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Modelling freeze-up of the lower Churchill River (Labrador) as input to an operational ice-jam flood forecasting system

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Ice jams occur along the (Atlantic) Churchill River during the river's freeze-up. Such events have led to flooding in the vicinity of Mud Lake and the fringes of Happy Valley – Goose Bay in Labrador, Canada, such as those that occurred in the autumn of 2006 and 2007. Unfortunately, data describing these events are scarce, hence a more recent freeze-up event (November 2016), for which extensive data was available (satellite imagery, time-lapse photography, extended flow gauging network) was drawn upon to help improve modelling of the freeze-up processes along the lower Churchill River. The model, which extends from Muskrat Falls to Lake Melville, is part of an operational real-time ice-jam flood forecasting system successfully operated by the Government of Newfoundland and Labrador since 2019.

1. Introduction

Ice jams occur along the lower Churchill River during the river's freeze-up. Such events, which led to moderate flooding in the vicinity of Mud Lake and the fringes of Happy Valley – Goose Bay, occurred in the autumn of 2006 and 2007. Unfortunately, data describing this event is scarce, hence a more recent freeze-up event (November 2016), for which extensive data is available (satellite imagery, time-lapse photography, extended flow gauging network) was drawn upon to model the freeze-up processes along the lower Churchill River. The model extends from Muskrat Falls to Lake Melville and is integrated into the Churchill River Flood Forecasting System (CRFFS) (KGS, 2020) to forecast freeze-up ice jams.

2. Study site description and data

This study focuses on the most downstream reach of the lower Churchill River (Figure 1). For the ice-jam flood forecasting system, the river ice model extends from just downstream of Muskrat Falls to the river's mouth at Lake Melville.

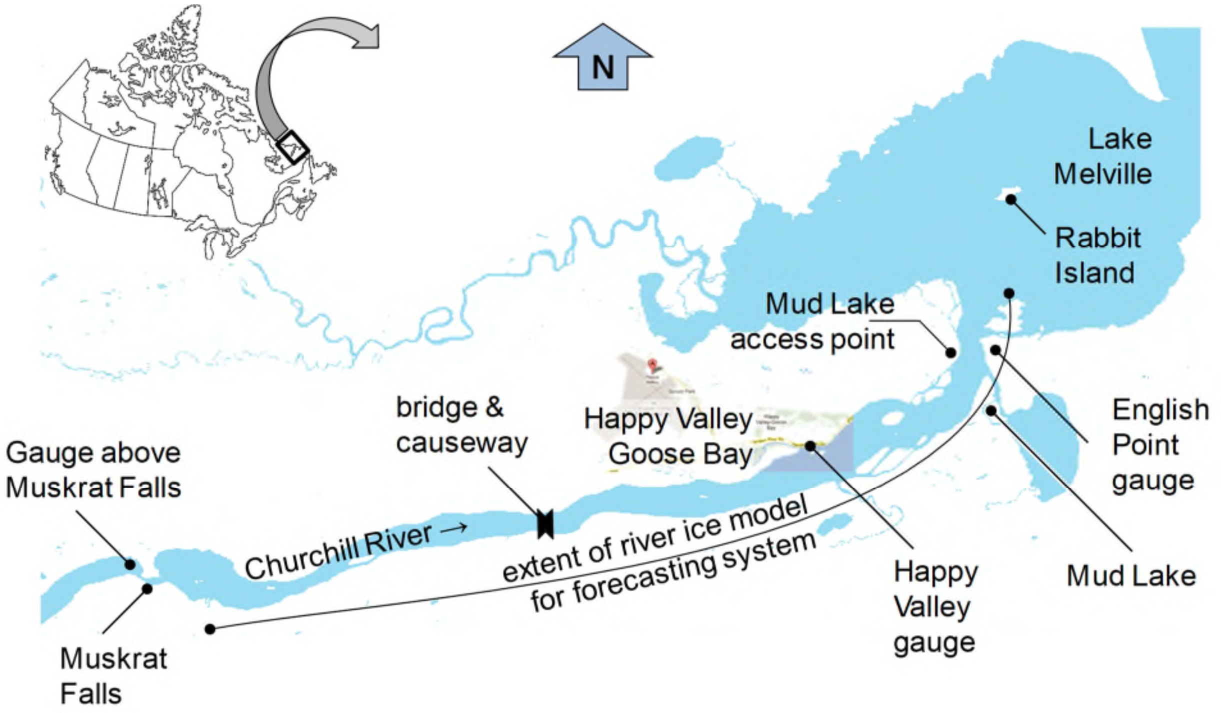


Figure 1: Study site: lower Churchill River

Freeze-up floods have occurred at the community of Mud Lake and its access point from freeze-up jam events, particularly in the autumn of 2006 and 2007. However, gauging did not commence at English Point until 2010, hence gauging data was not available to model these events. However, the freeze-up backwater levels were extreme in the fall of 2016 (see Figure 2), hence this event was taken to explore modelling freeze-up of the Churchill River.

