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A Tale of Two Basins: The 2020 river ice breakup in northern Alberta, part I: The Athabasca River

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The 2020 spring river ice breakup in northern Alberta was historic and significant. This set of two papers describes the 2020 breakup on the Athabasca River (Part I) and the Peace River (Part II). In both of these basins, a late spring and high snowpack contributed to the dynamic breakup of the river ice. A series of ice jams and ice runs resulted in catastrophic flooding in several communities in northern Alberta, evacuations, boil water advisories, and one death. In this paper we provide a description of the antecedent conditions leading to breakup and a description of breakup progression along the Athabasca River, including an analysis of the ice jam that caused the flooding of Fort McMurray. We discuss the challenges of forecasting dynamically-driven ice jam events and suggest avenues for future research.

1. Introduction

The 2020 spring river ice breakup on the Athabasca River (Alberta, Canada) was historic and significant. Several ice jams and ice runs on the Athabasca resulted in catastrophic flooding of the urban downtown of Fort McMurray, one death, more than seven weeks of boil water advisories, and the flooding of low-lying areas adjacent to hundreds of kilometers of riverbank. The total insured and uninsured losses in Fort McMurray are estimated to exceed \$1.1 billion CAD (Adriano 2021). The detailed documentation of extreme events like this one is important for informing future research into ice jam processes, for improving ice jam forecasting, and for the design of future works for flood mitigation, adaptation, and resilience.

Breakup ice jams and ice runs are a common and important river process on the Athabasca River. Historical records of significant flooding at Fort McMurray (then a Hudson's Bay Company post) date as far back as 1875 (e.g. Blench and Associates 1965, Zare et al 2019). Significant ice jam flooding occurred at Ft. McMurray in 1875, 1881, 1885, 1925, 1928, 1936, 1963, 1977, 1997 and 2020, and at the Town of Athabasca in 1904, 1943 and 1963 with minor ice jam flooding at Athabasca in 2018 (Hatch and Golder Associates 2018; Golder Associates 2020; Alberta Environment and Parks (AEP) 2018). In addition, significant large ice runs were observed in 1990 and 2018 (van der Vinne 1994, AEP 2018), and likely occurred in other years. Following the significant flooding at Fort McMurray in 1977, the Alberta Research Council, sometimes in conjunction with AEP monitored and analyzed the breakup of the Athabasca River on a nearly consistent basis from 1977 to 1990 (e.g. Doyle and Andres 1978, Andres and Doyle 1984, Andres and Rickert 1985, etc.). The University of Alberta conducted research into ice jam and ice run processes in the reach near Fort McMurray from 1998 to 2007 (see for example Robichaud 2003, Kowalczyk 2005, Friesenhan 2004, She et al 2009), and established part of the current ice observation network. AEP has conducted annual breakup observations since the early 1980s, with varying levels of detail and consistency. AEP completed an updated Flood Hazard Study for Fort McMurray (Hatch and Golder Associates 2018), and the Town of Athabasca (Golder Associates 2020) including ice jam flood frequencies, ice jam modelling, and flood mapping. The Fort McMurray Flood Hazard Study is currently being updated with an assessment of the 2020 flood (Hatch and Golder Associates 2021) and both studies are being updated in response to public consultation with a final release forthcoming. Draft ice jam flood mapping can be viewed interactively on the Alberta Floods website (AEP 2021). Currently, AEP monitors river ice on the Athabasca River annually during breakup. AEP's digital ice observation reports and digital maps are archived on the Alberta River Basins web application (<https://rivers.alberta.ca>) back to 2007.

This paper presents an operationally-focused documentation of the 2020 spring breakup of the Athabasca River. The reach of the river discussed here is 1000 km long from downstream of Whitecourt, Alberta to downstream of the River's divergence with the Embarras River at the start of the Peace-Athabasca Delta (PAD). Descriptions of the breakup of the PAD reaches of the Athabasca River, and the neighbouring Peace River can be found in Emmer et al (2021) and Beltaos et al (2021). The goals of the paper are to: (1) document the extreme event of the 2020 spring breakup, (2) describe the operational activities of AEP, providing insight into the challenges of real-time ice jam forecasting, and (3) describe areas of future research that have been highlighted by the 2020 extreme event.

2. Site Description

2.1 The Athabasca River

The Athabasca River flows generally south to north for more than 1450 km, from Alberta's Rocky Mountains to its mouths in the PAD at Lake Athabasca in northeastern Alberta (Figure 1). It is the primary water source for the Regional Municipality of Wood Buffalo (RMWB), of which the urban service district of Fort McMurray is part, and is a key feature of Canada's oil sands area. The section of river from the Town of Athabasca to Fort McMurray is remote with very few access points, and the 350 km upstream of Fort McMurray has no river crossings. The 130 km of the river from Grand Rapids to Fort McMurray is particularly steep and impassible to most watercraft, with several rapids, classed from IV to VI (Lund 2007). The slope of the river flattens significantly at Fort McMurray from 0.00067 to 0.00014, and the river changes from a steep single channel to a wider channel with more islands (Kellerhals 1972).

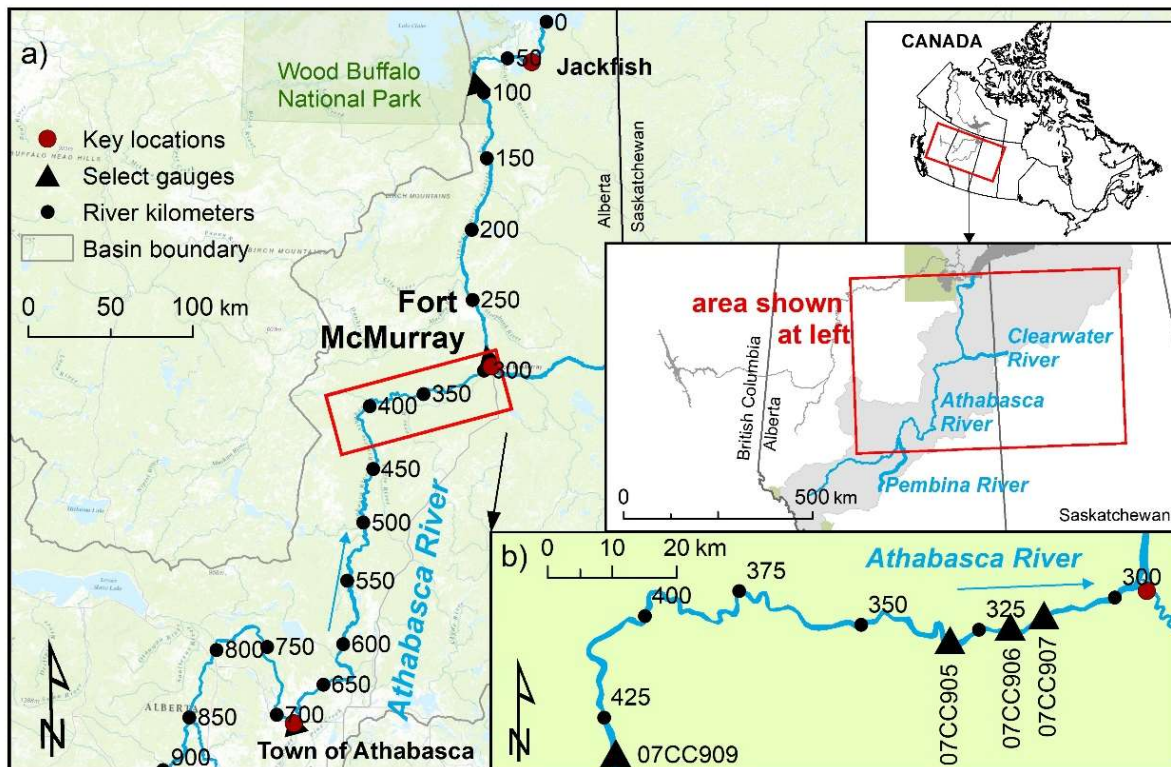


Figure 1: Location of the Athabasca River basin, key riverside communities, and gauge locations. Base data: ESRI.

