Canadian Journal of Civil Engineering
Revue canadienne de génie civil

**A Forecasting Methodology for Predicting Frazil Ice Flooding
along Urban Streams using Hydro-meteorological Data**

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2016-0158.R1
Manuscript Type:	Article
Date Submitted by the Author:	24-May-2016
Complete List of Authors:	Gholamreza-Kashi, Soheil; Exp Services Inc.; AECOM, Water
Keyword:	Frazil Ice, Flood Forecasting, Hydro-meteorological Data

A Forecasting Methodology for Predicting Frazil Ice Flooding along Urban Streams using Hydro-meteorological Data

Soheil Gholamreza-Kashi

Exp Services Inc., 1595 Clark Boulevard, Brampton, Ontario L6T 4V1¹

Draft

¹ Current affiliation and address: AECOM Canada Ltd., 300 Water Street, Whitby, Ontario L1N 9J2. Phone: (905) 668-9363, E-mail: Soheil.Kashi@aecom.com

Abstract - Flooding due to ice jams in urban streams, resulting in damages to residential and commercial property, is a common problem in northern regions. Ice-related flooding events have occurred on several occasions along the lower reach of Spencer Creek within Hamilton, Ontario. This study is completed to develop a methodology using the available flow and temperature data to predict the potential for occurrence of flooding due to frazil ice accumulation. Meteorological and hydrometric data as well as 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 is currently being used to predict potential occurrence of frazil ice flooding along Spencer Creek and may be adapted for use in other watercourses in Canada and elsewhere.

Keywords: Frazil Ice, Flood Forecasting, Hydro-meteorological Data

1. Introduction

Flooding due to ice jams in urban streams is a common winter phenomenon in northern regions (Beltaos 2013). Damages to residential and commercial property due to ice-related flooding can be significant. Spencer Creek is the major river within the Hamilton Conservation Area in Ontario, draining a 291 km² area. The main branch of the river is approximately 40 km long and flows into Lake Ontario at Hamilton Harbour. The upper reach of the creek passes through rural areas and agricultural lands, whereas the lower reach 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. As shown in Figure 1, 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. A map of the study area, showing the reaches prone to frazil ice generation and flooding due to frazil ice accumulation, is presented in Figure 2. In 2005 and 2009, accumulation of frazil ice at the Thorpe Street Bridge caused a blockage of Spencer Creek, which resulted in flooding onto nearby streets as shown in Figure 3.

In 2011, a study was completed to identify underlying causes of frazil ice generation in this area and recommend measures to prevent/mitigate the flooding due to frazil ice accumulation (Gholamreza-Kashi et al. 2011). A cost-benefit analysis was completed for the mitigation alternatives, identifying upstream dam operations and mechanical ice removal as the most effective measures, both of which would require an advanced warning system (Exp Services Inc., 2013). Following the recommendation of this study, a methodology for forecasting frazil ice

flooding in the lower reach of Spencer Creek using historical temperature and discharge data is developed.

2. Background

Frazil ice is formed when water flow is supercooled by turbulence and exposure to cold air during very low temperatures, typically accompanied by high winds. High flow velocities increase the turbulence and the surface area, providing more opportunity for heat loss to the atmosphere (Ashton 1986).

An ice cover can reduce heat loss from the water to the atmosphere, thereby decreasing the rate of frazil ice generation (Beltaos et al. 2007). Sui et al. (2002) investigated the conditions of ice cover formation and suggested a critical Froude number of 0.75, at which the cover can progress as a result of frazil ice juxtaposition at its upstream edge. In fast moving sections of a river, the hydrodynamic forces of high flow prevent the formation and development of ice cover. 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 was 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 cumulative 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 $-12.0\text{ }^{\circ}\text{C}$ and $60\text{ m}^3/\text{s}$ for the temperature and flow indices, respectively.