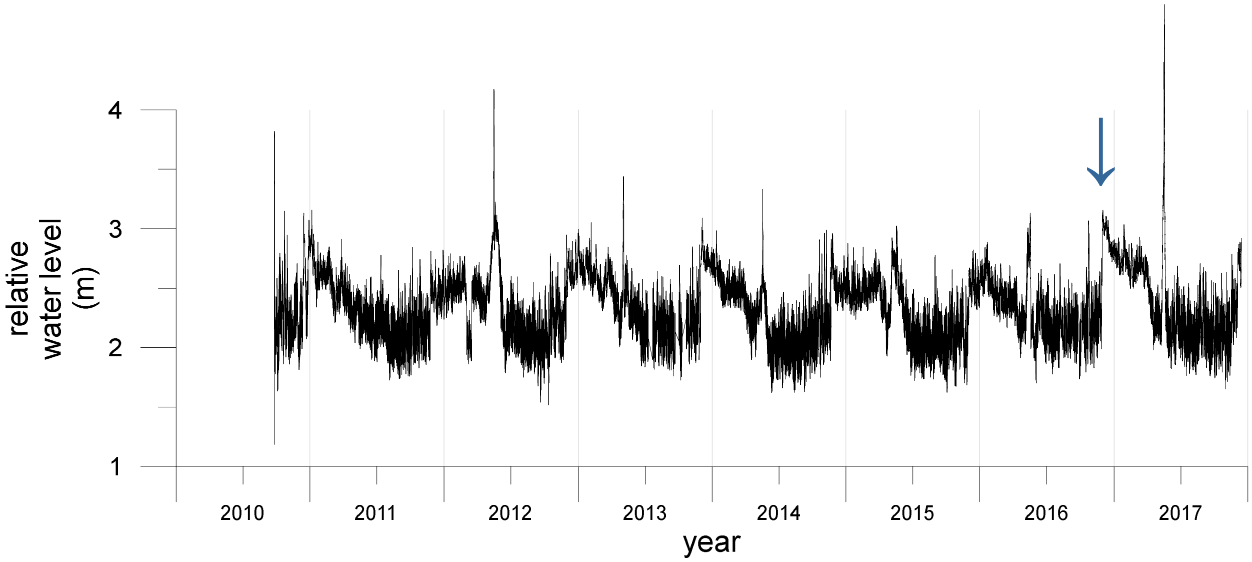


Figure 2: Water levels (relative datum) recorded at the gauge "Churchill River English Point" for the timeframe autumn 2010 – 2017. The arrow indicates the freeze-up event that was modelled in this study.

3. River ice modelling

The river ice model RIVICE was used to simulate the freeze-up event of 2016 which helped extend the development of the flood forecasting system. Lindenschmidt (2020) and Sheikholeslami et al. (2017; excerpts of which were used for this section with permission from ASCE) provide extensive descriptions of the river ice processes implemented in RIVICE. During freeze-up, frazil in the form of slush pans (A in Figure 3) is an important source of ice and is generated along the open water stretch upstream of the ice cover front (leading edge), when the water temperature T_w is at 0 °C and the overlying air temperature T_a is below freezing.

