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SIMULATION OF ICE AND SEDIMENT PROCESSES IN AN ALLUVIAL STREAM

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Abstract: The flow regime of streams in the northern hemisphere can be largely affected by ice formation during the winter period. The ice cover can affect not only the river hydraulics of a particular reach but can also influence important sedimentation processes. Although the effects that an ice cover may have on flow hydraulics are reasonably well understood, our understanding of its impact on sedimentation processes is much less developed. The sparse availability of continuous and comprehensive information on fluvial behavior during the winter period has contributed to this lack of understanding. Numerical models are one means by which to bridge this knowledge gap and improve our understanding of the complex interaction between ice covers, river hydraulics and sediment transport. Several ice simulation models have been developed and applied over the years. Of these, ICESIM has been widely (and successfully) applied in studies of several hydroelectric projects across Canada. The robust algorithms of the model have been successfully calibrated and utilized to simulate the river hydraulic characteristics and ice cover formation. The ICESIM model was originally developed by Acres International Limited (now Hatch) in 1973 for studies of the Nelson River hydroelectric plants and since then it has been continuously advanced and improved. In a recent series of improvements, the model was converted (from *Fortran*) to run on a *Matlab* platform, and a sediment transport simulation module was also added. The resulting model, ICESIMAT, is a one-dimensional, steady-state model capable of the simulation of ice cover formation and sediment transport in a river. In a recent study, ICESIMAT was applied to simulate ice cover formation and sediment transport on the Lower Nelson River in northern Manitoba, Canada. The results of the numerical simulations were validated by *in-situ* measurements performed during several field campaigns at the study site. This paper summarizes the model capabilities and the results of these investigations.

1 Introduction

The role that an ice cover plays in rivers of the northern hemisphere makes it a subject of importance for all industrial projects being conducted in these areas. Rivers in Canada, amongst other countries located in cold regions, are significantly affected by the presence of ice cover during winter. River ice introduces a dynamic boundary to the top of the river and alters flow magnitudes and patterns. Though these variations are temporary, the significant scale of the phenomenon often causes substantial impacts on the environment, economy and public safety.

The presence of an ice cover has some important implications for hydroelectric plants, too. The variation in flow and stream conveyance capacity is the main source of instability in the operation of hydroelectric generating stations during winter. Despite the fact that ice cover impacts are relatively well recognized, there are still gaps in understanding river ice processes and their consequences on hydraulic behaviour of the affected streams. This is mainly due to the difficulty associated with conducting comprehensive field investigations during the ice-covered period. Therefore, efforts have been made to overcome the shortage in this area using new field measurement techniques, as well as other approaches such as physical or numerical modeling of the ice cover processes.

1.1 Ice Processes in Natural Streams

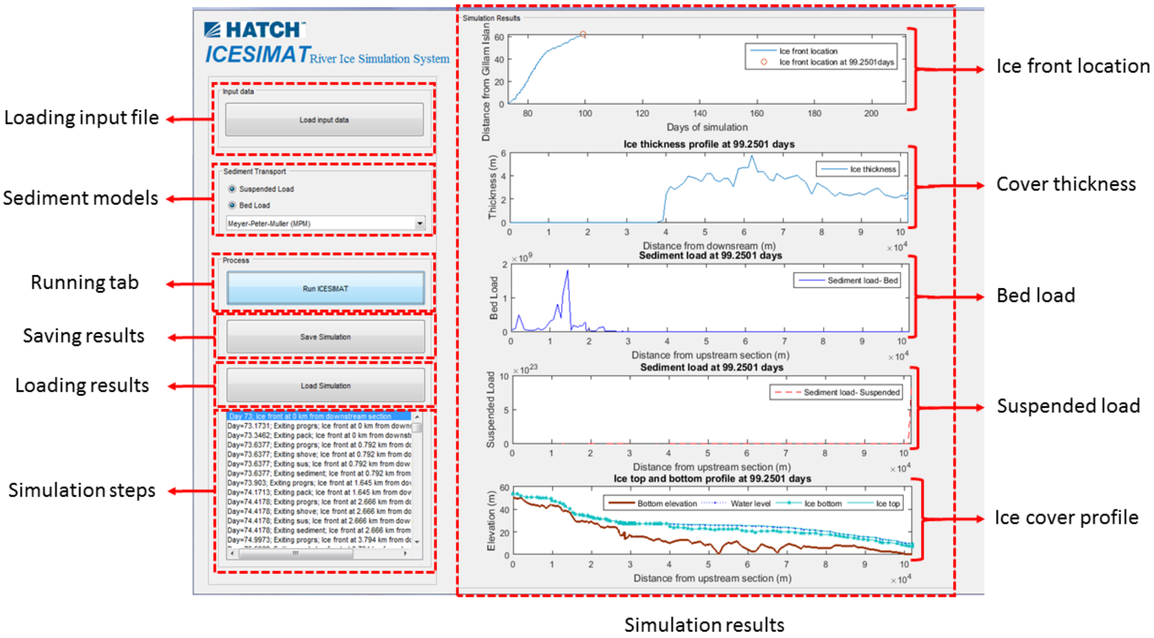
Ice processes in rivers can be categorized into three main stages: freeze-up, stabilization/consolidation and break-up. Each of these stages includes several sub-stages accompanied by various ice features. The complex process of river ice formation and evolution is the result of the combination of different meteorological, hydrologic, mechanical and thermal factors. However, the dominating element in the ice cover processes is river hydraulics. River hydraulics plays a reciprocal role in river ice formation. In other words, while it is the main element in ice cover formation, river hydraulics is also greatly affected by the formation of the ice cover.

