



CGU HS Committee on River Ice Processes and the Environment
20th Workshop on the Hydraulics of Ice Covered Rivers
Ottawa, Ontario, Canada, May 14-16, 2019.

**An Emerging Picture of Peace River Break-up Types that Influence Ice Jam
Flooding of the Peace-Athabasca Delta
Part 1:
The 2018 Peace River Break-up**

Martin Jasek

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

A very dynamic break-up with high discharges occurred on the Peace River in the spring 2018. Despite the associated extensive ice jam related flooding in the upper and middle reaches of the Peace River, the most downstream reach at the Peace-Athabasca Delta did not experience any ice jam related overbank flooding. This paper documents the break-up sequence of the Peace River in April-May 2018 in detail including aerial photography/video and land based video. Sheet type break-up fronts that are often difficult to study and record due to their highly transient nature and need for high vantage points were successfully documented. The paper also starts to examine the environmental parameters that explain how this particularly insightful break-up sequence unfolded.

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 a very large predominantly wetland area ranging in size from 5,200 to 6,200 km². bound to the south by the Athabasca River Delta, Lake Clair to the west, Lake Athabasca to the east and the Peace River that flows along its northern boundary (Figure 2). Most of the time, drainage from the PAD is northwards through a series of connecting channels as shown in Figure 2. During high Peace River flows these channels reverse direction and flow from north to south. During ice jams on the Peace River, water levels are higher than those present during open water floods and not only do these connecting channels reverse direction but overland flooding occurs supplying water to higher elevation basins that are not connected to the channels, replenishing them and thereby increasing their bio-productivity. It is for this reason that ice jams and their frequency of occurrence have been of considerable interest in this reach of the Peace River. These ice jams can stay in place for several days and up to one to two weeks. In addition to high water levels, the ice jam duration is also important for creating beneficial flooding as it takes time for the water to spread into such a large area as the PAD. The break-up also has to be dynamic for these ice jams to form as thermal break-ups do not create substantive ice jams that can raise water levels sufficiently to flood the PAD. Dynamic break-ups are driven by snowmelt run-off from the Smoky River and other tributaries with a smaller contribution from the Bennett Dam. If the snowpack or snowmelt run-off is low to around average in these watersheds, a thermal break-up will occur with the ice just melting in place and ice jam flooding of the PAD is not possible.

Previous studies have classified historical break-ups as either thermal or mechanical (Beltaos et al. 2006) (the latter also referred to herein as “dynamic”). However, it is evident from the 2018 break-up that there is a third type which will be described in this paper and that makes the classification of determining the conditions for a PAD ice jam flood more complex than if considering only two types. Beltaos et al. (2006) does allude to this third type where a “mechanical event is anticipated” but a jam still may not form in a given reach, in this case the PAD.

Some previous studies (Prowse and Conly 1998, Beltaos et al. 2006) have theorized that because Peace River winter discharges are higher post-regulation which causes higher freeze-up ice elevations, that this higher ice level requires greater discharge in the spring to create a dynamic break-up (Beltaos et al. 2006), thereby causing the frequency of ice jams to decrease post-regulation (Beltaos 2014, 2018). Although this is recently under debate (Timoney et al. (2018), Hall et al. (2018), Beltaos (2019)) there is another consideration on how break-up resistance contributes to PAD ice jam flooding that has not been previously considered.

Although it is true that the break-up resistance of the ice cover cannot be too high so as not to prevent a dynamic break-up, it also has to be strong enough in the PAD reach and/or upper Slave River to arrest a dynamic break-up in order to form an ice jam that floods the PAD. i.e. a dynamic break-up front may not be stopped to form an ice jam but simply flush through the PAD reach as an ice run, producing much lower water levels than if an ice jam had formed. Therefore, in terms of considering higher freeze-up stage post regulation and the associated higher break-up resistance, there are opposite effects on how regulation could affect the frequency of ice jam

floods at the PAD; on the one hand it may prevent a dynamic break-up from happening, on the other hand it may increase the likelihood of jamming in the PAD reach.

Freeze-up stage is not the only factor affecting break-up resistance. Ice strength and thickness play an important role which are determined by many factors such as how cold the winter is, how much snow falls on the ice cover, presence and porosity of slush under the ice cover, and in the spring, how much melt and strength degradation occurs prior to the arrival of the spring freshet discharge that may or may not be sufficient to create an ice jam flood of the PAD.

(Jasek, 2017a,b) described how fast moving break-up fronts documented during the 2014 break-up have the potential to release larger volume of water from channel storage post-regulation that counteract the effects of higher post-regulation freeze-up stage.

Storage release of water at break-up works in the following way: Once the ice is set into motion during break-up, the ice and the previously slower moving water underneath it (due to friction with the bottom of the ice) accelerates and both contribute to the volume of storage release, thereby increasing the water flow almost instantaneously when the ice cover mobilizes. This can increase the discharge by several factors.

Fast moving break-up fronts were again documented in the 2018 break-up indicating that such high break-up front celerities are not a rare occurrence and are an important contribution to driving dynamic break-ups post-regulation.

The break-up sequence leading up to the formation of ice jams in the PAD is important since water from channel storage is released as break-up propagates downstream, and this contributes to the factors that will sustain a dynamic break-up. The release of water from channel storage ultimately affects the discharge, which in turn determines if a dynamic break-up will advance into the PAD reach. This discharge also determines the height and thickness of the ice jam that forms, which in turn affects how much water flows into the Delta floodplain. Ice jams can form and release on the Peace River upstream of the PAD. When an ice jam releases it forms a wave or what is called a “jave” that can break-up more ice cover in front of it and may eventually create ice jam flooding at the PAD. The term “jave” defined in Beltaos, (2008).

3. Graphical representation of break-up data

The progression of break-up based on aerial surveys, satellite imagery, remote camera imagery, and ground based observations is summarized in Figure 3. The ice front in Figure 3 is denoted by the black diamonds connected with black lines. In the case of the thermal break-up on the Peace River, the receding ice front marks the location of the demarcation between solid winter ice downstream and the open water or a small amount of rubble ice upstream. In the case of a dynamic break-up, the ice front is also the break-up front, and if the dynamic break-up front is arrested, it becomes the toe of an ice jam. Each multi-coloured vertical line in Figure 3 depicts the ice conditions based either on aerial observations or satellite imagery. Horizontal lines indicate locations of interest, but some contain ice observation information based on ground observations or web cameras.

4. Break-up of the Smoky and Peace Rivers

4.1 Break-up of the Smoky River and Little Smoky River

A more detailed description of the break-up of streams in the Smoky Basin can be found in (Jasek, 2019b). The section in this paper describes some of the highlights that influenced the subsequent break-up on the Peace River.

Following a below freezing temperatures in early April (Figure 4a), significantly warmer temperatures started on Apr 18 and river level gauges in the Smoky Basin started to respond on Apr 20. There was significant snowmelt run-off by Apr 22 on the lower elevation (plains) of the Smoky River basin (Figure 5). Ice runs and jam formations on various streams in the Smoky Basin began on Apr 22 and by Apr 24 an 18 km long ice jam formed between 20 km and 2 km from the Smoky-Peace confluence, Figures 6 and 7 respectively. By this time, the lower 74 km of the Smoky River and another 159 km of the Little Smoky River had broken up.

At approximately 18:00 hrs on Apr 24, the 18 km long ice jam on the Smoky River started to release into the Peace River (Figure 8). This sudden release increased the discharge in the Peace River from about 3200 m³/s to about 6100 m³/s (Figure 4b). However, part of this increase was due to increasing inflows on the main stem of the Peace River as noted by the gauge at Dunvegan, about 100 km upstream of the town. This large discharge increase is significant because had there been an ice cover in the Peace River at the town at the time, the dykes would have likely been overtopped as the calculated capacity of the town dykes under ice jam conditions is 3500 m³/s (Andres, 1996). Even after the main jave had passed, the total flow at the town receded to only 5000 m³/s.

The next big event was a large jave from the Smoky River above the Little Smoky River that increased the discharge in the Peace River from about 5000 m³/s to 8200 m³/s on Apr 26 (Figure 4b). This produced the peak water level and flow for the entire 2018 break-up at the Town of Peace River. The WSC gauge in TPR was malfunction during this peak water level and the flow was determined from the gauge at the south end of town. The ice run that was documented by aerial recognisance extended from 44 km upstream on the Smoky from the Peace to 60 km downstream of the Peace-Smoky Confluence (Figure 9 and 10), a total length of more than 100 km. The peak water level for the entire break-up was confirmed by the Berreth Flats gauge 30 km further downstream from the Town of Peace River which was also under open water conditions (Figure 18).

Following the largest jave event on Apr 26, several smaller javes entered the Peace River between Apr 27 and Apr 30 whose origins are noted in Figure 4b and described in Jasek (2019b). These additional javes sustained the high discharge between 6500 and 7000 m³/s on the Peace River until Apr 30 (Figure 4b); once the javes stopped, the discharge in the Peace River at the Town of Peace River started to decline significantly.

4.2 Peace River Break-up between the Town of Peace River and Sunny Valley

The ice broke up, mostly thermally, in the 100 km reach downstream of the Town of Peace River and Sunny Valley. Figure 11a shows the 2 to 3 metre gradual drop at the Berreth Flats and Sunny Valley gauges on Apr 16 and Apr 23 associated with the benign thermal break-up at these two gauges respectively. The break-up front was traveling between 8 to 10 km/day around these dates (Figure 3), also indicative of a thermal break-up.

A change in break-up progression was noted on Apr 24-25, when the jave from the release of the 18 km ice jam just above the mouth of the Little Smoky River described in Section 4.1 travelled down the Peace River and encountered the solid Peace River ice cover and formed a 14 km long ice jam just downstream of Sunny Valley (See April 25, Figure 3). This produced significant flooding as the ice jam consolidated into the evening of Apr 25 and overnight to Apr 26 (See 6.5 m stage increase in Sunny Valley gauge, Figure 11a) and resulting flooding at Kalyna Flats, about 10 km further downstream in Figure 12). The missing data in the Fort Vermilion hydrograph was caused by declining water levels after the ice moved the sensor into a shallower area.

4.3 Documentation of sheet break-up front between Sunny Valley and Fort Vermilion

The 14 km ice jam downstream of Sunny Valley which was causing a flood at Kalyna Flats released on Apr 26, 2018 09:00 as indicated by the sudden drop in the gauge at Sunny Valley in Figure 11. The release was coincident with the arrival of the largest jave from the Smoky River above the Little Smoky River. The ice jam downstream of Sunny Valley was resting against a solid ice cover and once it mobilized it proceeded to break-up the Peace River as a “sheet break-up front” (defined in Jasek, 2003).

