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 April 15 and 18. 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 March 30 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 March 30. 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 April 2nd, 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 April 8 to 9 (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 April 14, 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 April 16 at 67.1 $m^3 s^{-1}$ (Fig. S1i).

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

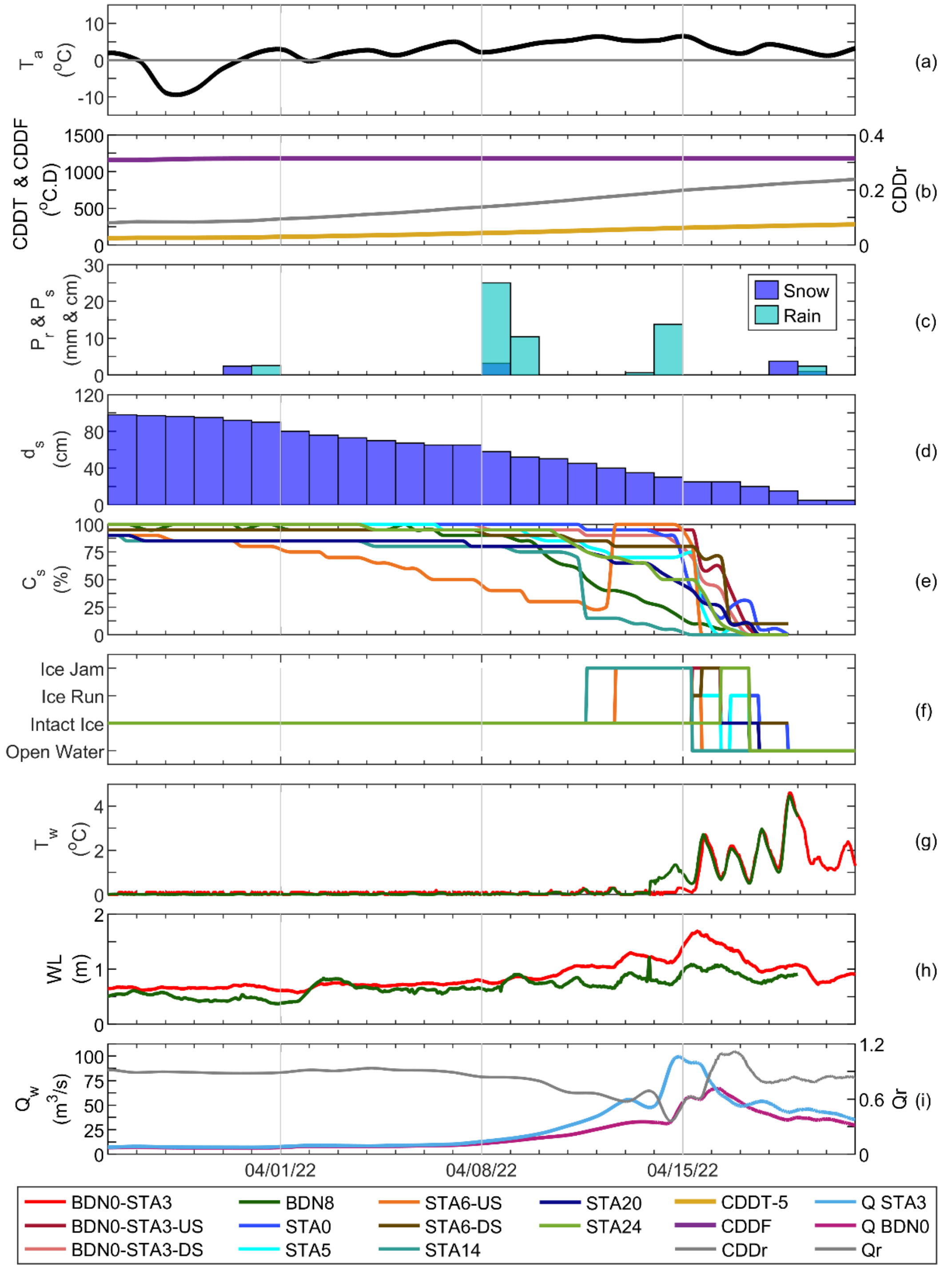
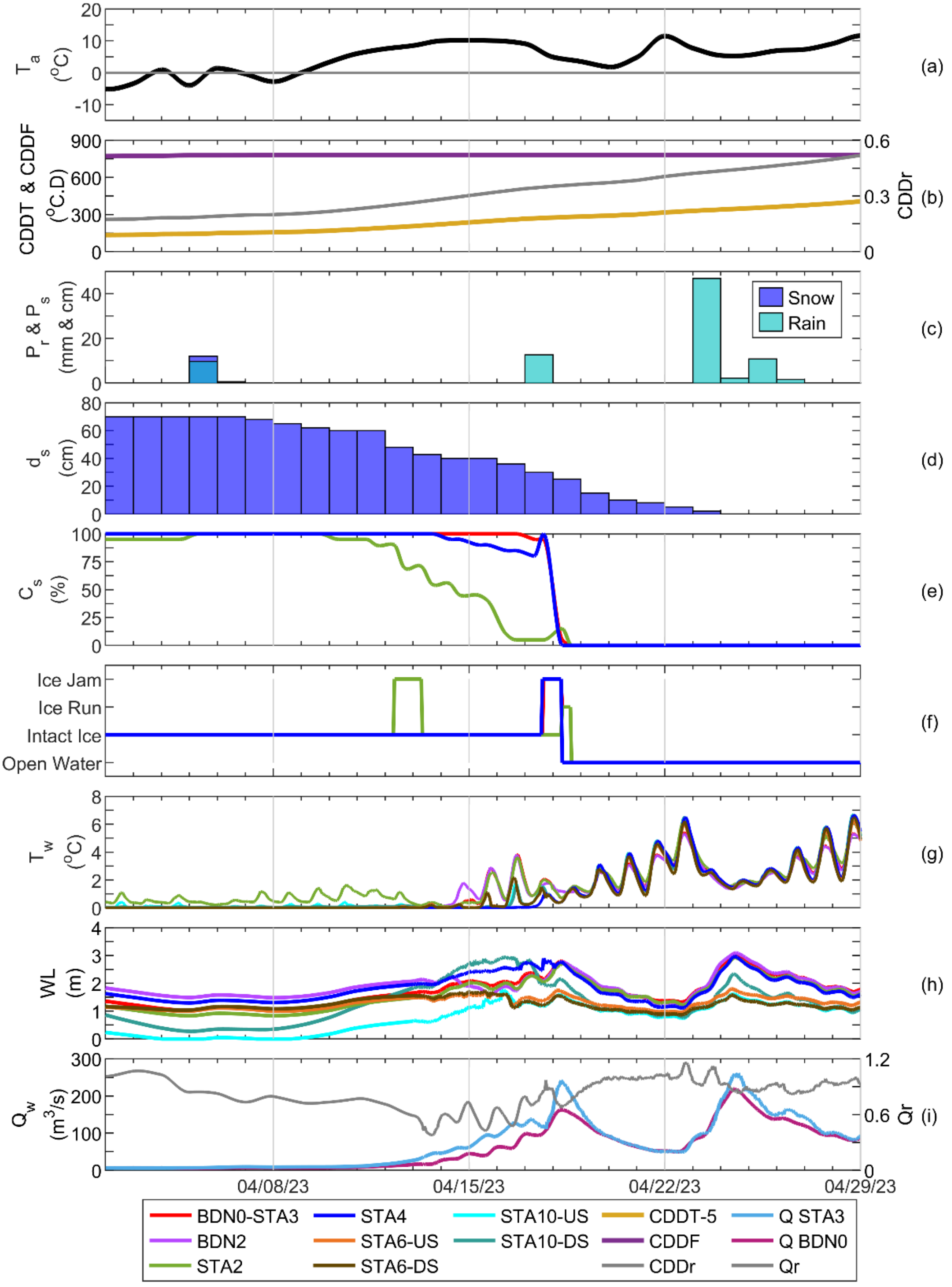


