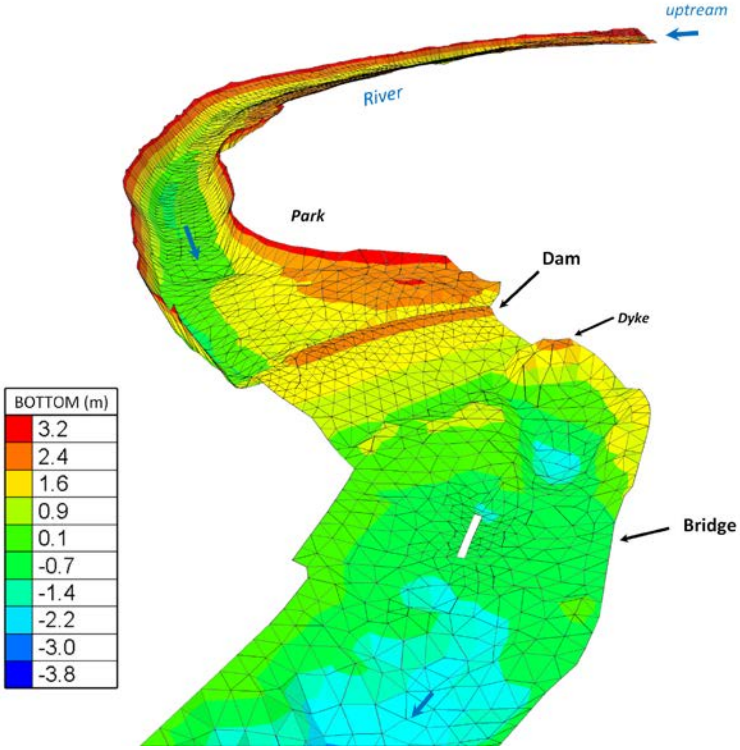

Figure 7. Isometric view of the CRISSP2D simulation mesh

4.2 Ice Jam Initiation

The standard method to initiate a jam in CRISSP2D is to place a fictitious barrier (boom) at a pre-defined location on the river and let the moving ice parcels accumulate against it. For this method, the user fixes the jam toe position based on his/her knowledge of local ice dynamics, river geometry and historical ice jam observations. The ice forces within the jam and on the boom are computed directly by CRISSP2D. The boom parameters are typically adjusted to ensure that no ice floe can pass under the boom and make its way downstream.

An alternative method was also used by WSP to initiate a jam at Mathieu-D'Amours Dam. Nonmoving parcels were placed along the longitudinal axis of each dam pillar, as illustrated on Figure 8. Moving ice floes were introduced at the upstream boundary and their interaction with the pillars was computed by CRISSP2D. This method has several advantages over the standard "fixed boom method" since it does not artificially force the ice to accumulate along a specific axis and allows the simulation of multiple dam geometries, including various gates widths.

Ice jam initiation at the Roche à Camel could only be modelled using the standard method as this natural obstacle (weir) cannot be simply represented with nonmoving parcels as for the dam pillars. Ice jam in this area seems to be initiated by grounded ice especially during low tide periods.

