Modelling Ice Formation on the Red River near Netley Cut

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This paper presents the preliminary results of a river ice dynamics study conducted on the Red River near Netley Cut in Manitoba, Canada. CRISSP2D, a two-dimensional finite element model typically used to study the characteristics of ice formation, movement, and break up, was used to simulate the hydrodynamics and ice dynamics in the study area. A field program was undertaken to obtain water depth, velocity and temperature measurements throughout the study area over a five month period. The data collected from this program was used in the hydrodynamic calibration and verification of the model. Results of these simulations indicate that the model is able to accurately simulate the measured data. The calibrated model was used as an input to the dynamic ice module of CRISSP2D and preliminary ice formation simulations were completed. Preliminary model calibration was attempted, but further data collection is required for successful calibration. This data will be collected during the 2011-2012 winter season.
1. Introduction

The province of Manitoba is home to a plethora of lakes, wetlands, and rivers. The Red River is one of the major rivers in the province, originating in South Dakota in the United States and flowing north and discharging into Lake Winnipeg. The river is approximately 885 km long and flows through several urban centres before it spreads into the Netley-Libau Marsh, a vast deltaic wetland that lines the south shore of Lake Winnipeg.

In the winter, sub-zero air temperatures cause the Red River and surrounding wetlands to freeze over. Typically, the freeze-up process begins with a skim ice cover forming on the lakes and wetlands. This is often followed by strips of border ice forming along the banks of the Red River. As winter proceeds, the skim ice thickens thermally downward and the border ice strips increase in size until a competent ice cover has formed. Once the ice cover has formed it generally remains in place for the entire winter (November to April).

When spring approaches, ice break up is typically triggered by snowmelt and warmer temperatures. Thermal processes cause the ice cover to deteriorate, while increasing flow rates cause the ice to detach from the river banks. The ice breaks into large pieces and, as discharge continues to increase, the pieces are transported downstream. Occasionally, these ice pieces become lodged between the river banks forming an ice jam.

The Red River is particularly susceptible to ice jamming. This can be partially attributed to the fact that the river flows north into colder regions where the ice is often still intact. Additionally, the meandering nature of the river provides many opportunities for ice to become lodged. Once an ice jam forms, the water level upstream continues to rise until the jam is released. This often results in severe flooding of the communities upstream of the jam. In Manitoba, the most severe ice jams occur north of Winnipeg, generally between Selkirk and Lake Winnipeg.

2. Study Area

This study concentrates on the portion of the Red River that extends from Selkirk to Lake Winnipeg, including all three branches of the Red River that flow through the Netley-Libau Marsh (shown in Figure 1). The total reach length included in this study was approximately 33km and includes two tributary inflows at Netley Creek and Devils Creek. Historically, this portion of the river has been most problematic to Manitobans with ice jam and flooding concerns nearly every break up season. In fact, the government of Manitoba has recently purchased specialized equipment to artificially cut the ice prior break up and has since implemented an annual cutting routine in this reach.

The study also included two larges lakes that store water from the Red River: Netley Lake and Hardmans Lake. These lakes have a combined surface area of approximately 53km², creating a large capacity for water storage, and thus were included in the study. Furthermore, a significant portion of the Red River flow is diverted through Netley Lake via an opening in the western bank of the Red River, known as Netley Cut (shown in Figure 1). The direct flow and storage contributions from the other lakes in the Netley-Libau Marsh were not considered to be substantial and were excluded from the model for computational efficiency.
3. Data Acquisition

Although interest in the previously mentioned portion of the Red River is high, there has not been any previous numerical modelling of the area. As a result, bathymetric data had to be compiled from a variety of sources and a field program was initiated to obtain water surface elevation (WSE) data for boundary conditions and hydrodynamic and dynamic ice calibrations.

3.1 Bathymetry Data

The bathymetry of the study area was obtained primarily from three sources. Lake bed elevations for Netley Lake and Hardmans Lake as well as river bed elevations for the portion of the Red River that extends from downstream of Netley Cut to Lake Winnipeg were obtained from a hydrometric survey that was performed in October 2009 by Aquatics ESI using sonar technology. The survey provided coverage of the aforementioned regions on a 1 m by 1 m grid. However, the west branch of the Red River was not covered in this survey because it was too shallow to accommodate the equipment used. Upstream of Netley Cut, river bed elevations were modeled using cross sections obtained from a hydrometric survey completed in 1957, due to a
lack of current, available data. The cross sections are approximately 200 m apart and extend to the upstream extents of the model. The age of these cross sections is not expected to have a significant effect on model results.

