Characterizing the response of Arctic streams and rivers to permafrost thaw

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Introduction

Contemporary climate change is driving the widespread degradation of permafrost across the circumpolar Arctic. This is impacting the water quality of freshwater systems, as permafrost is rich in organic and mineral material (Fouche et al., 2020). Furthermore, climate change and permafrost thaw is altering the hydrological processes that control the delivery of terrestrial material to and through aquatic networks (i.e., the frequency of extreme rainfall events, the timing and intensity of spring snowmelt, and lateral flow pathways) (Bintanja et al., 2018, Vonk et al., 2015; Chiasson-Poirier, et al., 2020; Smith et al., 2005). The water quality response of Arctic streams and rivers to climate variability and permafrost thaw is highly variable, depending on terrain features (e.g., organic material, surficial geology, relief), permafrost conditions (e.g., nature and magnitude of thermokarst), and hydroclimatic controls (e.g., summer rainfall, spring freshet, water residence time, hydrologic connectivity) (Vonk et al., 2019; Tank et al., 2020). A number of studies have established that permafrost thaw is a potential source of organic and mineral material to downstream aquatic systems (Shakil et al., 2020; Tank et al., 2020; Kokelj et al., 2021). There is still uncertainty, however, in how the water quality impacts of permafrost thaw vary spatially (in response to changes in permafrost and terrain conditions) and temporally (in response to seasonal variability in precipitation, thaw, and flow pathways).

Purpose:

The purpose of this study is to investigate the factors controlling the response of water quality to permafrost thaw in three neighbouring catchments with contrasting terrain and permafrost conditions.

Broad Objectives:

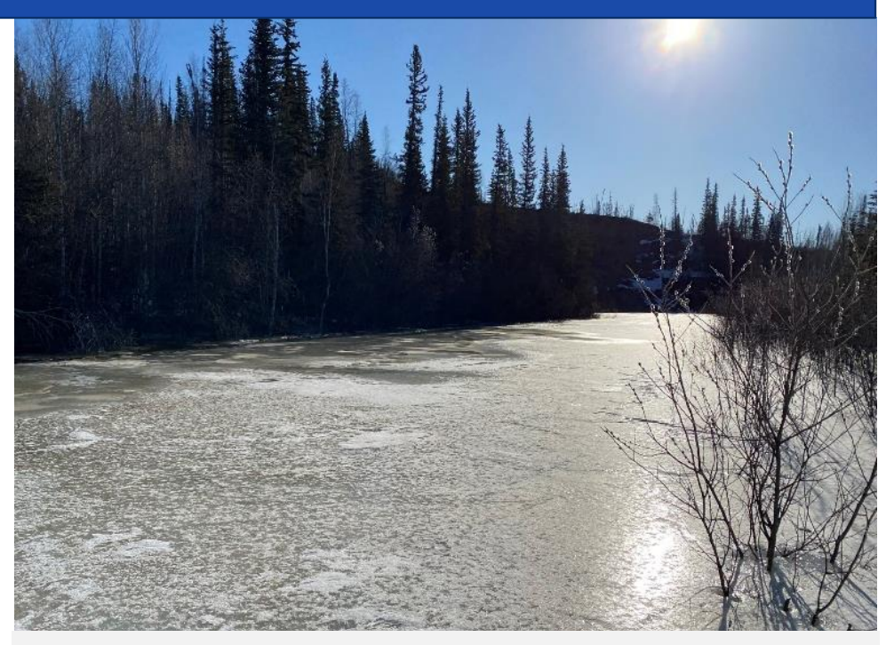
1. Investigate the cumulative effects of organic-rich peatland tributary streams and mass wasting on the chemistry of the Miner River, Imaryuk watershed, NT;
2. Compare and contrast the seasonal response of water quality to the emergence of winter streamflow in two organic-rich Arctic rivers not influenced by mass wasting (Rengleng River and Caribou Creek, NT); and
3. Characterize the permafrost conditions (type and magnitude of thermokarst) and terrain features (surficial material) within the contributing catchment of each river, in order to explain spatial variability in water quality.

