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Lower Spencer Creek Frazil Ice Flooding: A Case Study

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This study examines the underlying causes of flooding due to frazil ice accumulation along the lower reach of Spencer Creek in Hamilton, Ontario and investigates potential mitigation measures. Hydro-meteorological data during the past flooding events are collected and analysed. Hydraulic characteristics of the river, including the operating procedures of the dams within the study reach, are studied. A field investigation is completed to observe the effect of the river morphology on the generation of frazil ice and to assess potential locations for establishing mitigation measures. Potential measures to prevent or reduce frazil ice generation and accumulation and subsequent flooding are evaluated based on their feasibility, environmental effects, and cost.

1. Introduction

In January 2011, Hamilton Conservation Authority (HCA) retained **exp** (the new identity of Trow Associates) to undertake a study on frazil ice accumulation along the lower reach of Spencer Creek, which has caused flooding within the former Town of Dundas on several occasions (Figure 1).

Figure 1. Frazil ice in Spencer Creek (January 2005).

1.1. *Frazil Ice*

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).

Figure 2. Spencer Creek segment: open water in December (left); ice cover in February (right).

An ice cover, as shown in Figure 2, can reduce heat loss from the water to the atmosphere, thereby decreasing the rate of frazil ice generation (Beltaos et al., 2007). In fast moving sections of a river, the hydrodynamic forces of high flow prevent the formation and development of ice cover.

1.2. *Study Area*

Spencer Creek is the major watercourse within the Hamilton Conservation Authority’s jurisdiction 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. Three dams are located within the Spencer Creek watershed, namely Valens Dam, Christie Lake Dam, and Crooks Hollow Dam.

