CGU HS Committee on River Ice Processes and the Environment
19th Workshop on the Hydraulics of Ice Covered Rivers
Whitehorse, Yukon, Canada, July 9-12, 2017.

Modelling Ice Jam Formation in the Hay River Delta during 2009 Breakup

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Every spring the Town of Hay River, Northwest Territories, Canada, faces flooding threats associated with ice jam events in the channels of the adjacent Hay River delta. In this study a newly developed ice dynamic model, MPIce, was set up to simulate the ice jam forming process in the delta channels. MPIce uses a discrete parcel scheme based on the Moving Particle Semi-implicit (MPS) method to solve the ice dynamic equations, and is two-way coupled with the widely used open source three-dimensional hydrodynamic and transport model Delft3D (oss.deltares.nl). The model was first calibrated against water level and velocity measurements for open water conditions in the Hay River delta. The model was then used to simulate an ice jamming event occurred during the 2009 breakup. The model results followed well with the surveyed top of ice profile in the delta channels.

1. Introduction

In cold regions, removal of river ice can be either through gradual thermal deterioration or rapid dynamic breakup. Thermal breakup is characterized by in-place melting with limited ice movements; while dynamic (mechanical) breakup, triggered by hydrodynamic forces, is often associated with ice jams and could result in flooding. The Town of Hay River, located along the banks of the Hay River as it enters the Great Slave Lake (Figure 1), is threatened by ice jam flooding yearly. Each spring, the breakup of the river progresses downstream in a cascade of ice jam formation and release events. The resulted javes shove into the ice in the delta and can cause the ice to consolidate and water level to rise rapidly. The toe of the ice jams in the West and East Channels being pushed to the mouth of the river had been identified to be the worst flooding scenario (Gerard and Jasek, 1990). Flooding occurred every year between 2005 and 2010, with the most recent major event occurred in 2008. These emphasize the importance of a public warning system for predicting ice jam occurrence and inundation potential of the nearby communities. Numerical modelling is particularly suitable for such purpose.

Many modelling studies have been conducted for the Hay River and the Hay River delta. Wiens (1983) used HEC-2 to simulate a 1:100 year flood event assuming the ice jam was located at the mouth of the delta channels. Hicks et al. (1992) applied the cdg1-D model (the precursor to River1D) to simulate javes on the Hay River, and the resulting peak flows at the delta was used in the ICEJAM model (Flato and Gerard, 1986) to study the effect of javes on ice consolidation within the delta and to estimate the flood levels in the Town (Gerard et al., 1990). These one-dimensional models cannot provide accurate flow split between the delta channels. De Coste et al. (2017) utilized the River1D Network model, and the resulting peak flows in the West and East Channels were used in HEC-RAS (US Army Corps of Engineers) to estimate the ice jam profile and expected flood levels. Brayall and Hicks (2012) applied River2D to reproduce 11 documented ice jam events in the delta. The results were used to develop a tool called the ‘ice jam profile generator’ for predicting flood levels at key locations in the Town. However, none of the above modelling efforts considered ice dynamics and only stabilized static ice jams were modelled. This limits their application in modelling the dynamic ice events often occurring in the Hay River delta.

The objective of this study was to consider ice dynamics in the prediction of ice jam flood levels in delta regions. To achieve this, the 2D model MPIce (Moving Particle semi-implicit Ice dynamic model), coupled with the open source three-dimensional hydrodynamic and transport model Delft3D (Oveisy et al., 2015) was applied to simulate the Hay River delta. The model was validated for both open water condition observed in August 2005 and July 2007, as well as ice jam condition measured during the 2009 breakup event.