Figure S1: Time series of hydrometeorological conditions during the 2022 breakup at STA-BDN (March 26 to April 21, 2022) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above 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 April 18. 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 April 11. 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 April 14. 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 April 14 (Fig. S2g, h). Breakup at the confluence occurred on April 18. 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 April 24, 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 two days (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 April 23 (Fig. S2c, d).

As breakup began in the STA downstream of the confluence (STA2), an ice jam formed between April 12 and 13 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 April 16 (Fig. S2g, h). On April 17, 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 April 18, explaining the ice runs observed downstream of the confluence (STA2) before all sites were ice free.



60 **Figure S2: Time series of hydrometeorological conditions during the 2023 breakup at STA-BDN (April 2 to April 29, 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 April 12. 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 March 19 to 25, 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 March 27, 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 April 3rd. 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 April 12, when the snow on the ground had melted completely and rainfalls of 18 mm and 12 mm fell on April 11 and 12, respectively (Fig. S3c, d). The season's maximum discharge was observed on April 13 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 two days (Fig. S3h).

A brief ice jam formed upstream of the ice control structure on the STA (STA6-US) on March 30, before releasing in the form of ice runs until April 3rd. Ice runs also reached the site downstream of the confluence (STA2) from March 30 to April 2nd. With water temperatures rising at the site directly upstream of the confluence in the STA (STA4) from March 30, 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 April 2nd and 3rd. This jam released in the form of ice runs until April 5. All sites were ice free on April 12.

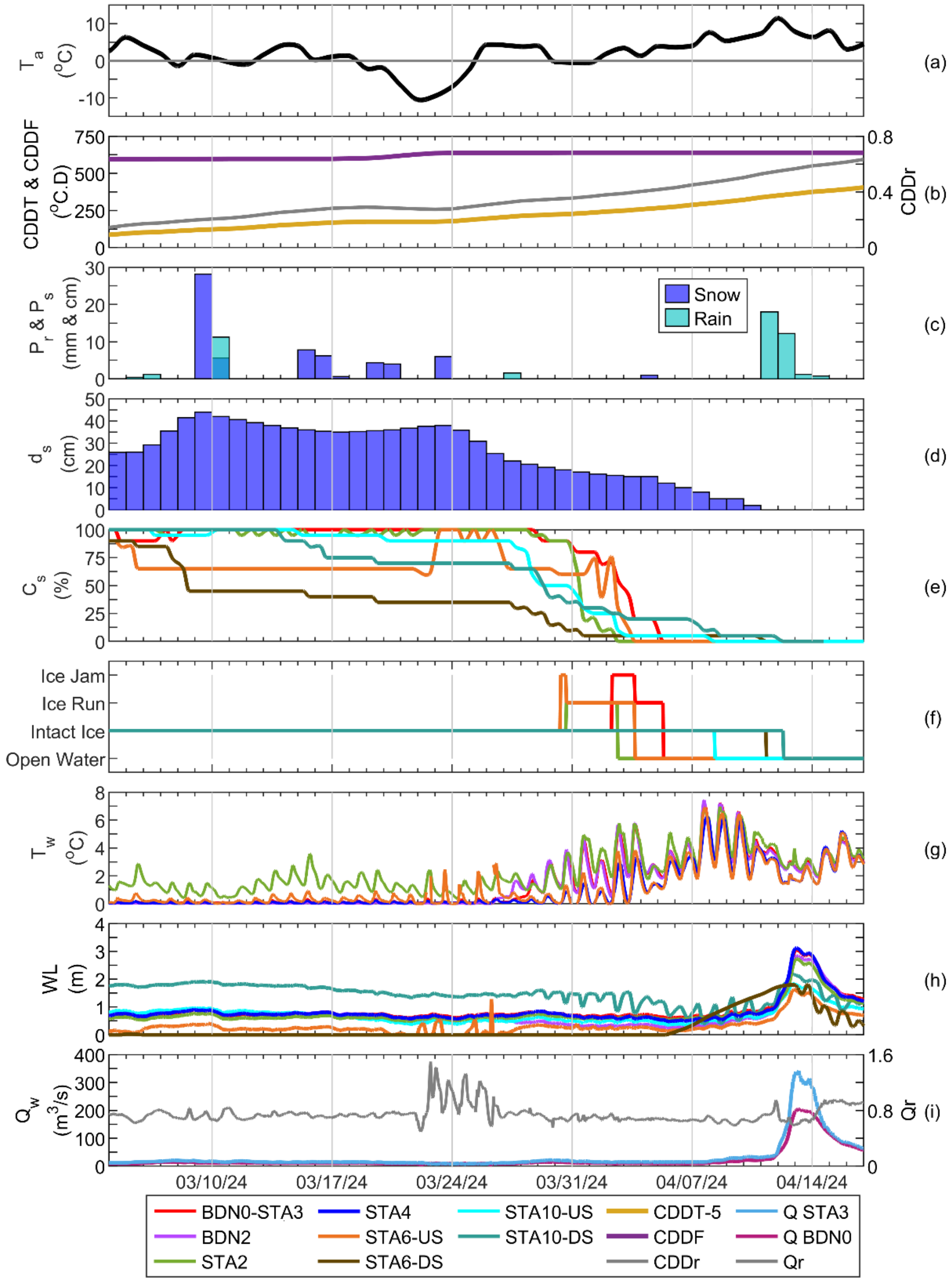


Figure S3: Time series of hydrometeorological conditions during the 2024 breakup at STA-BDN (March 4 to April 17, 2024) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above 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 April 12. 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 March 20 onwards, at the same time as the snow on the ground completely melted (Fig. S4a, d). A few days earlier, on March 16, 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 March 12, 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 March 23, 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 March 25 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 April 1st, becoming ice free on April 12.

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 March 26 to 27. 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 March 23 and is also evident in the rise in water level in the tributary (DL04) from March 19 (Fig. S4h). With rising water temperatures at this site from March 28 onwards, the tributary was likely ice free from that date (Fig. S4g).