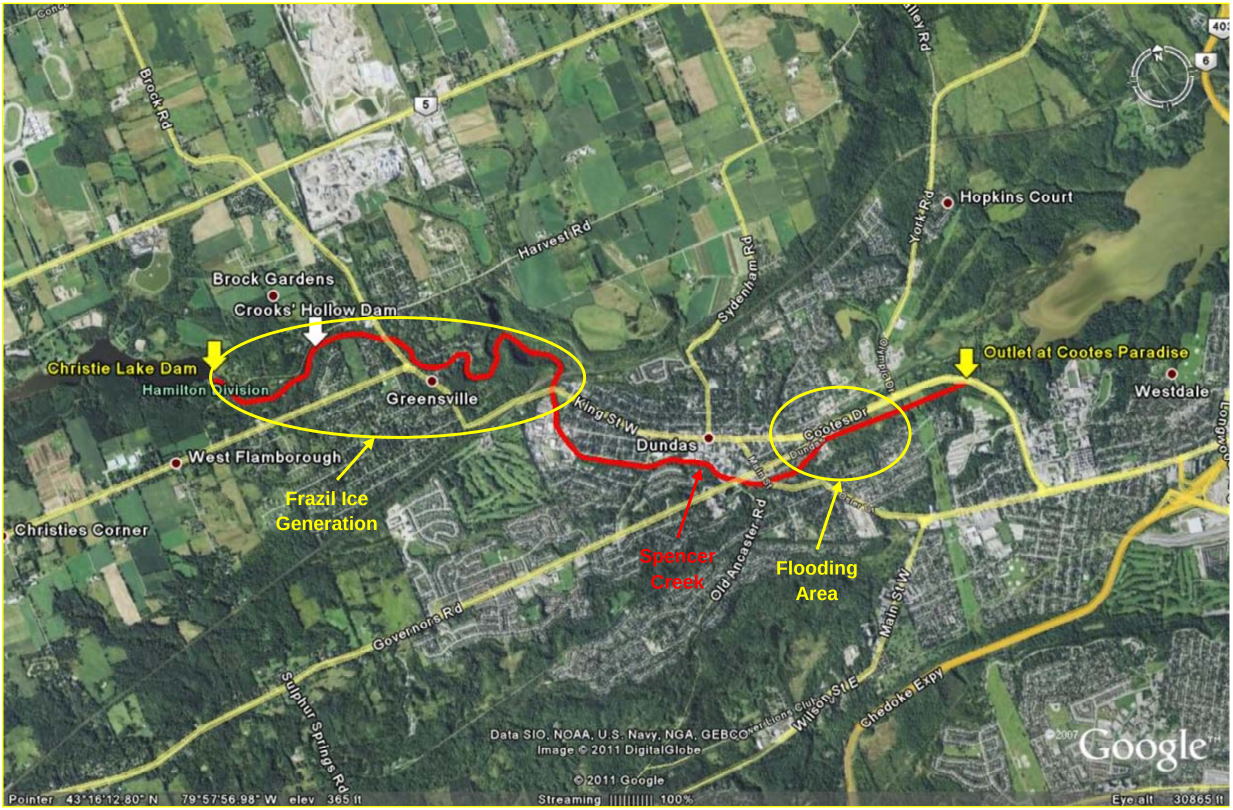

Figure 3. Study area along Spencer Creek.

The study area consisted of Spencer Creek and its floodplain between Christie Lake Dam and the river outlet into Cootes Paradise. The steep channel gradient 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 lower reach of Spencer Creek, where the gradient of the channel is low, and at bridges and culverts. The study area is shown in Figure 3.

1.3. *Objective*

The objective of this study is twofold: to identify the underlying causes of frazil ice generation and accumulation along Spencer Creek, and to evaluate measures to decrease the generation of frazil ice and to prevent the resultant ice jams and/or reduce their impacts.

To meet this objective, background information and previous studies were collected and reviewed, a field investigation of the study area was conducted, the hydraulic characteristics of the river within the study reach were investigated, and alternative mitigation measures, including associated costs, were evaluated.

2. Hydro-meteorological Data

Historical and event based climate and flow data for Spencer Creek and their effect on frazil ice generation and accumulation were investigated.

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

2.1 *Historical Data*

The climate normals for the City of Hamilton are summarized in Table 1. This information is provided by Environment Canada based on the data collected from the Hamilton A Station (ID #6153194). 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 data was collected from the Water Survey of Canada's gauge at Market Street (Station 02HB007). 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.

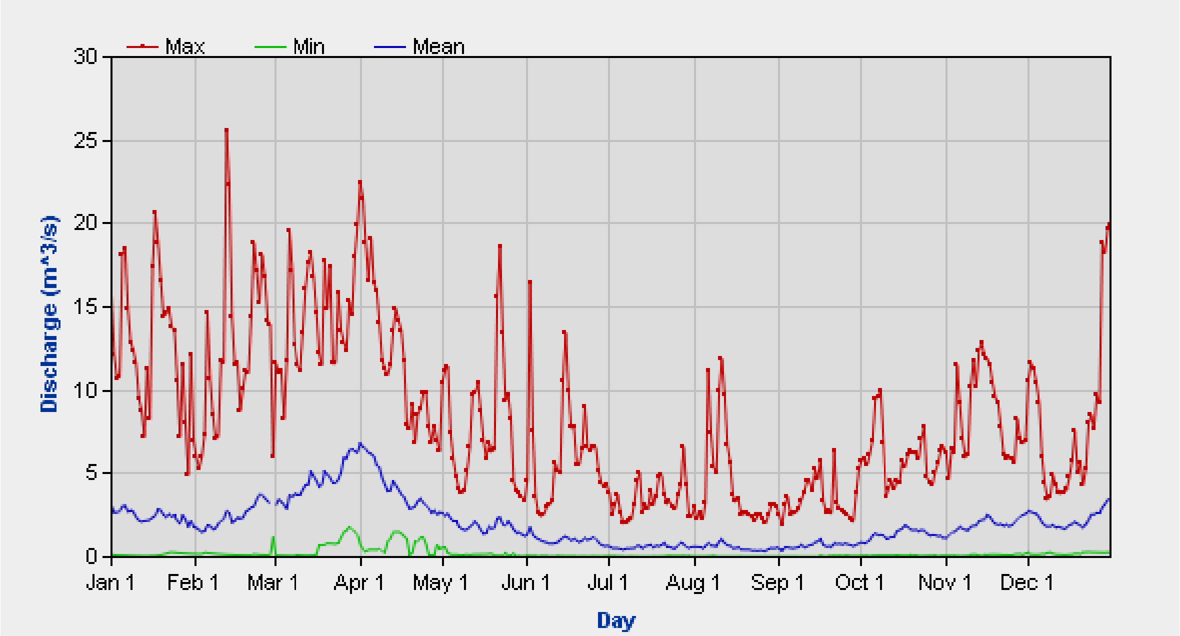

Figure 4. Average daily discharge for Spencer Creek.