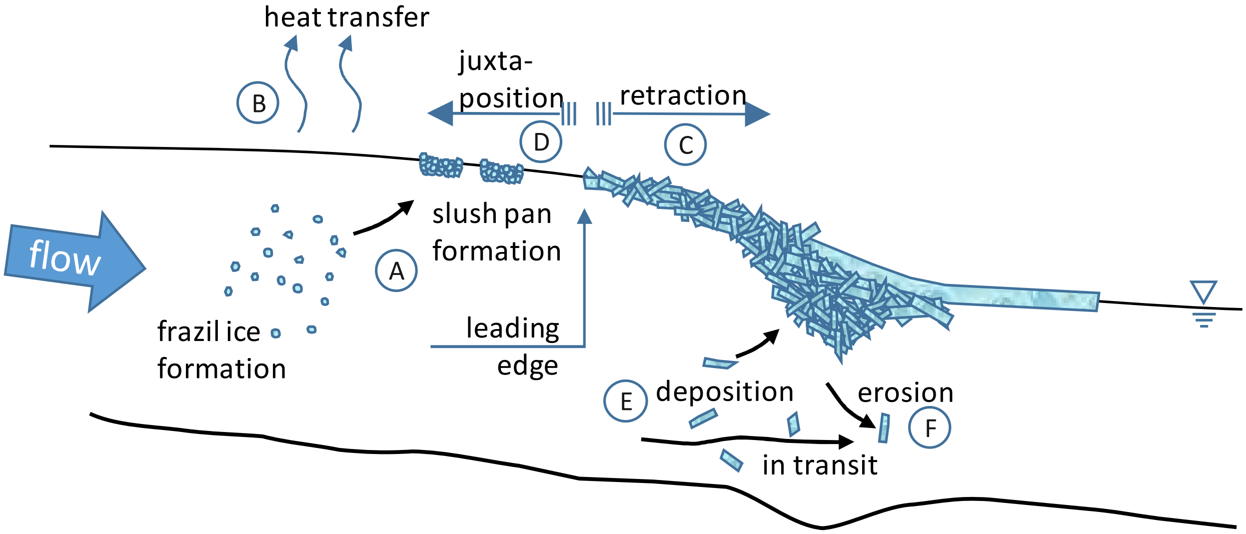


Figure 3: River ice processes simulated in the river ice model RIVICE; adapted from Sheikholeslami et al. (2017; used with permission).

The heat transfer q becomes (B in Figure 3):

$$q = H(T_w - T_a) \tag{1}$$

with H being the heat transfer coefficient typically ranging between 15 and 25 W/m^2/°C depending on how conducive the site conditions are to heat transfer. Many factors can affect the water-to-air transfer of heat, including wind speed, the degree of sheltering of the river from the wind (high sloping banks with trees provide more sheltering) and the amount of longwave radiation (cloudy conditions), an important heat source that can slow down the production of frazil ice. Only the open-water areas contribute to the heat loss; heat loss through moving ice is considered negligible.

The frazil crystals conglomerate into flocs and further into slush pans that float to the top and flow along the water surface to the leading edge of the downstream ice cover. Once the ice reaches the leading edge, two processes are at hand for the progression of the ice cover. The first process is the shoving of the ice cover (C in Figure 3) in the downstream direction through “telescoping” of the ice, which moves the already existing ice cover further downstream and thickens it. Shoving occurs when the summation of external forces on the cover (refer to Figure 4) – thrust of the flowing water against the leading edge F_T, the weight of the ice cover in the sloping direction F_W and the drag force on the ice cover’s underside by the flowing water F_D exceed the ice cover’s internal resistance F_I plus the frictional force of the ice cover along the river banks F_F, i.e. $F_T + F_W + F_D > F_I + F_F$. The second process is the progression of the ice cover upstream through juxtapositioning of the ice cover (D in Figure 3) when the internal resistance within the cover F_I plus the frictional force F_F remain larger than the summation of the external forces, F_T, F_W and F_D, i.e. $F_T + F_W + F_D < F_I + F_F$. The slush pans accumulate at the leading edge, stacking up against each other to extend the ice cover upstream. As more and more ice accumulates, external forcing anywhere along the juxtapositioned ice cover may be large enough to collapse and shove the ice cover in the downstream direction.

Ice under the cover may be eroded and transported downstream as ice in-transit. Should the mean flow velocity drop to below a velocity threshold value v_d, the ice will deposit on the ice cover underside (E in Figure 3). If the mean flow velocities underneath the ice cover increase and exceed a threshold value v_e the ice will erode from the underside (F in Figure 3).

