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A Model for Predicting Frazil Ice Flooding on Lower Spencer Creek

Soheil Gholamreza-Kashi
Exp *Services Inc., 500-220 Commerce Valley Dr. W., Markham, ON L3T 0A8*
Soheil.Kashi@exp.com

Spencer Creek is the major river within the Hamilton Conservation Authority watershed in Ontario. The main branch of the river is 40 km long and flows into Hamilton Harbour at the western end of Lake Ontario. Ice-related flooding events have been occurred on several occasions along the lower reach of Spencer Creek within the former town of Dundas. Spencer Creek descends the Niagara Escarpment in a very steep channel before reaching the flat urban areas in Dundas. During periods of sustained cold temperatures, turbulent flow descending the Niagara Escarpment can become super-cooled and generate frazil ice. The frazil ice quickly spreads and accumulates in the downstream flat reach and at bridges and culverts, which can lead to the development of ice jams and result in flooding. **Exp** had previously completed a study to examine the underlying causes of frazil ice generation and accumulation along Spencer Creek and the potential mitigation measures. The current study was completed to develop a model based on flow and temperature data to predict the potential for occurrence of flooding due to frazil ice accumulation. Meteorological and hydrometric data and historical information were collected and analyzed. Degree days of freezing and mass flow curves for previous events were investigated. Two indices for temperature and flow were defined. A methodology was developed to predict the potential of flooding using the defined curves and indices based on current temperature and flow data. This methodology was used during the 2015 winter to predict potential occurrence of frazil ice flooding.

1. Introduction

Spencer Creek is the major river within the Hamilton Conservation Area in Ontario, draining an area of 291 km^2. The main branch of the river is 40 km long and flows into Lake Ontario at Hamilton Harbour after entering an area known as Cootes Paradise. The upper portion of the river passes through rural areas and agricultural lands, whereas the lower portion near the lake flows through urban development. Two dams are located on Spencer Creek, namely Valens Dam and Christie Lake Dam. The steep slope of Spencer Creek downstream of the Christie Lake Dam generates fast moving turbulent flows, which in periods of sustained low temperatures, may lead to the generation of frazil ice. Frazil ice typically accumulates and creates ice jams in the downstream reach of Spencer Creek, where the slope of the creek is gentle, and at channel restrictions (such as bridges and culverts). In 2005 and 2009, accumulation of frazil ice at the Thorpe Street Bridge caused a blockage of Spencer Creek, which resulted in flooding on nearby streets. Figure 1 shows the study area and identifies the frazil ice generation and flooding locations.

