# ASSESSING THE IMPACTS OF RECENT, INTENSE PERMAFROST THAW SLUMPING ON LAKES IN THE MACKENZIE DELTA UPLANDS, NORTHWEST TERRITORIES, CANADA

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# Abstract

The Western Canadian Arctic is warming at a rate much more rapid than the rest of the globe. As a result, the rate of permafrost thaw is increasing throughout the Arctic. One of the most dramatic features that develop from permafrost thaw are retrogressive thaw slumps, which are rotational landslide features that develop along the shore of impacted lakes. In the Mackenzie Delta, there has been an observed increase in slump size and rate of slump growth. Using a paleolimnological and remote- sensing approach, this research aims to assess the impact that large, highly active slump activity has on the ecosystem of adjacent lakes. This research is important as temperatures are expected to continue to increase in the western Canadian Arctic, and therefore understanding the effects continued warming is having on slump development and their impacts on lakes is critical for assessing the health of the lakes throughout the region.

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# TABLE OF CONTENTS

**Abstract** ........ ii

**Acknowledgments** ........ iii

**List of Figures** ........ vi

**List of Tables** ........ vii

**Chapter 1: General Introduction and Literature Review** ........ 1

1.1 A Rapidly Warming Arctic ........ 1

1.2 Permafrost environments ........ 1

*1.2.1 Retrogressive thaw slumps in the Tuktoyaktuk Coastlands* ........ 3

1.3 The Tuktoyaktuk Coastlands ........ 4

*1.3.1 Landscape of the Tuktoyaktuk Coastlands and Mackenzie Delta* ........ 6

*1.3.2 Regional climate changes* ........ 6

1.4 Paleolimnological and remote sensing work on thaw slumps ........ 8

1.5 Thesis organization and rationale ........ 15

1.6 References ........ 24

**Chapter 2: A paleolimnological assessment of six lakes impacted by intense shoreline retrogressive thaw slumping in the Mackenzie Delta uplands (Northwest Territories, Canada)** ........ 33

2.1 Abstract ........ 33

2.2 Introduction ........ 34

2.3 Methods ........ 37

*2.3.1 Field Sampling* ........ 37

*2.3.2 Laboratory methods* ........ 39

*2.3.3 Mercury Analysis* ........ 40

*2.3.4 Elemental Analysis* ........ 41

2.4 Results ........ 42

*2.4.1 Surface water quality data* ........ 42

*2.4.2. Radiometric dating results* ........ 42

*2.4.2 Elemental Analysis* ........ 43

*2.4.3 Sedimentary Total Mercury Concentrations* ........ 47

2.5 Discussion ........ 49

*2.5.1. Water quality* ........ 49

*2.5.1 Thaw slump impacts on carbon dynamics within impacted lakes* ........ 49

*2.5.1 Thaw slump impacts on mercury delivery to impacted lakes* ........ 52

*2.5.3 Conclusions and future directions* ........ 53

2.6. Acknowledgements 54
2.7 References 55
**Chapter 3: Seasonal turbidity trends in lakes impacted by highly active permafrost thaw slumping in the Mackenzie Delta uplands, NT, Canada** 60
3.1 Abstract 60
3.2 Introduction 60
*3.2.1 Previous remote sensing work in the Western Canadian Arctic* 62
*3.2.2 Study region and previous research in the Mackenzie Delta uplands* 64
3.3 Methods 66
*3.3.1 Satellite comparison and selection* 66
*3.3.1 Study Lakes* 67
*3.3.2 Normalized difference turbidity index* 70
*2.3.3 Analysis in Google Earth Engine* 71
3.4 Results 72
*3.4.1 Turbidity results* 72
3.5 Discussion 80
*3.5.1 Drivers of satellite-inferred turbidity in slump-impacted lakes* 80
*3.5.2 Comparison to other potential turbidity analyses* 84
3.6 Conclusions 85
3.7 Acknowledgements 86
3.7 References 86
**Chapter 4: Discussion and Conclusions** 91
4.1 Thesis Summary and Conclusions 91
*4.1.1. How do large, highly active thaw slumps impact the lake environment differently than other slump lakes in the area* 92
*4.1.2 How do seasonal trends in turbidity differ from reference lakes?* 93
*4.1.3. Modelling thaw slump dynamics and the impact of continued warming on thaw slump dynamics* 94
4.2 References 96

## List of Figures

Figure 1.1: Conceptual Model (developed in Thienpont et al. 2025) proposing how the lake environment is impacted at different stages of thaw slump development and polycyclic slumping ........ 17
Figure 1.2: Map of study area ........ 19
Figure 2.1: Map of study site ........ 39
Figure 2.2: Total organic carbon (%) in each of the six slump impacted lakes ........ 44
Figure 2.3: Carbon: Nitrogen ratio at each of the six slump impacted lakes ........ 46
Figure 2.4: Total mercury concentrations (ng/g, dw) in each of the six study lakes ........ 48
Figure 3.1: Study site map of lakes in the Mackenzie Delta uplands (Tuktoyaktuk Coastlands) NE of the town of Inuvik, NT. ........ 69
Figure 3.2: Normalized Difference Turbidity Index analysis of ML-S_CH_1 ........ 72
Figure 3.3: Normalized Difference Turbidity Index analysis of ML-S_CH_8 ........ 73
Figure 3.4: Normalized Difference Turbidity Index analysis of ML-S_CH_14 ........ 74
Figure 3.5:: Normalized Difference Turbidity Index analysis of ML-S_CH_15 ........ 75
Figure 3.6: Normalized Difference Turbidity Index results ML-S_CH_16 ........ 76
Figure 3.7: Normalized Difference Turbidity Index results ML-S_CH_9 ........ 77
Figure 3.8: Normalized Difference Turbidity Index results Reference 1 ........ 78
Figure 3.9: Normalzied Difference Turbidity Index results Reference 2 ........ 79
Figure 3.10: Normalized Difference Turbidity Index results Reference 3 ........ 80
Figure 4.1: Conceptual model (developed by Thienpont et al. 2025) proposing how the lake environment is impacted at different stages of thaw slump development and polycyclic slumping ........ 95

# List of Tables

Table 1.1: Lake area and lake size of each of the six study lakes ................................................ 20
Table 2.1: Surface water quality data from each of the six study lakes ....................................... 42

# Chapter 1: General Introduction and Literature Review

## 1.1 A Rapidly Warming Arctic

The Arctic is warming at a much more rapid rate than the rest of the planet, estimated as being over two times faster than the global average (Rantanen et al. 2022, Li et al. 2023). Temperatures in the Canadian Arctic have increased about 2˚C over the period from 1948- 2016, and average temperatures are projected to increase 7.8˚C by 2081-2100 (Howell et al. 2019). In the western Canadian Arctic, this trend is particularly notable as it has been found to be one of the most rapidly warming regions on the planet (Murdryk et al. 2021, Ford et al 2018). In the Mackenzie Delta region / Tuktoyaktuk Coastlands, where this research was conducted, temperatures have increased dramatically over the past century (Lantz and Kokelj, 2008). The Mackenzie Delta uplands is experiencing greater average annual temperatures, greater average summer temperatures, as well as an increase in the number of days over 20˚C (Lantz and Kokelj, 2008). The Arctic is a very diverse environment, and the rise in temperatures that have been observed have resulted in a range of landscape changes that will continue to occur as temperatures are predicted to continue increasing.

## 1.2 Permafrost environments

Permafrost is defined as ground that remains frozen for two or more consecutive years and is present throughout high-latitude areas, underlying approximately 15% of the northern hemisphere (Obu, 2021). There are four different categories into which permafrost environments are spatially classified, which is determined based on how much of the environment is underlain by permafrost: continuous (90-100%), discontinuous (50-90%), sporadic (10-50%), and isolated (<10) permafrost (Vonk et al. 2015). Permafrost is a critical component of Arctic environments, and as such understanding how permafrost environments are responding to rapid changes in temperature is critical to maintaining the stability of the environment and predicting future ecosystem changes. One of the most significant impacts observed because of rapidly increasing air temperatures is the increase of permafrost thaw that has been observed throughout the Western Canadian Arctic.

While there is widespread understanding and acceptance of permafrost degradation throughout the Arctic, there is a gap in knowledge when it comes to our understanding of how environments, specifically aquatic environments, will respond to the degradation and how the impacts can be mitigated and better managed (Thienpont et al. 2013). Permafrost thaw is not just a local issue, or one that is contained to Arctic environments. Permafrost underlays approximately 25% of the globe and contains up to half of the accessible carbon pool, which has significant implications on a global scale (Droppo et al. 2022). As temperatures continue to increase and permafrost continues to thaw, there is anticipated to be a significant increase in greenhouse gases (specifically carbon dioxide and methane) released from the carbon pool stored in the permafrost (Droppo et al. 2022). This process is anticipated to create a positive feedback cycle wherein as temperatures increase and permafrost continues to thaw, this releases more carbon thereby continuing to warm the environment and enhancing this process. This process has already been observed, as from 1970 to 2006, there was an increase in active layer thickness throughout the circumpolar region, which has been found to be a net source of carbon to the atmosphere (Hayes et al. 2014).

### *1.2.1 Retrogressive thaw slumps in the Tuktoyaktuk Coastlands*

Permafrost thaw has already been dramatically altering Arctic environments. Permafrost degradation can have significant impacts on the geomorphology of landscapes, altering sediment flux, hydrology, nutrient and carbon cycling, as well as posing a significant risk to the overlying infrastructure (Farquarson et al. 2019). Permafrost degradation is resulting in an increase in thermokarst features, which results from subsidence of the ground due to the thaw of ice-rich permafrost. There are three groups of thermokarst features, including hillslope processes, wetland processes and thaw lake processes. Recent observations have identified accelerated thermokarst in locations near the terminal extent of the Laurentide Ice Sheet, which has been inferred to be delayed onset of deglaciation in this region, resulting in anthropogenic warming melting the last of the ice from the last glacial maximum (Kokelj et al. 2017). One of the most significant features resulting from permafrost thaw are the development and growth of retrogressive thaw slumps. Retrogressive thaw slumps are hillslope rotational slide features that develop in areas of moderate to high relief such as in valleys and along the shores of lakes, rivers and other water bodies. Retrogressive thaw slumps result in terrestrial material being translocated into the downslope environment, such as the adjacent lake ecosystem (Lantz and Kokelj, 2008). Thaw slumps are common features on the shorelines of lakes in the Tuktoyaktuk Coastlands, occurring on approximately 10% of study lakes larger than 1 ha in size (Lantz and Kokelj, 2008). In the Tuktoyaktuk Coastlands region thaw slumps are ‘polycyclic’ in nature (Kokelj et al. 2009b). This polycyclic pattern is a result of the stagnation of ice ablation at the headwall, resulting in the stabilization of the slump, and the slump is then reinitiated during the ice melt season, sometimes after being stable for decades or more (Lewkowitz and Way, 2019). Retrogressive thaw slumps have significant impacts to soil chemistry, surface runoff, and lake water in affected lakes and have implications to the carbon budget, as the organic carbon sequestered in the frozen ground is released (Cassidy et al. 2017, Broder et al. 2021, Lewkowitz and Way, 2019).

## 1.3 The Tuktoyaktuk Coastlands

The Tuktoyaktuk Coastlands, in the northern Northwest Territories, Canada is underlain by thick, continuous permafrost which can be found as thick as 500 m in some areas (Lantz and Kokelj, 2022). The temperature of the permafrost varies and can range from -2 to -7˚C depending on changes in soil moisture, vegetation, as well as snow conditions (Lantz and Kokelj 2022). As the Tuktoyaktuk Coastlands have experienced an increase in air temperatures, this has impacted permafrost temperatures, which have been observed to have warmed by ~2˚C over the last several decades (Lantz and Kokelj, 2022). This increase in permafrost temperature has led to an increase in near-surface permafrost thaw, as well as a deepening of the active layer. Disturbance regimes also play a key role in the deepening of the active layer. Modelling by Lantz and Kokelj (2022) examined drained lake basins and demonstrated that the presence of shrub vegetation causes increases in ground temperature, resulting in deepening of the active layer, leading to permafrost degradation. Retrogressive thaw slumps also have an impact on active layer thickness and ground temperatures. Burn (2000) examined a retrogressive thaw slump near Mayo, Yukon and demonstrated that the thermal disturbance imparted by the retrogressive thaw slump was +3-4˚C, which is sufficient to raise the mean ground surface temperature above 0˚C, causing the continued degradation of permafrost. This shows the connection between how changes in temperature and geomorphology of the environment, as well as disturbance regimes, are impacting permafrost degradation in the Tuktoyaktuk Coastlands and other permafrost regions.

The landscape of the Tuktoyaktuk Coastlands is greatly impacted by the legacy of glaciation stemming from when the area was covered by the Laurentide Ice Sheet (Steedman et al. 2017). The early Holocene was a period of extreme warming (also known as the Holocene Thermal Maximum) and this time period likely corresponds with widespread thermokarst development, as well as the formation of thermokarst lakes and extensive thaw slumping (Steedman et al. 2017). The Laurentide Ice Sheet was the primary driver for the distribution of surficial geological deposits. In the Tuktoyaktuk Coastlands, surficial materials consist of mainly morainal tills, and glaciofluvial materials (Stedman et al. 2017). The area is also characterized by drained lakes, resulting in widespread lacustrine basins, most prevalent in the northern areas of the region (Steedman et al 2017).

The Tuktoyaktuk Coastlands region is characterized by a steep latitudinal temperature gradient in the summer, with notably colder temperatures towards the coast. The mean annual air temperature in Inuvik is -9˚C, and in Tuktoyaktuk it is -10.2˚C. There is also a precipitation gradient in the region, with higher precipitation inland compared to the coast (Environment Canada 2025). The climatic gradient across the region is associated with changes in vegetation, with the open spruce and shrub tundra defining the southern extent of the region transitioning to dwarf shrub tundra in the north (Steedman et al 2017). Due mainly to thinner snow cover in the north, ground temperatures decrease northwards, with temperatures ~-3˚C in the south to ~-6˚C in the north (Steedman et al. 2017).

### *1.3.1 Landscape of the Tuktoyaktuk Coastlands and Mackenzie Delta*

It is estimated that throughout the Mackenzie Delta itself there are over 50,000 waterbodies, and the surrounding upland terrain is also lake rich, and as such the health of these waterbodies is very important to the region (Emmerton et al. 2007) The region also has very thick continuous permafrost throughout, in some places up to 100 m thick (Kohnert et al. 2018, Burn & Kokelj, 2009). Fires have also played an important role in shaping the landscape of the Mackenzie Delta region. Notably, a fire burned in 1968, impacting Inuvik and north up to Noell Lake. This fire caused the active layer to deepen and caused extensive permafrost thaw in impacted areas (Mackay, 1963).

The bedrock in the delta is categorized as clastic and carbonate sedimentary rock and reaches depths up to 10 km in some areas (Dixon et al. 1992). The surficial materials consist of till, ice contact deposits and material derived from the carbonate and shale bedrock of the Mackenzie Basin (Kokelj et al. 2005). Polygonal peatlands associated with ice wedge development is characteristic of low-lying areas in the uplands (Kokelj et al. 2005).

### *1.3.2 Regional climate changes*

Throughout the Mackenzie Delta uplands, there are significant regional changes to the climatic regime. Temperatures vary between coastal and inland sites, with coastal sites being cooler due to the presence of sea ice, and differences in albedo as solar radiation increases at the end of the winter season (Burn and Kokelj, 2009). Coastal conditions are also drier than inland, and as a result snow depth is greater at Fort McPherson when compared with coastal Tuktoyaktuk (Burn and Kokelj, 2009). Likely due to cooler temperatures at the coast, snow persists longer at the cooler coastal sites, when compared with warmer inland sites (Burn and

Kokelj, 2009). Precipitation is a harder climatic trend to be able to generalize and anticipate, as there is significant variation in precipitation characteristics regionally throughout the delta region (Burn and Kokelj, 2009). This is a knowledge gap that is important to address, as understanding changes in precipitation patterns can help us better understand its future impacts to both permafrost, and disturbance regimes.

Looking at the hydrology of the area, snow melt is the primary hydrological driver throughout the delta and uplands region (Burn and Kokelj, 2009). Snowmelt happens quickly, due to the abundance of solar radiation available as daylight increases in the late winter and early spring, corresponding with increasing temperatures (Burn and Kokelj, 2009). Peak water levels in the Mackenzie River Delta typically occur during the early summer, and flooding regimes have impacts on the regional vegetation in the area (Burn and Kokelj, 2009). In the uplands, the water balance of thermokarst lakes is changing due to the warming temperatures, causing the precipitation regime to shift from historical dominance by snow to rain (Wilcox et al. 2023). Lake water balances are not responding uniformly to climate change, as some areas have experienced the expansion of thermokarst lakes, and other regions have demonstrated the contraction of thermokarst lakes and lake level lowering (Marsh et al. 2009, Korosi et al, 2017). The drivers of this non- uniformity include differing meteorological conditions, as well as the makeup of the watershed.