Note: Sheet break-up fronts are known to travel much faster and for longer distances than the rubble front break-up type. Because sheet break-up fronts travel so quickly, and large scale ice movement at any point on the river occurs almost instantaneously, they are very difficult to document over the long distances for which they are known to cover. Two were documented by Jasek (2017a,b) where in 2014 over 395 km of the Peace River broke up between Sunny Valley and Fort Vermilion at a rate of 385 km/day (4.5 m/s) and another between the Vermilion Rapids and the PAD/Slave River where 342 km ice broke up at rate of 310 km/day (3.6 m/s).

The break-up of 2018 presented another opportunity to document a sheet break-up front on the Peace River since the break-up of 2014 (Jasek, 2017a,b).

About 3.75 hours after the ice jams release and about 95 km further downstream the break-up front was documented via a flight by BC Hydro. Figure 13 shows a sheet break-up front at km 605 on Apr 26, 2018 12:44 hrs with 10 km of moving ice sheet upstream of the break-up front. Numerous cracks in this ice sheet can be seen, these were progressive cracks getting more numerous as the ice sheets were moving.

About 3 hours later and 45 km further downstream at Carcajou, the sheet break-up front was captured by in a series photographs shown in Figure 14. Some local ice movement started at 15:25 MDT and the entire river mobilized 27 minutes later at 15:52 MDT. Large sheets of ice ran for about an hour transitioning to smaller and smaller pieces until there was mostly flowing ice rubble.

About 2 hours after the break-up front passed Carcajou it was observed by an Alberta Environment and Parks flight about 52 km further downstream, several km passed Thompkins Landing. The transition from sheet break-up at km 702 to flowing ice run of rubble at km 686 is documented in Figure 15. The following day this break-up was observed that it had stalled at km 723.

These four observation timing points were recorded for a sheet break-up front the initiated in the morning of Apr 26. The points are plotted in Figure 3 and are also summarised in Table 1 where the rate of break-up between each observation location is also listed.

Table 1. Break-up rates calculated over a 214 km reach of the Peace River that broke up on Apr 26, 2018. **originally reported as km 686 @ 18:05 MDT which was the leading edge of broken ice rubble but the sheet ice break-up front was at km 702 @ 18:08 based on AEP photographs.*

Date/Time (MDT)	Location (km)	Segmental and Cumulative Distances (km)	Break-up Rate (km/day)	Break-up Rate (m/s)	Comment
26-Apr-2018 09:00	510	- (0)			Toe of ice jam location not exactly know but last observed on Apr 25 and release time based on start of water level drop at Sunny Valley (km 491)
26-Apr-2018 12:44	605	95 (95)	610	7.1	BC Hydro Flight
26-Apr-2018 15:52	650	45 (140)	349	4.0	BC Hydro ground observation at Carcajou
26-Apr-2018 18:05	702*	52(192)	563	6.5	Alberta Environment and Parks (AEP) Flight Photographs
27-Apr-2018 11:19	723	21(213)	unknown	unknown	Observed location of arrested break-up front the following day

The break-up rates ranged from 4.0 to 7.1 m/s and were faster initially, slowed down and then sped up again, this likely in response to variable break-up resistance in different river reaches. Nevertheless, as in the 2014 break-up, these high celerities in 2018 indicate that large amounts of channel storage release occurs during a dynamic break-up of the Peace River and therefore this extra discharge is likely substantial and plays a significant role in break-up further downstream at the PAD.

This ice run stopped and formed a large ice jam about 108 km upstream of Fort Vermilion on Apr 26-27 causing significant flooding at the Thompkins Ferry crossing, and the farmlands and buildings around Carcajou (Figure 16).

The ice jam upstream of Fort Vermilion remained in place for about a day and released on Apr 28 and re-jammed just downstream of Fort Vermilion causing extensive flooding from km 728 to 838 including the town of Fort Vermilion on Apr 28-29 (Figure 17). The increasing water levels on Apr 28 are shown in Figure 11b as the ice jam initially formed. The water levels started fall after initial formation but started to rise again the next day on Apr 29. In the evening of that day the ice jam consolidated increasing the water levels further causing even more extensive flooding in Fort Vermilion; water levels exceeded the previous high water mark by almost 1 m in Figure 11b. Photographs showing the flood in Fort Vermilion are shown in Figure 17.

4.4 Peace River Break-up between Fort Vermilion and the PAD and the Slave River

While the Peace River was breaking up dynamically, causing a series of sequential and severe ice jam floods approximately 500 km upstream of the PAD, indicating that the ice there was strong and discharge high, by contrast, the ice in the PAD reach was starting to thermally deteriorate significantly more than the upstream reaches. This is evident in Figure 3 where solid ice cover denoted in bright green starts disappearing on Apr 27 in the PAD reach while there is an ice jam downstream of Thompkins Landing. Figure 18a is a high resolution Sentinel 2 satellite image showing the ice cover on Apr 25. Much of the ice cover is dark indicating water on the ice and likely a weakened ice cover with the exception of a reach from Boyer Rapids (km 1115) to km 1144. Note that this reach contains the Peace Point gauge at km 1130. Open water sections (black) are few and far between. Readers are encouraged to zoom into this high resolution image to see the details. Figure 18b shows a MODIS satellite image which is lower resolution than the Sentinel 2 and it does not discriminate as well between weaker and stronger looking ice, but it indicates that the ice is still intact in the Peace and Slave Rivers on Apr 26. Figure 19a shows another MODIS image from Apr 27 indicating big changes in the Peace River ice cover in the PAD reach and also in the Slave River. Lengthy open reaches (dark) downstream of Rocky Point (km 1227) and in the Slave River are visible. A flight on Apr 29 of the PAD reach and Slave River showed that there was barely any ice cover left (Figure 20), where typically ice jams form that flood the PAD.

Gauge records in the PAD reach did not show any indication of a dynamic break-up of the ice when the ice started disappearing from the PAD reach between the Apr 25 and Apr 29 (Figure 21); there are only gradual increases in water levels by less than half a metre during this time period. This indicates that much of the ice cover likely melted in place.

The jam which flooded Fort Vermilion released late on Apr 29 and by Apr 30 the ice from that ice jam had moved to the Vermilion Rapids and jammed there (Figure 3), causing extensive flooding upstream of the Rapids and the historical site of Adams Landing (Figure 22). However, a second dynamic break-up front likely triggered by the jave of the former continued on below Vermilion Rapids on Apr 30 that broke up more than 100 km of additional ice (Figure 3). This second break-up front stalled for about a day and caused flooding in the km 980 – 1108 reach (Figure 22). However, the jave continued underneath the ice cover and it travelled through the

PAD reach breaking and flushing what little ice was left downstream of Rocky Point and the Slave River and away from the PAD on May 1 (Figure 23). An ice jam at Boyer rapids and a solid ice cover in the Peace Point reach remained intact as the ice cover flushed out of the PAD reach (Figure 23). On May 2, a jave from the jam that eventually released from Vermilion Rapids flushed through the PAD reach on May 3, although it increased the water levels further in the PAD, the ice did not stop or jam in the PAD reach due to the lack of ice cover there (Figure 24). Reverse flow (from the Peace River into the PAD) was observed in the main PAD channels on May 3 (Figure 24). Ice was observed to run past the PAD from May 2 to May 4 (Figure 3). However, the break-up front apparently encountered more competent ice on the Slave River further downstream; a toe of an ice jam was documented by WBNP staff on May 2, 76 km downstream of the PAD on the Slave River and by May 4, a satellite imaged indicated a toe of an ice jam 82 km downstream of the PAD. However, this was too far downstream to flood the PAD as there was not enough volume to create an ice jam long enough to back up to the PAD reach even though some ice obviously ran into some of the PAD channels and jammed there due to reverse flow (Figure 24).

The Slave River ice jam was documented by a satellite image on May 4 (Figure 3) with the upstream end still consolidating, likely due to the jave from the release of the ice jam from Vermilion Rapids. The upstream end of the running ice was 16 km downstream of the PAD on May 4. An incomplete satellite image (due to cloud cover) on May 5 indicated at least 21 km of open water on the Slave River downstream of the PAD. A satellite image on May 7 indicated an ice run on the Slave River with its upstream end consisting of low ice concentrations 50 km downstream and highest ice concentrations starting about 100 km downstream on the Slave River.

Since the discharges were very high according upstream gauges and flooding, and no ice jam occurred at the PAD due to the apparent weak ice cover there, this was a disappointing outcome of an anticipated ice jam flood of the PAD; the high snowpack, rapid warming and resulting run-off, a dynamic break-up in the upstream reaches releasing a lot of water from channel storage, it was just the ice cover resistance in the PAD reach that was not sufficient to form an ice jam.

Water levels that occurred at the PAD were possibly close to that determined by open water stage-discharge relationships but there may had been some backwater effects in the PAD reach by the ice jam further downstream on the Slave River.

5. Possible reasons for non-jamming dynamic break-up through the PAD reach

Based on aerial observations and satellite imagery documented in Section 4, it was apparent that the ice cover was too weak, and in some reaches non-existing to stop the dynamic break-up in the PAD reach of the Peace River or the upper Slave River in the spring of 2018. This is in contrast to 2014 where the dynamic break-up was stopped by the ice cover about 10 km downstream on the Slave River, which was a good position to create an ice jam through the PAD reach and resulting flooding of the PAD.

There could be many reasons for the difference in the resistance of the ice cover between 2014 and 2018 just prior to the dynamic break-up fronts that arrived there. The variables include how

cold the winter was which determines the thermal growth of the ice cover over the winter. How much snow fell and was transport off by wind and what time of the winter it fell, how much it settled. All these processes that affect the snow cover would determine how much insulation it provided to inhibit thermal growth. Another factor would be how the river froze-up in terms of stage, discharge and frazil slush under the ice cover. Whether there were any dynamic ice consolidations during freeze-up?

Generally in the spring time, the reduction in ice cover break-up resistance also plays a role. This is determined by how much thermal decay occurred due to surface melt and solar radiation penetration that weakens the overall strength and reduced the thickness of the ice cover. Also, how much melt occurred from underneath the ice cover from warm water from open leads and along the river banks and spring melt water entering from tributaries, a major one being the Rivière des Rochers that would affect the ice degradation on the Slave River.

It is difficult to examine all these factors due to limitation in available data that would be needed to quantify all the parameters, but a preliminary investigation is described in Jasek, (2019a), part 2 in these Workshop Proceedings.

6. Conclusions

Due to high snowpack conditions and rapid warming, exceptionally high snowmelt run-off discharges occurred in the Peace River in late April 2018; at the Town of Peace River which was the most downstream non-ice affected hydrometric station. A peak instantaneous discharge of 8200 m³/s occurred on Apr 26 with discharges continuing in the 6500 to 7000 m³/s range until May 1. These high flows were the driver for a very dynamic break-up and extensive and sequential ice jam flooding in the downstream direction. This looked promising for the PAD as Beltaos et al. (2006) indicated that a discharge of 4000 m³/s or more was needed to create extensive ice jam flooding of this wetland.