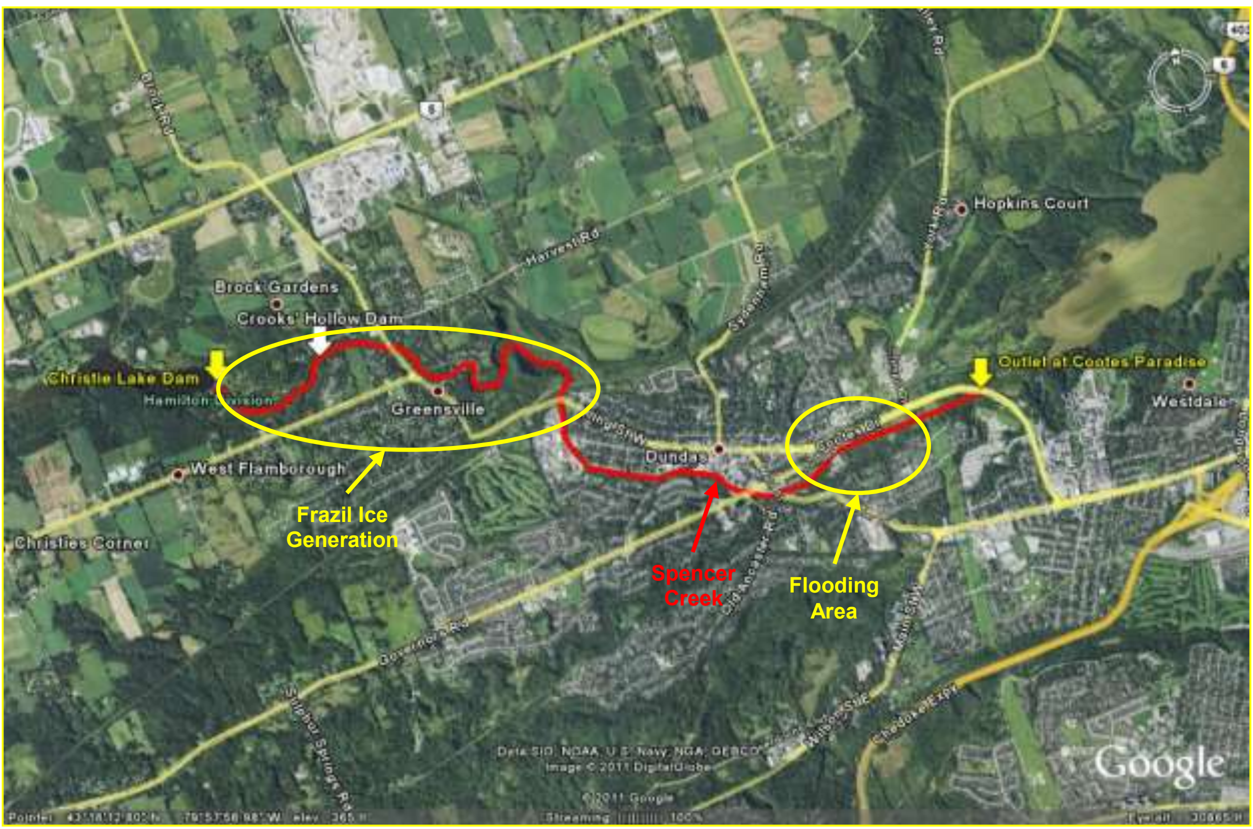

Figure 1. Study area and frazil ice generation and flooding locations.

In 2011, **exp** (formerly Trow Associates Inc.) completed the Lower Spencer Creek Frazil Ice Study report (Trow, 2011 and Gholamreza-Kashi et al., 2011), in which the causes of frazil ice generation in this area were identified, and measures to prevent/mitigate the flooding due to frazil ice accumulation were discussed. Following the recommendation of this report, in 2014 HCA retained **exp** to develop a method for frazil ice flood forecasting in the lower reach of Spencer Creek, using historical temperature and discharge data.

2. Background

A review of previous studies on the relationship between ice jams and air temperature and/or discharge was undertaken. Zufelt and Bilello (1992) investigated the effects of freezing periods and discharge on formation of ice jams in Salmon River at Salmon, Idaho. The flooding on Salmon River resulted from ice jams due to freeze-up conditions, which led to reduction of the hydraulic capacity of the river channel. They concluded that the occurrence of ice jams is directly related to the duration and intensity of cold periods and the air temperatures before the cold periods. This study identified a threshold condition, at which the probability of ice jams could be determined based on forecast temperatures. They did not find any relationship between the discharge and the occurrence of ice jams due to freeze-up.

A study of frazil ice flooding in the former town of Durham, Ontario, was conducted by Hatch Acres (2006). This study proposed a method for determining the probability of flooding due to frazil ice accumulation using Degree Days of Freezing (DDF) and mass flow curves. The method was comprised of monitoring the slopes of the cumulated DDF and mass flow curves.

Beltaos, Boyle, and Hryciw (2007) studied the flooding due to frazil ice jams on Kaministiquia River near Fort Williams Historic Park in Ontario. They investigated the causes of flooding in relation to historical information and hydro-climate data and concluded that the flooding is related to high flows during below freezing but relatively mild air temperatures.

Frazil ice flooding in Moira River at Belleville, Ontario was investigated by Beltaos et al. (2007). This study developed temperature and flow based indices to evaluate the potential for frazil ice flooding. The temperature-based index was defined as the minimum of the daily mean temperatures averaged over 15 consecutive days in January. The flow-based index was defined as the maximum January discharge on or before January 20. Analyzing the historical hydro-climate data, Beltaos et al. (2007) determined flooding threshold values of -12.0 °C and 60 m^3/s for the temperature and flow indices, respectively.

3. Data Collection

The air temperature (daily means) data was obtained from the Meteorological Service of Environment Canada. The data was collected from the Hamilton A station (ID# 6153194), from December 1959 to December 2011. The flow (daily means) data was obtained from the Water Survey of Canada. This data was collected from the Spencer Creek Gauge at Dundas Street from 1960 to 1984 (Station 02HB010) and from 1984 to 2012 (Station 02HB007).