There is a stark change in vegetation throughout the delta region, resulting from the transition from the boreal forest ecoregion in the south, to the low- shrub tundra region characteristic of the northern part of the coastlands. The characteristics of the soil differ throughout the delta, with the southern regions experiencing a thick organic layer, whereas more northern parts of the delta are dominated by poorly drained, hummocky areas (Burn and Kokelj, 2009). Flooding and sedimentation strongly influence vegetation, resulting in varied regional vegetation (Burn and Kokelj, 2009). Although fire events are rare due to abundant evaporation and water bodies, they play an important ecological role. A particularly significant fire event occurred in 1968, and impacted the Inuvik area, up towards Noell Lake. This fire greatly impacted the landscape of the area, as it caused intense permafrost thaw, and active layer deepening which impacted the permafrost table, causing release of water to the base of the active layer as well as a flattening of the permafrost table (Mackay, 1995). Another major fire burned into the delta upland terrain in the late summer of 2023. Natural and anthropogenic disturbances greatly impact the vegetation, including disturbances such as retrogressive thaw slumps and drained lake basins, all of which play a role in the anticipated ecosystem changes because of climate change. Changes in snow patterns and snow accumulation have impacts on vegetation, as snow accumulation impacts water availability of the soil and temperature of the soil thereby impacting vegetation growth. Areas in the southern region experience increased snow depth and thereby increased density and height of shrub coverage, whereas areas in the northern region of the delta and uplands generally have lower snow coverage which allows for increased ground heat loss (Burn and Kokelj 2009). It is important to note, however, that local variations can occur because of the built environment in more built-up areas and communities (Burn and Kokelj, 2009).

### 1.4 Paleolimnological and remote sensing work on thaw slumps

Paleolimnology uses chemical and biological indicators preserved in sediment to reconstruct the history of the aquatic environment (Smol 2008). Paleolimnological studies have been ongoing in the Mackenzie Delta since the 1990s with particular emphasis since 2007 tracking thermokarst activity (Kokelj et al. 2005).

Contemporary limnological studies have shown that lakes impacted by retrogressive thaw slumping are characterized by higher concentrations of major cations and anions, lower DOC concentrations, and lower nutrient concentrations (including total phosphorus and total dissolved nitrogen concentrations) (Kokelj et al. 2005, 2009b, Thompson et al. 2012, Houben et al. 2016). These changes in chemistry are shown to cause rapid shifts in the sediment environment and impacts to lake biota (Bouchard et al. 2016).

Retrogressive thaw slumps affect the limnology of impacted lake environments (Houben et al. 2017). This includes lake clarity as lakes impacted by retrogressive thaw slumps experience initial turbid conditions, and this can influence lake productivity (Lewkowitz and Way, 2019). Lakes with older, stable slumps exhibit greater water clarity, from decreased concentrations of dissolved organic carbon compared to unimpacted lakes (Kokelj et al. 2005, 2009b). Retrogressive thaw slumps have been intensely studied in the Tuktoyaktuk Coastlands based on a series of lakes initially established by Kokelj et al. (2005). These observations show that thaw slumps, even when small, significantly impact lake water quality, due to the transportation of terrestrial soil and melted excess ice (Kokelj et al. 2009b). As the rate of slumping is expected to further increase due to increasing temperatures accelerating permafrost thaw, this has implications for the water quality for thousands of lakes throughout the Arctic (Lantz and Kokelj, 2008). Retrogressive thaw slumps do not just have implications for the water quality of lakes but also impact the aquatic flora and fauna. Lakes impacted by slumps have observable differences in macroinvertebrates, macrophytes, and changes in diatom assemblages (Mesquita et al. 2010, Moquin et al. 2014, Thienpont et al. 2013). Sedimentary diatoms have been used to track the timing of slump initiation, which is important as the exact timing of slump initiation is often unknown (Thienpont et al. 2013). The change observed as a result of slumping initiation was an increase in planktonic taxa, and species associated with varied substrate colonization (Thienpont et al. 2013). There has been a regional increase in slump area observed in the Mackenzie Delta, as well as the frequency of slump reactivation, which has implications for water quality of slump impacted lakes throughout the delta (van der Sluijs et al. 2023). It is important to understand the trends in retrogressive thaw development and understand the dynamic changes that occur because of polycyclic slumping.

Retrogressive thaw slumps are shown to have chemical impacts to the impacted lake system, due to the input of terrestrial material into the aquatic ecosystem (summarized in Bouchard et al 2016). This influx of terrestrial material and the contaminants which they may contain can impact the aquatic ecosystem. Mercury is an element that is often examined in paleolimnological studies, as it can be toxic to the ecosystem in high quantities and can be found in the toxic form of methyl mercury. A study by Deison et al. (2012) found that both total and methyl mercury concentrations were lower in lakes impacted by slump activity when compared to lakes with no slump activity, due to the presence of a greater quantity of inorganic material. However, other contaminants such as polychlorinated biphenyls and pesticides were found in higher concentrations in lakes impacted by thaw slumps (Eickmeyer et al. 2016).

Retrogressive thaw slumps can impact the delivery of other contaminants to the aquatic environment, including polycyclic aromatic compounds (PACs) (Thienpont et al. 2020). PACs are found from both natural and anthropogenic sources, and some of these compounds have been found to be mutagenic and carcinogenic to aquatic biota, which is a concern when it comes to maintaining the health of aquatic ecosystems in the Arctic. These compounds are produced through combustion processes (pyrogenic) and from petrogenic sources (Korosi et al. 2015). The role of these contaminants is particularly important when it comes to the Mackenzie Delta region as PACs are associated closely with hydrocarbon deposits, which are abundant throughout the region (Thienpont et al. 2020). PACs had been found in sediment records of lakes in the Mackenzie Delta but had not been associated with permafrost thaw and resulting disturbances resulting from rapid change to the temperature and landscape. A study addressing this previous knowledge gap demonstrated that slump-impacted lakes showed higher concentrations of PACs in their sediments, as well as higher concentrations of several other metals, such as Ca, Sr, and Mn (Thienpont et al. 2020). When tracing the source of PACs to the system, it was found that the composition of PACs found in slump-impacted lakes were more indicative of petrogenic sources when compared to those in reference lakes. There are two main processes that can explain the elevated concentrations of PAC in lakes which are impacted by retrogressive thaw slump activity. The first is the input of PAC from terrestrial sources within the catchment when slumping occurs, and the second is solvent switching, which results from the low organic carbon content found in lakes with slump activity (Thienpont et al. 2020, 2025), similar to what was described for polychlorinated biphenyls (Eickmeyer et al. 2016). These impacts to the aquatic environment demonstrate the importance of using data preserved within the sediment to understand the impacts thaw slumps have to nutrient and contaminant delivery to aquatic ecosystems.

Remote- sensing techniques have also been used to track changes in the environment throughout the Mackenzie Delta, Tuktoyaktuk Coastlands, and western Canadian Arctic. Nguyen (2009) used remote-sensing techniques to estimate the extent of near-surface permafrost throughout the Delta region. This study used SPOT-5 imagery to validate the results of field surveys, using the Normalized Difference Vegetation Index (NDVI) and Modified Soil Adjusted Vegetation Index (MSAVI) for classification. The results from this research show that near-surface permafrost occupied over 93% of the land surface, which furthers findings that the

Mackenzie Delta is part of the continuous permafrost zone. This research demonstrates the advantage of using remote sensing and satellite data to validate and improve findings from the field across broad geographic areas.

Remote sensing techniques have also been used to track thaw slumping throughout the Mackenzie Delta region. Lantz and Kokelj (2008) used aerial photographs of the study area in 2004, 1950 and 1973 to track thaw slump growth in the Delta and surrounding uplands. The findings from this study demonstrated that from 1973-2004, the rate of slump growth increased, coinciding with increased temperatures.

Remote sensing data can be used to track not only changes to the physical environment but also changes to the chemical environment as a result of permafrost thaw. Kohnert et al. (2018) used remote sensing techniques to understand the impacts water bodies in the delta have on methane emissions. They did this by cross referencing the $CH_4$ flux map with waterbody maps at high resolution, and classifying waterbody depth based on Sentinel-1 data. This allowed for the examinations of trends between waterbody characteristics and the $CH_4$ flux. The results from this work showed that although waterbodies can have above average emissions on a small scale, on a regional scale it does not translate into significant $CH_4$ emissions. Techniques have also been employed to track dissolved organic carbon (DOC). Juhls et al. (2022) used Satellite Ocean Colour Remote Sensing (SOCRS) with Sentinel-3 data to examine seasonal variation of DOC concentrations in the surface waters of the Beaufort Sea, throughout the open water period. What the findings suggest is that the highest DOC concentrations were found in spring, following the ice breakup in the Mackenzie River and subsequent freshet, indicating strong seasonal variation in DOC transport in the Mackenzie-Beaufort region (Juhls et al. 2022).

Remote sensing techniques can aid in mapping and tracking the development and re-activation of retrogressive thaw slumps. Nitze et al. (2021) utilized a deep learning approach to map retrogressive thaw slumps. As monitoring retrogressive thaw slump activity is a labour-intensive task, the development of deep learning techniques and other high-resolution remote-sensing data can allow for more data to be mapped and collected in a more time efficient manner. This research found that the regional models developed worked well for some areas, but spatial transferability between regions was an issue (Nitze et al. 2021). This is a broader issue that is prevalent when it comes to using remote-sensing data; it can be difficult to draw conclusions about one region and apply it to another region, especially as the environment in the Arctic is very dynamic. Even with advances in remote sensing and deep learning technology, it is most effective to use these techniques in conjunction with field observations.

In Rodenhizer et al. (2024), comparisons were made between WorldView, PlanetScope, and Sentinel-2 in their ability to detect retrogressive thaw slumps, to improve mapping and selection of data used for mapping of retrogressive thaw slumps in future studies. This study is useful as deciding which satellite platform to use is very important as thaw slumps can be varying sizes, thus ensuring that the imagery has sufficient spatial resolution to allow for identification of even small retrogressive thaw slumps is essential. An important factor to think about when selecting data is the availability of open-source data, and the value in terms of improved analysis that comes with paying for higher resolution data, such as WorldView imagery. The findings from Rodenhizer et al. (2024) did show differences between the platforms. WorldView had the best performance and had a smaller detection threshold when compared against the results from PlanetScope and Sentinel-2 (Rodenhizer et al. 2024). With all three platforms, there were some retrogressive thaw slump features that were undetected, although no features that went undetected were larger than 0.46 ha (Rodenhizer et al. 2024). Interestingly, the size of the undetected features did not correspond to the image's spatial resolution, as it was found that despite Sentinel-2 being a lower spatial resolution that PlanetScope, it had less undetected retrogressive thaw slump features (Rodenhizer et al. 2024).

Along with differences resulting from the sensor platform, there are other characteristics of retrogressive thaw slumps that play a role in their detection. Luminance of the slump was found to be an important factor in their detections, especially in the PlanetScope images, where many times the slump could only be identified by their bright pixels (Rodenhizer et al. 2024). In contrast, slumps with higher plant cover made it challenging to detect slump activity, as models of detection often rely on identifying pixels consistent with bare soil (Rodenhizer et al. 2024). This makes it difficult to be able to track a slump when it stabilizes and becomes revegetated. Another challenge identified with the model was identifying areas that were wet, had patchy ground cover, or were additionally disturbed. This made it difficult to isolate the areas affected by slumping from the background pixels, especially in the PlanetScope model (Rodenhizer et al. 2024).

There are also regional challenges when it comes to using remote sensing data to track and map retrogressive thaw slumps. Rodenhizer et al. (2024) looked at seven sites, in both Arctic Canada and Russia: Banks Island, Herschel Island, Horton Delta, and Tuktoyaktuk in Canada; and Kolguev Island, Lena River, and the Yamal and Gyadan Peninsulas. For example, even using WorldView imagery, which has the highest spatial resolution of the three different platforms, 32% of thaw slump features in the Yamal/Gyadan region went undetected, which was the best performance of all the three platforms. Changes in headwall heights, and other morphological features of the slump change regionally. These findings show the advantages of being able to use remote sensing data in order to track and map retrogressive thaw slump development with increased accuracy, and over a larger area, but highlight the regional variability that can occur in model output and performance.

## 1.5 Thesis organization and rationale

Shoreline retrogressive thaw slumps are an important permafrost mass wasting feature in morainal terrain of the Tuktoyaktuk Coastlands (western Canadian Arctic), being found to impact ~10% of lakes in the region (Lantz and Kokelj 2008). Observations throughout the Tuktoyaktuk Coastlands have demonstrated that highly active retrogressive thaw slumps result in increased turbidity in impacted lakes, which alters the clarity of the water due to the increased presence of suspended sediments (Thienpont et al. 2013) (Figure 1.1). As the slumps stabilize overtime, the lakes undergo a transition in water chemistry and the aquatic environment becomes characterized by clear waters, low DOC and nutrients, and a high concentration of major ions (Kokelj et al. 2005, 2009a). The lake rarely recovers from this limnological state, instead undergoing repeated cycles of thaw slumping and stabilization, termed polycyclicity (Kokelj et al. 2009a, Thienpont et al. 2025). Historically, lakes impacted by thaw slumps that reactivate do not return to conditions associated with new slump activity, such as high turbidity, nor do they often fully recover to the high DOC condition associated with non-slumped reference systems. However, as climate warming intensifies the rate of slump growth and the size of thaw slumps, we are seeing in several cases that highly active thaw slumps result in an enhanced slumping affect and may return to the high turbidity state more alike the initial slump impacts observed with a naïve thaw slump (Figure 1.1). Previous paleolimnological evidence has been used to hypothesize that the initial onset of thaw slumping impacts is what causes the most significant changes to the lake water and sediment environment (Thienpont et al. 2025). This demonstrates that slump lakes exhibit a form of ecological memory, as a result of material legacy found in the translocated sediments, which may prevent aquatic ecosystem recovery over long timescales. Figure 1.1 shows a model developed to understand the changes in lake state associated with slump activity in polycyclic slumps of the Tuktoyaktuk Coastlands. The ball represents the lake state, and the height of the depression indicates the magnitude to change required to push the ball from one cup to another (i.e., change lake state). There is a lot of research that has been done looking at active/ stable slumps and their polycyclic nature. My thesis work focuses specifcally on the highly active, enhanced slumping effect using both a paleolimological approach and remote sensing analysis. This is especially important to look at as the temperatures continue to warm in the Arctic.

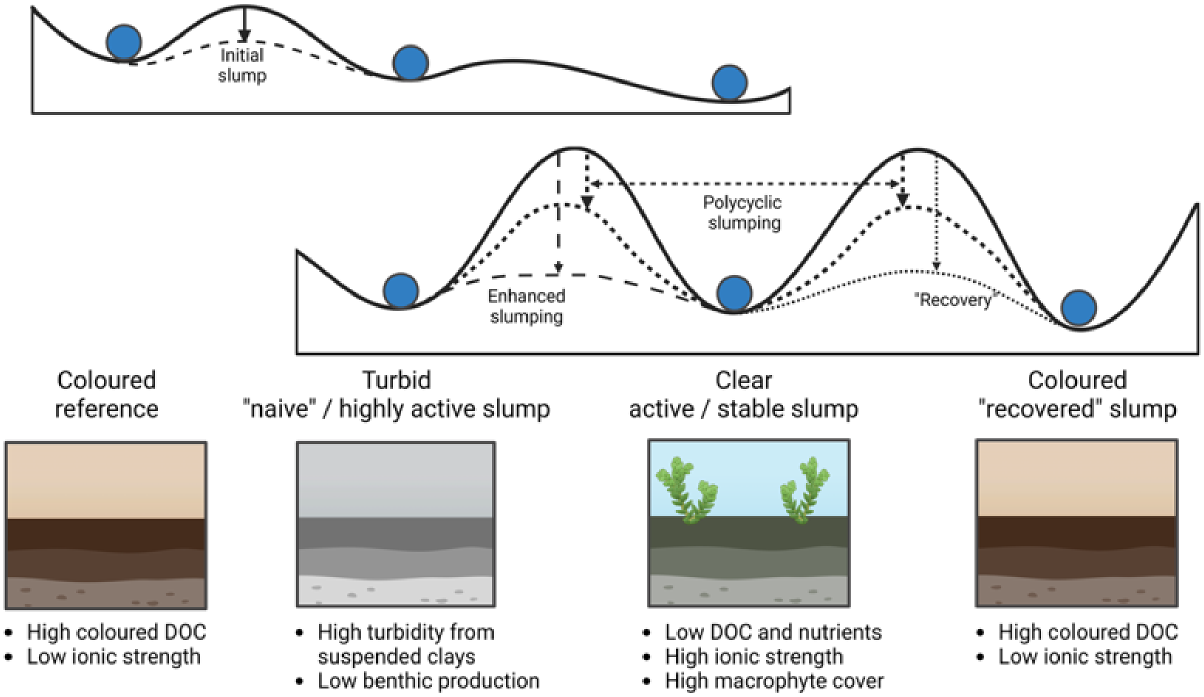

*Figure 1.1: Conceptual Model (Published under CC BY-NC-4.0 in Thienpont et al. 2025 ) proposing how the lake environment is impacted at different stages of thaw slump development and polycyclic slumping*

This project will examine six slump-impacted lakes throughout the Mackenzie Delta uplands / Tuktoyaktuk Coastlands, NWT (Figure 1.2) These lakes were selected as a subset of lakes from a larger group of lakes being studied as part of the NWT Thermokarst Mapping Initiative (TMI) (Kokelj et al. 2023). This initiative is a partnership with the purpose to improve our understanding of permafrost conditions and thermokarst dynamics throughout the Northwest Territories. The TMI also aims to inventory and map permafrost landscape features and improve mapping techniques. Unofficial lake names for this study follow nomenclature that is being applied to lakes in thermokarst terrain across the Northwest Territories. In my study, lakes are coded as morainal lakes (ML) in the Caribou Hills ecoregion (CH), that are slump- affected (S), resulting in a code of ML-S_CH, followed by a unique lake number. For example, lake ML-S_CH_14 was previously referred to as lake 14B in publications, but the new schema allows this lake to be better understood in ongoing comparisons across the Territory. The six study lakes for my thesis are located surrounding Noell Lake, a much larger lake in the Mackenzie Delta uplands region, approximately 25 km northeast of the town of Inuvik. The lakes were of varying sizes, ranging from 39,000 $m^2$ at the smallest, to 484,000 $m^2$ at the largest. The slump sizes also varied, ranging from 5,000 $m^2$ to 82,000 $m^2$ (Table 1.1). The thaw slumps take up varying parts of the lake catchment, as the lake with the largest lake area does not correspond with having the largest slump size.