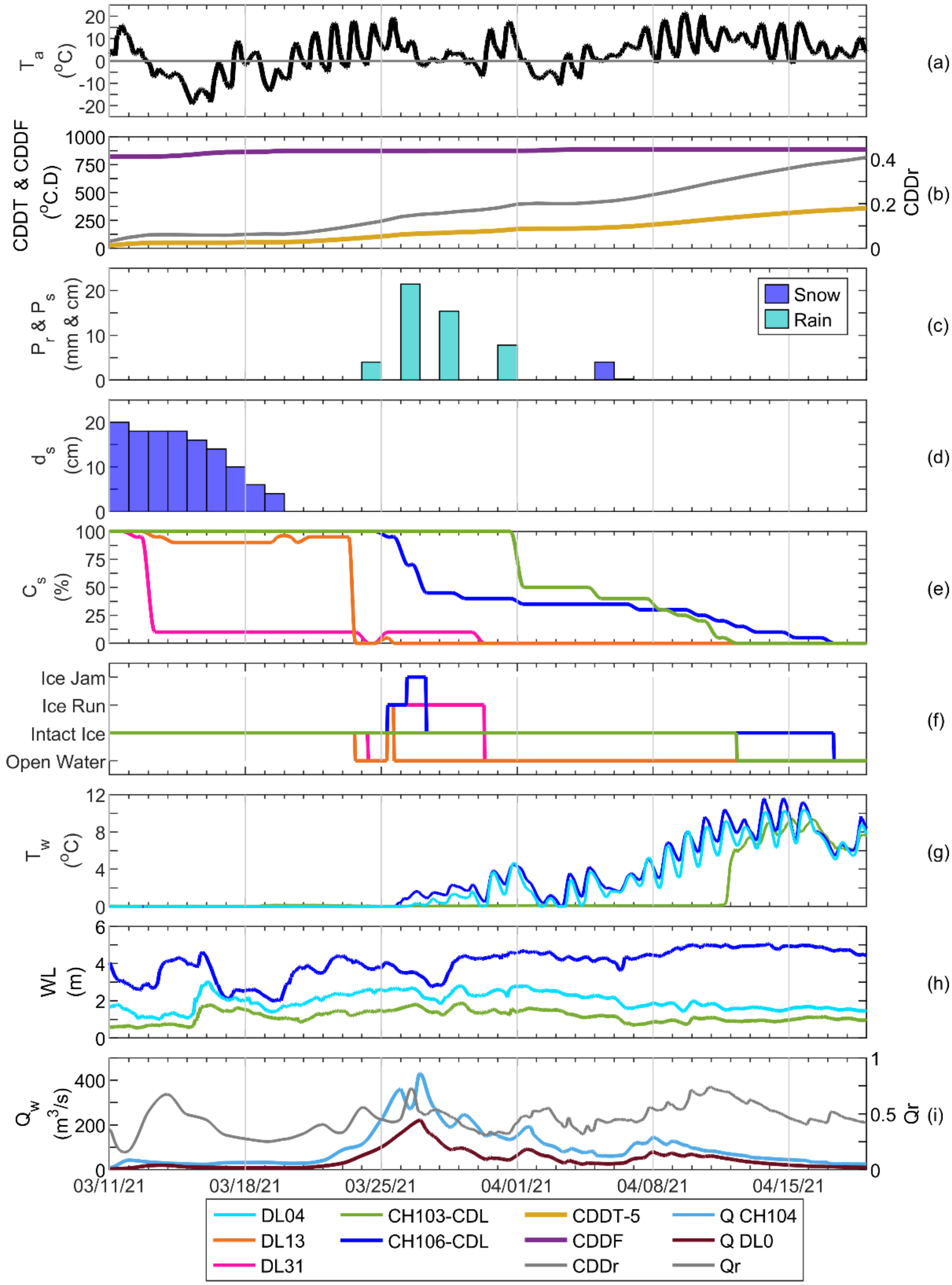
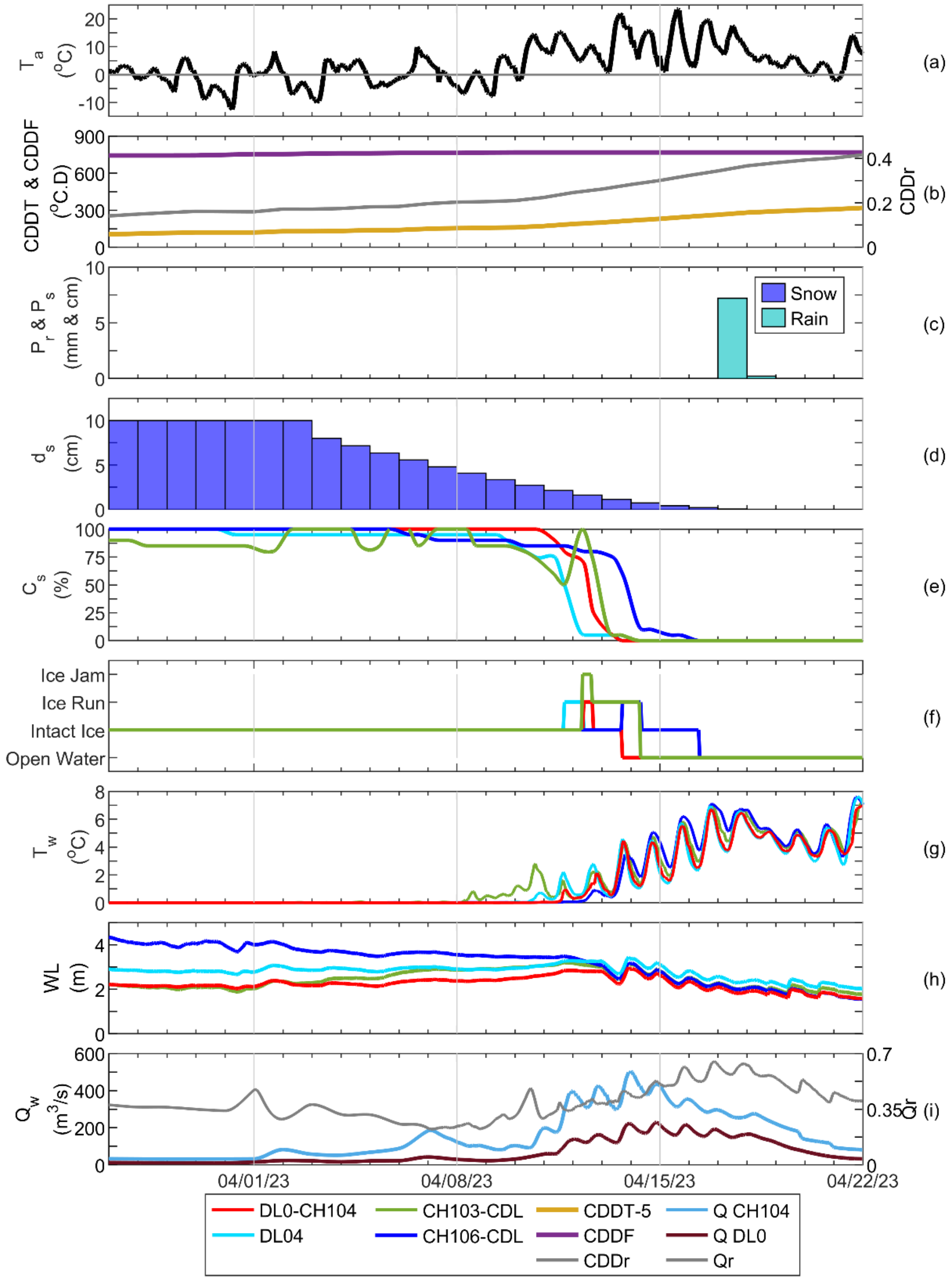


