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Near Real-time Ice-Related Flood Hazard Assessment of the Exploits River in Newfoundland, Canada

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In Canada, river ice jams can cause more severe flooding than open-water events with the same discharge ranges. It is imperative that flood hazard and risk mapping include ice-jam flooding to provide more accurate flood assessments and provide better information for policy-makers and stakeholders making pressing decisions related to flood risk management. The specific objectives of this research are to: (i) incorporate ice-jam modelling into flood hazard assessment to provide a basis for effective near real-time flood hazard forecasting, (ii) extend current ice-jam flood frequency analysis techniques using river-ice modelling tools to develop ice-affected stage frequency curves and (iii) map flood extents of various ice jam flood water levels to assess flood hazard. It is hoped that the project will provide a novel tool incorporating ice-jam modelling into flood hazard and risk assessment and better understanding of the risk of ice-jam flooding to property and human life so as to provide early warnings of possible ice-jam flood events and develop effective flood mitigation and prevention strategies. The town of Badger on the Exploits River in Newfoundland is used as a test case. The research is being funded under the Canadian Space Agency's Earth Observation Applications Development (EOADP) program.

1. Introduction

Floods account for the greatest number of hydrological/meteorological natural disaster events in Canada (Thistlethwaite and Feltmate, 2013) and, for most Canadian rivers, the annual peak water levels are due to ice jams (EC, 2013). Current ice-jam flood warning systems require extensive field observations, and have considerable uncertainty (Beltaos & Burrell, 2015) and thus lack reliability. Nonetheless, flood forecasting and hazard mapping, dynamically in near real-time, are urgently needed by government agencies and disaster managers to help prepare for and mitigate ice-jam flood events. This research strives to develop a novel methodology to forecast ice jams and assess their subsequent flood risk to communities along northern rivers.

Near real-time flood forecasting is an important component in minimizing adverse effects to human life from flooding. Typically, flood hazard assessments and maps provide flood depths and extents in areas of flood risk and serve as valuable information for flood mitigation measures, the organization of emergency measures, and the issuance of flood warnings. The use of flood hazard mapping for flood damage reduction has a long history in Canada (e.g., Canada Flood Damage Reduction Program 1976 – 2000). Mapping and assessing hazard from ice-jam flooding have recently been attempted for the Town of Peace River, Canada (Lindenschmidt et al., 2015) and Tornio, Finland (Ahopelto et al., 2015). Assessing and mapping flood risk (= hazard × vulnerability) is in its infancy in Canada, but is an essential step in developing more cost-effective flood-mitigation strategies and in improving flood warnings and forecasts.

Forecasting the occurrence of ice jams is challenging for several reasons. The processes of ice-cover breakup and ice jamming are complex and nonlinear, and numerous morphological, meteorological, and hydrological factors interact during ice-jam formation. Some empirical and process-based attempts have been made to develop forecasting methods (White, 2003, 2008), however, these often rudimentary models perform with limited success and tend to be very site specific. Forecasting systems have also been attempted with neural network and fuzzy logic systems (Sun and Trevor, 2015). Nevertheless, the physical processes underlying the cause-effect relationships of ice-jam formation are not considered in such approaches. Additionally, these approaches focus on the temporal occurrence of ice jams with a weak connection to the spatial context. Consequently, success rates for predictions with these approaches are low. For instance, Mahabir et al. (2008) reported that only four out of seven ice jams were predicted successfully at Fort McMurray over a 25-year period. Models have been developed to predict backwater levels of ice jamming events, e.g. River2D (Brayall and Hicks, 2012) and HEC-RAS (Beltaos et al., 2012), but these systems do not predict the ice jam locations, which must be prescribed in these models to simulate backwater levels.

Considerable progress has been made in modelling ice cover and ice-jam formation dynamically, allowing varying ice volumes to simulate ice cover and jam progressions (Lindenschmidt et al., 2012b), not statically where ice volumes must be input as a fixed parameter. In this context, the RIVICE model has been tested and applied to explore ice formation processes and identify flood protection requirements at several rivers across Canada (Lindenschmidt et al., 2012a; Lindenschmidt and Chun, 2013; Beltaos and Burrell, 2015).

The characteristics of the ice cover have important implications for ice jamming and ice-jam flooding. Using RADARSAT imagery, “determination of the extent of ice covers and ice cover types and characteristics, including ice thickness is becoming increasingly possible (e.g., Lindenschmidt et al., 2011)" (quote from Beltaos & Burrell, 2015). Different ice thicknesses and types can be determined by remote sensing imagery (Unterschultz et al., 2009; Lindenschmidt et al., 2011). White (rough) ice covers will retain their strength well into the breakup period whereas black (smooth) ice covers weaken when exposed to the impinging solar radiation that causes melting along the grain boundaries (Prowse and Demuth, 1993).