To supplement these two sources, and provide coverage of the smaller west branch of the Red River, cross sections measured with an Acoustic Doppler Current Profiler (ADCP) by the University of Manitoba in July 2009 were incorporated into the model.

3.2 Field Program
The University of Manitoba undertook an extensive field program to collect various data sets from the study area. This program included collecting water depth, temperature, and velocity measurements at 6 locations throughout the study area (shown in Figure 2), surveying relevant cross sections in the study area, and ice thickness and freeze up observations in the winter. This data was ultimately used for developing and calibrating a numerical model.

4. Numerical Model
The numerical model used in this study is CRISSP2D. This is a coupled, two-dimensional finite element model that contains hydrodynamic, thermodynamic, and dynamic ice components. These components work together to allow the model to simulate ice formation, movement, stoppage, and jamming in rivers and lakes.

The hydrodynamic sub-component of CRISSP2D can be used to simulate a variety of flow regimes and solves the two-dimensional, depth averaged, unsteady St. Venant equations for the conservation of mass and the conservation of momentum. The thermodynamic sub-component of CRISSP2D is governed by energy exchanges that are present between the atmosphere, ice cover, water, and riverbed.

When coupled with the hydrodynamic and thermodynamic modules, the ice dynamic sub-component of CRISSP2D can simulate a wide variety of ice processes. The model will simulate water temperature, supercooling, and frazil production by solving the energy equation for the body of water.

Additionally, CRISSP2D can simulate many thermodynamic processes including border and skim ice. The primary principles governing border ice growth typically fall into one of two categories: static or dynamic growth. Each of these processes is simulated using a threshold value that determines whether or not border ice will grow. The threshold value is based on border ice models developed by Michel et al. (1982) and Matousek (1984), two widely accepted models. Velocity and temperature calculations at each time step are compared to the threshold value to estimate the advance or retreat of the leading ice edge. A similar criterion is used to estimate the formation and transport of skim ice.
4.1 Mesh Development

The finite element mesh developed for the study area is shown in Figure 2. The mesh includes all branches of the Red River as well as Hardmans Lake and Netley Lake and its outlet to Lake Winnipeg. The model extends approximately 21 km upstream of Netley Cut and terminates approximately 12 km downstream of Netley Cut at Lake Winnipeg. For simplicity and to decrease computational time, the Netley-Libau marsh was excluded from the model.

The model domain required the use of 36,200 elements, covering a total surface area of 63 km². The elements vary in size based on channel width. The narrower channels required smaller elements in order to maintain the computational integrity of the mesh. These regions were integrated with gradual element size transitions to adjoining portions of the mesh. To decrease computational time, larger elements were used in Netley Lake and Hardmans Lake since they are low flow regions and are of less hydraulic importance than other portions of the mesh. The nodes
were numbered from downstream to upstream for computational efficiency since an upwind scheme is used to solve the unsteady flow equations.

4.2 Boundary Conditions

The hydrodynamic model required several boundary conditions to be established. At the upstream extent of the model, a discharge (flux) boundary condition was specified using hourly discharge data from Water Survey of Canada Gauge 05OJ005. Further downstream, two additional flux boundary were specified at Netley Creek (hourly discharge data from Water Survey of Canada Gauge 05OJ008) and Devils Creek (hourly data obtained in field program discussed in Section 3.2). All other incoming tributaries were considered to be negligible.

At the downstream extent of the model, the outflow into Lake Winnipeg, the water surface elevation was assumed to be identical at each of the four outlets (shown in Figure 2). Thus, hourly water surface elevation data collected from Gauge 7 was used to force the model at the downstream end. It was important to use a gauge immediately downstream of the model outlets due to the nature of the water level fluctuations of Lake Winnipeg. Since Lake Winnipeg is a large, shallow lake situated in the Prairies, its water surface elevation is highly affected by both wind speed and direction. Constant winds in a particular direction often result in wind setup over the lake. Due to this phenomenon, it is not uncommon for there to be an elevation difference of over a metre between the north and south shore of the lake. CRISSP2D does not have the capacity to deal with this phenomenon directly. Thus, it is important that the gauge be located close enough to the model boundary to incorporate these effects. Furthermore, wind set up and set down often result in backflow through the river channels. Thus, it was critical that the outlet boundaries also allow flow to return to the model.