Figure S4: Time series of hydrometeorological conditions during the 2021 breakup at CH-DL (March 11 to April 19, 2021) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above 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 April 17. 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 April 10 onwards (Fig. S5a). On April 11, 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 April 12, 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 April 13. 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 April 14 (Fig. S5i). On April 17, 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 April 12 (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 (March 27 to April 22, 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 April 10. 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 March 8. This date followed the season's maximum discharge on March 7 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 March 5 and 6 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 March 13 to 21, the tributary was likely ice free during this period (Fig. S6g). Following colder air temperatures reaching -15°C between March 21 and 25, 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 March 29 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 March 4 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 March 6 and 7, before releasing in the form of ice runs on March 8. 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 March 22 to 24. 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 March 23 to 27 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 April 10, a few hours before the confluence (DL0-CH104) (Fig. S6f).

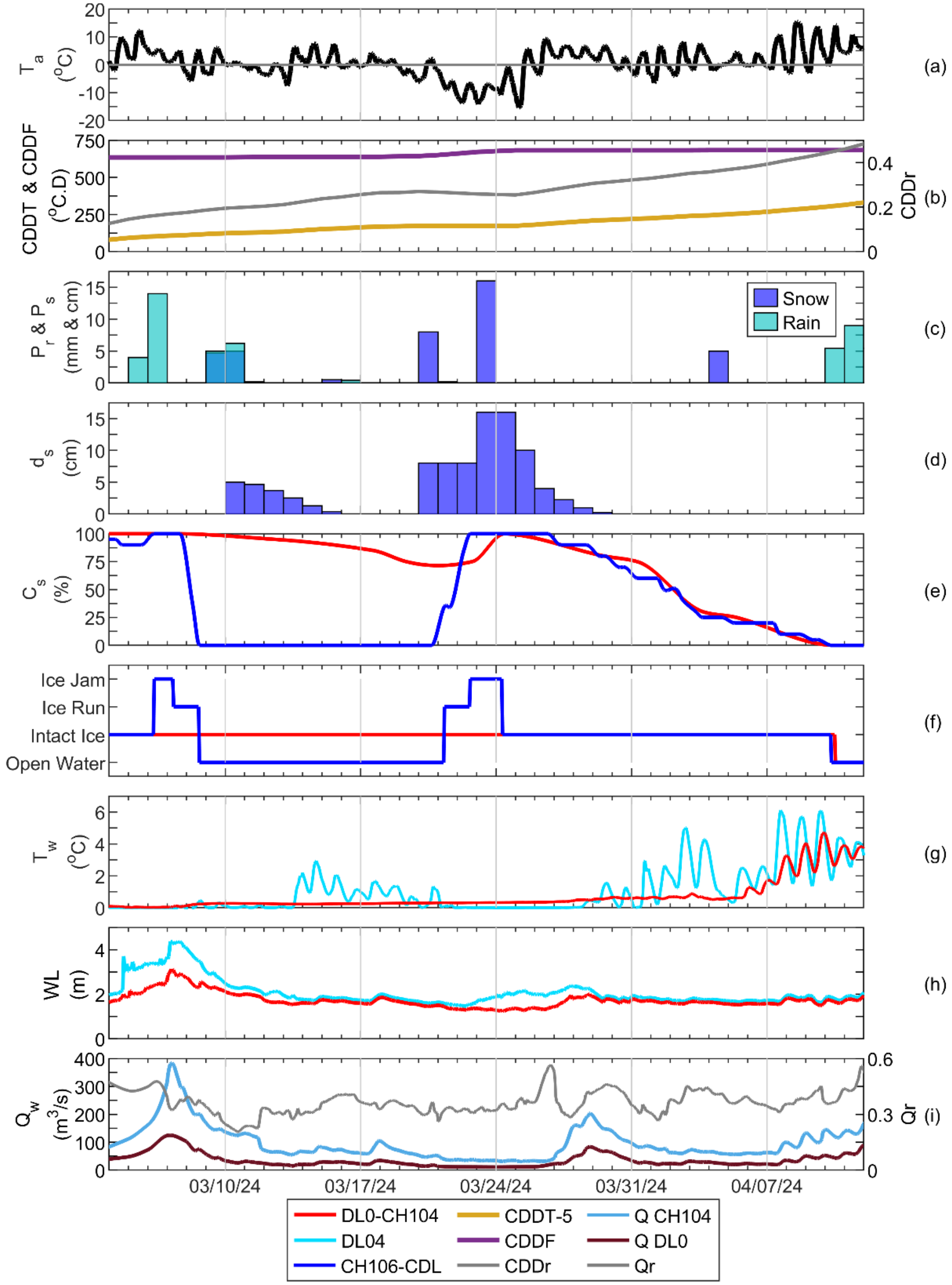


Figure S6: Time series of hydrometeorological conditions during the 2024 breakup at CH-DL (March 11 to April 10, 2024) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above 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 March 29. 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 March 20 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 March 13, the breakup started in the CH on March 23 and on March 25 in the FA (Fig. S7e). This sequence was triggered on March 24 by 4 mm of rainfall, as well as a few days after the complete melting of snow on the ground on March 20 (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 March 27, 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 March 14, 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 March 15 (Fig. S7h). The ice jam released on March 27. 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 March 23, while an ice jam formed at the upstream site on the CH a few hours later, before releasing on March 26. 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 March 25 and 26 within a few hours of each other. The most upstream observation site on the tributary (FA7) became ice free on March 29 due to the presence of a pronounced meander in the river at this point.

