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4ième ATELIER SUR L'HYDRAULIQUE DES GLACES EN RIVIÈRE

4th WORKSHOP ON HYDRAULICS OF RIVER ICE

19-20 juin 1986

CONTRIBUTION NO. 497

QUATRIEME ATELIER SUR L'HYDRAULIQUE DES GLACES EN RIVIERE

ECOLE POLYTECHNIQUE DE MONTREAL

ECOLE POLYTECHNIQUE DE MONTREAL

COMPTES RENDUS

PROCEEDINGS

TOME I

VOLUME I

Fourth Workshop on
Hydraulics of River Ice
Montreal, June 19-20, 1986

NATURAL REGULATION OF THE GREAT LAKES BY ICE JAMS: A CASE STUDY

by

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ABSTRACT

This study addresses the causes and the regulating effects on the Great Lakes levels and flows of the April 1984 ice jam in the St. Clair River. This jam had a duration of 24 days (5-29 April), established records for both magnitude and lateness of occurrence, and had a major impact on navigation throughout the Great Lakes. Changes in water levels were measured at a number of sites along the river and Lake St. Clair. Flows in the St. Clair River were monitored with two continuously recording electromagnetic current meters located in the upper river (Port Huron). Following the onset of the jam, Lake St. Clair water levels dropped about 65 cm because of drastically reduced inflow. The corresponding drop in the Lake Erie levels was about 20 cm. The levels of Lake Michigan-Huron were increased about 6 cm because of the reduced outflow and storage of water on the lake. At the peak of the jam the flows were reduced by approximately 65 percent. Following the jam breaking, the waters of Lake St. Clair rose rapidly, recovering approximately 75 percent of the drop in levels in 4 days. Computer simulations indicate that it will take

at least 3 years for the excess water stored during the jam to be dissipated and for levels in Lakes Michigan and Huron to return to pre-jam conditions. Additionally, both Lakes St. Clair and Erie will have higher water levels through 1987 as the stored water drains through them.

Cette étude traite des causes et des effets régulateurs de l'embâcle de glace de la rivière St. Clair en Avril 1984 sur le niveau et l'écoulement des Grands Lacs. Cette embâcle qui a duré 24 jours (du 5 au 29 Avril) a battu les records d'importance et d'arrivée tardive et a eu un très grand impact sur la navigation à travers les lacs. On a mesuré les changements du niveau d'eau à plusieurs endroits le long de la rivière et du lac St. Clair. L'écoulement de la rivière était contrôlé par un compteur de fluide électromagnétique à enrigistrement continu placé à l'amont de la rivière (à Port Huron). A la suite de l'embâcle le niveau d'eau du lac St. Clair a baissé d'environ 65 cm à cause de l'affluence d'eau qui était considérablement réduite. La baisse du niveau d'eau correspondante pour le lac Erie fut de 20 cm. Le niveau du lac Michigan-Huron a augmenté d'environ 6 cm à cause de l'écoulement réduit et de l'accumulation d'eau dans le lac. A la pointe de l'embâcle l'écoulement a baissé d'environ 65%. A la suite de la destruction de l'embâcle, le niveau du lac St. Clair a subitement augmenté et retrouvé en 4 jours environ 75% de l'eau retenue. Des simulations par ordinateur ont indiqué qu'il faudra au moins 3 ans pour que l'excès d'eau retenue par l'embâcle s'écoule et que les lacs Michigan et Huron retrouvent leur niveau d'avant l'embâcle. En outre,

les lacs St. Clair et Erie auront des niveaux d'eau supérieurs jusqu'en 1987 car l'eau retenue s'écoulera à travers eux.

Keywords: Lake regulation, ice jams, flow retardation, storage and depletion of water, Great Lakes, St. Clair River.

INTRODUCTION

The Great Lakes system (Fig. 1) contains a high degree of natural regulation because of the large surface areas of the lakes and the constricted lake outflows through the connecting channels. This natural regulation process is accentuated by ice retardation in the connecting channels during winter and early spring. Ice flowing down and accumulating in the connecting channels increases flow resistance and may substantially jam the channels, further decreasing their discharge capacity. This results in decreased water supplies to the downstream lakes and storage of water on the upper lakes, producing a natural regulation of the lake system. Ice retardation is particularly important on the St. Clair River, which has a very large potential supply of ice flows from Lake Huron and an extensive river delta that retards the passage of these ice flows. Ice retardation in the connecting channels has been decreasing over the past 100 years because of navigation improvements, such as dredging and channel realignments, but its continuing importance in the hydrology of the basin was vividly demonstrated by the record ice jam of April, 1984. This jam had a major impact on the levels and flows, and on the navigation throughout the system. This paper addresses the causes of the jam and its regulating effects on the adjacent Great Lakes levels and outflows.

