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Ice jam flood hazard assessment and mapping of the Peace River at the Town of Peace River

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Efforts are underway in Canada to develop, update and extend flood risk assessments and mapping for river sections prone to flooding. However, most of these previous works are limited to the open-water case. Very little has been done to include flooding related to the formation and breakup of ice cover on rivers, which can lead to ice jamming and subsequent flooding. River ice jams can cause high water levels that lead to severe flood events which can cause infrastructure damages, loss of human lives and adverse impacts on aquatic ecosystems. Therefore, extending flood risk mapping to include ice jam flooding would provide more accurate flood risk assessments for policy-makers and stakeholders to make pressing flood risk management decisions. The specific objectives of this research are (i) to use river ice modelling tools for ice-jam flood frequency analysis and (ii) to map flood extents of various ice jam flood water levels to assess the flood hazard. For developing effective flood mitigation and prevention strategies, this project will provide a novel approach incorporating ice jam modelling into flood hazard and risk assessment for a better understanding of the ice jam flooding risk to property and human life. The Peace River at the Town of Peace River is presented as a test case.

1. Introduction

Flood risk is an assemblage of both hazard and vulnerability. The probability of occurrence (return period) together with the intensity of an ice jam flood (flood water depth and extent) establishes the hazard induced by the flood event. Using land-use information and damage costs as functions of flood water depth, the vulnerability of certain land-use types (e.g. residences, industry and agricultural lands) that would be exposed to the flood and their susceptibility to damage by the flooding can be assessed. Both hazard and vulnerability are combined to calculate the flood risk, which represents the long-term annual expected damages. This study will focus on only flood hazard mapping and assessment; flood vulnerabilities and risk will be addressed in subsequent publications. The Peace River at the Town of Peace River (TPR) was chosen as the test site because of the river's high potential for flood risk along this section of the river. High flood stages from ice jams with subsequent flooding have occurred in the recent past, in particular the ice jams in the years 1979, 1982, 1992 and 1997.

An important first step in this methodology of flood hazard assessment is the establishment of stage-frequency curves in which river water levels or elevations are plotted against probability of occurrence. Although relatively straight forward for open water conditions, considerable effort is required to establish ice-affected stage frequency curves. Some methods have been outlined in Beltaos (2011) and White (2009). Historical data of discharges and ice-induced water levels are available at this site and some of the most extreme ice jam events are well documented, in particular the ice jams of 1979 (NSERC, 1990), 1982 (NSERC 1990; Andres, 1995) and 1992 (Fonstad, 1992; Andres, 1996).

A novelty of this work is using ice-affected stage frequency curves to calibrate a numerical hydraulic model. The hydraulic river ice model used in this study is RIVICE, a one-dimensional hydrodynamic computer model developed by Environment Canada. An important variable to simulate ice jams in RIVICE is the inflowing ice volume. Such information is sparse or unavailable and is difficult to estimate since the extent and thickness of the upstream ice cover, which is the source of the inflowing ice volume creating the jam, is not known. However, within the framework of a Monte Carlo analysis, the distribution of values for this variable could be calibrated against the observed stage frequency curve to develop a histogram of potential inflowing ice volumes.

The specific objectives of this research are to:

- incorporating river ice modelling tools to extend current ice-jam flood frequency analysis techniques
- map flood extents of various ice jam flood water levels to assess the flood hazard.

This is a collaborative research project between the Global Institute for Water Security at the University of Saskatchewan, and an industrial partner, Stantec, an architecture and engineering company that provides technical support to government agencies, property developers, insurance companies and communities regarding natural and manmade hazards and disasters. Both partners have expertise in river hydraulic and ice modelling and flood risk assessment and it is hoped that this research will (i) provide a novel approach to the scientific and consulting communities in which river ice jam modelling is incorporated in the flood hazard and risk assessment process and (ii) extend understanding on the risk of ice jam flooding to property and human life to develop effective flood mitigation and prevention strategies.

This project began in May 2015 and at the time of this writing had been underway for 2.5 months. Hence, this paper presents preliminary findings which may require refining and extension to address all aspects of flood risk mapping and assessment in subsequent research and publications. Additionally, the operation of regulated discharges during and after freeze-up were adjusted after the 1982 and again after the 1992 event making these two events less likely under the current operating regime and may make the analysis in this paper more conservative.

2. Study site

The study site (Figure 1) focuses on a 46 km stretch along the Peace River at the TPR, between Shaftesbury Ferry and Hwy 986 Bridge. The Peace River originates in northern British Columbia and flows 1923 km to its confluence with Slave River in northern Alberta. The gross drainage area and the mean annual discharge at the Water Survey of Canada (WSC) gauge at the TPR (number = 07HA001, name = Peace River at Peace River) are 194,374.2 km^2 and 1,905 m^3/s, repsectively. The river has been regulated since 1973 after the construction of the W.A.C. Bennett Dam, which formed Williston Lake in the river's headwaters. The TPR is approximately 400 km downstream of the dam. The widths of the river in this location vary between 500 and 2500 m and the channels geomorphology is characterised by intermittent islands and bars.