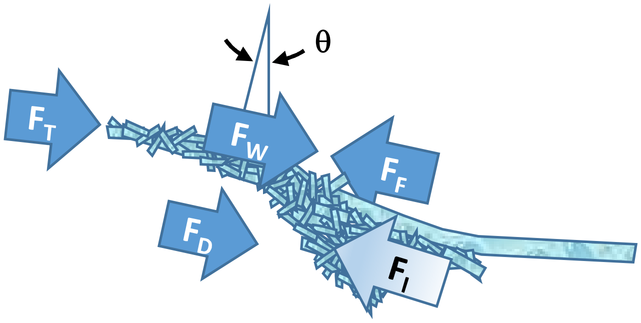
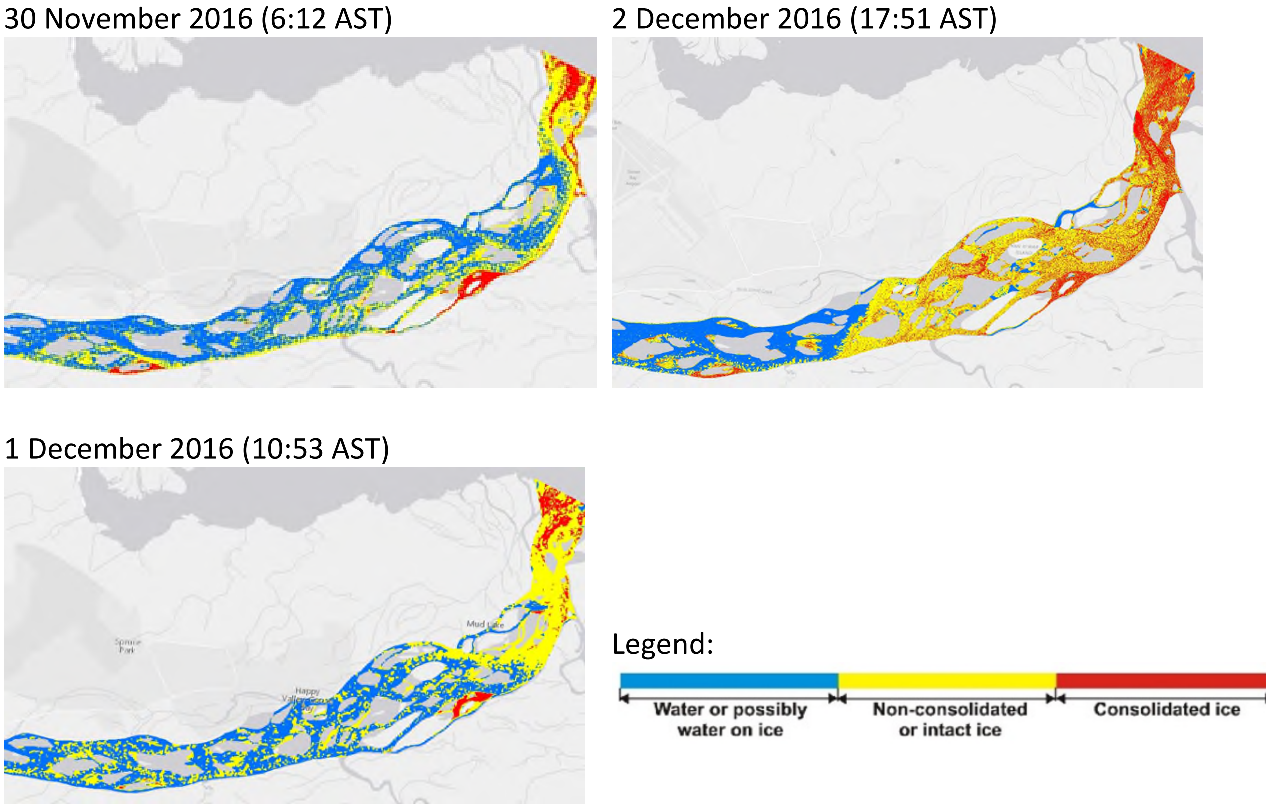


Figure 4: Forces applied to an ice-jam cover;
adapted from Sheikholeslami et al. (2017; used with permission)

4. Remote sensing data

Space-borne radar imagery of the Churchill River was used to determine the rate of extent of the ice cover front during initial freeze-up from Lake Melville upstream along the river. The images, provided in Figure 5, are snapshots of the ice cover during the first few days of the freeze-up event, which began 30 November 2016.


30 November 2016 (6:12 AST)

2 December 2016 (17:51 AST)

1 December 2016 (10:53 AST)

Figure 5: Ice-classification extracted from space-borne radar images, processed by C-Core.

