MAN-MADE ISLANDS IN THE MACKENZIE RIVER
NUMERICAL MODELLING OF ICE JAM DEVELOPMENT AND RELEASE

Abstract

The design of man-made islands in a river ice regime has to cope with the complex phenomena associated with the spring break-up of the river ice.

Spring break-up in northern rivers is often accompanied by ice jams, which form as a result of obstruction by ice floes. Development of such ice jams can cause a substantial upstream rise in water level due to the hydraulic resistance of the floating ice cover. This leads finally to a gradual collapse of the ice jam, resulting in strong surge velocities within a downstream propagating flood wave.

In order to be able to design the islands sufficiently accurately, Hydronamic bv of Sliedrecht, Holland, has developed a numerical flow model, that is capable of simulating the complex phenomena of ice jam release in natural rivers with an irregular channel geometry.

This model has been successfully applied in the comprehensive design study regarding six man-made islands in the Mackenzie River, conducted for Esso Resources Canada Ltd with respect to the Norman Wells Expansion Project.

This paper highlights the computational procedure and results of the numerical ice jam flow model and some computational results of the flow pattern around the man-made islands. The application of these numerical flow models is currently an effective tool for predicting the hydraulic conditions during planning, design, construction and operation of riverine and coastal projects.
1 INTRODUCTION

Esso Resources Canada Ltd intends to expand recovery in the Norman Wells oil field, which is located on the north bank of the Mackenzie River, 145 km south of the Arctic Circle, Northwest Territories, Canada. This secondary recovery scheme, referred to as the Norman Wells Expansion Project, makes use of a pool-wide water injection system. This will increase the field production from 3,000 to about 25,000 barrels per day.

The oil will be transported to the existing pipelines at Zama, Alberta, by a pipeline 866 km in length (see Figure 1).

The features of the oil-bearing structure call for six man-made platforms, permitting vertical access to the portion beneath the Mackenzie River (see Figure 2).

Hydronamic bv of Sliedrecht, Holland, was retained by Esso Resources Canada Ltd to develop a conceptual design, construction method and schedule for these man-made structures.

It has been concluded, in view of the expansion project's economic viability and the expected environmental loads, that the constructional and operational risks are minimal with man-made sand fill islands.

In the concept for these, Esso Resources and Hydronamic have incorporated the more than 10 years' experience in designing and constructing man-made islands in the Arctic, as illustrated by those already built in the Beaufort Sea.

The design, based on a well-tried concept proven under various conditions, takes into account various requirements such as:

* fulfilling the purpose of a safe drilling base
* resisting hydraulic and ice loads
* minimizing environmental risks
* presenting no problem to river navigation
2 MAN-MADE ISLAND DESIGN

The islands are located in shallow water near the edge of the main channel at a depth of about 5 m below Low Water. On the basis of comprehensive observations of the Mackenzie River \(3,4,5,9\), supplemented by data obtained from other sources \(6,7\), Esso Resources established the design criteria for the man-made islands in cooperation with Hydromatic. Finally, this resulted in the following design (see Figure 3) \(1,2\):

* hydraulically filled islands, each consisting of a sand core of about 200,000 m\(^3\) with layered rip-rap slope and toe protection over a heavy fabric filter cloth.
* at the toe of the 1 in 2 slopes, the rip-rap protection is extended, after excavating a trench in the sandy top layer, up to and over the clay layer lying beneath; apron slope is 1 vertical in 6 horizontal.
* working surface of 80 * 45 m at an elevation of 54.00 m+GSC (=Geodetic Survey of Canada), surrounded by a 1.00 m high dike.
* side slopes, 1 vertical in 2 horizontal, with a 5.00 m horizontal sloping berm, to be used as a ramp.
* upstream slope includes an ice pile-up storage berm, with a length of 50.00 m at a slope of 1 vertical in 10 horizontal.
* the corners of the upstream, bluntnosed storage berm are protected with concrete blocks, 1.00 m thick and 2.10 m long.

3 REGIME CHARACTERISTICS OF THE MACKENZIE RIVER

The Mackenzie River flows in a northwesterly direction at Norman Wells. From early June to late September the river is normally navigable over its 1600 km length between Great Slave Lake and the Beaufort Sea. In the vicinity of Norman Wells the river is exceptionally wide, with multi-channel reaches, encompassing several islands (see Figure 2). The main longitudinal energy gradient for Low Water, as measured by the Department of Public Works, Canada, has been determined at 9.1*10^-6 for the river section between Saizer Island and Patricia.
During the last four years, observations of break-up and ice jams in the Mackenzie River have been well documented. The conclusion reached is that break-up at Norman Wells is consistently accompanied by back-up conditions due to the formation of ice jams downstream. These jams are mainly initiated by the narrow single-channel reaches upstream of Ogilvie Island and downstream of Patricia Island (see Figure 1).

