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Ice jam formation at river confluences: comprehensive field investigation and comparison to laboratory-derived predictive equations

Laurence Charbonneau et al.

Correspondence to: Laurence Charbonneau (laurence.charbonneau.2@ulaval.ca)

Supplements

S1 : Bras-du-Nord and Sainte-Anne confluence

The 2022 breakup at STA-BDN initiated upstream in the main river and subsequently in the tributary, concluding at all sites between 15 and 18 April. Ice jams formed upstream in both rivers. The BDN cleared one day before the STA, and the tributary's discharge constricted the passage of ice from the STA, resulting in the formation of an ice jam upstream of the confluence in the main river.

The results of the meteorological, hydraulic and ice conditions at STA-BDN during the 2022 breakup are presented in Fig. S1. Air temperatures remained positive from 30 March onwards (Fig. S1a). The breakup sequence occurred gradually from late March to mid-April (Fig. S1e, f). Ice began to disappear from the upstream site on the STA (STA6-US) around 30 March. By this date, the CDDT reached 101.2 °C D while the CDDF reached 1176.4 °C D, resulting in a CDDr of 0.09 (Fig. S1b). Based on the rapid water level rise at the upstream site on the BDN (BDN8) on 2 April, breakup likely initiated at this site on that day (Fig. S1h). For the other sites on the STA, breakup began following 35 mm of rainfall on 8 to 9 April (Fig. S1c). On this date, discharge began increasing, starting at 16.0 m^3 s^{-1} in the STA and 13.3 m^3 s^{-1} in the BDN for a Qr of 0.83 (Fig. S1i). The CDDT reached 180.8 °C D and the CDDr 0.15 (Fig. S1b). Breakup downstream of the confluence began on 14 April, coinciding with a 14 mm of rainfall (Fig. S1c). The season's maximum discharge in the STA was reached on this date at 97.5 m^3 s^{-1}, while the BDN maximum was reached on 16 April at 67.1 m^3 s^{-1} (Fig. S1i).

An ice jam formed upstream in the STA (STA14) on 11 April. On 12 April, an ice jam also formed upstream of the ice control structure on the STA (STA6-US). Both jams released on 15 April within hours of each other. Based on the 0.5 m water level peak at the upstream site in the tributary (BDN8) on 13 April, an ice jam likely formed at this site (Fig. S1h). Rising water temperature at this site on 14 April indicated the tributary was ice free from that date, i.e. before the main river (Fig. S1g). With ice releases from upstream jams and ice runs on the STA while the tributary was ice free with constricted discharge, an ice jam formed at the confluence on 15 April. This jam slowed ice evacuation from the STA, causing ice jams at STA6-DS on 15 April and at STA24 on 16 April. When these jams released on 17 April, ice runs reached the Chute-Panet Dam (STA0), where they melted in place. All sites were ice free on 18 April.

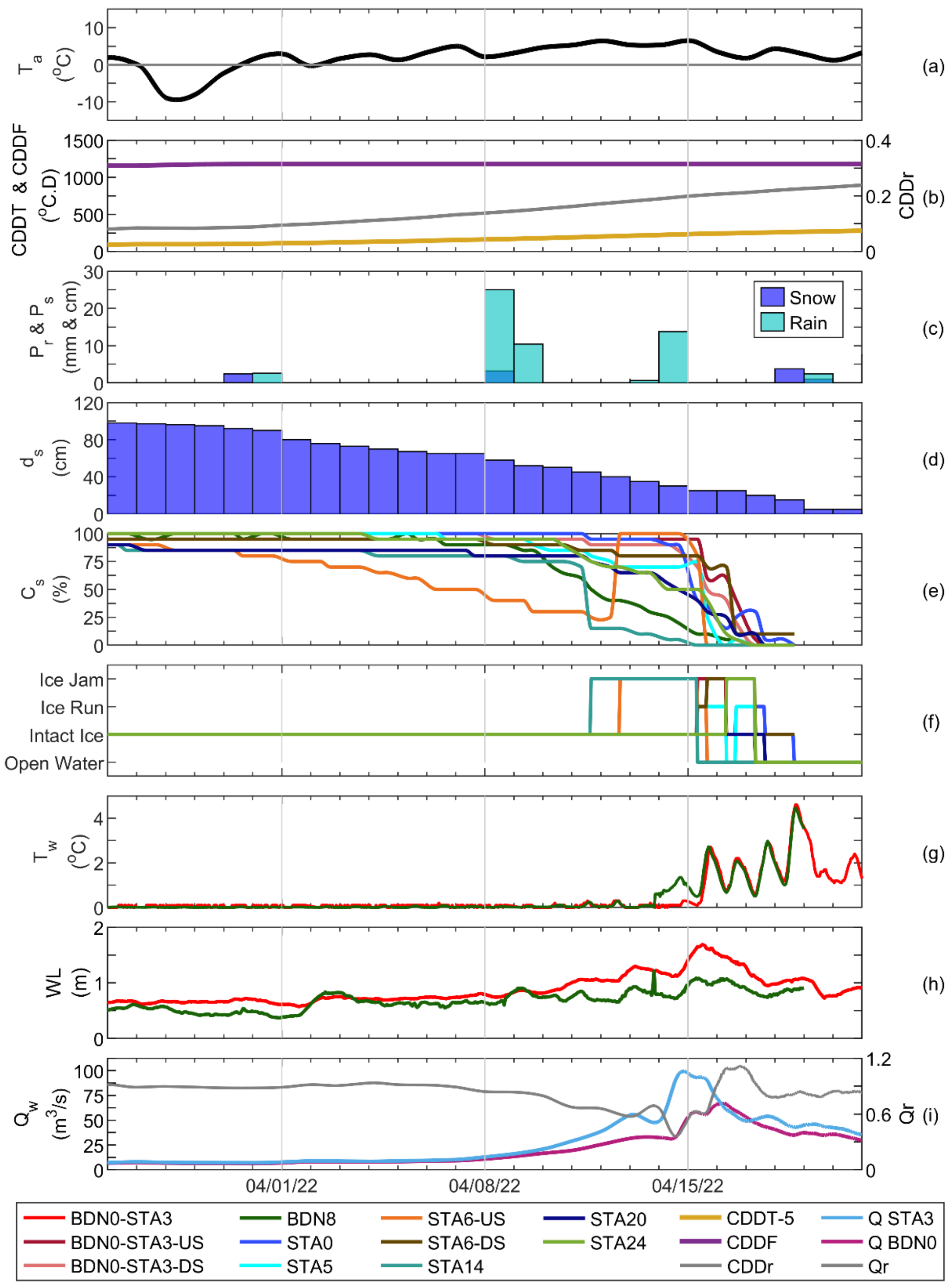


Figure S1. Time series of hydrometeorological conditions during the 2022 breakup at STA-BDN (26 March to 21 April 2022) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2023 breakup at STA-BDN initiated downstream in the main river and subsequently upstream in the tributary, ending at all sites by 18 April. Ice jams formed upstream and downstream of the confluence in the STA. Before the confluence began to lose its ice, the tributary was ice free. This ice-free discharge constricted the space available to evacuate the ice from the STA, resulting in the formation of an ice jam at the confluence.

The results of the meteorological, hydraulic and ice conditions at STA-BDN during the 2023 breakup are presented in Fig. S2. The breakup initiated from downstream to upstream in the STA, then from upstream to downstream in the BDN (Fig. S2e). The site directly downstream of the confluence (STA2) began to lose its ice on 11 April. From this date, discharges in both rivers began to increase, starting at 11.1 $m^3 s^{-1}$ in the STA and 8.5 $m^3 s^{-1}$ in the BDN for a Qr of 0.77 (Fig. S2i). By this date, the CDDT reached 180.1 °C D while the CDDF reached 782.0 °C D, resulting in a CDDr of 0.23 (Fig. S2b). Breakup upstream of the confluence on the STA (STA4) began on 14 April. With rising water temperatures and falling water levels at the upstream site on the tributary (BDN2) on that same date, the tributary was likely ice free by 14 April (Fig. S2g, h). Breakup at the confluence occurred on 18 April. This date coincided with a peak discharge of 238.6 $m^3 s^{-1}$ in the STA and 162.1 $m^3 s^{-1}$ in the BDN, for a Qr of 0.68 (Fig. S2i). By this date, the CDDT reached 275.3 °C D, resulting in a CDDr of 0.35 (Fig. S2b). A second discharge peak was observed on 24 April, at 261.0 $m^3 s^{-1}$ in the STA and 218.9 $m^3 s^{-1}$ in the BDN, for a Qr of 0.84 (Fig. S2i). This peak is also evident in the water levels at all sites rising by up to 2 m in 2 d (Fig. S2h). The rise is attributable to the complete melting of snow on the ground on the same day, as well as a series of rainfalls, including 47 mm on 23 April (Fig. S2c, d).

As breakup began in the STA downstream of the confluence (STA2), an ice jam formed between 12 and 13 April before giving way to a temporary ice cover. With the rapid drop in water level and subsequent rise in water temperatures at sites near the ice control structure (STA6-US and STA6-DS), an ice jam likely formed at these sites on 16 April (Fig. S2g, h). On 17 April, the same pattern was observed at the downstream site of a second ice control structure located further upstream on the STA (STA10-DS), again based on the rapid drop in water level followed by rising water temperatures (Fig. S2g, h). On the same date, an ice jam formed directly upstream of the confluence in the main river (STA4). The ice accumulated in this jam could not be evacuated due to the tributary's free discharge constricting the passage of ice. A further ice jam formed at the confluence a few hours later the same day. These last two ice jams released simultaneously on 18 April, explaining the ice runs observed downstream of the confluence (STA2) before all sites were ice free.