Operational satellite-based river-ice classifications have traditionally focused on ice types during the breakup period, with very coarse groupings (e.g., intact ice, rubble ice, and open water) (Puestow et al., 2004; Khan and Puestow, 2010; Khan and Puestow, 2015; van der Sanden and Deschamps, 2014; Deschamps et al., 2015). Recently, these capabilities have been extended to include ice type classification throughout the entire ice-cover period, from freeze-up into breakup (Chu et al., 2015). In a more recent study of the Slave River, Chu et al., (submitted) developed an automated approach to detect ice-cover behaviour using Moderate Resolution Imaging Spectroradiometer (MODIS) imagery. All of the information can be incorporated in the ice-jam forecasting model to identify the potential areas of initial or persistent ice cover during the breakup that define the risk areas of ice jam occurrences. Additional considerations for breakup predictability are the water level at freeze-up and the magnitude of freshet discharges (Beltaos, 2014).

Due to the stochastic nature of ice jams, it is advised to pursue a stochastic modelling approach to forecast ice jam flood events (Lindenschmidt et al., 2015, 2016). In this case, a Monte-Carlo framework is used to provide an ensemble of predicted flood water profiles and a probability of exceeding certain critical flood water levels. This is generated using a deterministic river ice hydraulic model that is run hundreds of times, with each run being defined using different parameters values that are randomly selected from a distribution range. Such parameters include river flow, incoming ice volume, and downstream water levels. The ranges of these parameters are continuously adjusted, as new remote sensing data is acquired to adjust the probability of flood water level exceedances.

The stochastic modelling proposed by Lindenschmidt et al. (2015, 2016) has only been carried out for a static case, with parameter distributions stemming from historical data. Accordingly, it is the objective of this investigation to pursue a dynamic stochastic modelling method in which parameter distributions are continuously updated as new information from field and satellite observations is acquired. In order to ensure applicability to the Canadian context, the capabilities will be demonstrated here for the Exploits River in Newfoundland.

Approach

Remotely-sensed ice conditions as well as in-situ observations (e.g., hydro-meteorological observations) are assimilated into the RIVICE modelling framework. Using the assimilated information as drivers, stochastic modelling is carried out to simulate ice-related flooding. Flood hazard maps indicating areas potentially vulnerable to flooding will be generated in near real-time based on updated satellite observations. Finally, the flood hazard information will be integrated into the Multi-Agency Situational Awareness System (MASAS) for dissemination to end user communities (CSSP, 2013). A graphical representation of the approach is presented in Figure 1.

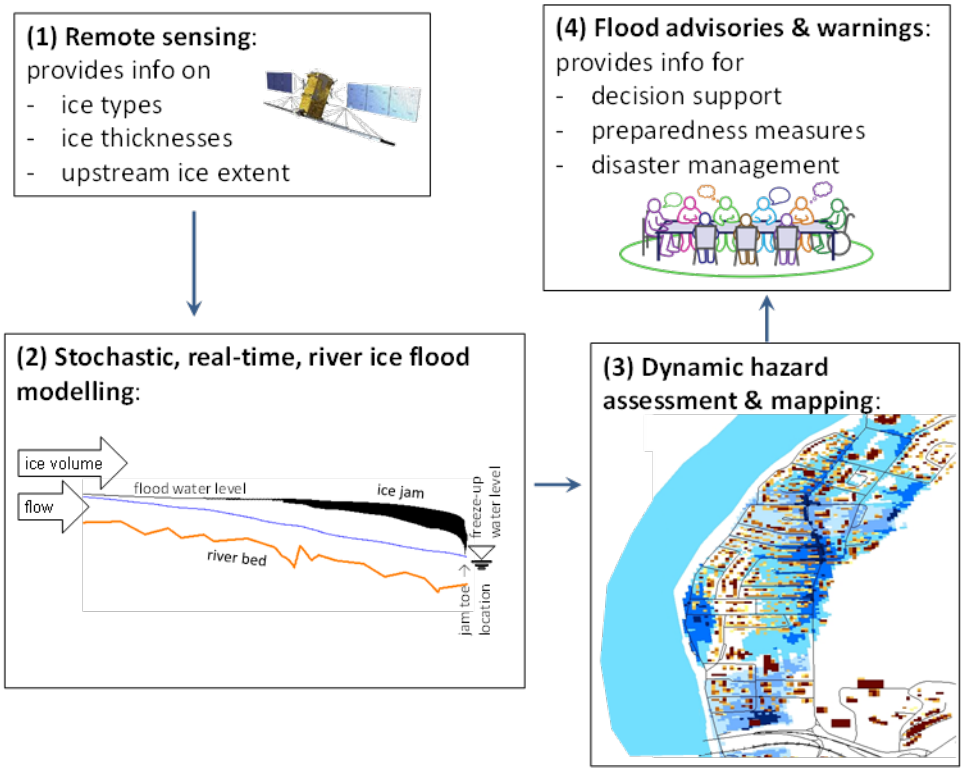

Figure 1. Overview of technical approach.