During the formation of an ice cover, the water temperature begins to drop at the interface of the water surface and the supercooled air above it. Frazil ice particles are the product of the heat transfer from the “warmer” water to the “colder” air. Hereafter, the flow intensity defines the type of ice being formed. In areas with low flow intensity, frazil crystals form at the flow edges, bond to each other and then expand laterally into the stream. This process creates the *skim ice* which thickens thermally and eventually forms *border ice*.

In more turbulent areas, frazil ice particles formed at the surface are distributed to various depths before traveling downstream. The adherent nature of frazil ice causes it to either accumulate on objects exposed to the flow (river bed material, vegetation, flow intakes, etc.) and form *anchor ice*, or to agglomerate and float at the surface in the form of *ice pans*. While traveling downstream, ice pans grow in size which leads to an increase in the concentration of river ice at the surface. At narrower cross sections (contractions due to change in morphology or border ice formation), the moving ice floes start to congest and bridge an ice arch at the cross section. The formation of an *ice bridge* acts as a barrier to the incoming floes, and ice pans start to accumulate at the bridge location. This process initiates the formation of an ice cover which then progresses upstream by the accumulation of incoming floes through a process called *juxtaposition.*

External forces such as water thrust and wind drag, along with internal forces due to the weight of the cover, mechanically thicken the ice through a process called *shoving*. Shoving causes the leading edge of the ice cover to retreat in order to provide the necessary strength against the imposed forces. When the ice cover reaches an equilibrium thickness that is capable of withstanding the above-mentioned forces, the ice cover progression continues. The thickness and strength of the resulting ice cover are dependent on several climatic parameters such as temperature, precipitation and solar radiation. Each of these elements can favorably or adversely affect the cover stability. Climatic factors affect the ice cover mainly by altering the thermal budget through the cover. This defines the heat transfer rate from the underside of the cover to the air in contact with the ice surface.

Variation in the thermodynamic balance of the ice during the spring triggers another important ice cover stage known as *thermal break-up*. Notably, the thermal break-up can start even before the air temperature starts to rise. The ice cover melting process is initiated due to incoming solar radiation which introduces another source of heat to the thermodynamic system of the river. Thermal break-up causes the cover to weaken, consequently reducing the mechanical resistance against the flow force (i.e. hydraulic thrust) and initiating ice cover destabilization through the process of *mechanical break-up*. During the break-up period, the cover starts to decay and retreat through a series of mechanical cover breakings accompanied by a retreat of the leading ice edge and open water emerging along the river reach. The process continues until the cover is completely removed and an open-water regime returns. Some of the most drastic ice cover features, such as an *ice jam* formation can take place during the break-up period.



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Day 73; Ice front at 0 km from downstream section
Day=73.1731; Exiting progrs; Ice front at 0 km from down
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Day=73.903; Exiting progrs; Ice front at 1.645 km from dov
Day=74.1713; Exiting pack; Ice front at 1.645 km from dov
Day=74.4178; Exiting progrs; Ice front at 2.666 km from dc
Day=74.4178; Exiting shove; Ice front at 2.666 km from do
Day=74.4178; Exiting sus; Ice front at 2.666 km from dow
Day=74.4178; Exiting sediment; Ice front at 2.666 km from
Day=74.9973; Exiting progrs; Ice front at 3.794 km from dc
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Figure 1 ICESIMAT Graphical User Interface (GUI)

1.2 River Ice and Channel Morphology

The effect of river ice on channel morphology peaks during the break-up period when the extreme river hydraulic condition is capable of causing significant erosional and depositional features. Several researchers such as Prowse and Culp (2003), Milburn and Prowse (2002), Milburn and Krishnapan (2002), and Turcotte and Morse (2012) studied the morphological effects of the ice cover on rivers.