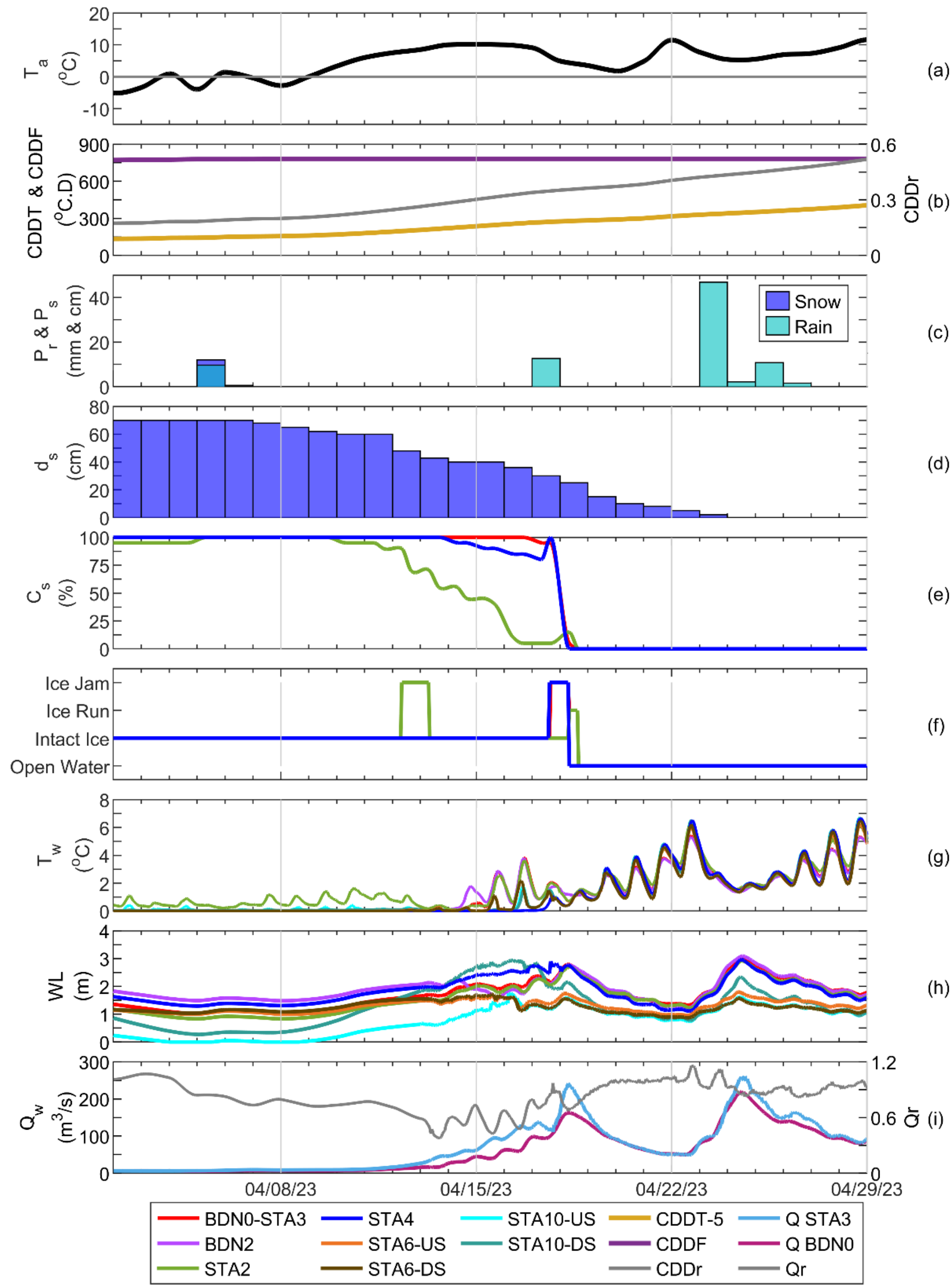


Figure S2. Time series of hydrometeorological conditions during the 2023 breakup at STA-BDN (2 April to 29 April 2023) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2024 breakup at STA-BDN initiated downstream in the main river and subsequently upstream, ending at all sites by 12 April. The tributary was ice free before the main river. This ice-free discharge constricted the space available to evacuate the ice from the STA, resulting in the formation of an ice jam at the confluence.

The results of the meteorological, hydraulic and ice conditions at STA-BDN during the 2024 breakup are presented in Fig. S3. Air temperatures were mostly positive during the breakup period, apart from 19 to 25 March, which experienced colder temperatures reaching -10.5 °C (Fig. S3a). The breakup started gradually at the upstream and downstream sites of the ice control structure on the STA (STA6-US and STA6-DS) (Fig. S3e). However, sites on the STA became ice free from downstream to upstream (Fig. S3f). On 27 March, water temperatures at the upstream site on the BDN (BDN2) began to rise, indicating this site was ice free, while all sites on the STA were still ice covered (Fig. S3g). The confluence (BDN0-STA3) began to lose its ice cover on 3 April. By this date, the CDDT reached 248.9 °C D while the CDDF reached 639.2 °C D, resulting in a CDDr of 0.39 (Fig. S3b). Discharge in both rivers was relatively low, at 15.3 $m^3 s^{-1}$ in the STA and 10.3 $m^3 s^{-1}$ in the BDN, for a Qr of 0.67 (Fig. S3i). The breakup was therefore thermal. All sites were ice free on 12 April, when the snow on the ground had melted completely and rainfalls of 18 mm and 12 mm fell on 11 and 12 April, respectively (Fig. S3c, d). The season's maximum discharge was observed on 13 April at 341.5 $m^3 s^{-1}$ in the STA and 203.0 $m^3 s^{-1}$ in the BDN, for a Qr of 0.59 (Fig. S3i). This peak is also evident in the water levels at all sites rising by almost 2 m in 2 d (Fig. S3h).

A brief ice jam formed upstream of the ice control structure on the STA (STA6-US) on 30 March, before releasing in the form of ice runs until 3 April. Ice runs also reached the site downstream of the confluence (STA2) from 30 March to 2 April. With water temperatures rising at the site directly upstream of the confluence in the STA (STA4) from 30 March, this site was likely ice free and releasing ice downstream (Fig. S3g). The accumulation of ice runs from upstream in the STA, with the downstream passage constricted by the tributary's ice-free discharge, led to the formation of an ice jam at the confluence (BDN0-STA3) on 2 and 3 April. This jam released in the form of ice runs until 5 April. All sites were ice free on 12 April.