The model RIVICE was implemented to simulate ice jams dynamically. RIVICE, developed by Environment Canada, is a one-dimensional hydrodynamic model which uses an implicit finite-difference scheme to simulate major ice phenomena and processes along rivers, including ice cover formation and ablation, frazil ice generation, border ice advancement, anchor ice, ice transport, hanging dams, breakup and ice jams (Lindenschmidt et al., 2012a; 2012b, 2015, 2016; Lindenschmidt and Chun, 2013; Lindenschmidt and Sereda, 2014). An in-depth description of RIVICE can be found in Lindenschmidt (2017).

Preliminary Results

The RIVICE model was set-up for the Exploits River using cross-sections from a previous HEC-2 model. The open-water calibration for the Exploits River was successfully carried out and initial ice-jam simulations with backwater staging at Badger, Newfoundland and Labrador (NL), was successfully demonstrated. Additional data for continued ice-jam flood modelling at Badger was acquired. Both Aster and Shuttle Radar Topography Mission (SRTM) DEMs were acquired with some processing for the Exploits River region and Geographical Information System (GIS) data of the Exploits River was prepared for flood-plain delineation. A revised stage of was established for the stage-frequency curve of the Exploits River at Badger (Water Survey of Canada hydrometric station 02YO013).

Figure 2 shows the simulated ice profile of an extreme ice-jam event that occurred along the Exploits River at Badger in 2003. There is good agreement between the modelled water levels and those recorded at the Badger gauging station. The pink crosses in the figure designate the instantaneous maximum and daily mean of the water level elevations recorded at the Badger gauge.

The black infill represents the ice, the blue line indicates the open-water level profile for the same discharge, and the orange line is the thalweg. The model is deemed calibrated due to the good agreement between simulated and observed values.

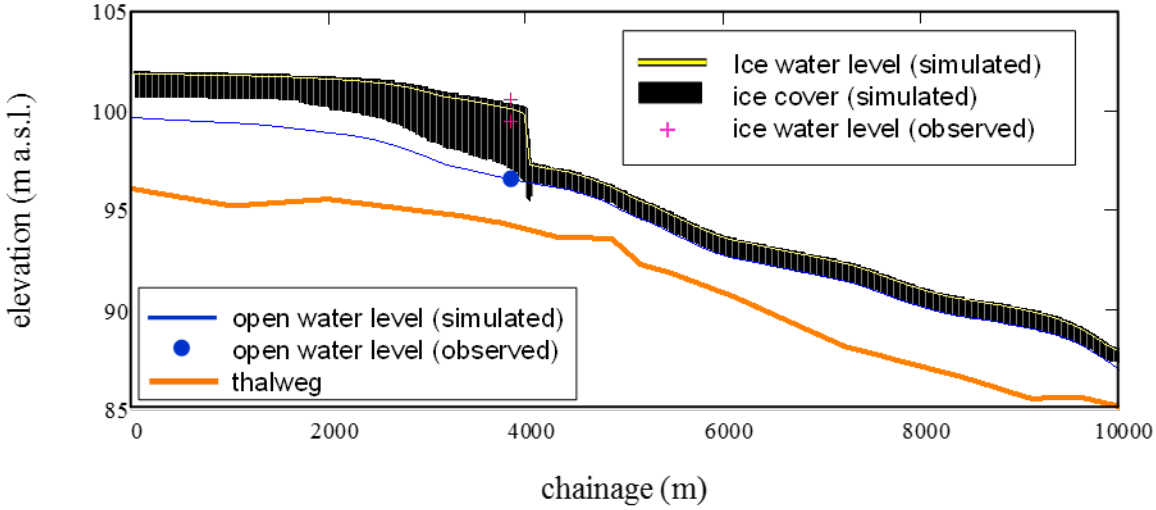

Figure 2. RIVICE simulation of the 2003 ice jam, which caused severe flooding at Badger along the Exploits River.

Monte-Carlo simulations were carried out with the calibrated model to yield an ensemble of backwater profiles, as shown in Figure 3. The water level elevations at the gauge location were compiled to construct a stage-frequency distribution that was compared to the stage-frequency distribution of observed extreme values, as shown in Figure 4. Agreement was obtained using an exponential distribution of the incoming ice volume.