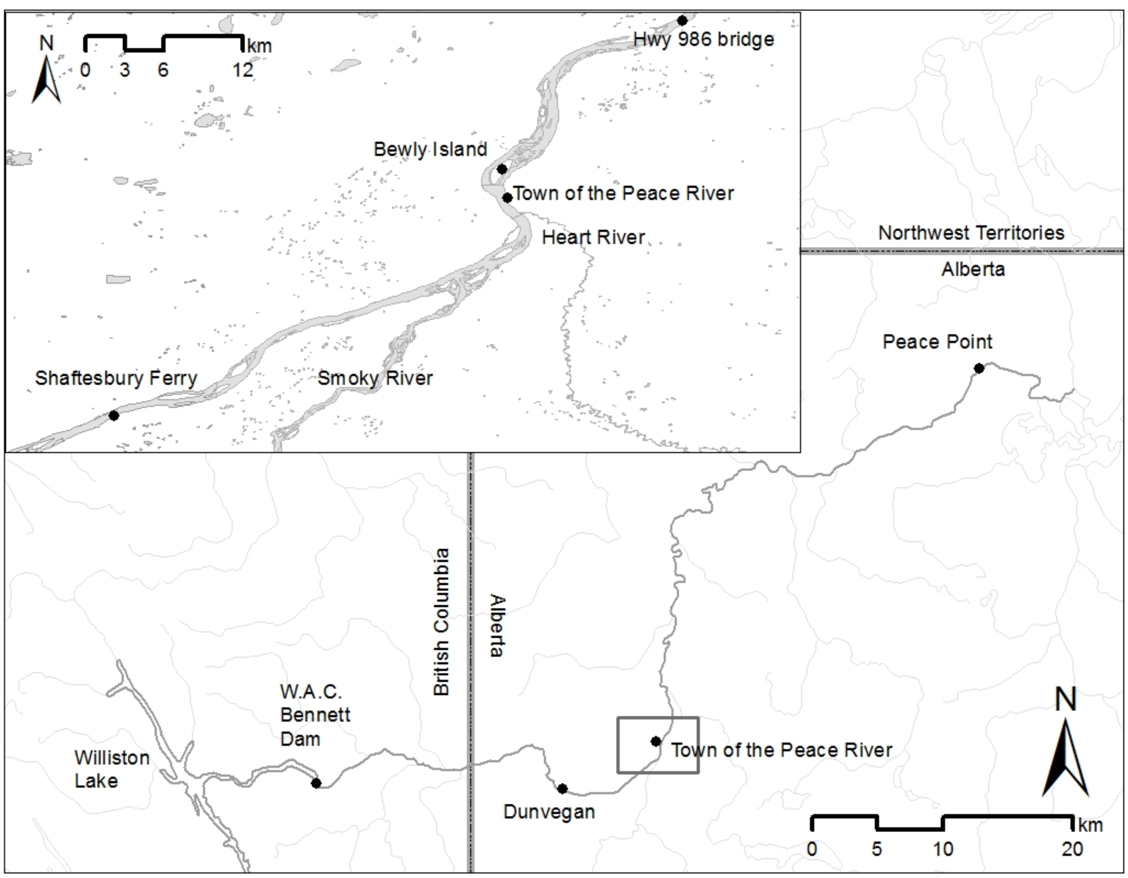

Figure 1: Study site along the Peace River.

3. Flood frequency analysis

Stage frequency curves are based on data recorded at the TPR gauge for the post-dam construction period 1972 – 2010. An Extreme Value Gumbel I distribution was used to determine cumulative distribution functions to flood discharge and water level data (Thompson, 1999, p. 248):

$$F(x) = P(X \leq x) = e^{-e^{-[(u+x)/\alpha]}} \qquad [1]$$

with location *u*:

$$u = 0.5772\alpha - \mu \qquad [2]$$

and scale α:

$$\alpha = \frac{\sqrt{6}}{\pi}\sigma \qquad [3]$$

where μ is the mean and σ is the standard deviation. Gringorton's formula was used to determine plotting positions (Thompson, 1999, p. 243):

$$P(X \geq x) = \frac{m-0.44}{n+0.12} \qquad [4]$$

where *m* is the rank order (1, 2, … *n*) of a descending series of a total number of *n* extreme values. The quantile function (inverse cumulative distribution function) *Q(p)* was used:

$$Q(p) = \mu - \sigma ln\big(-ln(p)\big) \qquad [5]$$

to randomly generate values of a Gumbel distribution from a uniform distribution *p* (range 0 - 1). Due to its simplicity, the Gumbel distribution is well suited for random generation of values required for repetitive model simulations within a Monte Carlo analysis framework (Section 5).

To construct the frequency curves, the highest daily stages and discharges during river ice-cover breakup and the open-water spring/summer period were selected for each studied year. Along the Peace River, open water events have higher stages in June or July whereas breakup usually occurs in April or May. The gauge at the TPR records water levels at a frequency of 15 minute intervals. For ice jams, both the day-averaged maximum water level (largest daily value calculated from the average of all recordings over a day) and the instantaneous maximum water level (single highest 15-minute water level recording during the year) from the ice-covered periods were used. A Gumbel distribution was fit to Gingorton plotting positions for all series, shown in the Figure 2. The results show that ice jam induced stages are higher compared to open water and breakup events. The open water distribution is higher than the distribution for breakup events. There is also a significant difference between the ice jam maximum day-averaged stages and ice jam instantaneous maximum stages. For an event with a 100-year return period (*p* = 0.01), breakup, open water, ice jam maximum day-averaged and ice jam instantaneous maximum stages are approximately 316, 317, 318.6 and 320.8 m a.s.l., respectively.

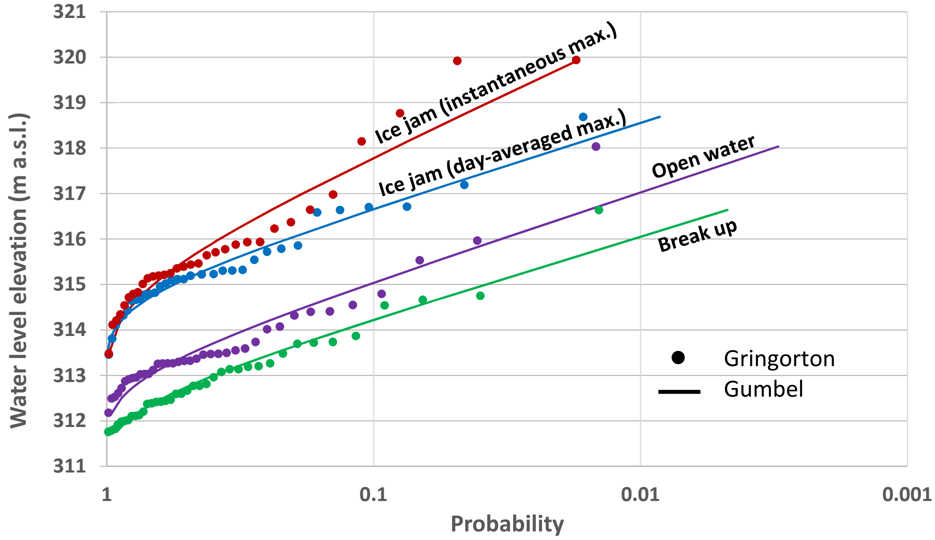

Figure 2: Stage frequency curves for the gauge on the Peace River at the Town of Peace River for the post-construction of the dam (1972 – 2010).