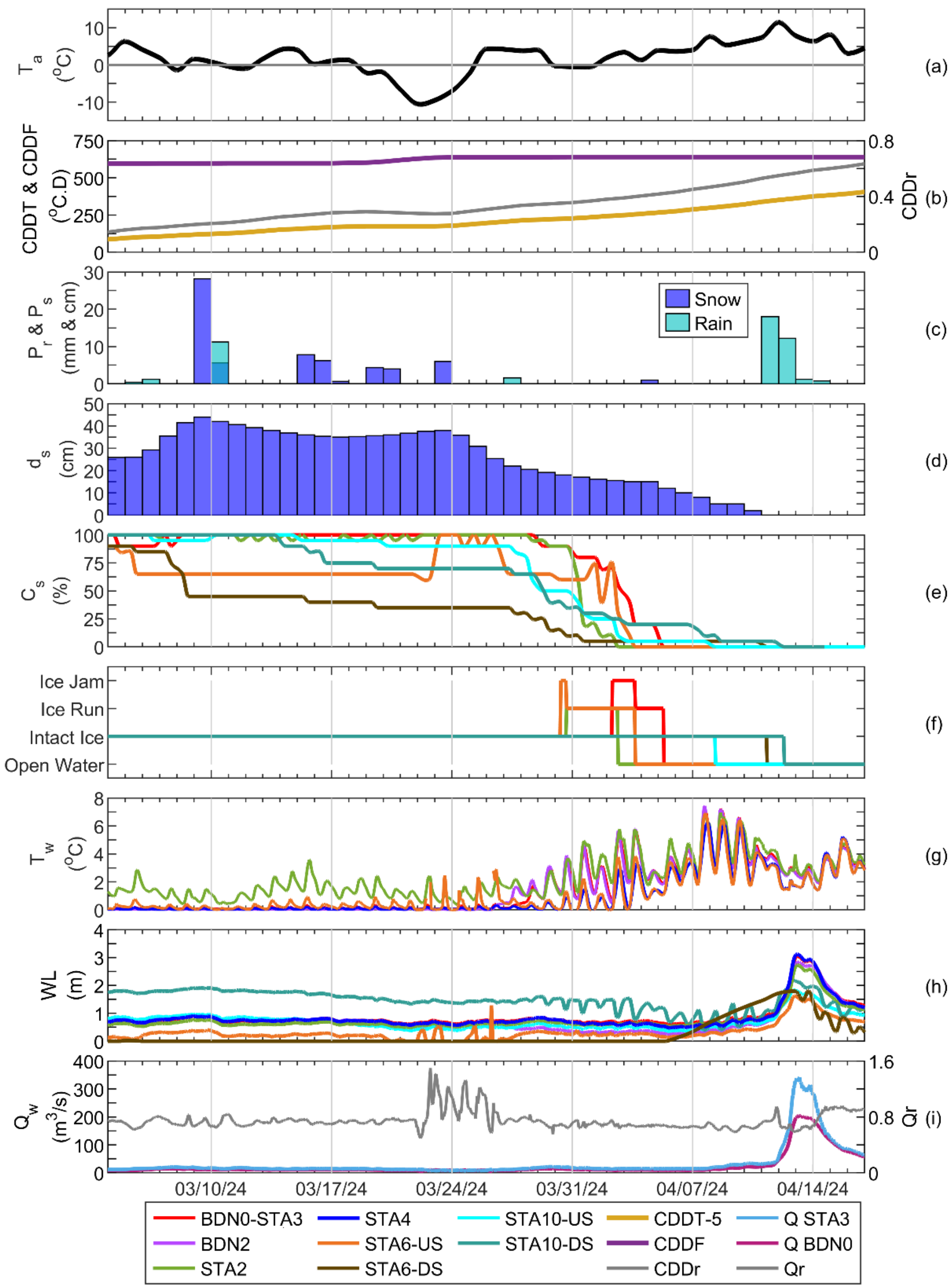


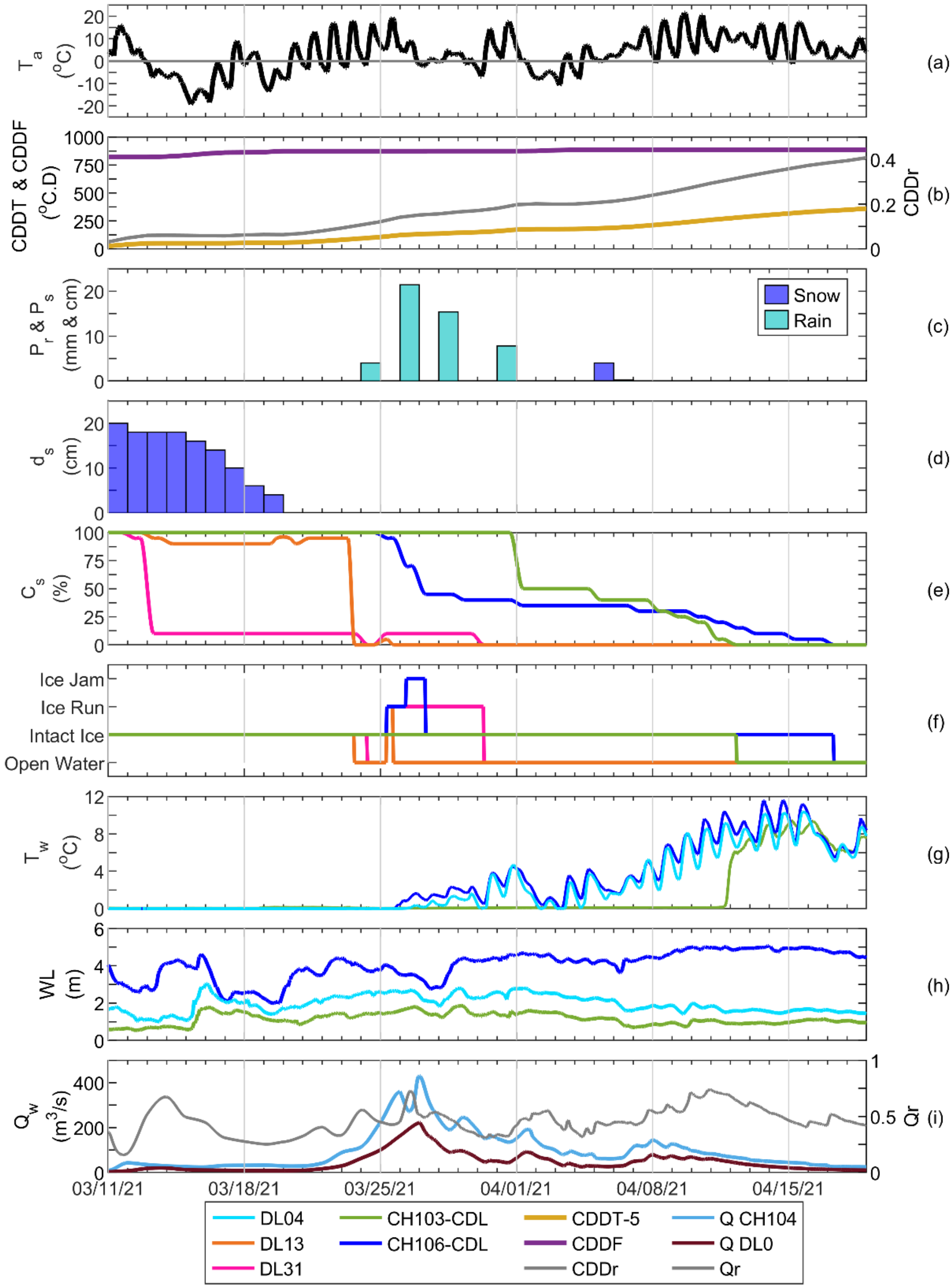
Figure S3. Time series of hydrometeorological conditions during the 2024 breakup at STA-BDN (4 March to 17 April 2024) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

S2: Du Loup and Chaudière confluence

The 2021 breakup at CH-DL initiated from upstream to downstream in the tributary and subsequently in the CH, ending at all sites by 12 April. Ice jams formed upstream of the confluence in both rivers. The ice cover induced by the Sartigan Dam constricted the passage of ice from upstream in the CH as well as from the DL, resulting in the formation of ice jams in both rivers.

The results of the meteorological, hydraulic and ice conditions at CH-DL during the 2021 breakup are presented in Fig. S4. Air temperatures remained positive from 20 March onwards, at the same time as the snow on the ground completely melted (Fig. S4a, d). A few days earlier, on 16 March, as air temperatures dropped to -16 °C, the Sartigan Dam gates were opened (Fig. S4a). This is evident in the nearly 2 m drop in water level upstream (CH106-CDL), which coincided with a 1.5 m rise in water level downstream (CH103-CDL) (Fig. S4h). The breakup started in the tributary from upstream to downstream (Fig. S4e). The most upstream observation site on the tributary (DL31) lost most of its ice cover on 12 March, when the CDDT reached 40.4 °C D while the CDDF reached 821.2 °C D, resulting in a CDDr of 0.05 (Fig. S4b). Discharge in the tributary was also still stable at 8.0 $m^3 s^{-1}$ (Fig. S4i). On 23 March, when a site further downstream on the tributary (DL13) lost most of its ice cover, discharge began to increase in the DL starting at 30.1 $m^3 s^{-1}$ and in the CH starting at 89.9 $m^3 s^{-1}$, for a Qr of 0.33 (Fig. S4i). While the ice cover upstream of the Sartigan Dam was still present, the ice at the upstream site of the confluence on the CH (CH106-CDL) began to lose its ice cover on 25 March following 4 mm of rainfall (Fig. S4c). This date coincided with 21 mm of rainfall and the season's maximum discharge of 418.7 $m^3 s^{-1}$ in the CH and 211.3 $m^3 s^{-1}$ in the DL, for a Qr of 0.50 (Fig. S4i). The site downstream of the confluence and dam (CH103-CDL) began losing its ice cover on 1 April, becoming ice free on 12 April.

Ice runs from upstream in the CH were blocked by the intact ice cover and formed an ice jam at the upstream site of the confluence on the CH (CH106-CDL) from 26 to 27 March. A temporary ice cover was then maintained at this site as the downstream dam stabilized the flow (Fig. S4f). Ice runs from the tributary also accumulated at the mouth (DL04), which could not evacuate its ice due to the stationary ice cover downstream. This ice jam was observed by drone flights on 23 March and is also evident in the rise in water level in the tributary (DL04) from 19 March (Fig. S4h). With rising water temperatures at this site from 28 March onwards, the tributary was likely ice free from that date (Fig. S4g).

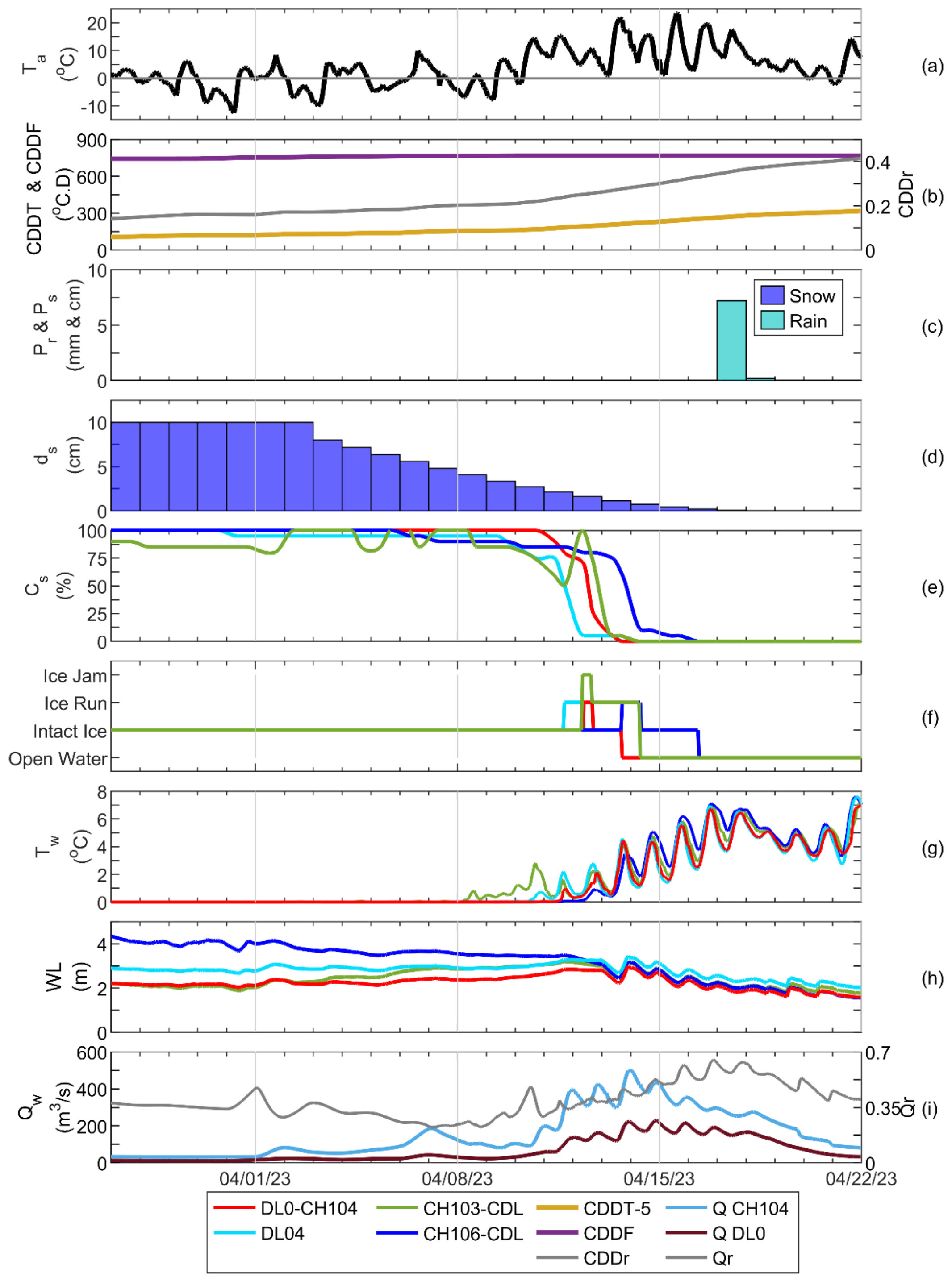


120 **Figure S4.** Time series of hydrometeorological conditions during the 2021 breakup at CH-DL (11 March to 19 April 2021) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2023 breakup at CH-DL initiated at the mouth of the tributary and subsequently at the confluence and upstream sites, ending at all sites by 17 April. No ice jams formed at CH-DL or upstream in 2023. The breakup was thermal, with all sites losing their ice cover as air temperatures rose. This gradual melting did not result in ice accumulation in the ice cover upstream of the Sartigan Dam, despite discharge peaking during the breakup period.