2.2 Typical Breakup Progression and Flooding Mechanism

Breakup on the Athabasca River follows a typical pattern. The tributaries of the Athabasca River that flow through agricultural plains typically breakup first, where the flat slope and uniform aspect causes the snowpack to melt quickly. The Paddle and the Pembina Rivers are thought to contribute much of the flow to the Athabasca River in the early part of breakup, as snowmelt in the forested plains and foothills in the upper Athabasca River basin typically happens later. Dynamic breakup and ice jam formation on the Pembina River has historically been monitored by AEP ice forecasters as an early sign of dynamic ice processes in the Athabasca River basin. As ice jams

begin to form on the Athabasca River, they release and then form larger ice jams and large ice runs. These ice runs may coalesce into a large ice jam at Fort McMurray where the river slope flattens. Major flooding may occur at Fort McMurray if an ice jam is located such that its backwater intersects the mouth of the Clearwater River. The downtown of Fort McMurray is situated along the Clearwater River, and when the backwater from the Athabasca River raises the water level, the downtown may flood.

2.3 Observation Network

The river observation network near Fort McMurray is operated by different agencies and provides different types of information during breakup (Figures 1 and 2). Gauging stations near Fort McMurray (Figure 2) measure water levels in near-real-time within Fort McMurray, providing awareness of water levels at breakup and therefore a measure of the extent of any flooding. Water Survey of Canada (WSC) operates 3 gauges in the Fort McMurray area: one on the Athabasca River below Fort McMurray (07DA001), on the Clearwater River at Draper (07CD001), and on the Hangingstone River at Fort McMurray (07CD004) (Figure 2). The next upstream WSC gauge on the Athabasca River is at the Town of Athabasca (07BE001), at km 687 (390 km upstream of Fort McMurray). RMWB operates a downward-facing sonar gauge at the Hwy 63 bridges at Fort McMurray. This gauge provides the elevation of the top of the ice or the top of the water, depending on which is below the sonar at the time of measurement. RMWB also operates vented pressure transducer gauges on the Clearwater River and the Hangingstone River (Figure 2), and cameras at the bridge, on “the Snye”, and at the confluence of Clearwater River. The RMWB system is currently being upgraded to include new gauges and cameras.

AEP operates 4 gauging stations on the Athabasca River upstream of Fort McMurray, which function as early warning stations (Figure 1b). AEP’s stations, location, and approximate travel time for javes to reach Fort McMurray are summarized in Table 1. AEP’s most upstream station “Athabasca River above Grand Rapids” was first installed as a water quality station; as such, dynamic ice impacts were not considered in its location, and ice destroyed it in 2020. The station has since been relocated ~20 km further upstream. Each AEP station consists of an air bubbler and orifice line water level gauge. The three stations closest to Fort McMurray also have ice movement sensors that consist of “pull-wire” circuits that are attached to logs embedded in the ice prior to breakup, and are set to alert AEP when the ice moves. The stations transmit hourly to a GOES satellite (operated by NOAA). The data transmission rate increases to every 5 minutes on a “random GOES” channel when a threshold for the rate of change of water level is reached, or when the ice pull wire is pulled. AEP operates a remote camera with satellite transmission capabilities at the “Athabasca River below Crooked Rapids” gauge, approximately 35 km upstream of Fort McMurray.

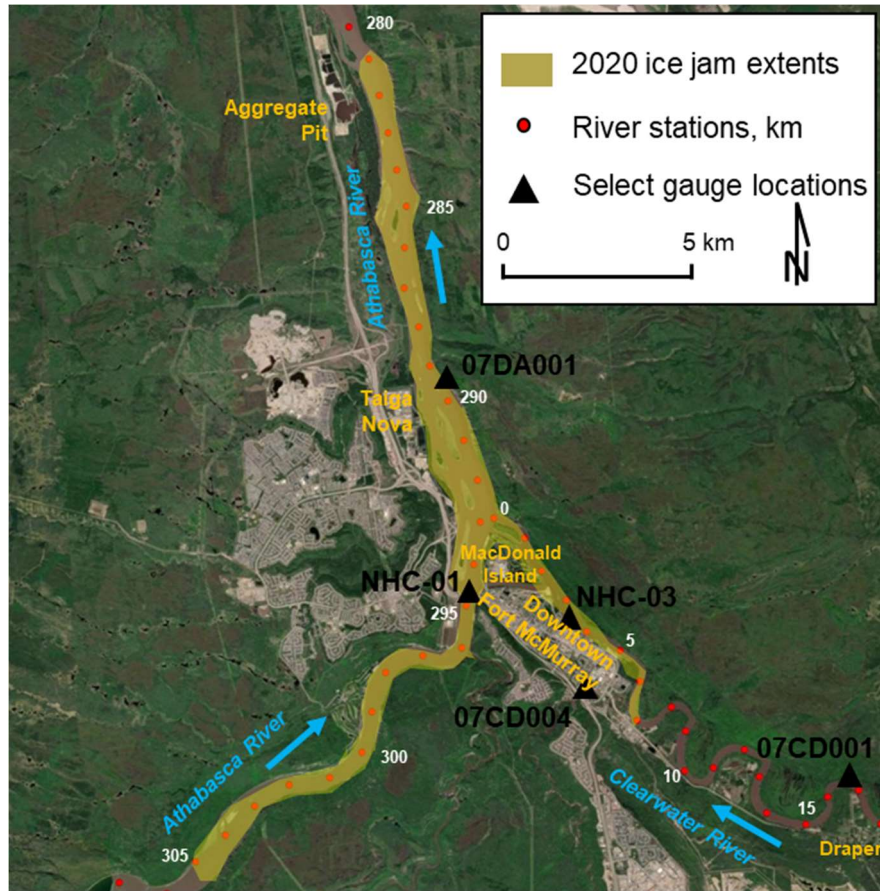


Figure 2: Configuration of confluence of the Athabasca and Clearwater Rivers and location of select RMWB and WSC observation gauges in Fort McMurray. Base image: ESRI.

Table 1: AEP’s Early Warning Gauge Locations for Fort McMurray

Station Name and ID	River km	Jave travel time to Fort McMurray	Notes
Athabasca River Above Grand Rapids (07CC909)	431	10 hrs (2018)	- Destroyed in 2020 - Relocated and renamed for 2021 - New station has a camera (2021)
Athabasca River below Crooked Rapids (07CC905)	330	3.5 hrs (2018)	- Satellite camera with illuminator - Ice movement pull-wire - Can transmit on Random GOES
Athabasca River below Cascade Rapids (07CC906)	321	2.5 hrs (2018) 2.4 hrs (2020)	- Ice movement pull-wire - Can transmit on Random GOES
Athabasca River above Mountain Rapids (07CC907)	312	1.7 hrs (2018) 2.0 hrs (2020)	- Ice movement pull-wire - Can transmit on Random GOES

3. 2020 Spring Breakup Description

3.1 Pre-Breakup Outlooks

The severity of spring breakup flooding is known to be dependent on the weather in the Athabasca River basin and the local ice conditions in the Fort McMurray area. AEP assesses these conditions on a continual basis and releases long-range “breakup outlooks” to stakeholders following the availability of March 1 and the April 1 snow survey results. The analysis for our breakup outlooks is based on the work of Mahabir (2007) and relies on four basin indicators, summarized below with their 2020 values. Indicators were considered in the “average range” if they fell within the second or third quartile of the dataset.