The open-water rating curve was also developed using data from the TPR gauge for the same time period (Figure 3). The maximum day-averaged water levels and their associated discharges were used for open water and ice jam events. Instantaneous maximum stage values were also considered for ice jam events. The graph shows that the most extreme flooding occurred from ice jamming. Although the discharges during ice-jam events are lower than for open-water conditions, ice jams induce higher staging. As expected, instantaneous maximum water level recordings are higher than maximum day-averaged values, however this gap widens with increased severity of events.

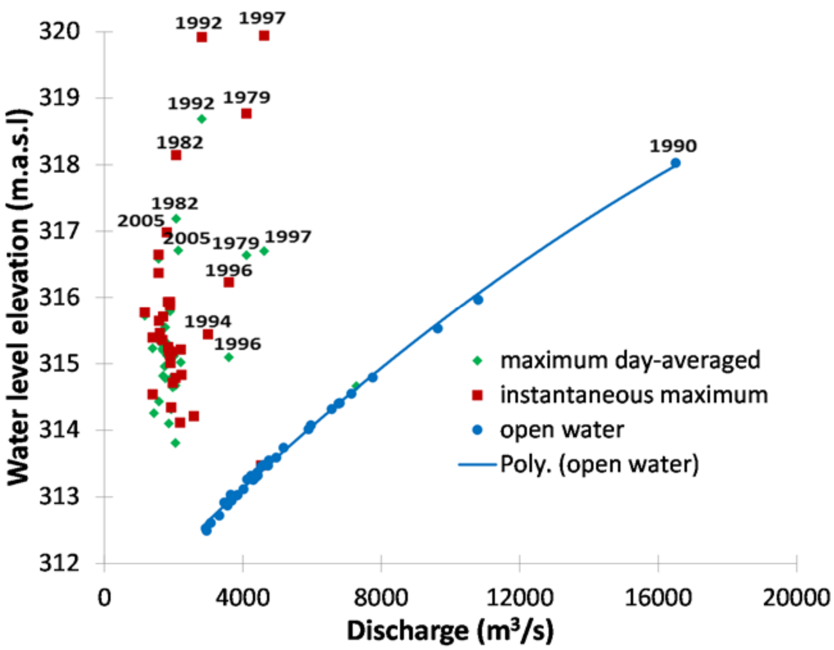

Figure 3. Rating curves for the gauge on the Peace River at the Town of Peace for the post-construction period of dam operations (1972 – 2010)

4. River ice model calibration

The model RIVICE was used to simulate ice jams dynamically along the Peace River (unlike HEC-RAS, which simulates jams in steady-state). 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. Details on the model structure and setup can be found in the literature for a number of different rivers: Dauphin River in Manitoba (Lindenschmidt et al., 2012a), Red River in Manitoba (Lindenschmidt et al., 2012) and Qu'Appelle River in Saskatchewan (Lindenschmidt, 2014; Lindenschmidt and Sereda, 2014). Examples of parameters used to calibrate the model include ice deposition and erosion velocity thresholds, ice cover and ice pan porosities, Manning's roughness coefficinets of the river bed and ice-cover underside and parameters that describe the distribution of forces through the ice cover. Ranges of parameter values for different fluvial geomorphological settings can be found in Lindenschmidt and Chun (2013).

The modelling domain extends approximately 46.45 km along the Peace River from Shaftesbury Ferry to Hwy 986 Bridge. Twenty eight cross-sections of a HEC-RAS model were used to interpolate 930 equidistant (50 m intervals) cross-sections for RIVICE. The model domain was divided into two reachs: Reach 1 is the upstream part of the study area, upstream of the Smoky River confluence, extending from km 0 to km 15.3 and Reach 2 is the downstream stretch extending from km 15.3 to km 46.45. The Manning's roughness coefficients for the upper and lower reaches were calibrated to be 0.028 and 0.035, respectively. RIVICE is a one-dimensional model with no allowance for split flow around islands. Only three cross-sections from the HEC-RAS model, adapte for the RIVICE model setup, represented an island, those of Bewley Island. Although a larger cross-section with the same cross-sectional flow area was used in RIVICE, as the two flow areas on other side of the island in the HEC-RAS cross-sections, the additonal wetting perimeter from the island banks providing higher flow resistance is missing in RIVICE. Hence, higher Manning's roughness coefficients are required compared to the HEC-RAS model (n = 0.025) to compensate for the loss in flow resistance. Smaller and fewer islands are found along the upper reach reflected in the lower value for the Manning's roughness coefficient.

The model was first calibrated for the 1990 open-water flood event using the observed data from mid-June 1990. The discharge of 12700 m^3/s at the gauging station was used with the incoming flow divided 55:45 between the upper Peace (Reach 1) and Smokey rivers, respectively. The water level for the downstream boundary condtion was estimated to be 313.53 m a.s.l. An observed water level profile was available to help with model calibration. Figure 4 indicates good agreement between simulated results and the surveyed water level profile. The simulation overestimates the water level at the gauging station due to a recognised bias in the rating curve. "A geomorphic anomaly exists in the river channel between the mouth of the Heart River and the head of Bewly Island. The channel here is about twice as deep as that upstream with a similar flow area at any given discharge. The WSC gauge is situated at the downstream end of this anomaly and most of the open water and ice covered discharge measurements and ice thickness measurements have been made in its deepest part. This has biased somewhat the at-a-section hydraulic characteristics gathered for the river at this gauge and they are not entirely representative of the reach of interest" (Andres, 1995, p. 293).

