Analysis of Ice Jam Surge and Ice Velocity Data

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Ground based and aerial observations of break-up on the Porcupine and Yukon Rivers were used to study the interaction of water and ice in surges resulting from the release of ice jams. The surges studied were of the type where open water conditions existed downstream of these jams. A qualitative description of the water-ice interaction was presented as well as quantitative data showing water and ice celerities for one detailed set of observation on the Porcupine River. This study has yielded insight into how the ice concentrations disperse over time and distance and the role this may play in augmenting the shape, magnitude, and timing of the resulting flood wave.

1. Introduction

Over the past decade, conventional unsteady flow models did not consider the frictional resistance of the ice when modeling the release of an ice jam. In Gerard et al (1990) and McKay and Hicks (1996), the ice jam profile was calculated, but upon release, it was assumed that the entire ice jam profile was made up of water only. The ability to model this ice-water interaction has been increasing over the last few years through advancements by Shen et al. (1994), Zufelt and Ettema (1997), and Daly and Hopkins (1998). These models that do simulate this behavior need data for calibration. It is the aim of this paper to provide such data and provide insight into the ice-water interaction. As well as presenting quantitative data, this paper will also qualitatively describe the effect of the ice particles or ice concentrations on the water surface profile of the surge.

Ice jam surges occur under two types of scenarios, those with open water downstream, and those with solid ice downstream. This paper will concentrate on the former as it was more commonly observed on the Porcupine and Yukon Rivers. Both types of scenarios are equally important as either can contribute to flooding.

2. Data Collection Program

The Department of Indian & Northern Affairs Canada has been conducting river ice break-up monitoring in the Yukon Territory. This function assists in providing early warning to the Town of Dawson City and the Village of Old Crow on the Yukon and Porcupine rivers respectively against potential ice jam flooding. Both ground based and aerial data is collected.

Ground based data consists of water surface elevation, ice conditions, and ice concentrations. Water level information is recorded every 2 minutes via a data logger and bubbler system. Manual water level readings are conducted daily or as needed to ensure gauge corrections can be applied should the orifice line change elevation. Ice conditions whether, solid, running, jammed, or open water are recorded in a notebook. An automatically triggered camera photographs the river surface every 20 minutes. Ice concentrations are subjectively estimated from these photographs as a percentage of the water surface area.

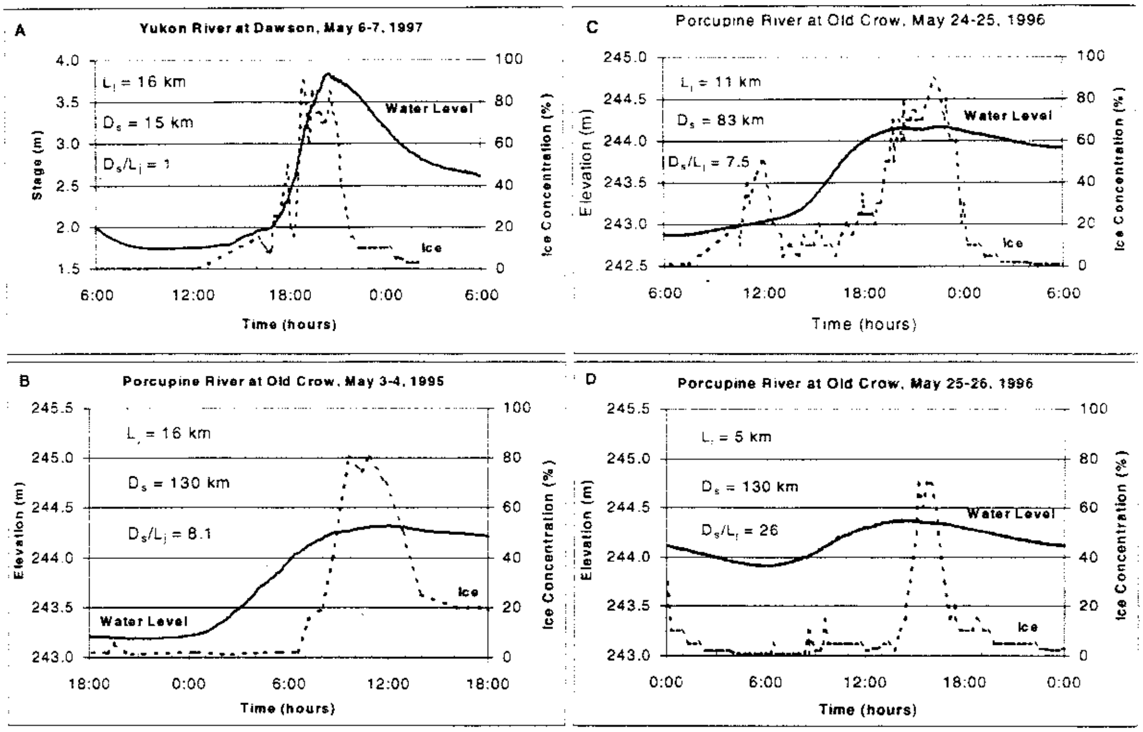
Air reconnaissance surveys are done at least once daily. The information collected during these surveys consists of photographs, video, map notated ice conditions and in the case of running ice, ice concentrations. The location and length of ice jams is recorded and on occasion one is fortunate enough to record the time of their release.