1. *Accumulated summer precipitation from May 1 to October 31 in the previous summer at Fort McMurray*: a measure of the soil moisture of the basin, higher values indicate higher runoff potential, and therefore more severe breakup
 - 349 mm in 2019, 33rd largest out of 50 years of data, **average range**
2. *Degree days of freezing between the October 31 and March 31 prior to breakup at Fort McMurray*: a measure of the severity of the winter, higher values suggest greater ice thickness, and less loss of snowpack, and therefore more severe breakups
 - 1912 °C days in 2019-2020, 22nd largest of 50 years of data, **average range**
3. *Athabasca River Ice thickness at Fort McMurray from the most recent WSC flow measurement* (normally, mid-March): a measure of the ability of the ice to stop ice jams at Fort McMurray, a larger value may contribute to more severe breakups
 - The method developed in Mahabir (2007) used ice thickness measured at a specific location, where data are no longer routinely collected. Using the overlapping historical record, a relationship between the ice thickness at the historical location and the WSC gauge (07DA001) was used to modify the ice thickness measured at the WSC location to be consistent with the record used for analysis. For outlooks released prior to April 1, the most recently-available data is used
 - 1.11 m in 2020, 4th highest of 48 years of data. Measured March 17, 2020, **above average range**
4. *Basin-averaged snow water equivalent (SWE) on March 1 and April 1 (most recent SWE used in the analysis)* from AEP snow surveys on the plains of the Athabasca River basin: a measure of the snow available for runoff. Higher values may contribute to more severe breakups.
 - 95 mm in 2020, 14th highest in 46 years for March 1, **average range**
 - 112 mm in 2020, 8th highest in 44 years for April 1, **above average range**

Based on the method of Mahabir (2007), the breakup outlook provided to local stakeholders in early March indicated an “average” level of risk for breakup flooding in Fort McMurray. However, the outlook released in early April indicated that the risk for breakup flooding at Fort McMurray was “above average”. While the snowpack was fairly average at the start of March, cold weather and precipitation in March and early April resulted in a much higher than average snowpack, notably in the agriculturally-dominated south-central portion of the basin (Figure 3).

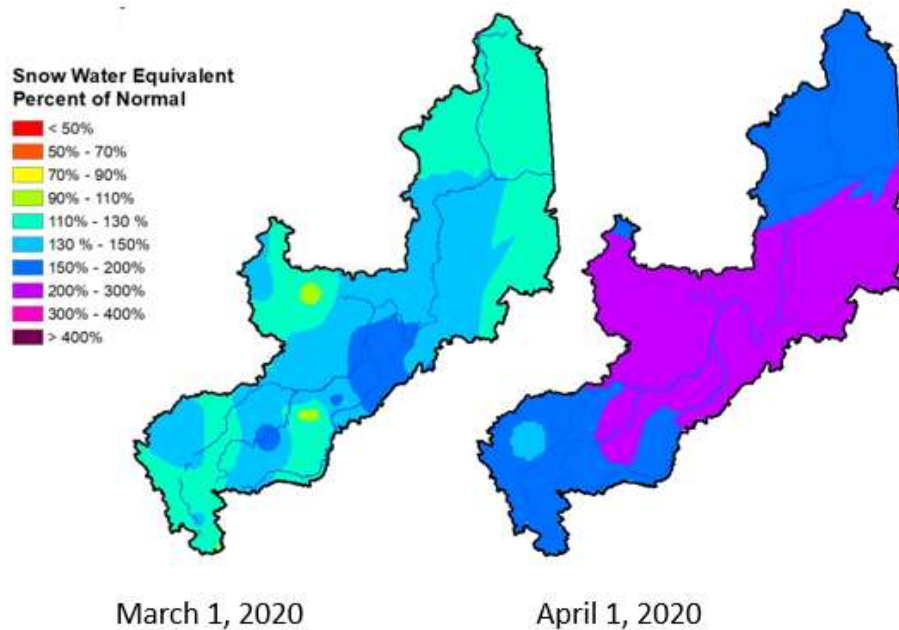


Figure 3: Distribution of March and April SWE for the Athabasca River Basin in Alberta for 2020, compared to average SWE (1974 to 2020), from AEP snow surveys.

3.2 Progression of Breakup on the Athabasca River

This section summarizes the progression of the 2020 breakup in the Athabasca River basin, synthesized from many sources of information. Figure 4 shows the progression of breakup from April 19 to May 5. Information from Sentinel 1 and 2 satellite imagery and from AEP observation flights were available during river ice operations (imagery with ~8 hr latency). RADARSAT Constellation Mission (RCM) images were made available after breakup and used to fill in gaps in the record. Water level gauge data was available in near-real-time to AEP forecasting staff; but corrections, shifts, and surveyed points were not available operationally. All quoted times are Mountain Standard Time (MST, UTC-7), unless otherwise noted.

April 16 - 18

- Spring snowmelt began in the Athabasca River basin later than normal when warm temperatures began on April 16 after a period of below-seasonal temperatures.
- Water levels on the Little Paddle and Paddle Rivers (tributaries of the Pembina River) rose between 3 and 4 m due to snowmelt and overtopped agricultural berms, high water levels continued for more than one week.

April 20

- On April 20, the ice on the Pembina River broke up at Jarvie (located km 85.5 upstream of the Pembina River mouth) followed by a sustained snowmelt wave.
- Observation flight in Fort McMurray showed very intact, undeteriorated ice on the Athabasca River.