The maximum water elevation observed at Norman Wells during an ice jam, initiated near Ogilvie Island, is 51.39 m-GSC (May 20, 1982).

In order to predict the severe flooding and surging associated with an acceptably low risk of occurrence during the lifetime of the man-made islands, all the available hydrological data have been analysed. Distinction has been made between pre-release floods, release floods and summer floods. Extreme value determination has been carried out for 3 distribution types, viz. the Gumbel distribution, the Weibull distribution and the Log-Pearson Type III distribution.

For the purpose of illustration, the floods and associated elevations, with a return period of 500 years, are used and have been estimated to be:

<table>
<thead>
<tr>
<th></th>
<th>pre-release flood</th>
<th>summer flood</th>
</tr>
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<tbody>
<tr>
<td>discharge</td>
<td>34,000 m$^3$/s</td>
<td>38,000 m$^3$/s</td>
</tr>
<tr>
<td>elevation</td>
<td>53.8 m</td>
<td>46.3 m-GSC</td>
</tr>
</tbody>
</table>

The pre-release flood condition corresponds to ice jams initiated downstream of Norman Wells.
4 FLOW SIMULATION OF INTERCONNECTED OPEN AND ICE-COVERED CHANNELS

The design of the six man-made islands must take into account the flood wave effects due to the sudden release of an ice jam. Both steady discharge conditions, as well as the unsteady discharge conditions during the build-up and release of ice jams, have been computed with Hydromatic's numerical model HYDFLOW-1. The method of computation is based on a finite difference representation of the mass and momentum equations, integrated across the flow sections. These equations are, respectively:

\[ b \frac{3h}{5t} + \frac{3Q}{5x} = 0 \]

\[ \frac{3Q}{5t} + \frac{3(Q^2/A)}{5x} + gA (\frac{3h}{5x} - b) + g \frac{Q^2J}{C=AR} = 0 \]

where: 
- \( h \): flow depth (m)
- \( Q \): flow discharge \((m^3/s)\)
- \( t \): time variable (s)
- \( x \): downstream direction (m)
- \( b \): storage width (m)
- \( A \): conveying cross section \((m^2)\)
- \( g \): gravitational acceleration \((m/s^2)\)
- \( i_b \): longitudinal bed slope (-)
- \( C \): Chezy coefficient \((m^{1/2}/s)\)
- \( R \): hydraulic radius (m)

The procedure of time and length integration employs an explicit leap-frog numerical scheme \([13]\). The discretization in time is achieved by using alternating time levels for the computation of the water elevation and the channel discharge.

About 185 km of the Mackenzie River have been schematized into various interconnected channel sections, 4-5 km in length (see Figure 1). At the nodes of each section the water level is computed; in the middle of the sections the discharge is computed. For each section, the flow coefficients have been determined from hydrographic charts and expressed as function of the elevation.
The time integration step for the leap-frog scheme is restricted by the Courant-Friedricks-Lewy stability condition. Here, a time step of about 200 s would be permitted but for reasons of numerical accuracy, e.g. minimizing the phase error and the amplification error, a time step of 30 s has been used.

Determination of the composite roughness, resulting from the obstructed ice cover and the bottom has been based on the commonly used Sabaneev hypothesis and the Strickler formula \( f = \frac{1}{8} \). This enables the composite Nikuradse roughness \( r_{ib} \) to be expressed as a function of the Nikuradse roughness of the bed \( r_b \) and the ice cover \( r_i \) viz.:

\[
r_{ib} = (r_i^{1/4} + r_b^{1/4})^4
\]

The stability of these floating ice jams is governed by the ice conditions, the flow velocity and the conveying width.

The thickness of a river ice jam is governed by the submergence potential and incipient motion of ice floes under the ice cover, the internal ice strength, the external resisting forces and the external active forces, such as flow and wind shear and the downstream weight component of the ice cover.