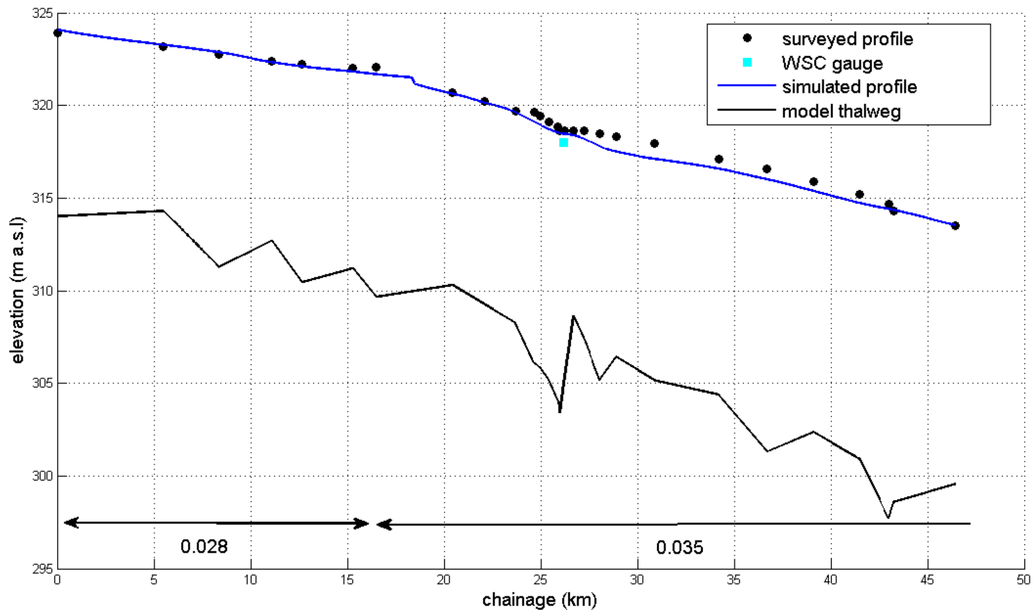

Figure 4. Open-water calibration: longitudinal profiles of the simulated and observed water levels along the Peace River from Shaftesbury Ferry to Hwy 986 Bridge during the 1990 open-water flood, with a discharge of 12,700 m^3/s.

The ice cover formation on the Peace River was simulated for the freeze-up scenario during early January of 1982, when the TPR experienced a high water level event during the formation of stable ice cover along the Peace River (Beltaos, 1995; NSERC, 1990). The initial ice cover formed at Peace River on 2 January 1982 and rapidly advanced to Dunvegan by 6 January 1982 when the discharge from the W.A.C. Bennett Dam reduced from 1700 m^3/s to 1000 m^3/s. The ice cover increased the water stage at the Peace River gauge from 312 m to 314.8 m. The discharge from the dam was then increased to 1750 m^3/s which caused the ice cover to breakup and jam about 20 km donwstream of Dunvegan. The stored water from the jam increased the discharge to approximately 2500 m^3/s when the jam released resulting a peak water level elevation of 318.15 m a.s.l. at the gauge, 3.4 m higher than of elevation of the initial ice cover. The freeze-up event was first modelled to determine an average ice thickness along the model domain. The ice-jam event was then modelled using an upstream boundary discharge of 2500 m^3/s (flow from the Smoky River was minimal) and a downstream water level elevation of 309 m a.s.l. An estimate of the volume of inflowing ice = length of the ice cover from upstream of Dunvegan to the TPR × average width of the same river stretch × average ice thickness determined from the freeze-up simulation.

The longitudinal profile of the ice-covered water levels are shown in Figure 5. There is good agreement between simulation results and the maximum instantaneous water level recorded at the WSC gauge station. The open water simulation for the same flow of 2500 m^3/s was also plotted for comparison to give an indication of the amount of water level increase due to the ice jam. The simulated ice-cover thicknesses varied between 1 and 3 m along the modelling domain.

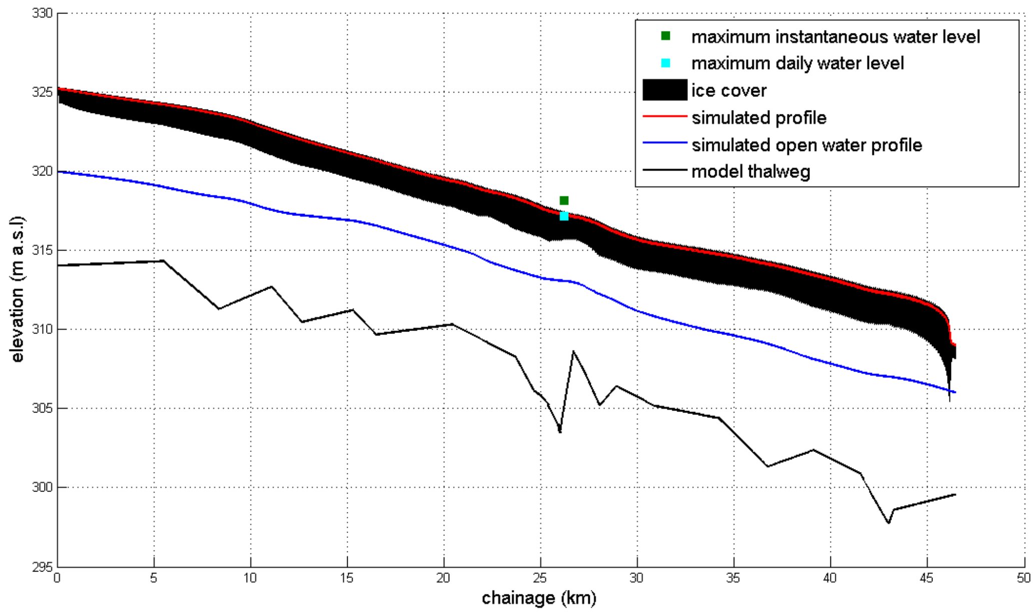

Figure 5. Ice cover calibration: longitudinal profiles of simulated and recorded water levels and ice cover along the Peace River from Shaftesbury Ferry to Hwy 986 Bridge at the beginning of January 1982, with a discharge was 2500 m^3/s.

