## Introduction

In high-latitude environments, cold climate causes rivers to freeze several months a year. As river-ice develops and changes with meteorological conditions, it influences hydraulic, bedload transport and erosion processes, which in turn affect channel morphology. In fact, the presence of river-ice changes the flow conditions, moving from free-surface to closed-surface flow. Cold temperatures alter the physical properties of flowing water, causing changes to sediment transport capacity (Beltaos and Burrell, 2000; Ettema, 2006; Lau and Krishnappan, 1985; Prowse, 2001a; Sayre and Song, 1979; Smith and Ettema, 1995). Furthermore, the presence of river-ice and snow affect water and sediment availability (e.g., Gatto, 1995), connectivity between the stream bed and banks, and streambank erosion (e.g., Chassiot et al., 2020). Thus, river-ice can influence key fluvial processes that drive fluvial morphological change.

However, insufficient information on the spatial and temporal variation of the processes under ice-covered conditions limits our understanding of ice-covered river dynamics, including estimation of stage-discharge relationships, sediment transport, ice-cover formation, and channel-thalweg alignment (Ettema, 2002; Lotsari et al., 2019; Turcotte et al., 2011; Polvi et al., 2020). For many reasons, collecting measurements from an ice-covered river is challenging. First of all, standing on river-ice can be dangerous, and river-ice thickness conditions are highly dependent on channel geometry, water depth, and hydrological and meteorological conditions (e.g., Prowse et al., 2007). Secondly, measuring flow velocities and bedload transport during the ice-covered season is difficult: holes can be drilled in the ice to access the water, but require a thick and stable ice-cover, and only provide spatially and temporally limited measurements (e.g., Lotsari et al., 2017, 2019; Polvi et al., 2020). Thirdly, these intrusive methods are not adapted for the study of certain processes that depend on a thick ice cover to operate, such as flow pressurization under ice, which hole-drilling through ice would interfere with. Furthermore, photographic data has been used to study river-ice and ice-affected river processes using satellite imagery and time-lapse cameras (McGinnis and Schneider, 1978; Cooley and Pavelsky, 2016; Beaton et al., 2019; Polvi et al., 2020) yet there is a lack of high-resolution continuous spatial and temporal information to enable high-precision monitoring.

To address these field measurement shortcomings, within the past decades, geomorphologists have started using seismic methods. Seismology covers the study of the generation and propagation of elastic waves through Earth, emitted by a source (Stein & Wyssesion, 2002). Seismometers record continuous and high-resolution seismic data, providing information about the source, its timing and location, as well as on the medium through which the wave travels. Earth surface dynamics can be detected and characterized by seismic signals described by specific waveforms, event durations, amplitudes and frequencies. This field of environmental seismology offers a promising opportunity for geomorphologists to collect continuous, temporally and spatially rich high-resolution data, otherwise not accessible using traditional measurement methods (Cook and Dietze, 2022).

Methods

Our project uses “fluvial seismology” to monitor ice-covered river dynamics in cold-climate high-latitude regions. We deployed seismic sensors for one full year on two rivers in the subarctic environment, spanning a latitude gradient and presenting different channel morphologies. From these continuous recordings, we characterized seasonal signals from river-ice, bedload, turbulence and streambank erosion events. Furthermore, we performed topographic measurements to monitor streambank erosion over one year. We start by hypothesizing that bedload transport and erosion increase during the ice break-up season from mechanical break-up of ice.

## Results

We detected X amount of river-ice cracking signals occurring during the ice break-up season. These mostly occurred over the late winter and early spring period (March to end of April), when air temperature increased, regularly distributed over this time period. We observed a sharp increase in the number of ice cracking signals mid-May following water discharge increase from upstream snowmelt flood. On the meander bend, where river-ice thickness and shape are heterogeneously distributed over the reach, we identify more ice-cracking signals on seismic data originating from the meander bend compared to the straight reaches. Furthermore, our topographic measurements show strong erosion in the river meander bend, whereas no significant erosion was detected on the straight reaches.

## Discussion

Our results suggest that the air temperature increase in the spring caused the river-ice sheet to melt gradually at first (thermal break-up), followed by mechanically-induced ice break-up from increased water discharge due to upstream snowmelt. Erosion rates on the meander bend could be explained by mechanical contact between the ice sheets and streambank sediment, where larger sediment can be moved by ice than from fluvial drivers. Furthermore, we note differences caused by different river morphologies : meander bend banks are more affected by fluvial and ice forcing during the ice break-up season than straight reaches, translating into higher erosion rates.

## Conclusion

Overall, our results show that streambank erosion due to river-ice is mainly caused by mechanical action from river-ice on bank material. The meander bend is the location where most ice cracking activity occurs during this time, suggesting that bend curvature influences ice dynamics. Therefore, seismic methods can be used to identify seasonal relationships between river-ice and sediment, and inform about river-ice effects on ice-covered river systems.