Possible effects of the 1984 St. Clair River ice jam on bed changes[1]

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Abstract: This study examines the possible effect of the record ice jam of 1984 in the St. Clair River on river bed changes and conveyance. Numerical simulations were made to examine the flow and bed shear stresses during the jam formation and release periods. Simulation results indicate that the ice jam in the river did not cause a significant increase in bed shear stress compared to pre- and post-jam open water conditions. The insignificant change on bed shear stress during the ice jam period is the result of the large flow depth and the limited jam thickness. The bed shear stresses are much less than the critical shear stress for bed particle movement. This implies that the jam may not have had a significant impact on the channel conveyance.

Key words: bed erosion, ice jam, mathematical modelling, river ice dynamics, St. Clair River.

Résumé : La présente étude examine les effets possibles des embâcles observés en 1984 sur la rivière Sainte-Claire sur les modifications du lit du cours d'eau et sur l'écoulement de ce dernier. Des simulations numériques ont été réalisées pour étudier le débit et les contraintes de cisaillement exercées sur le lit de la rivière lors les périodes de formation d'embâcles et pendant les débâcles de glaces. Ces simulations montrent que les embâcles de la rivière n'entraînaient pas d'augmentation significative des contraintes de cisaillement exercées sur le lit du cours d'eau, si l'on compare ces dernières à celles enregistrées dans la rivière avant et après la formation des embâcles. Les très faibles variations de contrainte de cisaillement observées dans le lit durant la formation des embâcles s'expliquent par la profondeur importante de la rivière et par la faible épaisseur de la glace au niveau des embâcles. Les contraintes de cisaillement exercées sur le lit sont bien inférieures aux contraintes de cisaillement limites liées au mouvement des particules du lit. De ce fait, les embâcles pourraient ne pas avoir d'impact significatif sur l'écoulement du cours d'eau. [Traduit par la Rédaction]

Mots-clés : érosion de lit, embâcle, modélisation mathématique, dynamique de la glace de rivière, rivière Sainte-Claire.

Introduction

The conveyance of the St. Clair River, which connects Lake Huron and Lake St. Clair (Fig. 1), has attracted much attention because of its impacts on upper Great Lakes water levels (International Upper Great Lake Study 2009). Large amounts of ice can enter the St. Clair River from Lake Huron during the winter and early spring. The extensive river delta at downstream, known as the St. Clair Flats, may slow down the ice run and initiate ice jamming. In 1984, a jam with record magnitude formed in the St. Clair River on April 4 and lasted until April 29 (USACE 1984; Derecki and Quinn 1986). It was suggested that this record jam might have caused sediment movement and changed channel conveyance of the river (Daly 2009; Holtschlag and Hoard 2009). However, Beltaos (2009) suggested that "the available evidence is not sufficient to justify a conclusion that the 1984 jam was indeed the cause of the change" and more direct corroboration is needed. This paper presents the results of a numerical model study to examine the possible effects of the 1984 ice jam on river bed and channel conveyance in the St. Clair River. The two-dimensional river ice dynamics model DynaRICE (Shen et al. 2000; Liu and Shen 2004) is used to assess ice jam formation and release effects on bed shear stress and possible bed sediment movement in the St. Clair River.

DynaRICE is a two-dimensional model for river ice dynamics. The model simulates the coupled dynamics of ice motion and water flow, including the flow through and under the ice rubble. It has the ability to model two-dimensional ice transport and jam dynamics in rivers. It is the only existing two-dimensional dynamic river ice model. Most of the other models, such as RIVJAM (Beltaos 1993), HEC-RAS (Brunner 2010), and MIKE11 (Thériault et al. 2010), are one-dimensional models that are not applicable to complicated two-dimensional domains, and cannot predict the initiation of river ice jams and the dynamics of jam development and release. DynaRICE has been validated and applied to field cases, e.g., Lu et al. (1999), Shen and Liu (2003), Shen et al. (2008), and Kolerski (2014). In this study, the model is used to produce the two-dimensional bed shear stress during both the jam formation and release periods to compare with the critical shear stress for the initiation of bed material movement and determine the potential of bed changes in the St. Clair River.

Model domain

The model domain, as shown in Fig. 1, covers the St. Clair River from the Fort Gratiot gauging station at the upstream boundary down to the mouth of the river and continues approximately 15 km into Lake St. Clair to the St. Clair Shores gauging station. The bed roughness is calibrated using water level data from nine gauging stations during a nearly steady open water period with no ice effect. Table 1 shows the calibrated Manning's coefficients for the nine reaches between gauging stations.

Ice jam development

Due to the complex evolution process of the ice jam and the lack of detailed information on ice conditions, it is difficult to re-establish what occurred in the field. To minimize these uncer-

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Fig. 1. The St. Clair River model domain with gauging stations marked by ▼.