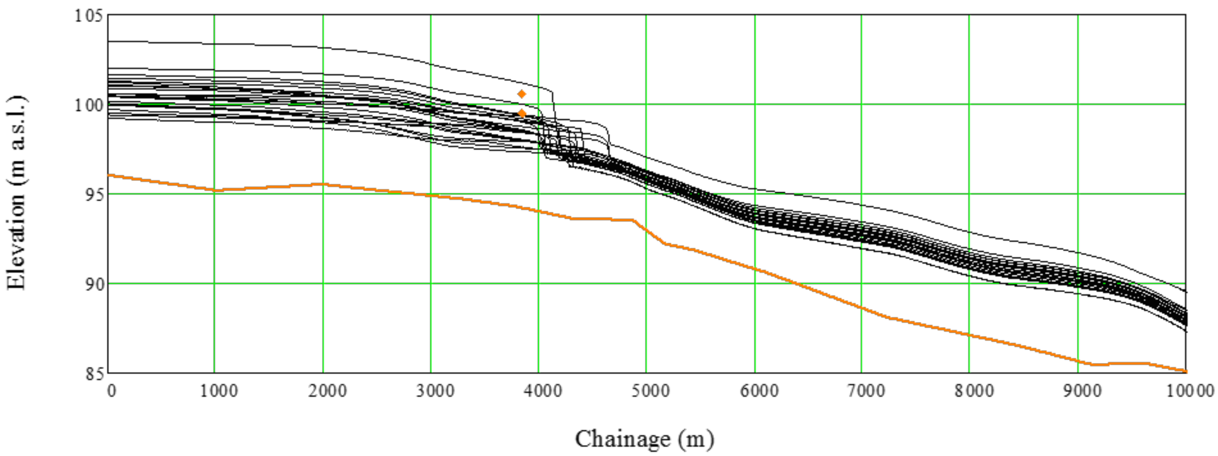

Figure 3. Ensemble of backwater level profiles from a Monte-Carlo simulation.

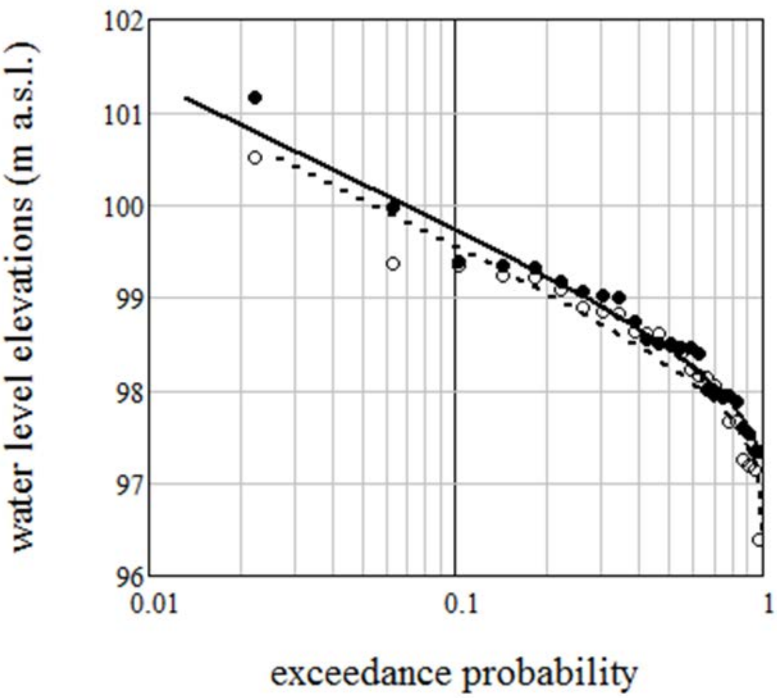

Figure 4. Good agreement between observed (dashed line, open circles) and simulated (continuous line, filled circles) stage-frequency distributions from water level elevations at the Badger gauge.

Conclusion and Future Work

The RIVICE model and Monte-Carlo stochastic simulation framework were successfully set up and validated for the Exploits River. The modelling framework is now ready for use within the context of near real-time parameterization and flood hazard mapping during subsequent project stages. To this end, the following tasks are required:

- Integration of near real-time (NRT) data streams (i.e. in-situ and satellite-derived observations) into the RIVICE Monte-Carlo modelling framework,
- Generation of NRT flood hazard maps based on updated information from dynamic data streams,
- Demonstration of new capabilities during 2017/18 ice season and implement protocol to make flood hazard maps available within Canada's Multi-Agency Situational Awareness System (MASAS) to reach as broad a user community as possible,
- Evaluation of the performance of project outcomes and develop a roadmap for the broader application of the approach across Canada.

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