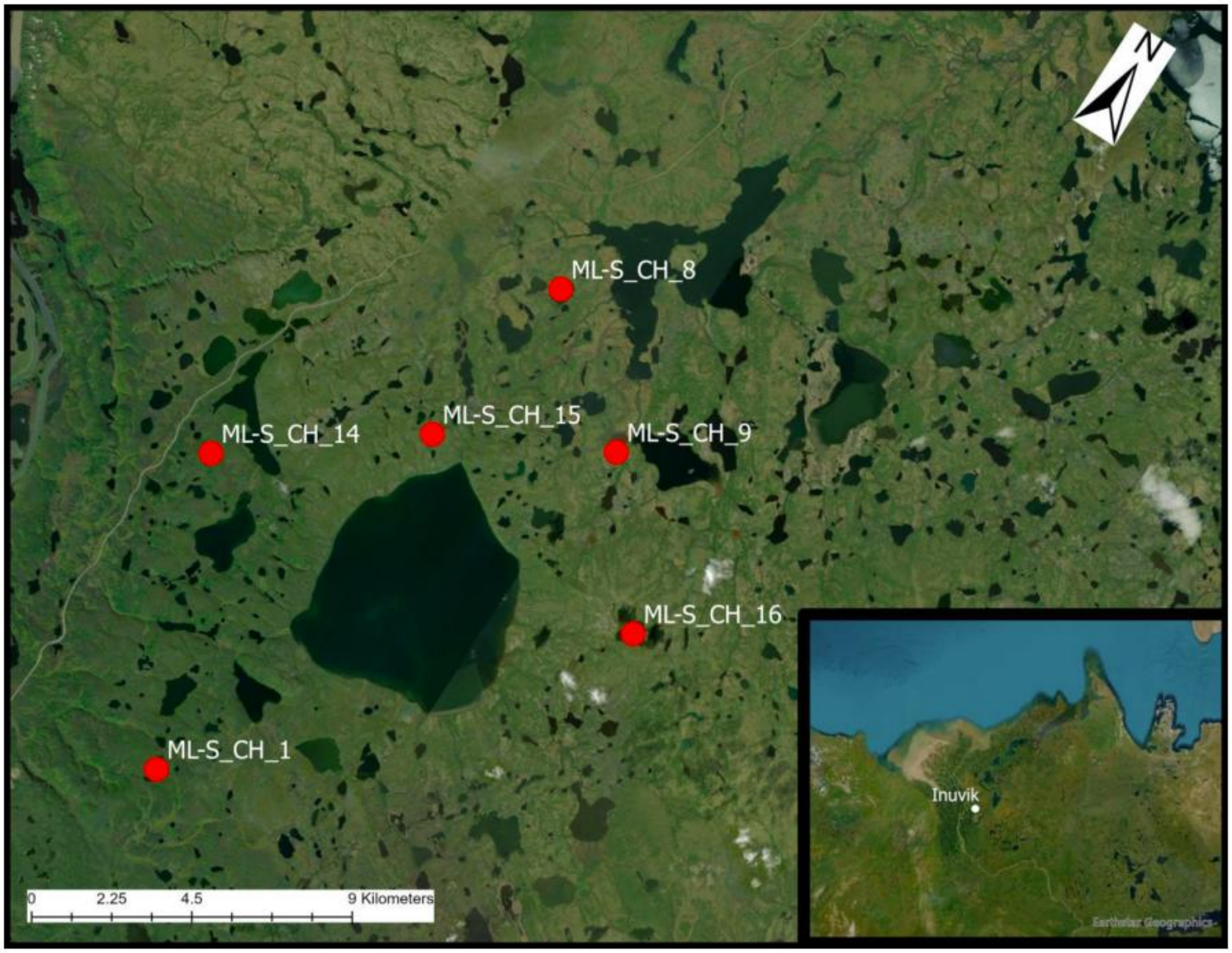

*Figure 1.2: Map of study area*

*Table 1.1: Lake area and lake size of each of the six study lakes*

| **Lake ID** | **Lake Area (m²)** | **Slump Area (m²)** |
|---|---|---|
| ML-S_CH_1 | 153,477.81 | 29,758.91 |
| ML-S_CH_8 | 314,878.29 | 56,923.79 |
| ML-S_CH_9 | 308,700.67 | 19,592.54 |
| ML-S_CH_14 | 81, 473.83 | 82,006.72 |
| ML-S_CH_15 | 39,009.41 | 5,253.37 |
| ML-S_CH_16 | 484, 055.75 | 19,958.16 |

The aim of this research is to assess the impacts of large retrogressive thaw slump in the Mackenzie Delta region and understand their unique impact on the aquatic environment. To test aspects of the model presented in Figure 1.1, the six lakes have large, highly active thaw slumps on their shorelines. As this enhanced slumping may become more important as the region rapidly warms and permafrost thaw accelerates, understanding the dynamics of this lake type is of particular concern. In addition, lakes with highly active thaw slumps have been understudied in paleolimnological and remote sensing analyses in the Tuktoyaktuk Coastlands to date. This is because most analyses have been carried out on the initial lake set developed by Kokelj et al. (2005), which focused on lake pair similarity between one slump-impacted and one reference system, and most of the slump-impacted lakes were of the clear, polycyclic lake type.

In Chapter 2, this research utilized a paleolimnological approach to assess the six lakes over time with the methodological approach focused on sedimentary geochemical characteristics using total organic carbon, total nitrogen, C:N ratios in organic matter, as well as total mercury. To be able to track the timing of changes in the sediment record, sediment core chronologies were established by dating the sediment core samples, using $^{210}$Pb radioisotopic techniques (Appleby 2001).$^{210}$Pb has a half life of 22.3 years, and thus this method can provide models of both sediment age and estimate the rate of sedimentation, spanning the last century, which covers the period of accelerated thaw slumping. Important chemical indicators such as mercury, carbon, and nitrogen were examined. Analyzing mercury in the lake sediment will help determine to what extent highly active retrogressive thaw slumps impact delivery of mercury to lakes. A knowledge gap when it comes to understanding mercury dynamics in lakes is the ability to analyze changes to mercury concentrations occurring because of climate change. Sedimentary carbon concentrations can also allow us to better understand mercury dynamics within lakes. Organic matter content has been previously shown to be a reliable indicator of thaw slump impacts in lake sediments (Thienpont et al. 2025) and will be applied here to track these enhanced slumps.

In Chapter 3, remote-sensing analyses were used to examine the impacts retrogressive thaw slumps have on the aquatic environment. Remote sensing techniques are useful, especially when used in conjunction with field observations, as they allow for visual analysis of data over the last several decades in regions that are difficult to access, and lack *in situ* monitoring stations. Choosing which satellite platform to use is an important step in analysis. Since the thaw slumps vary in size, it is important to take into the account the resolution of the imagery. Cost is an important factor as well, as there are many high-resolution satellites that are not broadly, freely available. As such, Sentinel and Landsat data were both considered for this project. Landsat imagery satellites have a spatial resolution of 30 m, and Sentinel-2 data has a spatial resolution of 10 m. Given the small size of the slump impacted lakes, Sentinel data was used.

Using available data, turbidity within impacted lakes was examined. As it is predicted that enhanced thaw slumping increases turbidity within impacted lakes, turbidity indices were used as a proxy for slump activity in this project. Normalized Difference Turbidity Index (NDTI) was computed using data from each slump lakes. NDTI uses the red and green bands, the ratio of which is a proxy for turbidity, and is especially useful in inland waters (Lizcano- Sandoval et al. 2022). The NDTI results of the six impacted lakes were compared against three reference lakes, in order to validate results and examine seasonal patterns in turbidity in both slump-impacted and non-slump impacted lakes in the Tuktoyaktuk Coastlands.

The overall goal of this thesis was to work towards a better understanding of the changes that are occurring to northern ecosystems because of warming temperatures in the Arctic, especially as temperatures continue to increase at a rapid rate. These changes have implications for the stability of the environment, and infrastructure. The aim of this study was to address research gaps in understanding the implications of permafrost thaw, which is critical as poor accessibility to much of the Arctic make long term, continuous monitoring difficult.

This work examining the impacts of large, highly active thaw slumps is significant as it is expected that as temperatures continue to increase throughout the Mackenzie Delta increasing the rate of permafrost thaw, the rate of retrogressive thaw development and re-activation of old slumps will also increase. The Mackenzie Delta uplands is a well-studied region, and as such there is research that demonstrates the impacts of polycyclic slumps, and many of these slumps have been studied and tracked over a long period of time. My research aimed to address the knowledge gap in our understanding of the impacts of large, highly active slumps occurring due to environmental change and their impacts to both the physical and chemical environment of impacted lakes. The findings from this research contributes towards a better understanding of the changes we can expect to see in lakes throughout the Arctic, as increasing temperatures accelerates permafrost thaw.

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# Chapter 2: A paleolimnological assessment of six lakes impacted by intense shoreline retrogressive thaw slumping in the Mackenzie Delta uplands (Northwest Territories, Canada)

## 2.1 Abstract

This paleolimnological study assesses the effects of thaw slump activity on six lakes impacted by retrogressive thaw slumps in the Mackenzie Delta uplands region, NWT. Paleolimnological techniques allow for changes within the lake sediment environment to be reconstructed, providing insight into how the lake environment has been changed over time, and how historical events have impacted aquatic systems. Sediment core samples as well as water samples were taken from each of the six slump-impacted lakes. The sediment samples were analyzed for total mercury and elemental analysis, to assess how thaw slump activity is impacting mercury and carbon dynamics within the lakes. These findings were compared with reference lakes and previous paleolimnological studies of slump-impacted lakes in the region, to assess if these lakes behave in a manner typical of other lakes impacted by stable/active slump activity. One lake, ML-S_CH_9 was an exception to the findings from the other five lakes. At this lake, there was very low mercury and very low/no organic carbon found in an interval near the top of the sediment profile. This demonstrates that there was a significant disturbance to the lake, due to a large influx of inorganic material. These findings are significant because it is important to examine how thaw slump dynamics will be impacted by continued temperature warming and climate change in the western Arctic.

## 2.2 Introduction

The Mackenzie Delta uplands is a region located in the Western Canadian Arctic and is an area that has experienced significant warming, as well as an increase in permafrost temperatures leading to permafrost degradation (Thienpont et al. 2013, Burn and Kokelj 2009). As a result of this permafrost degradation in locations near the extent of the Laurentide Ice Sheet, there has been an increase in thermokarst features on the landscape (Kokelj et al. 2017). One of these features are retrogressive thaw slumps which are a rotational slide feature found on the shore of water bodies and are one of the most widespread and significant disturbance mechanisms found in the Mackenzie Delta uplands (Costard et al. 2021). Previous studies that have been done comparing lakes impacted by slump activity to reference lakes without slump activity show that retrogressive thaw slumps have impacts on water quality, as well as the aquatic ecosystem (Kokelj et al. 2005, Kokelj et al. 2009a, Mesquita et al. 2010, Moquin et al. 2014).

Reconstructing the history of lakes can give us insight into how lakes have been changing overtime. Paleolimnology is the study of past aquatic environments, looking at physical, chemical and biological information stored within the sediment profile of a water body (Smol 2008). This can be especially important when it comes to tracking disturbances in the aquatic environment. Sediment is collected using sediment cores and are assessed using the paleolimnological assumption that sediment found at the top of the sediment profile was more recently deposited than sediment found deeper in the profile, meaning that sediment at the top of the core is newer than sediment found deeper in the profile (Glew and Smol 2002).

Each of the six study lakes chosen for this study were sampled for sediment mercury and carbon and nitrogen to assess the impacts thaw slumps have on mercury and organic matter dynamics assess the source of carbon to the system. Mercury is an important element in lakes, and previous analysis of slump-impacted lakes have shown that total mercury concentrations are lower in lakes impacted by thaw slumping when compared to reference lakes. (Deison et al. 2012). As a result of slump activity, lakes impacted by thaw slumps have a higher sedimentation rate when compared to lakes with no slump activity, which explains why slum- impacted lakes have lower total mercury and methylmercury concentrations due to inputs of inorganic, siliclastic material (Deison et al. 2012). In Deison et al. (2012), it was found that the mercury concentrations in the samples of clay taken from the slump were very low (~ 75 ng/g dw), so it follows that this material would play a role in the reduction of overall mercury within the impacted lakes. Thaw slumps have also been found to impact total organic carbon (TOC) concentrations in impacted lakes, as lakes impacted by thaw slumps have been found to have clearer waters with low TOC concentrations when compared to reference lakes with no slump activity (Kokelj et al. 2005, Deison et al. 2012). There is a strong relationship between mercury and TOC, which indicates that TOC plays an import role in the deposition of mercury to the sediment. As such, TOC concentrations were assessed in each of the six slump lakes, as research suggests that a decrease in organic matter driven by inputs of inorganic siliclastic material from the slump results in reduced mercury concentration in the sediment (Deison et al. 2012), but this has not been tested for enhanced, highly active thaw slumps. There was also observed to generally be higher algal- derived carbon in reference lakes than slump lakes, also a result of dilution from inorganic siliclastic matter from the slump (Deison et al. 2012).

There has been work done assessing the biological impact of slump activity on aquatic ecosystems, using a paired lake study examining diatoms in both slump-impacted and unimpacted lakes (Thienpont et al. 2013). The results showed a general shift in diatom species to a more complex assemblage in slump-impacted lakes, due to enhanced water clarity. However, the intensity of change and the timing of the shift varied, due to the size and intensity of the thaw slump, as well as the differences in sediment type which played a role in the biotic response. Thaw slump activity can also have impacts on the POP (persistent organic pollutants) in impacted lakes (Eickmeyer et al. 2016). POPs are problematic as they have significant impacts to health due to their ability to bioaccumulate, and their toxicity in low concentrations. What this research found was that due to the reduced organic carbon in slump -impacted lakes, this resulted in higher concentrations of POPs when compared to reference lakes (Eickmeyer et al. 2016). Higher POP concentrations observed in lakes impacted by thaw slumps are thought to be as a result of solvent switching processes of hydrophobic organic contaminants onto a smaller pool of available organic carbon when compared to neighboring lakes unaffected by thaw slump development. Thaw slumps were also found to impact the delivery of polycyclic aromatic compounds (PACs), as both TOC and PACs were higher in slump-impacted lakes when compared to reference lakes, especially within the surface sediments (Thienpont et al. 2020).

Loss on ignition (LOI) techniques have been used to examine changes in sediment composition between reference lakes and lakes impacted by thaw slump activity (Thienpont et al. 2025). By the combustion and weighing of samples at different temperatures, the content of organic matter, carbonate, and siliclastic material can be assessed. The results from this analysis demonstrate that lakes impacted by slump activity have higher amounts of siliclastic material in their sediment, whereas unimpacted lakes have higher concentrations of organic matter in the sediment (Thienpont et al. 2025). This research aims to answer and expand on our understanding of the impacts of large, highly active thaw slumps on the aquatic environment, and assess the drivers of these changes. We assess the differences between the identified highly active thaw slumps, and previous studies done on polycyclic slumps in the Mackenzie Delta uplands, to assess differences in the lake's response, as inferred from the sediment profile.

## 2.3 Methods

### *2.3.1 Field Sampling*

Six study lakes impacted by active, intense shoreline retrogressive thaw slumps were selected in the eastern uplands bordering the Mackenzie Delta (Figure 2.1). A paleolimnological approach allows us to reconstruct the history of each lake, and to understand the impact that the slump feature has had on the lake in the context of other environmental changes that may be occurring. This methodology was used to assess if any of the six lakes had undergone a change in state due to the presence of a recent, highly active slump and to observe how this affected the sediment record. This research also addresses how the lake responds to this change, and how the findings differ from other retrogressive thaw slump studies in the region (Thienpont et al. 2025; Figure 1.1). In the summer of 2023, each of the six lakes were accessed by helicopter, and a sediment core was taken from the lake. The core was taken from a small raft at an approximately central point of the lake, under the assumption that most of the sediment will end up deposited in the centre/deepest point of the lake, allowing us to reconstruct the whole of the lake community with a single core (Luo et al. 2023). Bathymetric data are not available for these small lake ecosystems, so a central location was selected. At the time of sampling, a water quality probe (Yellow Springs International) was used to take selected *in situ* measurements of surface water parameters at each of the six slump-impacted lakes.

Sediment cores were collected using a UWITEC gravity corer. The cores of each lake varied in length from 15 to 42 cm. After the cores were taken, they were transported to the Aurora Research Institute in Inuvik, Northwest Territories. Each core was sectioned at 0.5 cm intervals using a vertical extruder, to capture high-resolution data from the sediment samples (Glew 1988). The samples were then put into labelled Whirlpak bags for storage of each interval. They were then kept cool in the fridge (~4ºC) in the ARI lab, until they could be transported back to the lab at York University in Toronto for analysis. Samples of surface water were also collected during sampling, with samples analyzed at the Taiga Environmental Laboratory (Yellowknife, NT) a CALA accredited laboratory.