The sediment transport process consists of three main components: initiation of motion, transfer, and deposition, all of which are determined by local flow strength and sediment properties. Channel morphology dictates the spatial variation of flow strength and sediment properties, and thus potential scouring zones. As a simplified description, sediment tends to be eroded from areas where flow converges and is deposited at locations where flow diverges. An ice cover presence complicates this process by adding an upper boundary to the river, which is often as rough as the lower boundary, and temporarily changes the river sediment transport capacity compared to free surface conditions. Consequently, sediment transport tends to decrease under a floating ice cover due to reduced bed shear (Sayre and Song, 1979; Ettema et al., 2000). Conversely, an ice cover and/or ice jam can locally constrict the flow and thereby causes local scour (Neill, 1976; Sui et al., 2006), which can locally increase sediment transport (Sui et al., 2000). Furthermore, local flow concentration by river ice has been observed to cause direct geomorphic effects including thalweg shifting and cut-off of meander loops (Ettema and Zabilansky, 2004).

During spring ice break-up, increased freshet flow combined with flow surges (Jasek, 2003) due to temporary ice damming results in increased bed shear and sediment transport, and break-up flows can be the dominant channel forming flow (Beltaos, 2007). However, as mentioned, this critical process remains poorly studied largely because of the difficulty and danger of accessing rivers during the spring break-up condition. Heaving of ice on river banks can also scour the river bank (Smith, 1979; Doyle, 1988) which can both remove sediment from the bank and inhibit the growth of woody vegetation and thereby decrease bank strength which ultimately results in a wider channel (Smith, 1979; Hey and Thorne, 1986). It appears that only Prowse (1993), Milburn and Prowse (2002), and Beltaos and Prowse (2001) have reported sediment transport measurements during ice break-up. Notably, Prowse and Milburn described a field campaign on the Liard River, Northwest Territories, in which suspended sediment samples were collected from a

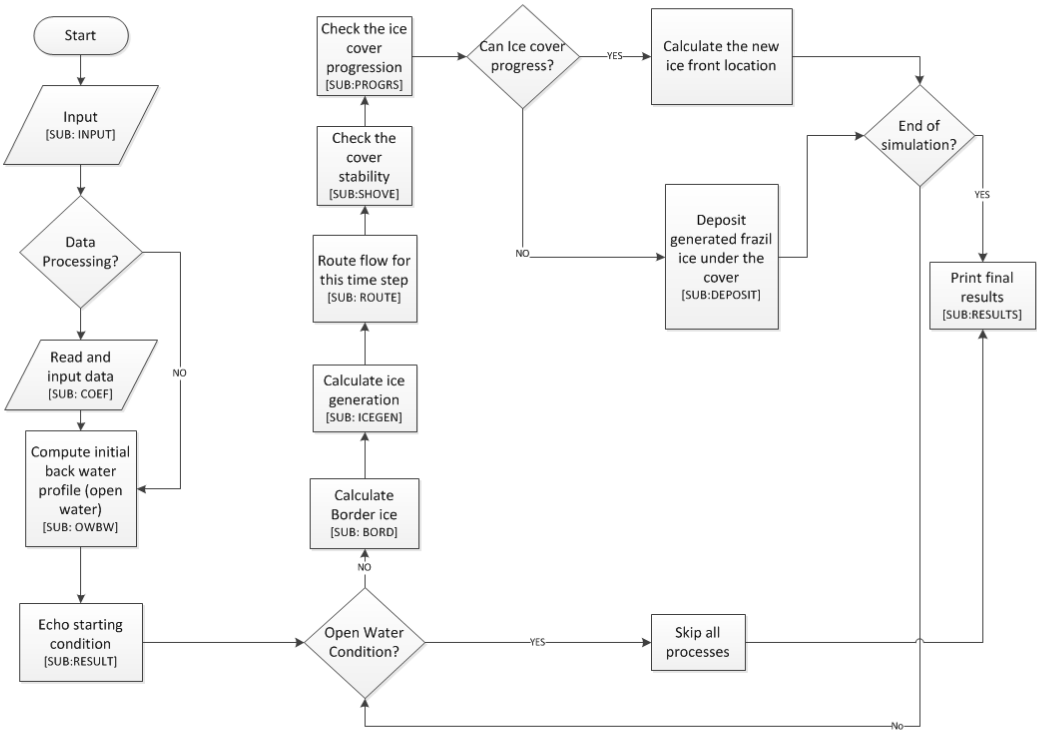

Figure 2 Flowchart of river ice simulation in ICESIMAT/ICESIM

helicopter during the break-up. They observed a 30-fold increase in suspended sediment concentration during the break-up.