2. MPIce Model

2.1 Governing equations of ice dynamics

MPIce model (Oveisy et al., 2015) considers ice as a continuum and the governing equation for the conservation of momentum in the two-dimensional horizontal plane can be written as,

$$M(DV_{ice} \,/\, Dt) = F_w + F_a + F_{ice} + F_g \qquad [1]$$

where M is the ice mass per unit area calculated by $N\rho_{ice}t_{ice}$; N is the ice concentration; ρ_{ice} and t_{ice} are the density and thickness of the ice; F_w and F_a are the water and air stress terms; F_{ice} is the ice internal resistance; and F_g is the gravitational force due to the water surface gradient. These forces are defined as,

$$F_w = N\rho_w c_w|V_w - V_{ice}|(V_w - V_{ice}) \quad [2]$$

$$F_a = N\rho_a c_a|V_a - V_{ice}|(V_a - V_{ice}) \quad [3]$$

$$F_g = -Mg\nabla\xi \quad [4]$$

$$F_{xice} = \frac{\partial}{\partial x}(\sigma_{xx}t_{\text{ice}}N) + \frac{\partial}{\partial y}\left(\sigma_{xy}t_{\text{ice}}N\right) \quad [5]$$

$$F_{yice} = \frac{\partial}{\partial y}\left(\sigma_{yy}t_{\text{ice}}N\right) + \frac{\partial}{\partial x}\left(\sigma_{xy}t_{\text{ice}}N\right) \quad [6]$$

where V_{ice}, V_w, and V_a are the velocities of ice, water, and wind; g is the gravitational acceleration; $\nabla\xi$ is the water surface gradient; ρ_a and ρ_w are density of air and water; c_a and c_w are the air-ice drag and water-ice drag coefficients, respectively. The ice parcels were assumed to move with water near the surface, therefore the equation of motion in the vertical direction was not included. The internal stress of the ice is calculated using a constitutive law following the viscous-plastic model (Wake and Rumer, 1983; Hibler, 1979),

$$\sigma_{ij} = 2\vartheta\dot{\varepsilon}_{ij} + (\zeta - \vartheta)\dot{\varepsilon}_k\delta_{ij} - P\delta_{ij}/2 \quad [7]$$

$$\Delta^2 = \left(\dot{\varepsilon}_{xx} + \dot{\varepsilon}_{yy}\right)^2 + \left[\left(\dot{\varepsilon}_{xx} - \dot{\varepsilon}_{yy}\right)^2 + 4\dot{\varepsilon}_{xy}{}^2\right]/e^2 \quad [8]$$

$$\dot{\varepsilon}_{xx} = \frac{\partial u}{\partial x}, \dot{\varepsilon}_{yy} = \frac{\partial v}{\partial x}, \dot{\varepsilon}_{xy} = \frac{1}{2}(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}) \quad [9]$$

where σ and $\dot{\varepsilon}$ are the internal stress and strain rate of the ice; u and v are the ice velocities in x and y directions; $\zeta = \frac{P}{2\Delta}, \vartheta = \zeta/e^2$ are the nonlinear bulk and shear viscosities respectively, where the ice force P is formulated following Lu et al. (1999) and Shen et al.(1990),

$$P = \tan^2(\frac{\pi}{4} + \frac{\varphi}{2})(1 - \frac{\rho_{ice}}{\rho_w})\frac{\rho_{ice}gt_{ice}}{2}(\frac{N}{N_{max}})^J, \quad [10]$$

in which φ is the internal friction angle of the ice, taken as 46° in this study; N_{max} is the maximum allowable value of the ice concentration; and J is an empirical constant and a constant value of 15 was used following Shen et al. (1990). It can be seen that the viscosities ζ, ϑ become infinitely large as the strain rate approaches zero, thus they are bounded with large values.