5. Freeze-up simulations

Simulations of the ice cover and the backwater staging during the 2016 freeze-up event are provided in Figure 6. Two objective functions were available for the calibration: (i) water level elevation at English Point and (ii) location of the ice-cover front as extracted from Figure 5. The heat transfer coefficient *H* (Equation 1) was calibrated to be 30 W/m^2/°C, a particularly high value. The high rate of heat transfer is necessary to compensate for the exclusion of islands and sandbars in the model. More ice is required to be generated to fill in the volume that would be taken up by the islands and sandbars. Good agreement was obtained between simulated and observed water level elevations. Agreement between the simulated and observed locations of the ice-cover front was generally good, although some disparity exists due to *H* being a constant, not time-varying, value during the simulation. It is also difficult to extract an exact location of the ice-cover front from the ice classification maps since the observed ice front is not perpendicular to the river's centreline.

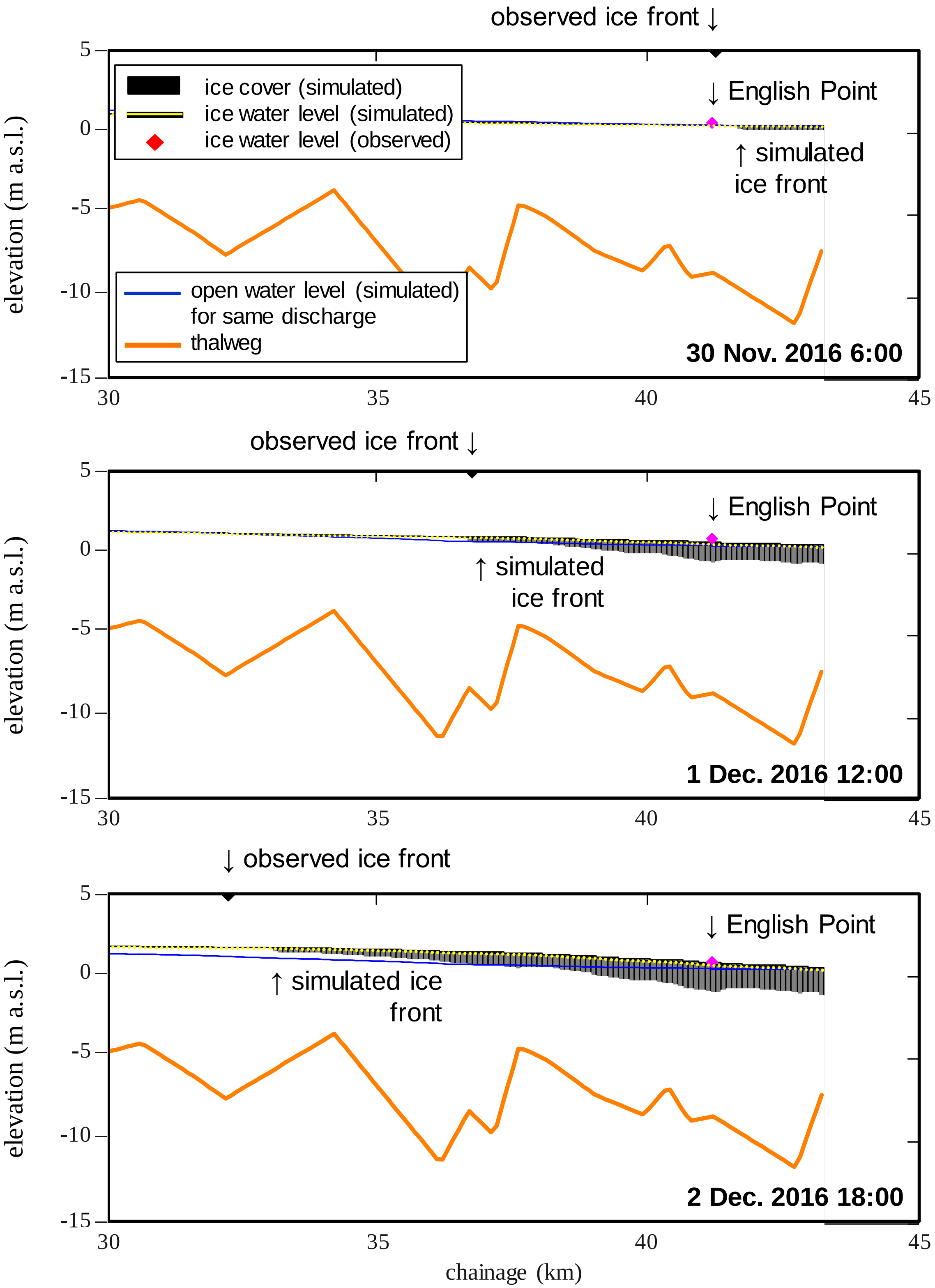


Figure 6: Backwater levels and ice cover progression for the 2016 freeze-over event.