2.2 *Data during Flooding Events*

Two recent flooding events caused by frazil ice accumulation occurred in January 2005 and January 2009 within the former Town of Dundas.

Flow rates and temperatures for Spencer Creek at Market Street for January 2005 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 cms between January 13 and 16. Subsequently, a cold snap began around January 14, with temperatures falling to -20 °C and a wind chill of -30 °C, which lasted for several days. Meanwhile, the flow rate in Spencer Creek decreased to approximately 2 cms.

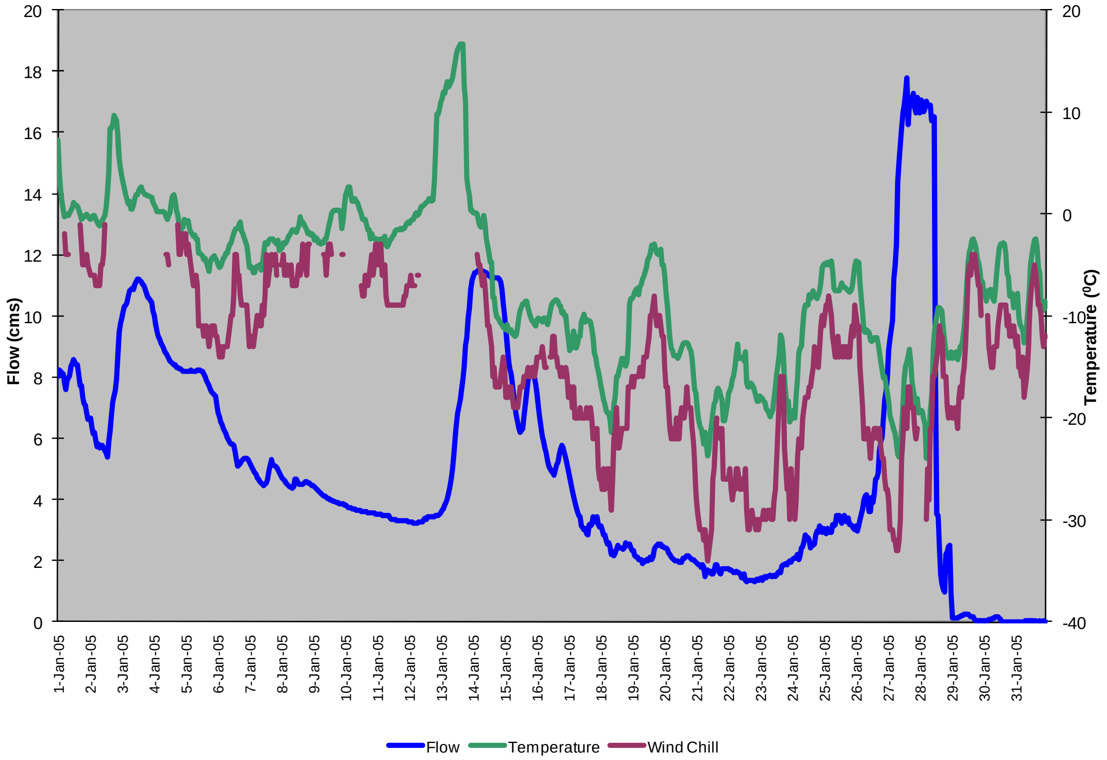

Figure 5. Flow and temperature data for January 2005.

Ice cover can form on Spencer Creek at various locations during the winter months (Figure 2). 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). 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 flow rates and temperatures for Spencer Creek at Market Street for January 2009. A cold snap was experienced beginning around January 14 with the temperature falling to -20 °C with a wind chill of -30 °C, which was 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.