3. Analysis of Water Level and Ice Concentration Data

Surges resulting from the release of ice jams are often complicated by other events on the river. Furthermore, the data can also at times be incomplete. For these two reasons, break-up data for the Yukon and Porcupine Rivers were reviewed for "ideal and data rich" ice jam surge events. Five years of data was examined on the two rivers covering the period from 1994 through 1998. Data on 13 and 17 surges were found on the Yukon and Porcupine Rivers respectively. Each were examined for acceptance in the analysis based on the following criteria:

1. Open water conditions had to exist downstream of the released ice jam and at the water level and ice concentration measurement location.
2. Any ice jams downstream of the measurement location had to be far enough downstream so the backwater effect from them would be minimal.
3. Both water level and surface ice concentration had to be measured at the same location downstream of the failed ice jam.
4. The release of the jam could not be complicated by the release of another jam, a break-up of a major tributary, or a rapid rise in base discharge.
5. The length of the jam prior to its release had to be known or easily estimated.

Of the 30 ice jam generated surges examined, only 4 met these "ideal and data rich" requirements. Figure 1-A through 1-D show the water level and ice concentration data attributed to these 4 surges.


A Yukon River at Dawson, May 6-7, 1997

C Porcupine River at Old Crow, May 24-25, 1996

B Porcupine River at Old Crow, May 3-4, 1995

D Porcupine River at Old Crow, May 25-26, 1996

Figure 1. Water level and ice concentrations recorded for 4 surges on the Yukon and Porcupine Rivers. L_j is the initial ice jam length. D_s is the distance the surge has traveled. Although other variables may be important, generally, the more jam lengths (D_s / L_j) the surge has traveled, the more the water level peak moves ahead of the peak ice concentration.

To obtain insight on how the water and ice components of the surges may be interacting, the length of ice jam before its release (L_j) and the distance the surge had traveled (D_s) were obtained. The dimensionless ratio D_s/L_j (the number of "jam lengths" the surge had traveled) was useful when comparing the 4 surges.

Figure 1-A shows that after a surge had traveled only a short distance (one jam length in this case), the majority of the ice concentration was on the rising limb of the surge. The ice concentration rose rapidly very soon after the water level started to rise, and the ice concentration dropped off rapidly after the surge crest had past.

After travelling 8.1 jam lengths, Figure 1-B shows that the water level started to rise long before the ice concentration started to increase. The majority of the ice concentration was still on the rising limb of the surge but near its crest.

After travelling 7.5 jam lengths, Figure 1-C shows that the majority of the ice concentration was centered around the crest of the surge.

After travelling 26 jam lengths, Figure 1-D shows that the majority of the ice concentration was still near the crest but on the falling limb side of the surge.

In summary, Figure 1 shows that shortly after an ice jam release, the peak ice concentration is ahead of the peak water level, however given enough travel distance the surge crest eventually overtakes the peak ice concentration. There is some discrepancy in the conclusion if one examines Figures 1-B and C. The two D_s/L_j are 8.1 and 7.5 respectively, but one would expect the peak ice concentration to be further behind the surge crest in the former. This is not the case. Clearly there are other important parameters that are not addressed by the dimensionless ratio D_s/L_j. A few that come to mind are the ice jam thickness, ice jam volume, the base discharge, channel slope and width. It also appears that the ice jam in 1-C may have released more slowly then in 1B and perhaps in two sections as evidenced by the slight double crest. The "suddenness" of the jam release may therefore play a role in how the water and ice components of the surge interact.