Study Area

Figure 1: The watershed boundary for Rengleng river (1), Caribou creek (2), and Miner river (3) delineated using the Arctic DEM. The basemap delineates the major watersheds within the study area and was obtained from NWT Geomatics (Government of the Northwest Territories).

Methodology

Rengleng River and Caribou Creek: The recent emergence of winter streamflow at Rengleng river and Caribou creek suggests an increase in the connectivity of the main river channel with groundwater flow pathways. In 2021, water samples were collected up to three times monthly from late-winter to late-summer (March to August). The sampling locations were collocated with a Water Survey of Canada hydrometric station, near the outlet of each river (see Figure 2) . Samples were analyzed for species of carbon, nitrogen, and phosphorus, as well as mineral ions. To try and ascertain the source of winter streamflow, water samples were also analyzed for 14C Age. Supplementary data is available from 2019 and 2020.



Rengleng River in winter

Miner River: The Miner river is impacted by numerous retrogressive thaw slumps (right). To measure the response of water quality to retrogressive thaw slumping, water samples were collected before and after each active thaw slump with a debris tongue that extended into the river (S7, S6, S8). Water samples were collected monthly during the flow period of 2023 and analyzed for species of carbon, nitrogen, and phosphorus, as well as mineral ions and trace metals. Additional data is available for 2021 and 2022.

The debris tongue of a retrogressive thaw slump blocking Miner river.

Catchment Characteristics

Surficial Geology:

The surficial geology of Rengleng river (bottom) and Miner river (top) catchments is predominantly Moraine Plain (Mp) and Hummocky Moraine (Mh) (Figure 2). Mp can have glacial till ranging from 2-20m thick and Mh can have glacial till up to 60m thick. By contrast, the majority of the Caribou creek catchment (middle) is characterized as Moraine Veneer (Mv), a thin (<2m) layer of glacial till overlying bedrock topography. In addition to glacial till, the landscape is rich in organic deposits, particularly in the Rengleng river catchment.