The high discharges started to decline after major javes in the Peace River from ice jam releases in the main streams of the Smoky River Basin were completed. This indicates that channel release storage from the break-up of the river ice covers in the tributaries is an important component in shaping and augmenting the snowmelt run-off hydrograph that drives the break-up in the Peace River. This suggests that using traditional hydrological models to determine/predict the driving discharge for break-up on the Peace River and likely other large rivers may not be adequate. A dynamic break-up river ice model coupled with a hydrological run-off model may be needed. Such a model is not known to exist by the author.

As in 2014 (Jasek 2017b), and again in 2018 a large ice jam was initially created downstream of the Town of Peace River by the javes from the break-up of the Smoky River below the Little Smoky River and the Little Smoky River itself and then this ice jam released due to a jave from the Smoky River above the Little Smoky River. This final push caused the Peace River break-up dynamically for significant distances thereafter. It appears; from these two years that break-up of the upper Smoky River is needed to trigger a dynamic break-up on the Peace River.

A break-up front travelling for large a distance exceeding 200 km was documented on the Peace River in 2018 to travel at very fast rates between 4 and 7 m/s. These high break-up rates cause

very high channel storage release that augments river discharge at break-up significantly. This was also found to occur in the break-up of 2014 (Jasek 2017a,b) where two ~300 km reaches of the Peace River broke up at rates between 3 to 4 m/s and this suggests that such high break-up rates occur in most if not all dynamic break-ups of the Peace River, with variations on the length and locations of these reaches from year to year.

Sheet break-up fronts were successfully recorded with aerial photography indicating how many km of river ice sheet is able to mobilize instantaneously despite there being a solid ice cover downstream. This is particularly illustrated in Figure 13 where the extensive cracking ice sheet is able to move in a bend in the river and through islands by shoving into open water areas along the banks and side channels, eventually crack into smaller pieces and keep moving.

The extensive flooding attributed to the 2018 Peace River break-up as indicated in the highlighted areas of Figure 1 and the many photographs in this paper suggests that a significant volume of water may have been lost due to overbank storage that would have likely affected the peak discharge further downstream.

In 2018, the PAD reach was made up of ice that was very thin and weak several days before the dynamic break-up arrived from the upper and middle reaches of the Peace River and thus there was not enough ice resistance to arrest the break-up front and cause an ice jam that would have likely flooded the PAD. Even had the break-up front arrived earlier, it likely would not have stopped due to the weak ice cover there in 2018. Local knowledge indicated that “the ice was too thin” this year to create an ice jam flood (Roland Hall, March 2018, personal communication with PAD resident).

For Peace River break-ups further back in history, where aerial or satellite observations were less frequent or absent, the thermal or dynamic break-up type classifications (two distinct types) has been based on the gauge records at Peace Point, about 100 km upstream of the PAD , (Beltaos et al. 2006). It is evident from the 2018 break-up that a third type where a dynamic break-up travels through weak or partially melted river ice in the PAD reach and upper Slave River and keeps on going without forming an ice jam. A suggested name for this third break-up type stated herein is “dynamic break-up flush-through”. It is unknown at this time, how many previously classified thermal or dynamic break-ups may in fact have been dynamic break-up flush-throughs.

Given the data collected in 2018, it becomes apparent that in some years, break-up resistance can be much higher upstream of the PAD and lower in the PAD reach, this possibly due to spatial varying environmental parameters that govern the thermal growth and decay of the winter ice cover.

In 2018, water levels that occurred in the Peace River at the PAD were possibly close to that determined by open water stage-discharge relationships but there may have been some backwater effects in the PAD reach by the ice jam further downstream on the Slave River.

7. Acknowledgments

The author would like to thank Kerry Paslawski Timberroot Environmental Inc. and David Verbisky, Trek Aerial Surveys for field support during the 2018 break-up monitoring., Stéphane Hardy, Dromadaire for providing Satellite imagery, Stefan Emmer, Alberta Environment and Parks for providing break-up data and photos of the Peace and Smoky Rivers, Queenie Grey, Wood Buffalo National Park for providing aerial photographs of the Slave and Peace Rivers on a day where BC Hydro was not able to carry out aerial reconnaissance. Hydrometric and weather data was obtained from Environment and Climate Change Canada. Also, the author would like to thank Dr. Richard Tortorella and the members of the CRIPE Scientific Committee for their thorough reviews.

8. References

- Andres, D. 1996. Ice formation and Break-up at the Town of Peace River – A study of regulated conditions, 1969-1994. A report prepared for The Town of Peace River, BC Hydro and Alberta Environmental Protection by Trillium Engineering and Hydrographics Inc., Northwest Hydraulics Consultants Ltd. and Thurber Engineering Ltd.
- Beltaos, S., Prowse, T.D., Carter, T., 2006. Ice regime of the lower Peace River and ice-jam flooding of the Peace-Athabasca Delta. *Hydrological Processes* 20(19): 4009–4029.
- Beltaos, S. (editor). 2008. *River Ice Breakup*. Water Resource Publications, LLC., Highlands Ranch, Colorado, USA, 462 pp.
- Beltaos, S., 2014. Comparing the impacts of regulation and climate on ice-jam flooding of the Peace-Athabasca Delta. *Cold Regions Science and Technology* 108: 49–58.
- Beltaos, S. 2018. Frequency of ice jam flooding in the Peace-Athabasca Delta. *Canadian Journal of Civil Engineering*. 45: 71-75.
- Beltaos, S. 2019. Reply to discussions by Timoney et al. (2018) and Hall et al. (2018) on “Frequency of ice-jam flooding of Peace-Athabasca Delta”. *Canadian Journal of Civil Engineering*. 00: 1–6 (0000) [dx.doi.org/10.1139/cjce-2018-0724](https://doi.org/10.1139/cjce-2018-0724).
- Hall, R.I., Wolfe, B.B., Wiklund, J.A. (2018). Discussion of “Frequency of ice jam flooding in the Peace-Athabasca Delta. *Canadian Journal of Civil Engineering*. 00: 1–3 (0000) [dx.doi.org/10.1139/cjce-2018-0407](https://doi.org/10.1139/cjce-2018-0407).
- Jasek, M., 2003. Ice jam release surges, ice runs and breaking fronts – field measurements, physical descriptions and research needs. *Canadian Journal of Civil Engineering*. 30: 113-127.

- Jasek, M., 2017a. The importance of break-up front celerity in the genesis of a spring flood: The 2014 Peace River Ice Jam Flood of the Peace-Athabasca Delta. Proceedings of the 19th Workshop on the Hydraulics of Ice Covered Rivers, Whitehorse, Yukon.
- Jasek, M. 2017b. Peace River 2014 break-up and ice jam at the Peace-Athabasca Delta – field investigations and analysis. BC Hydro Engineering Report No. E1312.
- Jasek, M., 2019a. An emerging picture of Peace River break-up types that influence ice jam flooding of the Peace-Athabasca Delta part 2: Insights from the comparison of the 2014 and 2018 break-ups. Proceedings of the 20th Workshop on the Hydraulics of Ice Covered Rivers, Ottawa, Ontario.
- Jasek, M., 2019b. Break-up of the Peace and Smoky Rivers in 2018. A BC Hydro Report currently in draft.
- Prowse, T.D., Conly, F.M. 1998. Effects of climate variability and flow regulation on ice-jam flooding of a northern delta. *Hydrological Processes*. 12, 1589-1610.
- Timoney, K., Smith, J.D., Lamontagne, J.R., Jasek, M. (2018). Discussion of “Frequency of ice jam flooding in the Peace-Athabasca Delta. *Canadian Journal of Civil Engineering*. 00: 1–4 (0000) [dx.doi.org/10.1139/cjce-2018-0409](https://doi.org/10.1139/cjce-2018-0409).

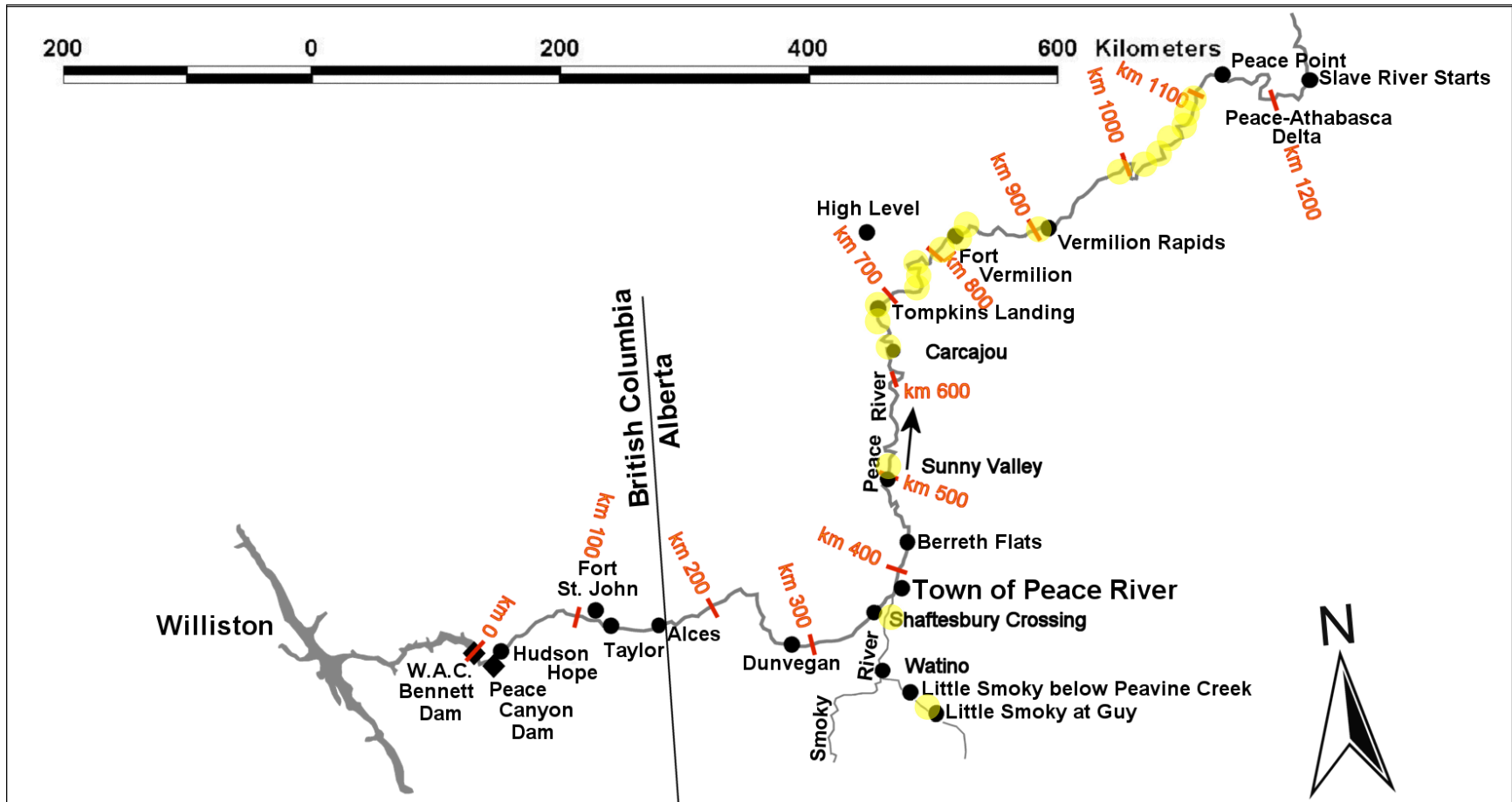


Figure 1. Map of the Peace River and pertinent locations. Yellow areas indicate significant ice jam related flooding in Apr 2018.

