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Observations of ice jam releases resulting from an incoming water wave

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Ice jams are generally believed to release as a result of the removal of geometric constraints at the toe. However, anecdotal observations by earlier researchers also mention ice jams that released after interacting with an incoming wave. This mechanism of release is difficult to verify without a network of water level observation stations. This study presents detailed observations of two ice jam releases which occurred after interaction with incoming waves. For the first ice jam, the slopes within the ice jam and the celerity of the release front were estimated for the first ice jam. For the second ice jam, the wave which precipitated the release of the second ice jam was tracked though the study reach, showing that the front of the wave arrived at the ice jam when it released. These observations reveal the mechanisms of ice jam release resulting from an incoming wave.

1. Introduction

The release of impounded ice and water from an ice jam can lead to rapidly-rising water levels and a fast-moving torrent of ice and water that can threaten riverside communities. It is important to understand the mechanisms of ice jam release in order to predict the behavior of ice jam release waves and ice runs, both of which can cause flooding. The mechanism of release may affect how the resulting ice run and the water wave interact. This interaction may affect the waveform and propagation of an ice jam release wave, particularly at the trailing end of the wave (Blackburn and Hicks, 2003; She and Hicks, 2006; Shen et al., 2008). Several different mechanisms of ice jam release have been observed or proposed: the formation of open leads, toe dislodgement, increases in discharge (such as incoming waves), thermal effects, and changes in ice competence are all believed to play a role (Beltaos, 1995; Beltaos, 2008a).

Interaction between an incoming wave and an ice jam may be an important mechanism of release because it affects all aspects of ice jam stability. An ice jam stays in place because the frictional forces at the downstream end and the channel margins counteract both the flow drag beneath the ice jam and the downslope component of the weight of the ice accumulation. These frictional forces are transmitted to the rubble ice accumulation through the frictional strength of the accumulation (Beltaos, 2008b). An incoming wave may act to release an ice jam by increasing the forces that tend to cause the ice jam to release and by decreasing those that tend to keep it in place. An incoming wave may increase the water surface slope and therefore increase the downslope weight component of the ice jam. An incoming wave raises water levels, which lifts and separates the ice pieces, reducing the internal strength of the accumulation. Also, the increased discharge associated with a wave increases the under-ice velocities which results in increased drag on the accumulation. In addition, the increase in water level may lift any intact ice at the toe of the ice jam and allow it to overcome the geometric constraints holding it in place and thus release the ice jam behind it. Finally, water waves from ice jam releases may be coincident with or closely followed by ice runs (Nafziger et al., submitted 2015). Upon impacting an intact ice jam, these ice runs can add momentum and mass to the accumulation, further contributing to its instability. Because an incoming wave has the potential to release a stable ice jam by many different mechanisms, it may be a common and important mechanism of ice jam release in natural streams.

Several researchers have observed ice jam releases that occurred after the ice jam was affected by an incoming water wave. For example Beltaos et al. (1994) noted that rain and a rapid increase in discharge caused release of an ice jam on the St. John River above Fort Kent, Maine in 1993. Jasek (2003) postulated that a “small surge” from the Bell River may have instigated the release of an ice jam on the Porcupine River in the Yukon Territory in 1995. Hutchison and Hicks (2007) observed an ice jam at Crooked Rapids on the Athabasca River in Alberta that released after a wave may have dislodged the sheets confining the ice jam it its toe. The authors also noted that this may be a significant process in ice jam releases. She et al. (2009) commented that ice jams on the Athabasca River upstream of Ft. McMurray, Alberta are often dislodged by incoming ice runs that result from upstream ice jam releases. They also observed an incoming ice jam release wave that initiated a series of shoving events in an ice jam impeded on an intact ice cover on the Athabasca River in Alberta in 2007. Kovachis (2011) also theorized that incoming water waves combined with ice from an incoming ice run often result in the release of ice jams on the Hay River in the Northwest Territories. Beltaos (2014) noted that an ice jam in East Channel of the Mackenzie River Delta, Northwest Territories released at the same time as rubble ice and high water levels propagated from the Middle Channel of the Mackenzie Delta in 2008. However, these studies did not focus on water waves as an important mechanism of release, nor did they provide detailed evidence of the cause of the releases of the ice jams.