The results of the meteorological, hydraulic and ice conditions at CH-DL during the 2023 breakup are presented in Fig. S5. Air temperatures remained consistently positive from 10 April onwards (Fig. S5a). On 11 April, breakup began at the mouth of the tributary (DL04) (Fig. S5e). By this date, the CDDT reached 172.2 °C D while the CDDF reached 767.6 °C D, resulting in a CDDr of 0.22 (Fig. S5b). On this date, discharges began to increase, starting at 196.5 $m^3 s^{-1}$ in the CH and 59.3 $m^3 s^{-1}$ in the DL, for a Qr of 0.30 (Fig. S5i). On 12 April, breakup began at the confluence (DL0-CH104) and downstream of the dam (CH103-CDL) (Fig. S5e). Breakup at the upstream confluence site on the CH (CH106-CDL) began on 13 April. On this date, the season's maximum discharge was reached at 499.1 $m^3 s^{-1}$ in the CH and 228.7 $m^3 s^{-1}$ in the DL the following day, on 14 April (Fig. S5i). On 17 April, the snow on the ground had completely melted, coinciding with 7 mm of rainfall (Fig. S5c, d). This date also marked all sites becoming ice free, while the CDDT reached 263.6 °C D with a stable CDDF, resulting in a CDDr of 0.34 (Fig. S5b).

Ice runs from the tributary reached the confluence and formed a temporary ice jam downstream of the dam on 12 April (Fig. S5f). Ice released in the form of ice runs at the upstream site on the CH (CH106-CDL) while the confluence was ice free.

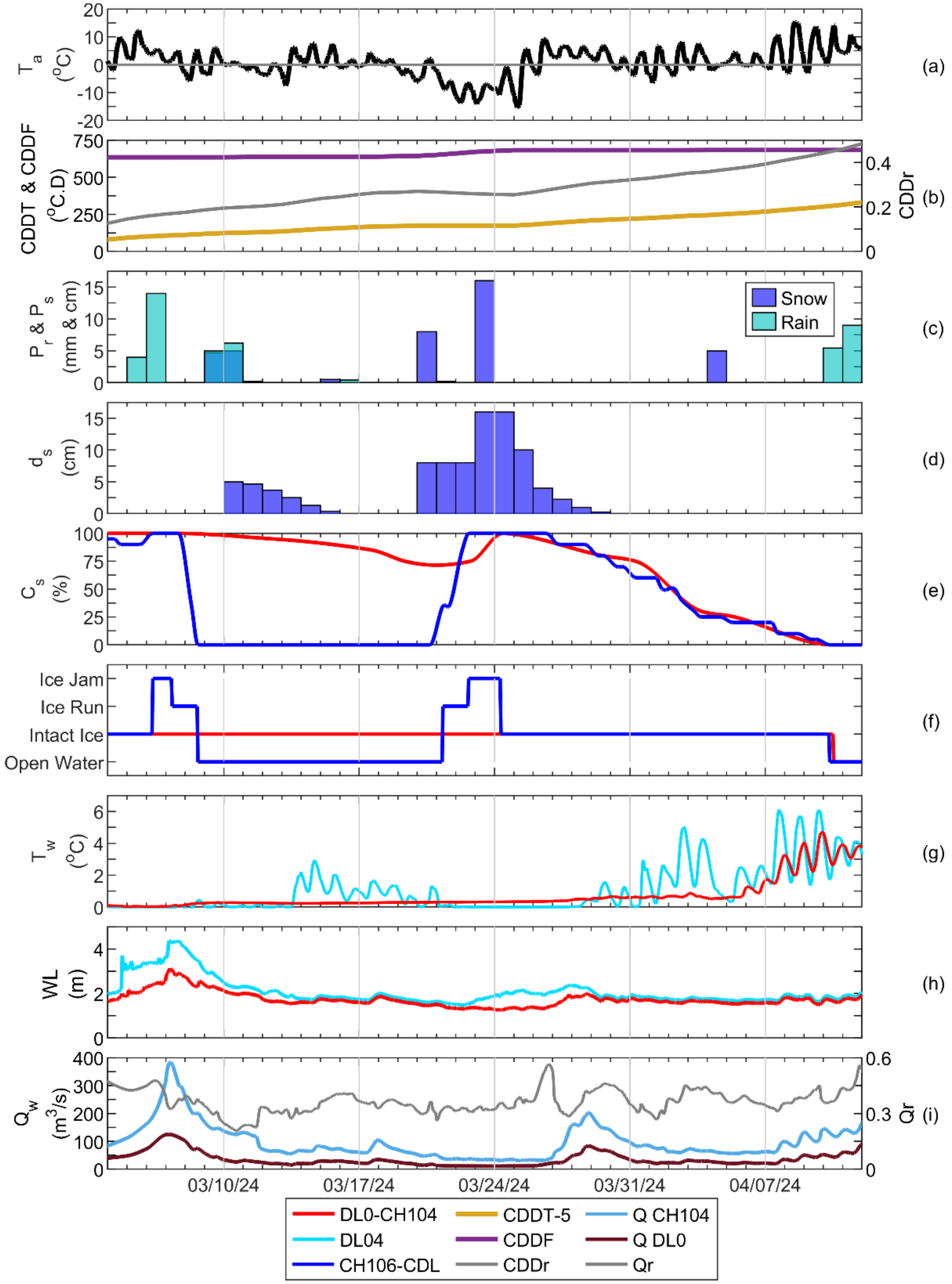


140 **Figure S5.** Time series of hydrometeorological conditions during the 2023 breakup at CH-DL (27 March to 22 April 2023) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2024 breakup at CH-DL initiated from upstream to downstream in the CH and subsequently in the tributary, ending at all sites by 10 April. Ice jams formed upstream of the confluence in both rivers. The Sartigan Dam's ice cover constricted the passage of ice from upstream in the CH and DL, resulting in the formation of ice jams in both rivers.

The results of the meteorological, hydraulic and ice conditions at CH-DL during the 2024 breakup are presented in Fig. S6. The breakup started from upstream to downstream in the CH before the tributary (Fig. S6e). The upstream confluence site in the main river (CH106-CDL) lost most of its ice cover on 8 March. This date followed the season's maximum discharge on 7 March at 380.5 $m^3 s^{-1}$ in the CH and 124.4 $m^3 s^{-1}$ in the DL, for a Qr of 0.33 (Fig. S6i). A total of 18 mm of rainfall on 5 and 6 March was responsible for this increase, also evident in the rising water levels at the confluence (DL0-CH104) and at the tributary mouth (DL04) (Fig. S6c, h). At the start of the breakup in the CH, the CDDT reached 111.5 °C D while the CDDF reached 634.6 °C D, resulting in a CDDr of 0.18 (Fig. S6b). Based on the rising water temperatures at the tributary mouth site (DL04) from 13 to 21 March, the tributary was likely ice free during this period (Fig. S6g). Following colder air temperatures reaching -15 °C between 21 and 25 March, the ice cover at the mouth of the tributary appears to have temporarily reformed as water temperatures at the site returned to 0 °C (Fig. S6a, g). The tributary was likely ice free from 29 March onwards, due to the steady rise in water temperatures (Fig. S6g). By this date, the snow on the ground had completely melted and a second peak discharge was observed at 204.4 $m^3 s^{-1}$ in the CH and 83.6 $m^3 s^{-1}$ in the DL, for a Qr of 0.41 (Fig. S6d, i).

With a peak water level of 1.5 m reached on 4 March at the mouth of the tributary (DL04), an ice jam likely formed at this site (Fig. S6h). An ice jam formed at the site upstream of the confluence on the CH (CH106-CDL) on 6 and 7 March, before releasing in the form of ice runs on 8 March. This site was ice free, while downstream, at the confluence and upstream of the Sartigan Dam, the ice cover was still intact. Ice runs from upstream in the CH struck against this intact ice cover and formed a second ice jam from 22 to 24 March. With the water level at the mouth of the tributary (DL04) rising over several days without any significant increase in discharge, an ice jam likely formed at this site from 23 to 27 March due to the accumulation of ice runs from upstream blocked by the intact ice cover at the confluence (Fig. S6h). The upstream site of the confluence on the CH (CH106-CDL) then formed a temporary ice cover and began to lose its ice cover at the same time as the confluence, becoming ice free on 10 April, a few hours before the confluence (DL0-CH104) (Fig. S6f).



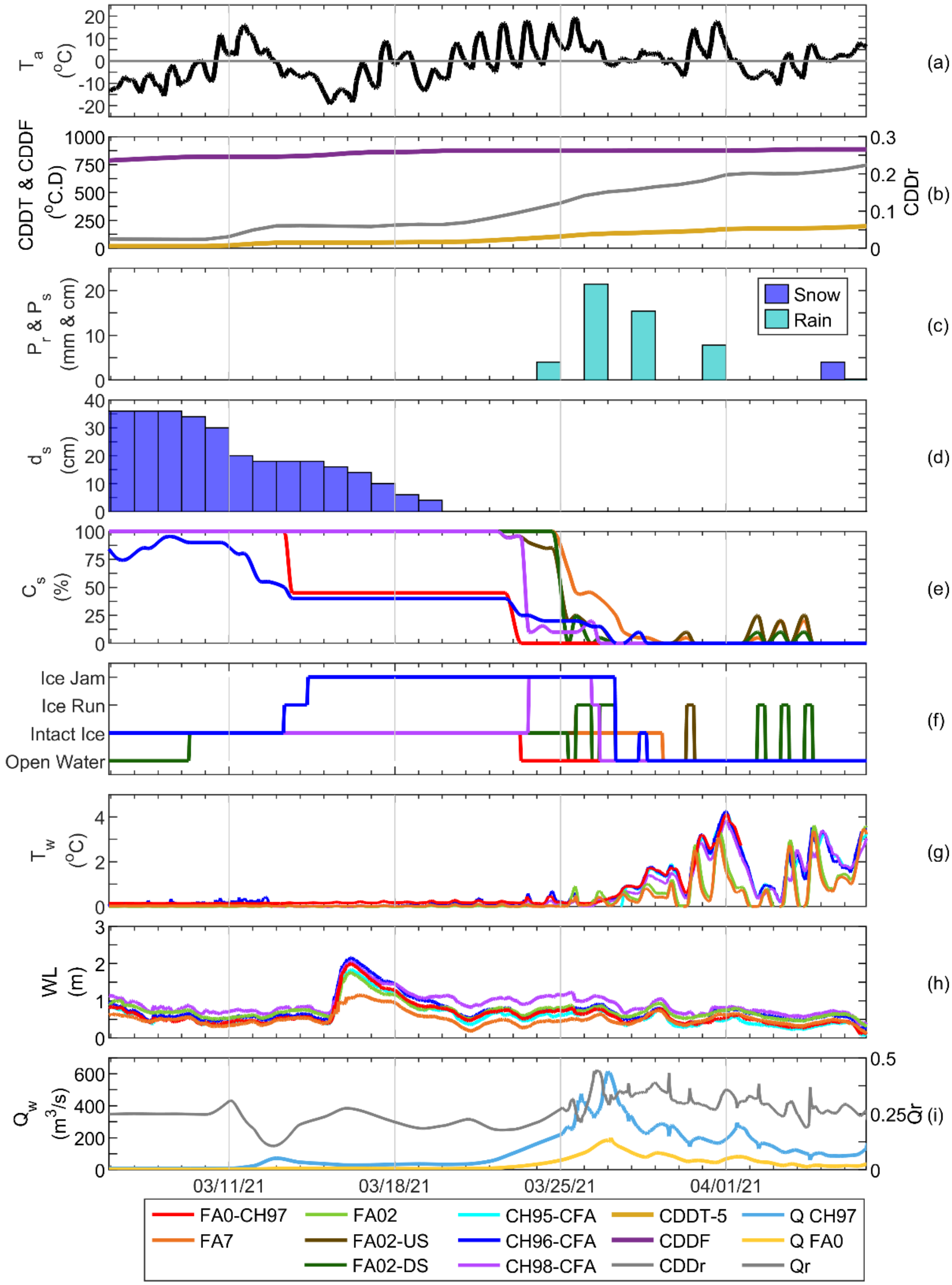
170 **Figure S6.** Time series of hydrometeorological conditions during the 2024 breakup at CH-DL (11 March to 10 April 2024) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