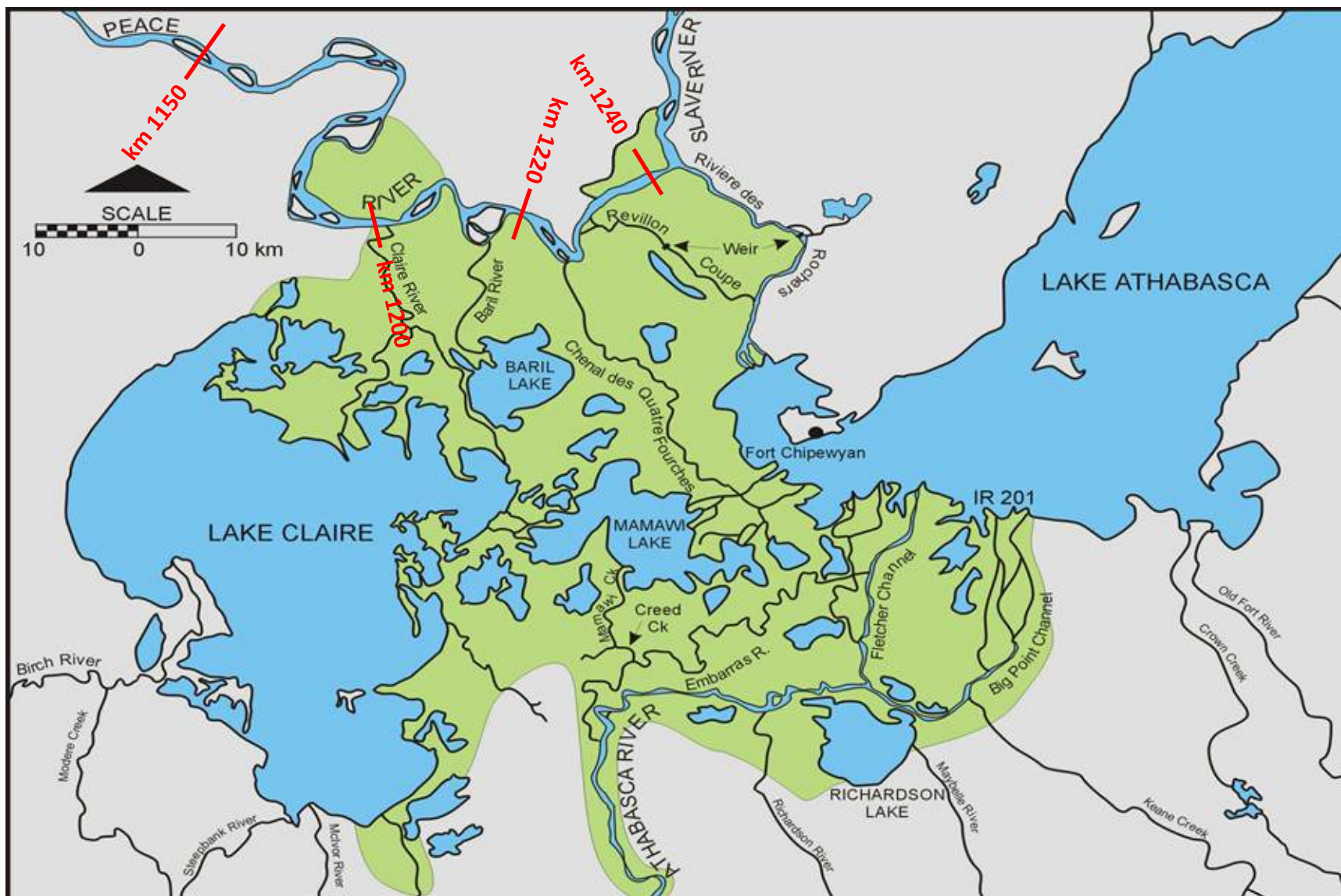


Figure 2. The Peace-Athabasca Delta.

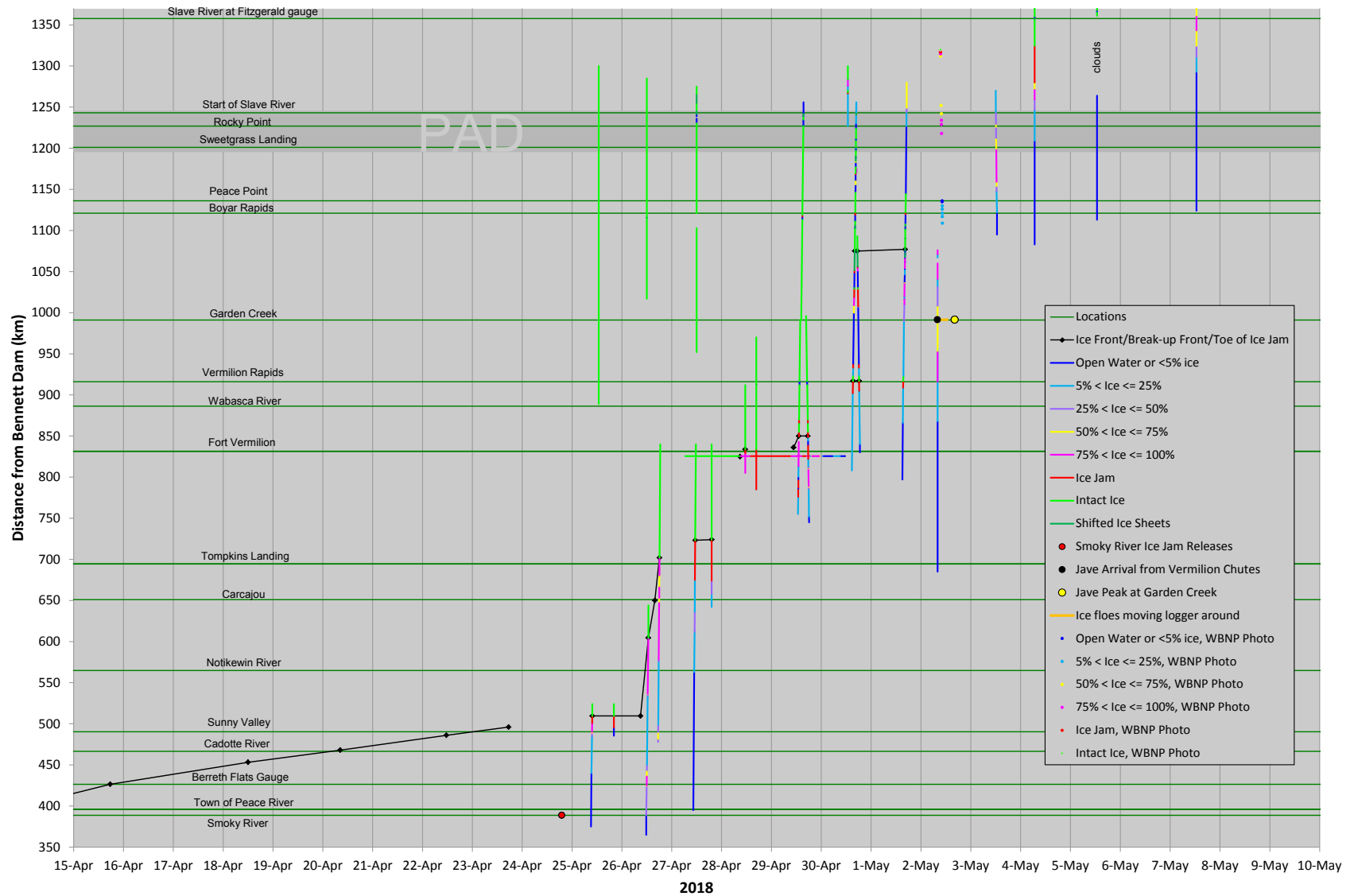


Figure 3. Ice conditions on the Peace River based on aerial, satellite and ground observations.

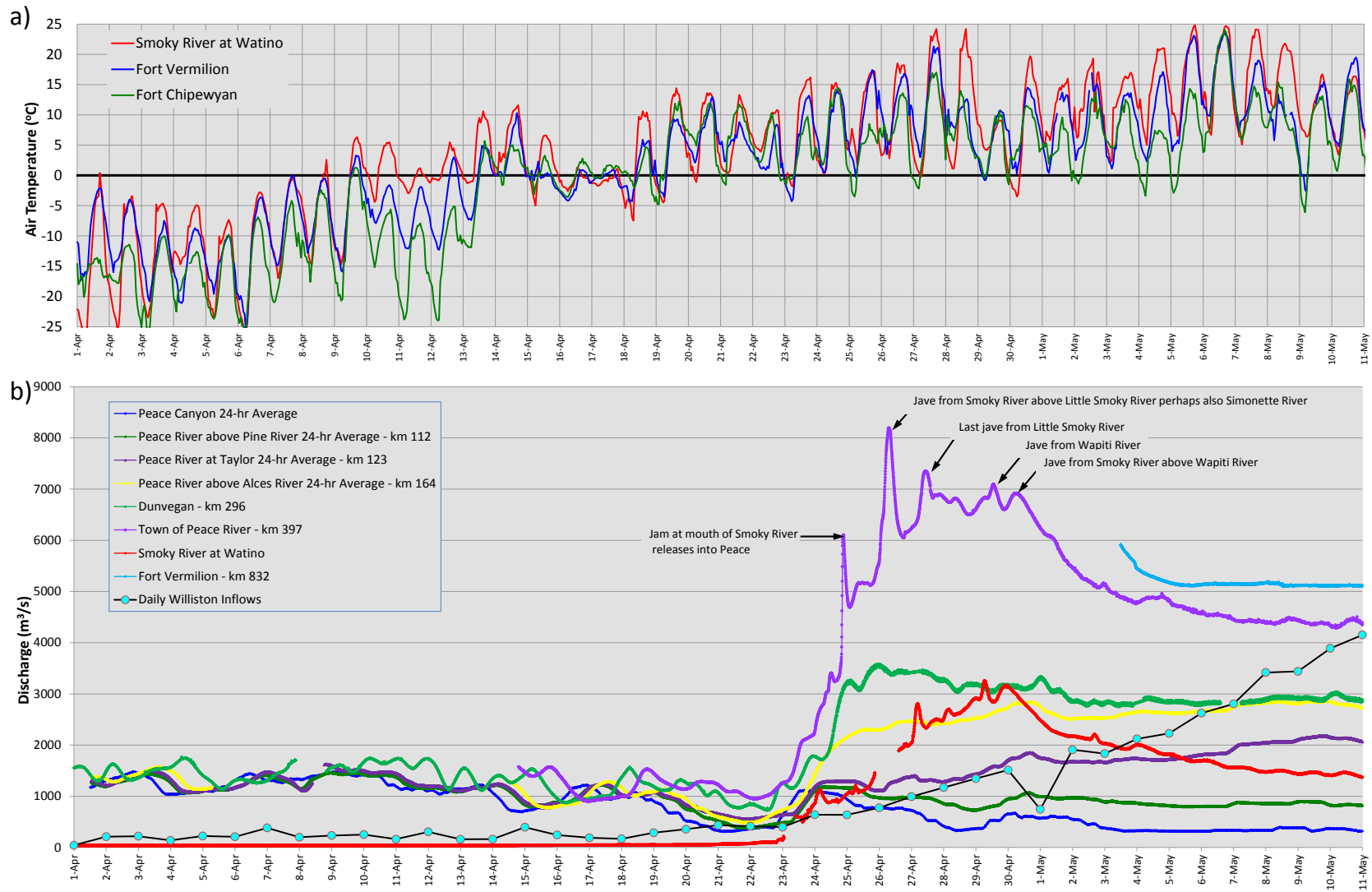


Figure 4. a) Hourly Air Temperatures at Smoky River at Watino, Fort Vermilion and Fort Chipewyan April 1 to May 11, 2018.
 b) Discharges of Peace River, Smoky River and Slave River Apr 1 to May 11, 2014. Ice affected or bad record removed.