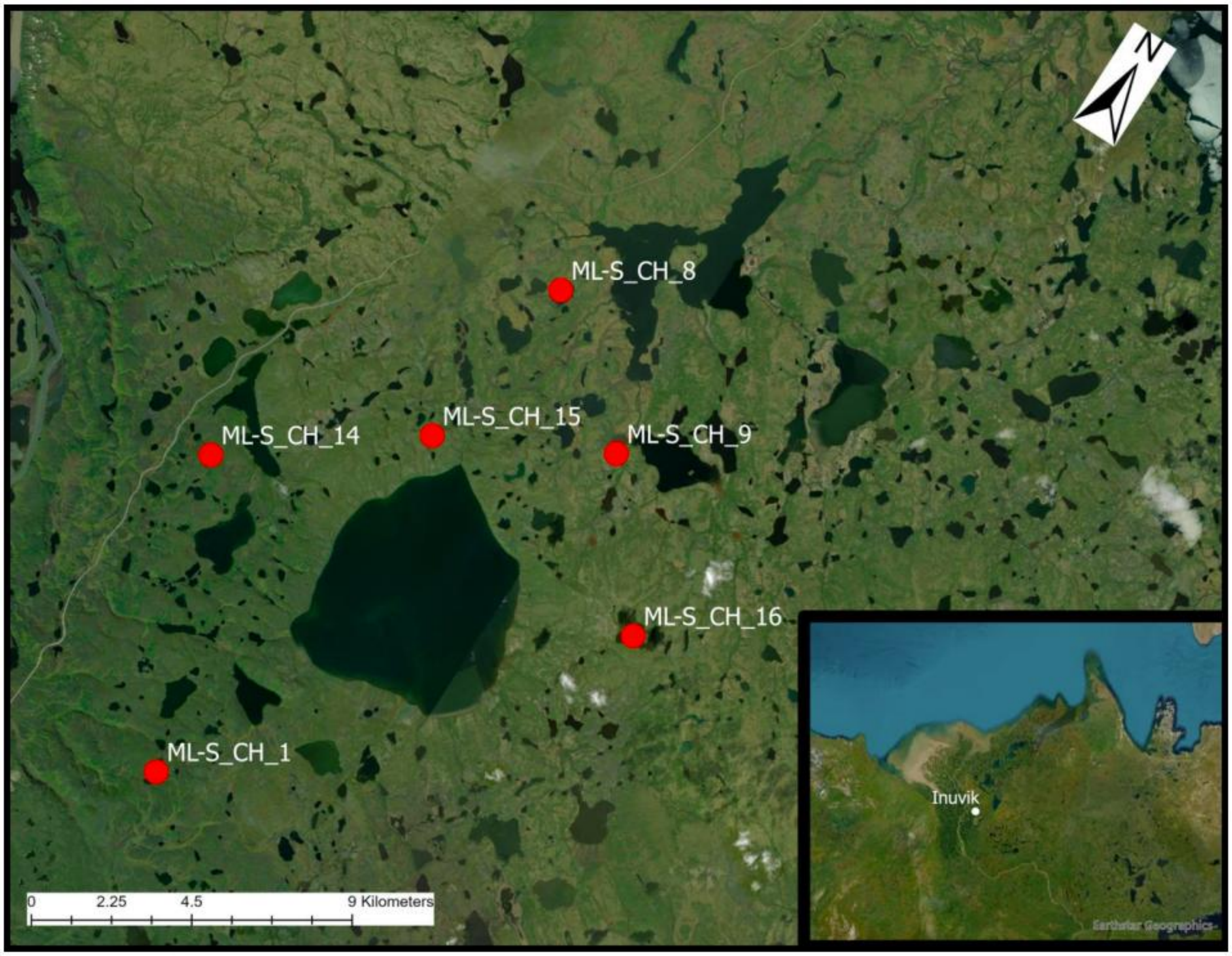

*Figure 2.1: Map of study site*

### *2.3.2 Laboratory methods*

Selected intervals were lyophilized in preparation for geochemical analysis and $^{210}$Pb dating. To determine sediment core chronologies, samples were dated using $^{210}$Pb radioisotopic techniques (Appleby 2001). This is one of the most important means for dating sediments in recent time, typically up to 150 years ago (Appleby 2001). This method of dating uses $^{210}$Pb, which has a half-life of 22.3 years and is a natural radioactive isotope of lead. This method of dating is the most useful and accurate for dating recent lake sediments, especially when used in stable environments that have a steady sediment accumulation rate (Appleby 2001). This method has also been proven to have good results in areas that do not have uniform accumulation, but there is more difficulty in this case when it comes to choosing the most appropriate method (Appleby 2001). Dried samples were entombed in epoxy resin, allowed to equilibrate, and analyzed on a high-purity Ortec germanium-well type detector via gamma spectroscopy at the Paleoecological Environmental Assessment and Research Lab at Queen's University. The constant rate of supply (CRS) model, which is representative of a constant rate of unsupported $^{210}$Pb from the atmosphere, was used to determine sediment ages in this study.

### *2.3.3 Mercury Analysis*

Freeze-dried samples were analyzed for total mercury using a Milestone DMA-80 Direct Mercury Analyzer. This method involves the process of thermal decomposition, gold amalgamation and detection atomic absorption spectrometry. Thermal decomposition releases volatile components (water, carbon dioxide, organic substances, etc.), and flowing oxygen carries the decomposition products to the amalgamator. The amalgamator traps mercury and is flushed with oxygen which removes all other degradation products, and then the amalgamator is heated rapidly to release the mercury vapour, which is carried to the absorbance cells. The mercury vapour is carried by flowing oxygen into the absorbance cells, and a detector measures the transmitted light to calculate absorbance. To ensure validity and accuracy of results, three blanks were run at the beginning of each run of samples, as well as the regular use of MESS-4 standard materials, which were run approximately every 15 samples to ensure accuracy throughout the run.

### *2.3.4 Elemental Analysis*

Elemental analysis was conducted on samples from each of the six lakes, to assess changes to total organic carbon, total nitrogen and the ratio of carbon and nitrogen. The C:N ratio is often used in paleolimnological studies to determine the source of carbon to the system. Sediment with autochthonous origin will have an elemental C:N ratio between 4 and 10, while allochthonous sources of carbon will have a C:N ratio >20 (Meyers and Terranes 2001). Our previous research has shown that lakes impacted by slump activity have lower organic matter and higher silicate concentrations, when compared to reference lakes unimpacted by retrogressive thaw slumps (Thienpont et al. 2025). TOC was assessed to see the impact that the slump activity had on organic carbon within the lake.

Prior to elemental analysis samples were acidified via fumigation in a hydrochloric acid bath to remove inorganic carbonates. After the digestion, samples were then rinsed at least 7 times with distilled water and centrifuged to facilitate faster settling. Samples were re-lyophilized and run on an Elementar Unicube elemental analyzer set to CN mode. Regular blanks, and soil standards were included in the analysis, and the instrument underwent twice daily correction using sulfanilamide, as well as comparison to reference soil standards.

## 2.4 Results

### *2.4.1 Surface water quality data*

*Table 2.1: Surface water quality data from each of the six study lakes*

| Site | Temperature (˚C) | Specific Conductivity( uS/cm) | pH | Turbidity (NTU) | O2 concentration (mg/L) | O2 Saturation (%) |
|---|---|---|---|---|---|---|
| ML-S_CH_9 | 21.7 | 140 | 7.4 | 6 | 9.5 | 107.6 |
| ML-S_CH_8 | 22.1 | 195 | 7.4 | 1.1 | 10.3 | 118 |
| ML-S_CH_1 | 21.5 | 249 | 7.4 | 0.9 | 9.53 | 107.9 |
| ML-S_CH_14 | 22.1 | 1053 | 7.4 | 1.4 | 9.8 | 112.4 |
| ML-S_CH_15 | 20.6 | 391 | 7.5 | 0.9 | 9.57 | 110 |
| ML-S_CH_16 | 22.3 | 122 | 7.3 | 5.3 | 9.55 | 109.7 |

Water quality was taken at each of the six slump lakes (Table 2.1). The temperature was similar in each of the six slump lakes, ranging from 20.7˚C to 22.3˚C. The specific conductivity ranged between 122-1053 uS/cm, with ML-S_CH_14 having a specific conductivity of 1053 uS/cm, substantially higher than the rest of the five lakes, which ranged between 122-391 uS/cm. pH was also sampled, and was very stable only ranging between 7.3-7.5. Turbidty (ntu) ranged between 0.9 and 6, with ML-S_CH_9 and ML-S_CH_16 having higher turbidity than the rest of the lakes, at 6 and 5.3 ntu respectively. $O_2$ concentrations in each of the six lakes ranged from 9.5- 10.3 mg/L. Based on these concentrations, $O_2$ saturation ranged between 107.6% and 118%.

### *2.4.2. Radiometric dating results*

The results of the dating analysis allow for us to infer when in time changes in the sediment core occurred. In ML-S_CH_1, the core reached background at the 4-4.5 cm interval, with a date of 1920. In ML-S_CH-9, the core reached background at the 7-7.5 cm interval, with a date of 1937. In ML-S_CH_14, the core reached background at the 7-7.5 cm interval, with a date of 1911. In ML-S_CH_16, the core reached background at the cm interval, corresponding with a date of 1968. Lakes ML-S_CH_8 and ML-S_CH_15 were both sent for dating but did not yield usable results.

### *2.4.2 Elemental Analysis*

In each of the six slump lakes, TOC (%) was analyzed (Figure 2.2). In ML-S_CH_15, TOC ranged between 1.5 and 3.2, indicating relatively stable TOC concentrations over the length of the core. In ML-S_CH_16, TOC concentrations ranged between 4.1% and 9.6, showing a wider range in its concentration over time. In this lake, there was a strong decrease in TOC at the top of the core. In ML-S_CH_9, TOC ranged from <0.1 to 4.5%. This lake experienced a large drop in TOC, from 3.8% at the 4 cm interval to <0.1% at the 5 cm interval, increasing back up to 4.5% at the 6 cm interval. In ML-S_CH_8, TOC ranged from 4.0% to 8.1%, with a general decreasing trend with depth. In ML-S_CH_1, TOC ranged from 3.6 to 5.9%, with a general decrease with depth from the top to middle of the core, and a general increase in TOC from the middle to bottom of the core. In ML-S_CH_14, TOC ranged from 2.1 to 5.9%, with a slight increase in TOC between the top and bottom of the core.

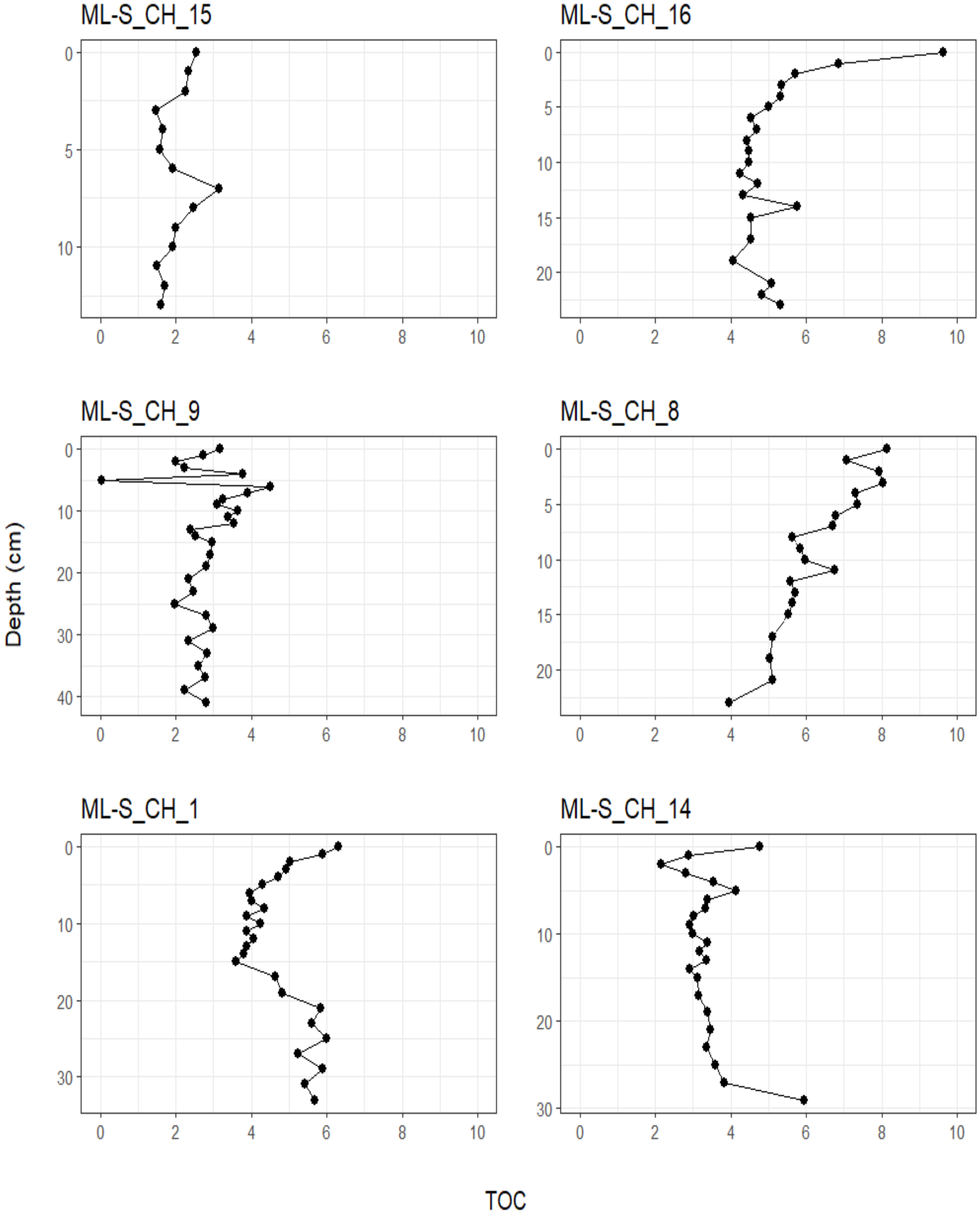

*Figure 2.2: Total organic carbon (%) in each of the six slump impacted lakes*

The C:N ratio was also assessed in each of the six slump-impacted lakes, to assess the source of carbon to the system (Figure 2.3). In ML-S_CH_15, the C:N ratio ranged between 14.7 and 36.5 The C:N ratio was relatively stable, apart from at the 7 cm interval, where the C:N ratio jumped to 36.5 from the 6 cm interval where it was 18.9, before dropping down to 18.1 at the 8 cm interval. In ML-S_CH_16, the C:N ratio was very stable with no discernable change, ranging from 7.5 to 10.2. In ML-S_CH_9, the C:N ratio was relatively stable ranging from 9.5 to 13.7. A notable exception to this trend was at the 5 cm interval, where the C:N was 2, dropping from 12.4 at the 4 cm interval and back up to 13.7 at the 6 cm interval. In ML-S_CH_8, the C:N ratio was relatively stable, ranging from 7.7 to 12.3. In ML-S_CH_1, the C:N ratio was very stable, ranging from 8.8 to 11.4. ML-S_CH_14 also had a very stable C:N, ranging from 9.4 to 12.0.

