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Insights from the 2022 mechanical breakup of the lower Peace River and contribution to flooding of the Peace-Athabasca Delta

Martin Jasek

*BC Hydro, 6911 Southpoint Drive, Burnaby, BC V3N 4X8
martin.jasek@bchydro.com*

Ice jam flooding of the Peace Athabasca Delta (PAD) has important ecological and socioeconomic implications. There are opposing theories in the literature about what defines the conditions that produce ice jam floods in the PAD and whether or not regulation from the Bennett Dam in British Columbia plays a role in the probability of these ice jam floods occurring. This paper sheds light on this debate, describes the antecedent conditions and the breakup that occurred in 2022 and the subsequent flooding in the PAD. The breakup was initially thermal but quickly evolved into a mechanical breakup for the last 200 kilometers of the Peace River and subsequently created an ice jam in the PAD that lasted several days and effected water levels in the PAD significantly. Discharge was augmented by significant tributary inflows in the northern Peace River basin that transformed a thermal breakup into a mechanical one. Detailed areal observations and satellite images were used to document the ice cover width where the ice sheet upstream was wider than the channel downstream. This indicated that a mechanical breakup through the PAD reach, ice jam formation and resulting PAD flooding were possible despite regulated freezeup levels.

1. Introduction

The Peace-Athabasca Delta (PAD) is located in northeastern Alberta about 1200 km downstream from the Bennett and Peace Canyon Dams in British Columbia (Figure 1). It is located in Wood Buffalo National Park (WBNP) and is a designated UNESCO World Heritage site. It is a very large, predominantly wetland area bound to the south by the Athabasca River Delta, Lake Claire to the west, Lake Athabasca to the east and the Peace River that flows along its northern boundary. It is home to large numbers of many wetland species. Periodic flooding from ice jams along the Peace and Athabasca Rivers are deemed beneficial to ecology of the PAD and are thought to be the primary source of recharge to its higher elevation lakes or perched basins (Peterson, 1992; Prowse and Lalonde, 1996; Timoney, 2002). There have been perceived changes in the PAD since the 1970s (Peterson, 1992), including to ice jam flood (IJF) frequency on the Peace River since the construction of the Bennett Dam. However, periods of drying from the 1970s to the early 1990s coincides with regional drying even outside of the Peace Basin unaffected by regulation by dams (Timoney, 2002). This has led to a debate among scientists on the possible primary causes of flooding, and whether or not a change in IJF frequency has actually occurred (Beltaos, 2017; Timoney et al., 2018; Hall et al., 2018; Lamontagne et al., 2021 and Jasek et al., 2021). The physical mechanism proposed for the reduction of IJF frequency is that higher freeze-up levels in the preceding winter due to regulation makes it more difficult for the spring flow to dislodge the ice ((Prowse and Conly, 1998; Beltaos et al. 2006; Beltaos, 2014; 2017) favoring thermal break-ups over mechanical ones. The theory being that the ice sheet would be wider and more difficult to mobilize through channel constrictions and around sharp channel bends under the regulated regime. However, Lamontagne et al., 2021 and Jasek et al., 2021 determined that any post regulation flood frequency change can be explained by climatic variables like winter precipitation (snowfall) in the southern tributary basins like the Smoky River (Figure 1) and other adjacent tributary basins and how cold the winter is in the north part of the basin to form a thick and more resistant ice cover that favours mechanical breakups and ice jam formation. Lamontagne et al., 2021 have shown that adding freeze-up elevation to the statistically predictive model did not provide any additional predictive power and in fact degraded the reliability of this model. Despite this, Beltaos and Peters 2021 used naturalized freeze-up elevations to calculate that there should have been 5 additional IJFs since regulation. Such conclusions could affect future management of the PAD and focus management efforts on responses that have no benefit.

In 2016 and 2022, UNESCO sent a joint World Heritage Centre/IUCN Reactive Monitoring mission (mission) to the PAD in WBNP to determine if the Heritage site should be classified as endangered. Preliminary findings are that the endangered classification is not warranted (draft report April 2023). As a result of the 2016 mission, the Canadian Government is implementing an Action Plan with participation by Parks Canada, Environment and Climate Change Canada, Alberta Environment and Protected Areas, Indigenous Nations and BC Hydro. The Action plan includes, amongst other things, feasibility studies to build local water control structures in the PAD, a protocol for strategic flow releases from the Bennett Dam that could enhance an ice jam flood event, enhanced monitoring, and an environmental flows assessment that incorporates multi-disciplinary and multi-jurisdictional studies along with indigenous knowledge to inform future and ongoing management actions.

This study provides additional knowledge on the role of the Peace River breakup and ice jam formation on flooding of the PAD by examining the 2022 breakup in detail. Specifically, the break-

up sequence and lateral measurements of the Peace River ice cover upstream and at the PAD reach just prior to the arrival of a mechanical breakup and subsequent ice jam formation and PAD flooding sheds insights on the proposed influence of the lateral boundary constraint criteria that is proposed to be affected by regulated freeze-up flows as described above.

2. The 2021-2022 winter and antecedent conditions

Lamontagne et al., 2021 determined that total Grande Prairie precipitation after the onset of sustained freezing temperatures (calculation described in Jasek et al. 2021) greater than about 150 mm were favourable for an ice jam flood at the PAD. This condition was met by 176 mm (116% normal) for the 2021-2022 winter. This was supported by the lower plains April 1st and March 1st Snow Surveys which were both 115% of normal for sites in the Smoky and adjacent basins to the north and east. Mountain snowpack survey sites were not counted as these melt off too late to contribute to Peace River flows during the breakup period.

There was however something unusual in the snowpack in the plains of the southern Peace basin. Snow water equivalent at individual stations ranged from 53% to 163% of normal for March 1st and 0% to 200% of normal for the April 1st snow surveys. This degree of variance was unusual and probably due to selective snow loss at sites due to an unusual mid-winter snowmelt event brought on by chinook winds which may have touched down in some locations and not others, a plausible situation in February 2022 (per communications with Tim Ashman, BC Hydro meteorologist). This snowmelt event produced a mid-winter breakup on the Little Smoky River in early February 2022 (Nafziger et al. 2023). This mid-winter loss of the snowpack created uncertainty if it significantly impacted the snow water content that would be able to drive the Peace River breakup to the PAD in April 2022. However, further to the north anecdotal information by locals and viewed by the writer during breakup monitoring in the Fort Vermilion area indicated that the snowpack was unusually high. In addition, during the breakup in early May, the writer noticed that streams in the area were running relatively high compared to other significant breakup years observed in 2014, 2018 and 2020. Examining the cumulative precipitation for the 2021-2022 winter (during sustained freezing temperatures as calculated in Jasek et al. 2021) at Fort Vermilion indicated a relatively large value of 155% of normal compared to the last previous significant breakup years; 2014 (105%), 2018 (127%), 2020 (42%). This larger than normal snowpack in the northern part of the basin, that runs off later than the Smoky basin due to being further north, suggests that it played a larger role in the breakup process in 2022 than in other years. This higher-than-normal snowpack was likely present further to the east and in and around the PAD as supported by much above normal stream flows in that area during and after the breakup period as described by Timoney and Jasek, 2023.

The other significant variable found by Lamontagne et al., 2021 and Jasek et al., 2021 that are favourable for PAD ice jam floods are the cumulative degree-days of freezing (DDF). Values of $DDF > 2250$ °C-days at Fort Vermilion and $DDF > 2500$ °C-days at Fort Chipewyan are favourable for ice jam floods in the PAD. For the 2021-2022 winter the DDFs were 2513 °C-days and 2903 °C-days respectively. Thus, with favourable DDF and snow to the south (although the latter uncertain) a PAD flood looked favourable.

3. Early breakup period

Figure 2 shows slow recession of the ice front from the Town of Peace River in late March to Fort Vermilion on April 30 indicating a thermal breakup in this reach. Temperatures were cooler than normal April 10-22 and April 27-May 2 (Figure 3 shows 3rd week of April and into May) and therefore did not produce significant run-off from the Smoky and adjacent basins in the southern part of the Peace River watershed. Discharges were still small in the third week of April, hovering around 2000 m³/s at the town of Peace River with the majority coming from Peace Canyon Dam which was discharging about 1600 m³/s around this time (Figure 4). Breakup continued in the thermal mode up to May 4 to just upstream of Garden River.

4. Assessment, characterization, and corrections of water level data during breakup at Fort Vermilion and Peace Point

Before the transition of the Peace River breakup from a thermal one to a mechanical one will be discussed, data from two key Environment and Climate Change Canada gauges; Fort Vermilion and Peace Point needed to be analyzed and post processed in light of field surveys and ice observations.

The data record for the Peace River at Fort Vermilion gauge during the breakup period started on April 28 just in time for the thermal breakup on April 29 (Figure 5). Two BC Hydro manual water level surveys on April 30 and May 2 indicated the record needed a small correction of +0.02m as indicated. The next task was to determine the end of the backwater affect due to ice downstream. A clue was the break in slope in the water level decrease on May 2, 2022, 12:30 MST which was supported by the fact that the thermal breakup front had made it down the Vermilion Rapids (Figure 5 satellite image inset) exposing the upstream end of the rapids to supercritical flow visible in the satellite image; the downstream control at Fort Vermilion was now at the rapids rather than the ice cover. The rating curve at Fort Vermilion could now be used to compute discharges going forward from May 2, 2022, 12:30 MST.