In this study, two different methods for forecasting frazil ice generation using temperature and flow data are considered: using Degree Days of Freezing (DDF) and mass flow curves and developing temperature and flow indices. In the first method, the indices proposed by Hatch Acres (2006) are applied, since the size and characteristics of the watershed in their study are similar to those of the Spencer Creek watershed. The curves for cumulative DDF (based on daily mean temperatures) and mass flows (based on daily mean flows) over a 5 day period are used. In the second method, the indices proposed by Beltaos et al. (2007) are revised to reflect the study area conditions. The area of Moira River watershed studied by Beltaos et al. (2007) is approximately 2772 km^2 (Quinte Region Watershed Characterization, 2008), which is considerably larger than the Spencer Creek watershed area. This would increase the response

time to changes in temperature and flows in Moira River watershed as compared to that in Spencer Creek watershed. The temperature index was defined as the minimum of the daily mean temperatures averaged over 5 consecutive days in January and February and the flow-based index was defined as the maximum daily mean discharge during the 15-day period prior to the occurrence of the temperature index.

3. Data Collection

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

The climate normals for the City of Hamilton are summarized in Table 1. Daily minima of -9.7 and -9.1 °C and number of days with minimum temperature below -10 °C of 14.5 and 12.5 for January and February respectively, indicate a potential for frazil ice generation in both of these months. Precipitation magnitudes for January and February are 65.8 mm and 55.3 mm respectively, of which more than half is snowfall. During these months, rainfall and above zero temperatures resulting in snowmelt runoff can increase the streamflow in Spencer Creek.

Figure 4 shows the maximum, mean, and minimum daily flow rates for a 51 year period (1959 to 2009) for Spencer Creek. The mean daily flow rates indicate that flow generally increases following the onset of the spring freshet in early March, when snowmelt and rainfall result in large runoffs. Flow then decreases throughout the summer, as rainfall is balanced by evaporation and infiltration. In the fall, rainfall and cooler temperatures, which reduce the rainfall abstractions, result in relatively higher flow from October to December. During the winter

months of January and February, flow is normally low since cold temperatures inhibit snowmelt and the rainfall is mainly absorbed in the snow pack.

The maximum daily flow rates indicate that flow can be significantly greater than the mean flow at any time of the year, including the winter months. High flows during January and February may be due to above zero temperatures, which induce snowmelt, occurring concurrently with a rainfall event.

The historical information regarding past ice-related flooding events was provided by the Hamilton Conservation Authority (HCA). 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. In February 2008, two relatively high flow events were experienced following short periods of temperatures above zero. No flooding was reported during this month.

January 2005 flow rates and temperatures for Spencer Creek at Market Street, where the WSC gauge is located, are shown in Figure 5. After January 22, flow measurements were likely impacted by the ice jam and cannot be considered accurate. Between January 12 and 14, the temperature rose well above 0 °C. This rise in the temperature resulted in high flows up to 12 m³/s between January 13 and 16. Subsequently, a cold snap with temperatures falling to -20 °C began around January 14, which lasted for several days. Meanwhile, the flow rate in Spencer Creek decreased to approximately 2 m³/s.

Ice cover can form on Spencer Creek at various locations during the winter months. This ice cover likely broke up at some locations due to the combination of high flows and temperatures between January 12 and 14. In the absence of the ice cover during the cold snap that followed, the rate of frazil ice generation likely increased significantly due to supercooling of the flow by

high turbulence and heat loss at the surface. As the flow rate decreased, the volume of frazil ice likely exceeded the carrying capacity of the river system, especially in the slower flowing downstream reach. The frazil ice accumulated in locations, where the flow velocity was not sufficient to carry it downstream. A frazil ice jam and the subsequent flooding event began around January 21.

A similar process for ice breakup due to the sudden increase in the basin runoff during a warm spell and the subsequent ice jam in a section with rapid reduction in the channel gradient was reported by Shen and Liu (2003). However, in the January 2005 flooding along Spencer Creek, broken pieces of ice were not observed and the river was blocked only by accumulation of frazil ice.

Figure 6 shows January 2009 flow rates and temperatures for Spencer Creek at Market Street. A cold snap with the temperature falling to -20°C was experienced beginning around January 14, which sustained for several days. However, this cold snap was not preceded by a period of high temperatures and resulting increased flows and the loss of ice cover. As a result, the flooding extent of the January 2009 event was very limited compared to the January 2005 event.