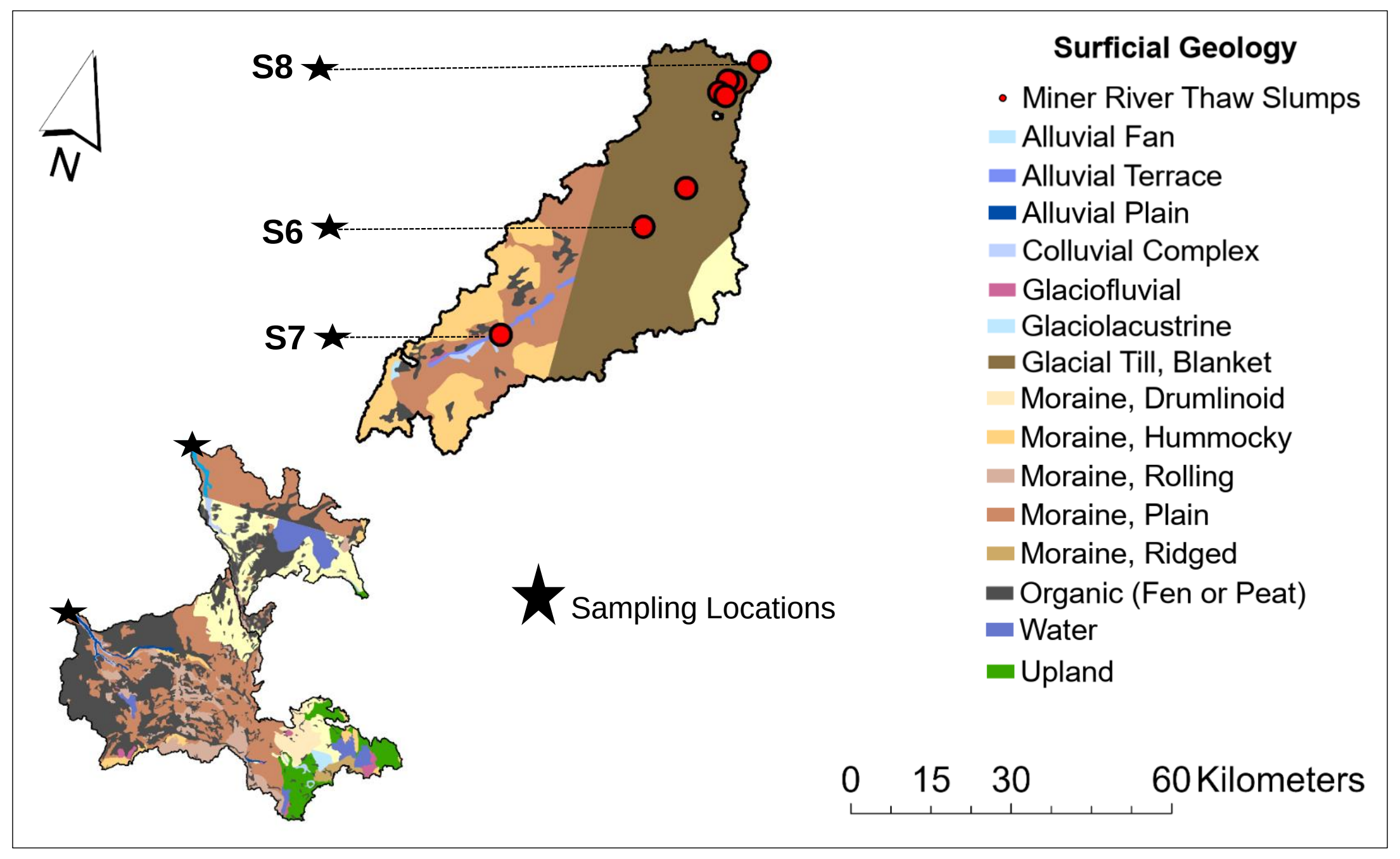


Figure 2: Surficial geology of the Rengleng river, Caribou creek, and Miner river catchments. The data was obtained from Cote et al. (2013).

Permafrost Conditions:

Polygonal terrain is distributed throughout each catchment. Notably, the polygonal terrain appears to be experiencing low levels of degradation. This is typical for peatland polygonal terrain in this area (Steedman et al., 2017).

Flowing south-north, the Miner river catchment crosses into an ice-marginal glaciated landscape. In this region, ice-marginal glaciated landscapes contain large volumes of massive ice that are often only protected by a thin layer of over burden. This makes them more vulnerable to mass wasting. In contrast with the Rengleng River and Caribou Creek catchments, Miner river is affected by numerous retrogressive thaw slumps (red dots).