The St. Clair River, along with Lake St. Clair and the Detroit River, forms the natural outlet from the upper Great Lakes, comprised of Lakes Superior, Michigan, and Huron (Fig. 1). The combined water surface area of these lakes covers 200,000 km^2, while the immediate upstream Lakes Michigan and Huron (roughly equal) have a combined surface area of 117,400 km^2.

Because of the broad and deep connection through the Straits of Mackinac, the latter two lakes are considered to be a single lake hydraulically and are frequently referred to as Lake Michigan-Huron. In contrast to these very large and deep lakes, Lake St. Clair is a relatively small and shallow basin, with a surface area of 1,110 km^2. Lake Erie is also considerably smaller than the upper Great Lakes with a surface area of 25,700 km^2. The response of these lakes to flow changes in the St. Clair River is proportional to their size. The St. Clair River is 63 km long and has a total fall of 1.5 m, of which the single-stem channel above the delta occupies about 45 km and 1.4 m. Flow in the river produces an average discharge of 5,100 m^3 s^{-1} which varies seasonally from a winter low of 4,200 m^3 s^{-1} to a summer high of 5,500 m^3 s^{-1} per month, with somewhat larger extremes for shorter periods.

Ice jams complicate normal flow processes in the connecting channels by altering normal open-water river profiles. For accurate flow determination during periods of heavy ice cover, river velocity measurements are needed. However, normal flow measurements in the connecting channels (which consist of velocity measurements along a river transect with a small boat) are impractical or impossible during severe ice conditions. Fortunately, during the April 1984 ice jam, continuous velocity measurements were available from an experimental winter flow project conducted on the St. Clair River by the Great Lakes Environmental Research Laboratory (GLERL).

VELOCITY MEASUREMENTS

St. Clair River flows are normally determined with mathematical flow models, which are calibrated from periodic discharge measurements taken over the years during the open-water season (Derecki and Kelley 1981). Consequently, these simulated flows normally exhibit good accuracy during ice-free periods but may contain large errors during winter months with extensive ice cover. The winter flow discrepancies are produced by heavy ice accumulation and/or ice jamming. Except for sheltered areas along the shore, the St. Clair River generally does not freeze over and the ice cover is transient in nature, formed by consolidation of ice flows supplied by Lake Huron. Under favorable weather conditions large quantities of the ice flows are transported rapidly to the lower river reaches, where they tend to jam.

A St. Clair River winter flow experiment was undertaken to improve methods for determining winter flow in the river and to produce more accurate estimates of winter flows. One of the objectives of the experiment was to determine the feasibility of using in situ current meters to monitor the winter flows, since accurate flow determination during periods of ice jams can only be accomplished by a time series of in situ winter current measurements. Practical requirements for these measurements dictated the use of current meters without moving parts (to avoid clogging), that are capable of prolonged operation (six months) at frequent sampling rates. Initial instrumentation that was in operation during the 1984 winter consisted of two electromagnetic meters (Marsh McBirney, Model 585), which were modified to include an externally located recording system. This arrangement permitted unlimited continuous operational capacity and access capability via the telephone-recorder to both the meter and a cable-connected recording system located on the shore.

The current meter location in the upper St. Clair River, near its head in Port Huron, MI, along with a typical winter ice bridge above the river's head is shown in Figure 2. The meters were installed on the western (United States) side of the river, outside the navigation channel about 50 and 70 m from shore, in 13 and 15 m of water with sensors positioned upward 2 m above the river bottom. All deployments and subsequent removals of meters took place with the assistance of the USCGC BRAMBLE and a commercial diver, who guided the underwater operation. The current meter field seasons normally cover late fall, winter, and spring months (November-June). The current meter records consist of continuous velocity data (speed and direction) recorded at 15-min. intervals, from which hourly and daily velocities are derived. The quality of the measured St. Clair River velocities can be verified with simulated model flows during ice-free periods or with flows transferred from the Detroit River, provided it is free of ice problems.

THE RECORD APRIL 1984 ICE JAM

Ice accumulation in southern Lake Huron leads to the formation of an ice bridge across the head of the St. Clair River (Fig. 2), which generally keeps the river free of ice. This ice bridge is broken up periodically by winter storms and finally during the spring thaw, producing drifting ice flows at the river entrance which eventually may cause ice jams. The 1983-84 winter season was characterized by severe, cold weather during the end of December and first half of January, producing a lot of ice. It was followed by a very warm February and cold March, producing some ice thawing and refreezing, respectively. April temperatures were normal, with a large volume of ice remaining in southern Lake Huron but no ice in Lake St. Clair. The ice cover conditions in southern Lake Huron prior to the ice jam and after its development (31 March and 8 April 1984) are shown in Figure 3.