S3: Famine and Chaudière confluence

The 2021 breakup at CH-FA initiated from downstream to upstream in the CH and subsequently in the tributary, ending at all sites by 29 March. Ice jams formed downstream of the confluence in the CH. Morphological features, including accumulation banks and the highway-bridge 173 at the mouth of the tributary, restricted ice evacuation.

The results of the meteorological, hydraulic and ice conditions at CH-FA during the 2021 breakup are presented in Fig. S7. Air temperatures remained positive from 20 March onwards (Fig. S7a). Apart from a drop in ice cover of around 50 % at the confluence (FA0-CH97) and downstream on the CH (CH96-CFA) on 13 March, the breakup started in the CH on 23 March and on 25 March in the FA (Fig. S7e). This sequence was triggered on 24 March by 4 mm of rainfall, as well as a few days after the complete melting of snow on the ground on 20 March (Fig. S7c, d). At breakup initiation in the CH, the CDDT reached 81.4 °C D while the CDDF reached 873.6 °C D, resulting in a CDDr of 0.09 (Fig. S7b). Discharges began to increase at the start of breakup in the main river, starting at 165.2 $m^3 s^{-1}$ in the CH and 33.6 $m^3 s^{-1}$ in the FA, for a Qr of 0.20 (Fig. S7i). At breakup initiation in the FA, the CDDT reached 106.3 °C D, resulting in a CDDr of 0.12 (Fig. S7b). Discharges reached 224.8 $m^3 s^{-1}$ in the CH and 63.8 $m^3 s^{-1}$ in the FA, for a Qr of 0.28 (Fig. S7i). On 27 March, a rainfall of 21 mm contributed to the season's maximum discharge of 605.5 $m^3 s^{-1}$ in the CH and 179.9 $m^3 s^{-1}$ in the FA, for a Qr of 0.30 (Fig. S7c, i).

The breakup occurred from downstream to upstream in both rivers (Fig. S7f). An ice jam formed downstream of the confluence (CH96-CFA) on 14 March, following the accumulation of ice runs. As the ice jam was downstream, it raised the water level at all observation sites on both rivers by almost 1.5 m on 15 March (Fig. S7h). The ice jam released on 27 March. It should be noted that the ice cover at this observation site (CH96-CFA) was affected by hot water discharges from the Saint-Georges wastewater treatment plant located approximately 1 km upstream of the site. As a result, an open channel occupying approximately 20 % of the river's width persisted throughout the winter at this site. No ice jams formed directly at the confluence (FA0-CH97) in 2021. The confluence was ice free on 23 March, while an ice jam formed at the upstream site on the CH a few hours later, before releasing on 26 March. Although the section in the CH downstream of the confluence (CH96-CFA) had lost its ice cover, the discharge in the FA was not sufficient to lift and dislodge the ice cover beyond the highway-bridge 173 and the accumulation bank at the mouth of the tributary (FA02-US and FA02-DS). The ice cover at the mouth of the tributary at the upstream and downstream sites (FA02-US and FA02-DS) released from downstream to upstream between 25 and 26 March within a few hours of each other. The most upstream observation site on the tributary (FA7) became ice free on 29 March due to the presence of a pronounced meander in the river at this point.

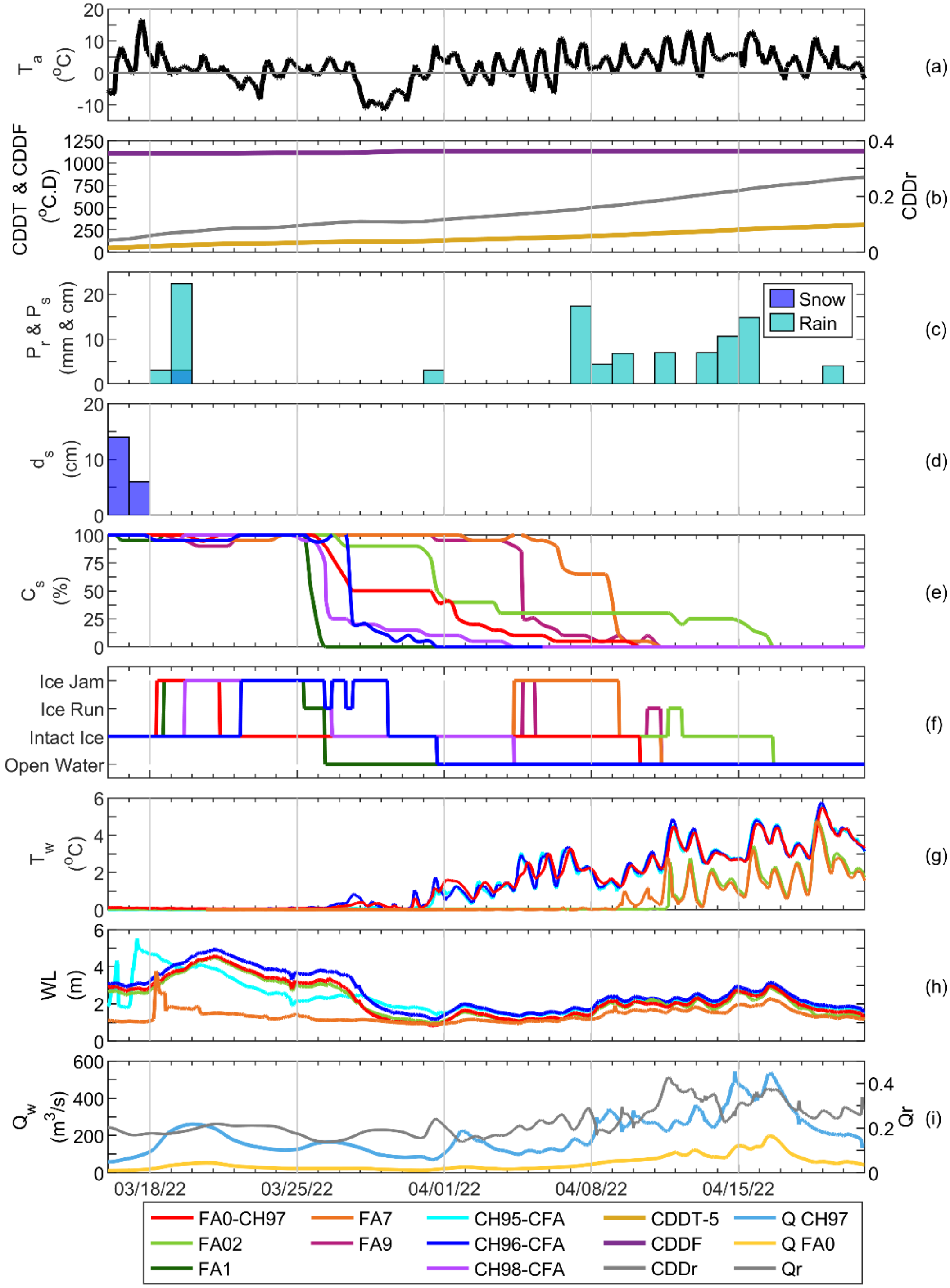


205 **Figure S7.** Time series of hydrometeorological conditions during the 2021 breakup at CH-FA (6 March to 7 April 2021) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2022 breakup at CH-FA initiated from upstream to downstream in the CH and subsequently from downstream to upstream in the tributary, ending at all sites by 16 April. Ice jams formed at the confluence and upstream in both rivers. Ice jams formed primarily due to morphological features.

The results of the meteorological, hydraulic and ice conditions at CH-FA during the 2022 breakup are presented in Fig. S8. Breakup started in the CH from upstream to downstream, then in the FA from downstream to upstream, except for one site near the tributary mouth (FA1) where breakup began on 25 March (Fig. S8e). This separation of the breakup is particularly evident in the two sequences of rising water temperatures starting first from the CH around 31 March, then from the FA around 9 April (Fig. S8g). At the initiation of the CH and the confluence breakup, on 26 March, the CDDT reached 111.5 °C D while the CDDF reached 1112.9 °C D, resulting in a CDDr of 0.10 (Fig. S8b). Discharges had also increased slightly that day, starting at 165.1 $m^3 s^{-1}$ in the CH (Fig. S8i). Downstream of the tributary, most of the ice cover disappeared on 31 March, while the CDDT reached 124.4 °C D and the CDDF reached 1135.0 °C D, resulting in a CDDr of 0.11 (Fig. S8b). From that date onwards, discharges began to increase, starting at 72.1 $m^3 s^{-1}$ in the CH and 17.5 $m^3 s^{-1}$ in the FA, for a Qr of 0.24 (Fig. S8i). The season's maximum discharge was reached on 16 April at 533.1 $m^3 s^{-1}$ in the CH and 197.4 $m^3 s^{-1}$ in the FA, for a Qr of 0.37 (Fig. S8i).