The historical information regarding past ice-related flooding events was provided by the Hamilton Conservation Authority. Two flooding events due to frazil ice accumulation in lower Spencer Creek were reported by HCA: January 2005 and January 2009 events. The flooding event in January 2009 was not as extensive as the January 2005 event, partly due to higher temperatures and partly because of HCA monitoring and preparation (e.g. installing a snow berm). In February 2008, two relatively high flow events were experienced following short periods of temperatures above zero. No flooding was reported during this period. All these events were described in detail in the Lower Spencer Creek Frazil Ice Study (Trow, 2011).

According to the report "Flooding in Dundas: a Summary of Historical Notes on Floods between 1847 and 1965", a flooding event occurred in lower Spencer Creek in February 1965. This flooding event appeared to be due to ice break-up as a result of temperatures above zero and flows as high as 24 m^3/s. Large pieces of ice were observed to have encroached onto the street, which indicates ice break-up. Therefore, the 1965 event was excluded from this study

4. Data Analysis

Frazil ice generation generally occurs during below freezing temperatures and high flows. The water temperature reduces to near freezing levels after a certain number of days with sub-zero °C temperatures. Hydrodynamic forces of high flows prevent the formation and development of ice cover over various parts of the watercourse that would have otherwise reduced heat loss to the atmosphere. High flow also increases the turbulence and the surface area, providing more opportunities to disperse heat to the atmosphere. Two different methods for forecasting frazil ice generation using temperature and flow data were considered: using Degree Days of Freezing (DDF) and mass flow curves and developing temperature and flow indices.

In the first method, which was proposed by Harch Acres (2006), two curves were considered. The cumulative DDF (in °C-days) curve comprises of the daily degrees below freezing summed over the total number of days that the temperature was below freezing. The slope of this curve indicates the intensity of freezing/warming. The cumulative mass flow curve consists of the total volume of flow over a certain number of days. The slope of this curve indicates the flow rate.

For this study, the curves for cumulative DDF (based on daily mean temperatures) and mass flows (based on daily mean flows) over a 5 day period were calculated for January 2005, February 2008, and January 2009. These curves are presented in Figures 2 to 4. Figure 2 shows increases in the flow rates in the beginning of January 2005 and just before mid-January. Around mid-January, a freezing period began, exceeding 70 °C-days and lasting for approximately 10 days. A flooding event due to frazil ice accumulation occurred during this freezing period.

A freezing period occurred in early February 2008 (Figure 3). This freezing event lasted less than 10 days and did not exceed 50 °C-days. No significant increase in the flow rates were observed. No frazil ice flooding occurred in February 2008. Another freezing period, lasting more than 10 days and exceeding 70 °C-days, occurred in early January 2009 (Figure 4). This freezing event was preceded by a significant increase in the flow rates in late December 2008. A frazil ice jam occurred at the end of this freezing period.

In the second method, following the approach proposed by Beltaos et al. (2007), two indices were defined: T_{min} – minimum of the daily mean temperatures averaged over 5 consecutive days in January and February, and Q_* – maximum daily mean discharge during the 15-day period prior to the occurrence of T_{min}. T_{min} times 5 produces the 5-day DDF.

A scatter plot of the joint occurrence of these indices for the months of January and February from 1969 to 2011 is presented in Figure 5. The climate data from 1960 to 1968 had too many missing points; hence, this period was not included. A maximum frazil ice generation zone is identified, where the T_{min} < -14 °C and Q_* > 11 m^3/s. The January 2005 and January 2009 flooding events fall within this zone.