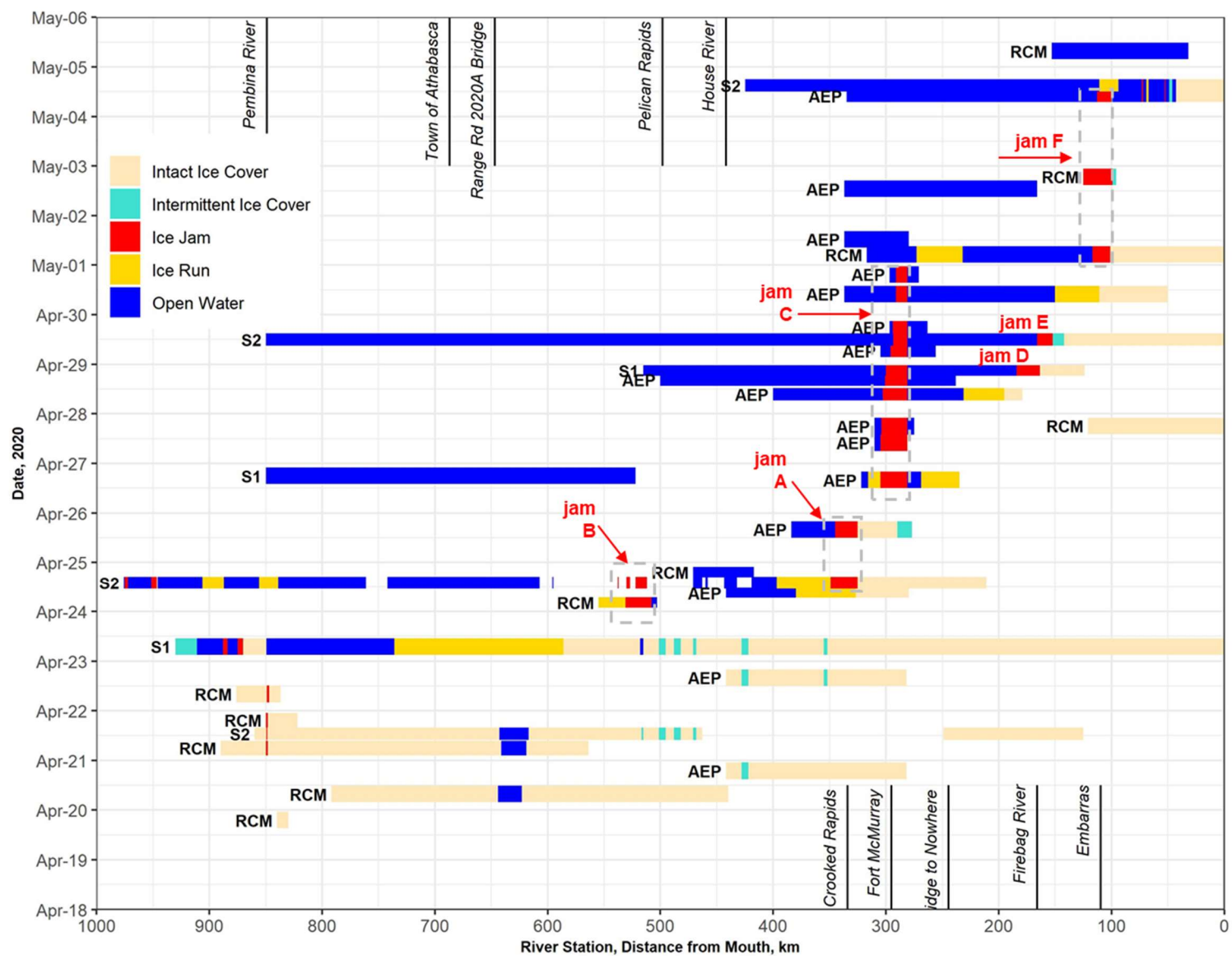


Figure 4: Ice cover progression on the Athabasca River in 2020. Data sources: AEP=AEP observation flight, S1= Sentinel 1 satellites, S2= Sentinel 2 Satellites, RCM = RADARSAT Constellation Mission satellites.

April 21

- An ice jam formed at the mouth of the Pembina River and pushed ice out into the intact Athabasca River ice at km 849 (Figure 4).
- AEP issued an Ice Advisory for the Breakup of the Athabasca River from the Town of Athabasca to Fort McMurray

April 22

- The ice jam at the mouth of the Pembina River released, and the breakup of the Athabasca River downstream of the Pembina River mouth followed.
- Ice shifted and then cleared in the morning at the Town of Athabasca (km 687). A minor ice jam formed at 19:25 MST, before it was released by a large incoming ice run (Figure 5).
- An ice run passed the Town of Athabasca at 23:00 MST on Apr 22 and continued to run until 16:00 MST on Apr 23 (17 hours). Water levels rose by approximately 3.3 m (Figure 5).
- AEP Communicated to RMWB: breakup between Grand Rapids and Fort McMurray could begin in next 12-24 hrs. Breakup in Fort McMurray could occur in the same time frame or could be delayed if the ice run is arrested and form an ice jam upstream of Fort McMurray.

April 23

- The Ice Advisory was upgraded to an Ice Jam Watch for the Athabasca River at Fort McMurray following the sustained ice run at the Town of Athabasca.

April 24

- The Grand Rapids gauge (km 430) stopped transmitting reliable data at 02:30 on Apr 24, after rising 1 m overnight (Figure 6a). This was interpreted as a major ice movement at Grand Rapids, and the planned afternoon observation flight time was advanced to “as soon as possible” and occurred in the late morning.
- During the observation flight, a major breaking front and ice run (Run A, Figure 4) was observed to be approaching Crooked Rapids (km 330) at 11:45 MST. Photos and videos taken during the flight revealed the breaking front was travelling at a rate of 16.2 km/hr or 4.5 m/s. This breaking front and ice run were causing high levels of backwater and had pushed ice up well into the mature tree line along the river.
- AEP communicated to RMWB, if the breaking front did not jam, expected travel time to Fort McMurray within 3.5 hrs.
- RMWB tweeted: “Warning, high risk of flash flooding. The ice on the Athabasca River is likely to break within the next few hours” (RM Wood Buffalo, 2021).
- The ice movement alarm was tripped at Mountain Rapids at 14:34 MST.
- The breaking front did not arrive in Fort McMurray. It was assumed to have jammed between the Fort McMurray Golf Club (km 300) and Mountain Rapids (km 312) because the ice movement alarm at Mountain Rapids had tripped, and water levels had risen at both Cascade Rapids (km 321) and Mountain Rapids. The jam was visible at the Crooked Rapids camera (km 330), confirming that the head was upstream of that location. Inclement weather precluded flying again later in the day to confirm the ice jam position.
- RMWB tweeted: “There is still a high risk of flash flooding to areas in the Lower Townsite, Waterways and Draper. At this time River Breakup has not been declared”.

- An RCM image taken April 24 (but made available to AEP after breakup) revealed that a second ice jam (Jam B) was in place upstream of Pelican Rapids (near km 508) (Figure 4). The optical Sentinel 2 image from this day was heavily obscured by clouds near Pelican Rapids, but glimpses of Ice Jam B were slightly visible through the clouds.

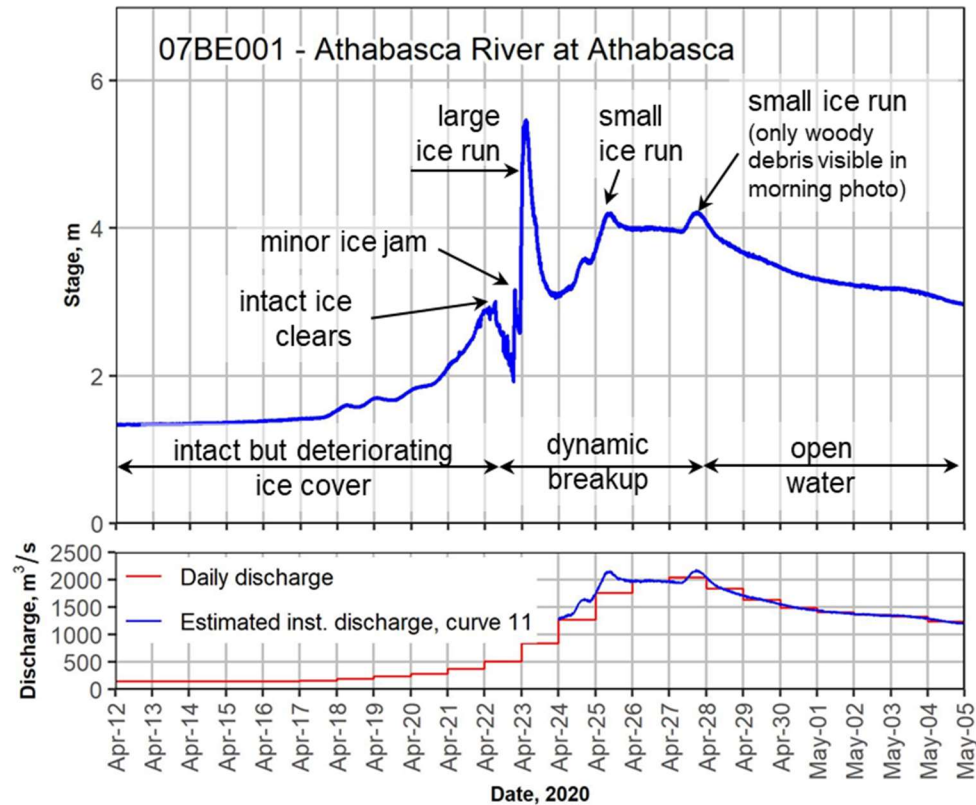


Figure 5: Water level (top) and flow (bottom) at the Town of Athabasca (07BE001, km 687) from finalized WSC data, annotated with ice movement information from remote camera observations

April 25:

- AEP's observation flight confirmed that the ice jam (Jam A) was 20 km long, with its toe at km 325, between the Crooked Rapids (km 330) and Cascade Rapids (km 321) gauges.
- The ice jam was not located downstream of Mountain Rapids, as had been assumed the day before. The ice movement alarm may have been tripped when the escaped wave from the formation of Jam A passed by Mountain Rapids.
- AEP communicated to RMWB that there was the potential for severe impacts: because overbank flooding was observed upstream of Jam A and water levels had risen 6 m in the ice jam at Crooked Rapids (Figure 6b), AEP expected that water levels could rise 4-7 m at Fort McMurray.
- The location of Jam A meant that there were gauges with water level alarms downstream of the ice jam toe, as well as a gauge and camera within the jammed section. This was an ideal configuration for instruments to provide warning should the ice jam release.