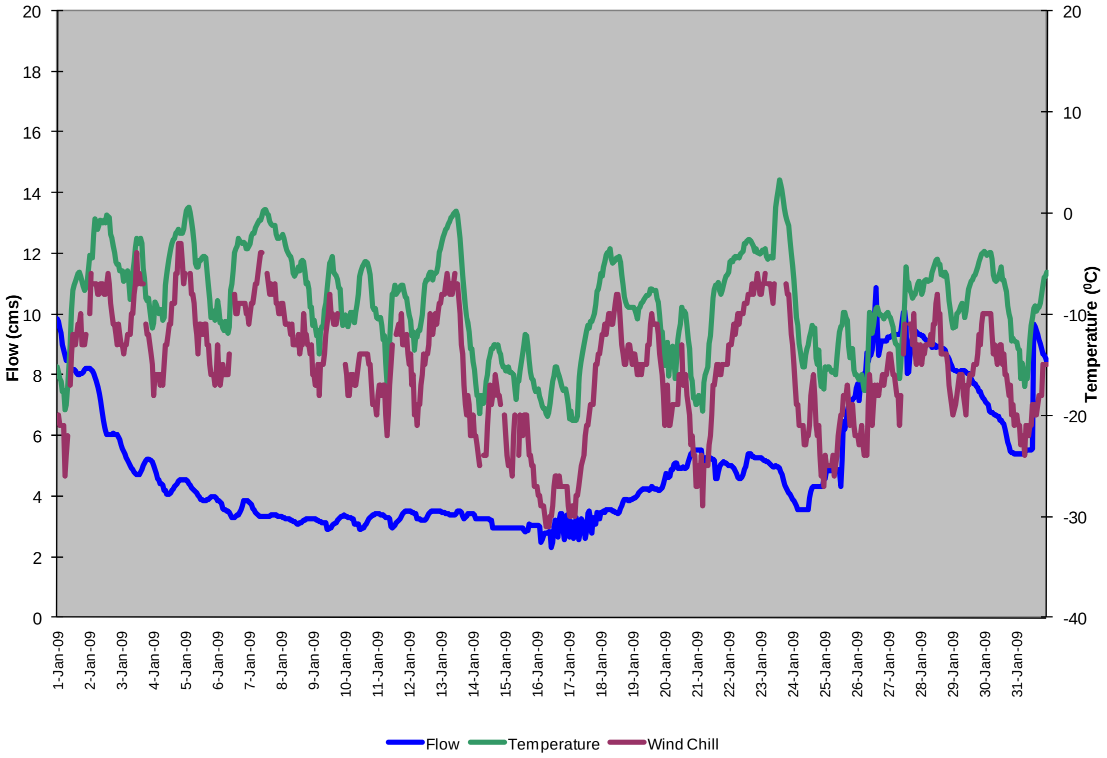

Figure 6. Flow and temperature data for January 2009.