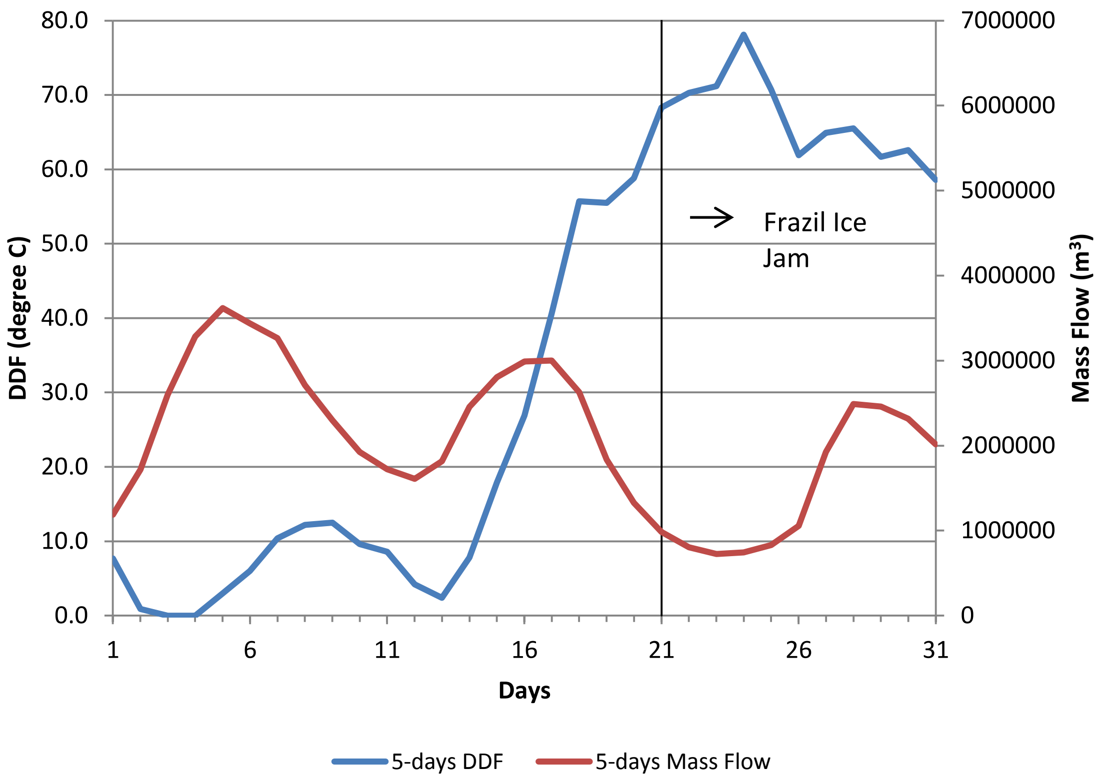

Figure 2. 5-day DDF and Mass Flow Curves for January 2005.

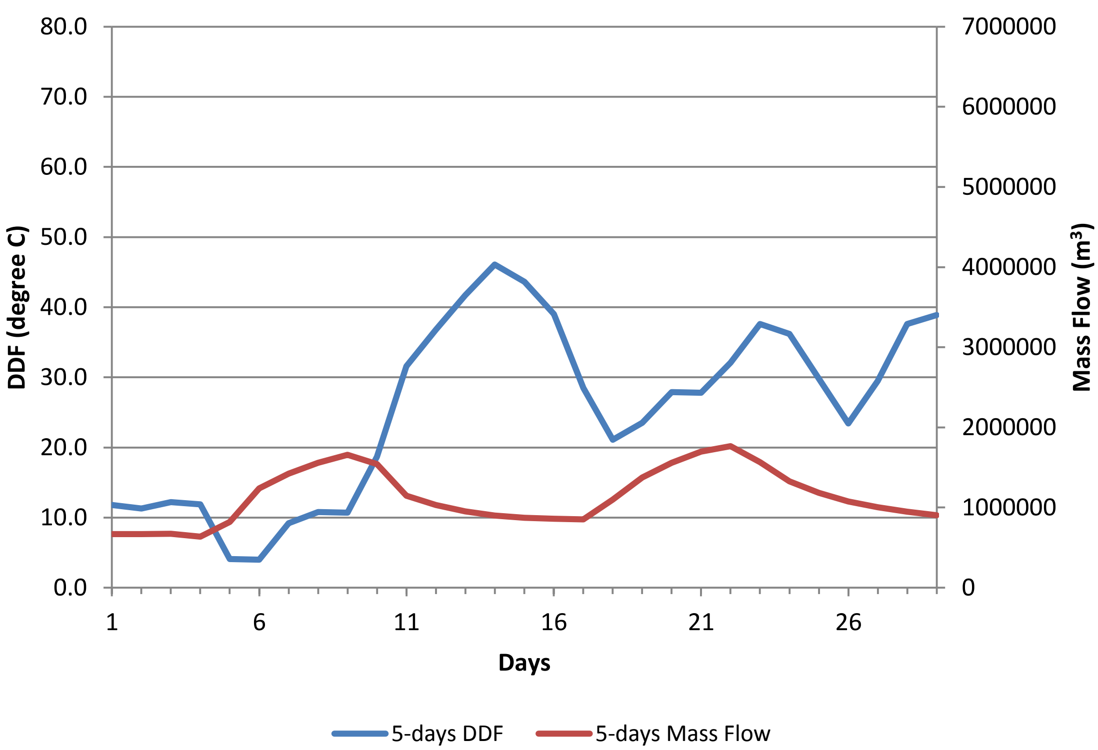

Figure 3. 5-day DDF and Mass Flow Curves for February 2008.