River Ice and Sediment Transport Modeling

The ICESIMAT model is programmed and developed in *Matlab* based on the Hatch river ice simulation model (ICESIM). ICESIMAT is designed to simulate the river ice cover formation, river hydraulics and sediment transport under the variety of ice cover stages. The model includes a multifunctional Graphical User Interface (GUI) to provide a direct user interaction with the model through graphical manipulation of model parameters. Simulation results are also simultaneously post processed and presented at each simulation time step. The simulation in total, or each individual time step, can also be loaded into the model through the GUI. ICESIMAT GUI and its components are shown in Figure 1.

ICESIMAT and its predecessor ICESIM mostly share the same type of required information to set up and perform the simulation. However, the ICESIMAT needs an additional set of geomorphological information to conduct the sediment transport modeling.

The necessary information for simulation of the river ice cover formation include daily air temperature, river discharge, observed water level and observed ice front location throughout the winter. Furthermore, ICESIMAT requires information about bed material at each cross section in order to estimate sediment load during the simulation. Figure 2 shows the river ice simulation flowchart in ICESIM/ICESIMAT.

1.3 Numerical Simulation of River Ice Processes

The major physical processes of ice cover formation are simulated in discrete time steps in ICESIMAT. The model is formulated to estimate the parameters that affect water stage and ice cover characteristics in the river. Amongst the numerous factors and features of river ice processes, important processes such as volumetric ice generation, ice cover frontal progression, ice floe transport and deposition, cover erosion, border ice formation and mechanical cover thickening, and ice front retreat are well characterized and modeled through several specific subroutines and algorithms.

As illustrated in Figure 2, the simulation of the river ice process starts with the estimation of frazil ice generation in the river. ICESIMAT calculates the frazil ice generation rate using the equation below.

$$[1]\ V_f = \frac{L_0 B_0}{\rho_i \lambda_t} C_0 (T_w - T_a)$$

In this equation, V_f defines the volumetric generation of frazil ice (m^3), $L_0 B_0$ is the upstream open water area (m^2), C_0 is the heat transfer coefficient (W/m^2 °C), λ_t is latent heat of fusion of ice (J/kg), ρ_i is the density of ice (kg/m^3) and T_w and T_a are water and air temperatures (°C), respectively.

The generated volume of ice then starts to accumulate at the bridging location(s) and forms the leading edge. ICESIMAT uses the following equation developed by Mitchel (1971) to calculate the ice front thickness:

$$[2]\ h_j = \frac{{V_u}^2}{\left[2g\left(1-\frac{\rho_i}{\rho_w}\right)(1-P_j)\right]}$$

In this equation, h_j represents the ice thickness (m), V_u is the water velocity under ice (m/s), ρ_i and ρ_w are ice and water densities (kg/m^3) and P_j is the ice cover porosity (dimensionless). Due to the difficulty of direct measurement of water velocity under the ice cover, ICESIMAT calculates the water velocity as:

$$[3]\ V_u = \frac{V}{\left(\frac{R_c - h_j}{R_c}\right)}$$

In which R_c is equal to the mean hydraulic radius (m) and V is the water velocity (m/s) immediately upstream of the ice edge.

The main criterion to define whether the frontal edge would progress or not is the Froude number at the leading edge location. Assuming the constant values of $P_j = 0.73$ and ρ_i=920 kg/m^3, the Froude number at the ice cover leading edge can be represented as:

$$[4]\ F_r = \frac{V}{\sqrt{gy}} = 208\sqrt{\frac{h_j}{y}}\ \left(1 - \frac{h_j}{y}\right)$$

The Froude number limit for the ice cover leading edge to progress upstream is about 0.12; for values greater than the limit, the incoming ice floes start to underturn and travel below the cover to reach the point where the velocity decreases and allows the floes to deposit under the existing ice cover.

According to Michel (1971), frazil ice starts to deposit under the ice cover at velocities equal to or less than 0.3 m/s. Deposited ice particles, as well as consolidated ice cover, start to be eroded at velocities between 1.5 m/s to 2 m/s. These mobilized ice particles then start to be conveyed until they reach a point where the velocity permits the floes to be re-deposited, otherwise they exit the simulated reach at the downstream model boundary.