Although the breakup had not yet truly begun, given that the ice cover at the observation sites had only melted by approximately 10 %, an ice jam formed at the confluence (FA0-CH97) on 18 March when the snow on the ground had completely melted (Fig. S8d, f). A few hours later, an ice jam formed upstream of the mouth of the tributary (FA1), with the accumulation banks and the constricted ice passage at the highway-bridge 173. A third ice jam formed on 19 March, upstream on the CH (CH98-CFA). These ice jams coincided with 25 mm of rainfall on 18 and 19 March, which increased the discharge to 260.4 $m^3 s^{-1}$ in the CH, also evident in the water levels at all sites rising by approximately 2 m during this period (Fig. S8c, h, i). The jam at the confluence released on 21 March, forming a new jam downstream on the CH (CH96-CFA) on 22 March. The two jams upstream of the confluence on the CH and FA (CH98-CFA and FA1) released simultaneously on 25 and 26 March. The site upstream of the tributary mouth (FA1) was ice free on 26 March, but the site upstream on the CH (CH98-CFA) reformed a temporary ice cover due to colder air temperatures between 27 and 31 March, and was not ice free until 4 April (Fig. S8a, f). The ice jam downstream of the confluence (CH96-CFA) had a few releases in the form of ice runs on 26 and 27 March before releasing completely on 29 March, forming a temporary ice cover until 31 March. For the breakup sequence on the tributary, an ice jam formed upstream in the tributary (FA7), on 4 April, and remained in place until 9 April. A brief ice jam also formed at the site further upstream (FA9) during the night of 4 to 5 April, due to a pronounced meander in the river at this location. After the evacuation of ice runs, these two upstream tributary sites (FA7 and FA9) were ice free on 11 April. These ice runs reached the mouth of the tributary (FA02) the next day, which became ice free on 16 April, requiring the maximum discharge of the season to dislodge the ice at the accumulation sites.



240 **Figure S8.** Time series of hydrometeorological conditions during the 2022 breakup at CH-FA (16 March to 21 April 2022) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2024 breakup at CH-FA was fragmented, initiating at the confluence and subsequently upstream and downstream in both rivers, ending at all sites by 28 March. Ice jams formed upstream and downstream of the confluence in both rivers. No ice jams formed directly at the confluence (FA0-CH97), but ice jams formed upstream in both rivers and downstream due to morphological features and ice accumulations.

The results of the meteorological, hydraulic and ice conditions at CH-FA during the 2024 breakup are presented in Fig. S9. Air temperatures were mostly positive during this period, but experienced two colder periods, reaching -17 °C between 29 February and 2 March, and -15 °C between 21 and 25 March (Fig. S9a). This second colder period coincided with a 16 cm snowfall on 23 March (Fig. S9c). Breakup started at the site downstream of the confluence (CH96-CFA) on 27 February, at the same time as rising water temperatures (Fig. S9g). This site is located approximately 1 km downstream from a water treatment plant, which warms the river water through its discharges. The confluence also began to lose its ice cover on 27 February. By this date, the CDDT reached 58.9 °C D while the CDDF reached 622.3 °C D, resulting in a CDDr of 0.09 (Fig. S9b). Discharge in the CH also began to rise from this date, starting at 19.7 $m^3 s^{-1}$ (Fig. S9i). Breakup in the tributary and the most downstream observation site in the CH (CH95-CFA) began on 6 March. A total of 18 mm of rainfall on 5 and 6 March likely contributed to breakup by increasing the discharge in the FA to 53.0 $m^3 s^{-1}$ (Fig. S9c, i). By this date, the CDDT reached 100.6 °C D with a CDDr of 0.16 (Fig. S9b). Rainfall combined with ice melt produced the season's maximum discharge on 7 March, at 403.7 $m^3 s^{-1}$ in the CH and 72.6 $m^3 s^{-1}$ in the FA, for a Qr of 0.18 (Fig. S9i). A second peak discharge occurred in the CH on 28 March at the same time as the complete melting of snow on the ground, reaching 306.8 $m^3 s^{-1}$ (Fig. S9d, i).

Ice runs from the confluence were evacuated at the downstream site (CH96-CFA) from 29 February to 2 March. As a result of this evacuation, the water level downstream (CH96-CFA) rose by 0.5 m, while it fell by 0.5 m at the confluence (FA0-CH97) (Fig. S9h). The downstream site (CH96-CFA) was ice free just before the formation of an ice jam on the night of 4 to 5 March, which released in the form of ice runs until 6 March. An ice jam at a site even further downstream (CH95-CFA) formed on the same day, 4 March, but a few hours later, and remained in place until 7 March due to the accumulation of ice runs. Also, the rising water temperatures at the upstream site on the CH at the same time as the confluence on 9 March indicated that this site was ice free by that date (Fig. S9g). Another ice jam formed at the mouth of the tributary (FA02) on 5 March and released in ice runs on 6 March, while a brief ice jam formed at the same time at a site further upstream in the tributary (FA7) and released a few hours later. These ice runs accumulated to form a second ice jam at the mouth of the tributary (FA02) on 7 March, due to the accumulation banks and the constricted passage at the highway-bridge 173. Several sequences of ice runs from the tributary and the main river from upstream to downstream were then observed until all sites were ice free. A final ice jam formed during these ice run release sequences at the upstream site in the tributary (FA7) due to the presence of a pronounced meander.