However, with the Grand Rapids gauge inoperable, any additional ice runs with the potential to cause the release of Jam A could not be detected by instruments.

- Near-real-time water levels at the Town of Athabasca (km 687) indicated that Athabasca River flow could be $\sim 2,000 \text{ m}^3/\text{s}$ or more (Figure 5). However, because the large ice run at that location on April 22-23 could have shifted the gauge orifice, the reliability of the near-real-time water level measurements (and thus flow estimates) was not known, nor was the extent to which the gauge data was ice-affected.
- The camera at Crooked Rapids (km 330) was set to take photos every 20 minutes. This was determined to be the optimal photo interval for satellite transmission, any shorter interval tended to create a transmission backlog and prevented the transmission of all photos.
- AEP forecasters monitored camera images and water levels throughout the night.
- Photos from the Crooked Rapids camera (km 330) indicated slight downstream “creeping” movement of Ice Jam A beginning around 22:41 MST.

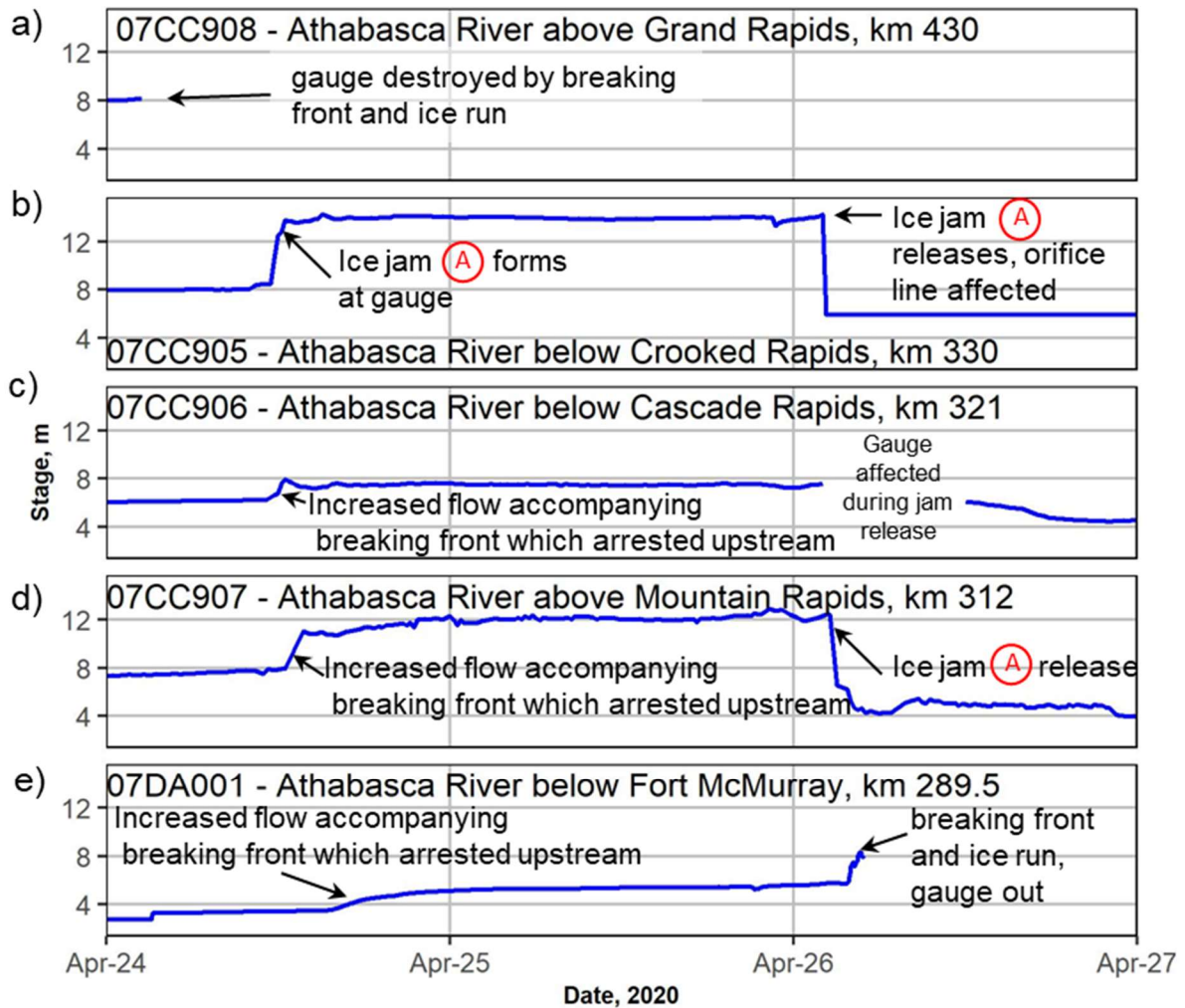


Figure 6: Water level hydrographs measured at Athabasca River gauges near Fort McMurray, annotated with breakup progression notes

April 26:

- Photos from the Crooked Rapids camera (km 330) showed Ice Jam A releasing at 02:21 MST.
- AEP contacted RMWB Emergency Managers, advised that the breaking front could arrive in Fort McMurray in the next few hours.
- The Cascade Rapids (km 321) ice movement pull-wire alarm tripped at 02:35 MST.
- RMWB Emergency Managers drove to meet the breaking front at the Fort McMurray water treatment plant (km 296.5) around 04:45 MST. It was still somewhat dark, and the ice “sounded and looked like a freight train going by.”
- The breaking front arrived in at the Hwy 63 bridge at Fort McMurray (km 294.7) around 05:00 MST (Figure 7).
- The ice ran on the Athabasca for several hours in the morning. Athabasca River ice was pushed up the Clearwater River and the Clearwater River flowed upstream.
- Movement of the ice run began to slow by mid-morning, forming an ice jam (Jam C) with its toe at km 281, downstream of the Clearwater River confluence and with the main body of the ice jam extending to upstream of mouth of the Clearwater River. Eventually, ice was pushed 7 km upstream on the Clearwater River.
- The first flooding occurred in low-lying areas. Evacuations were ordered and road closures occurred along Athabasca River (Taiga Nova industrial park, km 290) and the Clearwater River (Draper area, km 10-20). By this time, water levels had risen between 4.5 and 6 m on the Clearwater and Athabasca Rivers (Figure 7).
- AEP’s Ice Jam Watch was upgraded to Ice Jam Warning for the Athabasca and Clearwater Rivers in Fort McMurray.
- Top of ice levels measured at the Hwy 63 gauge (km 294.7, Figure 7), dropped below the peak level measured during the passage of the breaking front. However, water levels continued to rise along the Clearwater River as Ice Jam C formed (Figure 7).
- AEP’s afternoon observation flight revealed the toe of Ice Jam C was located at km 281 and the head at km 305 (24 km long).
- It appeared that Ice Jam C may have been originally longer, but the downstream portion of the ice jam had released downstream. The resulting ice run was observed from just upstream of Tar Island, continuing past Fort McKay (from km 235 to 268.5). This run likely formed a small jam downstream of Fort McKay (Jam D), but the extents of this jam were not observed.
- RMWB issued a State of Local Emergency.