Because of the numerous comments in the published literature of ice jam releases resulting from interactions with incoming waves, this study aims to articulate this mechanism as important in ice jam release and present two detailed examples where this occurred. In this study, two events where ice jams released due to incoming waves on the Hay River in the Northwest Territories were documented. One release was observed at two locations within the ice jam and the other was inferred from the tracking of ice jam release waves past several observation locations. These observations provide insight into the mechanisms of ice jam release and may be helpful in validating numerical models of ice jam strength and ice jam release wave propagation.

2. Study Reach and Methods

A reach on the Hay River in the Northwest Territories was instrumented for this study (Figure 1). In this reach, the Hay River meanders through alluvial plains and contains occasional islands. The average channel width is 117 m (min: 70 m, max: 210 m) with an average bed slope of 0.0002. The Hay River drains 51,700 km^2 before flowing into Great Slave Lake near the Town of Hay River and the K'atl'odeeche First Nation. Spring breakup in this reach is normally dynamic and often characterized by a series ice jam formation and release events. Both the settlements near the mouth of the Hay River have experienced severe flooding caused by ice jams.

The ice jam releases described in this study were observed from two stations in 2011 and six stations in 2013 (Figures 1 and 2). Each observation station was identified with a river kilometer, numbered from the origin of the Hay River (adapted from Hicks et al., 1992). Each station consisted of a self-contained submersible pressure transducer and datalogger for recording water levels (Schlumberger Diver models 501 and 601, accuracy: 1.0 and 0.5 cmH_2O, measurement interval: 1 or 2 min.) and a time-lapse camera mounted on a tree for observing ice conditions (various models were used: Reconyx PC800, Moultrie PlotStalker, and Moultrie I-65; photo interval: 5 min., 10 min., or 1 hr.). Remote lighting was not installed; therefore ice condition data were typically available only during daylight hours (~04:30-23:00). The pressure transducers' clocks were synchronized and the instruments were installed in silt socks and fixed inside perforated heavy steel cases. The cases were driven flush with the riverbed before the onset of breakup. The case elevations were measured with respect to control points established with a global positioning system static survey and processed with Natural Resources Canada's precise point positioning tool (vertical 95% error: 0.074 to 0.185 m). The pressure data were corrected to compensate for the effects of atmospheric pressure changes using data from a barometric pressure datalogger (Schlumberger Diver model DI500, accuracy: 0.5 cmH_2O) located along the river within 15.5 km of the observation stations. The cameras were retrieved after breakup was complete. The pressure transducers were retrieved later in the summer, after remnant shear walls had melted and high water levels had subsided.

Ice conditions were also observed from fixed-wing aircraft, allowing for periodic documentation of ice conditions between the ground-based observation stations, as well as upstream and downstream of the study reach from the Alberta-Northwest Territories border to Great Slave Lake (km 942 to km 1114). Observational flights were typically conducted daily during breakup, weather and equipment permitting, and more often if ice was moving. The ice jams described in this study were observed from the air on the afternoon of May 6, 2011, and in the morning and evening of May 11, 2013.

3. Results and Analysis

Several ice jam formation and release events were observed, which resulted from a cascade of ice jam release events in both years. The release of a single 13.6 km long ice jam in 2011 and a cascade of ice jam releases in 2013 were analyzed. Figure 2 shows the location of the ice jams prior to their release as estimated from aerial observations conducted before the ice jams released. Ice Jams 2011A and 2013D were still lengthening when last observed, so the locations of the heads of the ice jams were estimated based on the extent of the shear walls observed from the air after the ice jams had released. Where these estimates were necessary, they are noted on Figure 2. The cascade of releases in 2013 combined to form a single ice jam release wave, which propagated through the study reach. In both years, several other ice jams and ice jam release events were observed or inferred, but the number and quality of observations for these events were limited by darkness when ice conditions, and therefore ice jam release timing, could not be confirmed. More information regarding ice jam releases and the resulting water waves and ice runs on the Hay River in 2011 and 2013 can be found in Nafziger et al. (submitted 2015).

3.1 *Release of Ice Jam 2011A*

The release of the 13.6 km long Ice Jam 2011A was observed from two observation stations (km 993.4 and km 997.4) located along the ice jam. Figure 3a shows the water surface elevation and ice condition at both stations and Figure 3b shows the water surface slope between the two stations during the release of the ice jam. Continuous monitoring of water levels within an ice jam allowed for observation of the mechanism of release and the continuous measurement of water surface slopes within that ice jam.