4. A Qualitative Description of the Surge-Ice Interaction

The water level, ice concentrations, and aerial survey information in Section 3 provide at the very least a conceptual model of how the ice and water components interact following the release of an ice jam. Figure 2 illustrates this conceptual model.

Figure 2-A shows the ice jam at the moment if its release. In Figure 2-B and 2-C the majority of the jam is moving as one single unit (it is essentially a moving ice jam), while some pieces of ice accelerate away from the toe of the jam. The water component of the surge front accelerates even faster and is well ahead of the leading piece of ice.

Figure 2-C and 2-D show the "moving jam" getting shorter as pieces of ice keep accelerating away from its downstream end. Figure 2-D shows a key transition point during the evolution of an ice jam surge; the length of the "moving jam" is nearing zero. Up to this point there has been significant bank friction since confining stress of the moving accumulation is present. The peak water level or surge crest has essentially been held back and slowed by this "extra" bank friction. The upstream end of the 100% ice concentration corresponds closely to the peak water level.

Figure 2-E shows the surge shortly after there is no "moving ice jam" portion remaining. The confining stress has been removed and the surface ice concentration begins to fall below 100%. The extra friction, which was moving along with the surge, has been removed allowing the surge to flatten and diffuse. The peak ice concentration moves along with the surge crest for a considerable distance.

As the surge continues to travel, the maximum ice concentration peak slowly starts to fall behind the crest as shown Figure 2-F. Aerial observations have indicated a reason why this may be happening. It has been observed that particles of ice tend to be drawn to the outside of channel bends causing them to rub against the bank. This friction may be enough to slow them down below the mean velocity of the surge causing the peak ice concentration to travel slightly slower than the surge crest. Furthermore, since the