April 27

- Water levels continued to rise on the Clearwater River overnight (Figures 7), filling the Clearwater River valley (Figure 8).
- AEP’s morning observation flight showed that Ice Jam C remained in place, but had lengthened to 24.5 km long. Low-concentration ice runs had added to the length of the jam and cold air temperatures limited ice melt.
- Just before noon, the dike around Downtown Fort McMurray (Prairie Loop Boulevard) started breaching and large-scale direct inundation began in the downtown (Figures 7 and 8). Approximately 450 m of dike between Riedel and Hospital Streets was directly

overtopped by rising waters on the Clearwater River (Figure 7). The elevation of the dike crest in this reach was approximately 248.50 m (Hatch and Golder Associates 2018).

- AEP's 18:00 observation flight showed that Ice Jam C was still in place, 23 km long. The ice jam had begun to darken in the sun as the ice melted, leaving behind more sediment-rich ice.
- Downtown Fort McMurray was evacuated in stages throughout the afternoon. A mandatory evacuation notice for downtown Fort McMurray was issued at 19:27 PM MDT.
- Water levels on the Clearwater River continued to rise slowly throughout the day, from 248.07 to 248.74 (Figure 7).

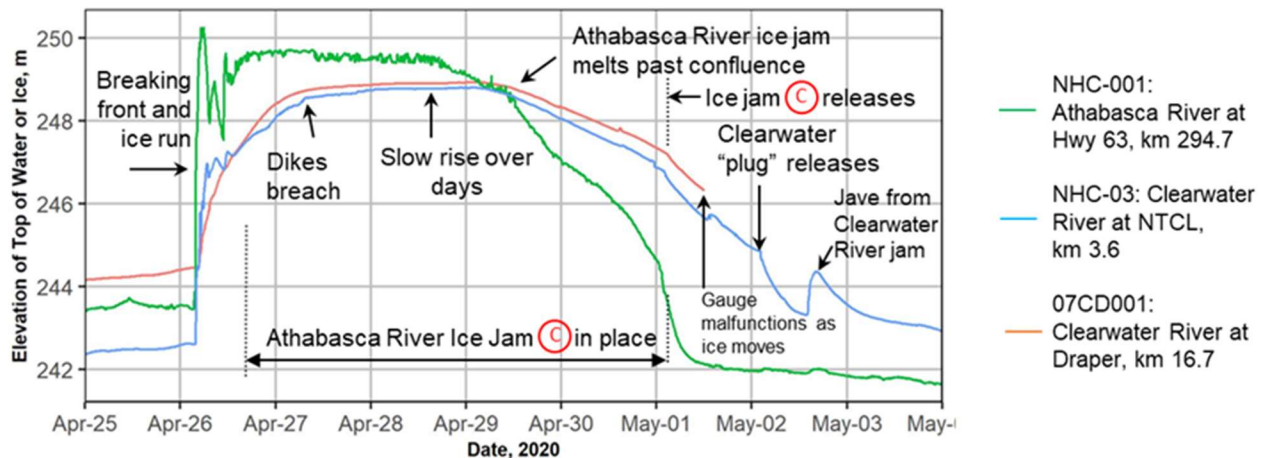


Figure 7: Top of water or ice (green) or water level (blue and pink) at Fort McMurray, annotated with breakup progression notes

April 28:

- AEP's morning observation flight showed that Ice Jam C remained in place, 22 km long. A 36 km long ice run was observed breaking into intact ice downstream of Fort McKay (Figure 4) with the toe of the breaking front at km 195. This was likely the released ice from the unobserved Ice Jam D. Flooding of low-lying areas adjacent to the river was observed.
- AEP issued an Ice Jam Warning for the Lower Athabasca River and PAD.
- Rescue operation occurred when two men were swept into the Athabasca River, downstream of Fort McKay. One man later died in hospital.
- AEP's 18:00 observation flight showed that Ice Jam C at Fort McMurray was still in place, 20 km long. The ice jam continued to darken and deteriorate over the course of the day.
- The Clearwater River ice cover upstream of Fort McMurray began to breakup.
- Water levels on the Clearwater River remained steady throughout the day and reached their peak level at 22:50 MST (Figure 7).

Apr 29:

- Water levels began to fall slowly on the Athabasca River at the Hwy 63 bridge (km 294.7) as the melting head of the ice jam approached the bridge (Figure 7). Water levels on the Clearwater River also began to fall slowly around 02:00. By the end of the day, water levels on the Clearwater River had dropped by 0.76 m (Figure 7).

- AEP's morning observation flight showed Ice Jam C at Fort McMurray was still in place, now 15 km long, with its head at the Water Treatment Plant. The head of the ice jam was expected to melt though Fort McMurray later that day.
- The evening observation flight showed that Ice Jam C was still in place, and was 13 km long, with its head at the Clearwater River confluence.
- Downstream of Fort McMurray, an ice jam (Ice Jam E, Figure 4) was observed causing flooding of low lying areas near the Firebag River (km 152, remnants seen in Figure 9c).

Apr 30

- AEP's mid-day observation flight showed that Ice Jam C was still in place, 9.5 km long
- The head was downstream of the Clearwater River confluence, and water levels on the Athabasca and Clearwater Rivers continued to fall slowly.
- A 'plug' of jammed ice remained in place at the confluence of the Clearwater River (Figure 9a), even as the Athabasca ice had melted out adjacent to it. As a result, water levels fell more slowly on the Clearwater River than the Athabasca River (Figures 7).
- The Clearwater River ice cover upstream of Fort McMurray broke into sheets, flowed downstream, and collected in river bends. Small ice jams formed just downstream of the Christina River confluence, and on the Christina River (2 and 6 km long).
- AEP's evening observation flight showed that Ice Jam C was still in place, now 9 km long.

May 1

- AEP's morning observation flight revealed that Ice Jam C at Fort McMurray had melted and released completely overnight. As a result, water levels on the Athabasca River at Fort McMurray fell by approximately 2 m and water levels on the Clearwater River fell by approximately 1 m (Figure 7).
- The ice jam "plug" at the mouth of the Clearwater River was still in place slowing the draining of the floodwaters along the Clearwater River. This plug was melting and eroding into the Athabasca River, from the downstream end (Figure 9a).
- Water levels on the Clearwater River had fallen below the height of the dike crest, but AEP was concerned that ice runs from the Clearwater River could still bring waves of incoming ice and water. This was a concern because re-entry into evacuated areas had begun.
- The ice jam that was on the Christina River released in the afternoon, reforming into a 5.5 km long ice jam on the Clearwater River with its toe at km 12.5 near Dunvegan Gardens.
- When the ice jam formed, the orifice line at the Clearwater River at Draper gauge (km 15.7) was dislodged and the gauge stopped providing reliable data (Figure 7).
- Water levels along the Clearwater River continued to fall slowly.
- Downstream of Fort McMurray, a 16 km-long ice jam (Jam F) was observed at km 101 near the Embarras River confluence in the Peace-Athabasca Delta (Figure 4).

May 2

- The ice jam "plug" (Figure 9a) that had been holding back water and ice at the mouth of the Clearwater River released overnight (May 1 to 2).
- The ice jam on the Clearwater River at km 12.5 released in the afternoon. The jave and ice run from the release of this small jam flowed past downtown Fort McMurray, remaining

in-channel and did not re-jam at the confluence. Water levels temporarily rose by ~1.2 m (Figure 7).