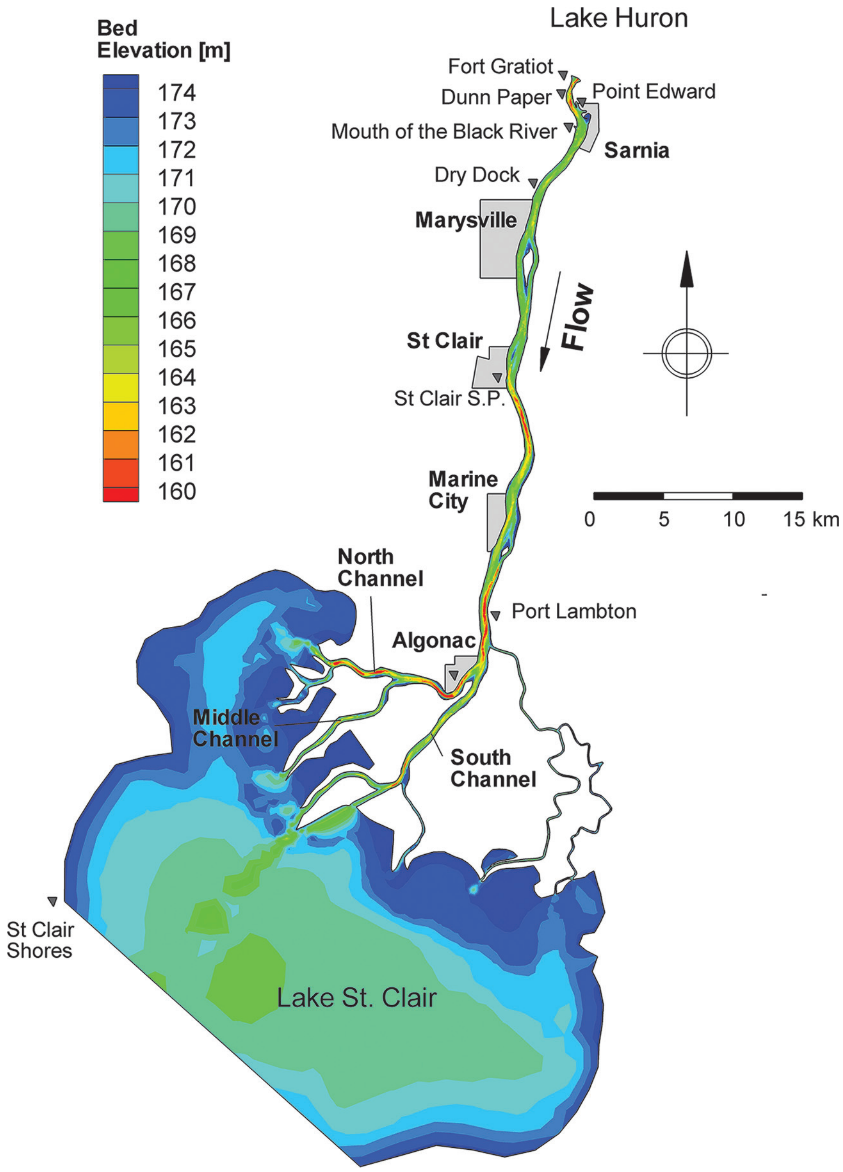


Table 1. Bed Manning's Coefficients.

River reach	Bed Manning's coefficient
Ft. Gratiot – Dunn Paper	0.028
Dunn Paper – Pt. Edward	0.020
Pt. Edward – Mouth of Black River	0.019
Mouth of Black River – Dry Dock	0.020
Dry Dock – St. Clair S.P.	0.021
St. Clair S.P. – Pt. Lambton	0.0215
Pt. Lambton – Algonac	0.023
Algonac – St. Clair Shores	0.024

tainties, detailed calibration of all input ice parameters is required (Kolerski and Shen 2010). Because there was no data on ice discharge from Lake Huron during the April 1984 ice event, ice supply is calibrated against observed data on ice jam initiation and progression together with the water level data (Fig. 2) and the very limited jam thickness data. During the simulations, ice was supplied with an initial floe thickness of 0.3 m and a variable concentration between 0.2 and 0.6. In the model the distribution of ice thickness in the domain is governed by all internal and external forces acting on the ice rubble. The calibrated ice Manning's roughness coefficient of the surface ice accumulation varies linearly with thickness between 0.02 and 0.06. Table 2 compares the observed ice jam process (USACE 1984) with the simulated results. Figure 2 shows the comparison of observed and simulated water levels along the river.

According to the simulation results the ice jam developed in three stages. In the first stage, ice slowed down in the St. Clair Flats and jammed in river branches. This process started in the Middle Channel, which was quickly filled up with ice (Fig. 3*a*). After this, the ice from upstream was transported to the North Channel, and caused another ice jam to form and progress upstream to the Algonac gauge (Figs. 3*b*, 3*c*). Consequently, all ice coming from upstream entered the South Channel. Finally, on April 6th, ice jammed in the downstream part of the South Channel where it splits into the St. Clair Flats Canal and the St. Clair Cutoff (Fig. 3*d*). This jam prevented ice discharge into Lake St. Clair. The second stage of the jam development was the upstream progression of the jam in the St. Clair River. The second stage ended when ice front reached the mouth of Black River (Port

Fig. 2. Comparison of simulated and observed water level during ice jam formation.