The process of ice generation, deposition/erosion, consolidation and frontal progression continues until the ice covers the entire river or reaches a point where it is hydraulically impossible for the cover to progress any further (i.e., due to a drastic elevation change or at a very fast flowing cross section).

1.4 Simulation of Sediment Transport Under the Ice Cover

ICESIMAT is capable of simulating sediment load in ice-covered rivers both in the form of suspended and bed loads. Suspended sediment calculation is based on the estimation of non-cohesive suspended materials using the method developed by vanRijn (1984). Bed load, however, can be calculated using several approaches available for this purpose. ICESIMAT includes Meyer-Peter-Muller (1948), Einstein (1950), Einstein-Brown (1950), Yalin (1963), Bagnold (1980), Modified Ackers-White (1982), Parker (1982, 2000), vanRijn (1984) and Wilcock-Crowe (2003) models to estimate the sediment bed load in the ice-covered river. The appropriate model to be applied in the calculations can be selected by the user during model set-up (Figure 1).

2 Field Investigations

Field investigations of this study were conducted on the Lower Nelson River (LNR) in northern Manitoba. The LNR is a regulated semi-alluvial river that drains Lake Winnipeg and flows into Hudson's Bay through the northern Manitoban shield. The study site of this research project was located upstream of Jackfish Island in the middle of the reach between the Limestone Generating Station (LGS) and Gillam Island at the mouth of the bay. The river stretches about 102 km along this section and flows fairly straight and fast. River banks are relatively steep along this reach. The elevation of the river thalweg undergoes two sets of elevation drops in the reach with an average slope of 0.0011 for the upper portion (about 28 km long) and 0.00018 for the remaining lower portion.

Ice processes in the LNR start with ice bridging at the lower boundary of the reach. Ice cover then propagates upstream toward the LGS and the leading ice edge stalls at Sundance Rapids about 3 km downstream of the LGS. The ice cover processes normally take place between mid-November to mid-May.

River hydraulics and ice cover variations were studied using acoustic techniques in this research. Autonomously recording acoustic instruments including a 1200 kHz Acoustic Doppler Current Profiler (ADCP) and 546 kHz Shallow Water Ice Profiling Sonar (SWIPS) were utilized to monitor the interactions between the ice cover and river hydraulics and sediment transport. Instruments were installed on a bottom moored aluminum mount and deployed in the river during three winter field campaigns. Recorded information was then analyzed and interpreted to evaluate the mentioned effects.

2.1 Estimation of Ice Cover Thickness Using Acoustic Data

Ice thickness can be calculated according to the data measured by the instruments in a time series format of river ice draft. The three equations corresponding to calculation of ice thickness are provided below.

Ice draft, *d*, can be calculated as the difference between the simultaneous water level and elevation of the bottom of the ice, which is derived from the peak in the vertical profile of backscatter intensity. The measured acoustic range of the underside of the cover is corrected for transducer tilt (θ).

[5] $d = H - \beta . D \cos\theta$

In which β is the correction for the actual sound speed to the nominal value.

Water depth, *H*, can be determined using the measured bottom pressure P_{btm} , which should be adjusted according to the atmospheric pressure P_{atm}, measured at a nearby weather station:

[6] $H = \frac{P_{btm} - P_{atm}}{\rho_w g}$

in this equation, ρ_w is the water density

Hence, for a fairly flat ice cover, the ice thickness, T_{ice}, can be calculated as:

[7] $T_{ice} = d . \frac{\rho_w}{\rho_{ice}}$

3 Results and Analysis

3.1 Ice Cover Formation

Figure 3 (left) shows the ice cover simulation results in the study area during the three main stages of formation, stabilization, and removal. As shown in the figure, the ice cover propagates upstream from Gillam Island (downstream boundary of the simulation) through the processes of juxtaposition. Juxtaposition relocates the leading edge of the ice cover upstream until the cover progresses to its most upstream