The data record for Peace Point gauge is shown in Figure 6. The green line is the raw data which is under blue line (corrected data) in some places. A secondary sensor is shown in yellow and a red dot on May 10 shows a manual survey by ECCC staff allowing for data corrections. There appears to be some disturbance to the record May 2 to May 3 indicating a slow downward trend followed by a sudden rise. At first this appears to be an indication of a local breakup but examination of images from a Parks Canada remote camera indicates a steady rise in the ice cover without the ice sheet shifting during this period (Figure 6 insets on right – more images than these three are available). The dip in water level later, on May 3, is noticeable in the camera images and is therefore real. The suspect data from May 2, 2022, 05:05 MST to My 3, 2022 09:30 MST is omitted in further graphs and a steady rise between these two points in time is assumed.

The secondary gauge at Peace Point was set in on the riverbank above the water level but then recorded good data once the water level rose above it; it nicely captured and followed the primary sensor data confirming that the increasing water levels May 4-5 and the mechanical breakup peak on May 5 as shown in Figure 6. This gives confidence that this important part of the record is accurate without any major sensor shifts.

5. Ice conditions of the lower Peace River prior to mechanical breakup

Figure 7 shows the Sentinel 2, May 4 satellite image of the ice cover in the lower Peace River. BC Hydro aerial observations at about the same time indicated that the ice was broken up to km 975.5 with the head of rubble ice at km 963, indicating the presence of a 12.5 km long ice jam. This amount of rubble was an indication that a transition from the thermal to a mechanical breakup may be imminent. Figure 7 also shows that the ice cover from the ice jam to the PAD and Slave River was intact except for a short reach upstream of Boyer Rapids which is typical. Also relevant for the forthcoming breakup are the various shades of the ice cover; brighter shades likely indicate more competent ice covers than darker ones; either they indicate snow on the ice cover or ice made of finer crystals, both of which reduce solar radiation absorption and resulting degradation. The ice is brighter upstream of Garden River, darker from Garden River to about km 1050, brighter from about km 1050 to Boyer Rapids and bright again from Boyer Rapids to Peace Point to km 1142, darker again from km 1142 to km 1162, brighter again from km 1162 to Rocky Point, darker from Rocky Point to the Slave River and bright again for the first 15 km of the Slave River. These different shadings are a function of several factors including the freezeup sequence which determines fine grained or large grained ice covers, the timing and spatial variation of early snowfall that plays a large role in ice thickness at the end of the winter. The spatial variation of snowfall on the ice cover that protects the ice from thermal degradation in the spring. These are all variables that play a role whether a reach breaks up thermally or mechanically. These variables are difficult to quantify of hundreds of kilometers of river, they change with time rapidly in the spring due to local air temperatures and cloud cover. They thus play a complex role in the breakup sequence and slight variances could determine if an ice jam forms at the PAD and causes a flood, stops short of the PAD and becomes thermal again not allowing for a PAD flood, or the mechanical breakup passes down past the PAD and far downstream on the Slave River which does not contribute as much water to the PAD as a stationary ice jam.

Figure 8 shows photos of the ice cover from Peace Point to the Slave River on May 5 that show where geometrical constraints (narrowing or sharp bends) need to be overcome if a fast (mechanical or dynamic) breakup were to occur. This shows there were plenty of locations that could arrest a mechanical break up if the boundary constraint due to high freeze-up levels was dominant.

6. The mechanical breakup of the lower Peace River and ice jam formation at the PAD

It is important to establish that a mechanical or dynamic breakup occurred on the lower Peace River in 2022 since at the heart of the debate (Section 1) is that regulation has caused more thermal breakups than mechanical ones leading to lowering of the ice jam flood frequency at the PAD. This section examines, satellite images, aerial reconnaissance, and gauge data to document this mechanical breakup event.

The discharge at the Town of Peace River started to increase on April 27-30 (Figure 4) due to warm weather that started on about April 22 (red line in Figure 3). The increase was modest considering that there were four days with highs around 15 °C at Grande Prairie prior; the discharge increase was about 1200 m³/s. It was also delayed by about three days after the peak air temperature. This muted and delayed response could have been the result of the slightly depleted snowpack in the plains due to the unusual mid-winter melt event back in February described in

Section 2 and indicative that some of it came from higher elevations of the Smoky Basin increasing the travel time to the Town of Peace River. Figure 4 shows that the base flow at the Town of Peace River was just over 3000 m³/s from Apr 29 to May 5. This was the flow magnitude from this part of the Peace basin that ultimately contributed to a mechanical break of the lower Peace River near the PAD. For comparison the flows in mechanical breakup years 2014 and 2018 were 3000 to 5000 m³/s and 6000 to 8000 m³/s respectively at this location (Jasek, 2019b).

Figure 4 shows that the discharge at Fort Vermilion from May 2 to May 6 was also modest and fairly constant at about 3600 m³/s indicating inflows of only about 600 m³/s between the Town of Peace River and Fort Vermilion. It thus appeared that a PAD ice jam flood was on the margin as about 4000 m³/s is estimated to be required to produce an ice jam flood at the PAD (Beltaos et al., 2006). However, evidence of flow contributions downstream of Fort Vermilion were forthcoming.

The normal flow travel time from Fort Vermilion to Peace Point is about 2 days but this can be substantially delayed due to the ice cover and due to the channel and off-channel storage related to breakup and ice jam formation between the two locations. However, despite this, the water level at Peace Point continued to rise May 2 to 5 while the discharge was fairly constant at Fort Vermilion (Figure 4). This indicated that either tributary inflows were significant between Fort Vermilion and Peace Point or channel and off channel storage was increasing, possibly a combination. Increase in inflows was corroborated with observations of some of these tributaries and presence of snow cover available for freshet discussed next.

The Wabasca is the largest tributary between Fort Vermilion and Peace Point and enters the Peace River at km 886 from the south. On May 1, a 4 km long ice cover was present upstream of the mouth of the Wabasca, and an 18 km long ice jam was in place upstream of the solid ice as indicated by a Landsat 8 satellite image. The thermal breakup front on the Peace River was just a few kilometres downstream of the Wabasca at this time. A May 2, Sentinel 2 image indicated the mouth of the Wabasca was open indicating that a significant inflow to the Peace River likely occurred from the Wabasca between May 1 and May 2. Unfortunately, the Wabasca River gauge record is missing until May 9, precluding quantification of the discharge contribution of this tributary.

Noted on the BC Hydro flight on May 3 was a 21 km long ice jam on the Mikkwa River, (Figure 9) from its confluence with the Peace River and was still in place on a May 4 Sentinel 2 satellite image and was 16.2 km long. The Mikkwa River enters the Peace River at about km 924 from the south. It too likely released and contributed to Peace River flows during the breakup further downstream. Note the presence of snow in the bush in Figure 9, probably melting quickly with high temperatures reaching about +17 °C in Fort Vermilion that day.

The Wenzel River that enters the Peace River at km 947 from the north, it too was observed to have ice jam at the mouth, this one via May 4 BC Hydro flight. This river drains from the higher elevations in the Caribou Mountains to the north which can be seen snow-covered in a May 4 Sentinel 2 satellite image (top left of Figure 7a).

Direct inflows could not be calculated between Fort Vermilion and Peace Point during the breakup period because of ice affected backwater that lasted at Peace Point until May 10. However, using

Peace Point flows from May 10 going forward and subtracting Fort Vermilion flows 2 days earlier gave inflow values as shown in Figure 4 (yellow line). It shows that the inflows between Fort Vermilion on May 10 were about 1800 m³/s and trending downward. The downward trend is an indication that they were likely higher before May 10 during the time that the ice jam was forming and was in place, when it was sending water into the PAD. This places the total discharge greater than 5,400 m³/s that drove the dynamic breakup and was present during the ice jam at the PAD May 6-10. This is well over the 4000 m³/s necessary for an ice jam flood at the PAD (Beltaos, 2003, found this to be the minimum discharge necessary to initiate flooding when a major ice jam has formed through the PAD reach).

Breakup observations by BC hydro flights on May 5 indicated the breakup had transformed from a thermal one to a mechanical one sometime over from late on May 4 to May 5 based on a significant increase in breakup celerity. During the thermal breakup the Apr 26 to May 4 the celerity was about 30 km/day, from May 4 to the first observation on May 5 it had increased to about 80 km/day, from about km 1045 to Peace Point it had increased to about 300 km/day (similar to the year 2014, Jasek, 2017a,b). Between Peace Point (km 1136) and the Peace River below Quatre Fourches gauge (km 1227) in the PAD it travelled at rate of almost 700 km/day (some multiple dynamic breakup fronts triggered by overall increasing discharge and dynamic forerunners would likely to explain such an exceptionally high rate). These high celerity values are characteristic of highly dynamic mechanical breakup events. Breakup celerities were calculated by taking the time difference of breakup front arrivals at two locations and dividing by the river distance. The timings of breakup front arrivals were based on either gauge data showing a sharp and significant increase in the river water level, or direct aerial observation, or remote camera observations, or satellite-based observations.

Another source indicating a mechanical event rather than a thermal one is based on a comparison of the water level trends at Peace Point and Peace below Quatre Fourches gauges with other events. Figure 10a shows the highly peaked mechanical breakup water levels on May 5, 2022 that is akin to the 2014 event also shown, which is an undisputed mechanical event. This is also supported by a sequence of Parks Canada photos on May 5, two of which are shown on left of Figure 6. A similar comparison at the Peace below Quatre Fourches gauge shows water level trends indicative of mechanical breakups in both 2014 and 2022. The slightly different shape of the persistent high-water levels after the sharp initial increase in the two years is due to downstream ice jam formation and position of the head of the ice jam relative to that gauge in those two years. Figure 10b compares the shape of the sharp peak characteristic of mechanical breakup at Peace Point to the gradual peak of a thermal breakup at Fort Vermilion in 2022.