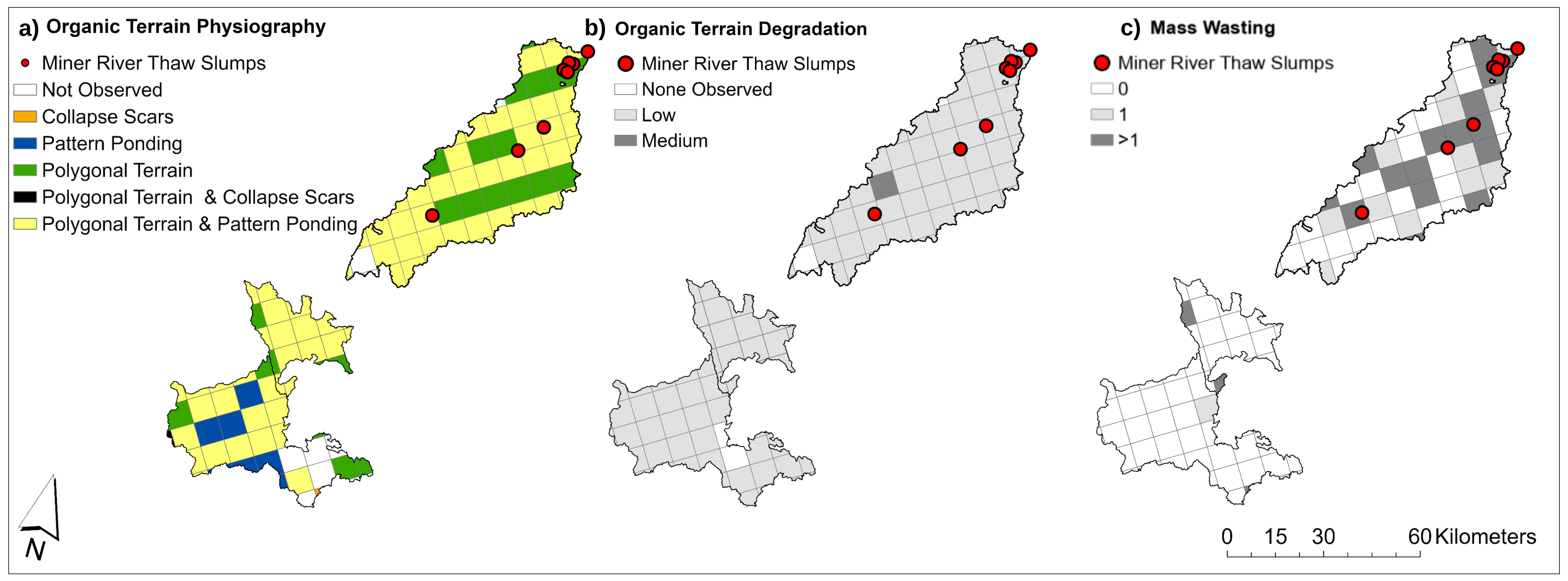


Figure 3: The presence/absence of periglacial features (a), the level of degradation associated with periglacial features (b), and the number of mass wasting events (c) within 7 Km² grid cell across the three study catchments. This data was obtained from the NWT Thermokarst Mapping Collective (see Kokelj et al., 2023).

Water Quality Response

1. Rengleng River

- Spring snowmelt led to the dilution of TDS and the mobilization of TSS via surface runoff.
- As the thaw period progressed, TSS decreased to near 0 mg.L^{-1} and the concentration of TDS increased. This indicates an increase in subsurface flow.
- In late summer and over winter, there was a marked increase in TDS, DOC, and DOC Age. This suggests that lateral flow through Talik zones is a source of solutes and aged DOC to Rengleng river.