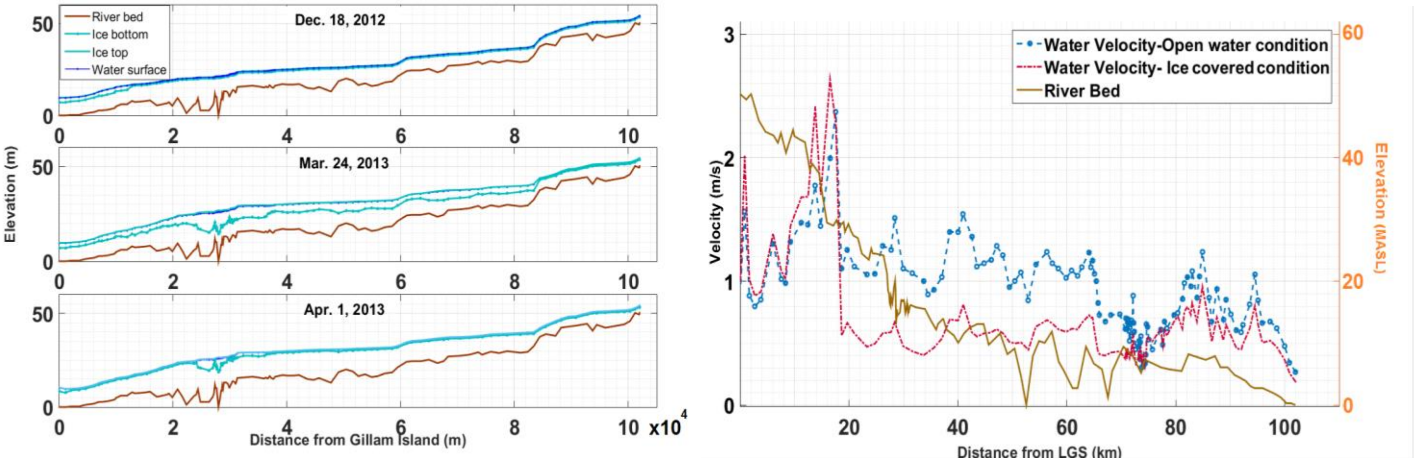

Figure 3 ICESIMAT results showing the ice-covered condition in three stages of progression, stabilization and removal (Left); Calculated flow velocity magnitude during open-water and ice-covered conditions (Right)

hydraulic extent. Subsequently, the generated ice volume passes under the leading edge (underturning) and deposits in downstream cross sections where the hydraulic condition meets the deposition limits. The process of propagation is presented in Figure 3 (left, upper plot).

Ice deposition under the existing cover, as well as the cover adjustment through the mechanical thickening, forms the stable ice cover over the study reach as shown in Figure 3 (left, middle plot). Once the ice cover is stable, it thickens and thins according to the thermal and hydraulic parameters of the flow, but is likely to be stable in terms of thickness and propagation extent if no drastic variation in temperature or flow occurs.

At the start of the break-up period, ice cover decays and retreats as previously described. Therefore, the cover state and condition differ according to the new thermal and hydraulic condition. The ice cover removal can be noticed from the difference between the cover condition at two days of model simulation presented in the middle and lower plots of Figure 3 (left).

Estimated ice cover thickness profiles during both the early and late stages of the winter 2012/2013 simulation are represented in Figure 4 (left). As shown, the ice cover experienced an increase in thickness twice during the winter. This is likely due to the mechanical thickening of the cover during the winter.

Figure 4 (right) shows the ice thickness variation in three locations along the reach calculated by the model. As illustrated in this figure, ice cover thickness varies drastically at different locations along the river reach. This is mainly due to the different parameters involved in ice cover formation at various locations. Hence, depending on how dynamically or statically the cover forms, it may evolve to different cover thicknesses to maintain the force balance on the body of the cover. Some interesting features can be addressed in this figure and are worthy of a more detailed discussion.

One interesting feature is the similarity in the start of ice cover formation between the presented locations, although the cover at each location forms at a different rate. This is mainly due to border ice growth and the approach that is taken in the model to calculate the border ice formation through the simulation. ICESIMAT uses different approaches to simulate the border ice growth including the Newbury (1967) method as well as the border ice factor (the second approach is applied in this study). Through this approach, the border ice growth is calculated using the border ice factor which relates the border ice growth to the Accumulative Freezing Degree-Days (AFDD) at the study reach. The AFDD is assumed to be uniform along the study reach and, consequently, applying the border ice factor results in the formation of border ice at the same rate and thickness for all the simulated river cross sections. However, the Newbury method leads to the formation of border ice at a different magnitude and rate