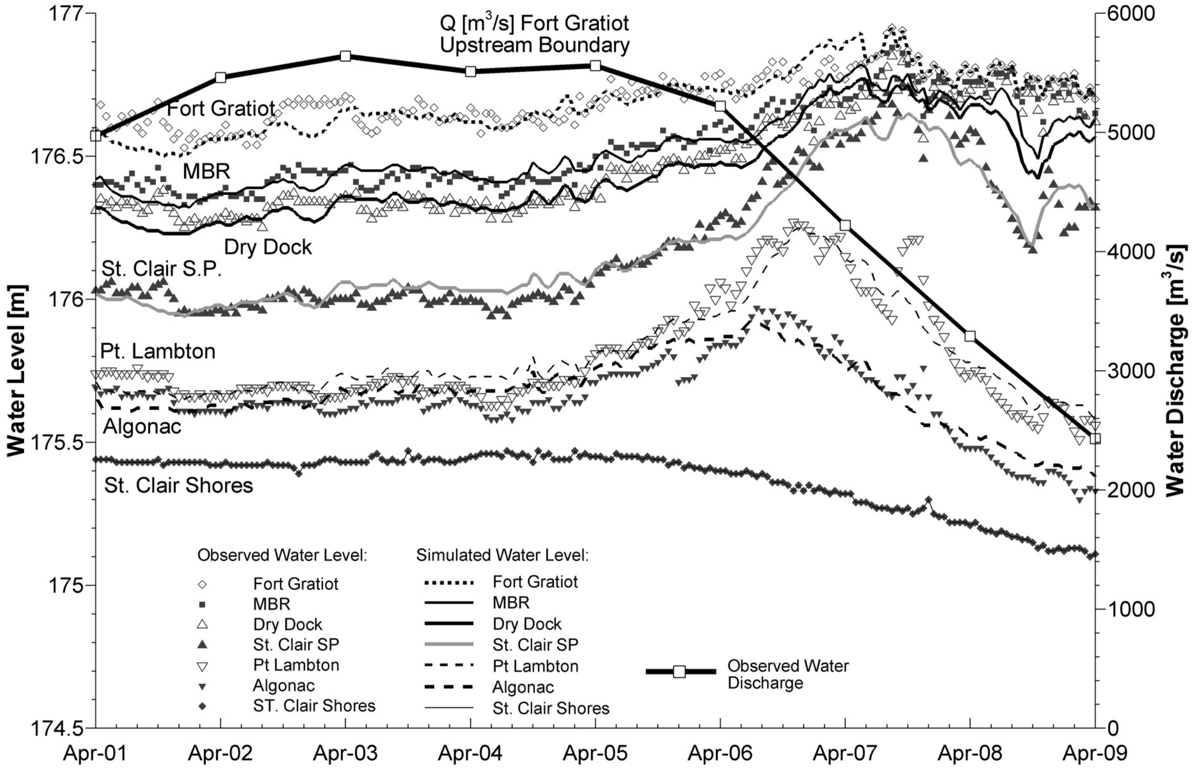
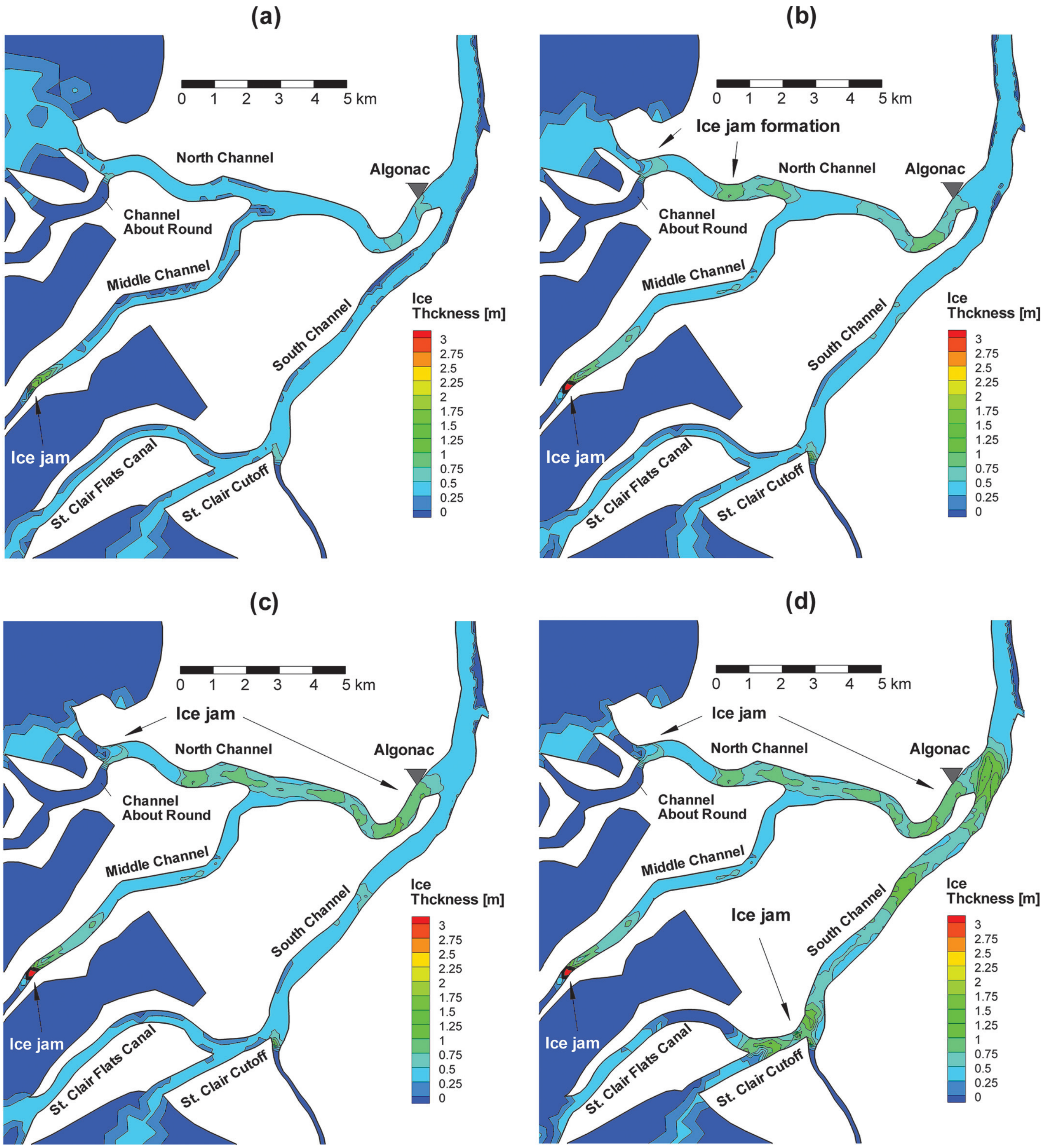