Ice Jam 2011A released as the result of a small (<0.5 m high) incoming wave. The origin of this wave was not observed. The ice jam released in the following sequence (numbers correspond to numbered time intervals on Figure 3): 1) the slope of the ice jam increased as the upstream end of the ice jam was lifted by the wave and water was stored behind the jam; the ice remained stationary at the downstream station; 2) the wave lifted the downstream section of the jam, causing the water surface slope to decrease; the ice at both locations shifted but did not release; 3) the ice rubble in the jam was released from the downstream end and the water surface elevation dropped more sharply at the downstream end than at the upstream end. This sequence resulted in two peaks in the slope-time graph (Figure 3b). The first peak occurred when then water wave lifted the ice at the upstream end and the second occurred as the water surface at the downstream end dropped. The maximum water surface slope was approximately 0.0005 and occurred when the upstream end of the ice jam was lifted by the incoming water wave.

These data can also provide an estimate of the celerity of the 'release front' of the ice jam. The 'release front' was defined as in Ferrick et al. (1993) as the dividing line between released ice and stationary ice that moves upstream as the ice jam releases. The photo interval was too coarse to distinguish the moment the ice started to advance downstream from that when the ice was shifting but had not yet released. Therefore, the time when the ice jam was completely released at an observation station was estimated as the point where the water level began to level out or where an inflection point in the hydrograph was observed, implying that the ice jam had released and had become an ice run. Ice Jam 2011A released at ~09:10 at km 997.4 and at ~09:22 at km 993.4 (Figure 3a). Therefore, the release front traveled upstream at an average rate of 5.6 m/s between the observation stations.

3.2 *Release of Ice Jam 2013D*

The 3.8-km-long Ice Jam 2013D also released due to an incoming water wave. This wave resulted from the release of Ice Jam 2013C, located 17.4 km upstream. Figure 4 shows hydrographs of the propagation of the water wave past each of the six observation stations. Three points on each hydrograph were highlighted to aid in describing the waves' behavior. First, the 'wave leading edge' was the point where the first water level rise was observed or where an inflection point in the hydrograph was noted. Second, the 'wave front' was the point on the steepest part of the hydrograph, where the water level was half-way between the elevation of the leading edge and the peak. Third, the 'wave peak' was the highest water level elevation measured on the waveform. Where the waveform was not obvious because of the presence of an ice jam (e.g. Figure 4c and 4d), these features were not recorded.

Figure 5 is a phase diagram showing the observed times that each wave feature passed each observation station. Again, where the waveform features were not obvious (km 993.4, km 997.4) they are not shown on Figure 5. The ice jam extents and their approximate times of release are also illustrated on these diagrams. Where uncertainty exists with respect to the extents or release time of an ice jam they are indicated with a question mark. The release of each ice jam is shown at a discrete time with a horizontal line in the phase diagram. Because ice jams do not release instantaneously, the release of the jam would be better represented with a curve or a sloping line; however, information on the rate of release of these ice jams was not available.

In Figure 5, the trajectory of the wave front is approximated as a straight line between km 986.8 and km 1004.1. This trajectory intersects with the documented release time of Ice Jam 2013D at km 997.4. The ice jam released at 16:20, which was estimated from the time of the peak water level and from ice condition observations. The trajectory suggests that the ice jam started to release at the same time that the main part of the wave (the 'wave front') contacted the ice jam. Therefore, it was not the small rise in water level at the leading edge of the water wave, nor the arrival of the peak of the wave that instigated the release of the jam. Furthermore, the ice jam did not release due to additional ice mass from the incoming ice run also released from Ice Jam 2013C. As shown by the trajectory of the front of the ice run in Figure 5, the start of that ice run did not arrive at km 997.4 until after Ice Jam 2013D had completely released and the ice had cleared. Therefore, interaction with the main part of the incoming wave was the most likely cause of the release of Ice Jam 2013D. Finally, the releases of the Ice Jams 2013D, 2013E, and the very small 2013F all released along the inferred trajectory of the front of the water wave, suggesting that the front of the water wave caused a cascade of ice jam releases.