February 2008 flow rates and temperatures for Spencer Creek at Market Street are shown in Figure 7 for comparison purpose to the January 2005 and 2009 events. No flooding events were reported during February 2008. Two relatively high flow events were experienced following short periods of above zero temperatures, one beginning around February 5 and the other beginning around February 18. The flow during the February 5 event increased to $8\text{ m}^3/\text{s}$. This high flow event was not immediately followed by a sustained cold snap. Rather, the temperature fell below -10°C beginning February 10, which lasted for only 2 days. The February 18 event, during which the flow increased to $6\text{ m}^3/\text{s}$, was immediately followed by temperatures below -10

°C. This cold snap also sustained for about 2 days. During February 2008, the flow did not increase as high as the flow during the January 2005 flooding event.

A flooding event occurred in lower Spencer Creek in February 1965 (Woodhouse, 1967). This flooding event appeared to be due to ice break-up as a result of temperatures above zero and flows as high as $24 \text{ m}^3/\text{s}$. 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 Hatch 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 8 to 10. Figure 8 shows

the increase 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, lasting more than 10 days and exceeding 70 °C-days, occurred in early January 2009. As shown in Figure 9, 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. Another freezing period occurred in early February 2008. As shown in Figure 10, this freezing event lasted less than 10 days and did not exceed 50 °C-days. No significant increase in the flow rates was observed. No frazil ice flooding occurred in February 2008.

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 five produces the 5-day DDF.

The scatter plot of the joint occurrence of these indices for the months of January and February from 1969 to 2011 is presented in Figure 11. 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 $Q^* > 11$ m³/s. The January 2005 and January 2009 flooding events fell within this zone.

5. Proposed Forecasting Methodology

Based on the results of the data analysis, the following methodology for forecasting frazil ice flooding in lower Spencer Creek was 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 either of the following criteria is met:
 - 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 $11\text{ m}^3/\text{s}$ 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.

6. Forecasting Application

The proposed methodology has been applied by HCA during the winter of 2015 and 2016 at Spencer Creek. Due to the unusually cold February temperatures in 2015, 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 during this year.

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

A methodology for forecasting frazil ice flooding in the lower reach of Spencer Creek using temperature and flow data is developed. Literature review and data collection analysis was undertaken. As a result, a methodology was 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; therefore, the effects of the climate change will be included in this methodology. 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. The proposed methodology can be adapted for use in other streams susceptible to frazil ice flooding throughout Canada and other cold regions. It can be used to develop an automated forecasting tool by linking temperature sensors and streamflow gauges, which provide a continuous data feed.

Acknowledgments

The contribution of the Hamilton Conservation Authority to this study is acknowledged. HCA funded this study and provided the historical data.

References

- Ashton, G.D. 1986. River and Lakes Ice Engineering. Water Resources Publications, Littleton, Colorado.
- Beltaos, S. 2013. River Ice Formation. Committee on River Ice Processes and the Environment, CGU-HS, Saskatoon, Saskatchewan.
- Beltaos, S., Boyle, P., and Hryciw, K. 2007. 2005-06 Ice-jam Flooding, Kaministiquia River near Fort Williams Historic Park. *In* Proceedings of the 14th Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, Quebec, June 19-22, 2007.
- Beltaos, S., Hulley, M., Keene, B., and Watt, E. 2007. Frazil-ice Flooding and Potential Mitigation: Moira River at Belleville, *In* Proceedings of the 14th Workshop on the Hydraulics of Ice Covered Rivers, Quebec City, Quebec, June 19-22, 2007.
- Exp Services Inc. 2013. Lower Spencer Creek Frazil Ice Flooding Cost Benefit Analysis of Mitigation Alternatives. Brampton, Ontario.
- Gholamreza-Kashi, S., Nelson, H., Ragaz, P., and Breton, H. 2011. Lower Spencer Creek Frazil Ice Flooding: A Case Study. *In* Proceedings of the 16th Workshop on River Ice, Winnipeg, Manitoba, September 18-22, 2011.
- Hatch Acres 2006. Former Town of Durham Frazil Ice Study. Niagara Falls, Ontario.
- Quinte Conservation 2008. Quinte Region Watershed Characterization. Belleville, Ontario.
- Shen, H.T., Liu, L. 2003. Shokotsu River Ice Jam Formation. Cold Regions Science & Technology, **37**(1): 35-49.
- Sui, J., Karney, B.W., Sun, Z., Wang, D. 2002. Field Investigation of Frazil Ice Evolution: A Case Study. Journal of Hydraulic Engineering, **128**(8): 781-787.