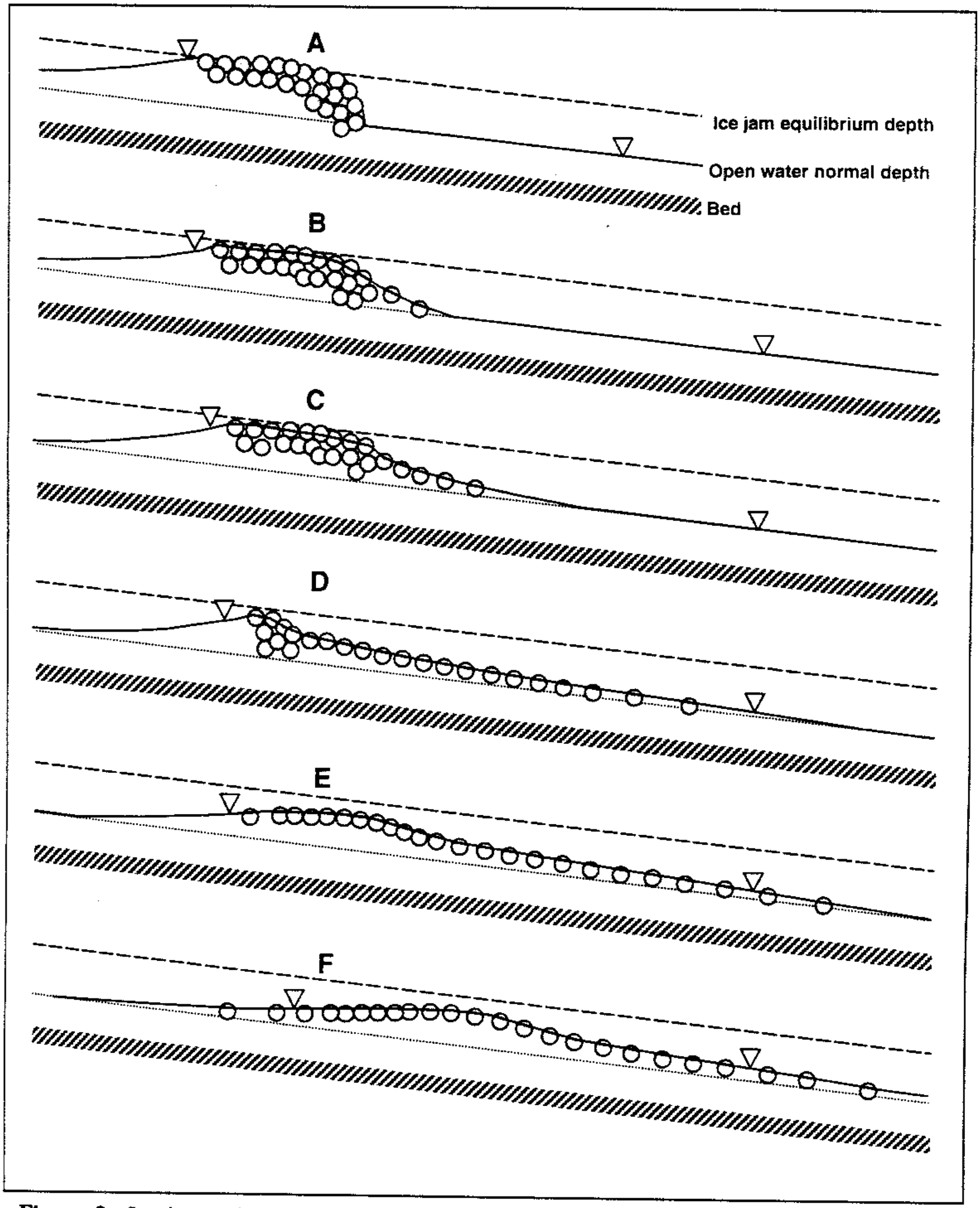


Figure 2. Ice jam release (A) and the resulting surge showing the behavior of the ice and water components (B-F). Frame of reference is moving with the surge. Open water conditions downstream of jam.

particles of ice are drawn to the outside of the channel bends, their path of travel may be longer than the mean path travel for the entire channel.

5. Surge and Ice Celerity Components

Before analyzing some quantitative data, it is useful to define some of the surge and ice celerity components of an ice jam surge. All components will be referred to as "celerities" even though some may in fact be "velocities". It is safer to do so since the velocity of any one piece of ice or the water was never explicitly measured.

Referring to Figure 3:

C_{Fw} = Celerity of the first water level increase

C_{Fi} = Celerity of the first pieces of ice

C_{Fi100} = Celerity of the downstream extent of ice run where ice concentration is 100%

C_{c100} = Celerity of crest water level while ice concentration remains at 100%

C_{Li100} = Celerity of the upstream extent of ice run where ice concentration is 100%

C_c = Celerity of crest water level after ice concentration falls below 100%

C_{icemax} = Celerity of the maximum point of ice concentration after the peak ice concentration falls below 100%

C_{Li} = Celerity of the last pieces of ice

6. Quantitative Data on Surge and Ice Celerities

On May 3 and 4 of 1995 an ice jam surge release was documented on the Porcupine River. A detailed description of the break-up can be found in Jasek (1996). McKay and Hicks (1996) performed an unsteady flow simulation of this surge using a cdg-1D hydraulic flood routing model.

Although the data obtained from this surge was not complete, it was the most extensive available in the Yukon from the departments database. A summary of the observations is as follows:

1. The moment of release of the 15 km long ice jam was observed from the air.
2. The stage was recorded about 7 km downstream of the released ice jam.
3. The ice concentrations were documented from the air after the surge had traveled about 40 km.

4. The ice concentrations were documented from the air after the surge had traveled about 120 km.
5. The stage and ice concentrations were recorded about 130 km downstream of the *released ice jam.*

Graphical representation of the data collected above can be found in Jasek(1996).