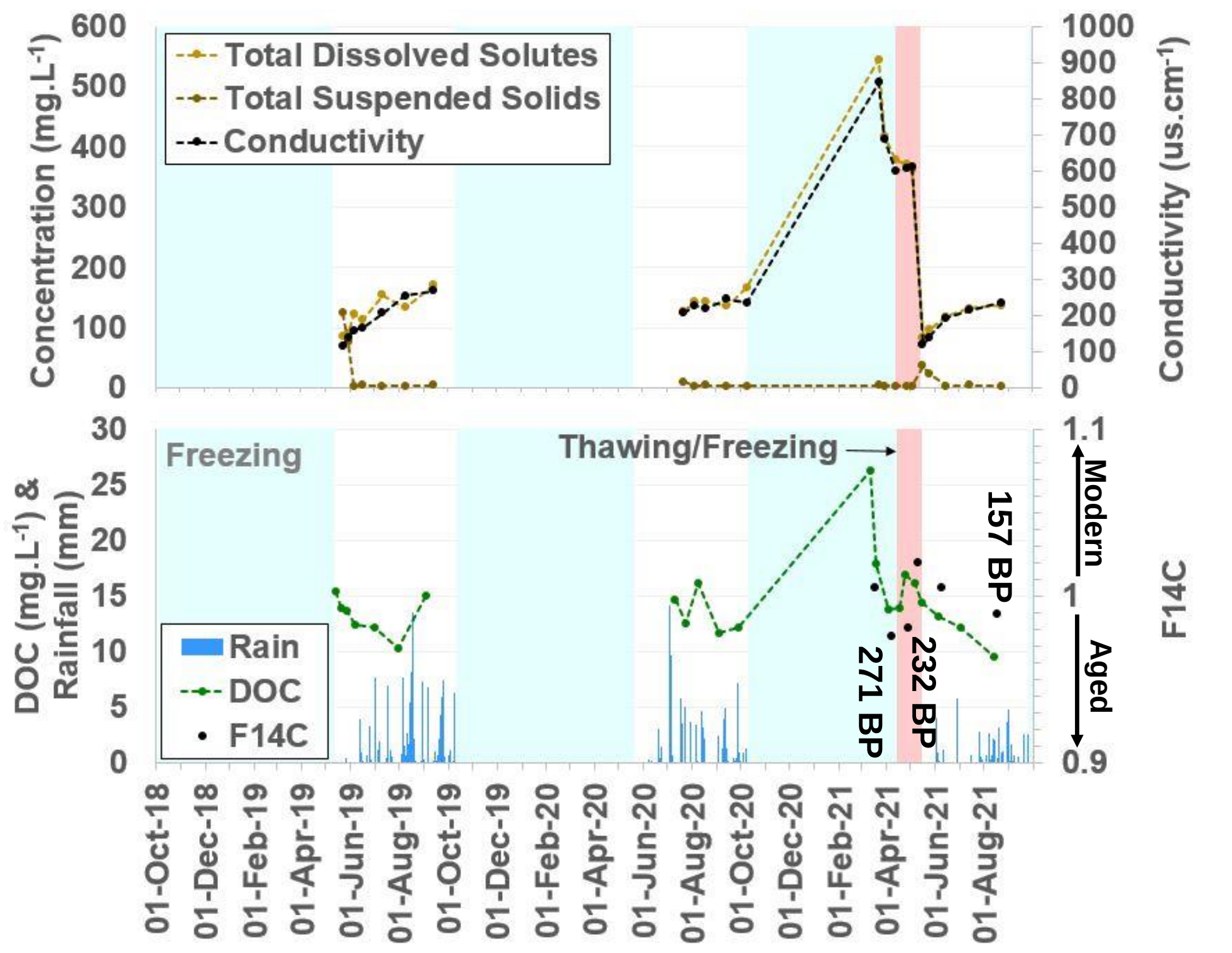


Figure 4: Seasonal variability in Total Dissolved Solids (TDS), Total Suspended Solids (TSS), Conductivity, Dissolved Organic Carbon (DOC), and F14C (an indicator of DOC age).

2. Caribou Creek

- Seasonal trends in TDS concentration resembled Rengleng river. The composition, however, changed across seasons.
- The role of H_2SO_4 in carbonate weathering increased from early-summer to Fall. This indicates deeper subsurface flow during this period.
- Also in contrast with Rengleng river, DOC was modern year-round.