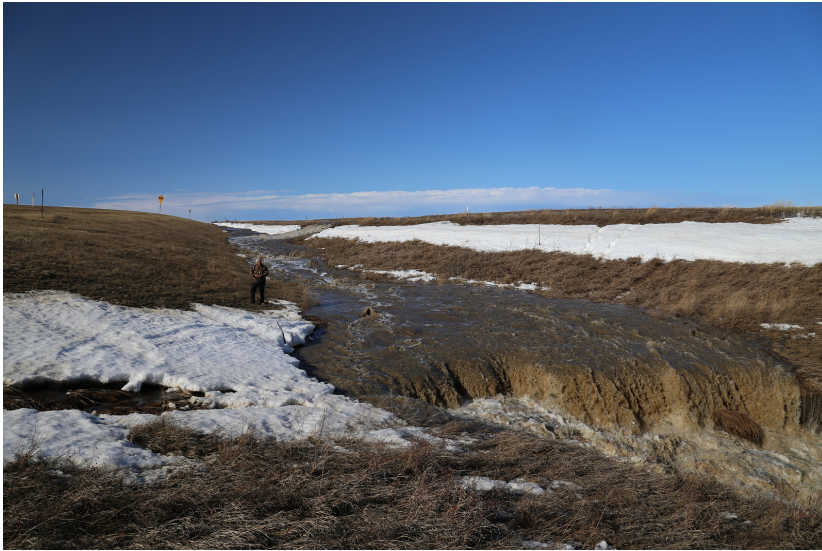


Figure 5. High snowmelt run-off on Apr 22, 2018 15:40 MDT in the Little Smoky Basin.

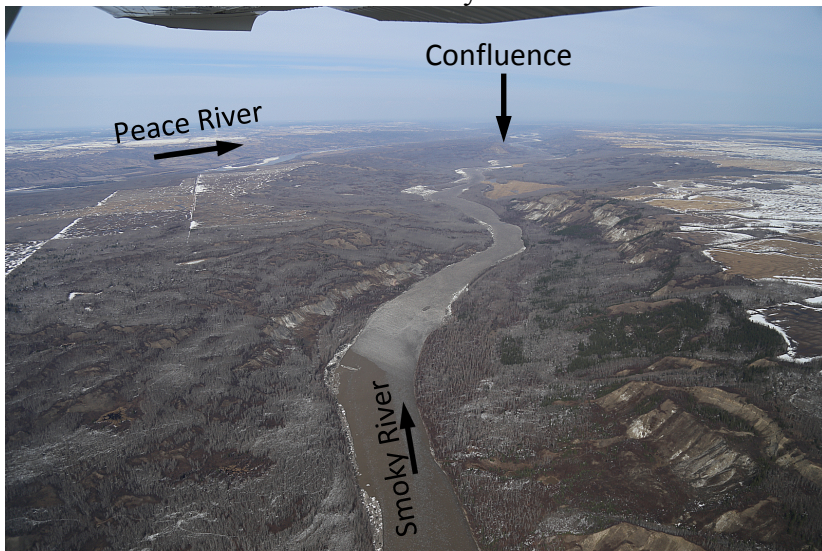


Figure 6. Head of an 18 km long ice jam on the Smoky River above the Peace River on Apr 24, 2018 15:40 MDT.



Figure 7. Toe of an 18 km ice jam on the Smoky River (left) on Apr 24, 2018 15:25 MDT, 2 km from the confluence with the Peace River (right) which had broken up thermally on Apr 12.



Figure 8. Smoky River 18 km long ice jam releasing into the Peace River on Apr 24, 2018 21:17 MDT (about 2.25 hours after the start of the release).



Figure 9. An ice run (jave) from the Smoky River on Apr 26, 2018 10:57 MDT that produced the highest water level and discharge on the Peace River in spring 2018.



Figure 10. Looking downstream from the Town of Peace River at an ice run on Apr 26, 2018 10:57 MDT that originated from the Smoky River and produced the peak flow in spring 2018.

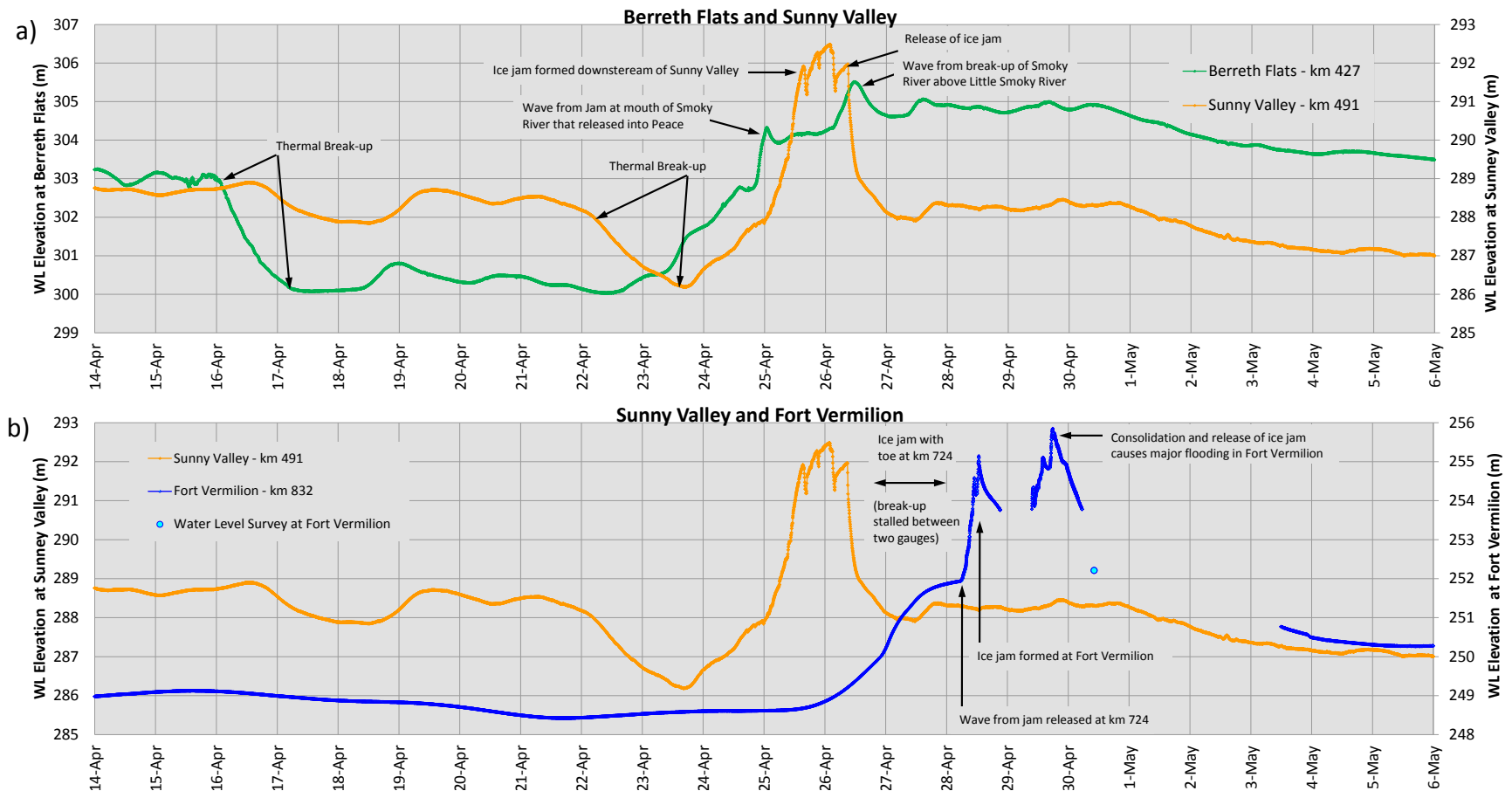


Figure 11. a) Water level elevation at Berreth Flats and Sunny Valley and b) Sunny Valley and Fort Vermilion April 14 to May 6, 2018.



Figure 12 a,b) Ice jam formation c) toe at km 509 on Apr 25, 2018 09:47 MDT. d,e) increasing water levels at Kalyna Flats. f) Head of ice jam at km 495.5 on Apr 25, 2018 20:09 MDT. g,h,i) flooding at Kalyna Flats.



Figure 13. Sheet break-up front at km 605 on Apr 26, 2018 12:44 MDT.



Figure 14. Sheet break-up front captured at Carcajou (km 650) on Apr 26, 2018. Local ice movement started at 15:25 MDT and lasted a few minutes. Sustained break-up arrived at 15:52 MDT. Ice sheets in ice-run getting more broken and smaller 15:52 to 17:12 MDT.