- The Ice Jam Warning was ended for Fort McMurray, however an Ice Jam Watch remained in place from the Firebag River to the PAD.



Figure 8. Top: looking downstream on the Clearwater River at Draper and towards downtown Fort McMurray on April 27, 2020, backwater from the ice jam has filled the Clearwater River from valley wall to valley wall. Bottom: flooding in downtown Fort McMurray on April 28, 2020.

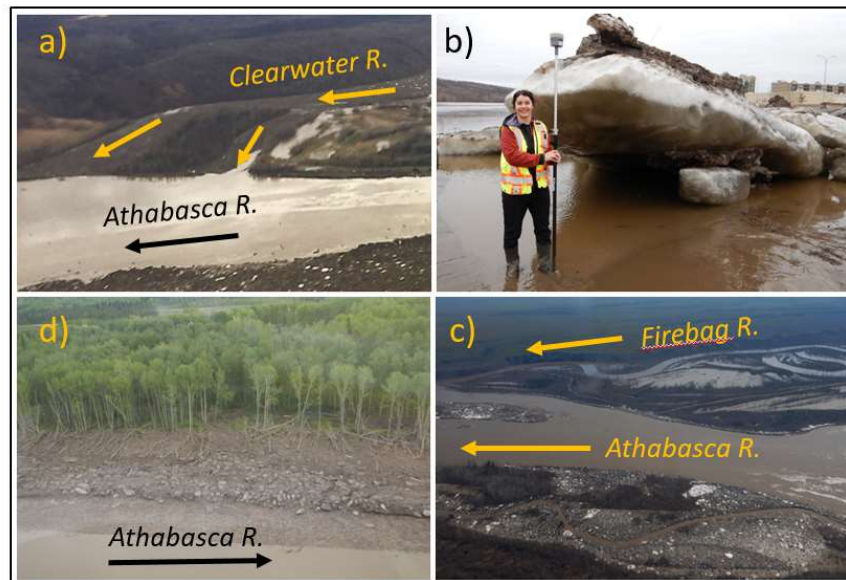


Figure 9. a) Ice jam “plug” at the mouth of the Clearwater River, while the Athabasca River was open, April 30, 2020. b) Remnant ice in downtown Fort McMurray on May 1, 2020. c) Flooding at the mouth of the Firebag River May 4, 2020. d) Remnant ice, riverbank erosion, and downed trees upstream of Grand Rapids, photo taken June 10, 2020.

May 3 - 12

- On May 4, Ice Jam F, with its toe at km 101, near the Embarras River, released. The ice run passed through 50 km of open water downstream of the jam, however an intact ice cover remained in the PAD channels closest to Lake Athabasca.
- High flows and small ice jams in the Athabasca PAD channels caused overland flooding in the Athabasca sector of the PAD.
- Buildings and residences were flooded at community of Jackfish, AB (Athabasca River km 31), when an ice jam formed downstream of the community on May 4-5.
- The Ice Jam Watch for the downstream Athabasca River was ended on May 12.

Detailed inter-agency reporting of the 2020 breakup of the PAD is currently underway. Additional information about the PAD breakup is available from Beltaos and Carter (2021), and Emmer et al (2021).

4. Flood Impacts

In Fort McMurray, flood damage was mostly caused by floodwaters as opposed to a combination of floodwaters and damage from ice blocks. In downtown Fort McMurray, dikes were overtopped, causing floodwaters (but not ice) to reach large areas of downtown. Flood damages in Fort McMurray were estimated to exceed \$1.1 billion: \$522 million in insured damages (Insurance Bureau of Canada (IBC) 2020), and \$617 million in uninsured damages (Adriano 2021). IBC estimates that 1230 structures were affected. Flooding occurred along the Athabasca River in Fort McMurray at the Fort McMurray Golf Course, Taiga Nova Industrial Park, and the Parsons Creek Aggregate pit. Along the Clearwater River, extreme flood impacts occurred in the lower town site of Fort McMurray and in the community of Draper. Floodwaters reached the hospital parking lot, but not the hospital building. Approximately 13,000 people were displaced between Apr 26 and May 2 (from 4-6 days) (Beamish 2020). Evacuations, accommodations, and the distribution of supplies to displaced people were challenged by the COVID-19 pandemic. Untreated water back-flowed into Fort McMurray's treated water system. This resulted in a boil water advisory, the final stage of which was lifted 55 days after it was put in place. One person lost their life in the floodwaters downstream of Fort McMurray.

Low-lying areas were flooded along hundreds of kilometers of riverbank (i.e. Figure 9c). Mature trees were pushed down (Figure 9d) and severe erosion was observed after breakup. Large accumulations of ice were still in place on June 10, 2020, more than 6 weeks after breakup.

5. Ice Jam Analysis and Documentation

AEP, with assistance from RMWB, surveyed highwater marks (HWM) along the Athabasca and Clearwater Rivers after peak flood levels occurred (Figure 9b). These HWM profiles are shown in Figures 10 and 11. In Addition, AEP collected aerial orthoimagery on April 28, on the day of peak water levels on the Clearwater River.

Hatch and Golder (2021) modelled the 2020 ice jam using the HEC-RAS model developed for the Fort McMurray Flood Hazard Study (Figure 10). The model domain was not large enough to

contain the upper ~4 km of the 2020 ice jam; however, the results of this modelling effort show that the ice volume¹ in the ice jam was in excess of 28 million m³. In addition, the 2020 ice jam produced water levels between the 1:50 and 1:100 annual exceedance probability ice jam water levels at Fort McMurray.

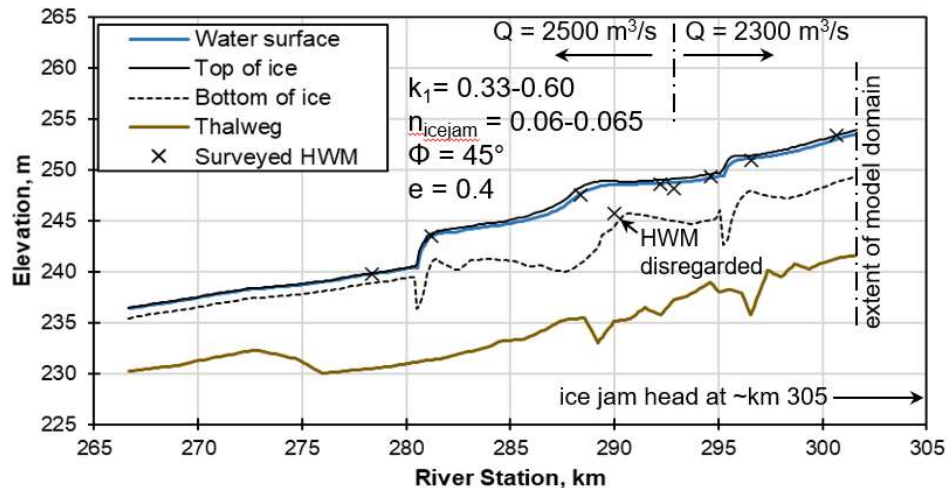


Figure 10: Highwater marks collected along the Athabasca River and modelled ice jam profile after Hatch and Golder Associates (2021).