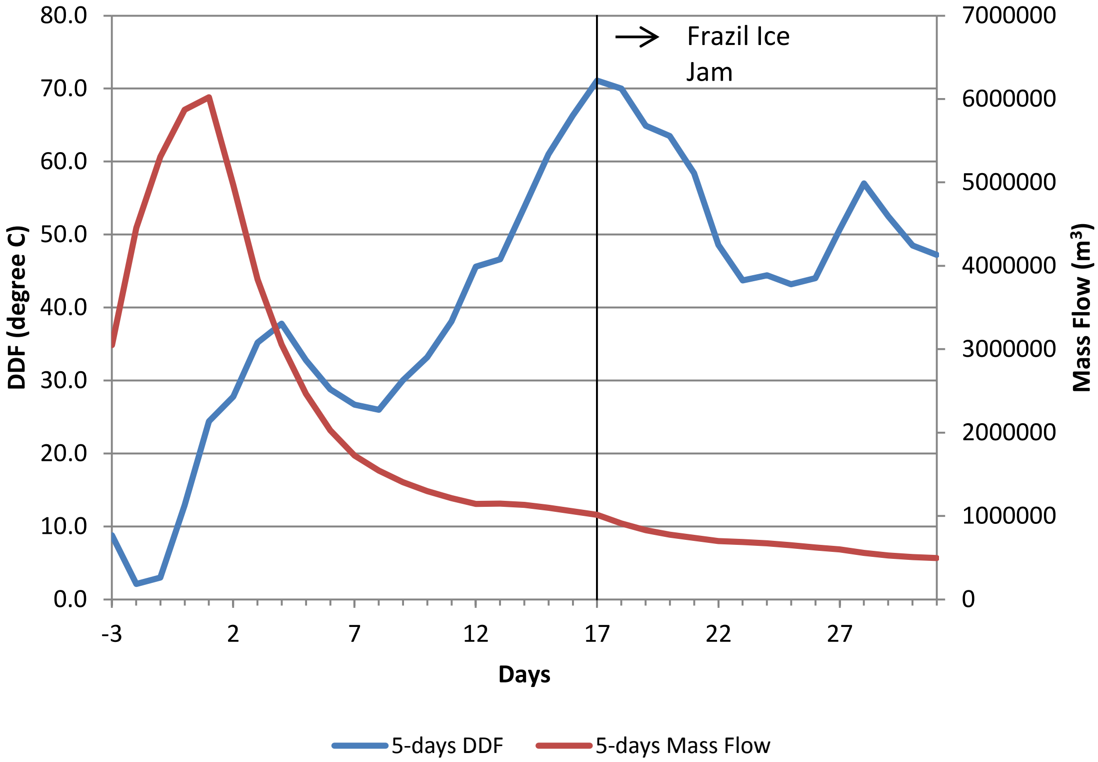

Figure 4. 5-day DDF and Mass Flow Curves for January 2009

5. Proposed Forecasting Methodology

Based on the results of the data analysis, the following methodology for forecasting frazil ice flooding in lower Spencer Creek is proposed. These steps are to be completed on a daily basis from beginning of January to end of February.

1- Collect the temperature data as well as forecast temperatures from Environment Canada's Hamilton A station (currently Station ID 6153193).
2- Collect the flow data from the Water Survey of Canada's Spencer Creek gauge at Dundas St. (ID 02HB007).
3- Calculate the 5-day DDF for the forecast temperatures and the 5-day mass flow for the measured flows. Note that the date for DDF will be 5 days ahead of the date for mass flow. Plot the calculated points on two separate curves (on the same graph).
4- Calculate the 5-day average of the forecast temperatures. If this average is smaller than -14 °C, determine the maximum daily flow rate within the past 15 days.
5- The probability of occurrence of a frazil ice flooding event is high when one of the following criteria is observed:
    a. A freezing period (positive slope of the DDF curve) with a DDF exceeding 70 °C-days occurs, which is preceded by a significant increase in the flow rates (positive slope of the mass flow curve);
    b. And/or, the 5-day average of the forecast temperatures is smaller than -14 °C with a maximum daily flow rate greater than 11 m^3/s within the past 15 days.
6- Update the previous DDF points with actual temperature data, on the following day.