The discussion in this section above presents strong evidence that leads to the conclusion that a mechanical breakup did occur in 2022. The next step is to establish the existence of resulting ice jam on the Peace and Slave Rivers and compare it with the 2014 “large” ice jam.

Weather conditions for areal observations were very poor on May 6, preventing BC Hydro flight from High Level but allowing for a limited low elevation flight out of Fort Smith, NT by Parks Canada. These observations indicated that toe of an ice jam had formed about 10 km downstream on the Slave River from the Peace River, similar to the location of the 2014 ice jam toe (Figure 11). Additional Parks Canada photographs indicated that the head of the ice jam was at km 1238

but with a significant running ice as far upstream as km 1171. Unfortunately, the weather deteriorated further after May 6 and flights were not possible until May 11, after the ice jam released on May 10. However, there were other source of information.

A Canadian Space Agency, RADARSAT Constellation Mission (RCM) satellite images that penetrate the cloud cover, provided documentary evidence of this ice jam. The first image was taken on May 7, 2022 and indicated that the ice jam toe was in the same place on the Slave River and the head had advanced upstream to km 1230.6 (Figure 12), about 3 km downstream of the Quatre Fourches gauge. At this point the ice jam was 22 km long. This is shorter than the initial ice jam formation length of 70 km in 2014 but was similar in length after it consolidated mechanically on May 6, 2014. It was after the major consolidation in 2014 that a major pulse of inflows entered the PAD and broke up its connecting channels allowing the water to flow more freely from the Peace into the PAD. See Figure 12 for comparison of ice jams May 7, 2022 and May 8, 2014. Thus, the 2014 and 2022 ice jams were similar in length during the major push of water down the Quatre Fourches although the 2022 level on the Peace River was between half to one metre lower on average than in 2014 (Figure 9a) and about two-fifths the duration. The 2022 ice jam was longer in duration than the 2020 ice jam that was only about 9 km long and was in place for only about 1.5 days. Based on the lengths and durations of the 2014 and 2020 ice jams quantified above, it is reasonable to quantify them as large and small respectively. Based on these two “book ends”, the 2022 ice jam at the PAD should be classified at least as medium.

Figure 13 shows an extended May 7 RCM image that includes the PAD channels indicating various states of ice cover and open water on those channels. Figure 13 inset shows a subsequent RCM image on May 8. Although the clarity is degraded (suspected to be because of wind waves on open water during the poor weather conditions aligning with the radar beam direction) the head and toes of the Peace River ice jam are visible and in about the same place as the previous day.

The water level at the Peace River below Quatre Fourches gauge started declining slowly from the time of the last RCM on May 8 to May 9 (Figure 10a) indicating that the ice jam was likely shortening due to thermal melt. Unfortunately, this gauge stopped transmitting valid data in the afternoon of May 9. However, water levels from May 9 to early on May 10 at Peace Point were increasing at this time due to the arrival of another snowmelt peak from the southern Peace River basin (Figure 4) due to warm weather in the Grande Prairie area May 4 to 6 (Figure 3). Evidence of the release of the Peace River ice jam on May 10 comes from the slight and smooth decrease amidst the rising trend on May 10 at Peace Point indicated in Figure 6. This likely signifies the sudden disappearance of the backwater at Peace Point indicating that the Peace-Slave ice jam moved out suddenly rather than thermally decaying. Examining Parks Canada photographs at Peace Point indicated no ice floes associated with this small apparent peak so it was not a result of ice being released from somewhere upstream. A subsequent flight by BC Hydro on May 11 indicated that the Slave River had broken up as far as km 1306, or 63 km downstream from the PAD confirming it likely the that the ice jam broke free in the PAD on May 10 suddenly.

7. Response of PAD water levels to Peace River breakup and ice jam

Figure 14 shows the water level in the Peace River below the Quatre Fourches (dark orange line) and central lakes central PAD Lakes (Lake Athabasca, Lake Claire, Mamawi Lake) and three gauge on the des Rochers. The Peace River below Quatre Fourches gauge indicates that Peace River water levels were over three metres higher than in the PAD during the ice jam on May 6-10. It is significant that the three lake gauges had the highest rate of rise during the presence of this ice jam, also from May 6 to 10, a clear response to inflows from the Peace River during this event. *(The gauges from the three gauges on the des Rochers in Figure 14 have missing data and show suspicious shifts. However, the sudden loss of data and sudden shifts indicate when ice movements may had occurred at these times and support the timing of dynamic breakup and ice jam formation on the Peace and Slave Rivers)*

Evidence of water making its way into the PAD due to the May 6-10 ice jam is presented in Timoney and Jasek (2023) where between 4000 and 5000 m³/s inflows into the PAD central lakes (Lake Claire and Mamawi Lake) and Lake Athabasca were estimated for the four days that the Peace River ice jam was in place. There are many smaller lakes that also received water. Timoney and Jasek (2023) also list many restricted-drainage and closed-drainage PAD lakes that received water in 2022. It is challenging to tease out if this was from the Peace River ice jam or subsequent highwater from the central lakes later in the spring or a combination unless there is some water level data from some of these basins themselves.

Fortunately, water level data from four PAD basins (obtained by Personal Communication, Daniel Peters, Environment and Climate Change Canada, Unpublished Data) indicated a response to the May 6-10 Peace River ice jam. These basins in decreasing order of response were Horseshoe Slough, which is an abandoned meander off the Quatre Fourches Channel 4.5 km from the Peace River, Pete's Creek (or PAD15) which is an abandoned meander off the Revilion Coupe about 6 km from the Peace River, Jemis Lake which is adjacent to Mamawi Lake which is about 50 km via the Quatre Fourches from the Peace River, and lastly Spruce Island Lake (or PAD5) which is 8 km straight distance from the Peace River but away from any major PAD channels (See locations of the four basins in Figure 7b).

Horseshoe Slough started rising slowly from its winter base elevation on May 4 and started rising much more rapidly early on May 6 and stopped rising late on May 6 with a depth increase of over 2 metres. It remained flat until early on May 10 and then started to drop slowly. This is a clear indication of the influence of the ice jam on the Peace River May 6-10 discussed in Section 5.

Pete's Creek (PAD15) also started rising slowly on May 4 and very abruptly early on May 6 for a total increase of over 1 m before mid-day on May 6. It stayed elevated and flat until May 12 after which it started decreasing slowly. A plausible explanation for the lack of drop from May 10 to May 12 (since the Peace River ice jam released on May 10) is that there could have been ice blockage at the entrance to Pete's Creek for the two days following the ice jam release. The Revilion Coupe branches off from the Peace River at a ~45-degree angle that would promote ice getting into this channel as the ice jam was forming on the Peace River allowing it to block outflow from Pete's Creek back to the Revilion Coupe until after it had melted.

Jemis Lake had been flat and started to increase rapidly on May 6 and peaked on May 9 for a total increase of about 0.6 m after which it declined slowly until May 14 and then increased again, this latter and more slow increase was in response to open water inputs resulting in Jemis Lake peaking in early July which was coincident with the peak of Mamawi Lake. The increasing response May 6 to 9 supports the effect of the Peace River ice jam on Jemis Lake. When Jemis Lake first started rising at 07:30 on May 6, Mamawi Lake at Old Dog camp just exceeded an elevation of 209.8 m. This agrees well with the lowest sill elevation between Mamawi and Jemis Lakes. The sill elevation between Mamawi and Jemis was surveyed in 1995/1996 and when converted to CGVD2013 datum lies somewhere between 209.8 and 209.9 m but caution is advised due to the length of time elapsed and should be resurveyed (Personal Communication, Daniel Peters, Environment and Climate Change Canada).

The raw water level data for Spruce Island Lake (PAD 5) indicated many discontinuities indicative of sensor movements between May 14 to June 13 and a last one on September 1. However, the smooth trace prior to May 14 indicated a very slow and small rise from mid-March to just before the ice jam on May 6 (probably due to local snowmelt contributions). The rate of rise increased to May 6 to 9 after which it decreased very slowly until the first instrument shift on May 14. The total increase for the May 6 to 9 period was small, of the order of 0.1 m, but since this was the highest rate of increase (excluding obvious sensor movements), and was coincident with the Peace River ice jam, the Peace River ice jam may have affected this basin. This is also supported by the finding that an adjacent basin (West Pushup Lake) did get water in the spring of 2022 (Timoney and Jasek, 2023).

It is apparent, that these four basins at least, reacted quite quickly to the Peace River ice jam. This is expected for Horseshoe Slough and Pete's Creek since they are adjacent to main connecting channels. It is likely that Jemis Lake likely did not receive water directly from overland flooding from the north from the Peace River since the northern portions of the sill are higher than the one adjacent to Mamawi Lake to the west (Peters et al, 2006); thus, Jemis Lake received its water from the Mamawi Lake which received a lot of water from the Peace River ice jam via the Quatre Fourches. This indirect flooding is also called backflooding. Mamawi Lake increased substantially and quickly due to the Peace River ice jam due to its direct connection via the Quatre Fourches but the quick response in Spruce Island Lake (if not just coincidental) indicates that a small, lengthy and unknown connecting channel rather than overland flooding is how it received water. This preferential path for other isolated basins in general is also described by (Timoney 2022, 2023).