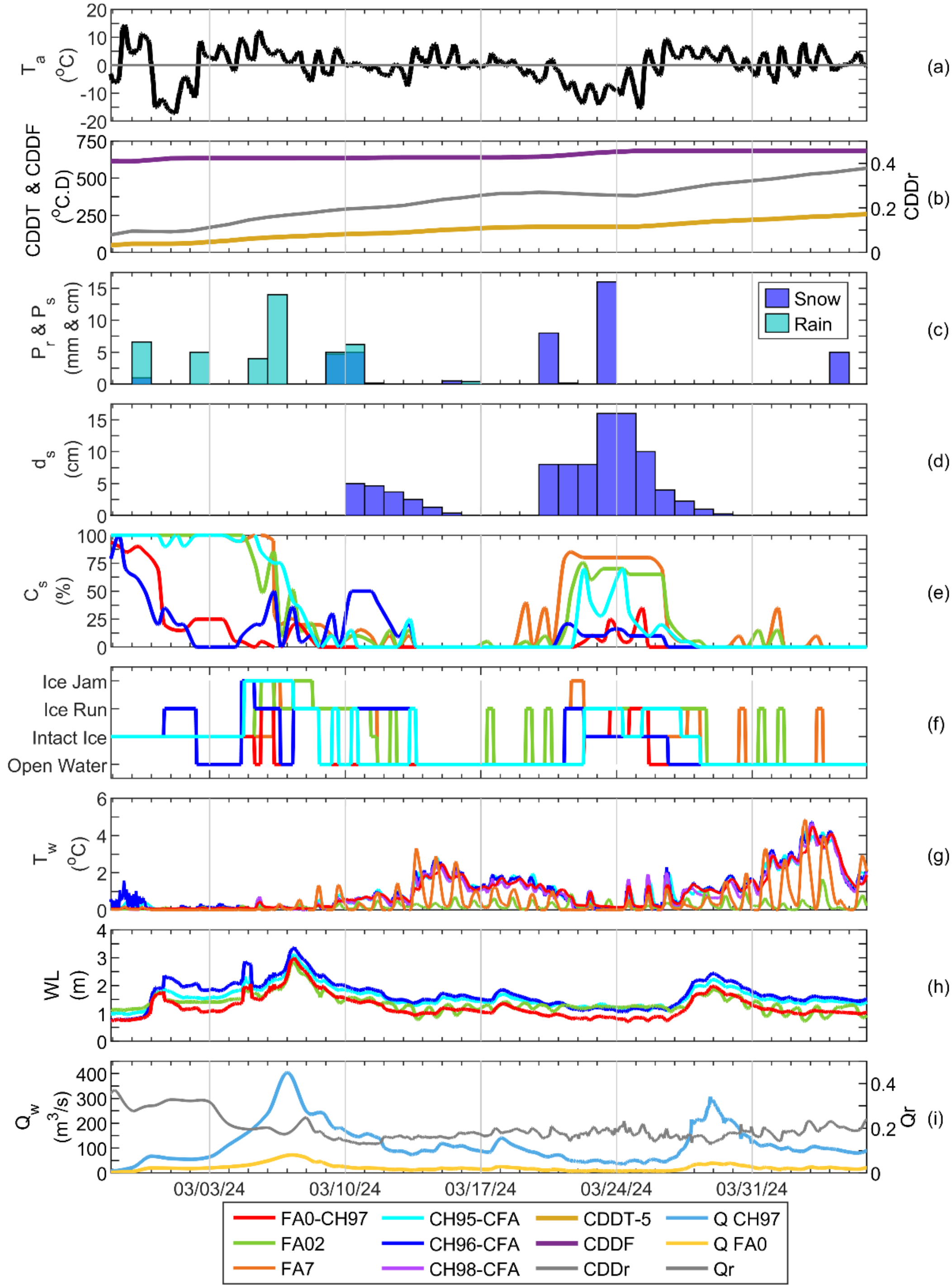


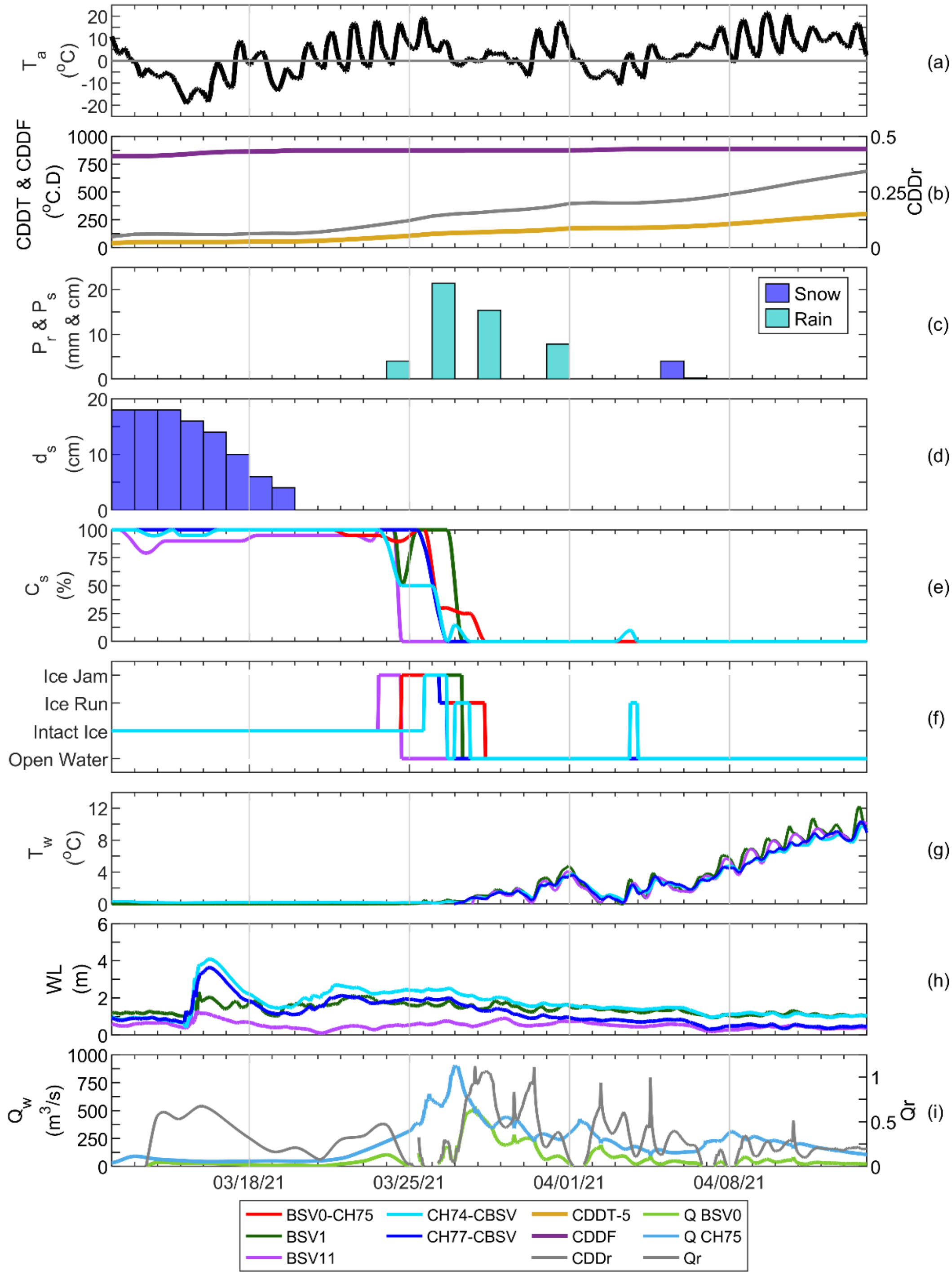
Figure S9. Time series of hydrometeorological conditions during the 2024 breakup at CH-FA (27 February to 6 April 2024) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

S4: Bras Saint-Victor and Chaudière confluence

The 2021 breakup at CH-BSV initiated simultaneously at all observation sites on both rivers on 24 March, ending at all sites by 28 March. Ice jams formed upstream and at the confluence in both rivers. The confluence geometry constricted the passage of ice from both the tributary and main river, resulting in the formation of an ice jam at the confluence. Ice jam formation and downstream propagation were controlled by morphological features.

The results of the meteorological, hydraulic and ice conditions at CH-BSV during the 2021 breakup are presented in Fig. S10. Air temperatures remained positive from 20 March onwards (Fig. S10a). Breakup started simultaneously on 24 March at all observation sites on both CH and BSV rivers (Fig. S10e). When breakup initiated, the CDDT reached 93.7 °C D while the CDDF reached 873.6 °C D, resulting in a CDDr of 0.11 (Fig. S10b). This CDDr indicate that the breakup occurred relatively early in the thermal season (Fig. S10b). The discharge increased gradually from the complete melting of the snow on the ground on 20 March (Fig. S10d). Breakup initiated when discharge reached 230.4 $m^3 s^{-1}$ in the CH and 104.1 $m^3 s^{-1}$ in the BSV, for a Qr of approximately 0.45, coinciding with 4 mm of rainfall (Fig. S10c, i). On 27 March, the season's maximum discharge was reached at 904.1 $m^3 s^{-1}$ in the CH and 491.2 $m^3 s^{-1}$ in the BSV, for a Qr of 0.54, coinciding with 21.4 mm of rainfall (Fig. S10c, i).

The breakup occurred from upstream to downstream in the tributary (Fig. S10f). An ice jam formed at the upstream tributary site (BSV11) on 23 March. This ice moved rapidly downstream to form jams near the mouth of the tributary (BSV1) and at the confluence (BSV0-CH75) on 24 March, leaving the upstream site on the BSV (BSV11) ice free. Due to the constricted ice passage at the BSV bridge located 1.1 km from the confluence and the presence of an accumulation bank immediately upstream of the bridge, the jam at the mouth of the tributary (BSV1) did not release until 27 March. The jam at the confluence (BSV0-CH75) released one day earlier on 26 March. The ice was then evacuated at the confluence (BSV0-CH75) until 28 March. The breakup in the main river also occurred from upstream to downstream. Ice jams formed at both sites upstream (CH77-CBSV) and downstream (CH74-CBSV) of the confluence on the CH by the end of the day on 25 March. The jam at the upstream main river site released a few hours before the one at the downstream main river site on 26 March. These ice runs were observed at the site downstream of the confluence (CH74-CBSV) on 27 March. This same day coincided with rising water temperatures at all sites (Fig. S10g). The thermal response lagged the mechanical breakup by 3 d, indicating that ice clearance was primarily driven by hydraulic forces rather than thermal melting. The confluence (BSV0-CH75) was the last observation site to become ice free, on 28 March, as ice accumulations on the riverbanks at the downstream site (CH74-CBSV) required additional time to evacuate.

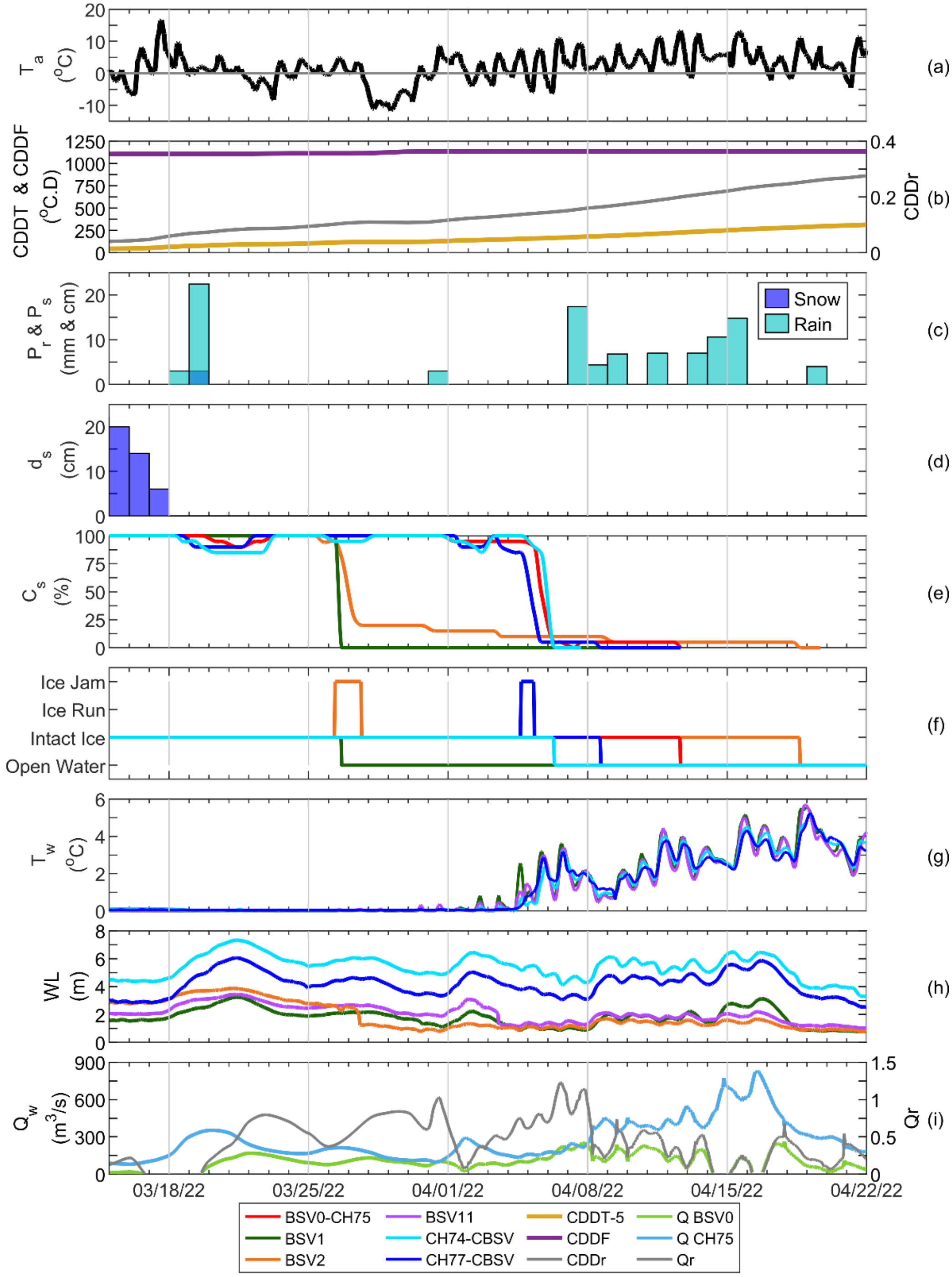


310 **Figure S10.** Time series of hydrometeorological conditions during the 2021 breakup at CH-BSV (12 March to 14 April 2021) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2022 breakup at CH-BSV initiated from downstream to upstream in both rivers, starting in the tributary on 26 March and in the main river on 4 April, ending at all sites by 12 April. Ice jams formed upstream of the confluence in both rivers but not at the confluence itself. The breakup was primarily thermal, with peak discharges occurring after ice clearance.