5. Inflowing ice volume distribution

Four variables that significantly impact the formation and morphology of ice jams along the Peace River at the TPR are (i) river discharge, (ii) initial water level at the most downstream cross-section, (iii) location of the toe of the ice jam and (iv) inflowing ice volume. Data is available for the first three variables. River discharges were extracted from Environment Canada's database HYDAT to which a Gumbel distribution was fit. The water levels at the downstream boundary were determined by proportionately reducing the freeze-up water level recorded at the TPR's gauge (from Figure 5 in Jasek, 2012) by the river's slope of 0.0003 (from Figure 3 in Jasek and Pryse-Phillips, in press) along that reach. Both uniform and Gumbel distributions of the initial water levels produced similar results. The toe of the ice jam was assumed to be located downstream of the TPR along a 10 km stretch between Bewley Island and Hwy 986 Bridge. A uniform distribution of the toe location was assumed.

Data for the fourth variable, inflowing ice volume, are not available and were calibrated against the ice jam stage frequency curve (Figure 2) within the framework of a Monte Carlo analysis. A Gumbel distribution of ice volumes was generated via its mean and standard deviation, using Equations 1 to 3, and adjusted (Figure 6) until the resulting simulated ice jam stage frequency matched well with the stage frequency curve of the recorded water levels of the observed ice jams (Figure 7). The ensemble of ice jam water level profiles, from which the stages were extracted to construct the stage frequency curve, are shown in Figure 8.

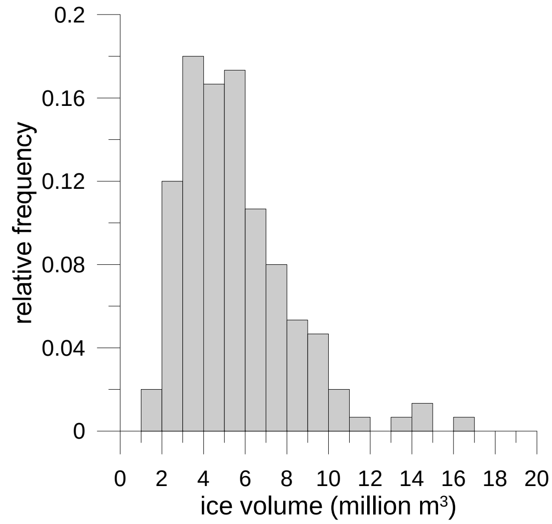

Figure 6: Histogram of inflowing ice volumes used to simulate an ensemble of ice jams within a Monte Carlo analysis framework.

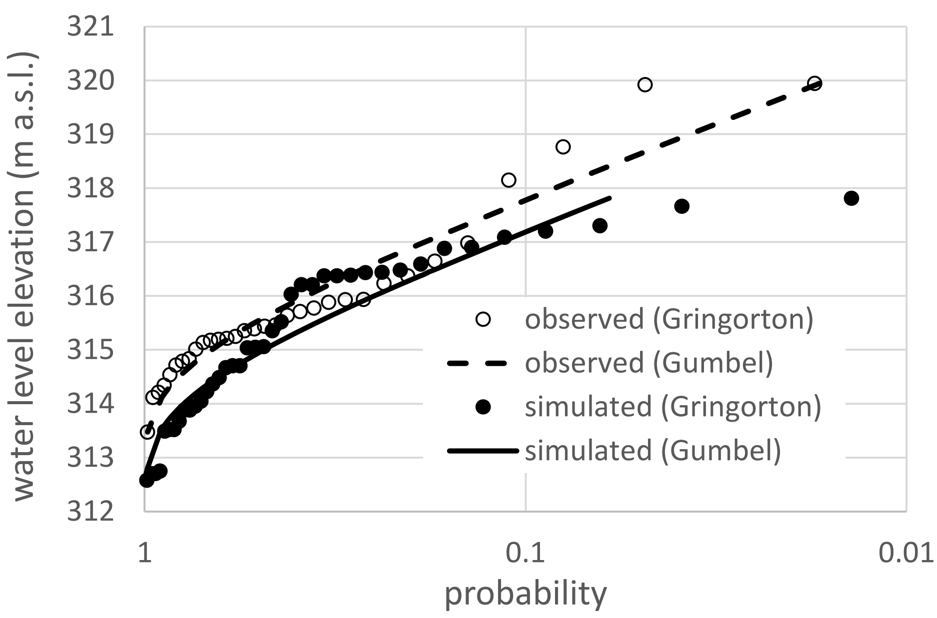

Figure 7: Simulated and observed ice jam stage frequency distributions (Gumbel) with plotting positions (Gringorton) at the gauge at the Town of Peace River.

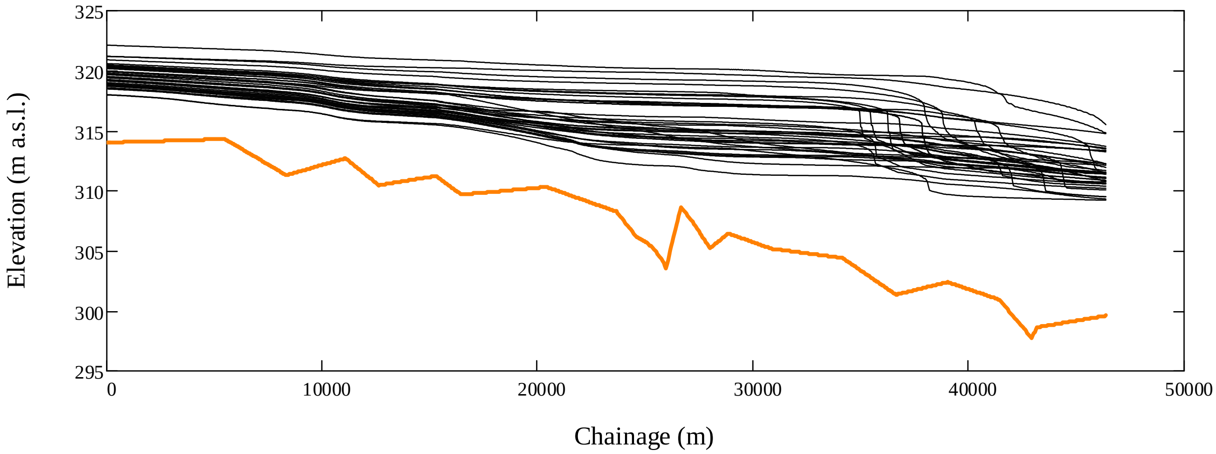

Figure 8: Ensemble of water level profiles of ice jams simulated along the Peace River at the Town of Peace River.