4. Summary and Conclusions

When an ice jam dislodges a torrent of water and ice is released. Understanding the mechanisms that cause the release of ice jams is important for predicting the release of ice jams and the downstream movement of ice jam release waves and ice runs. Several researchers have mentioned the release of ice jams after they were affected by waves propagating from upstream. Given that there are many accounts of this occurring and that incoming waves act in several different ways to destabilize an ice jam, interaction with an incoming wave may be a common and important mechanism for ice jam release.

In this study, two ice jam release events were observed in detail on the Hay River in the Northwest Territories. Ground-based observation stations consisting of water level sensors and time-lapse cameras were used to verify the incoming water waves and the ice conditions at the time of release. The release of Ice Jam 2011A was observed at two stations within the ice jam, allowing the continuous calculation of the water surface slope between the stations during the release. The maximum slope observed during the release was approximately 0.0005. The average upstream celerity of the release front between the observations stations was 5.6 m/s. The release of Ice Jam 2013D was observed at a single location within the ice jam and the leading edge, front, and peak of the incoming wave were tracked at nearby observation stations. This ice jam released at a time close to when the front of the incoming wave arrived at the ice jam.

Evidence presented in this paper suggests that incoming waves may be an important mechanism of ice jam release. This may be particularly true where cascades of ice jam releases are often observed (i.e. the Hay River, the Athabasca River). When investigating ice jam releases, water levels should be measured upstream of the head of the ice jam as well as downstream of the toe in order to verify whether an incoming wave precipitated the release of the jam. Ground-based observations are important as water waves may not travel coincidently with ice runs and are therefore difficult to detect from aerial observations. This will allow the determination of how widespread this ice jam release mechanism is.

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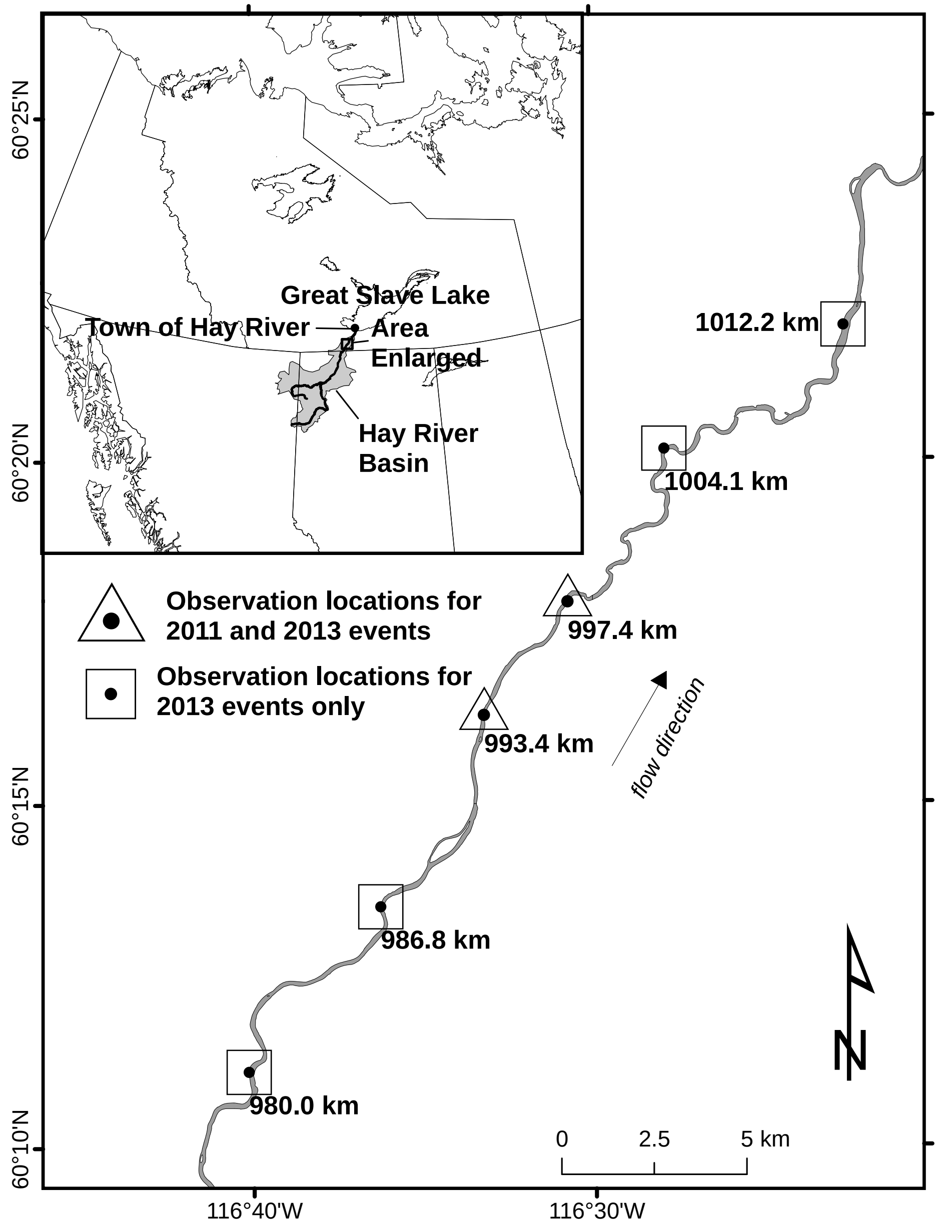