8. Detailed examination of the ice cover that experienced a mechanical breakup

Figure 8 shows the ice cover on May 5 hours before a mechanical breakup that show just a few examples where the ice sheet would not get around bends or narrowings without breaking into smaller pieces. To show more examples of narrow constrictions, ice widths scaled from Sentinel 2 May 4 Satellite image the day before a mechanical breakup and total width scaled from Google Earth between channel banks or vegetation trimlines or ECCC surveyed cross sections are plotted in Figures 15. The yellow ellipses indicate where the ice width in the river upstream is wider than the width available to pass it downstream without fracturing into smaller pieces. The ice did break and pass downstream a day after the Sentinel 2 satellite image and hours later after the photos were

taken on May 5 despite the ice forming at regulated Peace River discharges in the preceding winter. This indicates that the temporal and spatial variability of the ice strength determines if a breakup can become mechanical rather than the geometric constraint associated with high regulated freeze-up levels.

The question one may ask is if the ice was unusually weak during the 2022 mechanical event that allowed it to breakup more easily through narrowings and channel bends. This is challenging to quantify because the history of the snow cover on the ice cover is not known temporally for the entire ice season, or spatially over the river reach that broke up mechanically. Snow cover plays a strong role in insulating the ice cover that slows down thermal ice growth in the winter but on the other hand shields it from solar radiation in the spring that reduces its internal strength and surface melt. However, it is still useful to examine the degree of possible degradation irrespective of the snow cover.

Bilello (1980) proposed using the sum of degree-days above $-5\text{ }^{\circ}\text{C}$ as a surrogate for energy available for ice deterioration. The reason for above $-5\text{ }^{\circ}\text{C}$ rather than above $0\text{ }^{\circ}\text{C}$ is that solar radiation (that is responsible for melting of ice at crystal boundaries due to impurities trapped there, Butyagin (1972)) could be overcome or protect the ice cover at temperatures less than $-5\text{ }^{\circ}\text{C}$. There are drawbacks to using this surrogate but due to lack of detailed meteorological data along the Peace River, this at least provides some measure of the energy input for ice deterioration. This value for 2022 was compared to other significant PAD floods to determine if the potential energy input into the ice cover was higher than in those significant flood years to see if there was a greater potential for a weaker ice cover in 2022. Only years for which the start date of ice jam formation or PAD flooding is known can this value be calculated are provided in Table 1.

Table 1. Cumulative Degree-Days above $-5\text{ }^{\circ}\text{C}$ at Fort Chipewyan as a surrogate for energy input for ice deterioration for large PAD flood/ice jam years compared to 2022. (Only years for which the start date of ice jam formation or PAD flooding is known can this value be calculated so this table does not include all large ice jam floods.)

Year	Fort Chipewyan Sum DD > $-5\text{ }^{\circ}\text{C}$
1943	108
1965	169
1974	167
1996	78
1997	107
2014	105
Average	122
2022	114

Table 1 indicates that the potential energy transferred to ice deterioration in 2022 was not unusually high compared to large ice jam flood years, in fact it was lower than the average of those years

and much lower than that of the largest documented ice jam flood in 1974. This is an indication that the ice cover was likely not unusually deteriorated in 2022 and yet the mechanical breakup proceeded to overcome the boundary constraint criteria of narrower and more sinuous geometry downstream.

9. Discussion and Conclusions

The snowmelt runoff that drove the breakup of the Peace River in 2022 was reduced by a mid-winter melt event in the Smoky and other nearby basins but was augmented by higher-than-normal snowmelt contributions in the northern part of the Peace River basin that transformed a thermal breakup to a mechanical one.

Satellite images, aerial observations and gauge information indicated that the last 200 km of the Peace River in the spring of 2022 broke up mechanically, broke the ice cover through many geometrically constrained reaches despite a regulated freeze-up elevation, and produced an ice jam that lasted for 4 days with a discharge and associated water levels that significantly affected water levels in the PAD central lakes and basins. If the 2014 ice jam is classified as large, and the 2020 ice jam is classified as small, the 2022 ice jam at the PAD should be classified as one of at least medium in size.

Recently, Beltaos (2023a) formulated ice strength and freeze-up level into one resistance coefficient and produced a relationship for determining breakup celerity based on three mechanical breakups. This formulation is a simplified method that does not consider the spatial and temporal variability of ice cover resistance nor the variability of tributary inflows along the reach of the river, both factors played a key role in determining the breakup sequence of the Peace River in 2022 that produced a PAD ice jam flood. These simplifications potentially could affect the relationship between celerity and the resistance coefficient based on three points, especially since error propagation was not provided to develop confidence bands on this relationship.

Potentially, there are situations where the probability of IJF occurring is increased when the river ice breakup is slow at first, which allows time for the downstream ice to deteriorate. The dynamic breakup can then proceed to the PAD more easily before encountering more competent ice in the Slave River, which arrests the breakup and causes an ice jam flood (like in 2022). One can envision a whole host of ice cover resistant combinations that produce ice jam floods or not rather than a simplified version that assumes that ice resistance decreases at the same rate in all reaches going forward in time. This is perhaps why one single parameter like freeze-up stage does not have the predictive power to determine its effect on ice jam flood frequency (Lamontagne et al. 2021 and Lamontagne and Jasek, 2023), that is even if it has much effect on the breakup sequence to begin with.

Comparing cumulative degree-days above $-5\text{ }^{\circ}\text{C}$ in 2022 with past major ice jam flood years indicated that the potential energy input to deteriorate the ice cover prior to the mechanical breakup was not unusually high and in fact lower than average. This is an indication that the ice cover was likely not unusually deteriorated in 2022 and yet the mechanical breakup proceeded to overcome the boundary constraint criteria of narrower and more sinuous geometries downstream.

The fall 2021 freeze-up stage was 214.0 m (Parks Canada 2020 breakup data report in preparation with elevation provided by S. Beltaos, ECCC). The discharge at Peace Point was somewhere in the 5000 to 7000 m³/s range (based on hydrographs in Figure 4) but ECCC data is provisional. Beltaos (2023b) that shows a Peace Point breakup flow-freezeup level diagram delineating regions of likely IJFs and non-flood events. This diagram indicates that the 2022 would plot somewhere close to the margin that delineates floods and non-floods. However, the breakup celerity was very high (700 km/day). If the 2022 breakup was on the margin and this diagram truly delineated floods and non-floods one would expect a series of break-up starts and stops through the PAD reach which was not the case as indicated in Section 6. It was a decisive mechanical breakup through the PAD reach that was able to break through many reaches of geometrical constraints.

Future work needs to consider longitudinal variation of ice cover strength, thickness, deterioration rates attributable to the temporal and spatial variation of air temperatures, snowfall, and cloud cover that all affect the ice resistance to vary significantly over the hundreds of kilometres of the Peace River, coupled with the channel plan form. It is currently not possible to know all these parameters everywhere and for all time during a breakup event. Monte Carlo modelling of all these parameters could possibly provide insight into which variables effect ice jam flood frequency at the PAD.

Further work should also consider local inflow of tributaries and not just Peace River mainstem discharges. Since this data is often missing due to instrumentation challenges associated with mobile ice covers and not every basin is gauged, a hydrological run-off model is also needed to advance understanding of various parameters on the frequency of ice jam floods in the PAD and to forecast their occurrence.

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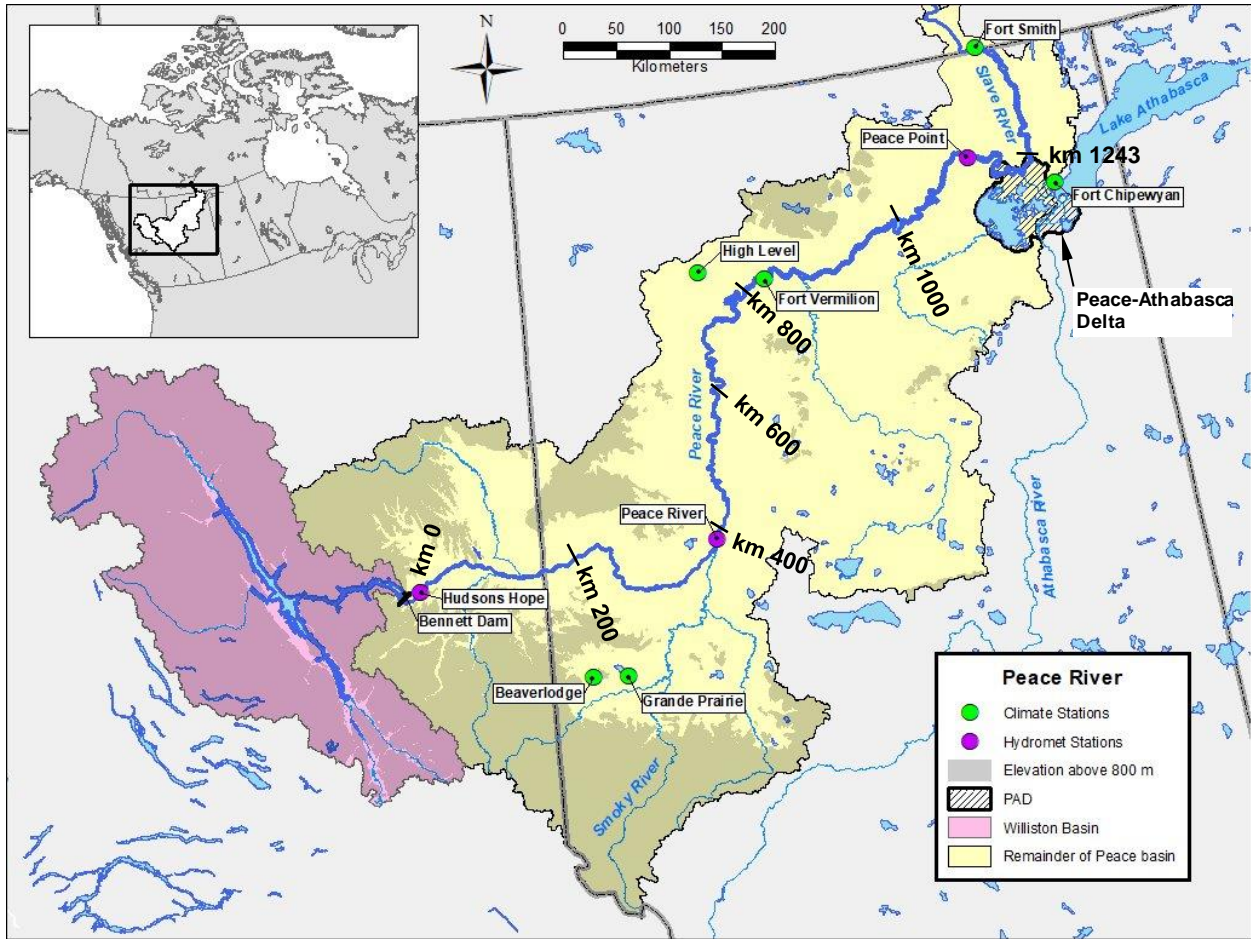