Boundary data at Gauge 7 was only available between June 16, 2010 and October 16, 2010. Thus, outflow boundary data was not directly available for any winter freeze-up season. To remedy this, an empirical relationship between the water surface elevation at Gauge 7 and Water Survey of Canada Gauge 05SB006 (Lake Winnipeg at Gimli) was developed:

\[
E_7 = 1.0997E_G - 21.7677
\]  

[1]

Where \(E_7\) is the water surface elevation at Gauge 7 and \(E_G\) is the water surface elevation at Water Survey of Canada Gauge 05SB006. Using this relationship, the boundary data for the model outflow could be extrapolated into the winter season since Gauge 05SB006 is operated year round.

Similarly, the discharge data at Devils Creek was only measured for a two week period in the summer of 2010. In order to obtain data for the entire calibration, verification, and winter freeze-up time frames, the existing data needed to be extrapolated. The magnitude of the discharge that enters or exits the Red River via Devils Creek is largely governed by water levels in the Netley-Libau Marsh, which are in turn governed by the water level of Lake Winnipeg. As a result, it was found that an empirical relationship could be developed using data from Gauge 05SB006:

\[
Q_D = -71.5642X_1 - 83.0538X_2 - 251.396X_3 - 177.180X_4 - 28.2553
\]  

[2]
Where, at each time step, $X_1$ is the change in water surface elevation at Gauge 05SB006 over the following 5 hours, $X_2$ is the change in water surface elevation at Gauge 05SB006 over the previous 5 hours, $X_3$ is the change in water surface elevation at Gauge 05SB006 over the following 3 hours, lagged 5 hours, and $X_4$ is the change in water surface elevation at Gauge 05SB006 over the previous 5 hours, lagged 3 hours. The previously described variables were chosen based on a detailed stepwise regression analysis. $Q_D$ can be either negative or positive to represent inflows and outflows, respectively.

The dynamic ice module of CRISSP2D requires an additional water temperature boundary condition to be specified. Since no water temperature data was available within the study area, this boundary was established at the upstream extent of the model and was assumed to be constant at 0.1°C during the freeze-up period.

4.3 Initial Conditions

At the beginning of a new hydrodynamic simulation, CRISSP2D sets a constant water surface elevation throughout the entire model domain. As such, hot start files for each simulation were generated, where the model was allowed to reach steady state using discharge and water surface elevations corresponding to the first hour of each simulation. This allowed an appropriate water surface profile to be generated, as well as appropriate velocity and depth values at each node to be calculated and input as the initial conditions of the model.

5. Hydrodynamic Calibration

The time period chosen for hydrodynamic calibration was June 24, 2010 to July 31, 2010. This period was chosen because it was deemed representative of the large fluctuations that can occur in the water surface elevation of Lake Winnipeg. The range in measured water surface elevation at Gauge 7 during this period was 217.6 m to 218.5 m, including many peaks and troughs to test the model’s ability to simulate relatively rapid changes in water surface elevation. There were two primary objectives during the hydrodynamic calibration of this model: preserving continuity throughout the model and obtaining simulated water surface profiles matching those measured during the field program.

In order to preserve continuity throughout the model, the finite element mesh was adjusted iteratively such that smaller elements were used in areas of hydraulic importance, including some outlets and near Netley Cut, and larger elements were used in non-critical areas, such as Netley Lake and Hardmans Lake to decrease simulation time. Additionally, the number of elements across each branch of the Red River remained relatively constant, causing element size to vary between each channel. Adjusting the finite element mesh in this manner allowed a continuity error of 3% to be obtained, which was deemed acceptable for this application. Minimizing the continuity error proved to be very critical during the hydrodynamic calibration of this model. Large continuity errors were found to be associated with having an insufficient number of elements across any channel, and led to falsely high steady state water surface profiles during the hot start simulations. This was corrected by using an appropriately fine computational mesh and keeping the number of elements across each channel consistent.
In the model, discharge, and ultimately water surface elevation, could be controlled by adjusting the Manning’s roughness coefficients in different portions of the mesh. The mesh was divided into ten distinct reaches (shown in Figure 3) so that the properties of each section of the model could be adjusted independently of the others. Typically, the reaches were chosen such that the beginning and end coincided with a calibration gauge (shown in Figure 3). To obtain the correct water surface profile, the roughness coefficient of each reach was adjusted iteratively until the desired water surface profile was simulated. The final values of the roughness coefficients ranged from 0.01 to 0.025. Using this method, the measured water surface profile could be accurately simulated by the CRISSP2D model, as shown Figures 4 and 5.

Figure 3. Reach Boundaries.
6. Hydrodynamic Verification

In order to verify that the model parameters chosen during the calibration phase were adequate, a hydrodynamic verification was performed. The verification simulation was run between August 5, 2010 and September 12, 2011. Again, this time period was chosen to ensure that the model could sufficiently simulate the peaks and troughs in water surface elevation that are characteristic of the study area. The simulated and measured water surface elevations at Gauge 4 and Gauge 1 during this time period are shown in Figure 6 and Figure 7, respectively.