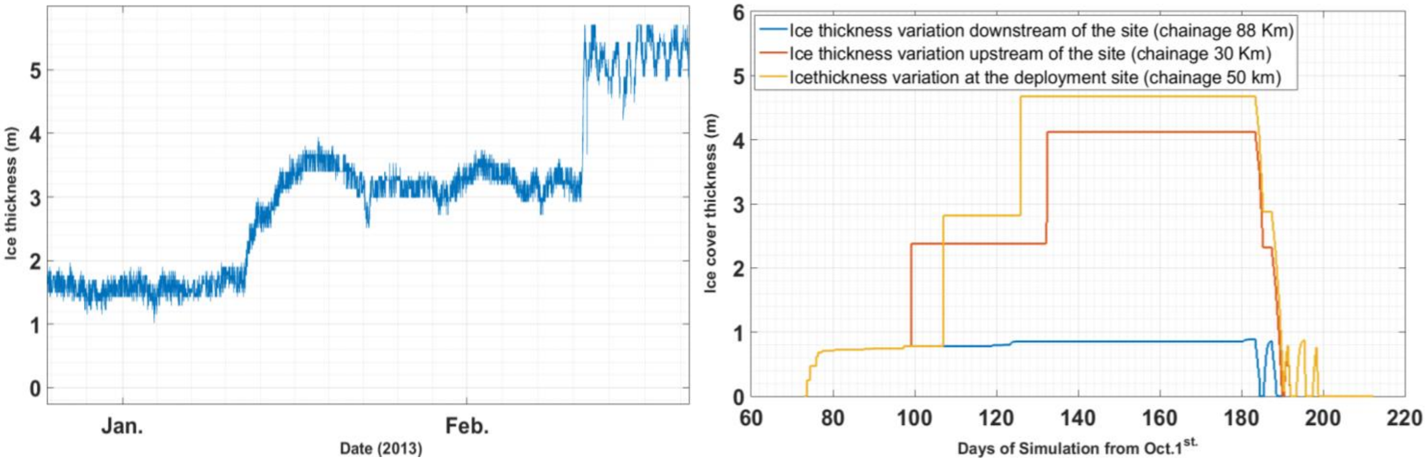

Figure 5 River ice thickness; field estimation (Left), Simulated (Right)

between the cross sections. Selecting the method of border ice simulation is based on the direct observations or experience / interpretations of the user from the study site, which results in some variability between different simulation cases.

Another important feature that can be observed in the cover thickness results is the significant difference between the ice cover thickness values upstream and downstream of the deployment site. As described before, the simulated reach of the LNR experiences two sets of different bed slopes before reaching the estuary at the mouth of Hudson Bay. Hence, different hydraulic conditions affect the cover, causing it to form different cover thicknesses. Due to the relative similarity in ice thickness between the deployment location and upstream site, the cover decayed at almost the same rate in both places. However, the downstream cross section experienced a completely different decay process than its upstream counterpart both in terms of timing and value.

The other important feature shown in the figure is the formation and removal of mechanically thickened ice covers in different locations presented in the figure, during the break-up period. These mechanically-thickened ice covers are shown graphically in the form of ice cover thickness peaks before the complete removal occurs. It should be noted that the ICESIMAT model is not capable of simulating an ice-jam formation during the freeze-up and break-up periods. Therefore, the calculated ice cover thickness during the break-up period is based on the equilibrium cover thickness calculation. This is the reason why even the timing and duration of the peaks vary while the ice thickness values are almost identical. This happens because ICESIMAT currently simulates the ice cover removal process using a series of equilibrium, steady ice cover formation processes at sites where open water emerges while the ice cover is still present in adjacent cross sections. As a result, the cover will only thicken enough to resist the thrust forces at the time of simulation based on the ice volume available from upstream cross sections.

As it can be seen, the model simulated the trend of ice cover thickness variation, but there is a slight difference in the thickness values. The difference between the observed and simulated ice cover thickness values can be explained according to the nature of the ICESIMAT model. Estimated thickness values are more representative of the local thickness whereas the ICESIMAT estimation, considering the 1D nature of the model, is basically a cross-sectional average value. Hence, considering the assumption of the uniform cover condition in ICESIMAT calculations for each cross section, local variations in ice cover thickness are not simulated in the model at the current stage.