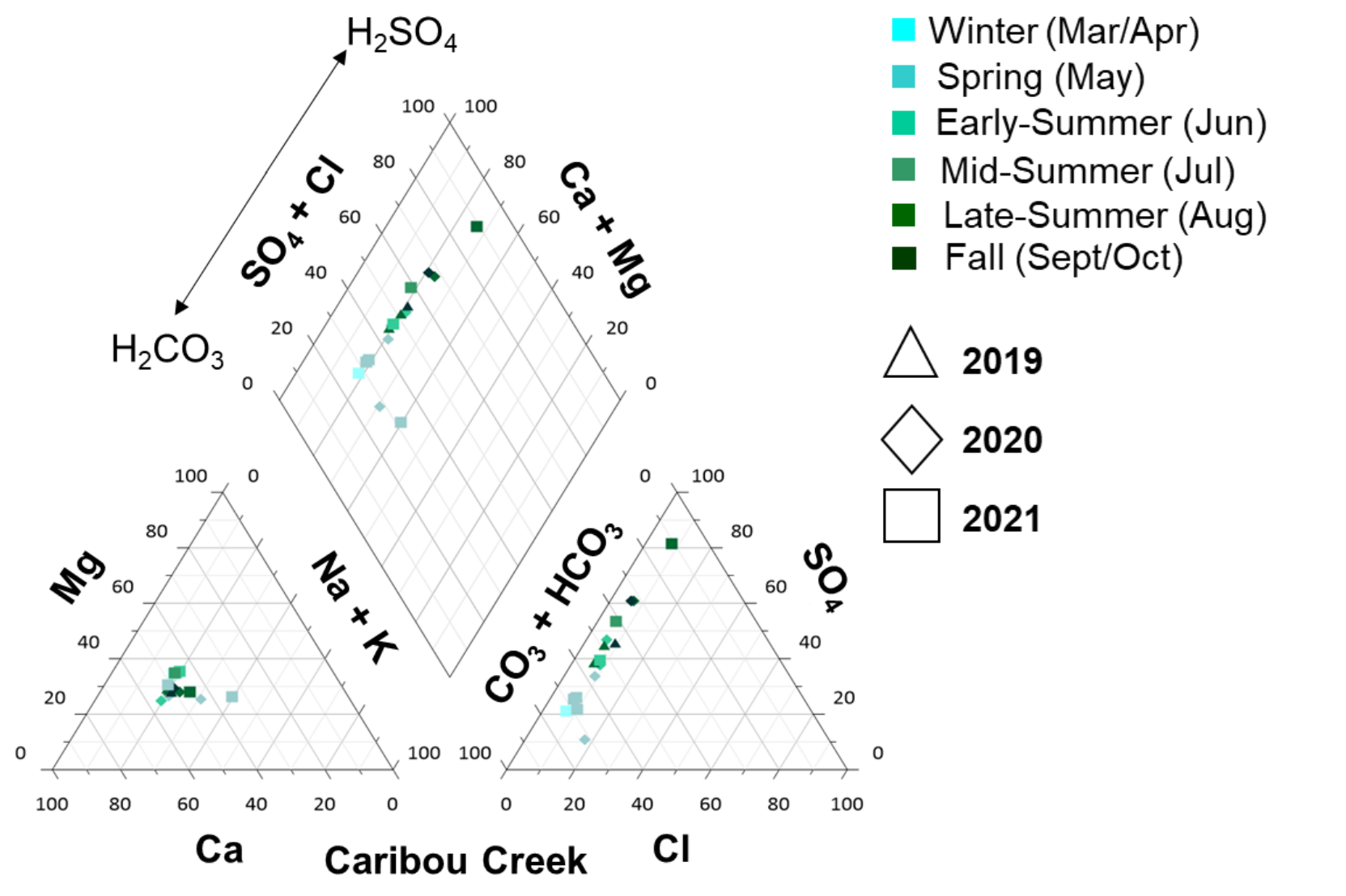
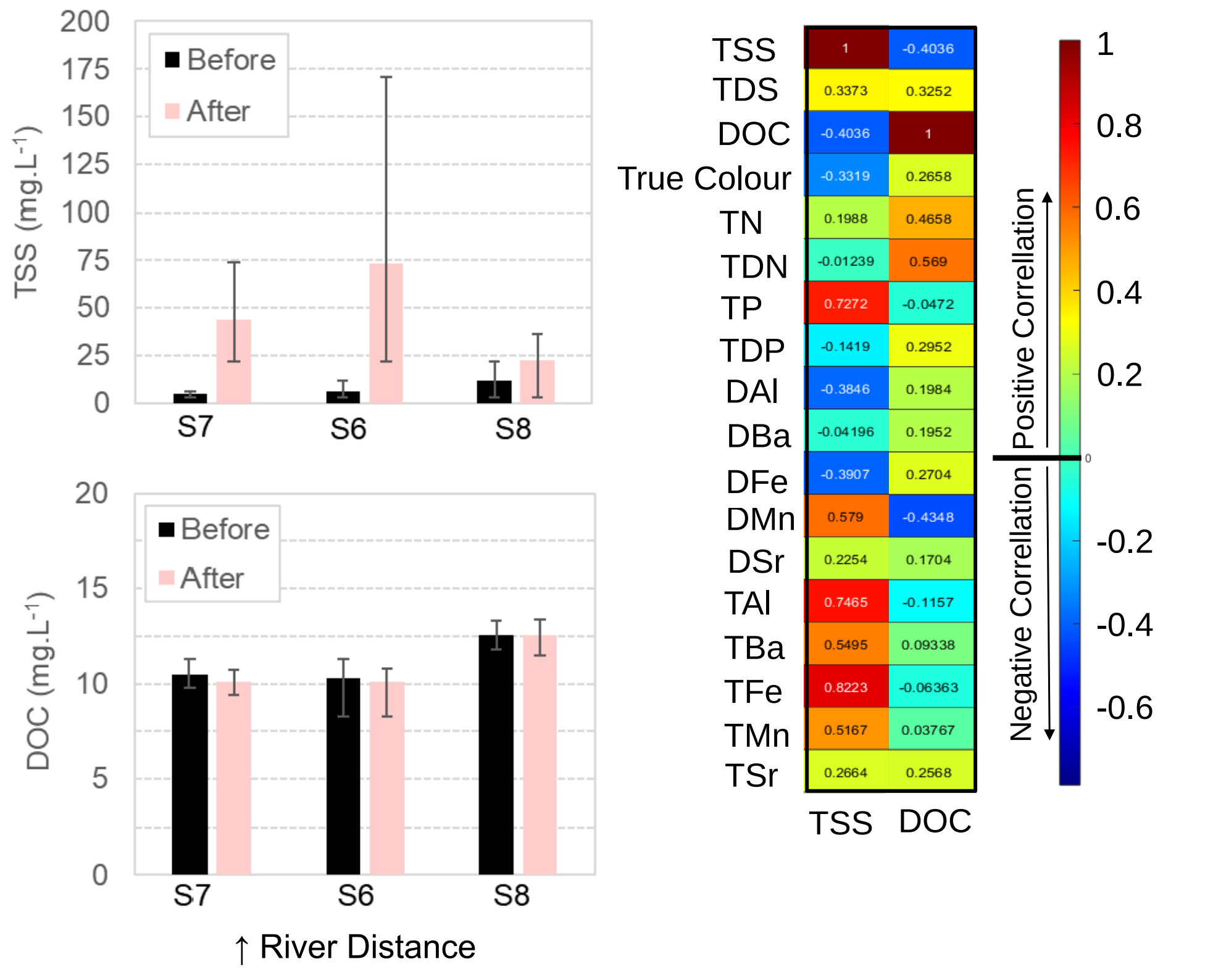