Table 2. Chronology of the 1984 ice jam event.

Time	Observed (USACE 1984)	Simulated
April 1	No data	Ice supply from upstream
April 5	Great deal of ice was floating downstream in the vicinity of Marine City	Beginning of ice jam in North Channel
April 5–6	Ice jam started to develop	Ice jam in North Channel reached Algonac
April 6, 2:45 pm	An ice jam exists near City of Algonac	Ice jam in the South Channel; near Algonac ice move slowly downstream
April 6, 3:00 pm	Willow Point (upstream of Algonac) and the Cutoff Channel were completely jammed with ice	Ice jam reached City of Algonac; entire St. Clair delta jammed with ice
April 7, morning	Ice jam continued to move upstream of Marine City	Ice jam reached Marine City; ice jam continues to move upstream
April 7, afternoon	The river had a packed ice cover that extends from Algonac to Marysville	Ice jam reached City of St. Clair (5 pm); ice jam reached City of Marysville (10 pm)
April 8, morning	Water levels along the river dropped below flood stage	Ice jam release upstream of St. Clair SP gauge (22 km long section); ice cover downstream stays in place
April 8, 1–3 pm	Increase of water level at St. Clair SP gauge; water level at Algonac and Pt. Lambton gauges did not change	Thicker ice accumulation in the vicinity of the City of St. Clair
April 10	The St. Clair River was full of ice Ice thickness of up to 0.65 m with ridges 1.2 m thick; brash ice in the river up to 1.8 m thick	Final ice jam profile; ice jam thickness from 0.3 to 2.1 m
April 28	Water discharge increased; water level at St. Clair SP rise	Beginning of the ice jam release; the 42 km long ice jam upstream of Pt. Lambton was released at 11 am; 3.3 m ice jam formed near Marine City
April 29, 5–8 am	Sudden drop in water level at Algonac, Pt. Lambton and St. Clair SP	Entire ice jam was released; ice accumulated near Algonac
April 30	NWS reported that ice in St. Clair river was rapidly moving south with current	Ice moves downstream

Huron) at noon on April 8th. In the last stage of the simulation, the upstream section of the ice jam was released to cause the increase in water level observed at the St. Clair State Police gauge. This release caused thickening of the ice jam near the Town of St. Clair (Fig. 4). The ice jam stabilized on April 9th at 11:00 am. At that time, the entire St. Clair River was packed with ice extending from the St. Clair Cutoff to Marysville-Port Huron. The simulated thickness of the ice jam varied from 0.3 to 2.1 m in the vicinity of the Town of St. Clair, which is consistent with the field observation (USACE 1984).

Fig. 3. Ice jam formation in the St. Clair Flats at (*a*) 7 am on April 2nd, (*b*) at 6 am on April 5th, (*c*) at 12 am on April 5th, and (*d*) at 2 pm on April 6th (*d*). Note ▼ indicates Algonac gauging station.



Ice jam release

It is known that an ice jam release in a river can produce a flood wave due to the release of water mass stored under and behind the jam (Beltaos 2009; Jasek 2003; Liu and Shen 2004). Such a flood wave could produce high velocities, to cause bed changes. The 1984 ice jam remained in the St. Clair River for a period of almost one month. After its formation, the jam remained relatively stable until about April 28th when the jam began to release. In this section, the ice jam release will be simulated to provide an estimate of bed shear stress and the potential of bed changes.