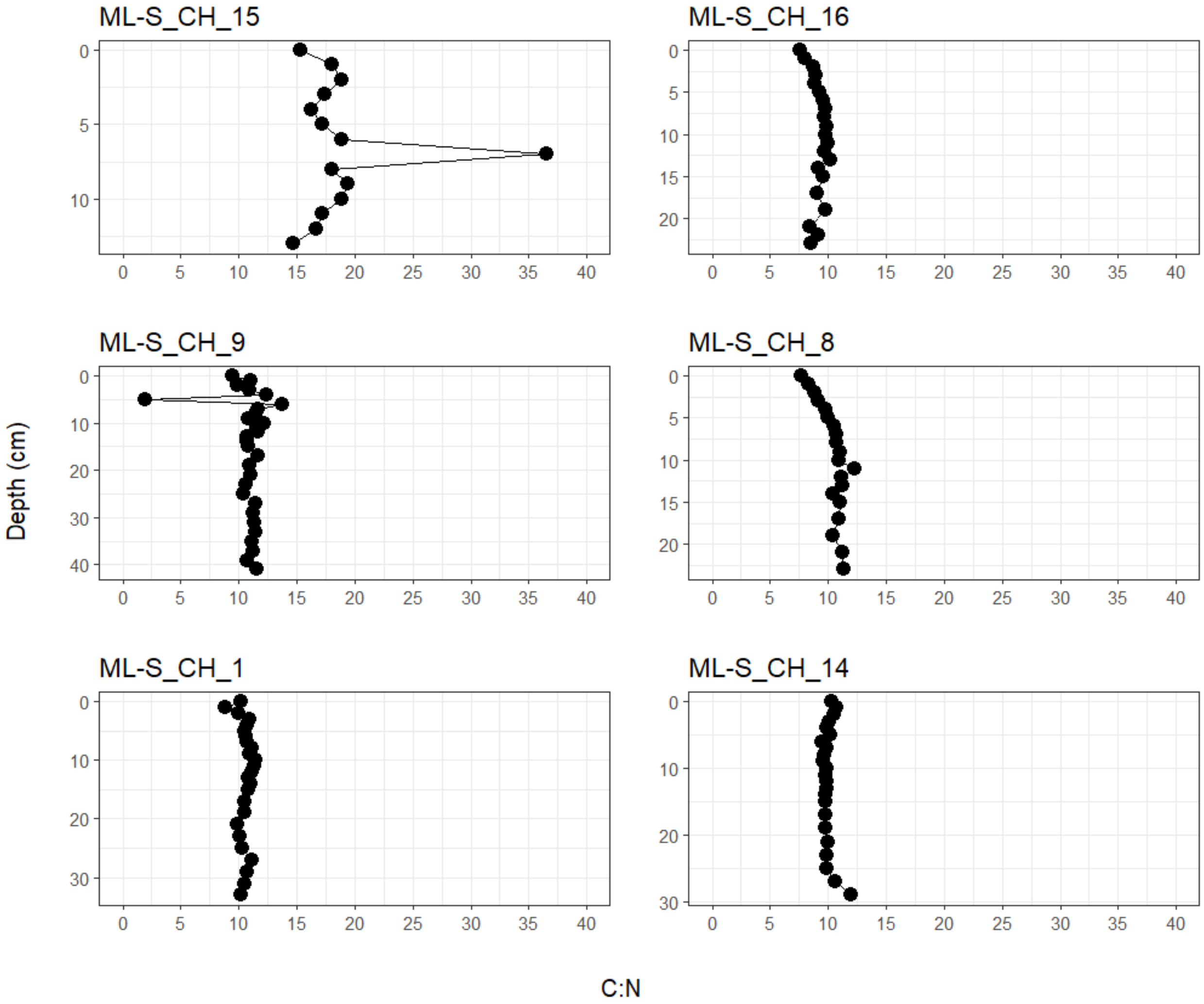

*Figure 2.3: C:N ratio at each of the six slump impacted lakes*

### *2.4.3 Sedimentary Total Mercury Concentrations*

Mercury was assessed in each of the six slump-impacted lakes (Figure 2.4). In lake ML_S_CH_15, total mercury concentrations ranged from 58.6 to 86.2 ng/g, dw. In lake ML-S_CH_16, total mercury concentrations ranged from 68.7 to 104.1 ng/g, dw. In lake ML-S_CH_9, total mercury concentrations ranged from 15.1 to 127.7 ng/g, dw. There was a significant drop in total mercury at the 4 cm interval to 15.1 ng/g, dw, dropping from 67.3 ng/g, dw at the 3 cm interval, and increasing to 118.5 ng/g, dw at the 5 cm interval. ML-S_CH_8 had relatively stable mercury, ranging from 61.2 to 106.2 ng/g, dw. ML-S_CH_1 had generally stable mercury, ranging from 73.1 to 92 ng/g, dw, with generally higher mercury found in surface sediments when compared to the bottom of the core. ML-S_CH_14 had mercury concentrations that range from 83.1 to 97.1 ng/g, dw and had a very stable profile.

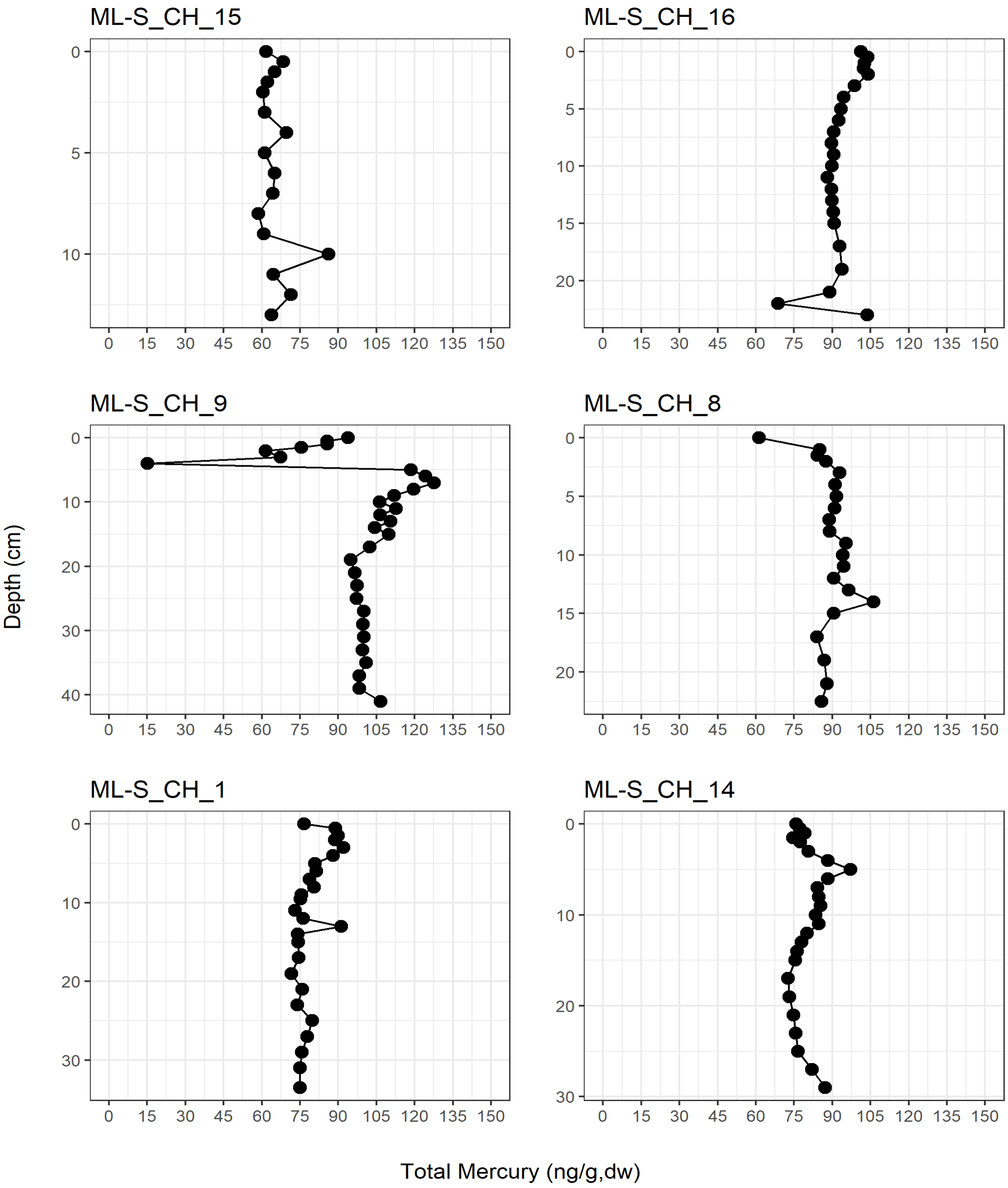

*Figure 2.4: Total mercury concentrations (ng/g, dw) in each of the six study lakes*

## 2.5 Discussion

### *2.5.1. Water quality*

The water quality results show that pH, temperature, $O_2$ concentration (mg/L) and $O_2$ saturation were all similar between the six slump-impacted lakes. With regards to specific conductivity, ML-S_CH_14 had a specific conductivity much greater than the rest of the lakes, similar to previous measurements from this well-studied lake (Thienpont et al. 2025). Turbidity was more variable, with ML-S_CH_9 and ML-S_CH_14 having higher turbidity at the time of measurement when compared to the other four lakes. It should be noted the mean pH and specific conductivity were 7.4 and 358.3 respectively, which is lower than the mean pH and specific conductivity of slump-impacted lakes in Kokelj et al. (2005). The techniques and equipment used in Kokelj et al. (2005) differed from our use of a YSI for sampling data, which could play a role in these differences.  Yearly variations are also important and has been noted (Thienpont et al. 2025), as the amount of permafrost thaw annually can differ and as the ground ice is often ion rich, years with greater permafrost thaw can have greater impacts on the water quality (Kokelj et al. 2005).

### *2.5.1 Thaw slump impacts on carbon dynamics within impacted lakes*

It has been observed that slump-impacted lakes have lower TOC when compared to slump impacted lakes, due to the siliclastic nature of the terrestrial sediment (Deison et al. 2012; Thienpont et al. 2020). Following this trend found in previous studies, the six large, highly active slumps examined in this study demonstrate low, relatively stable TOC when compared to previously studied unimpacted lakes (e.g., Deison et al. 2012). In each of the six study lakes, the

TOC concentration ranged between ~ 2-10%, indicating low/stable TOC. This demonstrates that with one exception, the lakes studied here align with paleolimnological results from previous research done on slump-impacted lakes in the Mackenzie Delta uplands. This is the case despite these lakes being impacted by large, highly active slumps. When compared with reference lakes (Deison et al. 2012) sediment TOC concentration are regularly greater than 10%. This contrasts with the slump-impacted lakes in this study, with none of the TOC concentrations exceeding 10%.

A notable exception to the findings of fairly quiescent, low TOC concentration profiles is the results from lake ML-S-CH_9. In this lake, we see there was a significant drop in the TOC concentration at the 5 cm interval where the TOC concentration was <0.1%, compared to the rest of the core which, while low, ranged between ~2-4% (Figure 2.2).  These changes show that there was little to no organic carbon deposited within the sediment at that time, likely as a result of the impacts from large inputs of siliclastic terrestrial material from the slump. When compared to the other five study lakes which exhibit characteristics of active/stable slumps aligned with the polycyclic activity proposed in the model by Thienpont et al. (2025), we can see that lake ML-S_CH_9 exhibited anomalous changes. As such, based on the conceptual model (Figure 1.1), we suggest that lake ML-S_CH_9 has undergone enough change to create a state change back to sedimentary environment indicative of highly active, enhanced slump status. This is notable because it has been hypothesized that the most significant changes to lakes impacted by thaw slump activity occur as a result of the initial slump event, and events that occur after that have a muted response in response to the ecological memory based on a material legacy within the lake. These findings show for the first time that it is possible for a slump-impacted lake to return to a lake state that is likely indicative of a highly active thaw slump. However, we were surprised that this was only recorded in one of the six study lakes, despite them all being impacted by large active slumps. This suggests the barrier to enhanced slump effects may be very high, which has implications for the impacts of future accelerated permafrost-thaw induced limnological changes in the Tuktoyaktuk Coastlands and beyond.

The C:N ratio in each of the slump lakes was examined, to assess the source of organic matter to the system. C:N ratios between 4 and 10 generally indicate autochthonous sources of organic matter to the system. C:N ratio > 20 indicate allochthonous sources of organic matter to the system. C:N values between 10 and 20 indicate that there is a mix of aquatic and terrestrial material in the system. The results from the analysis of the six study lakes demonstrate that the C:N ratio ranged from ~8-11 in most of the lakes throughout these sediment cores. This indicates that generally, the lakes are receiving inputs of organic matter from aquatic sources, with some intervals being slightly more influenced by terrestrial sources. When we look at lake ML-S_CH_9, we see that at the same interval (5 cm core depth) we saw the drop in total mercury concentration and total organic carbon concentration, there is a substantial drop in the C:N ratio from 12 to 1.9. At this interval organic carbon was 0.04%, and nitrogen was 0.02%, pushing the limit of detection of the elemental analyzer. As C:N ratios are commonly greater than 4, this C:N change is therefore related to analytical uncertainties due to the very low TOC concentration, and not a rapid shift in organic matter source (Glew and Smol, 2002). This is the likely result of a significant influx of siliclastic material from the terrestrial environment, which is likely indicative of significant slump activity. It was observed that C:N ratio increased to 36 in ML-S_CH_15 at the 7 cm interval, showing an influx of organic matter originating from outside the system (Meyers and Terranes 2001). We also see that compared to the other five slump impacted lakes, ML-S_CH_15 in general has a higher C:N ratio. The C:N ratio in ML-S_CH_15 are nearly all >15, whereas the other five lakes do not have a C:N ratio at any interval that exceeds 14. This demonstrates that ML-S-CH_15 has a greater amount of sediment organic matter originating from terrestrial sources when compared to the other five study lakes. These findings are consistent with previously published loss-on-ignition analysis results (Thienpont et al. 2025).

### *2.5.1 Thaw slump impacts on mercury delivery to impacted lakes*

Previous studies have shown that increased overall sediment delivery to aquatic ecosystems has resulted in an increase in contaminants in the sediment, including pesticides, mercury, and other contaminants (Lehnerr et al. 2018, Deison et al. 2012). Mercury in the context of permafrost is important to research, as it is estimated that ~ 5% of the mercury stored in the permafrost is susceptible to release into the atmosphere due to further thermokarst formation, driven by climate change (St. Pierre et al. 2018). The soils in the Arctic region store more mercury than all other sources combined, demonstrating the importance of high-latitude regions to the overall mercury cycle (St. Pierre et al. 2018). Most of the mercury is stored within the active layer, with can drive temporal and seasonal variations in mercury cycling, during the seasonal thaw period (St. Pierre et al. 2018). Mercury can also be found in its more toxic form of methylmercury. Methylmercury can bioaccumulate in fish and other aquatic inhabitants, which can be harmful both to the biota themselves and the humans who ingest the contaminated biota (Lehnherr 2014). Delivery of mercury to aquatic systems is impacted by drivers such as the source of the carbon, the type of carbon, and how much carbon in the system is of aquatic origin, and how much of it is terrestrial origin (Lehnherr 2014). In the Mackenzie Delta uplands, mercury tends to be lower in slump-impacted lakes when compared to reference lakes. In the study by Deison et al. 2012, it was found that lakes impacted by retrogressive thaw slumps had mercury concentrations generally less than 150 ng/g, dw, whereas lakes that had no slump activity had mercury concentrations generally higher than 150 ng/g, dw.

What this suggests is that the inputs of siliclastic terrestrial material to the aquatic system results in decreased organic carbon. As organic carbon has an affinity for mercury, decreases in organic carbon concentrations can result in decreased delivery of mercury to the sediment environment (Deison et al. 2012). This was found in all six of the slump lakes examined for this research. In general, the mercury concentration in each of the six slump lakes was less than 130 ng/g, dw, generally ranging from ~ 60 ng/g dw to 125 ng/g dw. A notable exception to this trend was observed in lake ML-S_CH_9. In this lake, at the 4 cm interval, there is a decrease in total mercury in the sediment core, dropping to 15.1 ng/g, dw. This is further indication of the likely rapid influx of terrigenous materials to the lake environment with slump activity, which diluted all of the geochemical indicators measured in this study, including total mercury.

### *2.5.3 Conclusions and future directions*

The findings from the paleolimnological analysis demonstrate that most of these study lakes with highly active thaw slumps show sediment characteristics and changes over the recent past comparable with lakes exhibiting polycyclic slump activity. This demonstrates that large, highly active thaw slumps may not behave differently when compared to other retrogressive thaw slumps in the region, and that the barrier to sediment and lake ecosystem change with enhanced slumping may be very large and only occur with the most significant slumps. In keeping with this, a notable exception to these findings was lake ML-S_CH_9, which has the largest slump in the data set. In this lake, there were short duration changes at the top of the sediment profile that deviated from the findings of the other five slump lakes in this study, including a dramatic drop in both TOC and total mercury indicative of an influx of siliciclastic terrestrial material from the landscape. This suggests that this lake shows recent slump activity of a sufficient magnitude to elicit a sediment environment change towards an enhanced, highly-active thaw slump status (Thienpont et al. 2025; Figure 1.1). This shows that with enough change to the environment, it is possible for a slump lake to revert to the highly active slump status typically characteristic of slump onset, but the scale of the slump necessary may be very large. This has implications for the nature of thaw slumps in the area, as we continue to see an increase in climate change impacts on the environment.

## 2.6. Acknowledgements

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# Chapter 3: Seasonal turbidity trends in lakes impacted by highly active permafrost thaw slumping in the Mackenzie Delta uplands, NT, Canada

## 3.1 Abstract

The Arctic is warming at a rate much faster than the rest of the globe. As a result, there has been an observed increase in the rate of permafrost thaw throughout much of the western Canadian Arctic. One of the most significant features resulting from permafrost thaw are retrogressive thaw slumps, which are rotational slide features that form on the shore of lakes. This research used a remote-sensing approach based on Sentinel- 2 imagery, processed in Google Earth Engine (GEE), to assess the seasonal turbidity trends between 2019-2023 for six lakes impacted by highly active retrogressive thaw slumps, as well as three unimpacted lakes for comparison. The normalized difference turbidity index (NDTI), based on the relationship between the red and green band, was used to assess surface-water turbidity in the lakes. NDTI recorded a distinct pattern of moderately turbid to non-turbid conditions within slump-impacted lakes, and moderately turbid to highly turbid conditions within reference lakes. There is some variation found within this pattern between lakes and over time, which demonstrates the importance of prior understanding of the lake environment to draw conclusions and demonstrates that assessing remotely sensed turbidity alone is not sufficient to identify and examine slump-impacted lakes without prior knowledge of the landscape.