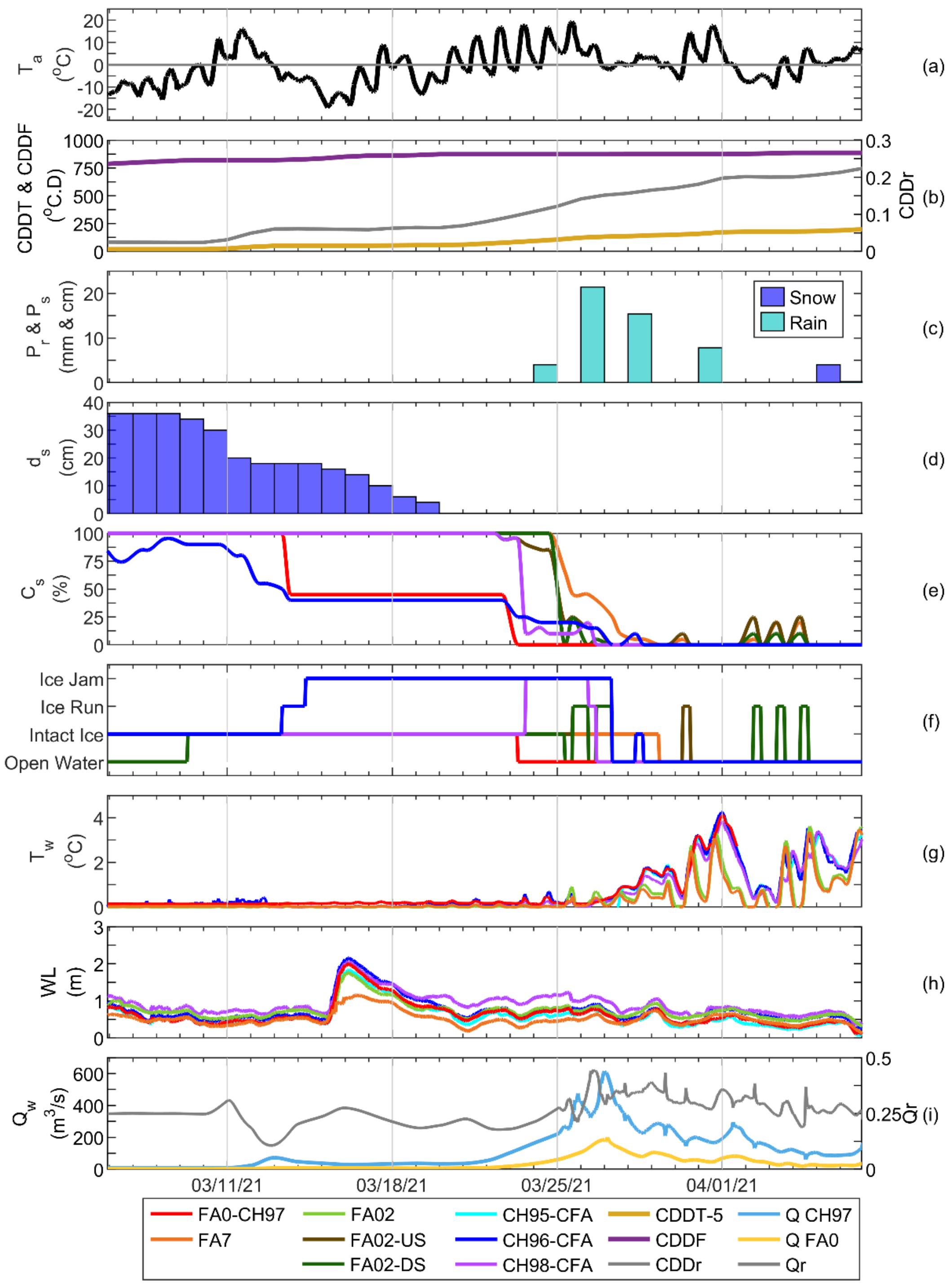
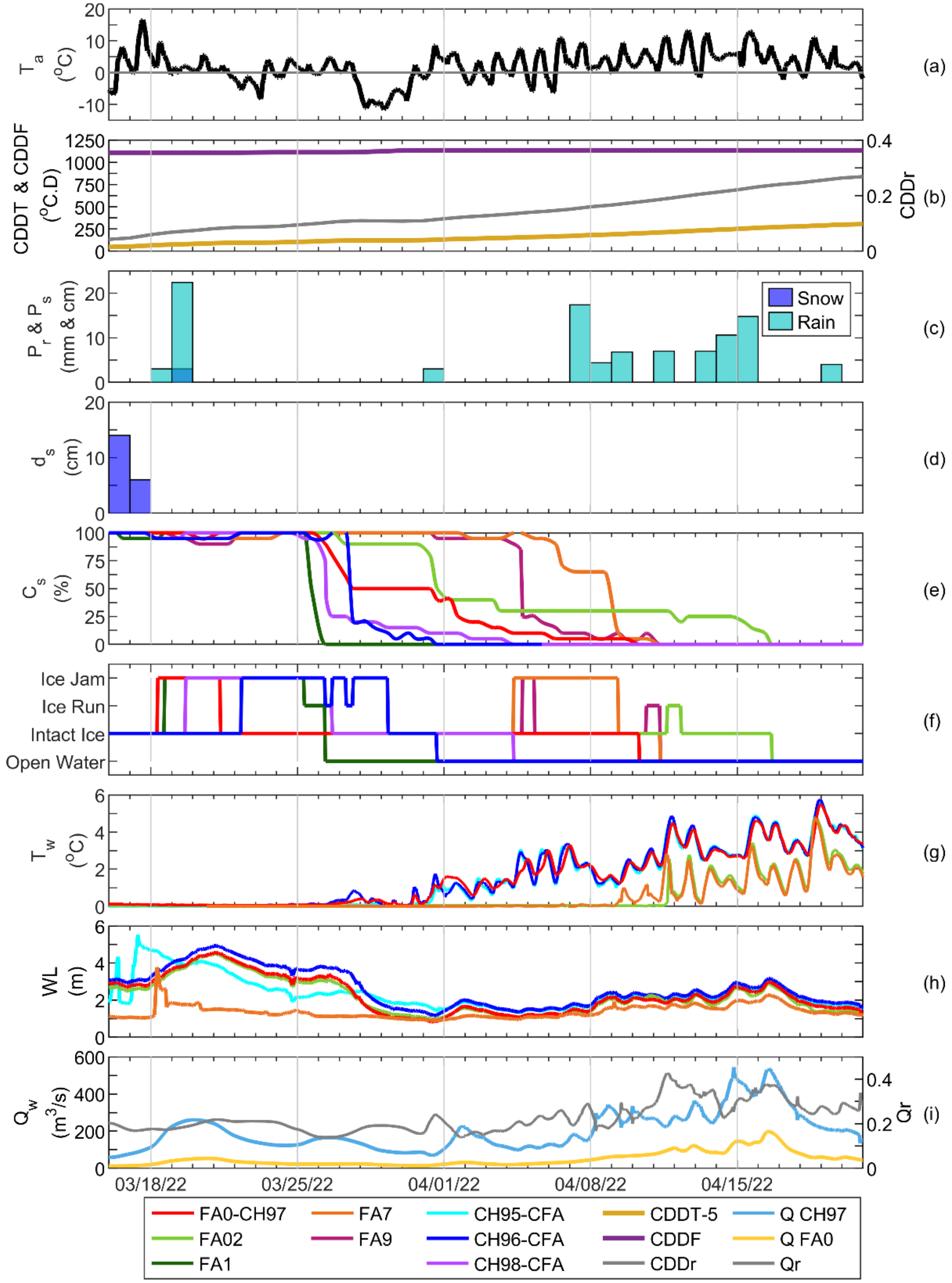