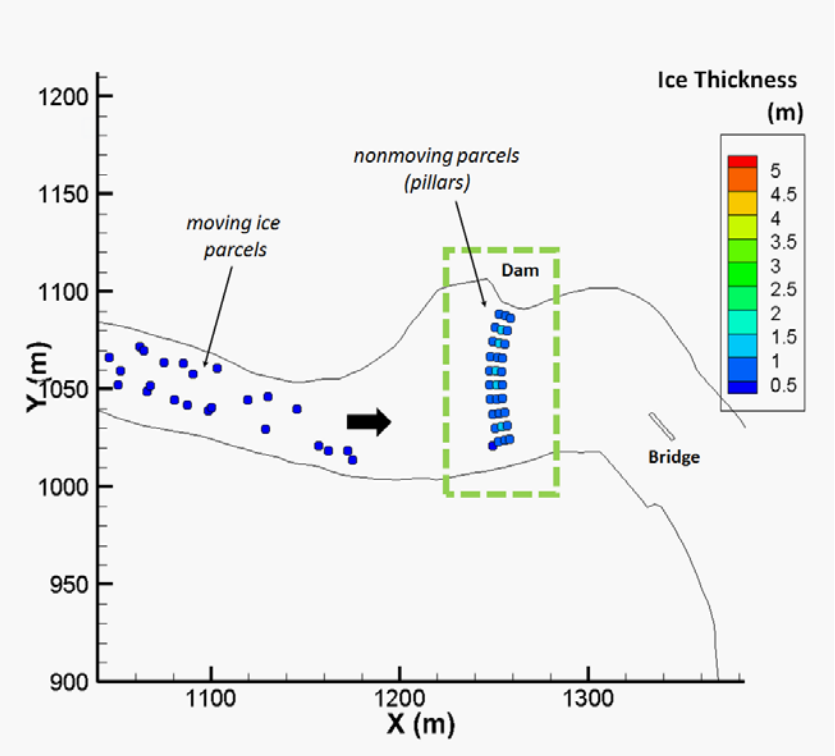

Figure 8. Plan view of moving and nonmoving parcels near the dam.

4.3 Scenario

Two historical ice jam events were simulated using CRISSP2D: April 1993 (jam downstream of the dam) and April 1994 (jam at the dam). The 1993 jam on the "Roche à Camel" was used to calibrate the model in the downtown area. The 1994 jam was used to calibrate the model upstream of the dam. This paper only present results for the 1994 event.

In May 1994, a significant ice jam occurred at the Mathieu-D'Amours Dam. During this event, the discharge was approximately 286 m³/s and the St. Lawrence River water level was around 1.0 m. In comparison, the 2-year flood discharge is 398 m³/s (MDDELCC, 2016) and the 2-year St. Lawrence water level in Matane is 2.6 m. The ice passing through the gates of the dam caused damages to its deck. The ice jam profile upstream of the dam was estimated based on pictures of the shear walls in the upstream reach.

4.4 Results

The 1994 jam at the dam was modelled using the standard method (fixed boom) and alternative method (nonmoving parcels). Preliminary results are presented below.

4.4.1 Standard Method

A first simulation was performed by placing a fixed boom directly upstream of the dam, on the entire river width. The ice jam profile obtained from this simulation was clearly overestimating the ice retention capacity of the dam, as the computed jam levels were more than 1 m above the observations. A second simulation was run by placing the fixed boom only in front of the 10 radial gates (6.1 m-wide). Thus, the overflow gate (12.2 m) was intentionally left unobstructed, as this gate is known to be efficient to convey ice during breakup. The results obtained were similar to the first simulation (full-width boom) and were still overestimating the jam elevations. A third simulation with the fixed boom was run by blocking the six radial gates on left-bank side, as they are known to have poor ice conveyance capacity. For this simulation, the computed upstream ice elevations were approximately 1.5 m below the observations, which indicates that the ice retention capacity of the dam was clearly underestimated.

No further simulation was conducted using the standard method, as additional fixed boom blockage scenario would not be based on field observation or evidence. Therefore, an alternative jam initiation method was used to obtain a satisfactory ice jam profile.

4.4.2 Nonmoving Parcels

The 1994 jam at the dam was modelled using the nonmoving parcels technique. Nonmoving parcels were placed approximately 3 m apart from each other along the longitudinal axis of each pillar. These parcels were set as “stopped” in the CRISSP2D ice dynamic information file and a hot start run was performed.

Figure 9 presents the 1994 ice jam profile calculated using the nonmoving parcels method. The computed ice elevations in the upstream reach are similar to the observations. During the simulation, many ice parcels were deported toward the left bank-side where they accumulated. This behaviour is consistent with the dam operator observations of the ice movements during breakup. The 12.2 m wide gate on the right-bank side was the main outlet for ice parcels during all the simulation. However, some parcels were still able to pass through the smaller gates (6.1 m wide), especially when the forces in the jam toe region were high. Results showed that the existing dam allowed the passage of approximately 20% of the total incoming ice discharge during the 1994 event.