The navigation season on the Great Lakes officially opened on 26 March 1984 and persistent attempts by the shipping industry to use the waterway contributed to the ice jam problems on the St. Clair River. Large amounts of accumulated lake ice were being forced downstream through the St. Clair River by predominantly northerly winds during that period (26 March - 30 April 1984), as shown in Figure 4, producing a huge ice jam which lasted 24 days (5-29 April 1984) and established records for both magnitude and lateness of occurence. Throughout the ice jam period the Detroit River was free of ice, and along with Lake St. Clair and western Lake Erie served as a holding area for many ships awaiting passage through the St. Clair River. The transit of ships through the river was very slow, with numerous stranded vessels, despite continuous assistance from all available ice breakers.

EFFECT ON LEVELS AND FLOWS

In conjunction with the current meter winter flow experiment, ice conditions in the river are monitored and checked as needed by periodic surveys. Changes in water levels were measured at a number of sites (water level gages) along the river and adjacent lakes. The water level conditions in the St. Clair River and Lake St. Clair before, during, and after the 1984 ice jam (March-May) are indicated in Figure 5. The figure shows the changes in river stages and lake levels associated with this huge ice jam. Only a small effect occurred at the head of the river (Ft. Gratiot) because Lake

Michigan-Huron is large enough to absorb even drastic changes in the river flows. Large storage of water occurred in mid-river above the jam (St. Clair) and a large withdrawal of water occurred below the jam in the lower river and Lake St. Clair (Algonac and St. Clair Shores). The water level in Lake St. Clair dropped about 0.6 m during most of April because of the ice jam. It is impossible to determine from the water level measurements similar ice jam impacts on the levels of Lakes Michigan-Huron and Erie. These lakes are much larger and their response to changes in flow (outflow and inflow, respectively) is measured in years, as opposed to days for Lake St. Clair.

The collection of high quality current meter data during this record ice jam represents invaluable information on the St. Clair River winter flow regime. Results of the current meter program (Figure 6) show the effect of the ice jam on the upper river flows (velocity and direction). The velocity during most of April was reduced about 50%, changing near the river bottom at the meter location from about 1.0 to 0.5 ms^{-1}. The effect on natural regulation of the lakes produced by this ice jam was the reduction of the upper Great Lakes outflow to approximately one-half of its normal value for about a three-week period. Higher velocities following the jam breakup at the beginning of May (Figure 6) were produced by the release of water stored on Lake Michigan-Huron during the ice jam.

Verification of the St. Clair River current meter results with extrapolation of measured velocities to the entire river cross-section is provided by flow transfer from the ice-free Detroit River, which is shown in Figure 7. Conversely, good agreement in derived flows by these two independent methods demonstrates the usefulness of the flow transfers between the two rivers, provided one of them is free of ice problems. The difference between the flows of the Detroit and St. Clair Rivers is contained in the transfer factor, which represents a summation of the precipitation on Lake St. Clair plus tributary runoff minus evaporation from the lake and the storage of water on the lake. The agreement between meter and transferred flows is good during most of the March-May period, and particularly during the ice jam. In the few instances when these flows deviate substantially, it is the transferred flow that is more suspect. Thus, the high peak in transferred flow at the beginning of May is caused by an extremely high storage of water on Lake St. Clair following the jam breakup, which appears to be overestimated. Larger deviations between the two sets of flows at the beginning and near mid-March appear to be caused by model oversimulation of the Detroit River flows (Quinn and Hagman 1977), probably due to some ice presence (March ice cover was not observed).

The intermediate to long-term effects of the jam on the water levels and flows of the system cannot be measured directly and must be determined by analysis of results from the Great Lakes hydrologic routing model (Quinn 1978). The current meter data, which provided St. Clair River flows during the ice jam, can be used in conjunction with the flows recorded prior to the jam to estimate the volume of additional water stored above the jam on Lake Michigan-Huron. The required response model inputs, in addition to the starting lake levels, are monthly values of lake precipitation, land drainage runoff, lake evaporation, and diversions. Since availability of some of these data normally lags by months or even years and were not yet available for 1984, the conditions for 1973 through 1979 were used as surrogate variables.