Figure 5: The proportion of major ions (in meq) in Caribou creek for each sampling years.

3. Miner River

- Before S7 (the initiation of thaw slumping), TSS was present in low concentrations.
- Thawing slumping led to a notable increase in the concentration of TSS. This was strongly correllated with subsequent increases in Total Phosphorus (TP), Total Aluminum (TAl), and Total Iron (TFe).
- TSS was negatively correlated with DOC. This could be explained by the adsorption of DOC to mineral sediment.



	TSS	DOC
TSS	1	-0.4036
TDS	0.3373	0.3252
DOC	-0.4036	1
True Colour	-0.3319	0.2658
TN	0.1988	0.4658
TDN	-0.01239	0.569
TP	0.7272	-0.0472
TDP	-0.1419	0.2952
DAl	-0.3846	0.1984
DBa	-0.04196	0.1952
DFe	-0.3907	0.2704
DMn	0.579	-0.4348
DSr	0.2254	0.1704
TAl	0.7465	-0.1157
TBa	0.5495	0.09338
TFe	0.8223	-0.06363
TMn	0.5167	0.03767
TSr	0.2664	0.2568

Figure 6: The minimum (lower limit), maximum (upper limit), and mean concentration of Total Suspended Solids (TSS) and Dissolved Organic Carbon (DOC) in the Miner river (*left*). The Pearson correlation coefficient between TSS and DOC and other variables (*right*).