6. Sensitivity analysis

A local sensitivity analysis was carried out for the freeze-up event of autumn 2016. To determine the amount of influence each parameter and boundary condition has on model output, in this case backwater level elevations, one factor (parameter or boundary condition) was first increase by 10% to determine the percentage change in the output. The factor was set back to its original value and the next factor increased 10% before the next simulation was carried out, from which the percentage change was again calculated. The percentage changes in the backwater level profiles are summarised in Figure 7 for the freeze-up event. The different parameters and boundary conditions are described in Chapter 6 of Lindenschmidt (2020). Evident are the high sensitivities of the roughness coefficients for both the river bed n_{bed} and the ice cover underside n_{8}. Very important are the boundary conditions, upstream discharge Q and downstream water level elevation W. Characteristics of the ice cover, its porosity PC, front thickness FT and inflowing ice rubble V_{ice}, have less impact on staging during freeze-up ice cover formation, unless the cover is well advanced upstream along the river. Also the parameters of the slush ice pans, porosity PS and thickness ST are only important for a well progressed freeze-up ice cover. Strength factors, $K1$ and $K2$, play a subordinate role in backwater staging, as do transport velocity thresholds v_d and v_e, the location of the ice-jam toe x and the thickness of the intact ice cover h downstream of the jam toe location x.

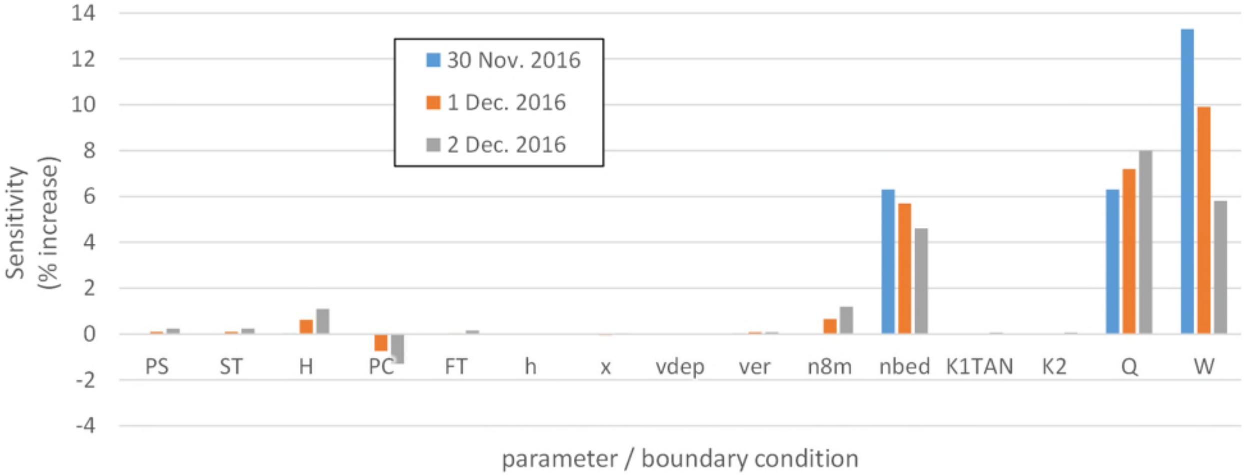


Figure 7: Percentage change in backwater levels given a 10% percentage change in one of the parameters or boundary conditions for intervals of 1.5 days during the freeze-up event of autumn 2016.

7. Integration in CRFFS

The forecast model cycle starts with the open water condition and converts the forecast flows from a hydrological model (HEC-HMS) to water levels using rating curve tables defined using an open-water hydraulic model setup (HEC-RAS). Prior to the model cycle moving forward to the ice formation condition in the fall, the system begins retrieving and checking the water temperature data from temperature sondes against threshold values that trigger the ice formation modelling in RIVICE. Currently, the start date for retrieving the water temperature data is set for 1 November but can be adjusted in the CRFFS configuration file. The temperature threshold for the Rabbit Island and Happy Valley gauges (see Figure 1) were set to 1.0 °C and 0.15 °C based on a review of available water temperature and freeze-up information. Both temperature thresholds must be met to trigger the freeze up modelling in RIVICE. Once the freeze-up condition is met, CRFFS continues to operate under the freeze-up condition regardless if the temperature condition changes.