The model runs were made assuming Lake Superior outflow conditions were similar to 1973. The reported results could vary slightly due to minor changes in the regulation of Lake Superior resulting from the ice jam.

Two model runs were made, a base condition assuming the ice jam did not take place, and a second run starting with the conditions due to the jam. The impact of the jam on the levels and flows in the system was determined by subtracting the run with the jam from the base run. The results for the effects of ice jam on the beginning-of-month levels are given in Figure 8. The figure shows vividly the rapid recovery of Lake St. Clair due to its small surface area, the more gradual recovery of Lake Erie, and a very slow depletion of Lake Michigan-Huron. Both Lakes St. Clair and Erie rose above the levels that would have occurred without the jam due to increased inflows produced by storage of water on Lake Michigan-Huron during the jam. It is apparent that measurable effects of the jam will remain through 1987 [redacted] and that the ice jam contributed to the record high lake levels which occurred during the spring of 1985. The maximum effects on Lakes Michigan-Huron, St. Clair, and Erie are +0.06, -0.65, and -0.20 m, respectively.

Computer simulation of results for the effects of ice jam on flows is given in Figure 9, which shows the rapid increase in St. Clair and Detroit River flows following the jam break. The recovery of the Niagara River flow lags behind because it is a function of the elevation of Lake Erie, with much longer response time than Lake St. Clair. The figure also shows that it will take at least 3 years for the excess water stored on Lake Michigan-Huron during the jam to be dissipated and for the flows in these rivers to return to the pre-jam conditions. The maximum flow differences in the St. Clair, Detroit, and Niagara Rivers are about +400, +200, and -400 $m^3 s^{-1}$, respectively.

Ice jams in the connecting channels are usually catagorized by the amount of flow retardation resulting from the jam. By this criteria, the April 1984 ice jam was the largest in the historical records since 1900. A comparison of the St. Clair River ice retardation during January-April with more recent data (1937-84) is shown in Figure 10. The figure indicates that April ice jams of any significant magnitude are rare events and that this jam with an average retardation of about 2,700 $m^3 s^{-1}$ is the largest jam during this period, regardless of date. It is approximately 42% larger than the second largest jam which occurred in February, 1942 (1,900 $m^3 s^{-1}$). Additional analysis conducted by the U.S. Army Corps of Engineers (1984) indicates that the April jam was also larger than any during the 1900-36 period.

CONCLUSIONS

The record April 1984 ice jam in the St. Clair River had a significant regulating effect on the Great Lakes levels and flows. This jam lasted 24 days (5-24 April) and during most of that time reduced the St. Clair River flows by about 50%. As a result, the water levels of Lake St. Clair dropped about 0.6 m, producing successive reductions of the Detroit River flows, Lake Erie levels, and Niagara River flows. Computer simulations indicate that it will take at least 3 years for the excess water stored on Lake Michigan-Huron during the jam to be dissipated and for the lake levels and river flows to return to pre-jam conditions. The maximum effects on levels are +0.06, -0.65, and -0.20 m on Lakes Michigan-Huron, St. Clair, and Erie, respectively. At the peak of the jam the St. Clair River flows were reduced by approximately 65%. Because of its magnitude, this ice jam illustrates vividly the process of natural regulation of the Great Lakes system on the seasonal cycle of levels and flows.

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FIGURE CAPTIONS

Fig. 1. Great Lakes basin.

Fig. 2. St. Clair River ice bridge and location of current meters.

Fig. 3. Southern Lake Huron ice cover, 31 Mar.-8 Apr. 1984.

Fig. 4. Wind rose for Port Huron, MI, 26 Mar.-30 Apr. 1984.

Fig. 5. St. Clair River stages, Mar.-May 1984.

Fig. 6. St. Clair River current meter velocity and direction, Mar.-May 1984.

Fig. 7. Detroit-St. Clair River flow transfer, Mar.-May 1984.

Fig. 8. Effect of ice jam on B-O-M levels, 1984-87.

Fig. 9. Effect of ice jam on flows, 1984-87.

Fig. 10. Ice retardation of flows in the St. Clair River, Jan.-Apr. (1937-84).