## 3.2 Introduction

The rapid air temperature increases and changing climate of the Arctic has a significant impact on the permafrost landscape (Nitze et al. 2021). This has implications for the global environment, as permafrost stores vast amounts of carbon, and the continued thawing of permafrost is expected to contribute to a positive feedback cycle greatly impacting the climate on a global scale (Schuur et al. 2015). One of the most significant landscape features to result from permafrost thaw are retrogressive thaw slumps. Many recent remote-sensing studies have found that due to increasing rates of permafrost thaw, the rate of thaw slump development is also increasing (reviewed in Nitze et al. 2021). As a result, it is important to consider ways that slump activity can be quickly and accurately assessed and monitored. There are many areas, particularly in the western Canadian Arctic, associated with the margins of the former Laurentide Ice Sheet, where thaw slump development is prevalent in the landscape (Kokelj et al. 2017). As this is one of the most rapidly warming regions of the Arctic, it is expected that thaw slump activity will continue to accelerate as ongoing climate change impacts are observed (Kokelj et al. 2014; Nitze et al. 2021). A shortcoming of using remotely sensed data for assessing thaw slumps is their relatively small size, as they are typically <10 hectares in area, and have many different appearances (e.g., irregular shape, re-vegetation in stable slumps) in the way they appear in satellite imagery. This makes their detection difficult, especially for a larger scale monitoring project (Nitze et al. 2021). Because of this a larger remote-sensing-based project in the Western Canadian Arctic is challenging, as thaw slumps are prevalent but very dynamic, making detection and analysis difficult. Several studies have attempted to use high-resolution imagery to detect and monitor thaw slump activity, but processing these data are difficult and time-consuming, as thaw slumps are typically delineated manually (Nitze et al. 2021). There have been some studies using automated processing approaches (Nitze et al. 2018, Lara et al. 2019), but they are less common and have their own limitations. Deep learning approaches have been increasingly applied as a tool for thaw slump analysis due to their ability to take spatial context into account, but deep learning applications remain very scarce to date (Nitze et al. 2021). The findings in Nitze et al. (2021) show the promise for using a deep learning methodology on a large scale, although this will require more training data, as well as better access to data sources with high spectral, spatial, and temporal resolutions.

### *3.2.1 Previous remote sensing work in the Western Canadian Arctic*

Nguyen et al. (2009) used remote-sensing data to estimate the extent of near-surface permafrost in the Mackenzie Delta, including the eastern uplands where this current research took place. SPOT 5 data was used, as it has 10 m spatial resolution in multispectral mode and 2.5-5 m in panchromatic mode, which provides the high spatial resolution required. To classify the landscape the normalized difference vegetation index (NDVI), modified soil adjusted vegetation index (MSAVI), and textural analysis was used. To estimate the extent of near surface permafrost throughout the Delta, the research area was divided into southern, central and northern areas. The results from this research found that the near-surface permafrost extent ranged from 92% in the southern region, to 97% in the northern region (Nguyen et al. 2009). As the definition of continuous permafrost indicates that 90% of the land surface is underlain by permafrost, the results demonstrate that the Mackenzie Delta does fall within the continuous permafrost zone. In this case, SPOT 5 was useful due to its high spatial resolution, and it demonstrates the importance of selecting the most optimal satellite based on the needs of the study. A shortcoming of this satellite platform is that SPOT 5 was decommissioned in 2015, and SPOT 6 and 7 are not open access and therefore it is not always the most accessible, especially for research where many images may be required.

In Juhls et al. (2022), a remote-sensing approach was used to examine seasonal and spatial variability in dissolved organic carbon (DOC) in the transition zone between the Mackenzie River and near offshore Beaufort Sea region. The aim of their research was to use both ground-based *in situ* monitoring data as well as satellite ocean colour remote sensing data (SOCRS), to gain a more comprehensive understanding of how DOC varies seasonally and spatially in the Mackenzie River – Beaufort Sea transition zone. A large increase in DOC flux in the Mackenzie Delta due to permafrost thaw has already been observed, and this has important implications as temperatures continue to increase, and permafrost continues to thaw (Tank et al. 2016). In Juhls et al 2022, *in-situ* data was collected during a field campaign from April-September 2019 with four different legs encompassing the late spring, early summer, mid summer and late summer respectively. The remote-sensing data were from the Ocean and Land Colour Instrument (OLCI) aboard the Sentinel 3A and B satellite platforms, with imagery taken from the open water season of 2019. Different atmospheric correction algorithms and match up statistics were evaluated to compare the validity of the data, test the various algorithms, and compare remote sensing data to ground truth data.

This research showed that the spatial distribution of DOC was highest during the first half of June and that DOC concentrations within the transition zone were greatest during the spring freshet period (Juhls et al. 2022). The findings also show that the highest concentrations of DOC in the transition zone were aligned with the peak water level in the Mackenzie River, demonstrating the impact that seasonal changes to river discharge have on DOC in the transition zone. This research also highlights the challenges of using remote-sensing data in the Arctic, such as the difficulties associated with assessing performance of atmospheric corrections in the area due to lack of usable match up data, and difficulties associated with collecting field data to validate findings. These challenges demonstrate the need for *a priori* understanding of the research area and the need to use field data to validate findings, which can be limiting when it comes to remote-sensing analysis at high latitudes. This is in line with earlier discussion asserting that while remote- sensing analysis is useful, it is often not enough to make analyses without ground monitoring data (Juhls et al. 2022, Nguyen et al. 2009)

One way in which it may be possible to track and better understand directional changes in thaw slump activity, as well as seasonal variations, is by examining lake colour, and/or turbidity, in downslope, impacted waterbodies. In Lewkowitz and Way (2019), visible changes in lake colour in satellite imagery were observed in thaw slump-impacted lakes. The results from their analysis show that there were intermittent changes in lake colour, demonstrating that changes in lake colour did not always correspond with the status of the slump. This demonstrates that visible effects can vary through time and depend upon the strength of the hydrological connection between the shoreline thaw slump and the impacted water body (Lewkowitz and Way, 2019). In a study of mega-slump activity in the Richardson Mountains, rainfall events were found to impact both mega slump-impacted and non-slump impacted environments, but that turbidity in slump-impacted streams remained elevated after the rainfall event into the flow recession period (Kokelj et al. 2013). This is indicative of the impact that thaw slumps have on turbidity of downstream aquatic environments, and that slump size can have a positive association with lake

### *3.2.2 Study region and previous research in the Mackenzie Delta uplands*

This research takes place in the Mackenzie Delta uplands, in the Northwest Territories, Canada. This is a well-studied region, as the impacts to the environment due to warming temperatures in the region have been significant. As a result, thaw slump activity is increasing throughout the Mackenzie Delta uplands (Kokelj et al. 2009a). In Lantz and Kokelj (2008) aerial photographs were used to record thaw slumps in a study corridor covering 3739 km$^2$ of the upland terrain surrounding the Mackenzie Delta, and to track the rate of thaw slump activity by contrasting aerial photos from 2004 with aerial photos taken in 1973. Their findings demonstrates that morainal deposits, which made up just over half the landscape, were associated with most of the thaw slumps in the study area. Lantz and Kokelj (2008) also showed that while slumps are widespread across the Mackenzie Delta uplands and the extent of disturbance is growing, the rates of slump activities found in the uplands were lower than those found in other areas of the Arctic, demonstrating widespread variation in slump growth across the landscape. This was largely attributed to the decadal time periods for which they estimated the growth rates and is a shortcoming of many studies using satellite imagery and other remotely sensed images for tracking the development of thaw slumps. Since thaw slumps are so dynamic, the temporal resolution used is often unable to track and assess the nature of slump activity on shorter timescales at single lake perspectives. However, Lantz and Kokelj (2008) did show that the rate of slump growth from 1973 to 2004 was almost 1.5 times greater than the period from 1950-1973, indicating that there has been an increase in thaw slump activity at a landscape scale due to warming temperatures.

Turbidity has also been examined in thaw slump-impacted lakes using *in-situ* monitoring approaches. In Kokelj et al. 2009a polycyclic/stabilized slumps were examined and exhibited increased water clarity in slump-impacted lakes compared to unimpacted lakes. Turbidity was also assessed in Kokelj et al. (2013) using direct measurement by sensors in both impacted and unimpacted streams within the Stony Creek watershed, located within the Peel Plateau region of the Northwest Territories. One issue with taking measurements using sensors is that they can experience failure, as the turbidity sensor in Stony Creek did after 14 days.

The objective of this study was to build on previous field-based research examining thaw slump activity and lake impacts in the Mackenze Delta uplands. Previous work has focused primarily on the polycyclic / stable thaw slumps more common in the area (Kokelj et al 2005). As there has been an increase in the number of large, highly active thaw slumps in the region over the recent past associated with warming, this work aimed to assess how they impact associated lakes. This was done by using remote-sensing techniques to examine turbidity as a metric of slump activity, combined with a paleolimnological assessment of ecosystem changes (Chapter 2). Lakes with highly active thaw slumps may have higher turbidity that unimpacted lakes and lakes impacted by stable thaw slump activity, existing in a transitionary state associated with significant inputs of terrigenous materials from the highly active slumping (Thienpont et al. 2013). This research was conducted on lakes with a relatively well-defined history of recent slump activity from field observations, in order to determine if turbidity patterns exist and can be reconstructed using NDTI, to compare the patterns found in highly active thaw slumps, and the turbidity patterns found in reference lakes with no slump activity.

## 3.3 Methods

### *3.3.1 Satellite comparison and selection*

When using remote sensing imagery, considering the satellite that is best suited to the project is an important first step, and one that is critical to ensure clear and accurate results. In Rodenhizer et al. (2024), a comprehensive assessment of satellite imagery sources was assessed and compared for the automated detection of thaw slumps. In their analysis, three sensors were assessed with varying spatial and temporal resolutions and costs and compared to see which was most effective for the automated detection of retrogressive thaw slumps. The first, a proprietary product, was WorldView which is high-spatial resolution with a short revisit time. The second proprietary product was PlanetScope, which has a coarser spatial resolution than the WorldView product but has daily global coverage and lower associated costs. Of the platforms compared, Sentinel-2 has the lowest spatial resolution at 10 m with the highest revisit time of 5 days. This spatial resolution is sufficient to map many thaw slump features and easy and free to access and usable in GEE. WorldView performed the best missing 24% of the thaw slump testing features, Sentinel 2 performed second best missing 27% of the testing features, and PlanetScope missed 37% of the features (Rodenhizer et al. 2024). This demonstrated that resolution is not always correlated with thaw slump detection, as PlanetScope resulted in more undetected features. Area was observed to be the driving feature that played a role in thaw slump detection, but luminance, plant cover and the nature of landscape where the features occur were other important factors and should be considered. Given the nature of the project where the thaw slump features on the six slump-impacted lakes were already known from field observations and it was the lakes themselves being assessed for turbidity, Sentinel-2 was deemed to be the satellite most suitable for this research.

### *3.3.1 Study Lakes*

To examine the impacts of large, highly active slump lakes six slump-impacted lakes and three reference lakes were selected. The reference lakes were chosen from a larger subset of lakes assessed as part of the Thermokarst Lakes Mapping Initiative (Kokelj et al. 2023). The impacted lakes chosen (part of a larger scale program sampling lakes in permafrost land systems across the Northwest Territories) were identified by the identifier code ML-S_CH (referring to morainal lakes (ML) that are slump-impacted (S) in the Caribou Hills (CH ecoregion) followed by a unique number (Figure 3.1).

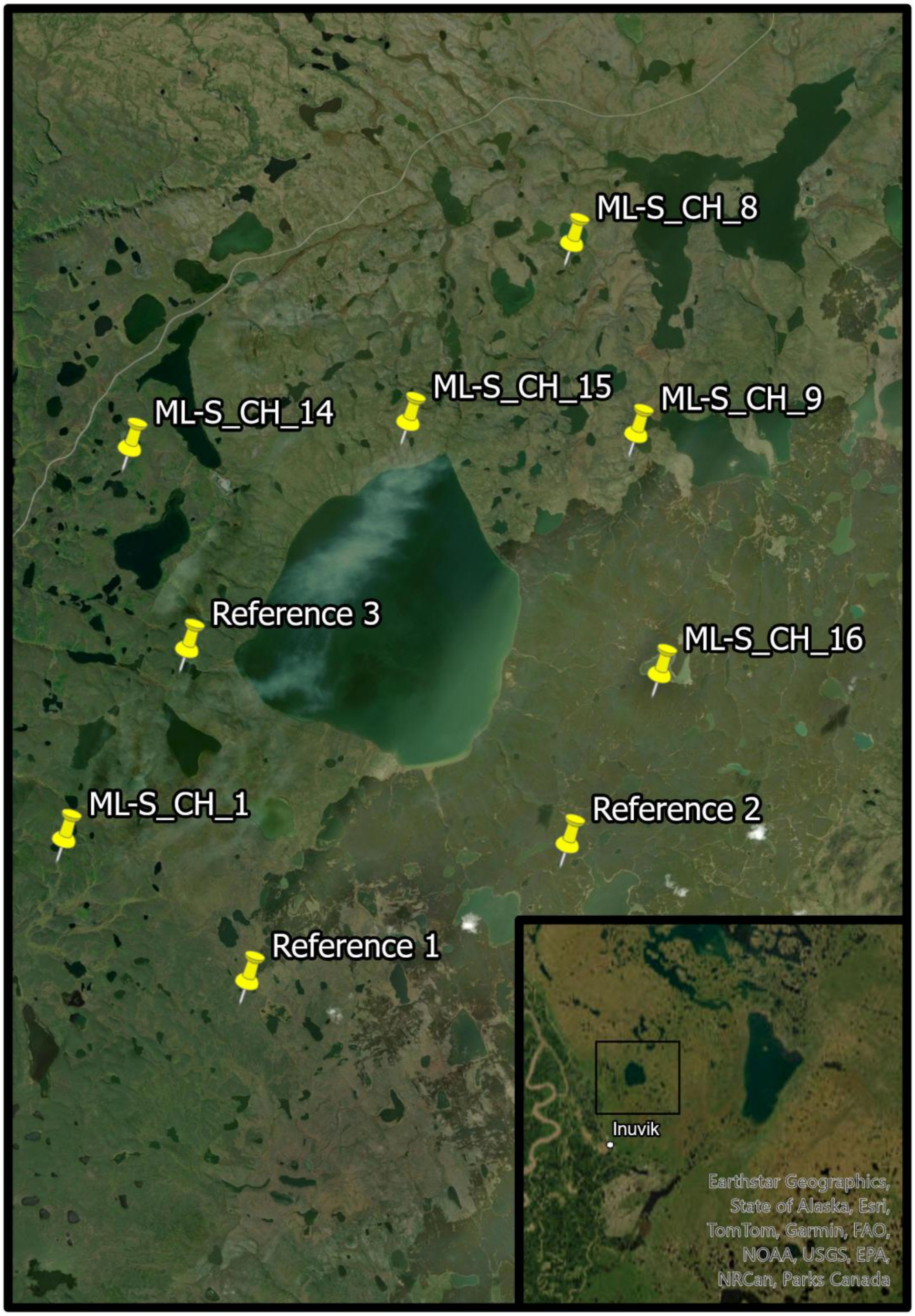

Figure 3.1: *Study site map of lakes in the Mackenzie Delta uplands (Tuktoyaktuk Coastlands) NE of the town of Inuvik, NT.*

### *3.3.2 Normalized difference turbidity index*

Water turbidity affects the scattering of light as it scatters or absorbs light rather than transmitting it in a straight line (Kolli and Chinnasamy 2024). Turbidity is an important metric to examine when assessing water quality, as it affects the transparency of the water thus impacting the nutrient and ecosystem function, as well as the aquatic life (Kolli and Chinnasamy 2024), and is a known outcome of retrogressive thaw slump impacts to surface waters. For this research, the normalized difference turbidity index (NDTI) was used to assess turbidity in each of the six slump-impacted lakes, as well as three reference lakes. NDTI is calculated using the spectral reflectance values of the water pixels (Kolli and Chinnasamy 2024). The formula uses the relationship between the red and green bands, as the reflectance of the red spectrum increases with an increase in turbidity. As a result, the relationship between the green and red wavelength is reversed (Kolli and Chinnasamy 2024). This results in a formula developed by Lacaux et al. (2007):

$$\mathrm{NDTI}=\frac{\mathrm{Red}\text{-}\mathrm{Green}}{\mathrm{Red}+\mathrm{Green}}$$

Where Red is the reflectance in the red band (Sentinel-2 Band 4) and Green is the reflectance in the Green band (Sentinel-2 Band 3). NDTI values found in clear water typically range from -0.2 to 0.0, while moderately turbid waters range from 0.0 to 0.2 and are >0.25 in highly turbid waters (Alka et al. 2014).

### *2.3.3 Analysis in Google Earth Engine*

Satellite imagery data and analysis of the NDTI was conducted in Google Earth Engine (GEE) using Sentinel 2 imagery. This satellite program was first launched in 2015, so the data was selected from 2015- 2024 for analysis. After which, the data was filtered to only include images where cloud cover was less than 30%, to ensure the reflectance signal was not affected by cloud cover. Each of the six slump-impacted lakes were identified, and the geometry was created for each lake using the *Draw a Shape* tool. While outlining the geometry, care was taken to draw just a bit in from the shore of the lake, ensuring that only the water signal was captured, with no interference from the land. The same methodology was used for the three reference lakes. The output was a time series of NDTI for each lake, from approximately 2019 to 2022. Although the time period was set from 2015 (when Sentinel 2A was launched) to 2023 (when the lakes were sampled), the full time series proved not to be usable in our analysis, possibly due to filtering out unusable imagery for those years. As a result, we were left with an approximately three-year time series chart for each slump-impacted lake and reference lake.

## 3.4 Results

### *3.4.1 Turbidity results*

NDTI values for all lakes cover the open water period only, extending from May to November; there is no data from approximately November to March each year, due to ice and snow cover over the lakes. In lake ML-S_CH_1, the NDTI values range from approximately 0.1 to -0.6, indicating clear, non-turbid to moderately turbid conditions (Figure 3.2). The trend also shows that the clearest conditions occur in the late summer to late fall period, typically from August to November, indicating that the lake becomes increasingly clear and less turbid as the summer and fall period progresses.