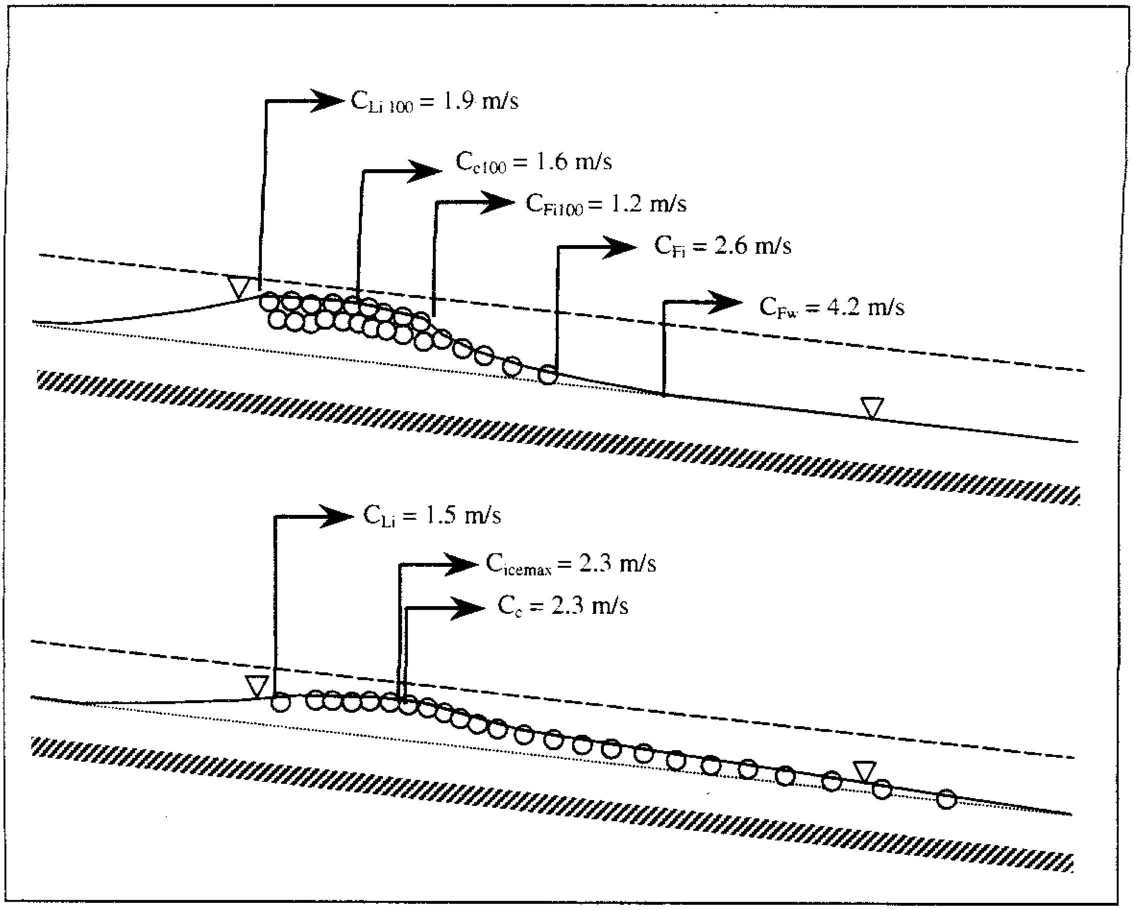


Figure 3. Diagram indicating water and ice celerity components of an ice jam surge. The values corresponding to each variable were obtained from the 1995 break-up of the Porcupine River.

The surge and ice celerities obtained from these observations are shown in Figure 3. Of particular interest from a flood forecasting point of view, are the celerities of the maximum water level or surge crest C_{c100} and C_c, the values of which are 1.6 and 2.3 m/s respectively. This shows that in this case, the celerity of the maximum water level sped up 1.44 times after the ice concentration fell below 100%.

Also shown was that the front of the surge traveled much faster than the ice. Jasek(1996) showed that at a point 140 km downstream of the released ice jam, the first stage increase (C_{Fw}) arrived 6 hours after the first ice (C_{Fi}). By the time this first ice arrived, the total stage increase as a result of this surge had reached 80% of its peak value. This has important implications to aerial flood monitoring efforts. As C_{Fw} is invisible from the air then the only visible evidence of an approaching surge is C_{Fi}. This may give a false impression that there is more time than actual before the discharge starts to increase at a particular point of interest downstream.

A good way to summarize the celerity information is through the use of a celerity diagram (Figure 4). Although the celerities have been drawn as straight lines, it is likely that they should be curves, especially at the onset of the jam release. However, the limited number of observations did not allow for this refinement. Therefore, these celerities can be regarded as time and distance averaged.