Figure 1. Location of the Hay River basin and observation locations.

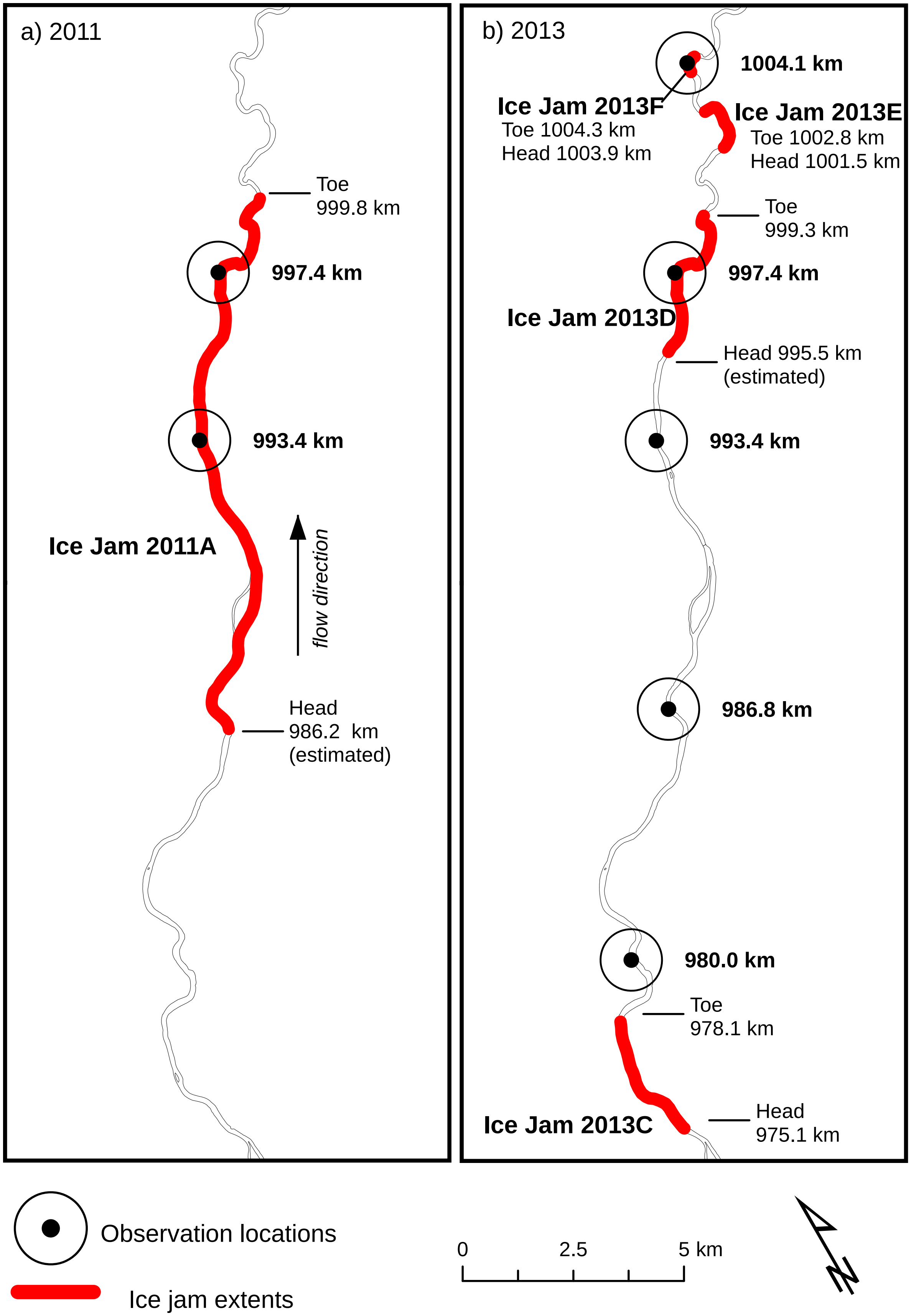

Figure 2. Location of ice jams released in a) 2011 and b) 2013 on the Hay River.