Figure 9 shows how the location and scale parameters (Equations 2 and 3) of the ice volume Gumbel distribution affects the annual maximum river water level simulations. The dark blue diamonds are the historical annual maximum water levels, the dark solid lines are the Gumbel fit whereas the dotted lines are the 99% confidence bounds which show that higher water level values are more uncertain because of less data to support the estimations (c.f. Chun and Wheater, 2013). Before running the Monte Carlo analysis, we identified the possible location and scale parameter ranges by trial and error. When the location and scale parameters of the ice volume distribution are respectively 10.4 and 2.6 million m^3, the simulated maximum water levels are too high (red line); when the location and scale parameters of the ice volume distribution are respectively 2.6 and 1.3 million m^3, the simulated maximum water levels are too low (green line). Location and scale parameter values of 4.5 and 1.9 million m^3 yielded simulated maximum water levels (thick purple line) whose fit coincided with the observed water level plotting positions (black dots). To further explore the uncertainty of the ice volume distribution on the maximum water level simulations, we used a multiple normal distribution with a mean vector of location and scale parameters equal to:

$$\begin{bmatrix} \mu \\ a \end{bmatrix} = \begin{bmatrix} 4.5 \times 10^6 \\ 1.9 \times 10^6 \end{bmatrix} \quad [6]$$

and a variance matrix:

$$\begin{bmatrix} \sigma_\mu^2 & \sigma_{\mu\alpha} \\ \sigma_{\mu\alpha} & \sigma_\alpha^2 \end{bmatrix} = \begin{bmatrix} 150 \times 10^6 & 0 \\ 0 & 150 \times 10^6 \end{bmatrix} \quad [7]$$

to simulate 30 location and scale parameter sets. The 30 water level simulation results are drawn as thin purple lines. The fairly consistent spread of the 30 sets simulated maximum water levels (thin purple lines) and observed water level plotting positions further show that the identified ice volume location and scale parameters of the Gumbel distribution are realistic. A discussion of its distribution to the Generalized Extreme Value (GEV) distribution is provided in the Appendix.

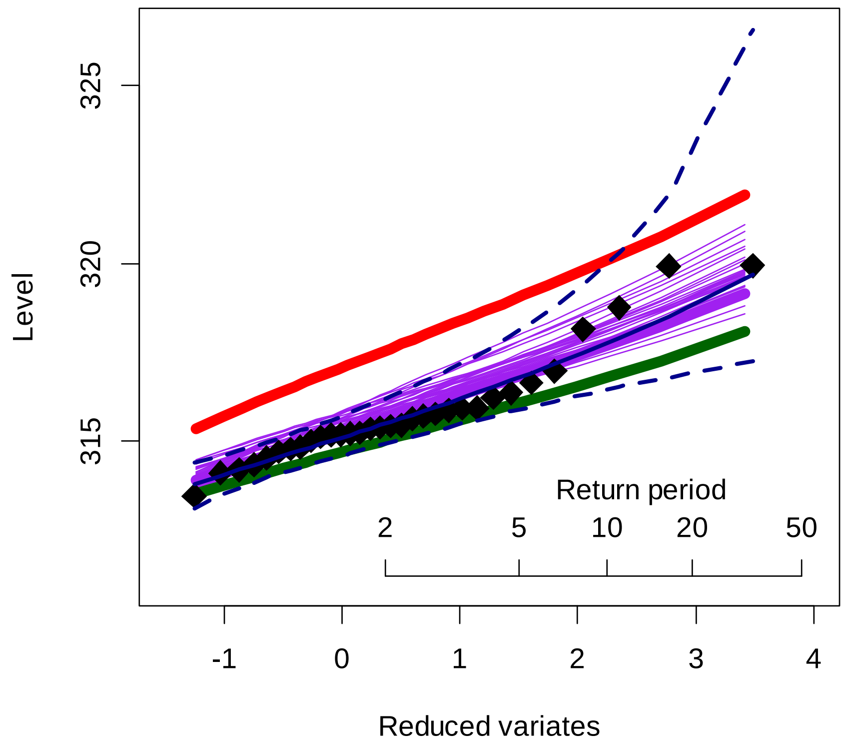

Figure 9. The extreme value plot of the annual maximum water levels and their return periods at the WSC gauge at the Town of Peace River. The black diamonds are the observed water levels. The dark blue solid and dashed lines are the Gumbel distribution fit and its 99% confidence bounds for the observations. The red, purple and green lines are trial-and-error simulations yielding respectively too high, good agreement and too low results.

6. Flood hazard mapping

Flood hazard is usually defined by the extent and category of flood depth. Flood vulnerability refers to the ability of society, environment and economy to resist the hazard event as well as to return to the original state following the flood hazard event. As an important prerequisite for developing the mitigation of damages in the future events, mapping flood risk identifies potential areas of hazard in addition to the physical vulnerability of the land use (or land cover) areas to that hazard value. In this study, we focused on mapping the hazard of breakup ice jam, one of important indicators of flood risk assessment, occurred at the TPR in 1982, 1997 and the flood hazard of 1:100 year ice-jam event.