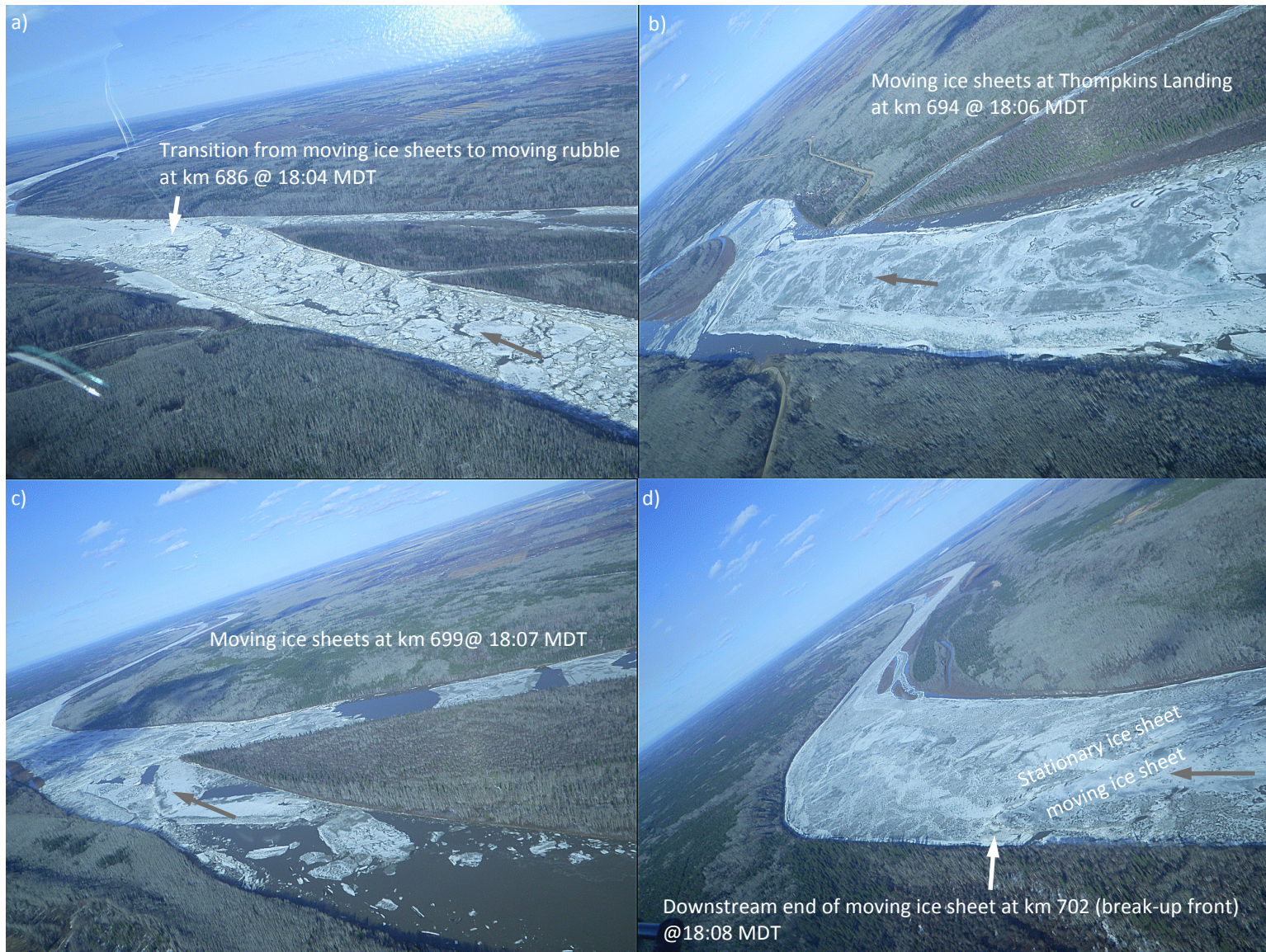


Figure 15. Sheet break-up front documented on Apr 26, 2018 18:08 MDT at km 702. Photographs courtesy of Stefan Emmer, Alberta Environment and Parks.

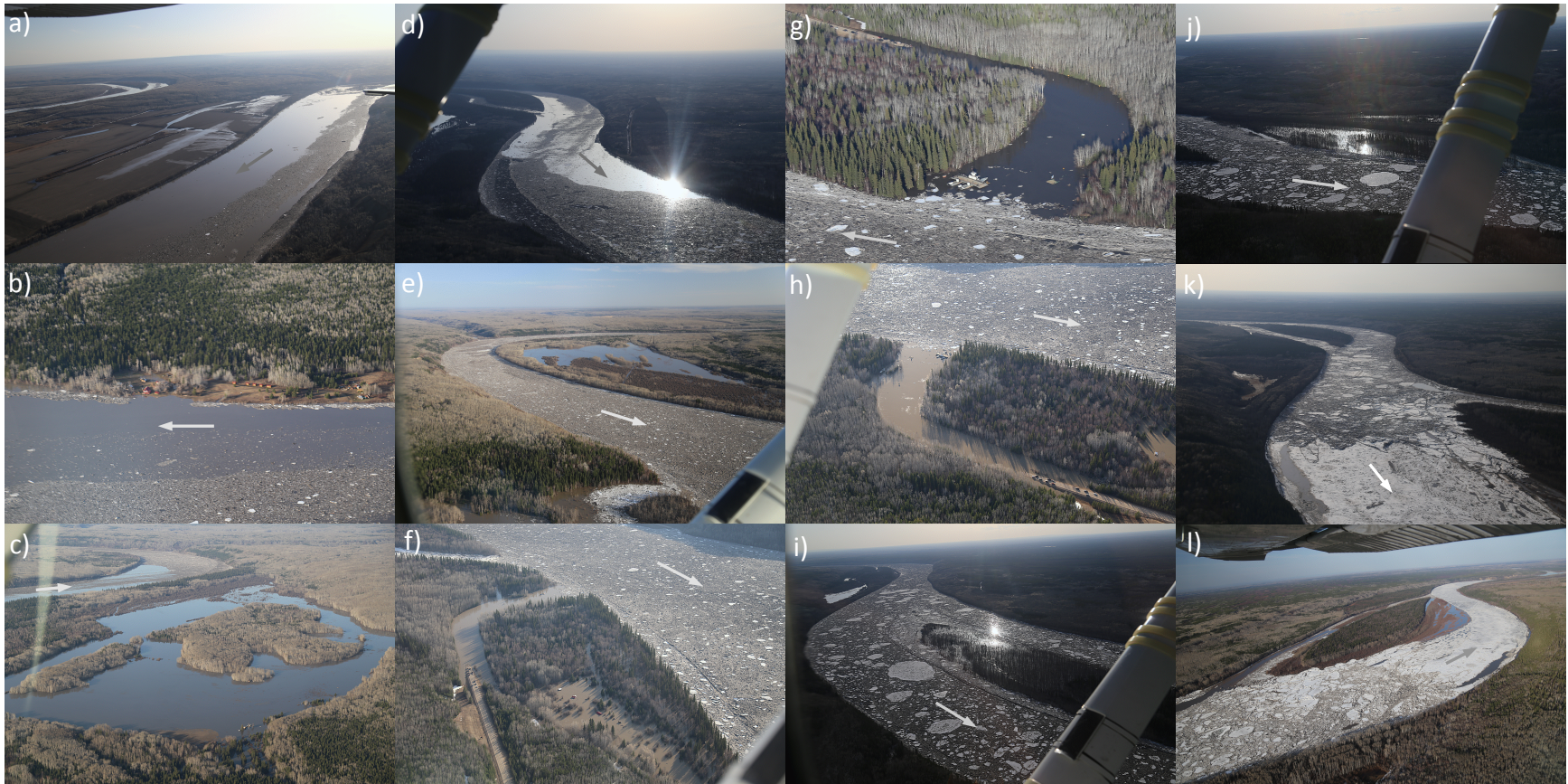


Figure 16. Ice jam flooding on Apr 27, 2018 at a) km 660 at Carcajou, b) km 663 at Carcajou, c) inside meander bend km 664 – 673 at Carcajou, d) head of ice jam at km 674, e) ice jam flooding at km 677, f,g,e) ice jam flooding at La Crete Ferry at Thompkins Landing at km 694, i) ice jam flooding at km 710, j) ice jam flooding at km 713, k,l) toe of ice jam at km 724.

Photos taken between 19:15 to 19:45 MDT downstream to upstream.

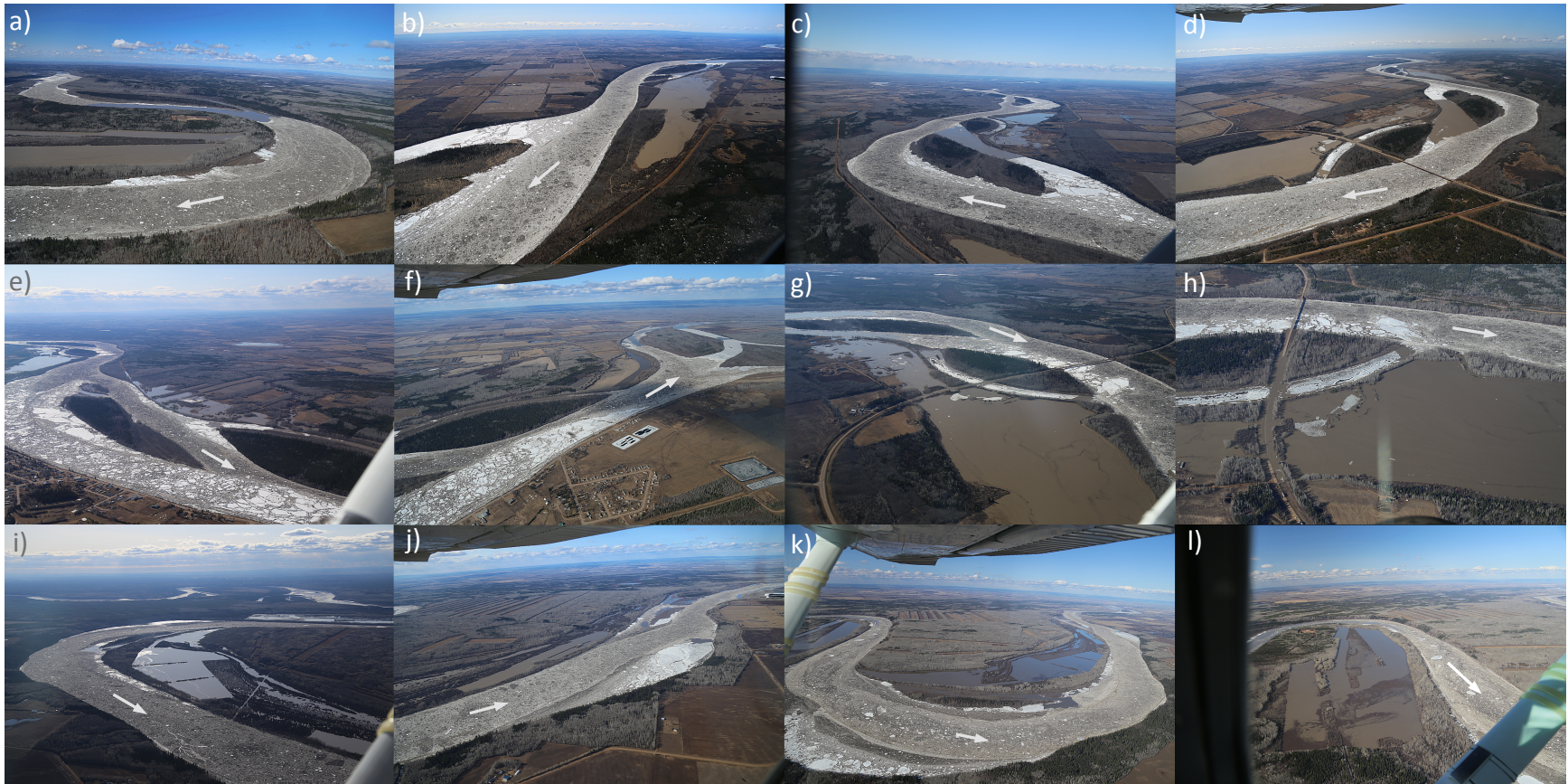
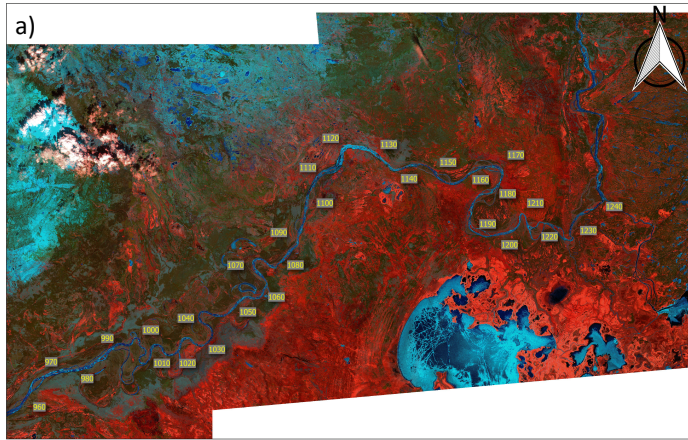
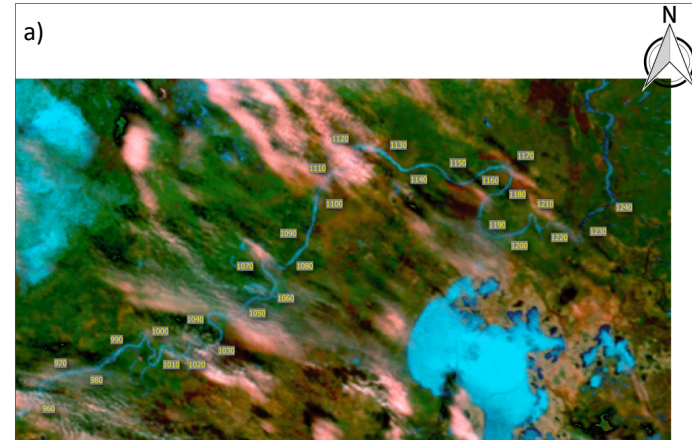
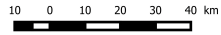