Figure S7: Time series of hydrometeorological conditions during the 2021 breakup at CH-FA (March 6 to April 7, 2021) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above the 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 April 16. 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 March 25 (Fig. S8e). This separation of the breakup is particularly evident in the two sequences of rising water temperatures starting first from the CH around March 31, then from the FA around April 9 (Fig. S8g). At the initiation of the CH and the confluence breakup, on March 26, 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 March 31, 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 April 16 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 March 18 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 March 19, upstream on the CH (CH98-CFA). These ice jams coincided with 25 mm of rainfall on March 18 and 19, 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 March 21, forming a new jam downstream on the CH (CH96-CFA) on March 22. The two jams upstream of the confluence on the CH and FA (CH98-CFA and FA1) released simultaneously on March 25 and 26. The site upstream of the tributary mouth (FA1) was ice free on March 26, but the site upstream on the CH (CH98-CFA) reformed a temporary ice cover due to colder air temperatures between March 27 and 31, and was not ice free until April 4 (Fig. S8a, f). The ice jam downstream of the confluence (CH96-CFA) had a few releases in the form of ice runs on March 26 and 27 before releasing completely on March 29, forming a temporary ice cover until March 31. For the breakup sequence on the tributary, an ice jam formed upstream in the tributary (FA7), on April 4, and remained in place until April 9. A brief ice jam also formed at the site further upstream (FA9) during the night of April 4 to 5, 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 April 11. These ice runs reached the mouth of the tributary (FA02) the next day, which became ice free on April 16, 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 (March 16 to April 21, 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 March 28. 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 February 29 and March 2, and -15°C between March 21 and 25 (Fig. S9a). This second colder period coincided with a 16 cm snowfall on March 23 (Fig. S9c). Breakup started at the site downstream of the confluence (CH96-CFA) on February 27, 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 February 27. By this date, the CDDT reached 58.9°C.D. while the CDDF reached 622.3°CD, 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 March 6. A total of 18 mm of rainfall on March 5 and 6 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 March 7, 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 March 28 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 February 29 to March 2nd. 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 March 4 to 5, which released in the form of ice runs until March 6. An ice jam at a site even further downstream (CH95-CFA) formed on the same day, March 4, but a few hours later, and remained in place until March 7 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 March 9 indicated that this site was ice free by that date (Fig. S9g). Another ice jam formed at the mouth of the tributary (FA02) on March 5 and released in ice runs on March 6, 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 March 7, 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.