- Woodhouse, T.R. 1967. Flooding in Dundas: A Summary of Historical Notes on Floods between 1847 and 1965. Hamilton Region Conservation Authority, Hamilton, Ontario.
- Zufelt, J.E. and Bilello, M.A. 1992. Effects of Severe Freezing Periods and Discharge on the Formation of Ice Jams at Salmon, Idaho. Cold Regions Research & Engineering Laboratory Report 92-14, United States Army Corp of Engineers, Hanover, New Hampshire.

Draft

Table 1. Climate normals for the City of Hamilton

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Temperature:												
Daily Average (°C)	-6	-5.2	-0.3	6.3	12.9	18	20.8	19.8	15.5	9.1	3.3	-2.7
Daily Maximum (°C)	-2.2	-1.2	4	11.2	18.5	23.7	26.3	25.1	20.7	13.8	7	0.9
Daily Minimum (°C)	-9.7	-9.1	-4.5	1.2	7.3	12.4	15.1	14.5	10.2	4.4	-0.4	-6.2
Precipitation:												
Rainfall (mm)	29.5	25.7	48.6	69.6	75	83.9	86.5	80.6	82.1	71.6	68.1	43.7
Snowfall (cm)	43.2	35.2	25.8	8.6	0.5	0	0	0	0	0.6	11	36.8
Precipitation (mm)	65.8	55.3	74.8	78	75.6	83.9	86.5	80.6	82.1	72.5	78.6	76.6
Days with Minimum Temperature:												
> 0 °C	1.8	2.1	6	17.9	30.1	30	31	31	29.8	26.5	13	3.9
<= 2 °C	30.4	27.7	28.3	17.5	3.2	0.1	0	0	0.97	9.6	22	29.6
<= 0 °C	29.2	26.2	25	12.1	0.87	0	0	0	0.17	4.5	17	27.1
< -2 °C	26.6	23.2	19.8	6.3	0.03	0	0	0	0.03	1.6	10.6	22.2
< -10 °C	14.5	12.5	5.2	0.23	0	0	0	0	0	0	0.37	7.7
< -20 °C	1.8	1.1	0.1	0	0	0	0	0	0	0	0	0.37
< -30 °C	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1. Frazil ice accumulation in Spencer Creek (Source: HCA)

Figure 2. Study area map (Source: Land Information Ontario)

Figure 3. Frazil ice flooding in (a) January 2005; and (b) January 2009 (Source: HCA)

Figure 4. Average daily discharge for Spencer Creek (Source: Water Survey of Canada)

Figure 5. Flow and temperature data for January 2005

Figure 6. Flow and temperature data for January 2009

Figure 7. Flow and temperature data for February 2008

Figure 8. 5-day DDF and Mass Flow Curves for January 2005

Figure 9. 5-day DDF and Mass Flow Curves for January 2009

Figure 10. 5-day DDF and Mass Flow Curves for February 2008

Figure 11. Joint occurrence of Jan. and Feb. discharge and temperature indices from 1969 to 2011

Figure 1. Frazil ice accumulation in Spencer Creek (Source: HCA)
143x108mm (220 x 220 DPI)

Figure 2. Study area map (Source: Land Information Ontario)
302x181mm (96 x 96 DPI)

(a)

(b)

Draft

Figure 4. Average daily discharge for Spencer Creek (Source: Water Survey of Canada)
156x88mm (96 x 96 DPI)

Figure 5. Flow and temperature data for January 2005
238x161mm (96 x 96 DPI)

Figure 6. Flow and temperature data for January 2009
238x161mm (96 x 96 DPI)

Figure 7. Flow and temperature data for February 2008
238x161mm (96 x 96 DPI)

Figure 8. 5-day DDF and Mass Flow Curves for January 2005
240x174mm (96 x 96 DPI)

Figure 9. 5-day DDF and Mass Flow Curves for January 2009
240x174mm (96 x 96 DPI)

Figure 10. 5-day DDF and Mass Flow Curves for February 2008
240x174mm (96 x 96 DPI)

Figure 11. Joint occurrence of Jan. and Feb. discharge and temperature indices from 1969 to 2011
240x175mm (120 x 120 DPI)