The air temperatures in the area were relatively high in April 1984 with an average of 8.2 °C. After April 12th, air temperature remained above 0 °C even during the night. This could have caused the melting of ice mass and enhanced the potential for jam

Fig. 4. Simulated ice jam profile at 11 am on April 9 when ice jam stabilized.

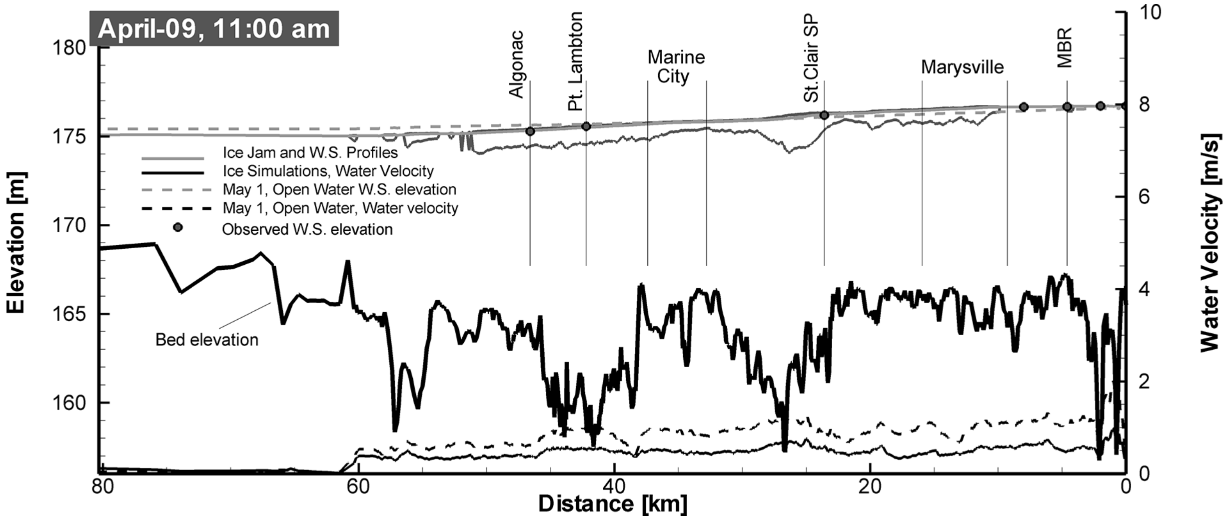
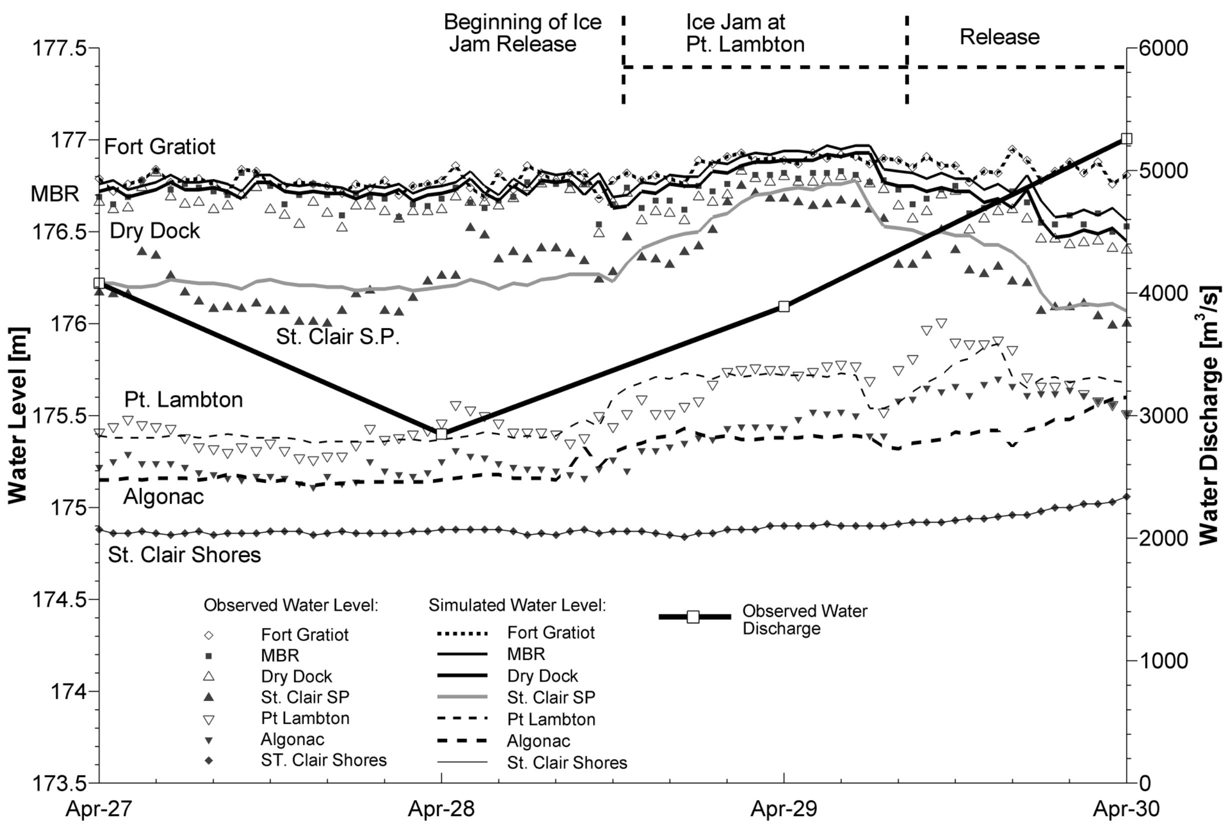