2.2 Solution method

The MPS method (Koshizuka and Oka, 1996) was used to discretize the governing differential equations. As a mesh free method, all differential operators in the equations are replaced by particle interactions. A particle interacts with its neighboring particles within the smoothing length r_e. That is, two particles i and j, interact with each other only if their distance $R_{ij}$is smaller than r_e. A weight function, defined as $W\left(R_{ij}, r_e\right) = (1 - \frac{R_{ij}}{r_e})^{\ k=3}$ (Shakibaeinia and Jin, 2010) was used as the smoothing function to define the physical quantities around a particle. The derivative of any variable Φ is defined as,

$$\langle\frac{\partial\Phi}{\partial x}\rangle_i = \frac{2}{n}\sum_{j\neq i}[\frac{\Phi_j - \Phi_i}{R_{ij}}\frac{x_j - x_i}{R_{ij}}\ W(R_{ij}, r_e\ )] \quad [11]$$

$$\langle\frac{\partial\Phi}{\partial y}\rangle_i = \frac{2}{n}\sum_{j\neq i}[\frac{\Phi_j - \Phi_i}{R_{ij}}\frac{y_j - y_i}{R_{ij}}\ W(R_{ij}, r_e\ )] \quad [12]$$

The density number (n) around a particle and the density of the continuum (ρ) are defined as,

$$\langle n\rangle_i = \sum_{j\neq i}[\ W(R_{ij}, r_e\ )] \quad [13]$$

$$\langle\rho\rangle_i = \frac{\sum_{j\neq i} m_i W(R_{ij}, r_e\ )}{\int_A\ W(R_{ij}, r_e\ ) dA} \quad [14]$$

in which m is the mass of the particles and A is the effective area.

2.3 Coupling with Delft3D

MPIce has been developed as a separate ice dynamic model and can be coupled with any two-dimensional or three-dimensional hydrodynamic model. In this study MPIce coupled with Delft3D is used. Delft3D is a widely used open source three-dimensional hydrodynamic and transport model (oss.deltares.nl). The ice thickness, concentration and velocity calculated by MPIce are sent to Delft3D and the water velocities and water surface elevation are read back from Delft3D. In Delft3D ice is considered as a floating rigid lid. The ice depth is subtracted from the water level and the pressure of the ice is added on the water surface (De Goede et al., 2014). For calculating water drag, the water velocity at the top layer in Delft3D is used. The ice stress on the water equals to the water stress on the bottom of the ice but in opposite direction. The coupling can repeat at a user-defined time interval, which is chosen depending on the dynamic nature of the ice transport.

3. Model setup and results

The Hay River delta is a complex multi-channel system, with two main channels (West and East Channels) flowing around the Vale Island, several narrow branches such as Fishing Village Channel and Rudd Channel, as well as several islands (Figure 1). The narrower channels may be wet or dry depending on the flow and ice conditions. A curvilinear grid was set up for the modelling domain with grid size ranging from 10 m to 60 m to resolve the complex geometry (Figure 2). The wet and dry region module was activated in the model. The discharge data from the Water Survey of Canada (WSC) gauge (07OB001) was used to set the inflow boundary just upstream of the East-West Channel split. The water levels on the Great Slave Lake recorded at WSC gauge (07OB002) were used to set the downstream boundaries for the model, one in the East Channel and one for all the sub-channels of the West Channel.

3.1 Open water modelling

The model was first set up to simulate the open water conditions experienced during August 2005 survey (Brayall, 2011). During the seven days of surveying, the discharge measured at the WSC gauge decreased from 258 m^3/s to 160 m^3/s. A constant Manning's n of 0.025 for the bed roughness as previously calibrated by Brayall (2011) was used. The model was run separately for 258 m^3/s and 160 m^3/s and the profiles of water level were compared with the observations in Figure 3. It can be seen that the model result compared reasonably well with surveyed water level profiles for both discharges.

The model was further validated with the velocity profiles measured using an Acoustic Doppler Current Profiler (ADCP) during the July 2007 survey (Brayall, 2011). The cross sections where velocity profiles are available are shown as red lines in Figure 2. The inflow discharge of the model was set to be 254 m^3/s according to WSC gauge measurements. Figure 4 shows the comparison of the velocities at three cross sections just upstream and downstream of the channel split in the main, East and West Channels, respectively. It can be seen that the modelled velocity profile shape is similar to the ADCP measurements at all three cross sections but was higher in the center of the channel and lower close to the banks.

