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Backwater Effects and Sediment Pulses during Ice Break-up in Permanently Connected Arctic Delta Lakes

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1. INTRODUCTION

In Arctic conditions, ice and snow cover can serve as significant sources of water supply, but also as a physical barrier to water flow within river deltas. The breakup of ice triggers hydrological pulses that play a crucial role in the exchange of water and sediment within the delta. In the late winter and early spring, the ice cover in river channels and lakes begins to crack and drift, leading to dynamic and difficult-to-predict directions and intensities of water flow. A key phenomenon during this period is the formation of ice jams and backwater effects, i.e., the reverse flow of river water caused by the obstruction of the channel by residual ice.

Lakes within deltaic plains exhibit varying degrees of hydrological connectivity with the network of distributary channels. The hydrological function and dynamics of these lakes are strongly influenced by the degree of connection to river channels. A critical moment affecting the water and sediment balance of these lakes is the period of ice breakup a dynamic yet short-lived phase that determines the direction and intensity of water and sediment exchange.

According to studies such as Dolan et al. (2024), one method for investigating the hydrological connectivity in the Arctic is the use of satellite data. These data can be used to analyze the seasonal variability in the hydrological connection between the lakes of the Mackenzie Delta and river waters. According to Lesack et al. (1998), lakes in the Mackenzie Delta can be classified according to their flooding regimes as frequently flooded, infrequently flooded or isolated. This classification is crucial for analyzing the impact of flood events and ice phenomena on water and sediment transport.

The aim of this study is to investigate frequently flooded lakes during the initial phase of the spring flood, which coincides with the period of ice breakup. The research also seeks to contribute to the development of methodologies for monitoring water and sediment exchange dynamics between lakes and the river.

2. STUDY AREA

The research was conducted in the Mackenzie Delta (specifically on the East Channel of the Mackenzie River), which is one of the largest river deltas in the Northern Hemisphere located outside the Arctic Circle. The Mackenzie Delta is a unique polygenetic region that has developed under the combined influence of fluvial hydrology, glacial and periglacial processes, and marine dynamics. Within the delta, which covers an area of 13,000 km², there are over 45,000 lakes (Marsh and Hey 1989). This study presents the results of field observations conducted at Boot Lake in Inuvik (68.35106N; 133.7108). This 23-hectare lake maintains a permanent connection with the East Channel of the Mackenzie River.

3. RESEARCH METHODS

During the field campaign conducted from May 24 to 31, 2025, water samples were collected at the inflow to the lake and at the point where the lake is hydraulically connected via a channel to the East Channel of the Mackenzie River. Water samples were taken at 12-hour intervals, and an automatic turbidity and water temperature sensor was installed at the lake's connection point with the East Channel. The sensor recorded data every 20 minutes. Collected water samples were subjected to vacuum filtration using cellulose membrane filters in laboratory conditions to determine the concentration of suspended particulate matter – expressed as SSC (Suspended Sediment Concentration) in $mg \cdot L^{-1}$.

4. RESULTS

During the field investigations, it was observed that the studied lake received several pulses of river water, indicated by a reversal of flow direction in the connecting channel, increased turbidity, and a drop in water temperature during the river water transgression. Field observations revealed that the movement of ice floes and slush obstructs and slows water flow within the river channel. When the channel cross-section becomes blocked, a temporary water level rise of 20–30 cm occurs, resulting in the flooding of the lake by river water. Over the eight-day period, several episodes of intrusions of cold, turbid river water into the lake basin were recorded, each lasting 2–3 hours. These intrusions were accompanied by intense mixing of colder river water (approximately 1.5 °C) with warmer lake water (2.5–3.5 °C). The pulses of river water caused temporary increases in lake water turbidity (from 5 to 18 NTU), with SSC ranging from 3 to approximately 80 $mg \cdot L^{-1}$. The observations clearly indicate episodic inflow of the river water into the lake occurring in the period preceding the arrival of the flood wave peak (the duration of hydrological connectivity ranged from 8 to 11 hours). At the end of the observation period, a sudden rise in the water level of the East Channel – by approximately 2 meters – was recorded, resulting in the complete and sustained inundation of the lake basin. This marked the peak of the flood wave in the Mackenzie Delta, a flash flood triggered by the release of an ice jam at the delta separation point.

5. DISCUSSION

Pulsed deliveries of riverine sediments to lakes play a significant role in their long-term geomorphological evolution and in the functioning of aquatic ecosystems. These sediments can contribute to the enrichment of bottom layers with organic and inorganic matter, as well as modulate water transparency and temperature, thereby influencing the development of phytoplankton and benthic communities.

Observations carried out in the Mackenzie River Delta, at the channel connecting one of the permanently connected lakes to the river, confirm the hypothesis that the final phase of ice cover – specifically, the processes associated with ice breakup – acts as a key mechanism initiating episodic sediment input into lakes. Such sediment delivery would not be possible to the same extent without the backwater effect caused by temporary flow restriction in the East Channel of the Mackenzie due to lingering ice.

The research also confirms that monitoring water temperature can serve as an indicator of river-lake connectivity. Accurate water temperature monitoring during spring freshet flows enables precise determination of the timing of sediment delivery from river channels to lakes. This represents a valuable complement to field observations and satellite-based analyses, which are limited by their spatial and temporal resolution.

Episodic events, such as those observed in Boot Lake in Inuvik, may contribute more significantly to the annual sediment budget than long-term processes associated with rainfall or permafrost thawing. Moreover, predicting these events is challenging, as they depend on the interaction of meteorological, hydrological, and ice-related factors occurring within a very short time window.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the conducted observations and literature analysis, the following conclusions can be drawn:

- The ice regime during the final phase of ice cover plays a crucial role in shaping sediment transport from rivers to lakes;
- The backwater effect caused by ice break-up results in episodic yet intense influxes of turbid river water into lakes;
- Lakes that are permanently connected to river channels (such as Boot Lake with the East Channel of the Mackenzie River) are particularly vulnerable to this phenomenon;
- Remote sensing and real-time monitoring are essential for effectively tracking changes in hydrological connectivity;
- Episodic sediment influxes should be incorporated into sedimentation models and Arctic delta management strategies, especially in the context of climate change.

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