The profile of water surface elevation in the 1982 ice-jam event derived from the modelling of river ice (Section 4) were used to delineate flooding extent on the flood plain and then identify the flood depth. The flood depth in this study was defined as the difference between water surface elevation and the terrain elevation. First, the cross-sections along the river chainage at the TPR were extracted, using the width of 5 km that covered all possible floodplains in the area. The water surface level was then assigned to each cross-section to derive triangular irregular networks (TIN) model, representing the surface morphology of the flood-water surface. This TIN model of water surface was finally interpolated to a raster that contains the value of water surface elevation at a specific location (i.e. cell size). For the delineation of the flood extent and depth, the water elevation model of the ice jam event was subtracted from the digital elevation model (DEM) in the study area. The positive cell values in this surface difference represent the flood extent and flood depth. The LiDAR15 that features 30 cm vertical, 50 cm horizontal accuracy and processed into 15 m post spacing was used for the DEM. The water surface raster model was also interpolated using the cell size of 15 m. The influence of existing river dykes on the flood extent in the hinterland was taken into account by comparing the dykes' crest elevation with the water level during the ice-jam event. In this context, only the areas with water levels overtopping the dyke crests were considered as the flood extent in the hinterlands. The dyke elevation before the upgraded 1999 dykes (Peace River Dykes project, 1999) was used in the analysis of the 1982 ice-jam flood. All processing steps were conducted using ArcGIS 10.2 software by ESRI (http://www.esri.com/). The result of flood hazard mapping in the 1982 ice-jam event is shown in Figure 10. The 1982 ice-related water levels were 2.3 to 3.4 m below the top of the dykes, hence resulting in no overland flooding at the TPR.

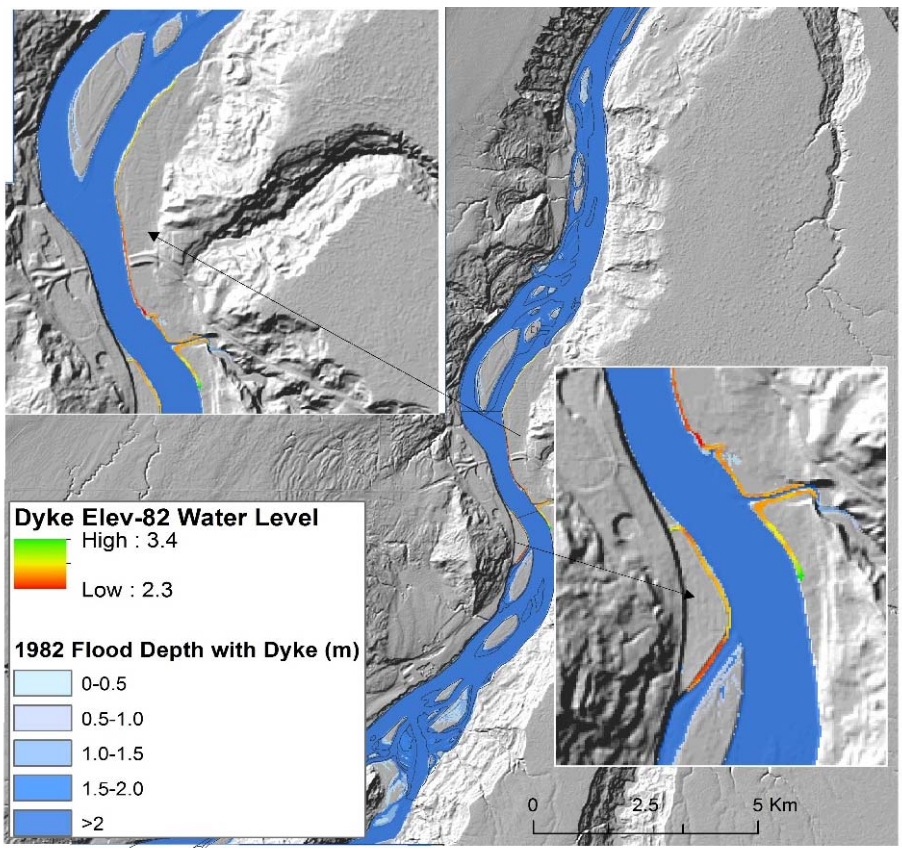

Figure 10. The flood extent and flood depth in the 1982 ice jam event. The dyke elevation before the upgraded 1999 dykes was extracted from the project document of the Peace River Dykes in 1999 to estimate the surface difference with the water level during the flood.

Similar processing steps as the mapping of the 1982 flood hazard was applied to derive the 1:100 year flood hazard map, and the result is shown in Figure 11. Compared with the 1982 flood hazard, the 100 year ice-jam flood can cause some flooding in the TPR, particularly along the east bank in the north part of the town, even with the upgraded dyke elevations of 1999. The water level of the simulated scenario can potentially overtop the existing dyke elevation by up to 40 cm. The water profiles may change, however, depending on the conditions leading to the formation and morphology of the ice jam, in particular the magnitude of the inflow, the volume of inflowing ice, the location of the ice jam toe and the initial downstream water level when jamming occurs (as discussed in Section 5). Work is planned to simulate, within the context of a Monte Carlo analysis, an ensemble of water level profiles from different ice jam configurations producing similar water levels at the gauge.