3.2 Ice jam modelling

The model was then run to simulate an ice jam event occurred on 3 May 2009. An ice jam in the Hay River released and most of the ice pushed into the West Channel of the delta, forming an ice jam toed just beyond km 1110. In the East Channel an ice jam had toed at km 1110.5. The top of ice profile was surveyed after the ice jams stabilized (Brayall, 2011). The measured discharge on that day was 268 m^3/s and was set at the inflow boundary. The monitored lake level of 156.52 m was used at the downstream boundary. The incoming ice was assumed to have a thickness of 1.0 m with a concentration of 0.75. The initial ice cover in the delta was assumed to be 1.0 m. In the East Channel, it was specified that the ice parcels do not pass km 1110.8 and the downstream ice remained intact. Upstream of this point ice was assumed to be broken and ice particles were free to move. In the West Channel, toe location was not specified and the model determined where the ice will stop.

The model was run until the East Channel jam had stabilized. The West Channel jam did not come to a full stop and was showing slow movement. The modelled ice jam profiles are shown in Figure 5 together with the surveyed top of ice elevations for both East and West Channels. It can be seen that the modelled top of ice elevations match well with the surveyed profile in both channels. In the East Channel (Figure 5a), the ice thickness is fairly constant of 1.0 m from the head of the jam to ~ km 1108 and gradually increases to 1.5 m at km 1110. In the toe region the ice thickness sharply increases to 3.5 m. In the West Channel delta (Figures 5b and 5c), the modelled jam is significantly thinner and do not have a thick toe compared to the East Channel jam. The ice slightly thickened between km 1111-1112 where the channel splits into the Rudd Channel, Island Channel and Fishing Village Channel. This is likely due to the lower flow in the West Channel and geometry can play a role. There is no field data to prove whether the West Channel jam is often more temporary and do not have a thick toe compared to those in the East Channel, but field observations had indicated that the West Channel jam often moves over its whole length with ice spilling out onto the lake ice; while it has been relatively rare occurrence for the ice runs to shove the jam to down to the lake in the East Channel. A possible explanation is that the small islands and low lands in the West Channel delta trap ice pieces and result in temporary ice jam. These islands and low lands get partially submerged with increased water level and provide more space for the ice to move again.

4. Conclusion

The Hay River experiences dynamic breakup yearly. The broken ice, carried by snowmelt runoff or javes, pushes into the delta ice, causing consolidations of the ice and ice jams in both West and East Channels. As a result, the water level rises rapidly which poses high flood risk for the Town of Hay River and nearby residential and commercial communities. Therefore, it is desirable to study the dynamic process during the consolidation events in the Hay River delta, and a numerical model which incorporates ice dynamics is essential.

The MPIce, a newly developed model (Oveisy et al., 2015), was employed to model an ice jam event during the 2009 breakup in the Hay River delta. The two-dimensional ice model includes the full ice dynamics, and is two-way coupled with the hydrodynamic model Delft3D. The model was first set up for the Hay River delta and calibrated for two open water periods. The model performed well in comparison to the surveyed water level and water velocity profiles. The model was then run for an ice jamming event occurred on 3 May 2009. The model results agreed well with surveyed top of ice profile in both East and West Channels. The delta jams experienced several consolidation events in the next few days following 3 May, and the toe of the ice jams in both channels were pushed towards the mouth of the river. Multiple top of ice profiles were surveyed during this period (Brayall, 2011). Considering the important role of jam toe shift in flood forecasting, future work will focus on validating the model’s capability of determining the toe location and simulating ice jam movements in the delta, with the ultimate goal of providing a reliable flood forecasting and mitigation tool for the Town of Hay River and other similarly situated communities.