Figure 1. Peace River Basin and location of the Peace-Athabasca Delta.

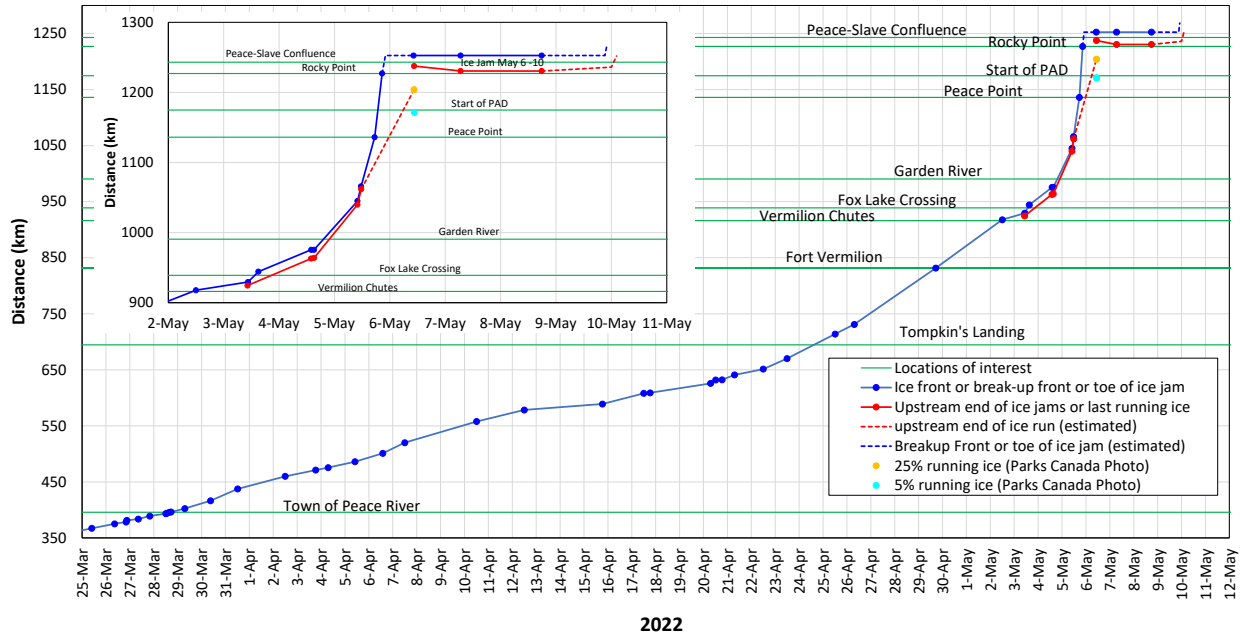


Figure 2. Locations of ice fronts, breakup fronts, ice runs and ice jams on the Peace and Slave Rivers in the spring of 2022. Inset shows detail of mechanical breakup and ice jam at the PAD.

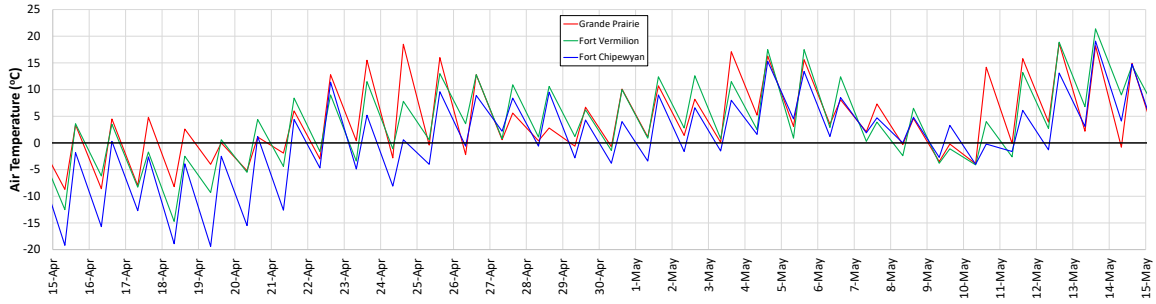


Figure 3. Daily maximum and minimum air temperatures plotted at 0800 and 1500 hrs respectively for Grande Prairie, Fort Vermilion, and Fort Chipewyan during spring 2022.

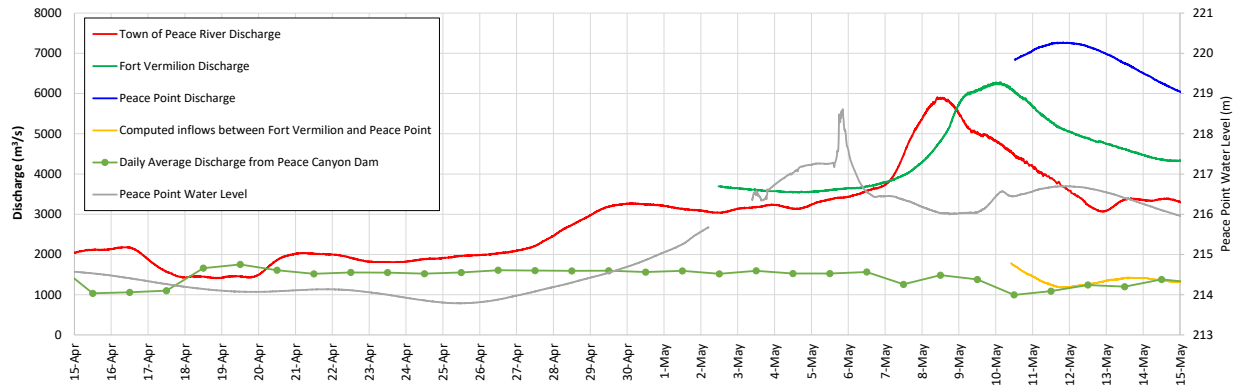


Figure 4. Peace River discharges in spring 2022 and water level at Peace Point. The Town of Peace River Discharge - ECCC Provisional, Fort Vermilion Discharge - verified and corrected slightly based on BC Hydro water level surveys with ice backwater period omitted, Peace Point Discharge - ECCC Provisional (ice affected period omitted), Computed inflows from Fort Vermilion to Peace Point using a 2-day lag, Daily Average Discharge from Peace Canyon Dam, and Peace Point Water Level - best of primary and secondary sensors incorporating ECCC manual surveys with suspect data on May 2-3 omitted.

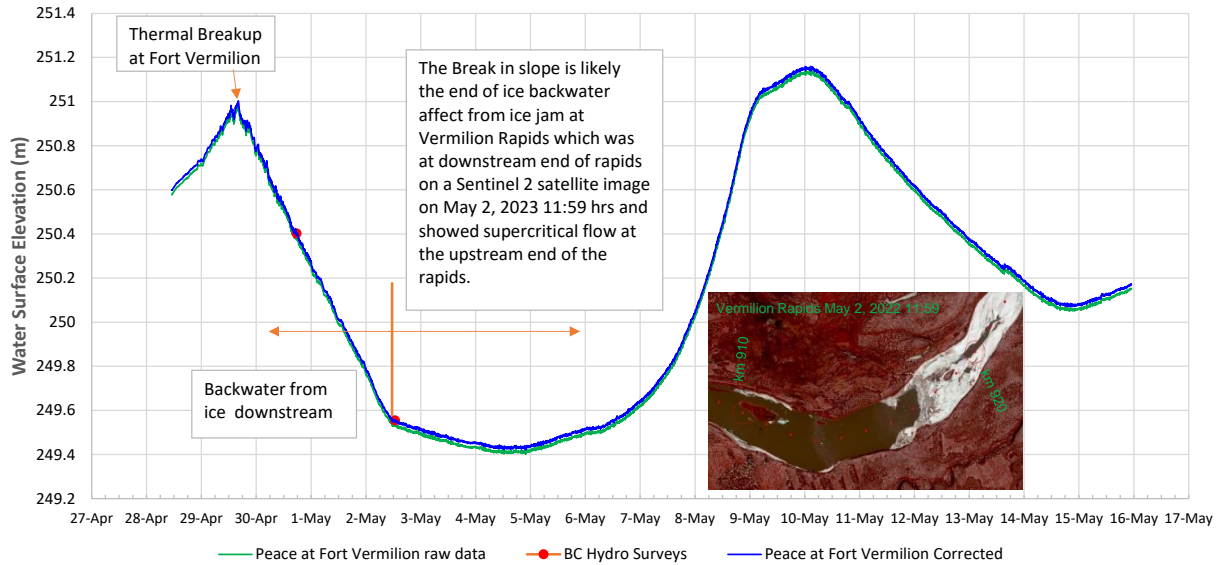


Figure 5. Raw and corrected water level data at Fort Vermilion gauge (km 832) (gauge data was corrected by +0.02 m based on two river surveys shown). Break in slope on May 2, 2022 12:30 MST is the end of ice backwater which is supported by the Sentinel 2 Satellite image (inset) taken at 11:59 MST on May 2, 2022 showing the ice front at km 917, past the downstream end of the rapids (km 916) with supercritical flow noticeable at the upstream end of the rapids at km 913.