An important point of interest in Figure 4 is the point and time where the peak ice concentration starts to fall below 100%, about 6.5 hours after the jam release. This seems to be a transition point for the peak water level celerity speed. The celerity C_{c100} of 1.6 m/s increases to C_c of 2.3 m/s, a 44% increase. Of particular note is that the jam has traveled almost 3 jam lengths for the ice concentration to start falling below 100%.

After the ice concentration fell below 100%, the peak ice concentration C_{icemax} and the surge crest C_c traveled at the same speed. Data from other surges suggests that the peak ice concentration travels slightly slower than the surge crest. It is possible that a small surge from the Bell River which triggered the release of the jam in the first place, had caused the two celerities to travel along together for a longer period than otherwise would have occurred in the more "ideal' case.

The celerity of the last ice is also shown in Figure 4. The arrival of the small quantity of the Bell River ice at the upstream end of the surge made the accurate determination of this celerity difficult. The celerity of the last ice C_{Li} was about 1.5 m/s, slower than the celerity of the maximum ice concentration C_{icemax}, 2.3 m/s.

Although this documented ice jam release event is one of the most detailed to date, there are some aspects about the case that are somewhat less than the "ideal release of an ice jam in an ideal channel". These deviations from "ideal" should be kept in mind when comparing this data to numerical or physical modeling work. Here are some of them:

1. The release of this jam appeared to be caused by the break-up of the Bell River, a tributary to the Porcupine River a few kilometers upstream of the jam. Although the jam released before the Bell River ice arrived, it probably did produce a condition where the base discharge was increasing behind the surge. However, the amount of ice produced by the Bell River paled in comparison to the amount in the jam on the Porcupine River. Therefore, it is likely that most of the "ideal"