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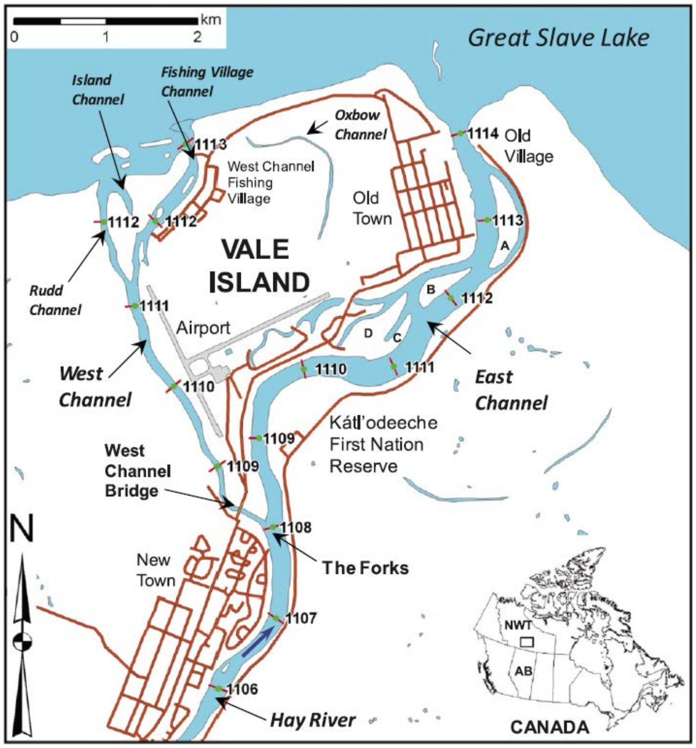

Figure 1. Map showing the Town of the Hay River at the Hay River delta (adapted from Brayall and Hicks, 2012).