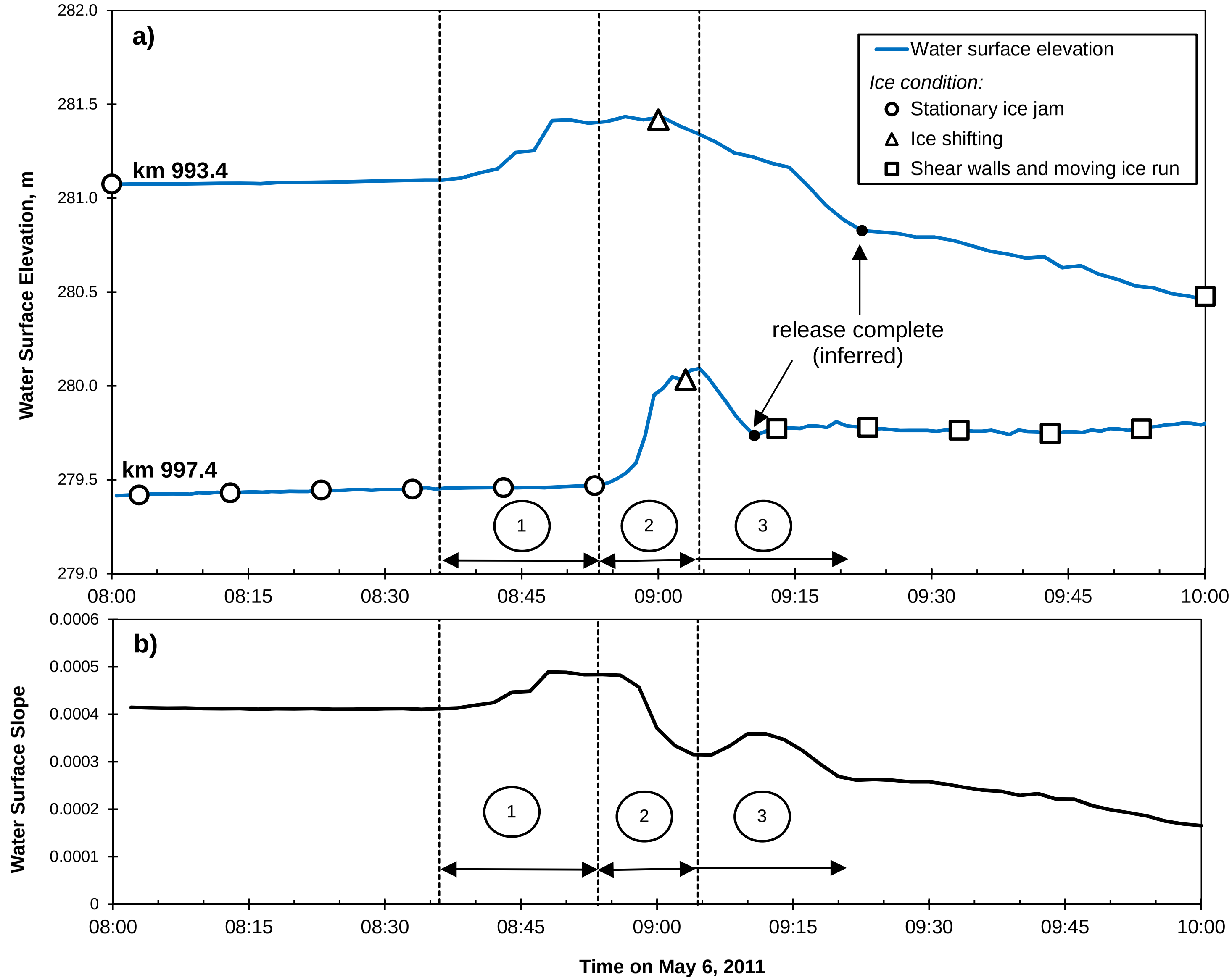

Figure 3. Release of Ice Jam 2011A including: a) water surface elevation and ice condition, b) water surface slope between observation stations at km 933.4 and km 997.4 on the Hay River in 2011. Open data points in a) represent photographic observations. Circled numbers refer to the release sequence described in the text.