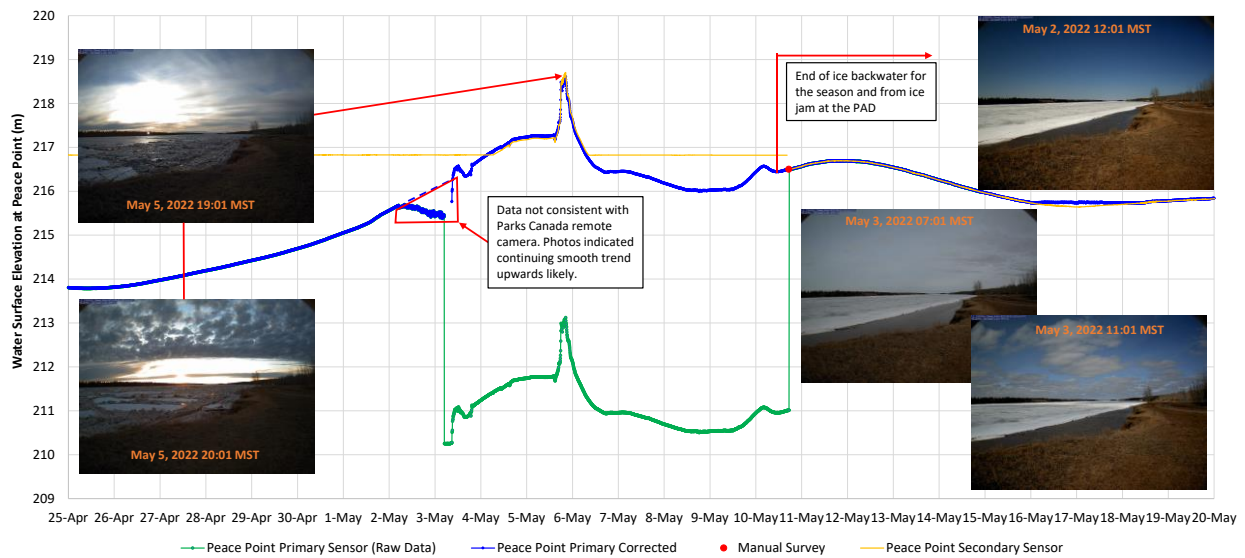


Figure 6. Raw and corrected water level data at Peace Point during the breakup period in 2022. Inset pictures are Parks Canada photos upstream of the Peace Point gauge that indicate water levels in red polygon are erroneous, the ice cover gradually rose from picture to picture during this period and there was no large-scale movement of the ice cover. Canadian Geodetic Vertical Datum 2013:EPOCH2010.

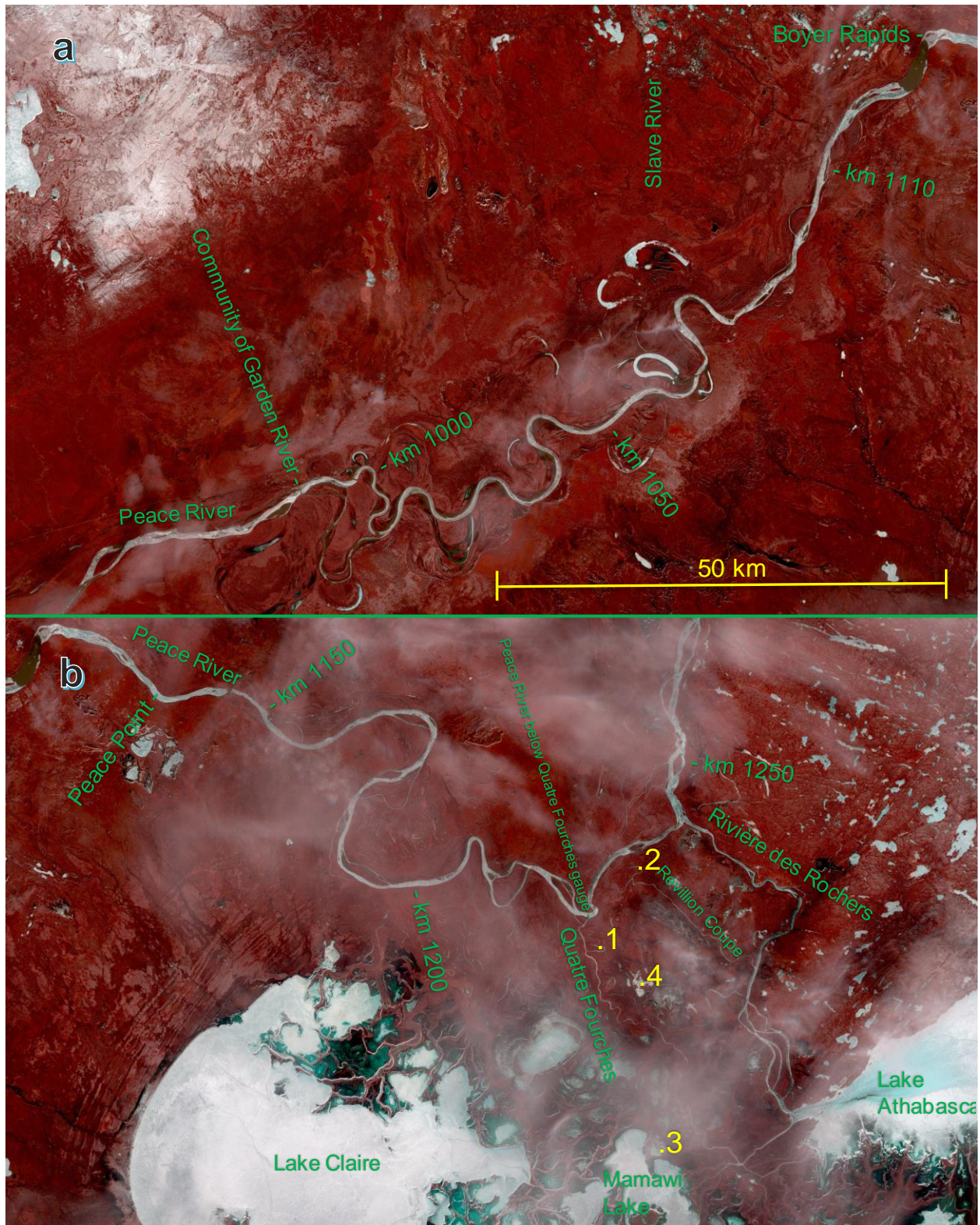


Figure 7. Sentinel 2 satellite image on May 4, 2022, showing an intact ice cover prior to its mechanical breakup on May 5. a) Peace km 960 to km 1125, b) km 1114 to the PAD and the Slave River. Main PAD channels and lakes are identified as well as four selected basins: 1. Horseshoe Slough oxbow, 2. Pete's Creek oxbow, 3. Jemis Lake and 4. Spruce Island Lake.