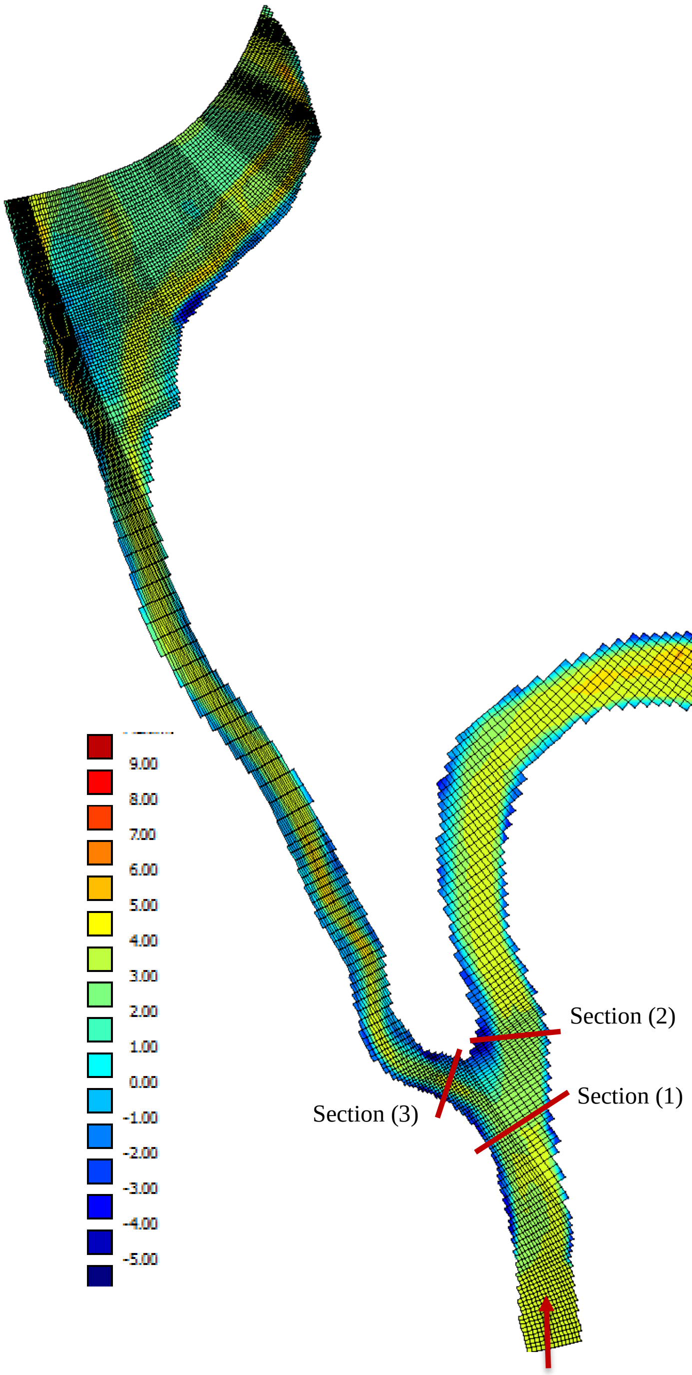

Figure 2. The computational mesh for the model of the Hay River delta and the depth (color shows the bed elevation with a datum at 160.0 m); locations of ADCP velocity measurements conducted in July 2007 are indicated with red lines.

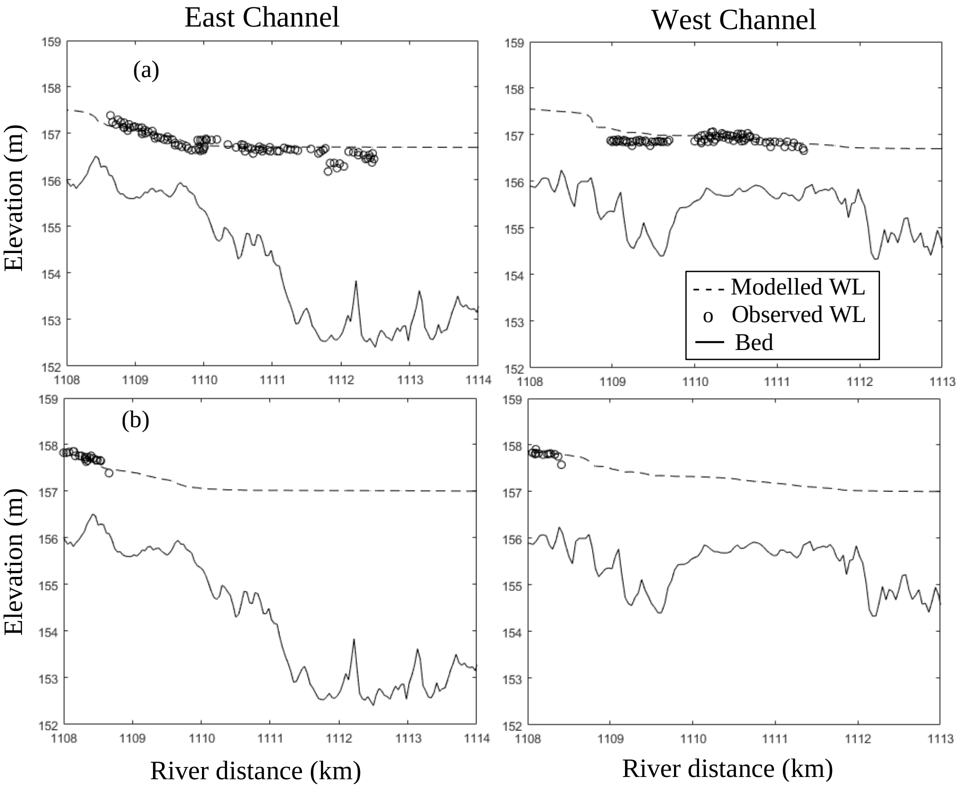

Figure 3. Comparison of modelled water level profiles with observations at: (a) discharge of 160 m^3/s; (b) discharge of 258 m^3/s.