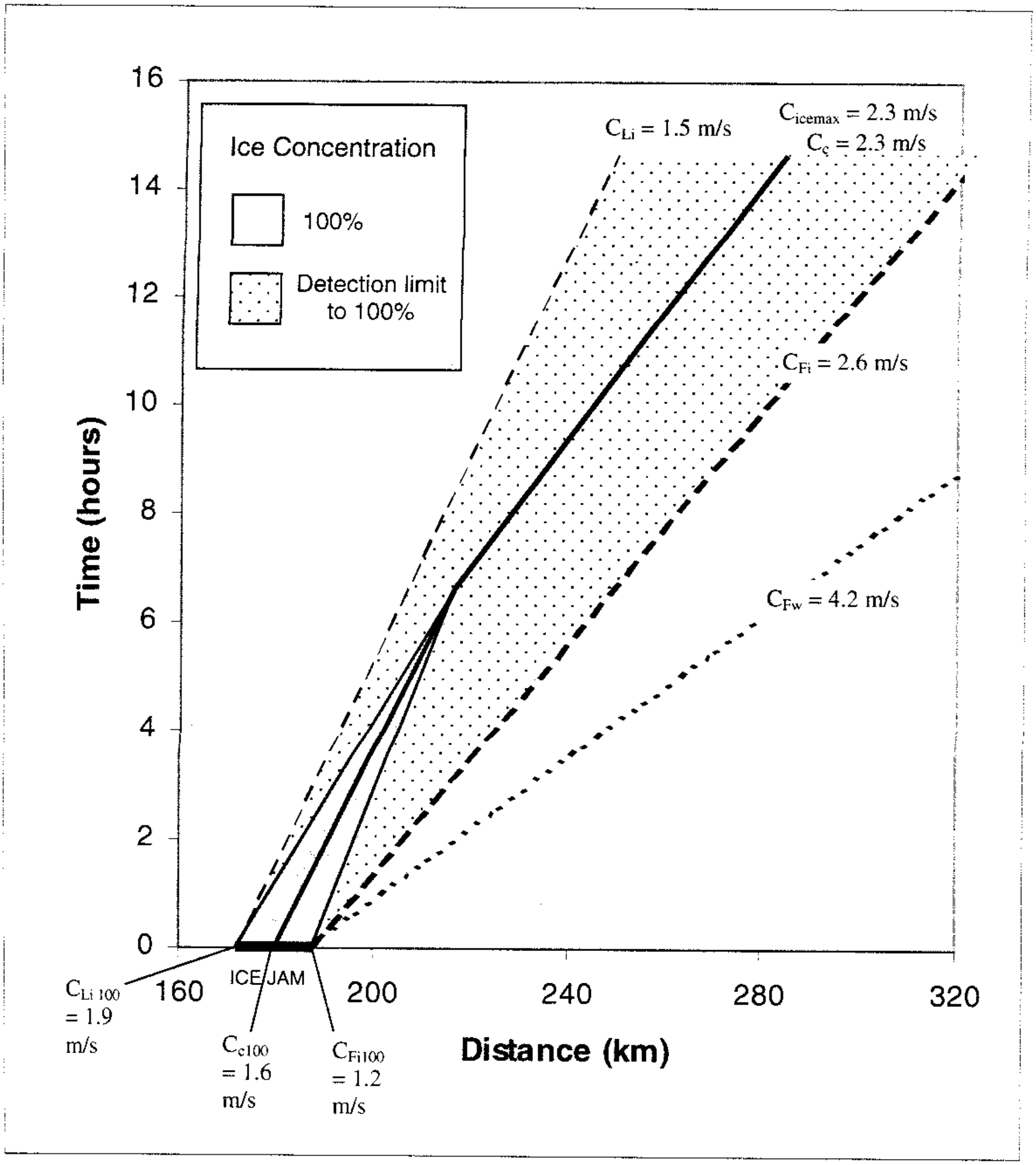


Figure 4. Surge and ice celerity diagram resulting from the release of an ice jam with open water conditions downstream. The values corresponding to each celerity type were obtained from the 1995 break-up of the Porcupine River. Due to the limited number of observations, celerities are distance and time averaged and therefore presented only as straight lines.

aspects of the surge release were preserved. If there was some effect, this would have been greater on the upstream celerities and less so on the downstream.

2. There was also tributary inflow downstream of the ice jam. However, these tributaries were open and therefore the rate of discharge input was nearly constant relative to the surge on the Porcupine River. Over the 140 km study reach, it was estimated that the base flow discharge increased from 1850 to 2650 m^3/s, a 43% increase (Jasek, 1996). This has consequences, especially in the dispersion of the ice concentrations.
3. The slope is not constant within the 140 km long study reach (McKay and Hicks, 1996).
4. The channel width is not constant and in general, increasing in the downstream direction (McKay and Hicks, 1996).

Recognizing that natural conditions are always more complicated than the idealized channel, it is believed that some aspects of the idealized case have been preserved.

7. Conclusions

Detailed break-up observations can provide insight into the behavior of the water-ice interaction of surges produced by the release of ice jams. This study has yielded insight into how the ice concentrations disperse over time and distance and the role this may play in augmenting the shape, magnitude, and timing of the resulting flood wave. For the case where there is open water downstream of the released jam, several conclusions can be drawn.

Shortly after a jam release, the peak ice concentration is ahead of the maximum water level and on the rising limb of the hydrograph. The first stage increase travels faster and well ahead of the fastest pieces of ice. This has important implications to aerial flood monitoring efforts. As this water level increase is nearly invisible from the air, the only visible evidence of an approaching surge is the ice run. This may give a false impression that there is more time than actual before the discharge starts to increase at a particular point of interest downstream.

In the early stages of the water-ice surge, the ice behaves essentially as a moving jam. This moving jam provides extra resistance and holds the peak water level at the upstream end of the peak ice concentration and causes it to move slower than a surge with no ice. The moving jam gets shorter as pieces of ice accelerate away from the downstream end. A key transition point occurs when the peak ice concentration falls below 100%, were essentially the moving jam length goes to zero. In the one detailed observation on the Porcupine River, it took about 3 ice jam lengths for this to occur. Due to the reduced ice-bank friction at this key transition point, the celerity of the peak water level increases; a 44% increase in peak water level celerity was observed on the Porcupine River in May of 1995 which is of particular interest from a flood forecasting point of view.

After the ice concentration falls below 100%, the surge flattens considerably and the peak ice concentration moves along with the surge crest for a considerable distance. As the surge continues to travel, the maximum ice concentration peak slowly starts to fall behind the crest.

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