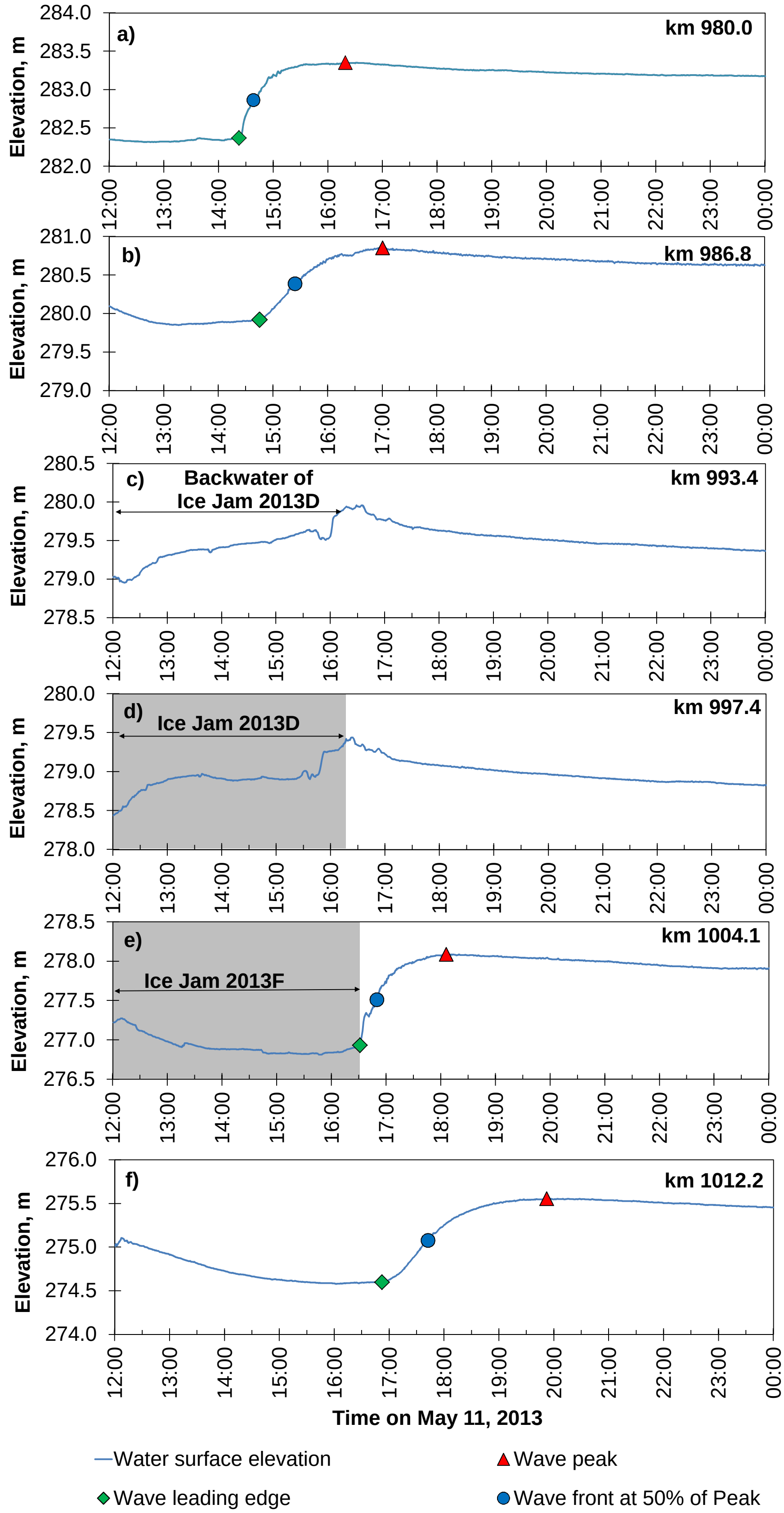

Figure 4. Water surface elevation and wave features observed in 2013 on the Hay River.