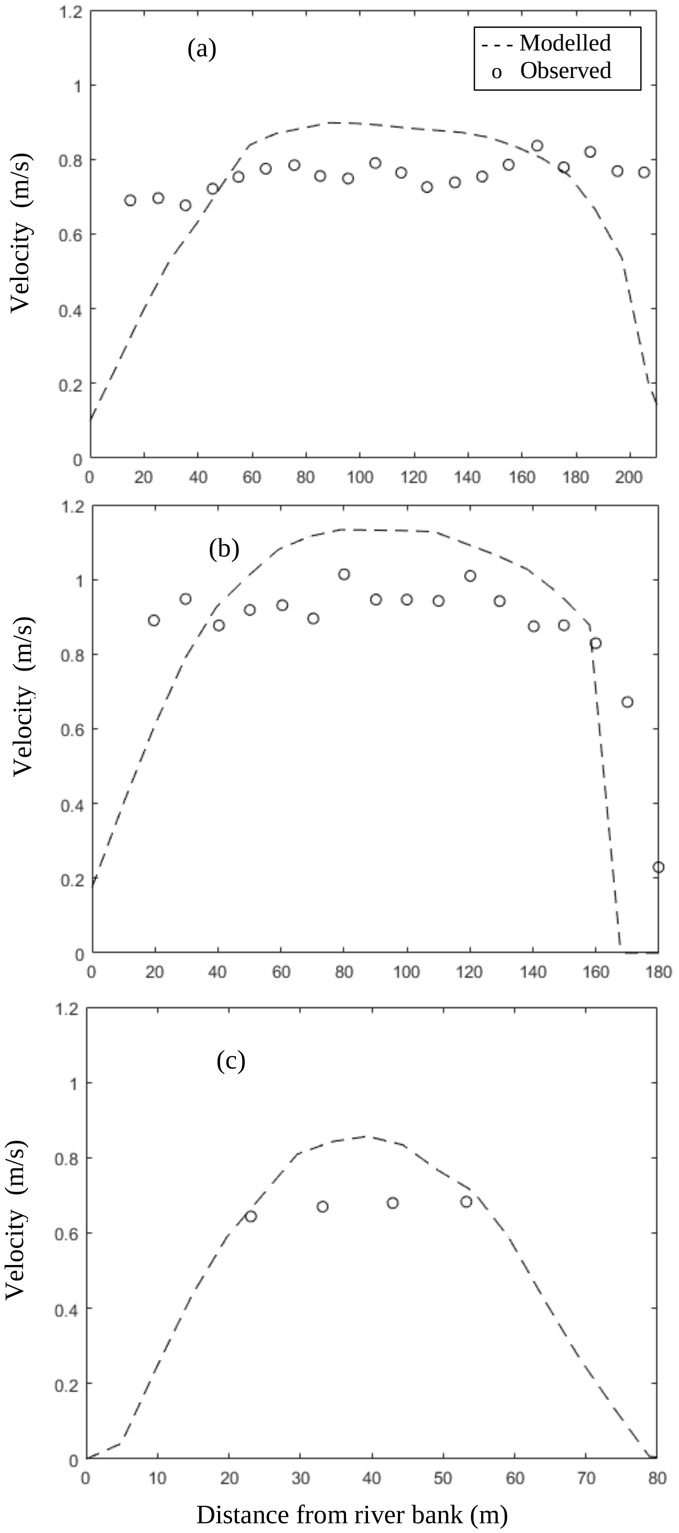

Figure 4. Modelled velocity profile against observation. a) Section (1) in Main Channel; b) Section (2) in the East Channel and (c) Section (3) in the West Channel.