The results of the meteorological, hydraulic and ice conditions at CH-BSV during the 2022 breakup are presented in Fig. S11. Air temperatures fluctuated around 0 °C with multiple freeze-thaw cycles from mid-March onwards (Fig. S11a). The snow on the ground melted completely on 18 March (Fig. S11d), coinciding with 25.4 mm of rainfall on 18 and 19 March (Fig. S11c). Following this rainfall, water levels at all sites rose by up to 3 m in 3 d (Fig. S11h). Surface ice concentration at all observation sites also decreased by approximately 20 % between 19 and 23 March (Fig. S11e), but the ice cover subsequently reformed completely as air temperatures fluctuated around 0 °C (Fig. S11a). Breakup started in the tributary on 26 March and in the main river on 4 April (Fig. S11e). By the start of the breakup in the tributary, the CDDT reached 111.5 °C D, while the CDDF reached 1112.9 °C D, resulting in a CDDr of 0.10 (Fig. S11b). On that same day, discharge reached 209.7 $m^3 s^{-1}$ in the CH and 77.6 $m^3 s^{-1}$ in the BSV, for a Qr of 0.37 (Fig. S11i). At the initiation of breakup in the main river, the CDDT reached 150.9 °C D, while the CDDF reached 1135.1 °C D, resulting in a CDDr of 0.13 (Fig. S11b). By this date, discharge reached 146.4 $m^3 s^{-1}$ in the CH and 99.1 $m^3 s^{-1}$ in the BSV, resulting in a Qr of 0.68 (Fig. S11i). Discharge continued to increase until 16 April, reaching a season's maximum of 818.1 $m^3 s^{-1}$ in the CH and 226.5 $m^3 s^{-1}$ in the BSV, for a Qr of 0.28 following several consecutive rainfalls (Fig. S11c, i).

Breakup occurred from downstream to upstream in the tributary (Fig. S11f). The site at the mouth of the tributary (BSV1) became ice free on 26 March, a few hours after an ice jam had formed at the site further upstream in the tributary (BSV2). This ice jam released by the end of the day on 27 March, resulting in a sudden water level drop of more than 1 m at this site during the night of 27 to 28 March (Fig. S11f, h). Water temperatures at the most downstream site in the tributary (BSV1) began to rise a week after the site was ice free, on 2 April (Fig. S11f, g). On 3 April, the ice cover likely disappeared at the upstream site in the tributary (BSV11), based on the rising water temperatures and the sudden drop in water level that day (Fig. S11g, h). Breakup also occurred from downstream to upstream in the main river (Fig. S11f). At the upstream confluence site on the CH (CH77-CBSV), an ice jam formed on 4 April and released on 5 April. However, an ice cover remained due to chunks of ice from this jam until 8 April. As for the site downstream of the confluence (CH74-CBSV), the ice cover disappeared following the ice jam on 6 April. No ice jams formed directly at the confluence (BSV0-CH75) in 2022. The site became ice free on 12 April. However, the ice likely retreated simultaneously at the confluence (BSV0-CH75) and downstream (CH74-CBSV) on 6 April, given the low surface concentration remaining from that date (Fig. S11e, f).

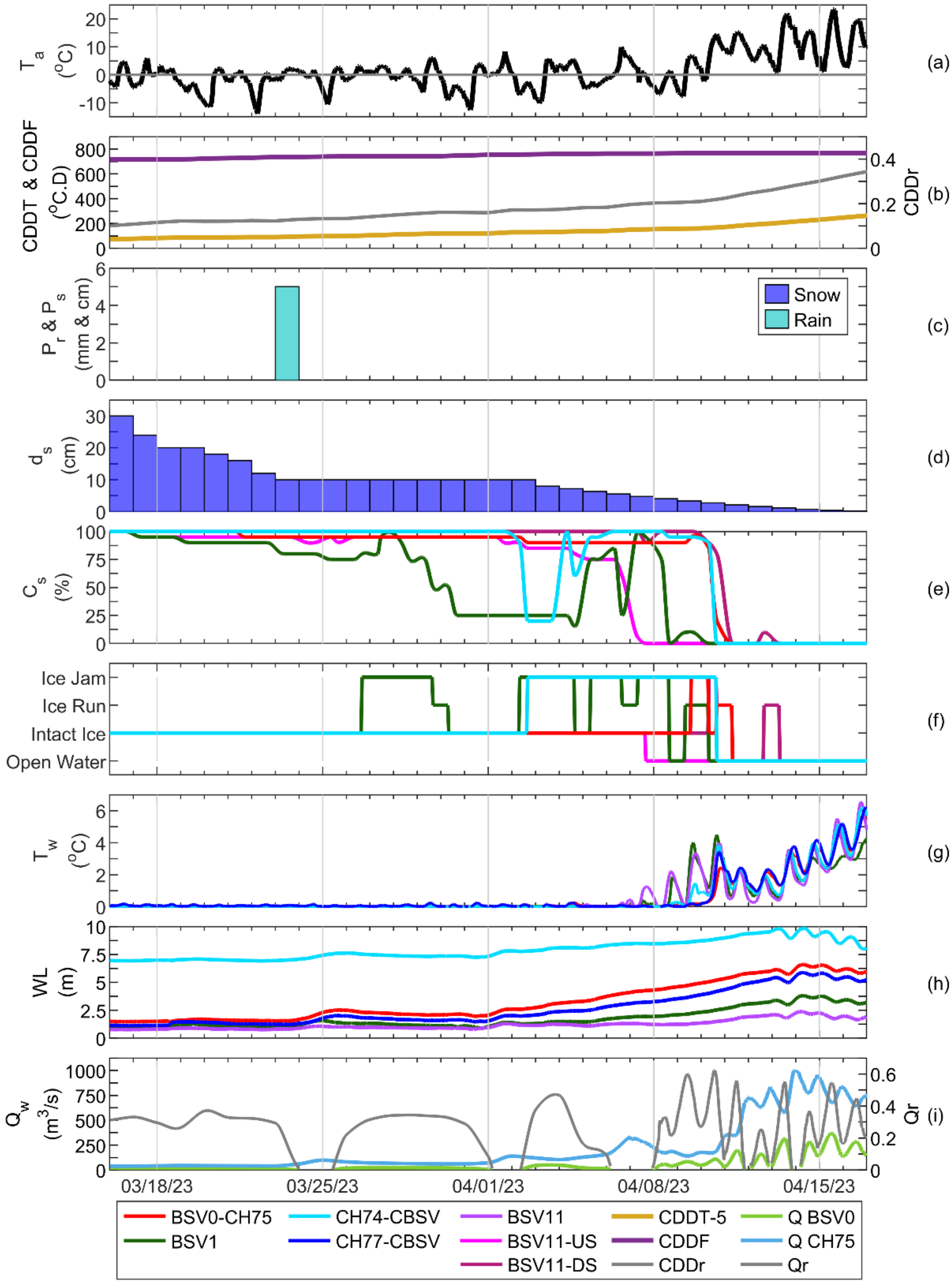


345 **Figure S11.** Time series of hydrometeorological conditions during the 2022 breakup at CH-BSV (15 March to 22 April 2022) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.

The 2023 breakup at CH-BSV initiated at all sites around 2 April, except at the mouth of the tributary (BSV1) which began on 27 March, ending at all sites by 13 April. Ice jams formed downstream of the confluence, at the mouth of the tributary, and at the confluence itself. The tributary lost its ice cover first, resulting in the formation of ice jams at its mouth due to constricted hydraulic passage. Subsequently, the main river lost its ice cover simultaneously at all sites, creating jams near the confluence and contributing to ice jam accumulation at the confluence.

The results of the meteorological, hydraulic and ice conditions at CH-BSV during the 2023 breakup are presented in Fig. S12. Air temperatures showed prolonged periods below freezing throughout March, with sustained positive temperatures only occurring after 9 April (Fig. S12a). At the start of the breakup, the CDDT reached 129.6 °C D while the CDDF reached 753.7 °C D, resulting in a CDDr of 0.17 (Fig. S12b). This CDDr indicate that the breakup occurred relatively late in the thermal season compared to previous years of observation at this confluence (Fig. S12b). By this date, discharge reached 139.7 $m^3 s^{-1}$ in the CH and 43.1 $m^3 s^{-1}$ in the BSV, for a Qr of 0.31 (Fig. S12i). Snow on the ground also melted gradually to completely disappear on 16 April (Fig. S12d). A rainfall of 5 mm occurred on 23 March, resulting in a water level rise at all sites on 24 March (Fig. S12c, h). Discharge continued to increase since breakup initiation, reaching the season's maximum on 13 April at 996.5 $m^3 s^{-1}$ in the CH and 279.4 $m^3 s^{-1}$ in the BSV, for a Qr of 0.28 (Fig. S12i).

Breakup occurred from upstream to downstream in the tributary (Fig. S12f). An ice jam formed at the tributary mouth site (BSV1) on 26 March. This jam remained in place until 29 March, before being evacuated during the night of 29 to 30 March. A second ice jam at this location formed on 2 April. A few hours later, on 2 April, an ice jam also formed at the site just downstream of the confluence (CH74-CBSV), remaining in place until 10 April. The site at the mouth of the tributary (BSV1) experienced several ice jams, given the presence of many islands that constrict ice evacuation at this location. The jam at this site remained in place until the night of 4 to 5 April, before reforming into another jam on 5 April. This last jam remained in place until 8 April, except for a few ice releases on the night of 6 to 7 April. Further ice runs were also released between 9 and 10 April. With this release, an ice jam formed at the confluence (BSV0-CH75) from 9 to 10 April, before releasing on 11 April. An ice jam at the tributary's upstream observation site with a view downstream (BSV11-DS) formed on 10 April and released with ice runs on 11 April, at the same time as the confluence (BSV0-CH75). This is the only site that does not follow the upstream-downstream breakup sequence, as even the upstream tributary observation site with a view upstream (BSV11-US) was ice free first, on 7 April. Breakup in the main river occurred simultaneously at all sites as the site upstream of the confluence (CH77-CBSV) was likely ice free on the same day as the site downstream of the confluence (CH74-CBSV) on 10 April with the rising water temperatures (Fig. S12g). Finally, some ice runs likely remaining on the banks passed at the site upstream of the tributary looking downstream (BSV11-DS) on 13 April. On that same day, water levels rose rapidly (Fig. S12h).



380 **Figure S12.** Time series of hydrometeorological conditions during the 2023 breakup at CH-BSV (16 March to 17 April 2023) showing **(a)** air temperature, **(b)** CDDT, CDDF and CDDr, **(c)** daily precipitation, **(d)** snow on ground, **(e)** surface ice concentration, **(f)** ice states, **(g)** water temperature, **(h)** water level above the pressure probe and **(i)** discharge and Qr.