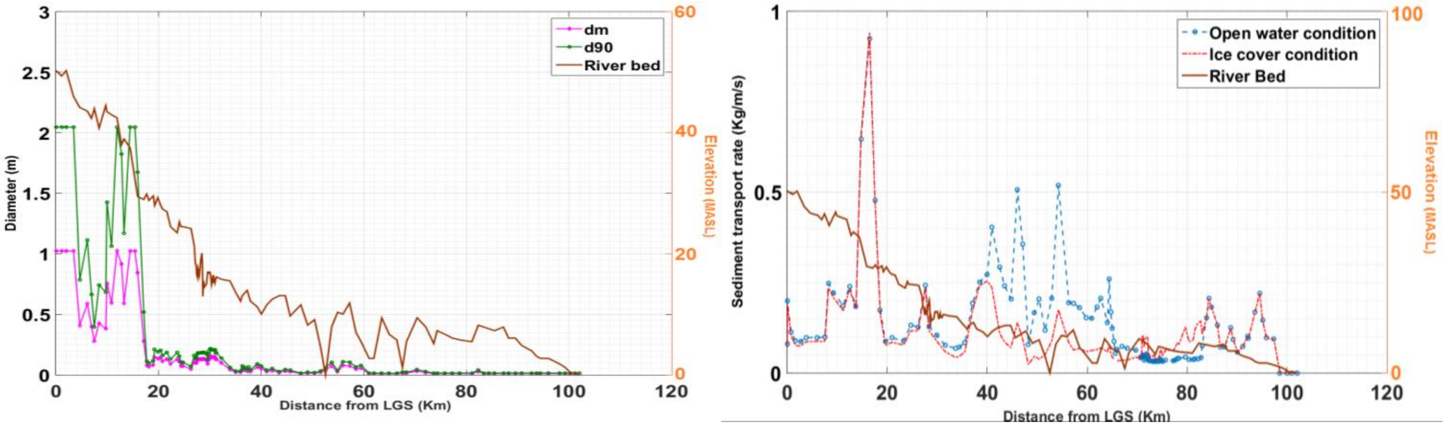

Figure 6 Bed material size distribution along the study reach (Left); Simulated sediment transport rate during the open-water and ice-covered periods (Right)

3.2 Water Velocity

River hydraulic conditions play an important role in defining the stage and condition of the ice cover. This is particularly important in ice cover modeling since the model calculates the ice cover thickness based on the water velocity and elevation at each cross section. Figure 3 (right) compares flow velocity magnitude in all simulated cross sections during two stages of open-water and ice-covered conditions.

As shown in the figure, the ICESIMAT results show the flow velocity magnitude during the ice-covered period to be lower than the open-water period. These results confirm the model consistency with the theory in terms of ice cover effects on flow velocity magnitudes and also match the field observations of the ice cover condition (also refer to Figure 4) and water stage (not shown here).

The lower velocity magnitudes of the model simulations can be explained by the extra resistance added to the stream at the top of the water column in places where the ice cover formed. However, higher simulated water velocities on upstream cross sections, beyond the cover extent, can be described as the results of higher water stages (i.e., greater hydraulic gradient occurred due to the backwater effect from the downstream ice covered cross sections). Notably, the hydraulic simulation of ICESIMAT during the open-water stages was also compared with HEC-RAS during the model calibration process (not shown here), and the results were found to be almost identical.

3.3 Sediment Transport

According to the variation in water velocity (i.e., shear stress), the sediment transport rate estimation in the river is expected to be different between ice cover and open water conditions. As previously discussed, lower water velocities and shear stresses during the stable ice cover period cause the sediment transport rate to decrease, except for the break-up period when the initiation and transport rate significantly increase due to the highly dynamic stages of flow and ice cover.

Figure 6 shows the bed material distribution (left) and sediment transport rate estimation (right) for the study reach during both the open-water condition and the ice-covered period. Comparing the results, it is clear that the sediment transport occurred at a lower rate at the study reach during the ice-covered period. There are two important points to note in terms of sediment transport rate, as discussed below.

1. The calculated sediment rate is based on the vanRijn method for suspended loads and the Wilcock-Crowe method for bed load. According to the included models, it can be concluded that the current stage of ICESIMAT is developed for non-cohesive suspended sediment materials, though it can calculate the bed load using almost all available bed load models. This is mainly due to the fact that

the sediment load in the LNR, which ICESIMAT was originally developed for, is mostly in the form of bed load.

2. The ICESIMAT is limited to a single model application for the calculation of bed load over the study reach even though the cross sections might be different in terms of bed material size and distribution. As shown in Figure 6 (left), the mean particle diameter, d_m, and 90th percentile diameter, d_{90}, of the bed material change from the scale of meters to millimeters (i.e., from boulder/large gravel to sand particles or smaller). Therefore, the selection of a sediment transport model should be performed cautiously to ensure the model simulations are accurate and consistent with observed data on sediment load. However, similar to all numerical simulation models for river hydraulics and sediment transport, it is important to select an appropriate approach for estimation of sediment load based on the nature of the flow and morphological characteristics of the channel.

4 Conclusion

Considering the capabilities and limitations of ICESIMAT, its performance was found to be acceptable in terms of simulation of river hydraulics and sediment transport under an ice cover. Further improvements to upgrade the model capabilities are under consideration to account for the appropriate suspended and bed load calculation approaches according to the varying bed material and size distribution. The performance of the ice simulation model will evolve as it continues to be used to simulate real-world river ice scenarios. Potential future developments in this field will include model enhancements to simulate ice jam formation and removal, as well as the hydraulic features associated with it.

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