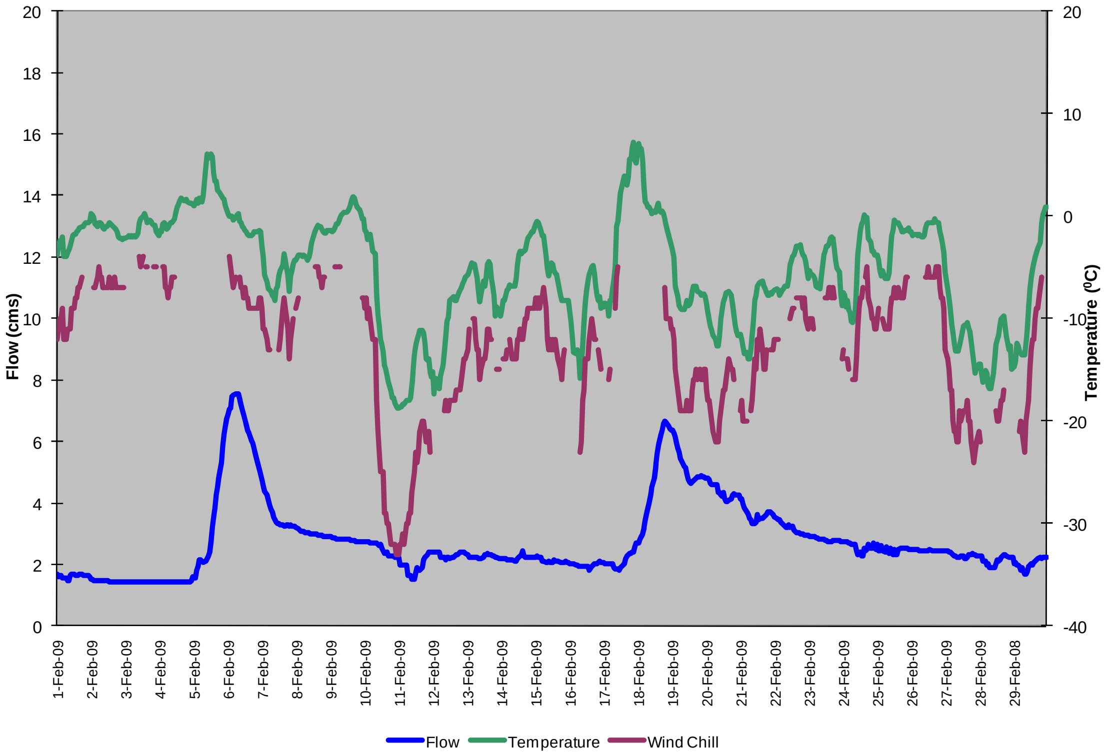

Figure 7. Flow and temperature data for February 2008.

Flow rates and temperatures for Spencer Creek at Market Street for February 2008 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 cms. 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 cms, was immediately followed by temperatures below -10 °C. This cold snap was 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.

3. Hydraulic Characteristics

3.1. *Channel Morphology*

Spencer Creek channel cross section is typically 10 m wide with vegetated banks. The longitudinal profile of Spencer Creek downstream of the Christie Lake Dam is shown in Figure 8. The river is divided into four sections based on their average channel gradient.

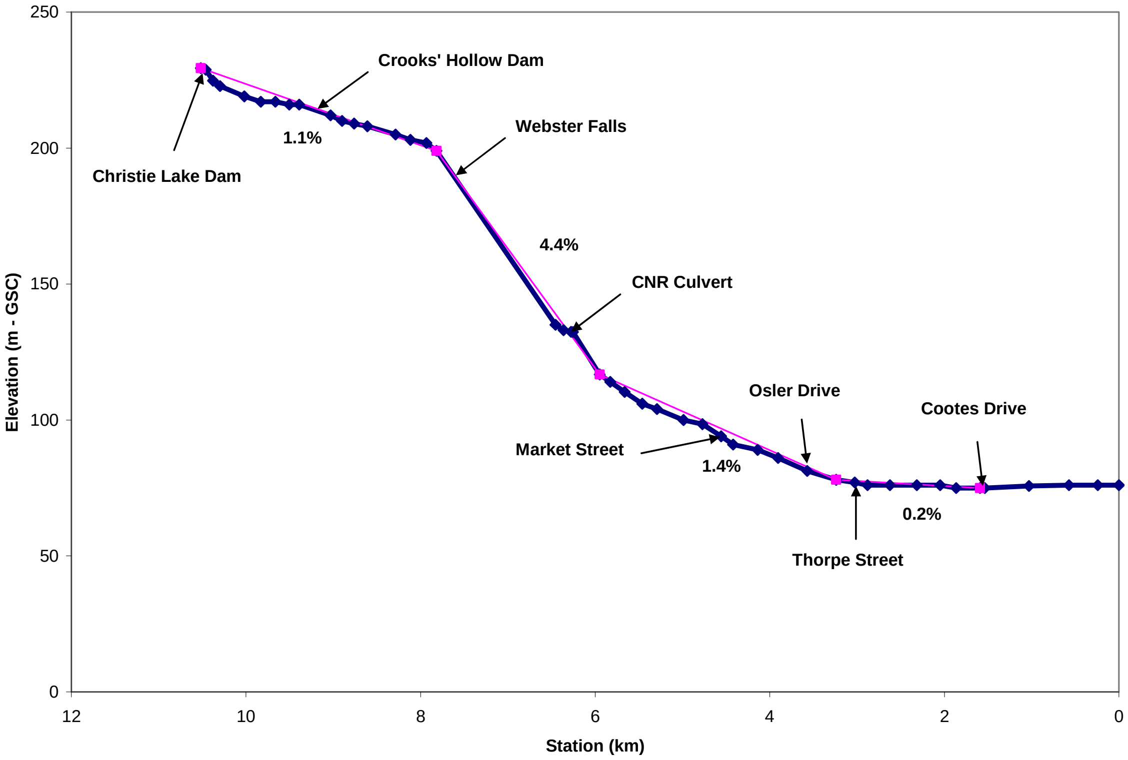

Figure 8. Spencer Creek longitudinal profile.