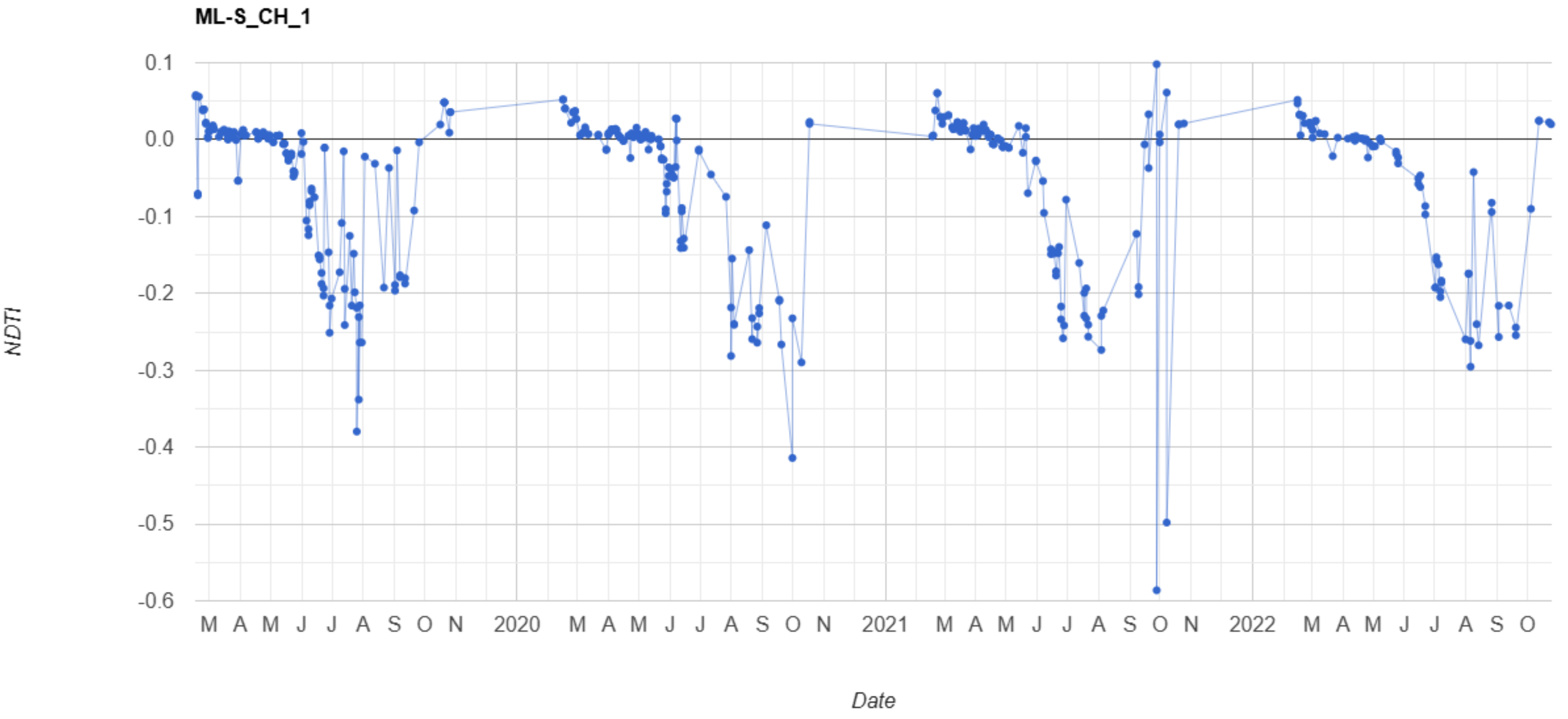

*Figure 3.2: NDTI analysis of ML-S_CH_1*

In ML-S_CH_8, the NDTI values range from approximately 0.1 to -0.8, indicating clear, non-turbid to moderately turbid conditions (Figure 3.3). In this lake, the clearest, non-turbid conditions were seen between July and October, a little earlier in the season, but still very similar to what was found in ML-S_CH_1.

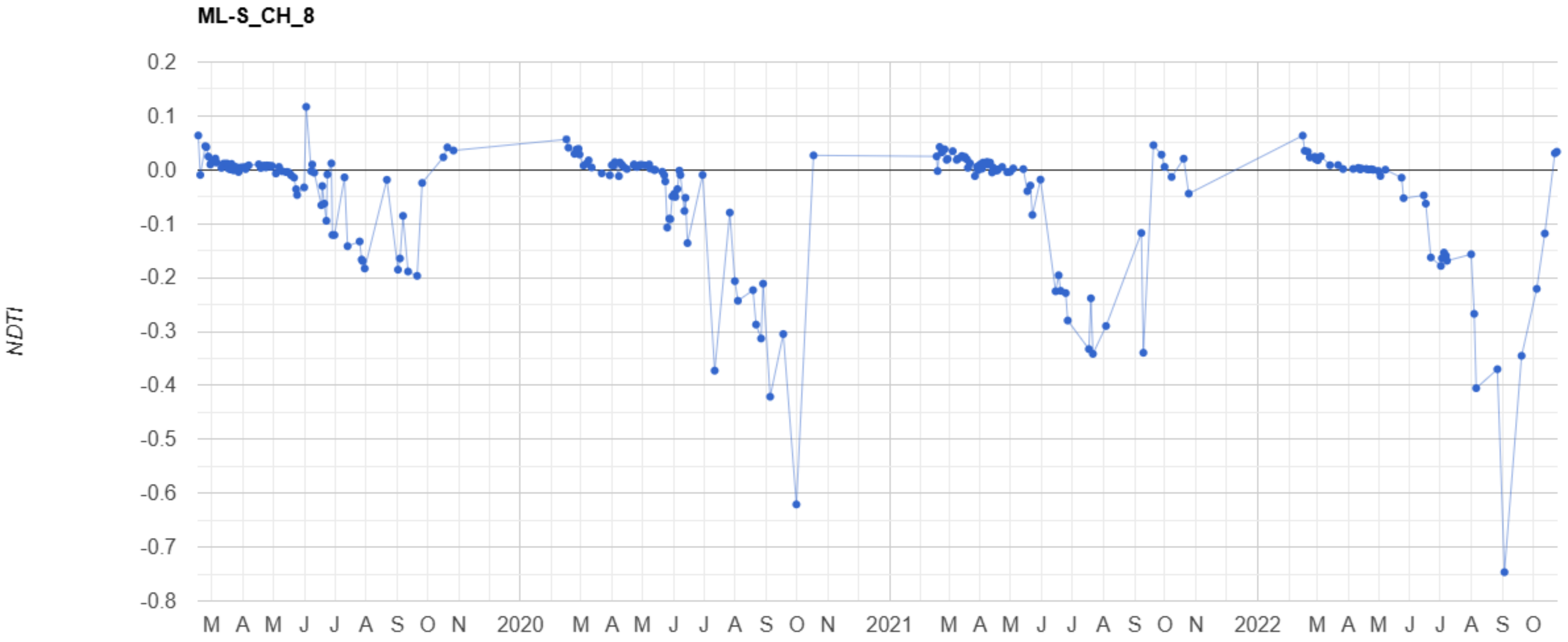

*Figure 3.3: NDTI analysis of ML-S_CH_8*

In ML-S_CH_14, the NDTI values ranged between approximately 0.15 to -0.65, indicating clear, non-turbid to moderately turbid conditions (Figure 3.4). The clearest conditions in this lake were found generally between July and October, aligning with the pattern found in the other lakes.

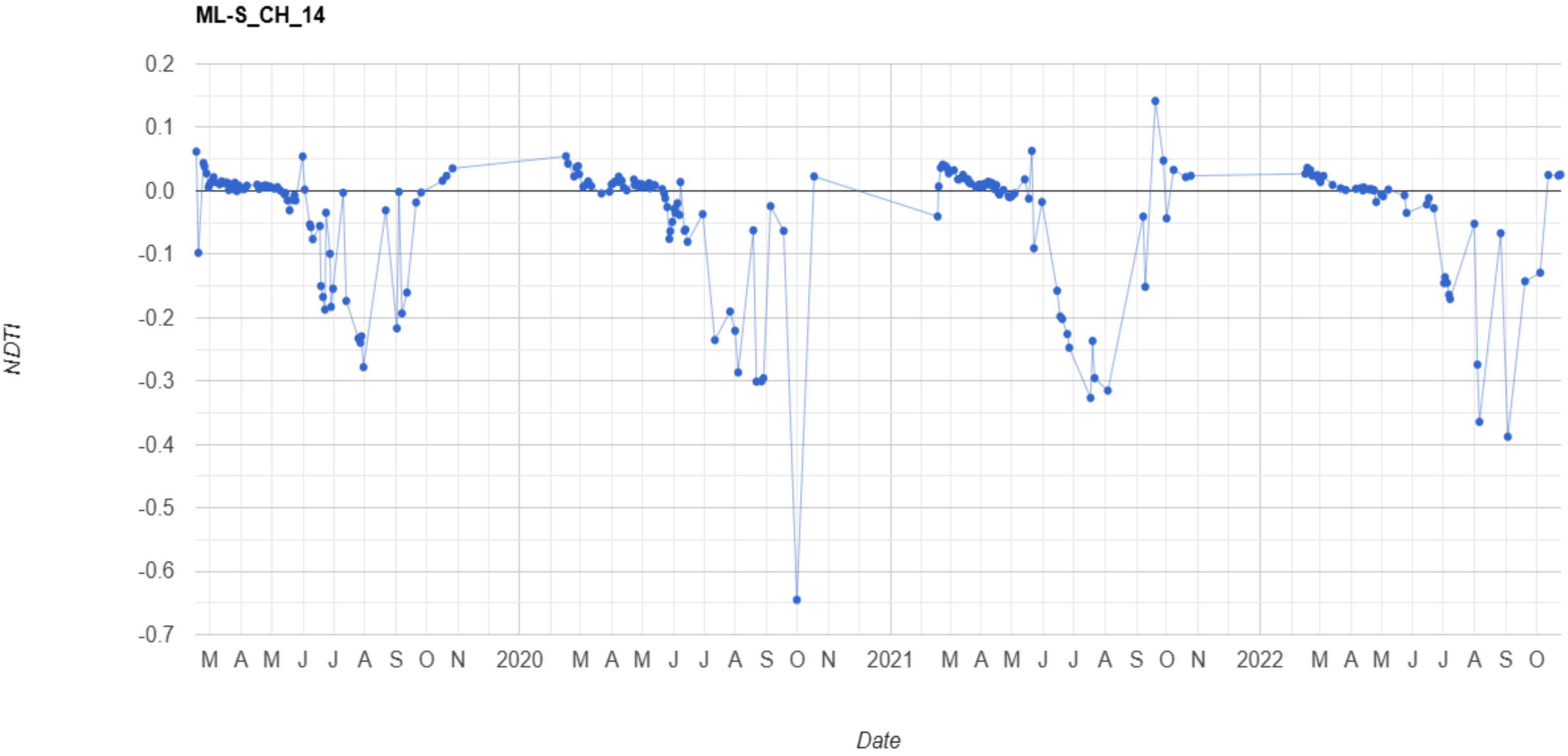

*Figure 3.4: NDTI analysis of ML-S_CH_14*

In ML-S_CH_15, the NDTI values range from approximately 0.15 to -0.8, demonstrating clear, non turbid to moderately turbid conditions (Figure 3.5). An exception is the late summer/early fall of 2021, where there is some turbidity experienced in the middle of September 2021, with the NDTI value at that time being just above 0.2, indicating an increase in turbidity at that time, and approaching 0 again indicating a return to clear, non turbid conditions around the end of October. Similar increases, though of slightly smaller magnitude, were observed at the same time in ML-S_CH_1 (Figure 3.2) and ML-S_CH_14 (Figure 3.4).

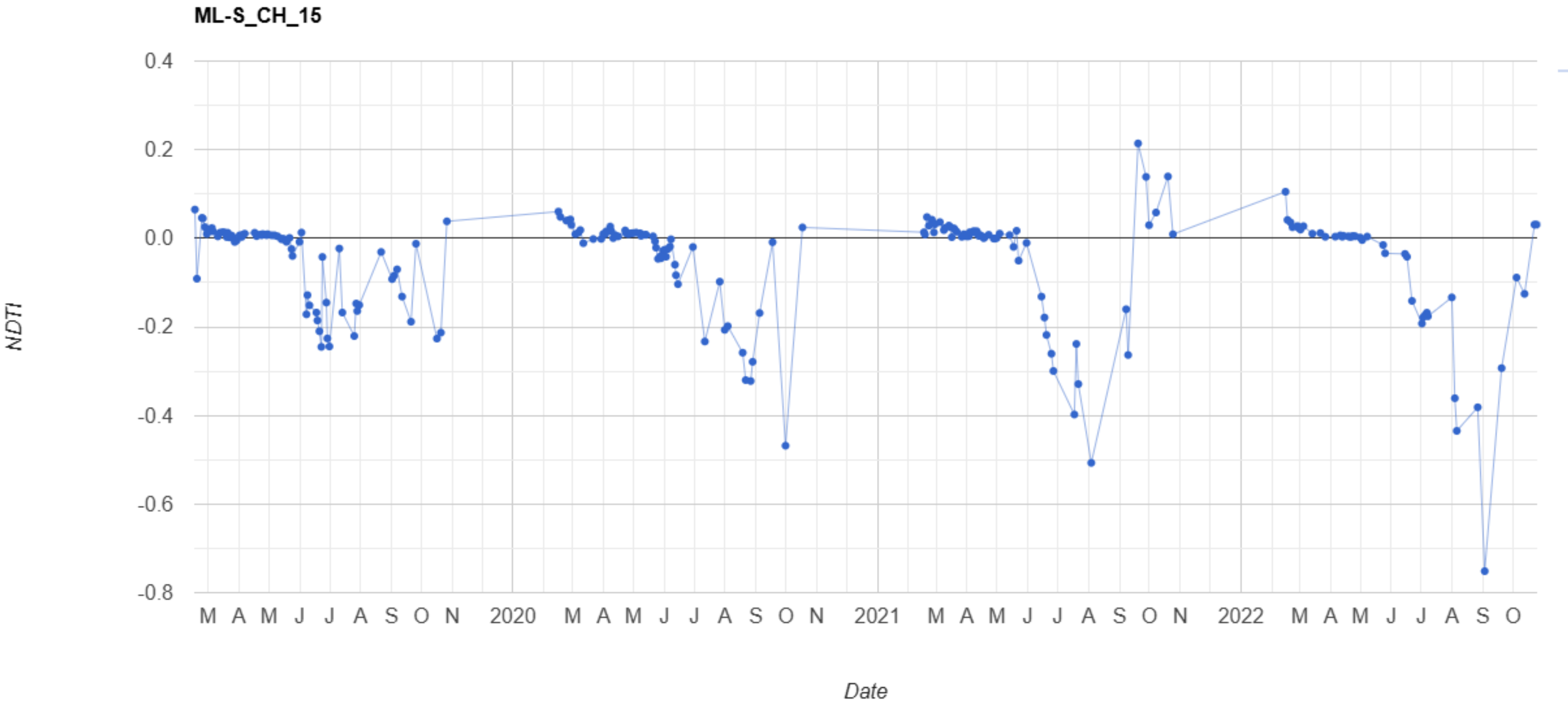

*Figure 3.5:: NDTI analysis of ML-S_CH_15*

In ML-S_CH_16, the NDTI values range from approximately 0.06 to -0.32, indicating clear, non-turbid to moderately turbid conditions (Figure 3.6). The clearest conditions were found generally between July and October, following the general seasonal pattern seen in the other five study lakes.

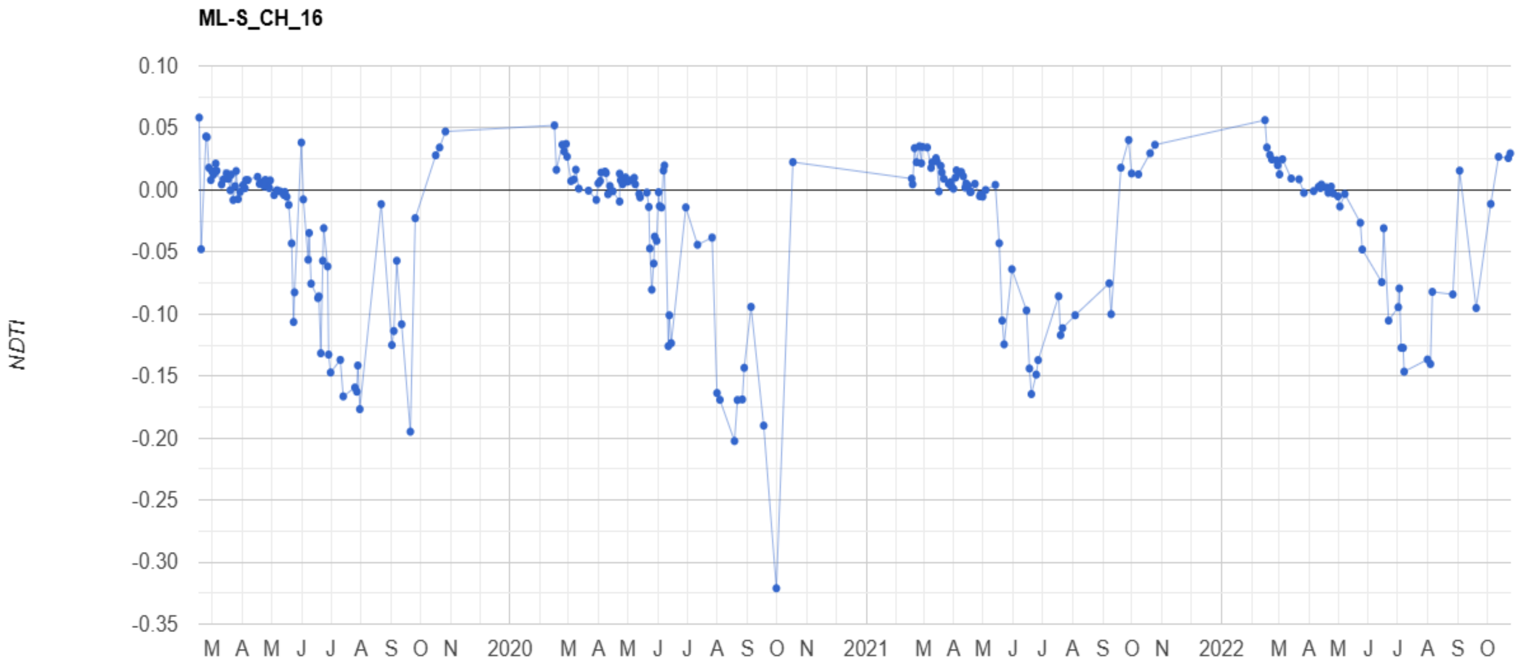

*Figure 3.6: NDTI results ML-S_CH_16*

In ML-S_CH_9, we see a difference from the pattern that was found in the other five slump-impacted lakes (Figure 3.7). In 2019, 2020, and the beginning of 2021, the results are in line with what was observed in the other slump-impacted lakes inferred to be low to moderately turbid conditions. The deviation from this pattern occurred in September 2021, and September 2022. In September 2021, there was an NDTI value of approximately 0.33 in the middle of September, before dropping to just below 0.05 in October. This was a rapid spike, indicating a change in the lake at that time. Another change in the turbidity conditions of ML-S_CH_9 occurred in 2022, where we recorded an NDTI value of approximately 0.23 in September. This period was less of a single, rapid spike, and more of steady increase in NDTI from August 2022, followed by a drop, returning to an NDTI around 0 by October 2022 (Figure 3.7).