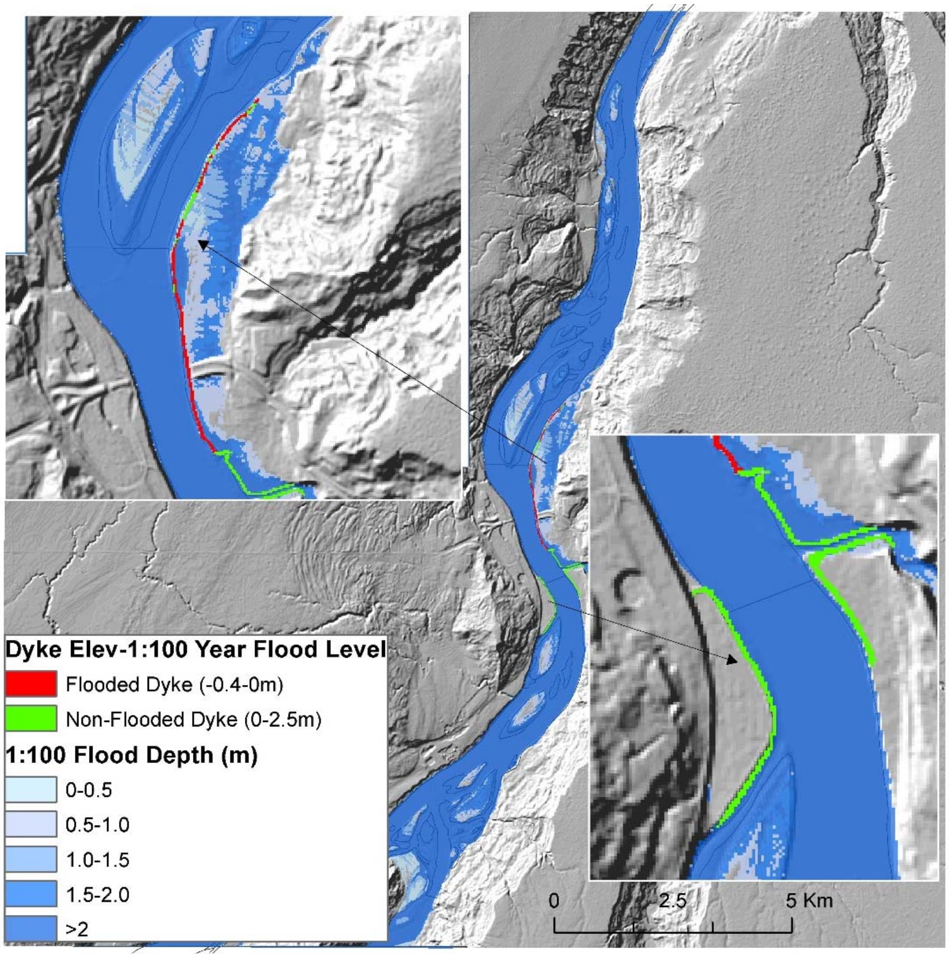

Figure 11. The simulation of flood inundation and depth for the 1:100 year ice-jam flood in the Town of Peace River. The dyke elevations from the last upgrade in 1999 were used to estimate the difference between the dyke crest elevation surface and the 1:100 year flood water surface.

7. Conclusions

Stage frequency curves were established for the open water, ice-cover breakup and ice jam events. Instantaneous maximum water levels from ice jams induce the most severe flood events with a 1:100 year ice jam stage of 320.8 m a.s.l. at the gauge location in the TPR. This curve was also used to calibrate a river ice model to determine a histogram of potential inflowing ice volumes required to generate such ice jams. Flood mapping shows that some areas along the banks of the town are potentially at risk for the 1:100 ice-jam flood event. This may have important implication for future developments in the town as well as the operation of the regulated discharges from the upstream dam. However, to accurately estimate costs and effects of such extreme events, an assessment of ice jam related flood vulnerability and risk is imperative in providing guidance in flood mitigation, which is the next phase of this project.

Acknowledgments

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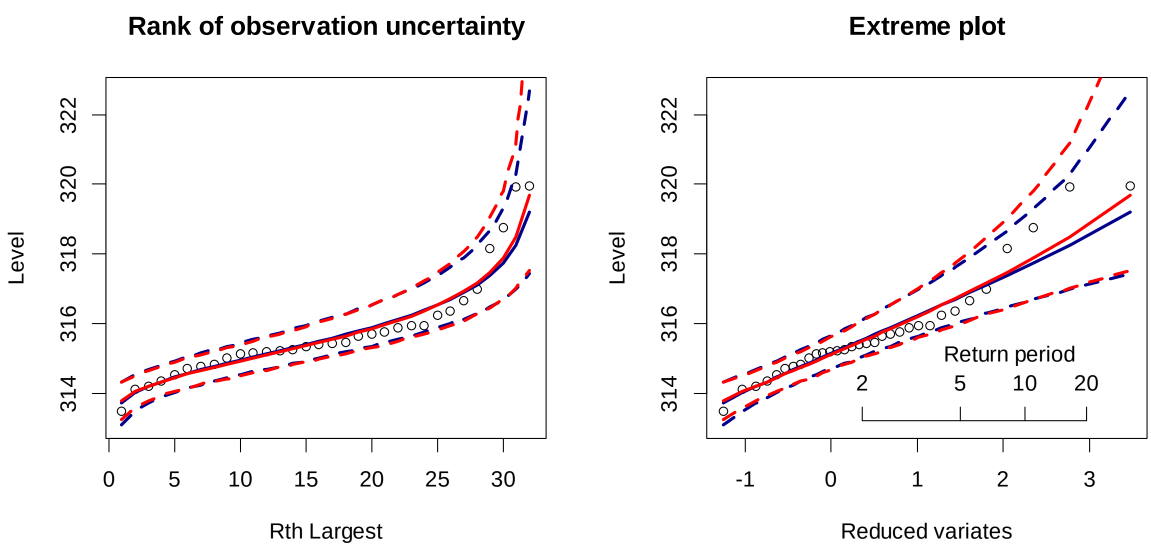
Appendix

Inflowing ice volume is a very sensitive input variable in a river ice model and in this study, a new framework based on ice jam stage maxima for estimating ice volume is proposed. By assuming that the ice volumes can be drawn from a Gumbel or a Generalised Extreme Value (GEV) distribution, we quantified the ice volume by comparing the simulated stage frequencies to the stage frequencies constructed from the water levels recorded at the Town of Peace River gauge. The figure below shows the annual maximum water levels recorded at the gauge (open circles) and the fitted GEV (red) and Gumbel (black) distributions with their confidence intervals using the Rth largest method (left panel) and the maximum likelihood approach (right panel) (Chun, 2011). Overall, the fitted results from the two fitting methods are similar. Moreover, the Gumbel and GEV fits are very similar because the fitted shape parameter of GEV is close to zero (see Coles, 2001). In the current study, we use the Gumbel distribution because of its parsimony.



Chun, K.P. (2011), Statistical downscaling of climate model outputs for hydrological extremes. PhD thesis, Department of Civil and Environmental Engineering, Imperial College London, London, U K. https://workspace.imperial.ac.uk/ewre/Public/KPChunPhDThesis%5B1%5D.pdf
Coles, S. (2001) An introduction to statistical modeling of extreme values. Springer Verlag.