After an occurrence of frazil ice flooding is observed, the thresholds for DDF, T_{min}, and Q_* should be modified based on the observed data.

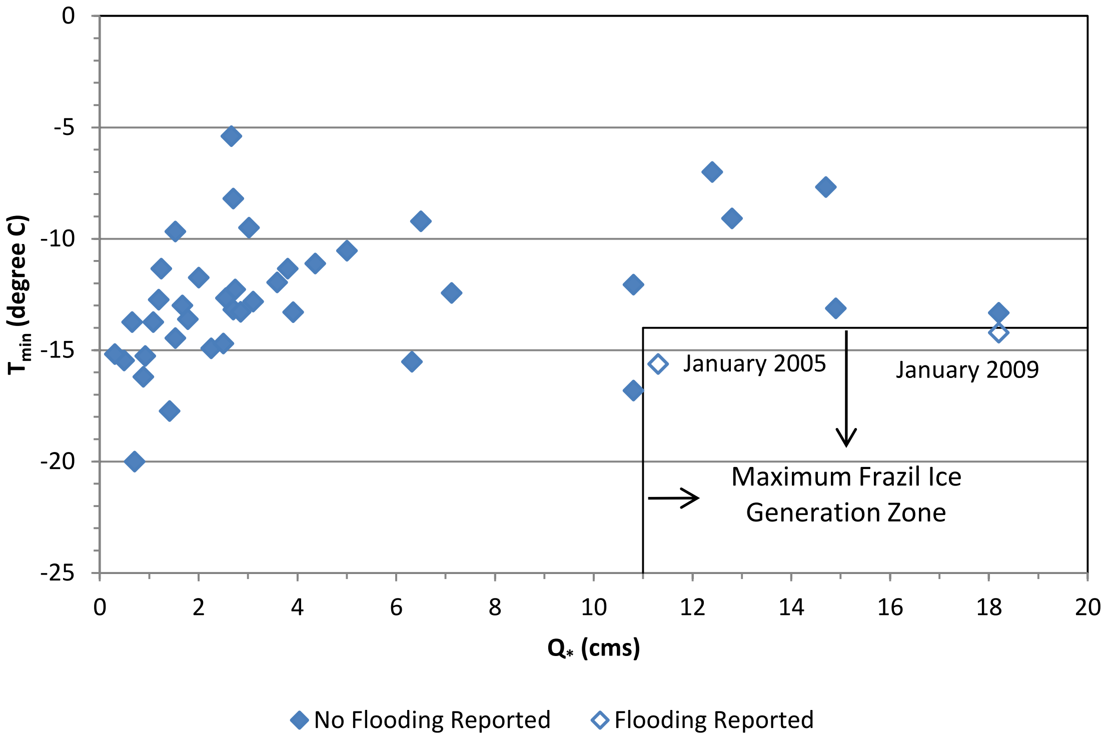

Figure 5. Joint occurrence of Jan. and Feb. discharge and temperature indices from 1969 to 2011.

6. Forecasting Application

The proposed methodology was applied during the winter of 2015. Due to the unusually cold February temperatures, river ice conditions resulted in unreliable discharge at the Dundas streamflow gauge. As a result, HCA predominantly focused on tracking of the 5-day DDF and the T_{min} Index, along with routine site observations.

Between February 10 and February 23, the forecasting model indicated 5-day DDF above 70 °C-days and T_{min} smaller than -14 °C. However, no frazil ice development or related flooding was observed. It was expected that the thick river ice cover helped to limit frazil ice generation during this time.

7. Conclusions

In 2014, HCA retained **exp** to develop a method for frazil ice flood forecasting in the lower reach of Spencer Creek, using temperature and discharge data. **Exp** completed a literature review, collected the data, and undertook data analysis. As a result, a methodology is proposed for predicting high probabilities of occurrence of frazil ice flooding in lower Spencer Creek. This methodology may be modified by HCA as more data points become available in the future.

Although there currently are some limitations to the benefits of the frazil ice forecasting model due to river ice and associated flow index unreliability, the model provided useful monitoring benefits. HCA plans to continue using the model for subsequent winter seasons, as part of their winter Flood Forecasting & Warning monitoring.

Acknowledgments

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