Fig. 5. Observed and simulated water level for ice jam release.



release. The reduction of ice mass in the jam as well as the icebreaker operations affected the stability of the jam in the channel. These effects are taken into account in the simulation by adjusting the ice mass in the calibration to match the observed flow and ice conditions.

On April 27, 1984, the National Weather Service reported that the ice jam at the upstream of the St. Clair River had decreased. On April 30th the ice in the St. Clair River was rapidly moving south with the current (USACE 1984). After that the ice jam observation ceased. The best evidence of ice jam breakup can be observed from the water level and water discharge data. Figure 5 shows a decrease of water level in the upstream portion of the river and an increase of water level downstream on April 28th. Water discharge at Fort Gratiot also increased significantly around April 28th and reached its maximum on May 2nd. These observations suggest that the beginning of the ice jam release occurred around April 28th. Figure 5 also suggests that the ice jam release ended around May 1st. At that time water discharge started to decrease and water levels stabilized. After May 1st, observed water levels showed that the entire St. Clair River was open.

At the beginning of the ice jam release, water level data showed an increase of head loss between St. Clair SP and St. Clair Shores (Fig. 5). This indicated that on April 28th the ice jam was temporarily thickened in the reach between these two stations. Water

Fig. 6. Simulated ice jam and water velocity profiles at 5:00 am on April 29, 1984.

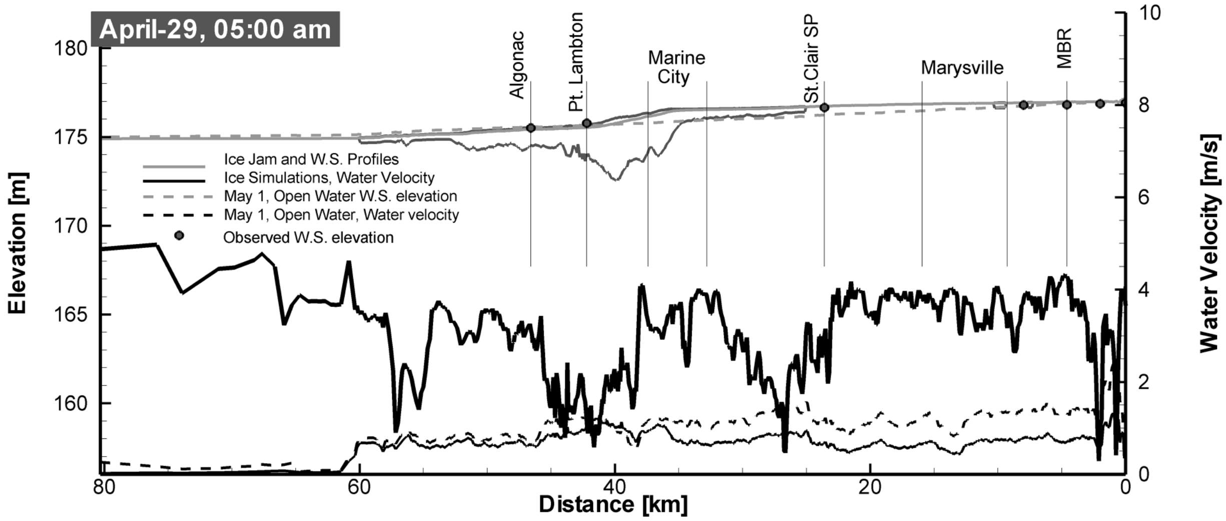
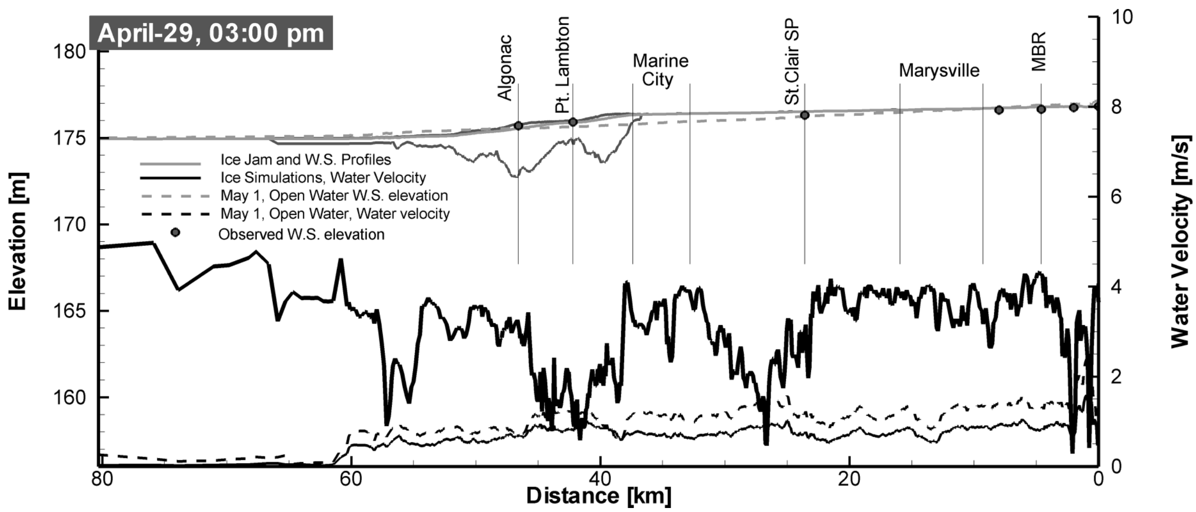