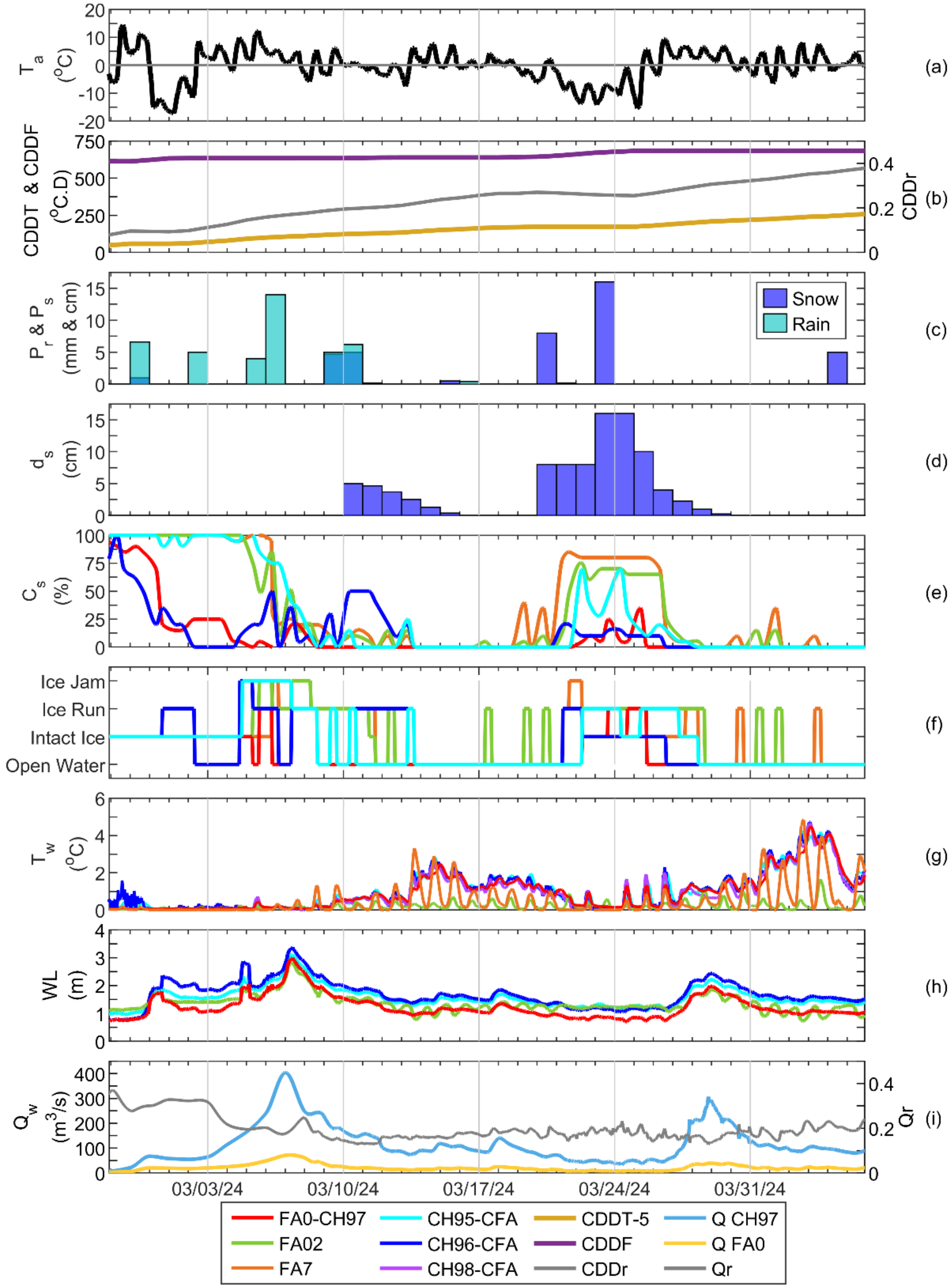


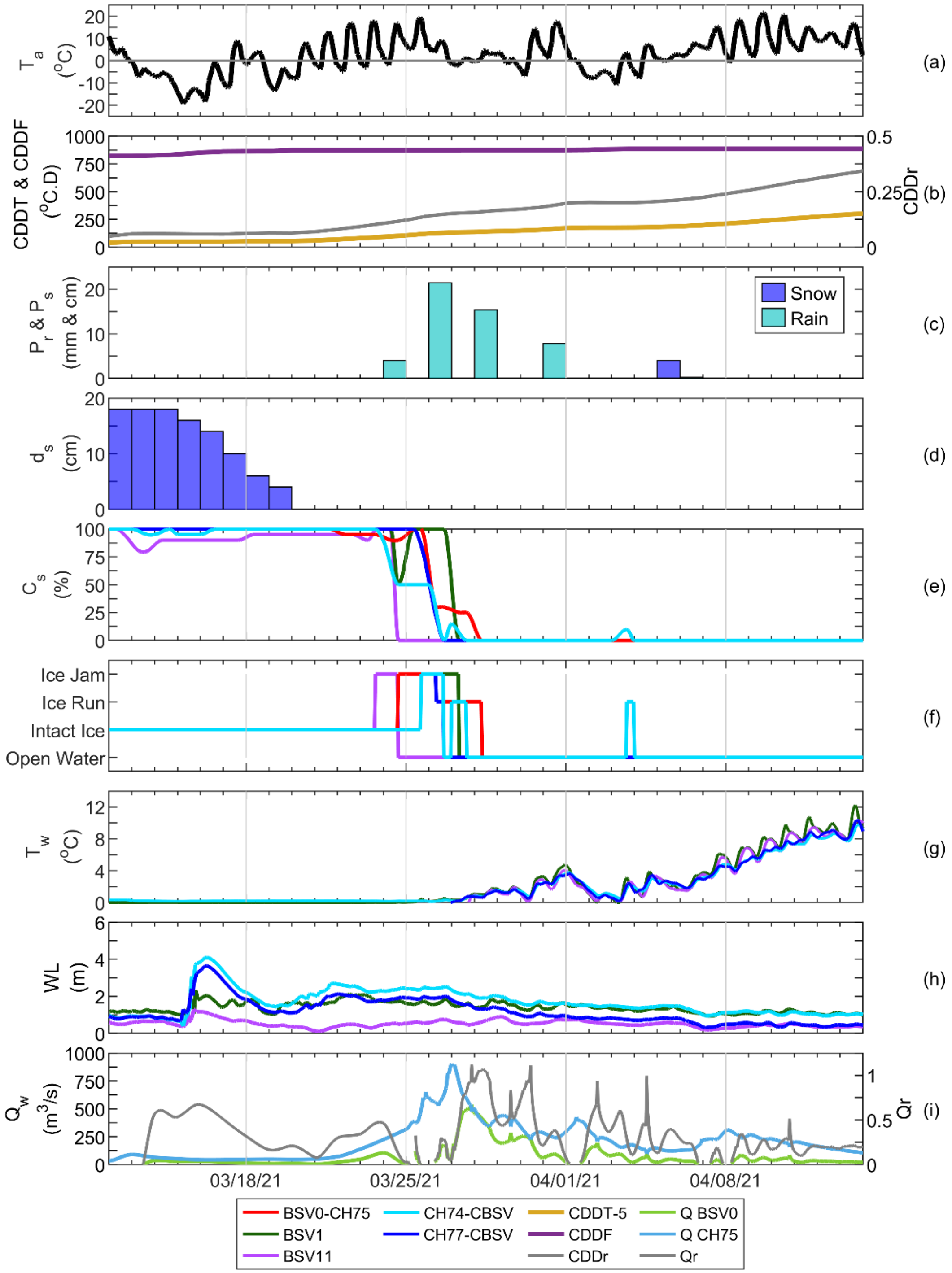
Figure S9: Time series of hydrometeorological conditions during the 2024 breakup at CH-FA (February 27 to April 6, 2024) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level above 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 March 24, ending at all sites by March 28. 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 March 20 onwards (Fig. S10a). Breakup started simultaneously on March 24 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 March 20 (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 March 27, 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 March 23. This ice moved rapidly downstream to form jams near the mouth of the tributary (BSV1) and at the confluence (BSV0-CH75) on March 24, 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 March 27. The jam at the confluence (BSV0-CH75) released one day earlier on March 26. The ice was then evacuated at the confluence (BSV0-CH75) until March 28. 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 March 25. The jam at the upstream main river site released a few hours before the one at the downstream main river site on March 26. These ice runs were observed at the site downstream of the confluence (CH74-CBSV) on March 27. This same day coincided with rising water temperatures at all sites (Fig. S10g). The thermal response lagged the mechanical breakup by 3 days, 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 March 28, as ice accumulations on the riverbanks at the downstream site (CH74-CBSV) required additional time to evacuate.