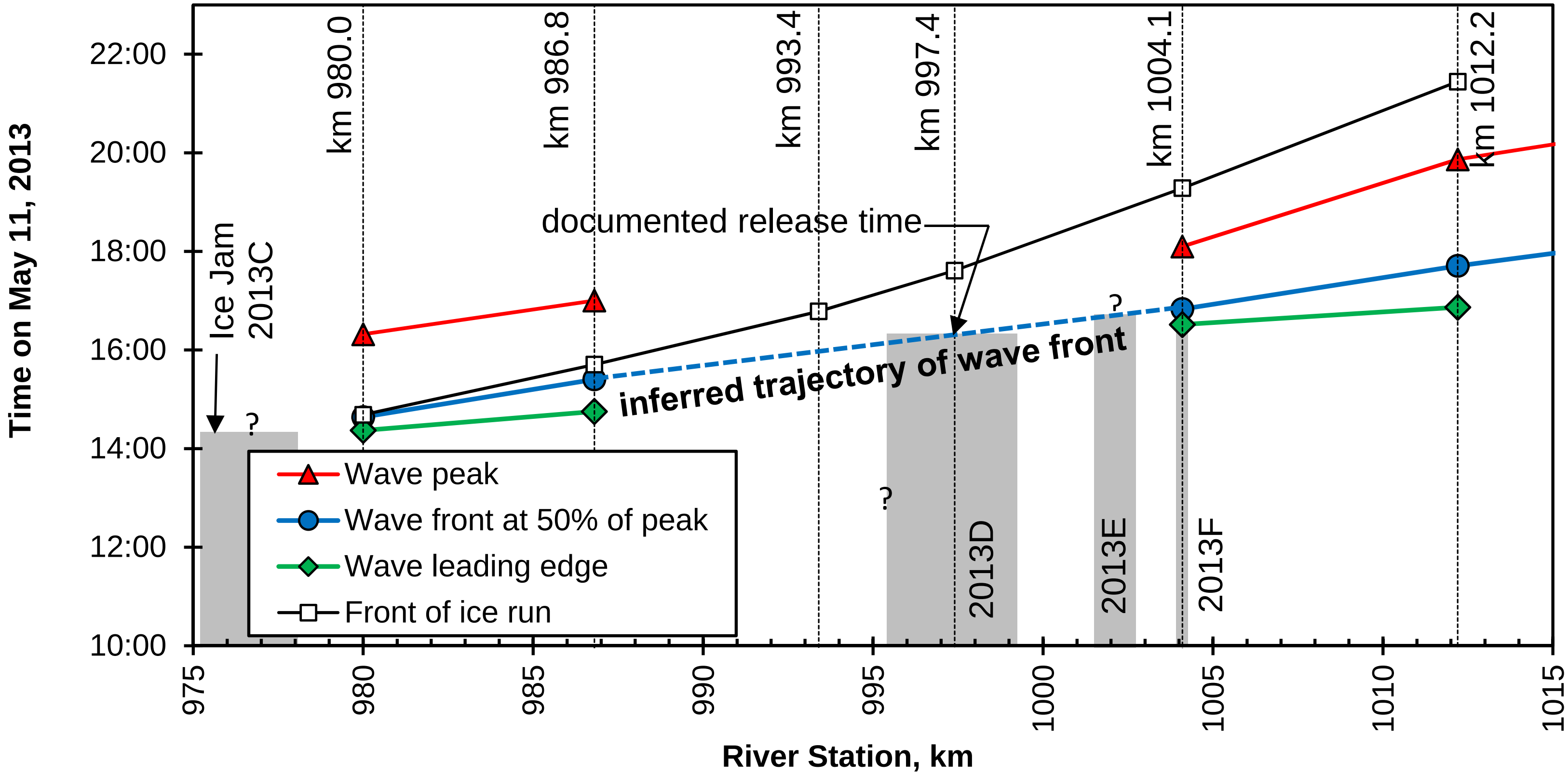

Figure 5. Phase diagram of water wave and ice jam features showing release of Ice Jam 2013D as the result of interaction with the front of the incoming water wave released from Ice Jam 2013C, observed on the Hay River in 2013. Ice jam extents are shown with gray boxes. Question marks indicate uncertainty in the extent or release times of the ice jams.