From downstream of the Christie Lake Dam to upstream of Webster Falls, Spencer Creek average channel gradient is about 1.1%. From this point to downstream of the CNR Culvert, where Spencer Creek descends the Niagara Escarpment, the channel is relatively steep with an average gradient of 4.4%. The channel average gradient between the CNR Culvert and Osler Drive is about 1.4%. At this point the channel becomes relatively flat, with an average gradient of 0.2%.

The relatively steeper upper and middle sections are suitable for frazil ice generation because high velocities and turbulence inhibit ice cover formation and induce the supercooling of the flow. There are rapids and waterfalls within this reach of Spencer Creek, including Webster Falls.

Downstream of Osler Drive, the channel gradient of Spencer Creek is considerably reduced. This change in channel gradient reduces the flow velocity, providing an opportunity for the frazil ice to accumulate and block the channel.

3.2. *Dam Operations*

There are two dams located within the study area on Spencer Creek: Christie Lake Dam and Crooks' Hollow Dam.

Christie Lake Dam, located at the upstream limit of the study area, is the largest flood control structure within the Spencer Creek watershed with a reservoir storage capacity of 228 ha-m. The reservoir water level and the outflow from the dam are controlled by an overflow spillway, two radial gates, and a low flow outlet structure (Trow Associates Inc., 2005).

Crooks’ Hollow Dam is located approximately 1.2 km downstream of the Christie Lake Dam. The dam is not operated for flood control and hence does not have any significant active storage. As a result, the dam passes the Christie Lake Dam outflow with minimal flow attenuation. A Class Environmental Assessment completed in 2009 concluded that the Crooks’ Hollow Dam should be removed (Hatch, 2009). Removal of this dam can increase the channel gradient at this section of the river, thereby increasing the potential for frazil ice generation. This increase is not likely to exacerbate the problem downstream, considering the steep gradient of the channel downstream of the Crooks’ Hollow Dam.

4. Mitigation Measures

There are a number of different approaches utilized throughout Southern Ontario to address frazil ice flooding (Hatch Acres, 2006, Beltaos et al., 2007). These include methods to prevent or reduce the frazil ice generation and accumulation and measures to mitigate or control the impacts of flooding. Some of these measures were evaluated in this study based on feasibility, environmental effects, and cost of implementation along Spencer Creek.

4.1 *Ice Cover Formation*

In areas of open water upstream of an ice cover, the incoming frazil ice may be arrested at the edge of the ice cover. The ice cover can progress upstream by stable accumulation of frazil ice.

The Froude number can be used as a measure of stability of frazil ice accumulation at the upstream edge of an ice cover. If the Froude number at the upstream edge exceeds a critical value, the frazil ice will not be incorporated into the ice cover, but will be submerged and carried away under the ice cover and eventually accumulate downstream or bond to the underside of the ice cover.

The critical Froude number varies from case to case. Using a void ratio of 0.5 for the frazil ice, the maximum F_C for stable frazil ice accumulation can be calculated to be 0.1 (Ashton, 1986). Sui et al. (2002) used field measurements and developed an empirical relationship to estimate a critical Froude number of 0.075. For practical purposes, a value of $F_C = 0.08$ has been proposed by other studies (Beltaos et al., 2007).

Low-head weirs can be installed at locations with moderate channel gradient to encourage the formation of an ice cover by reducing the Froude number on the upstream side of the weir. The approximate height of the weir required to achieve a Froude number of 0.08 can be calculated.

The use of ice barriers (i.e. ice boom) can also encourage the formation of an ice cover. An ice barrier is most effective in flat sections of a river, where the flow velocity is relatively low and the ice cover can progress upstream. Installing a permanent boom in the river may be deemed to interrupt navigation, in which case a seasonal ice boom may be considered.

Openings can be installed through the low-head weir to minimize the environmental impact and fish habitat disruption. There is no significant environmental impact associated with an ice barrier, except for the disturbance that can occur during the installation and maintenance of the boom. The cost of installation of low-head weirs and ice barriers is relatively low. For a low-head weir, the cost of completing a Class Environmental Assessment should be considered as well. For a seasonal ice boom, there will also be the cost of removing and reinstalling the boom.