Fig. 7. Simulated ice jam and water velocity profiles at 3:00 pm on April 29, 1984.



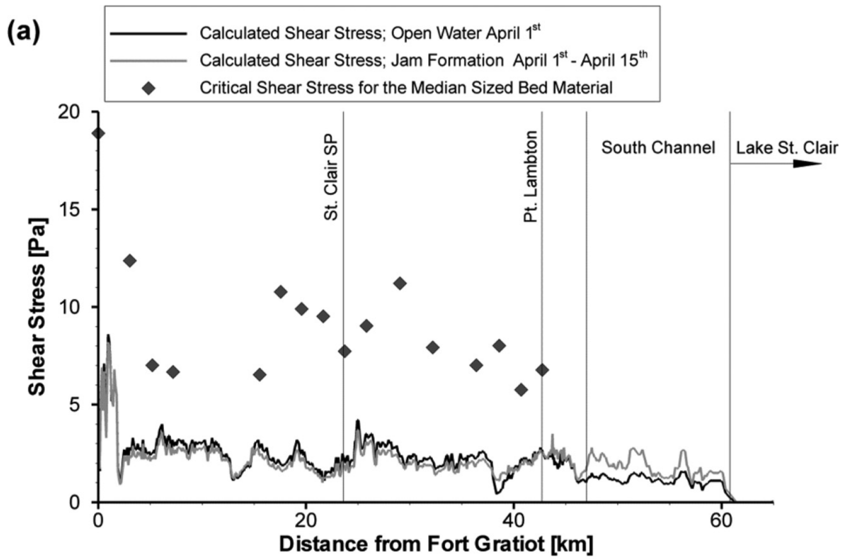
level data from Pt. Lambton and Algonac shows a rapid drop suggesting that the jam that formed downstream of St. Clair SP was probably released at 5:00 am, April 29th. Around that time, the water level at St. Clair SP started to drop and finally reached its normal level on May 1st. In the afternoon of April 29th, the water level data at Pt. Lambton and Algonac suggested that the ice upstream of Pt. Lambton moved and was deposited downstream of Algonac. Near Algonac, the width of St. Clair River increased significantly from 650 m downstream of Chenal Ecarte to 1250 m before the river branches into two channels. The water and ice velocity slowed down and caused the thickening of the ice accumulation there. However, since there was no additional ice supply from Lake Huron and the air temperature was relatively high, the ice that had accumulated near Algonac released quickly. The ice condition on April 12th with the mass reduction due to melting was used to simulate the jam release. During the jam release simulation, to match the observed water levels, the ice jam volume was reduced from the April 12th value by approximately 40%. This reduction is reasonable because of the high air temperature and rainfalls. Such conditions favor significant reduction of ice volume.