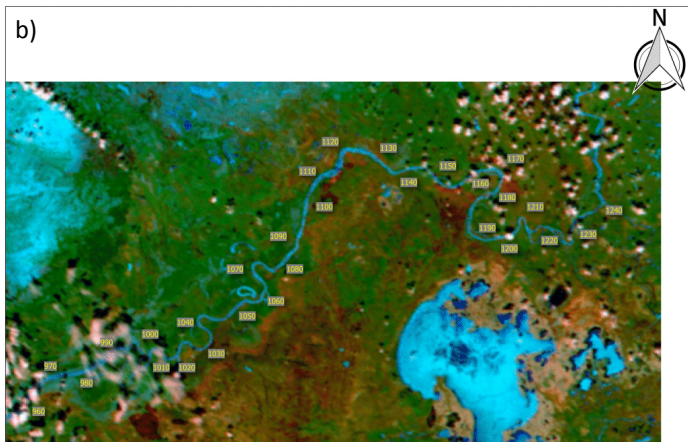
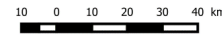
Figure 17. Ice jams and flooding at Fort Vermilion and upstream in early afternoon on Apr 29, 2018 at, a) km 790 @ 12:50 MDT, b) km 820 @ 13:00 MDT, c) km 821 @ 12:58 MDT, d) km 826 @ 13:02 MDT. The same reach was flown again in late afternoon showing ice jam at Fort Vermilion at e) km 833 @ 17:37 MDT, toe of ice jam at f) km 834 @ 17:38 MDT, g) km 826, @ 17:40 MDT h) km 826 @ 17:41 MDT, and an ice run from a released ice jam at i) km 819 @ 17:49 MDT, j) km 799 @ 17:50 MDT, k) km 796 @ 17:52 MDT, l) km 793 @ 17:53 MDT.



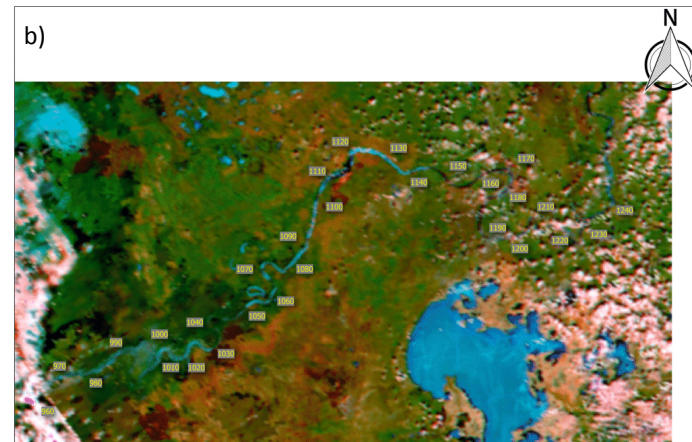
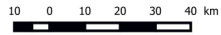
Sentinel 2A: S2A_MSI_L1C_20180425 UTC18H50
 Date Acquired: 2018/04/25
 Scale: 1/750000 (subset 1:375000).
 Map produced by DGI on April 26th, 2018



ModisTerra: MOD09GA_A2018117.h11v03.006.NRT
 ModisTerra: MOD09GQ_A2018117.h11v03.006.NRT
 Date Acquired: 2018/04/27
 Scale: 1/750000 (subset 1:375000).
 Map re-produced by DGI on October 26th, 2018



ModisAqua: MYD09GA_A2018116.h11v03.006.NRT
 ModisAqua: MYD09GQ_A2018116.h11v03.006.NRT
 Date Acquired: 2018/04/26
 Scale: 1/750000 (subset 1:375000).
 Map produced by DGI on April 27th, 2018



ModisAqua: MYD09GA_A2018121.h11v03.006.NRT
 ModisAqua: MYD09GQ_A2018121.h11v03.006.NRT
 Date Acquired: 2018/05/01
 Scale: 1/750000 (subset 1:375000).
 Map produced by DGI on May 2nd, 2018

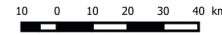


Figure 18a) Apr 25 and b) Apr 26 satellite images.

Figure 19a) Apr 27 and b) May 1 satellite images.



Figure 20. Photographs taken on Apr 29, 2018 showing that most of the ice cover had melted in the Peace River PAD reach from Rocky Point and Slave Rivers where ice jams that typically flood the PAD form. a, b) Rocky Point at km 1228 , c) km 1236 , d) km 1238, e, f, g, h) Peace-Slave-Rivière des Rochers confluence at km 1243, i) Slave River 3 km downstream of confluence , j) Slave River 12 km downstream of confluence, k) Slave River 13 to 25 km downstream of confluence, l) Slave River 11 km downstream of confluence.

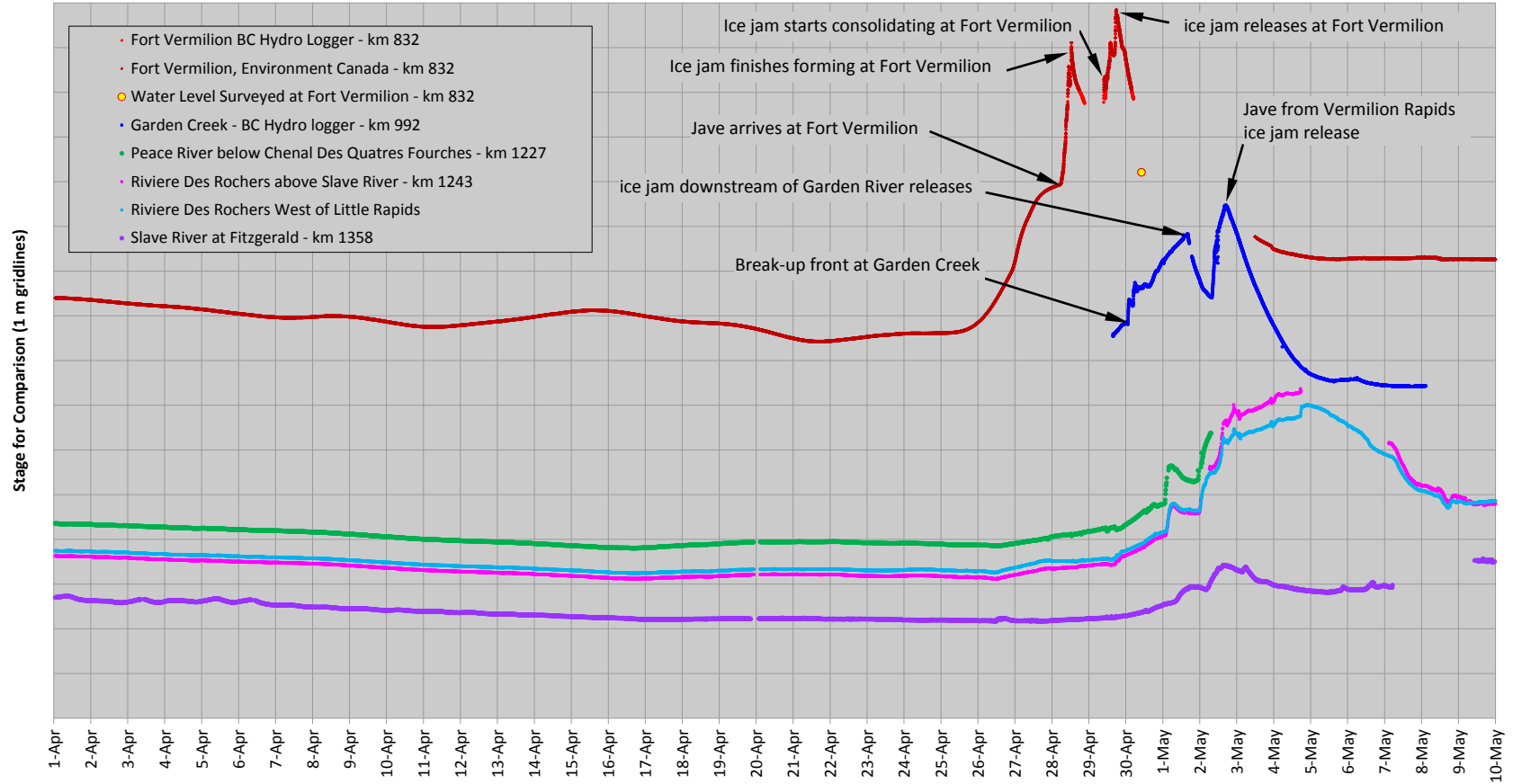


Figure 21. Relative water levels at Fort Vermilion, Garden Creek, gauges in the PAD reach and Slave River at Fitzgerald. Gauges in the PAD reach have a common offset.