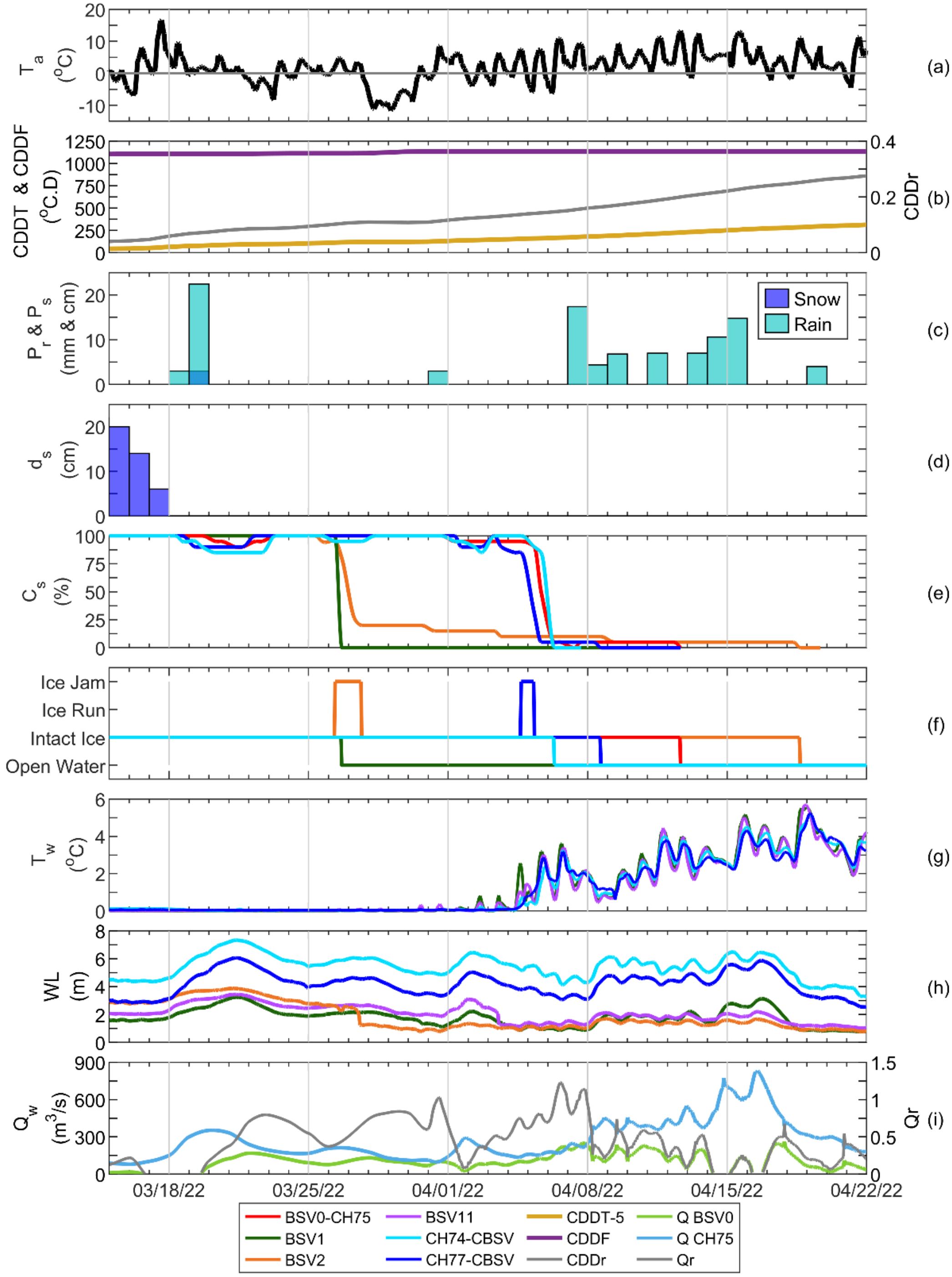


310 **Figure S10: Time series of hydrometeorological conditions during the 2021 breakup at CH-BSV (March 12 to April 14, 2021) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level 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 March 26 and in the main river on April 4, ending at all sites by April 12. 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 March 18 (Fig. S11d), coinciding with 25.4 mm of rainfall on March 18 and 19 (Fig. S11c). Following this rainfall, water levels at all sites rose by up to 3 m in 3 days (Fig. S11h). Surface ice concentration at all observation sites also decreased by approximately 20 % between March 19 and March 23 (Fig. S11e), but the ice cover subsequently reformed completely as air temperatures fluctuated around 0°C (Fig. S11a). Breakup started in the tributary on March 26 and in the main river on April 4 (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 April 16, 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 March 26, 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 March 27, resulting in a sudden water level drop of more than 1 m at this site during the night of March 27 to 28 (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 April 2nd (Fig. S11f, g). On April 3, 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 April 4 and released on April 5. However, an ice cover remained due to chunks of ice from this jam until April 8. As for the site downstream of the confluence (CH74-CBSV), the ice cover disappeared following the ice jam on April 6. No ice jams formed directly at the confluence (BSV0-CH75) in 2022. The site became ice free on April 12. However, the ice likely retreated simultaneously at the confluence (BSV0-CH75) and downstream (CH74-CBSV) on April 6, given the low surface concentration remaining from that date (Fig. S11e, f).

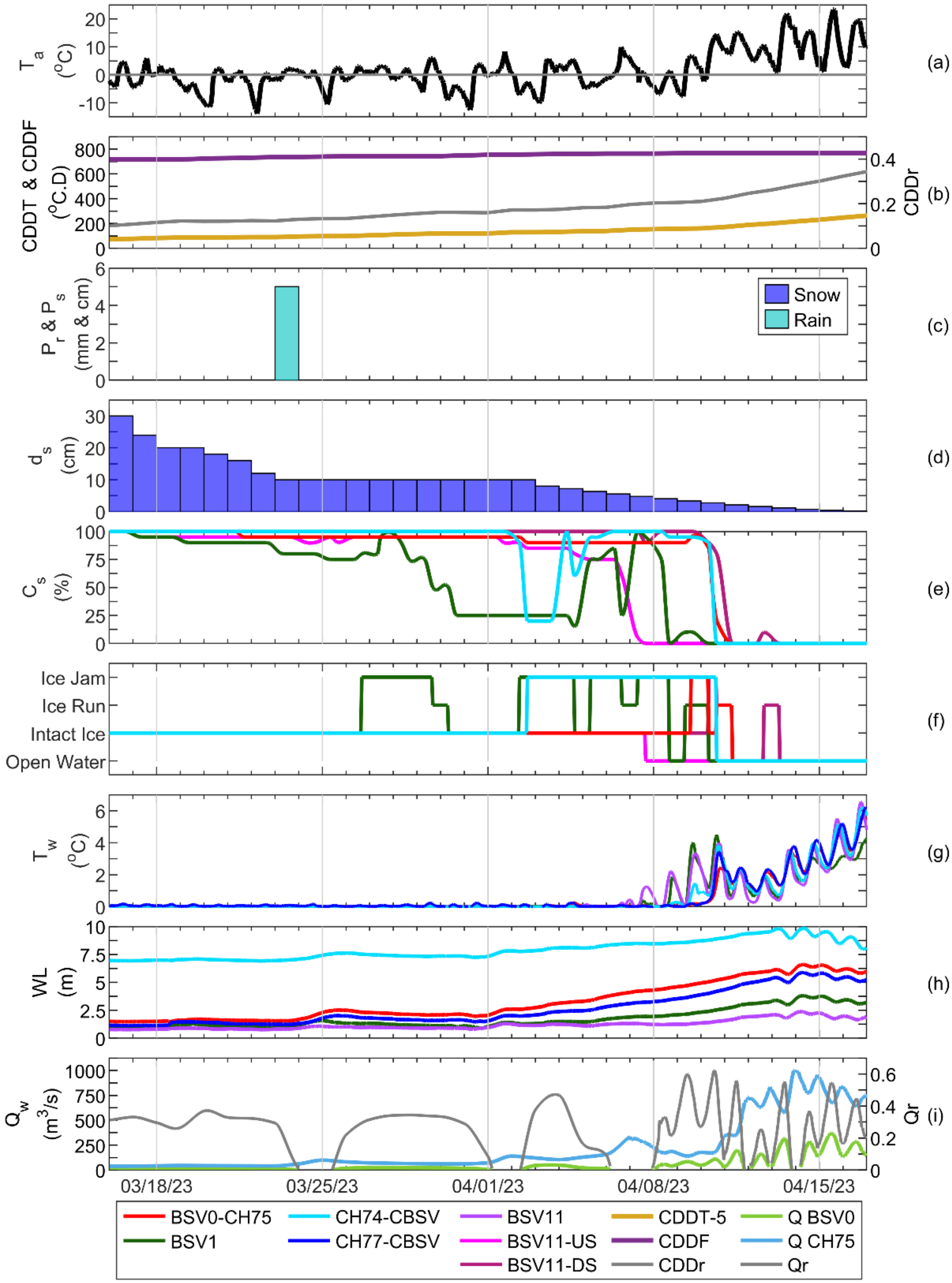


345 **Figure S11: Time series of hydrometeorological conditions during the 2022 breakup at CH-BSV (March 15 to April 22, 2022) showing a) air temperature, b) CDDT, CDDF and CDDr, c) daily precipitation, d) snow on ground, e) surface ice concentration, f) ice states, g) water temperature, h) water level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

The 2023 breakup at CH-BSV initiated at all sites around April 2nd, except at the mouth of the tributary (BSV1) which began on March 27, ending at all sites by April 13. 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 April 9 (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 April 16 (Fig. S12d). A rainfall of 5 mm occurred on March 23, resulting in a water level rise at all sites on March 24 (Fig. S12c, h). Discharge continued to increase since breakup initiation, reaching the season's maximum on April 13 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 March 26. This jam remained in place until March 29, before being evacuated during the night of March 29 to 30. A second ice jam at this location formed on April 2nd. A few hours later, on April 2nd, an ice jam also formed at the site just downstream of the confluence (CH74-CBSV), remaining in place until April 10. 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 April 4 to 5, before reforming into another jam on April 5. This last jam remained in place until April 8, except for a few ice releases on the night of April 6 to 7. Further ice runs were also released between April 9 and 10. With this release, an ice jam formed at the confluence (BSV0-CH75) from April 9 to 10, before releasing on April 11. An ice jam at the tributary's upstream observation site with a view downstream (BSV11-DS) formed on April 10 and released with ice runs on April 11, 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 April 7. 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 April 10 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 April 13. 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 (March 16 to April 17, 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.**