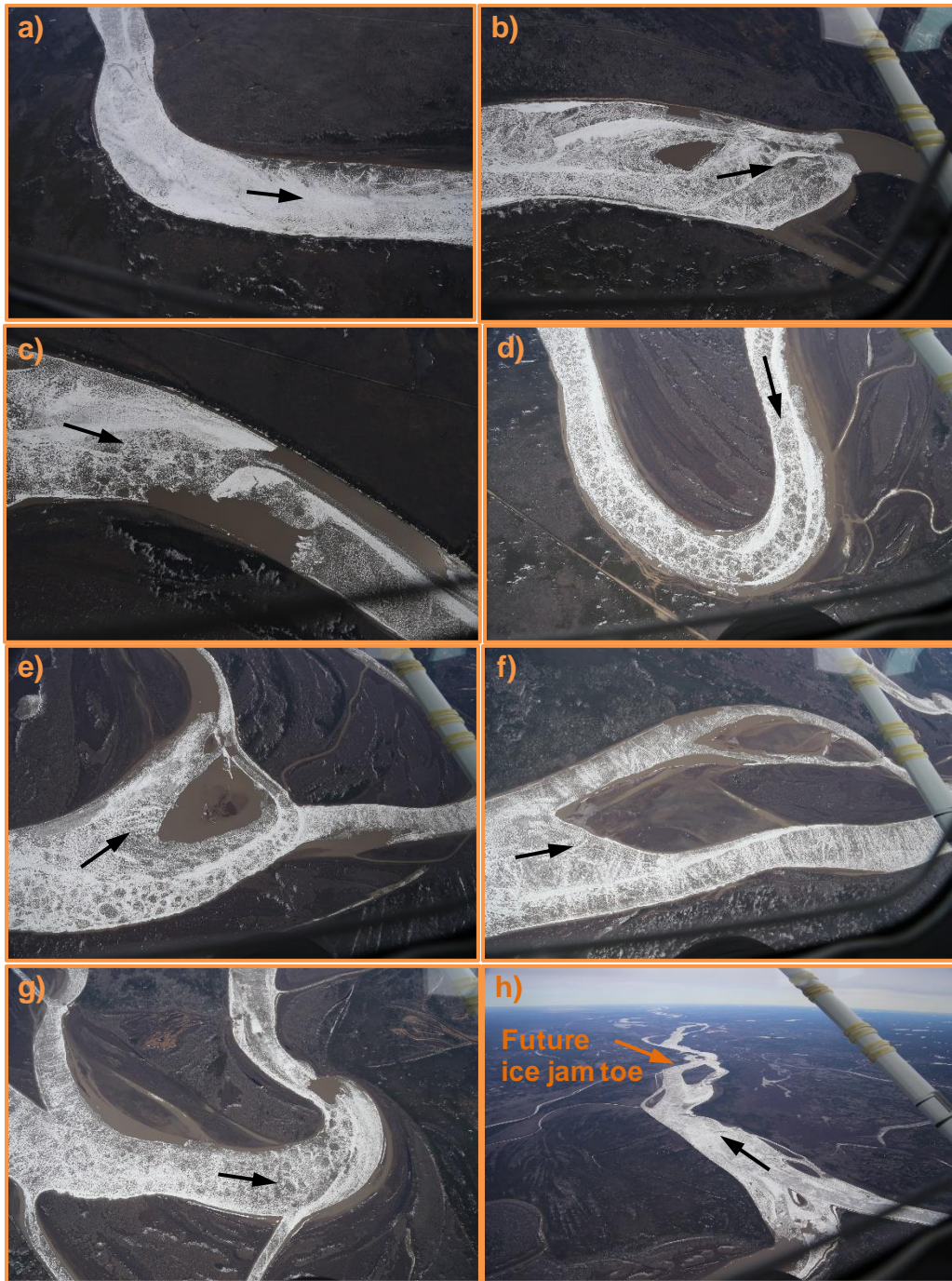


Figure 8. Peace River ice cover between Peace Point and Slave River on May 5, 2022, hours before a mechanical break through this reach. Photos selected as examples where width of ice sheet or curvature would not allow ice sheet to move freely unless the ice broke up dynamically, a) channel curve downstream of Peace Point, b) narrowing at km 1143 to 1145, c) narrowing at km 1171 to 1173, d) sharp bend at Carlson's Landing (km 1209.5), e) narrowing km 1212 to km 1217 at the upstream end of Moose Island, f) narrowing km 1220 to 1221, g) sharp bend and narrowing at Rocky Point (km 1228), h) ice on Slave River with future location of May 6-10 ice jam toe indicated (km 1252.6).



Figure 9. Photos of ice jam on the Mikkwa River on May 3, 2022.

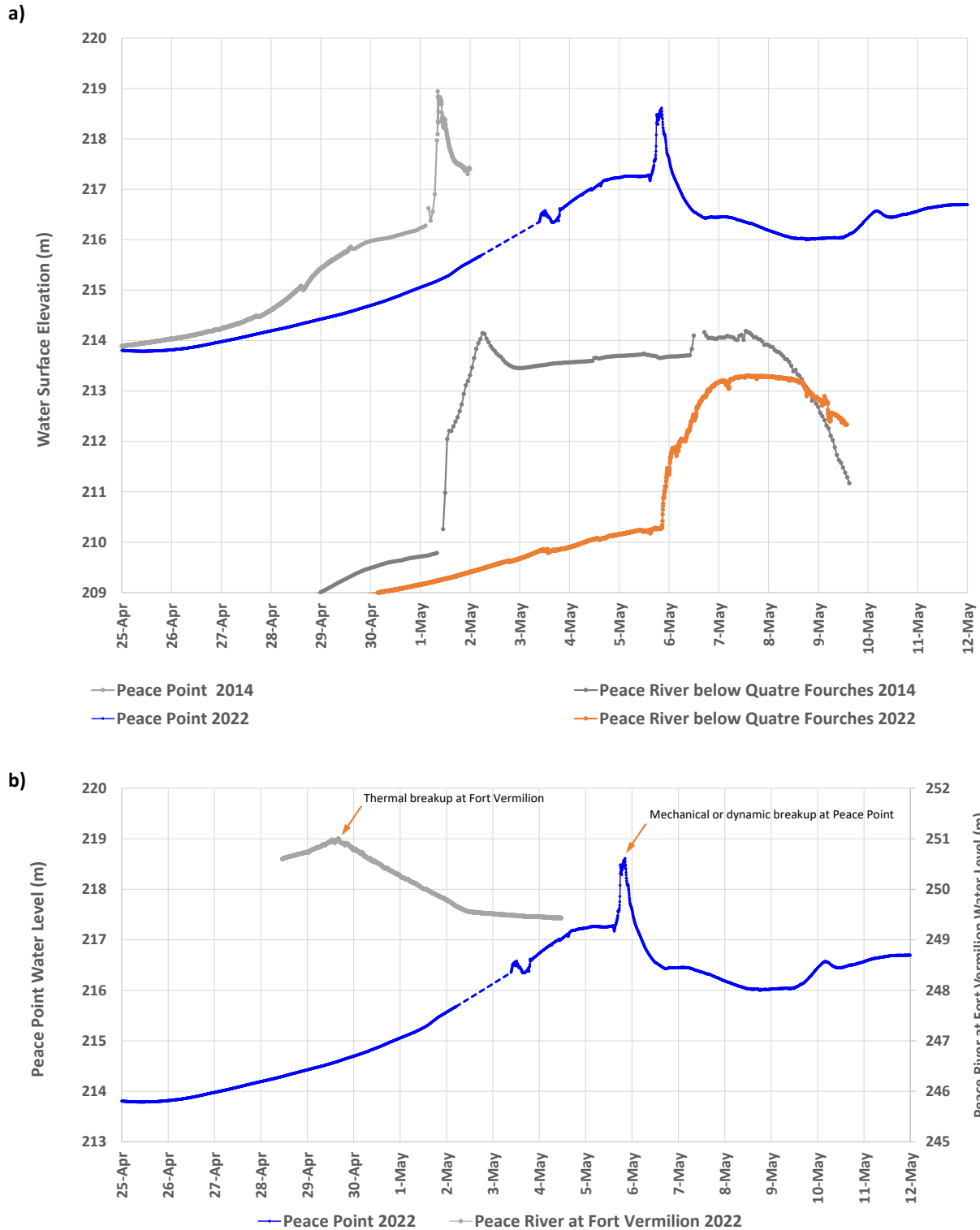


Figure 10. Water Levels at Peace Point and Peace below Quatre Fourches in 2022 a) comparison with 2014, b) comparison of mechanical breakup at Peace Point and a thermal breakup at Fort Vermillion.



Figure 11. Photographs looking upstream at ice jam toes on Slave River a) May 3, 2014, and b) May 6, 2022, taken by BC Hydro and Parks Canada respectively.

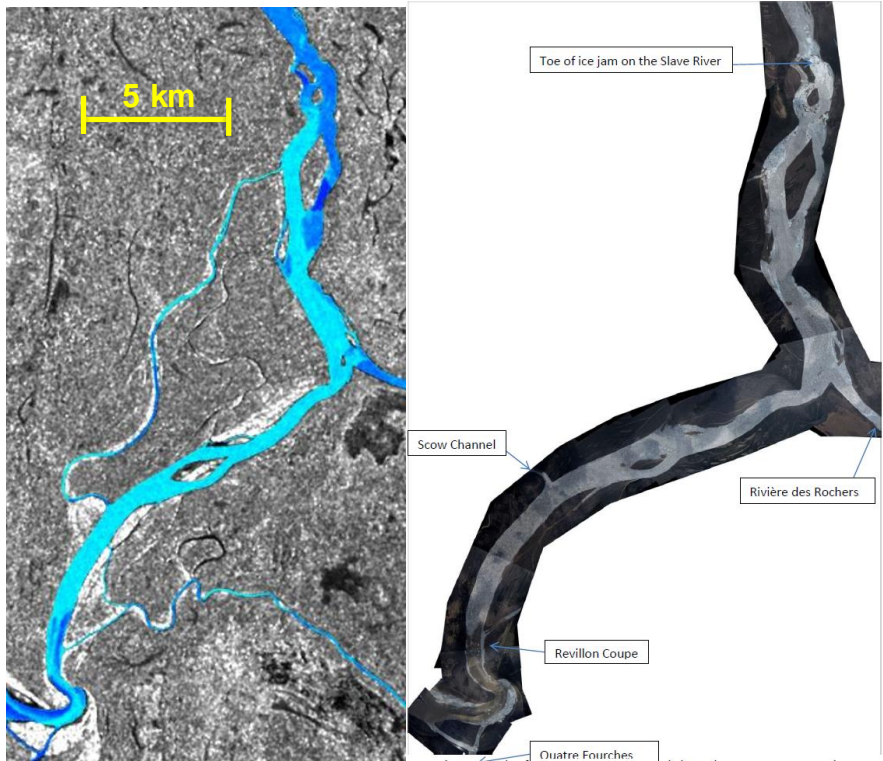


Figure 12. Comparison of May 7, 2022 (RCM image) and May 7, 2014 (aerial photos) ice jam extents.