From Figures 6 and 7 it is evident that model is able to accurately simulate the observed water surface elevations, including all peaks and troughs in the measured data. This indicates that the model parameters chosen in the calibration stage were appropriate for the model.
6. Dynamic Ice Modelling

Following the successful hydrodynamic calibration of the model, the dynamic ice sub-component was enabled. Simulations were run for the 2009-2010 winter freeze-up season. In order to reduce computational time during the calibration of the dynamic ice model, a simpler, coarser finite element mesh was used. This adjusted mesh excluded Hardmans Lake and generally contained larger elements throughout the entire model domain.

Several difficulties were encountered while calibrating the dynamic ice model, largely due to the unavailability of data. In order to accurately calibrate the dynamic ice model, water temperature, air temperature, and ice thickness measurements are required throughout the winter season. In addition, it is essential to have knowledge of the date of freeze-up onset and which freeze-up processes occurred at that time.
Water temperature data was not available at any location within the reach and thus, it had to be assumed. This assumption may have a substantial effect on the model results since the temperature of the water will have significant influence on when the onset of freeze-up occurs. Additionally, neither the date of freeze-up onset nor the types of ice process occurring throughout the winter have been well documented in any existing freeze-up season. This made it difficult to verify that the model was responding appropriately to the forcing data.

Due to the difficulties described above, it was deemed that further data collection is necessary to properly calibrate the dynamic ice model. Accordingly, the University of Manitoba has planned an extensive field program for the 2011-2012 winter season to collect all necessary data for calibrating the dynamic ice model, including collecting ice thickness measurements, water temperature data, and freeze-up observations.

Although not properly calibrated, the model generally responded to the forcing data as expected and as described in Section 1.0. Figure 8 shows the progression of the different ice processes throughout the freeze-up period. Freeze-up is induced with the production of skim ice over Netley Lake. As time progresses, skim and border ice begin to form along the banks of the Red
River and the skim ice on the lake thickens into border ice. Finally, the border ice in the river grows inward until bridging occurs and the whole model domain is covered with a competent ice cover. This sequence is typically observed most winters. However, more data is required to verify the above results, including detailed observations throughout the freeze-up period and without these observations, the validity of the model results can only be speculated.

Ice formation in the vicinity of Netley Cut is of particular interest in this study and is shown in Figure 9. From this figure it is evident that the ice downstream of Netley Cut is inherently thicker than that upstream Netley Cut. This can be attributed to the fact that up to 50% of the upstream flow exits the main channel through Netley Cut, significantly decreasing the discharge and water velocity downstream. Water velocity has a significant influence on ice production, as ice will grow more quickly in low velocity regions. Water velocities are even further decreased in Netley Lake, resulting in even thicker ice in this region. Although no ice thickness measurements in this region were available for the 2009-2010 winter season, field measurements taken the 2010-2011 freeze-up season support the simulation results.

![Figure 9. Simulated ice thickness at Netley Cut.](image)

During the 2009-2010 winter season, two ice thickness measurements (on February 12 and March 9) were taken at Peguis Church, a station located approximately 5 km downstream of Selkirk. Simulated ice growth at Peguis Church is shown in Figure 10. From this figure it is evident that model significantly overestimated the observed ice thickness. Significant error was introduced into the model due to data unavailability. The date of freeze-up had to be estimated and only two field observations existed near the end of the freeze-up period, making it difficult to reproduce processes occurring at the beginning of the freeze-up season. Ideally, detailed observations of the onset of freeze-up and a more representative set of ice thickness
measurements would be available so that parameters in the energy budget (including heat loss coefficients and permeability values) can be calibrated properly. Additionally, the water temperature had to be assumed due to data unavailability, possibly introducing further error into the model. Along with air temperature, water temperature is a major factor in determining when ice crystals will start forming. Overestimating or underestimating water temperature will result in the model simulating the onset of freeze-up after or prior to the correct date, respectively.

![Figure 10. Simulated ice thickness at Peguis Church.](image)

7. Future Work
The University of Manitoba has planned an extensive field program for the 2011-2012 winter season. This program will involve collecting all necessary data to properly calibrate the dynamic ice model, including collecting ice thickness measurements, water temperature data, and freeze-up observations. This data is integral to the success of the dynamic ice model. Following the successful calibration of the simplified dynamic ice model, a similar calibration procedure will be applied to the finer, more detailed model in order to obtain more accurate results.

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