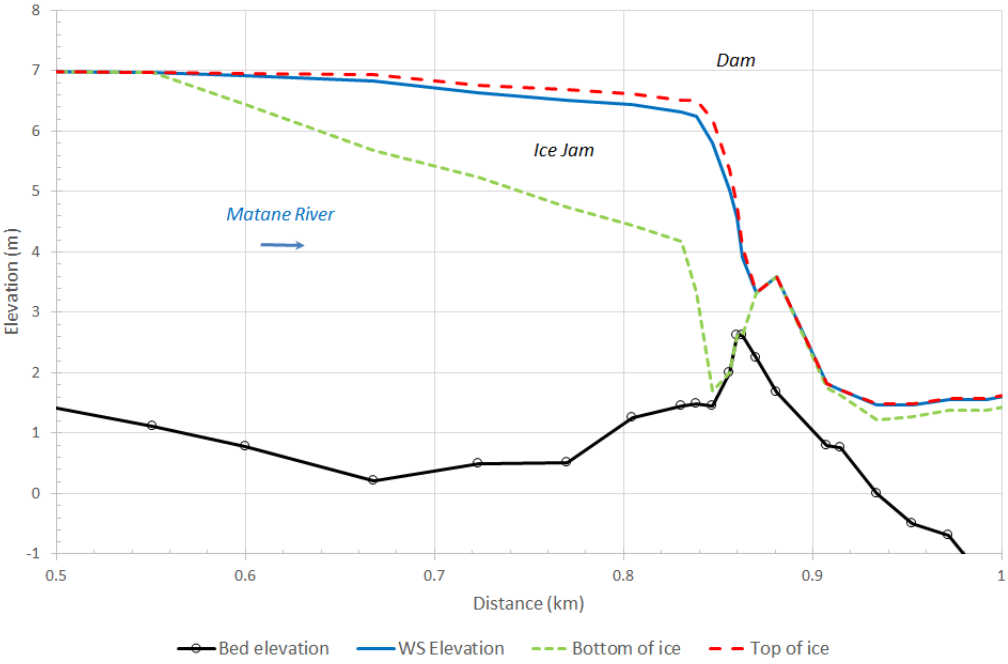

Figure 9. 1994 ice jam profile calculated using the nonmoving parcel method.

To assess the impacts of dam rehabilitation on the ice jam conditions, the existing dam configuration was modified in the CRISSP2D model by changing the location of the nonmoving parcels and by simulating the 1994 ice jam with these modified dam geometries. Table 1 presents the results obtained for two rehabilitation scenarios: all pillars removed and 5 pillars removed. By removing all pillars, the upstream ice elevation is reduced by 2.6 m but, in return, the ice discharge downstream of the dam is increased by 400%. Similarly, by removing 5 pillars, the upstream ice elevation is reduced by 1.7 m and the ice discharge is increased by 300%.

Table 1. Results of two rehabilitation scenarios for the 1994 ice jam scenario.

Dam configuration	ΔZi (m)	ΔQi
Existing dam	-	-
All pillars removed	-2.6	+400%
5 pillars removed	-1.7	+300%

ΔZi: difference in top of ice elevation compared to existing dam

ΔQi: difference in ice discharge trough the dam compared to existing dam

5 Conclusion

WSP was mandated by the MDDELCC to assess the impacts of dam rehabilitation of the Mathieu-d’Amours Dam on river ice jam. To quantify these impacts, a CRISSP2D numerical model representing the hydrodynamics and ice dynamics near the dam was developed. Two methods were considered to initiate the jam at the dam: 1° standard method using a fictitious fixed boom and 2° alternative method using nonmoving parcels to represent the multiple dam pillars. Model calibration results showed that the standard method was not well suited to represent jam conditions near the dam, because the structure only retains a certain amount of ice. This method required a trial-and-error process that was time-consuming and did not lead toward a partial blockage solution in agreement with jam observations. An alternative method was tested by placing nonmoving parcels along the longitudinal axis of the pillars. Results obtained with this method were in agreement with the 1994 ice jam observations. The nonmoving parcels method was also successfully used to model dam rehabilitation scenarios.

Although not presented in this paper, the 1993 jam on the “Roche à Camel” was used to calibrate the model in the downtown area. The calibrated model was used to assess the impacts of different rehabilitation scenarios on ice jam and associated flood risks.

Discussions between the MDDELCC and other stakeholders are currently in progress. Therefore, no decision has yet been made about the future configuration of the dam. Once the geometry of the new dam will be defined, additional hydrodynamics and ice dynamics simulations will be performed. These simulations will include the assessment of ice jam conditions in the downtown area given the new dam configuration.

6 Acknowledgments

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