References

1. Bintanja, R. (2018). The impact of Arctic warming on increased rainfall. Scientific Reports, 8(1), 16001–16006. https://doi.org/10.1038/s41598-018-34450-3
2. Chiasson-Poirier, G., Franssen, J., Lafrenière, M.J., Fortier, D., & Lamoureux, S.F. (2020). Seasonal evolution of active layer thaw depth and hillslope-stream connectivity in a permafrost watershed. Water Resources Research. 56: e2019WR025828.
3. Côté, M.M., Duchesne, C., Wright, J.F., and Ednie, M., 2013. Digital compilation of the surficial sediments of the Mackenzie Valley corridor, Yukon Coastal Plain, and the Tuktoyaktuk Peninsula; Geological Survey of Canada, Open File 7289. doi:10.4095/292494
4. Fouche, J., Christiansen, C.T., Lafrenière, M.J., Grogan, P., & Lamoureux, S.F. (2020). Canadian permafrost stores large pools of ammonium and optically distinct dissolved organic matter. Nature Communications, 11, 4500-4500.
5. Kokelj, S.V., Kopkoszka, J., Sluijs, J. Rudy, A., Tunnicliffe, J., Shakil, S., Tank, S., & Zolkoz, S. (2021). Thaw-driven mass wasting couples slopes with downstream systems, and effects propagate through Arctic drainage networks. The Cryosphere, 15, 3059-3081.
6. Kokelj, S.V., Gingras-Hill, T., Daly, S.V, Morse, P.D., Wolfe S.A, Rudy, A.C.A, van der Sluijs, J., Weiss, N., O'Neill, B., Baltzer, J.L., Lantz, T.C., Gibson, C., Cazon, D., Fraser, R.H., Froese, D.G., Giff, G., Klengenberg, C. Lamoureux, S.F., Quinton, W.L….. 2023. The Northwest Territories Thermokarst Mapping Collective: a northern-driven mapping collaborative toward understanding the effects of permafrost thaw. *Arctic Science*. **e-First** https://doi.org/10.1139/as-2023-0009.
7. Shakil, S., Tank, S.E., Kokelj, S.V., Vonk, J.E., & Zolkos, S. (2020). Particulate dominance of organic carbon mobilization from thaw slumps on the Peel Plateau, NT: Quantification and implications for stream systems and permafrost carbon release. Environmental Research Letters, 15(11), L114019.
8. Smith S.L., Burgess M., Riseborough D., & Nixon F.M. (2005). Recent trends from Canadian Permafrost Thermal Monitoring Network Sites. Permafrost and periglacial processes,16, 19-30.
9. Steedman, A. E., Lantz, T. C., & Kokelj, S.V. (2017). Spatio-Temporal Variation in High-Centre Polygons and Ice-Wedge Melt Ponds, Tuktoyaktuk Coastlands, Northwest Territories. *Permafrost and Periglacial Processes*, 28(1), 66–78.
10. Tank, S.E., Vonk, J. E., Walvoord, M.A, McClelland, J.W., Laurion, I., and Abbott, B.W. (2020). Landscape matters: Predicting the biogeochemical effects of permafrost thaw on aquatic networks with a state factor approach. Permafrost and Periglacial Processes, 2020, 1-13.
11. Vonk, J. E., Tank, S. E., Bowden, W. B., Laurion, I., Vincent, W. F., Alekseychik, P., Amyot, M., Billet, M. F., Canário, J., Cory, R. M., Deshpande, B. N., Helbig, M., Jammet, M., Karlsson, J., Larouche, J., Macmillan, G., Rautio, M., Walter Anthony, K. M., & Wickland, K. P. (2015). Reviews and syntheses : Effects of permafrost thaw on Arctic aquatic ecosystems. Biogeosciences, 12(23), 7129–7167.