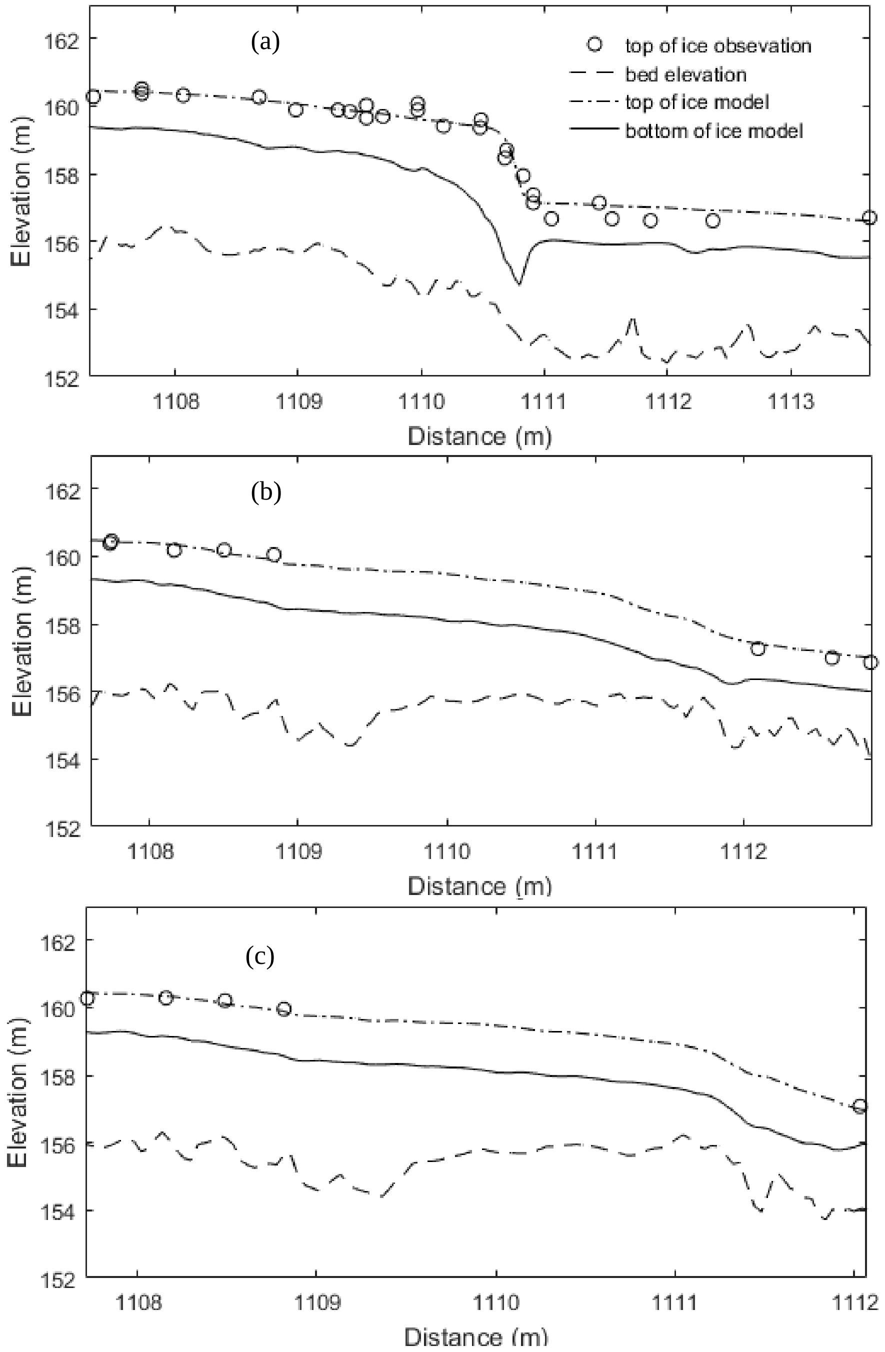

Figure 5. Ice jam profile on 3 May 2009 a) East Channel, b) Fishing Channel, c) Rudd Channel.