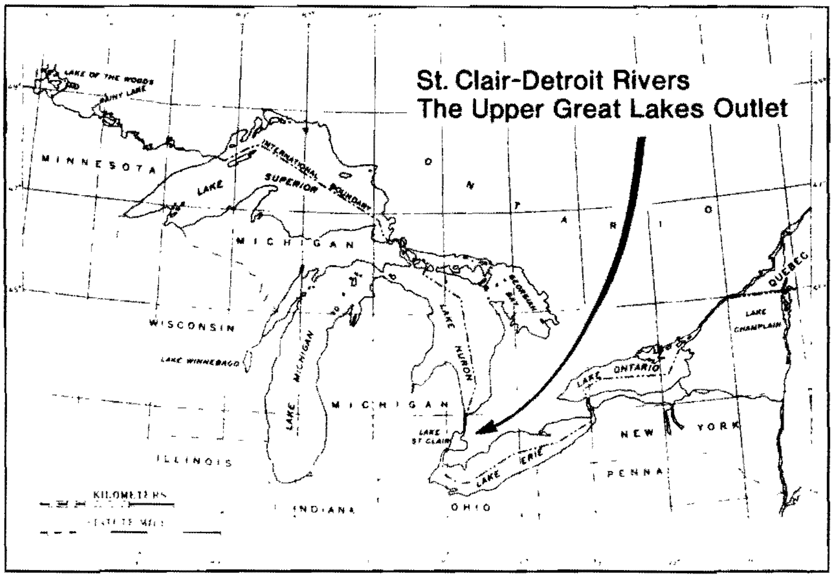

FIG. 1 GREAT LAKES BASIN.

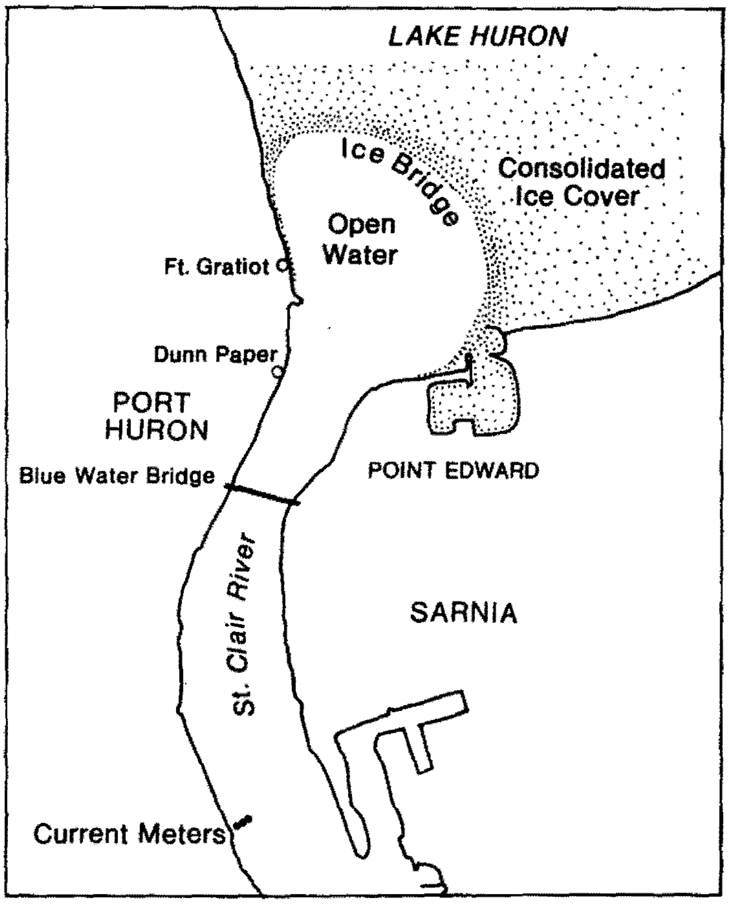

FIG. 2 ST.CLAIR RIVER ICE BRIDGE AND LOCATION OF CURRENT METERS.

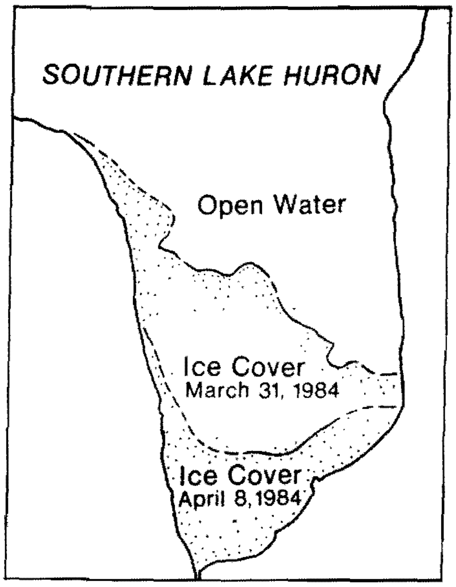

FIG. 3 SOUTHERN LAKE HURON ICE COVER,
31 MARCH - 8 APRIL 1984.