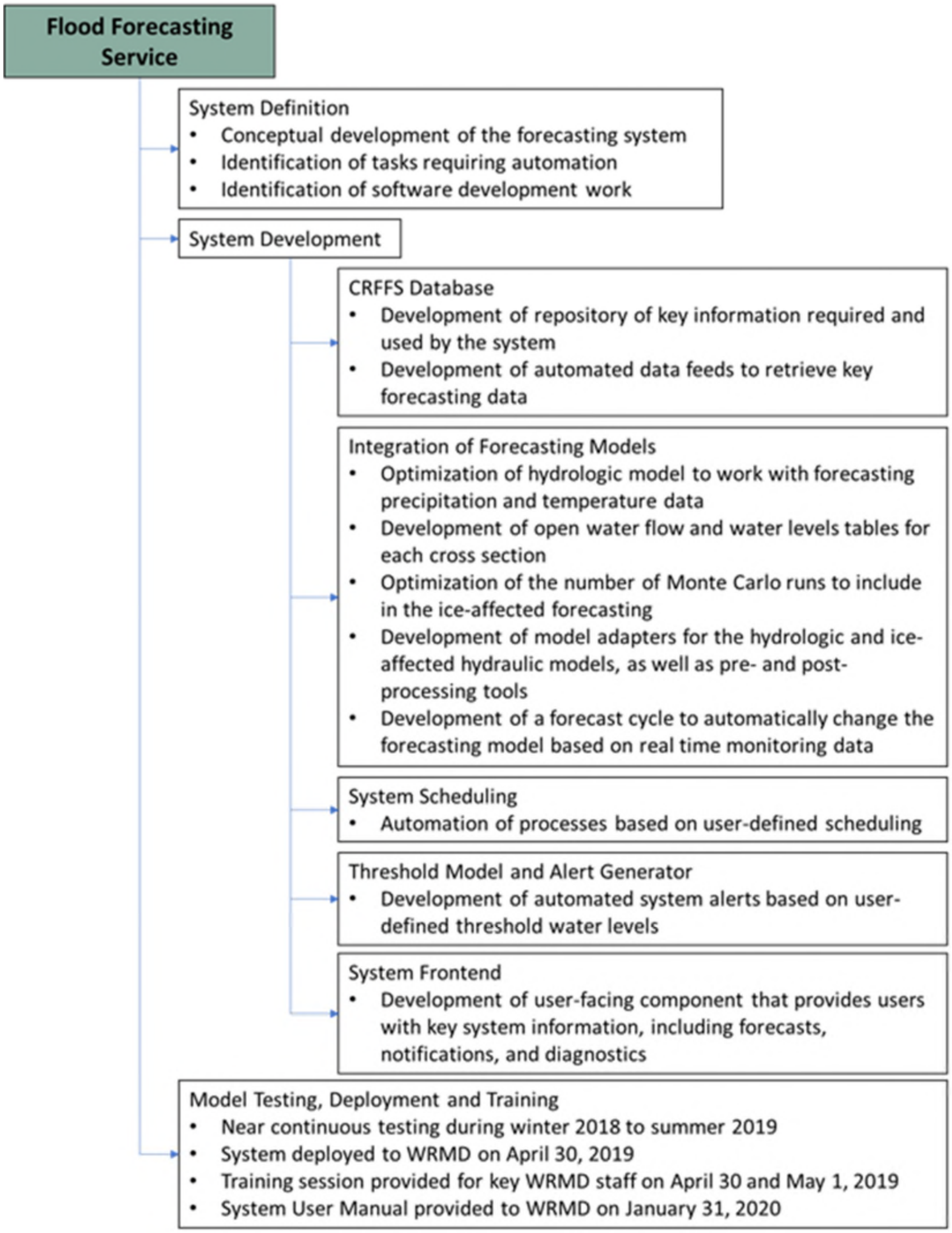
Freeze-up conditions are simulated in the RIVICE model by the generation of ice from the heat loss from the water to the freezing air temperatures (forecasted). Additionally, the possible ice jam toe location is limited to between Happy Valley – Goose Bay and English Point, since any jams outside of this area will not affect any of the communities on the Churchill River. Once CRFFS is forecasting in the freeze-up condition, the system retrieves the ice coverage data and checks the coverage against a threshold condition of 50%. Once the threshold is exceeded, the forecast model cycle proceeds into a stable winter ice condition where RIVICE is used to simulate a stable intact ice cover. The stable ice coverage is simulated in RIVICE by setting the jam toe location to the upstream extent of the model at Muskrat Falls, downstream of which a uniform ice coverage is forced that extends to Lake Melville. The ice thickness is defined based on measured ice thicknesses. Ice coverage and flows are monitored by the model cycle, and once ice coverage drops below 90% in the spring and the flow exceeds a threshold value of 2000 m^3/s, the cycle moves into the ice breakup condition.