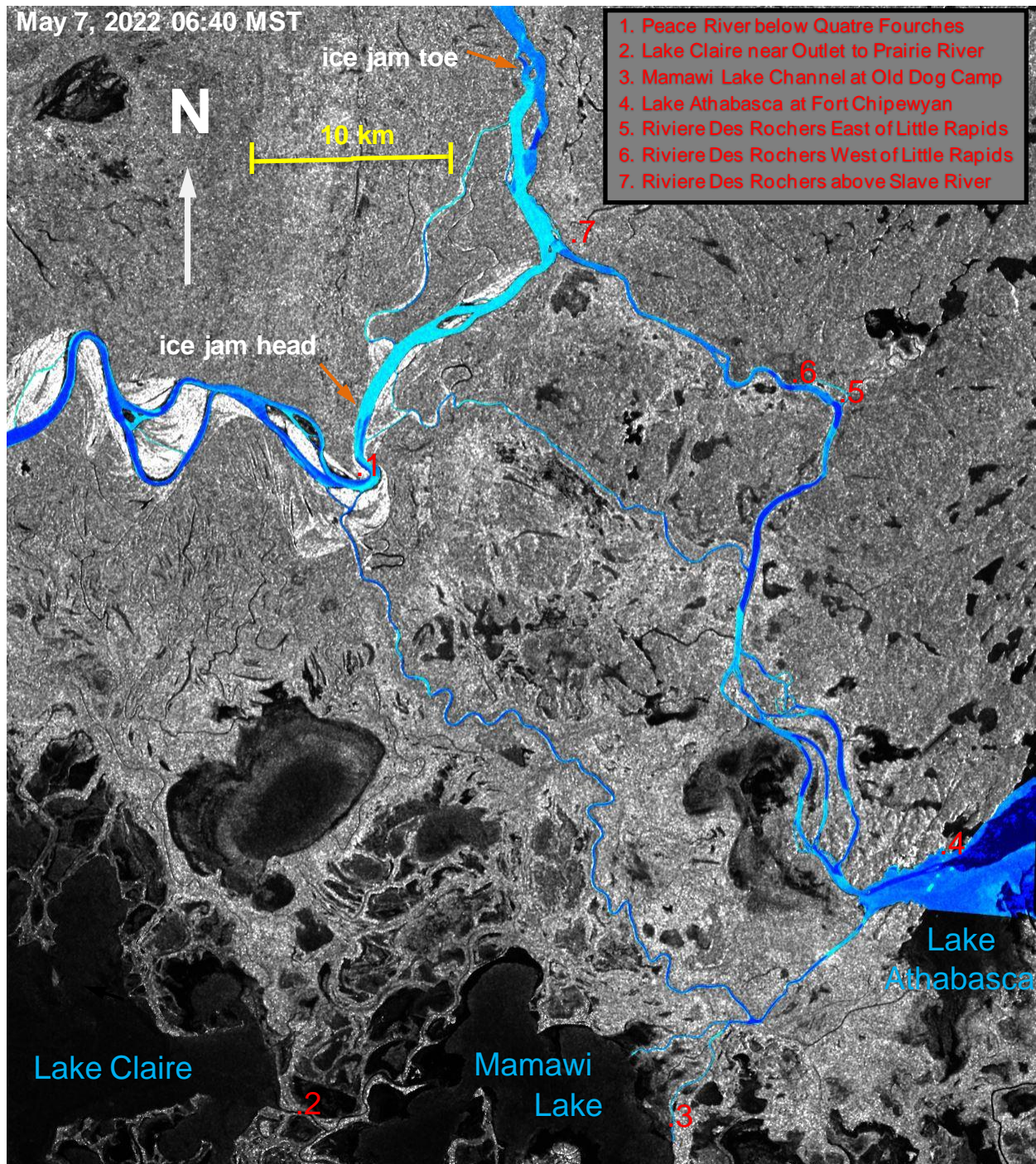


Figure 13a. Canadian RADARSAT Constellation satellite images showing the Peace River ice jam on May 7, 2022 06:40 MST, Light blue is rough ice (ice jam) and dark blue is open water. Locations of ECCC water level gauges for which data is plotted in Figure 14 are also shown.

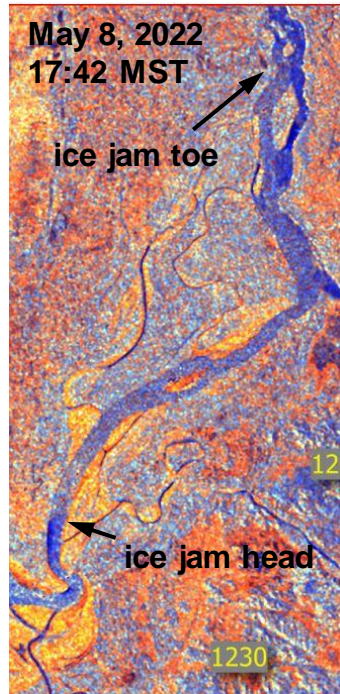


Figure 13b. Canadian RADARSAT Constellation satellite images showing the Peace River ice jam on May 8, 2022 17:42 MST. Wind wave interference coincident with radar looking angle in the May 8 image made post-processing difficult and different from Figure 13a but the toe and head of the Peace River ice jam can be seen.

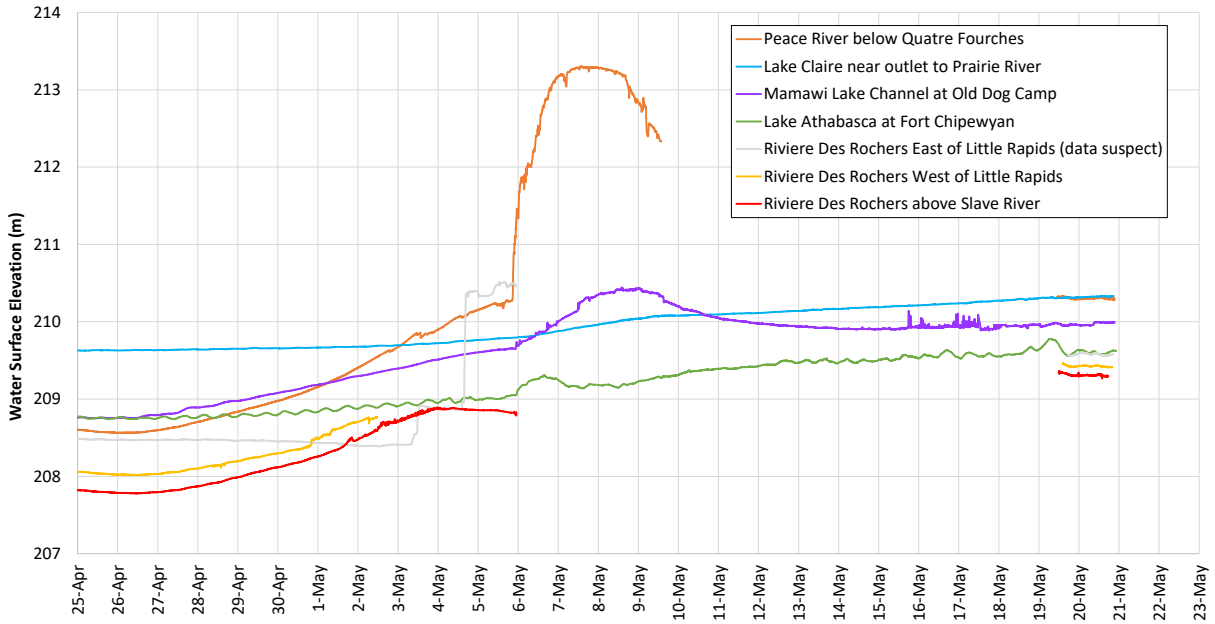


Figure 14. Peace River below Quatre Fourches and PAD water levels in spring 2022.

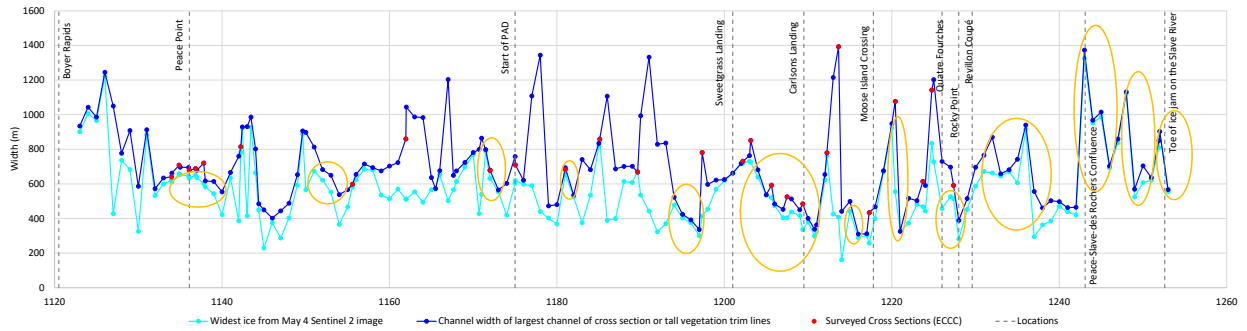


Figure 15. Ice widths scaled from Sentinel 2 May 4 Satellite image the day before a mechanical breakup and total width scaled from Google Earth between channel banks or vegetation trimlines or ECCC surveyed cross section if available (red dots). Yellow ellipses indicate where ice width upstream is greater than the channel width downstream that would not allow the ice sheet to pass unless it broke into smaller pieces.