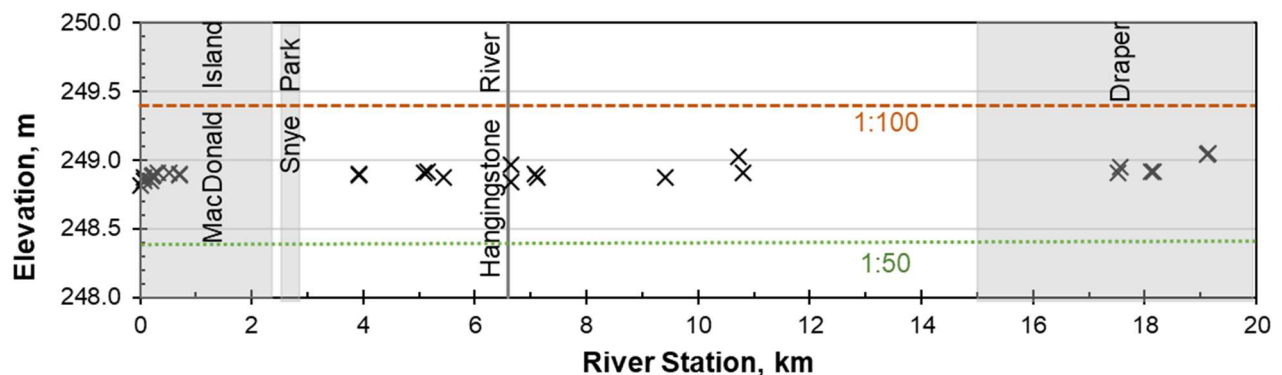


Figure 11: High water marks collected along the Clearwater River in 2020 and the 1:50 and 1:100 annual exceedance probability ice jam flood elevations from Hatch and Golder Associates (2018).

6. Discussion

6.1 Forecasting Challenges

Communicating timely, accurate predictions and situational reports to emergency managers during an extreme event like the 2020 spring breakup flood was challenging. Many challenges arise from the uncertainty inherent in data and ice processes.

¹ Calculated as:

(HEC-RAS's "ice jam volume" in the reach containing only the ice jam) x (1-e)

where e = jam porosity = 0.4

Uncertain water level measurements and gaps in real-time water level records contributed to uncertainty at breakup. Orifice line water level gauges are vulnerable to shifting or being ripped out during periods of ice movement. It was not known if upstream water level measurements (and thus discharge estimates) were accurate until they were surveyed and the data corrected. Extreme ice movements caused several gauges to stop reading or to record bad data, making them unusable for keeping track of ice movements. This happened during the most critical periods of breakup.

Additional uncertainty stemmed from delays in the availability of satellite imagery. Satellite imagery has become a valuable tool for monitoring river breakup. Delays of several hours between image acquisition and public availability make the use of satellite imagery in quickly changing situations difficult. Often, once imagery is available, the information contained in it is “stale”, and no longer relevant. Imagery was very useful in re-creating and evaluating the progression of the 2020 breakup, but most of these data was available with considerable delay or, in the case of RCM data, available months after breakup. RCM images were being captured during breakup of 2020, but there was not yet an established arrangement for provincial governments to obtain them in near-real-time. This process came online later in 2020. Most RCM imagery shown in Figure 4 were obtained several months after breakup. The April 24 RCM image (Figure 4) showing Jam B was provided to AEP as a courtesy in June 2020 by Natural Resources Canada (NRCAN). NRCAN also provided digitized flood extents in Fort McMurray during the event, with very little delay. This information was useful to determine flooded extents, but not useful in a forecasting context, because the ice jam had already formed and the flooding had already occurred.

The largest source of uncertainty during breakup was due to the dynamic nature of breakup on the Athabasca River. It is highly uncertain whether, when, and where ice runs and breaking fronts will stop, and whether and when ice jams will release. The potential severity of impacts of an ice jam at Fort McMurray was apparent as the ice broke up, but whether such an ice jam would form at Fort McMurray was not apparent. The formation of ice jams is a natural part of the Athabasca River ice breakup process, and large ice jams are common during breakup every year. However, large-scale breaking fronts that mobilize hundreds of kilometers of ice at once is the scenario associated with higher flood risk. The key question is if and where these ice runs will arrest and jam. Whether an ice run jams downstream of the Clearwater River confluence has a critical impact on flood severity in Fort McMurray. For example, conditions on the Athabasca River were roughly comparable in 2018 and 2020 (high snowpack, late onset of spring snowmelt, large-scale breaking front mobilizing hundreds of km of ice, similar pre-breakup indicators). However, in 2018 the large ice run did not jam near Fort McMurray as the breaking front moved past Fort McMurray without arresting and forming a jam. Because a jam did not form on the Athabasca River at Fort McMurray 2018, water levels on the Clearwater River were > 4 m lower than in 2020, and only minor flooding occurred (AEP 2018).

The uncertainty of whether or not an ice run will arrest and form a jam is a challenge when communicating flood risk to emergency managers. AEP’s river ice forecasters interpret river conditions to support local emergency decision making. This includes informing the timing of when municipal teams stand up their monitoring crews, anticipating the arrival of ice runs/breaking fronts, monitoring the river upstream of Fort McMurray for rapid changes in ice conditions and communicating the potential for flood severity. The envelope of what is possible is enormous.

Every year, there is a possibility that ice jams will form at Fort McMurray. This uncertainty, in turn, makes it difficult for emergency managers to act until impacts are imminent or occurring.

6.2 Future Research

Extreme events are very important to study because they provide insight into the hydro-cryo-meteorological processes that occur when extreme flooding occurs. “Typical” or “normal” breakup conditions may not exhibit processes that can be “scaled-up” to more extreme events. As such, the 2020 breakup has highlighted a few areas that could be the subject of future research. Additional areas of future research can be found in Emmer et al (2021).

Gauge technology. Standard orifice and bubbler gauge technology often fails during ice movements, with the orifice line being moved or entirely ripped out. This makes it difficult to determine peak water levels, be warned of incoming javes, or to accurately estimate discharge. The need for improved gauge technology was well described more than 30 years ago by Gerard (1990), and has only been partially satisfied by bridge-mounted, downward-facing sonar sensors. The development of laser-based (e.g. Johnson et al 2019) or photo-based oblique-looking technology and its validation for ice-covered rivers in remote locations is welcome.

Dynamic Stopping (Breakup) and Release Thresholds. A large source of uncertainty in ice jam forecasting on Alberta’s large northern rivers is predicting whether and where a breaking front will be arrested. Breaking fronts, ice jams, and ice runs are very common on the Athabasca River, but they cause the most severe flooding if they are arrested near or downstream of communities or infrastructure. In addition, prediction of the release of an existing ice jam due to dynamic forces is needed. Models that can predict this accurately and that are well-validated would be very helpful to ice jam forecasting operations. The 2020 event may provide an important validation test case.

The influence of freeze-up patterns on breakup. Observations indicate that consolidated ice accumulations from freeze-up are more likely to arrest ice runs at breakup. But to our knowledge this has not been systematically tested, and may assist with validation of research into dynamic thresholds (above). In addition, targeted mitigation (i.e. targeted artificial breaking) could be informed by such a systematic analysis. The recent availability of a significant amount of remote sensing data may help answer this question.

7. Conclusion

The late onset of spring and high snowpack led to a dynamic breakup of the Athabasca River in spring 2020. A cascade of ice jams and releases occurred, including a 26-km long ice jam that formed at Fort McMurray. The 2020 breakup of the Athabasca River led to one fatality, extensive flood damages, and the evacuation of more than 13,000 people. Flood levels at Fort McMurray were the 3rd highest observed since 1875. A major breaking front was observed to travel with a celerity of more than 4.5 m/s and the ice jam at Fort McMurray was modelled to contain more than 28 million m³ of ice. Forecasting and communicating the potential severity of such a dynamic event was challenging, given the uncertainty in near-real-time data and potential future ice movements. The 2020 Athabasca River breakup may inform future research efforts as a case study in dynamic breakup process.

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The 2020 ice jam flooding in Fort McMurray and along the Athabasca River was catastrophic. Although the river ice processes are described herein, we acknowledge the devastating impact it had on communities, families and livelihoods, as well as the tragic loss of life that occurred on the Athabasca River.

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