8. CRFFS on HydrologiX platform

The Churchill River Flood Forecasting System was developed for the lower Churchill River downstream of Muskrat Falls that predicts flows on the river using the hydrological model HEC-HMS and predicts water levels using the hydraulic models HEC-RAS (for open water) and RIVICE (for ice conditions). The forecasting system was developed using 4DM's HydrologiX software as the backbone for the system, which gathers a wide variety of near real-time or forecast information from several different sources to generate a forecast of the river conditions. The near real-time and forecast information includes forecast temperature and precipitation data from Environment and Climate Change Canada, near real-time water level, water temperature, and flow data on the Churchill River and tributaries from both Water Survey of Canada and the Water Resources Management Division of the Government of Newfoundland and Labrador, ice thickness and ice coverage information from C-Core, near real-time generating station outflows from Nalcor, and forecast tidal levels on Lake Melville from the Department of Fisheries and Oceans Canada. All of the data is stored in a database in the system for future reference. Some of the data is used as inputs to the forecasting system, while other data is used to check the quality of the forecast on an ongoing basis.

The forecasting system feeds the forecast temperature and precipitation data, as well as the Churchill Falls Generating Station outflows, into the hydrological model of the Churchill River basin to establish a flow forecast on the Churchill River at Muskrat Falls. Depending on the season, the flow forecast is converted to water levels at several locations on the Churchill River using either the open water forecasting model or the ice-affected forecasting model. The forecast water levels at key locations are then automatically compared by the forecasting system against ground levels at those key locations at which flooding is anticipated to start. If the forecast water levels are higher than the ground levels, the system automatically sends warnings to the Government of Newfoundland and Labrador.

The forecasting system runs every day and provides a different type of forecast depending on the seasonal condition of the river, specifically open water conditions, freeze-up conditions, mid-winter conditions, and breakup conditions. The system automatically changes between each different seasonal condition based on data that is automatically collected by the system. The Churchill River Flood Forecasting System was deployed in April 2019 and successfully forecast high water levels on the lower Churchill River. An overview of the flood forecasting tasks is shown in Figure 8.



Flood Forecasting Service

System Definition
- Conceptual development of the forecasting system
- Identification of tasks requiring automation
- Identification of software development work

System Development

CRFFS Database
- Development of repository of key information required and used by the system
- Development of automated data feeds to retrieve key forecasting data

Integration of Forecasting Models
- Optimization of hydrologic model to work with forecasting precipitation and temperature data
- Development of open water flow and water levels tables for each cross section
- Optimization of the number of Monte Carlo runs to include in the ice-affected forecasting
- Development of model adapters for the hydrologic and ice-affected hydraulic models, as well as pre- and post-processing tools
- Development of a forecast cycle to automatically change the forecasting model based on real time monitoring data

System Scheduling
- Automation of processes based on user-defined scheduling

Threshold Model and Alert Generator
- Development of automated system alerts based on user-defined threshold water levels

System Frontend
- Development of user-facing component that provides users with key system information, including forecasts, notifications, and diagnostics

Model Testing, Deployment and Training
- Near continuous testing during winter 2018 to summer 2019
- System deployed to WRMD on April 30, 2019
- Training session provided for key WRMD staff on April 30 and May 1, 2019
- System User Manual provided to WRMD on January 31, 2020

Figure 8: Overview of flood forecasting tasks.

9. Conclusions

RIVICE successfully simulated the freeze-up conditions along the lower Churchill River. Using two objective functions, backwater level elevations and ice-cover front extent, allowed better calibration of the model and reduced the uncertainty in the parameterization of the model, particularly the heat transfer coefficient. The model setup provided a solid basis for freeze-up forecasting in the CRFFS.

10. References

KGS (2020) Climate change flood risk mapping study and the development of a flood forecasting service: Happy Valley - Goose Bay and Mud Lake (final report). Prepared by KGS Group for the Government of Newfoundland and Labrador, July 2020. https://www.gov.nl.ca/ecc/files/Volume-1-Main-Report.pdf

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