4.2 *Dam Operation*

One approach to mitigate frazil ice flooding is to store the generated ice in a reservoir (i.e. at a flow control structure). Since the frazil ice in Spencer Creek is mainly generated downstream of the Christie Lake Dam, and since the Crooks' Hollow Dam is scheduled to be removed, this approach will not be applicable to this study.

Large runoffs resulting from snowmelt can be controlled by dam operation. Minimizing the outflow by modifying the operating procedures at the Christie Lake Dam during the winter months can reduce the flow velocity and turbulence in the downstream reach and lower the potential for frazil ice generation.

When frazil ice accumulation occurs in the downstream reach during low flow conditions, the discharge from the Christie Lake Dam can be increased to flush the accumulated ice and carry it downstream. The dam outflow should not be increased to flow levels that may contribute to further generation of frazil ice, ice cover break up, or flooding downstream. Downstream conditions need to be closely monitored to determine if the flow increase has the desired effect.

The environmental impact associated with modifying the dam operation will be minimal, since there will be little change to the overall downstream flow. The cost of modification to the dam operation will consist of salary and expenses of staff required to operate the dam over and above the normal winter operation.

4.3 *Localized Measures*

Using thermal bubbler plumes is a simple method to control ice in slowly moving water. In this method, air bubbles are generated to create a rising plume. The plume can entrain heat from the warmer layers near the bottom, bring it up to the surface, and transfer it to the ice (Baddour, 1990). This method is most effective in deep waters, where the temperature gradient between the bottom and the surface is considerable, unless the air bubbles are externally heated.

The flow temperature can also be locally raised by providing an available heat source, such as treated sewage water. This approach can be very expensive if a heat source is not readily available.

These techniques can help keep the water around road crossings clear from ice, and hence, prevent frazil ice accumulation and the resulting ice jam at the site. However, the frazil ice can still accumulate further downstream resulting in an ice jam.

There can be environmental concerns associated with heating of the water, such as disturbing the aquatic habitat. The cost for installing a bubbler system is relatively low, however, the ongoing energy cost to operate the system should be considered. By closely monitoring the condition of frazil ice generation and accumulation, the bubbler system can be activated only when required, in which case the energy cost will be lower.

4.4 *Dyke and Bypass Channel*

Dykes with bypass channels can be constructed at locations susceptible to frazil ice accumulation to facilitate the flow of the frazil ice downstream and to divert the flow away from developed areas.

A dyke and a bypass channel can also be used as a temporary measure to contain overbank spillage. An example is the temporary channel that was created during the January 2005 flooding event by constructing a snow berm to re-route the flood flow back into Spencer Creek. When snow is not available, other materials such as Jersey barriers or sand bags can be used.

There will be environmental impacts associated with creating a bypass channel, including terrestrial and aquatic habitat disruption. The cost for constructing a bypass channel, including the cost for disposal of the excavated material, is relatively high. The cost of completing a Class Environmental Assessment should be considered as well. Creating temporary bypass channels using physical barriers such as Jersey will have a relatively low cost.

4.5 *Mechanical Removal and Storage*

When other approaches are inadequate to prevent frazil ice from blocking the river channel, the ice can be removed from the channel using mechanical equipment such as excavators or suction dredges. This approach was proven an effective reactive measure during the past flooding events along Spencer Creek.

The mechanical removal of ice can potentially disrupt terrestrial and aquatic habitat. The cost for mechanical removal of frazil ice depends on the volume of the ice to be removed over the period of potential risk.

6. Conclusions and Recommendations

Flooding due to frazil ice accumulation and the subsequent ice jam is a recurring problem in the lower reach of Spencer Creek. Measures to prevent or reduce the generation and accumulation of frazil ice and to mitigate the impact of flooding can be undertaken. These measures can be implemented at various locations along Spencer Creek.

A formulation for estimating the potential of occurrence for frazil ice flooding should be developed by analysing several years of flow and weather data and correlating them to those collected during the past flooding events. The existing monitoring program to issue flood warnings and to trigger appropriate actions to mitigate flooding should be expanded to include the developed formulation.

Test sections can be installed at critical locations along Spencer Creek in order to experimentally evaluate the performance of various mitigation measures.

Acknowledgments

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