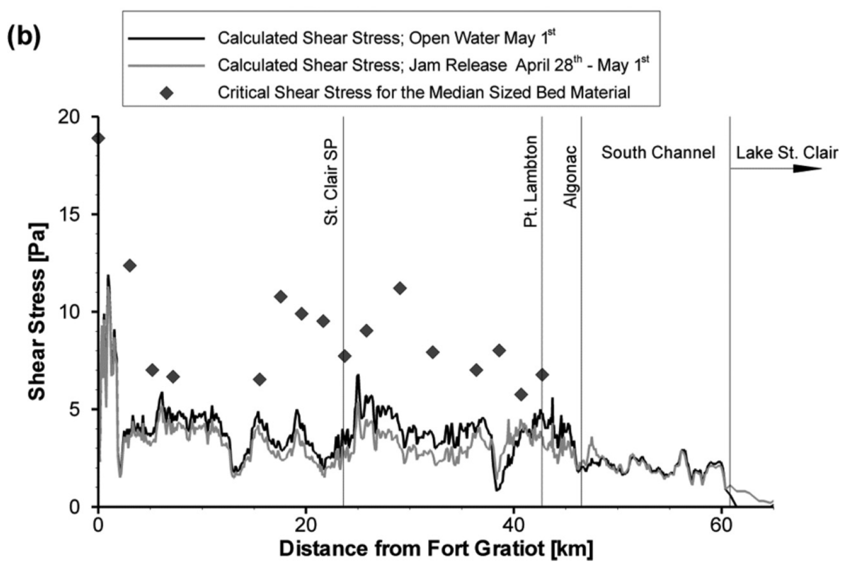
The ice jam release simulation is carried out in two stages. The water level data suggested that at the beginning of the ice jam release, the jam upstream of Pt. Lambton was released and caused thickening downstream of St. Clair SP. In the first stage of the simulation, ice jammed in the river section upstream of the Pt. Lambton gauge. The simulated results showed that ice piled up between Marine City and Port Lambton, which caused an increase of water level at St. Clair SP (Fig. 6). The second phase of the jam release simulation started at 5:00 am on April 29th. The entire ice jam mass was released downstream. In this part of the simulation, the ice mass between Marine City and Port Lambton moved downstream and created another thick accumulation at Algonac (Fig. 7). In the next 24 h, all ice from the St. Clair River passed the river delta and moved into Lake St. Clair. The simulation ended on May 1st when there was no ice in the St. Clair River and water levels returned to normal.

Possible impact of 1984 ice jam on river bed

Because bed erosion may cause an increase in the conveyance of the St. Clair River, it is important to investigate the impact of the ice jam on bed change. The surface ice will produce flow resistance in addition to the bed shear stress (Shen et al. 1990). The bed shear stress during the simulation periods was calculated and compared with those under open water conditions and the threshold

Fig. 8. Comparison of (*a*) maximum bed shear stress during ice jam formation period with the critical bed shear stress, and (*b*) maximum bed shear stress during the ice jam release period with the critical bed shear stress.





value for the median sized bed material. Bed shear produced by water current with surface ice can be expressed as:

$$\tau_{bx} = \rho g \frac{n_b{}^2}{H_b^{1/3}} \frac{q_x (q_x^2 + q_y^2)^{1/2}}{H'^2}; \quad \tau_{by} = \rho g \frac{n_b{}^2}{H_b^{1/3}} \frac{q_y (q_x^2 + q_y^2)^{1/2}}{H'^2} \tag{1}$$

in which, ρ = water density; $q_{x,y}$ = components of unit width water discharge; H' = water depth beneath the ice layer; H_b = water depth affected by the bed shear stress; and n_b = bed Manning's coefficient. The critical bed shear stress for the median size bed sediment can be calculated using method of Parker et al. (2003) from measured data at 15 cross-sections along the St. Clair River (Krishnappan 2009; Liu and Parker 2009). No sediment data from St. Clair Flats was available.

Kolerski and Shen (2010) presented detailed comparison of bed shear stress changes during the jam formation and release. Figure 8 compares the calculated maximum bed shear stress along the thalweg for both open water and ice jam conditions with the critical bed shear stress for median size of the bed material. This figure shows the bed shear stress for ice jam conditions are generally lower than that for open water conditions immediately before and after the jam, and both bed shear stresses for open water and ice jam conditions are lower than the critical shear stress. This implies that the jam may not have had a significant direct impact on the channel conveyance. This is reasonable because the backwater effect and channel storage of the jam was not significant as it is constrained by the limited level difference between Lake Huron and Lake St. Clair, and the large depth of river flow relative to the jam thickness. In fact, the pre- and post-jam conveyance values for the 1984 ice season did not change significantly (Daly 2009). However, the report by Daly (2009) did show a general trend of increase in conveyance since 1984. One possible indirect contribution of ice jams to the conveyance increase is the excess water stored in Lake Huron during ice jam periods. This increase in water storage increases the water level difference between the two lakes to produce larger discharge into the St. Clair River, which may have caused a gradual increase in conveyance.

Conclusions

The record 1984 ice jam on the St. Clair River had a major impact on the level and flow of the St. Clair – Detroit River system. The 24-day ice jam caused the level of Lake St. Clair to drop by approximately 0.6 m. The flow in the St. Clair River was reduced by approximately 65% at the peak of the jam. It has been specu-lated that the 1984 ice jam might have caused bed scour and changed the hydraulic regime of the river. Because there are very limited measurements during the ice jam event, a definite answer to the effects of the ice jam on the sediment transport in the St. Clair River was not available. This study used the DynaRICE model to re-establish the ice jam formation and release processes based on the limited field data. The simulated ice and flow conditions are then used to examine the possible impacts of the jam on the bed change and conveyance of the river. The study showed the 1984 ice jam in the St. Clair River did not cause a significant increase in bed shear stress compared to pre- and post-jam open water conditions. The bed shear stress was much less than the critical shear stress of the river bed material. Hence sediment scour and deposition did not occur as a resultant of the ice jam, and the conveyance of the river was not affected. This study also demonstrated that river ice models can be used to reconstruct the flow conditions during an ice event for examining the bed change potential under the influence of ice jams when there is limited field data, which is typical during winter ice periods.

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