For the purpose of analysing the Mackenzie River ice jams several published theories on the stability of river ice jams have been reviewed \( 8,10,11,12 \). These theories are all based on a steady force equilibrium analysis of the lengthening and thickening phases in prismatic channels. The flow shear stress acting upon the obstructed ice cover, following the M2-backwater profile, is the main external active parameter. It has been concluded that, for the time being, the above theories cannot be reliably applied to non-prismatic natural rivers, with single-channel and multi-channel reaches, as stability conditions differ from those of prismatic channels and there is a complex feeding of ice floes at tributaries, bifurcations, confluences and open leads. Consequently, the submerged ice thickness \( r_i \) and the ice cover roughness \( r_{ib} \) have been assumed constant along the ice jam.

Following calibration of several ice jams the values have been estimated at \( r_i = 3.00 \text{ m} \) and \( r_{ib} = 1.30 \text{ m} \) for \( r_b = 0.015 \text{ m} \).

Figures 4 and 5 show the results of calibrating the steady open
flow conditions. The correspondence between the measured and calculated values is extremely good.

Figures 6 and 7 show the computed equilibrium backwater curves for pre-release conditions with a return period of 500 years at time \( t = 0 \) hr for ice jams initiated at Patricia Island (node 33) and Norman Wells (node 11), respectively.

Although it is hardly conceivable that an ice jam could be initiated by the man-made islands, which would reduce the conveying cross-section by only 5%, Esso Resources emphasizes the integrity of the man-made island design by taking this unlikely event into account. From observation, it has been concluded that in the worst possible event the obstructed ice cover will extend to the upstream single-channel reach at Gaudet Island (node 47).

The computed water elevation at Norman Wells for the Patricia Island jam is 53.6 m-GSC, almost resembling the extreme value prediction. The computed maximum surface gradient is 700*10^{-6} for the Patricia Island jam and 552*10^{-6} for the Norman Wells jam. The former is of the same order as observed.

Both ice jams have been released instantaneously, which is an unrealistic but conservative approach, since actually the disintegration of the ice cover proceeds over a period of time.

Figures 6 and 7 show the computed propagation and deformation of the flood wave. The time development of some water elevations and channel-averaged velocities is illustrated in Figures 8, 9, 10 and 11. The computed peak surge velocity for the estimated 500 year return period event in the Norman Wells section, branch 17, is about 2.9 m/s for the Patricia Island jam and about 3.4 m/s for the Norman Wells jam.

5 COMPUTATION OF FLOW PATTERN AROUND MAN-MADE ISLANDS

In order to determine the local peak surge velocities across and along the flow section at Norman Wells, an overall model and a detailed model have been constructed.

The overall model encompasses the six man-made islands. The detailed model comprises the deepest side of a man-made island.

The results of the ice jam release simulation provide the boundary
conditions for the overall model, which in turn provides the boundary conditions for the detailed model.

The computation of the local peak surge velocities has been carried out with the aid of Hydronamic's numerical flow model, HYDFLOW-2, for unsteady, 2-dimensional depth-averaged flow.

The numerical model is based on a finite difference representation of the shallow water equations. The computation method is an improved version of the semi-implicit Landartts scheme, employing a space-staggered grid.

The overall model and the detailed model have a square mesh-size of 125 m and 10 m, respectively.

Figures 12 and 13 illustrate the computed flow pattern for the overall and detailed model, respectively, during the peak-surge condition of an ice jam initiated and released at Norman Wells.

The ultimate local velocity has been computed for the 500 year return period event at 6.8 m/s at the upstream corners of the blunted ice pile-up berm.

6 CONCLUSIONS

The hydraulic consequences of the rise and release of ice jams have been computed with the aid of an explicit numerical model, permitting open channel flow as well as flow with an ice jam.

For 185 km of the Mackenzie River the steady discharge conditions were adequately reproduced.

The computed channel-averaged surge velocities of the ice jam release have been transformed to local surge velocities by means of a semi-implicit numerical model for computation of the 2-dimensional, depth-averaged flow.

These results could be used for the detailed design of the slope protection of the man-made islands, as well as for the prediction of morphological changes.
REFERENCES

1. HYDROMATIC bv, Design and Construction Plan for Development Islands at Norman Wells. March 1979


3. KAMPHUIS, J.W., Ice Break-up and Ice Jamming along the Mackenzie River between Fort Simpson and Fort Good Hope. Esso Resources Canada Limited, May 1981


Fig. 12 Surge Flow Pattern in River Reach after Release of Norman Wells Ice Jam

Fig. 13 Surge Flow Pattern around Island after Release of Norman Wells Ice Jam