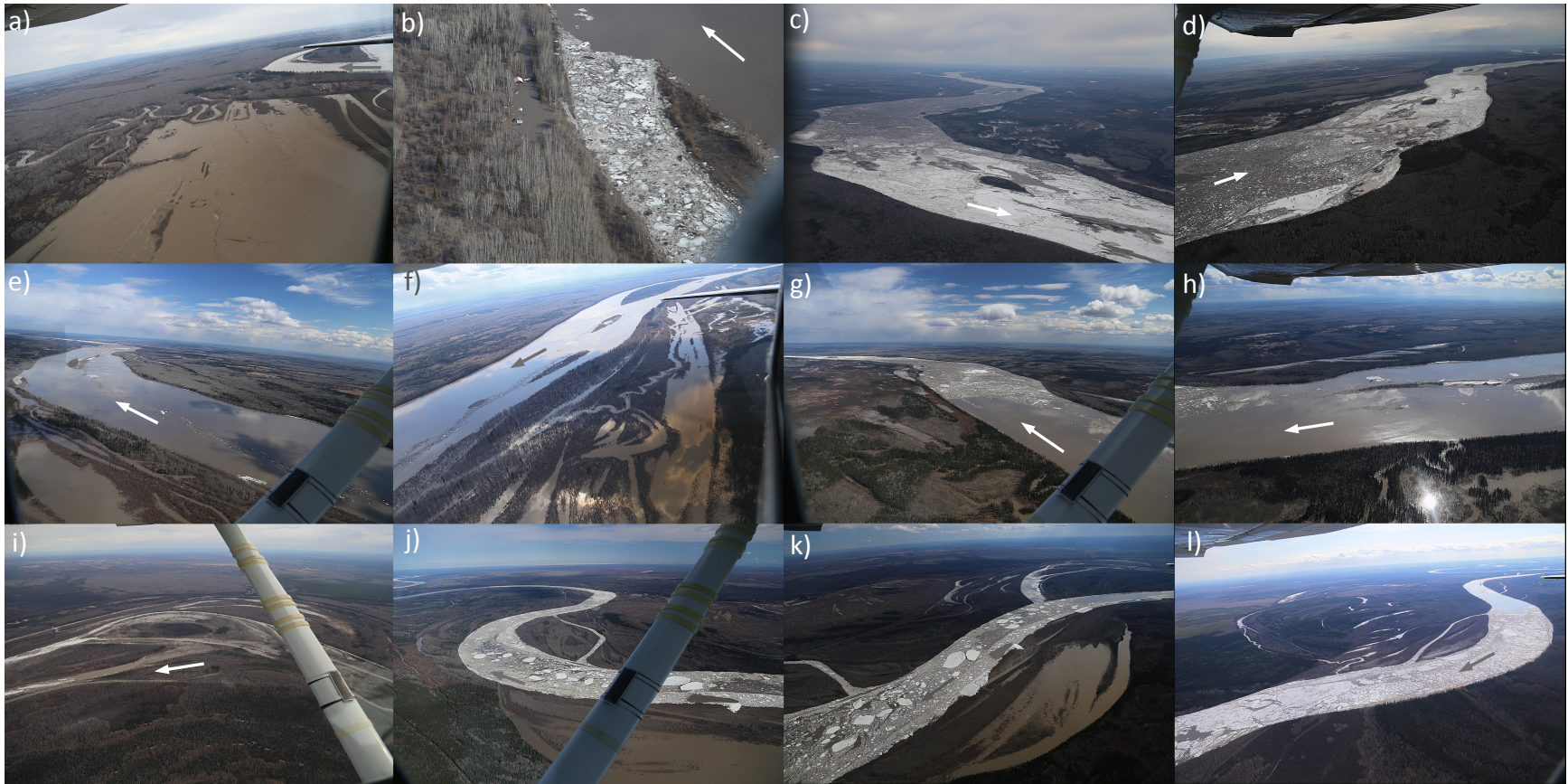


Figure 22. Photos of break-up and ice jams, and flooding on the Peace River between Fort Vermilion and the PAD at a) km 868 on Apr 30, 2018 18:28 MDT, b) Adam's Landing at km 903 on May 1, 2018 15:25 MDT, c) toe of ice jam at Vermilion Rapids at km 914 on Apr 30, 2018 18:10 MDT, d) toe of ice jam at km 914 at Vermilion Rapids and head at km 905 on Apr 30, 2018 18:10 MDT, e) ice jam backwater at km 901 on May 1, 2018 15:24 MDT, f) ice jam backwater at km 899 on May 1, 2018 15:24 MDT, g) head of ice jam at km 909 on May 1, 2018 15:27 MDT, h) ice jam backwater at km 907 on May 1, 2018 15:27 MDT, i) overbank ice jam flooding at km 1018 over 6 km away from the Peace River main channel on Apr 30, 2018 17:39 MDT, j,k) running ice and overbank flooding at km 1022 on May 1, 2018 16:04 MDT, l) running ice and overbank flooding at km 1056 on May 1, 2018 16:17 MDT.



Figure 23. a,b) Ice jam at Boyer rapids at km 1122 on May 1, 2018 16:37 MDT, c-e) extent of solid and more competent ice from Boyer Rapids to past Peace Point (km 1122 – 1144) on May 1, 2018 16:41 MDT. Peace point shown in (d). e,f,g) Open water from km 1144 past Peace Point to Rocky Point km 1228 on May 1, 2018 17:03 MDT. i,j) remnants of ice run between Rocky Point and start of Slave River (km 1243) on May 1, 2018 17:05 MDT, k) running ice 0 to 10 km downstream on the Slave River on May 1 2018 15:10 MDT, l) running ice 10 to 25 km downstream on the Slave River on May 1 2018 15:08 MDT.

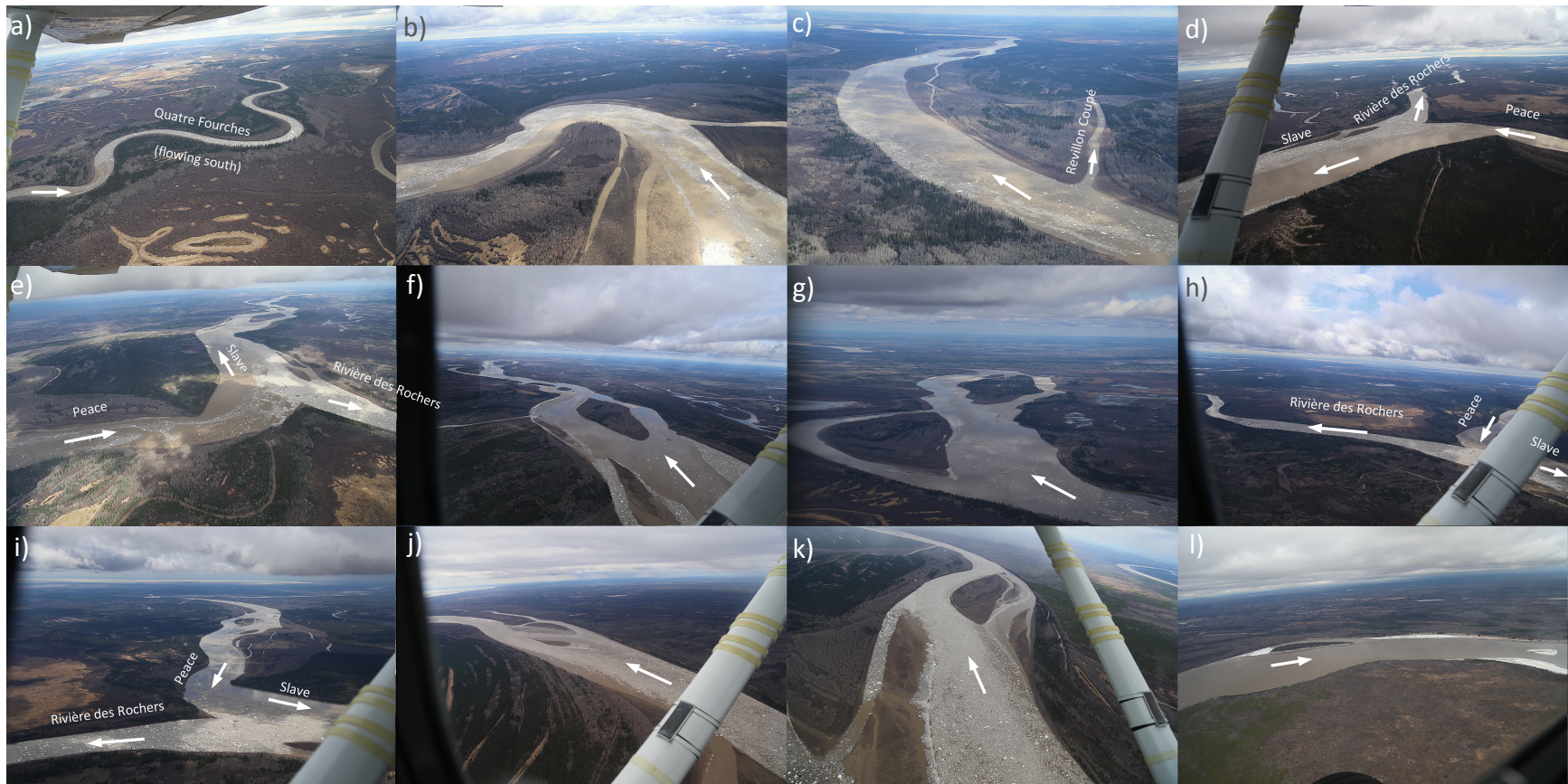


Figure 24. a) High water on the Peace causing break-up and ice jam on the Quatre Fourches flowing south on May 3, 2018 11:44 MDT, b) ice run by Rocky Point at km 1228 on May 3, 2018 11:44 MDT c) ice run between Rocky Point and start of Slave River causing reverse flow on the Revillon Coupé on May 3, 2018 11:49 MDT d,e) ice flowing by the PAD reach down the Slave River and reverse flow in Rivière des Rochers causing a short ice jam on May 3, 2018 11:54 MDT, f,g) running ice up to 25 km downstream on the Slave River on May 3, 2018 11:56 MDT, h,i) ice flowing by the PAD reach down the Slave River and reverse flow in Rivière des Rochers causing a short ice jam on May 3, 2018 12:02 MDT, j,k) ice run from Vermilion rapids ice jam on May 3, 2018 at km 1185 on May 3, 2018 12:52 MDT and km 1177 on May 3, 2018 12:19 MDT, l) open water at Boyer Rapids at km 1120 on May 3, 2018 12:37 MDT.