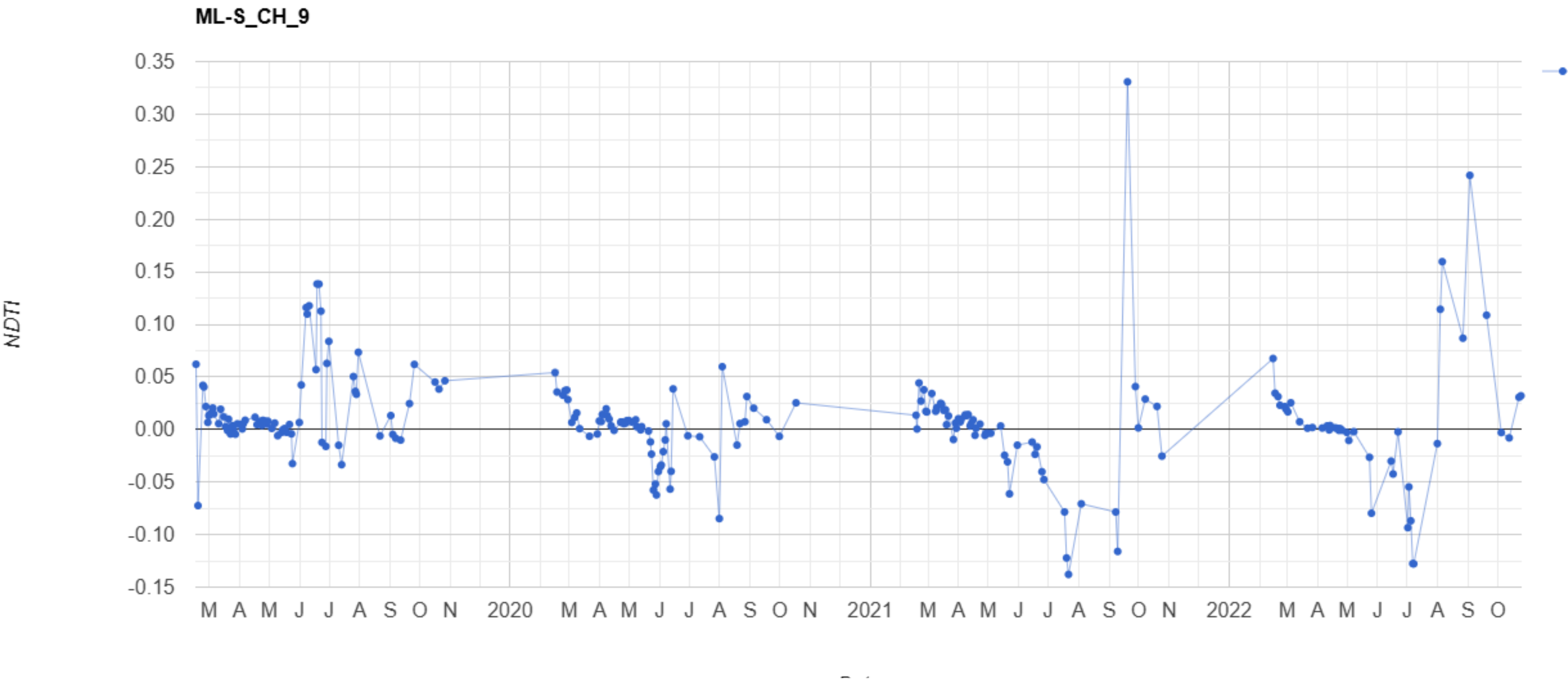

*Figure 3.7: NDTI results ML-S_CH_9*

Turbidity patterns in the three reference lakes were also examined. In Reference 1, NDTI values range between approximately 0.75 and -0.1, indicating generally turbid conditions (Figure 3.8). In this lake, the most turbid conditions occur between June and October, coinciding with the summer and early fall season.

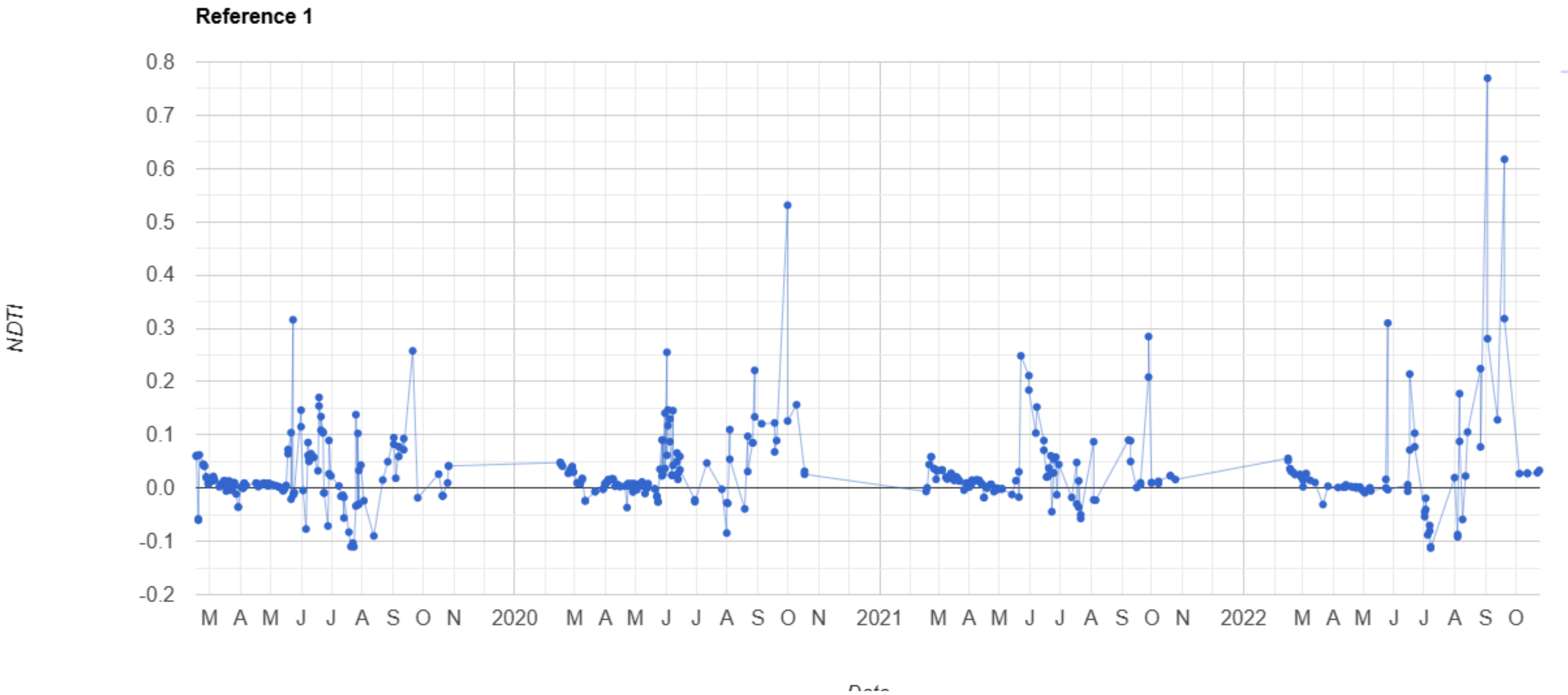

*Figure 3.8: NDTI results Reference 1*

In Reference 2, the NDTI values range between 0.6 and -0.15, indicating generally turbid conditions (Figure 3.9). In this lake, the most turbid conditions occur between June and October, aligning with what was found in Reference 1.

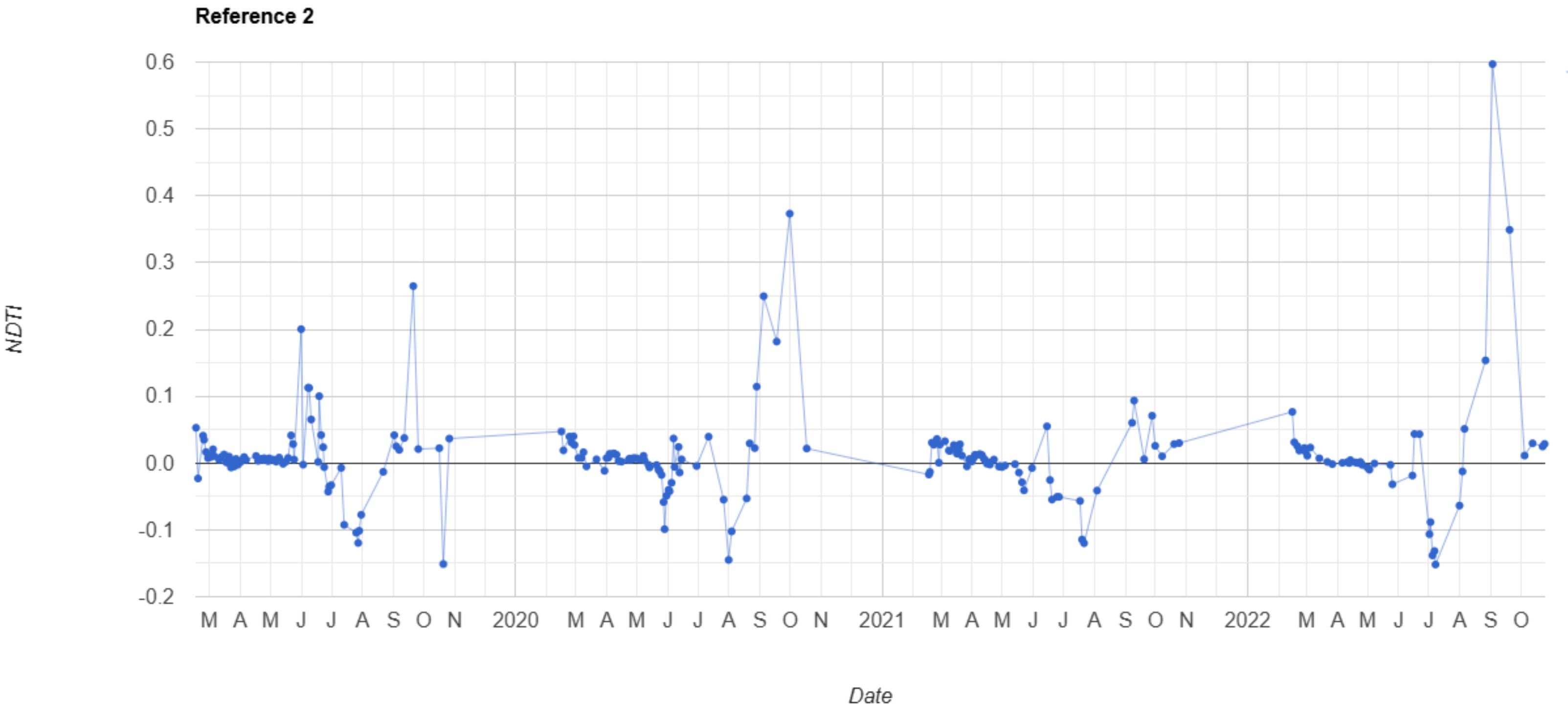

*Figure 3.9: NDTI results Reference 2*

In Reference 3, NDTI values range between 0.23 and -0.3, indicating that the lake is generally clear, non turbid/moderately turbid (Figure 3.10). In this lake, the clearest, non turbid conditions occurred between June and September, generally aligning with what was observed in the slump-impacted lakes.

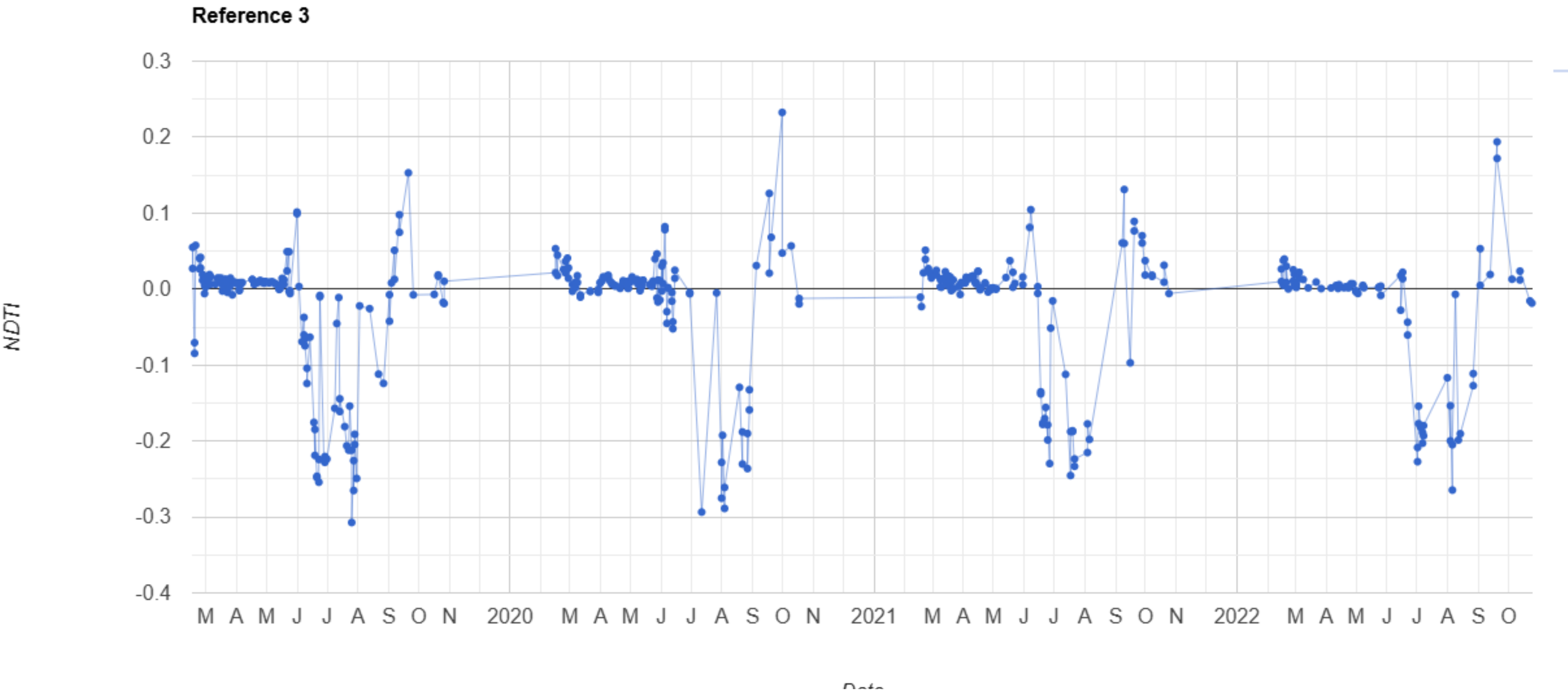

*Figure 3.10: NDTI results Reference 3*

## 3.5 Discussion

### *3.5.1 Drivers of satellite-inferred turbidity in slump-impacted lakes*

The results of the NDTI analysis demonstrate that five out of the six lakes studied exhibit results in line with what has been observed in previous research on thaw slump activity throughout the Mackenzie Delta uplands. Previous research demonstrate that stable, polycyclic slumps have lower turbidity, and clear waters when compared to unimpacted lakes (Kokelj et al; 2009a), and from this research it suggests that most lakes with highly active shoreline thaw slumps follow a similar trend. An exception to this was lake ML-S_CH_9. This site, with the largest, most active thaw slump, showed a different trend and demonstrated what might have been expected with regards to highly active thaw slumps, an increase in water turbidity. The NDTI results from this lake show that the system experiences periods of high turbidity, especially in late summer / early fall (Figure 3.7). The findings from this lake demonstrate that highly active slumps may return to enhanced turbidity conditions more typical of what is believed to occur at initial slump initiation, in contrast with the low turbidity conditions typical of polycyclic stable slumps (Thienpont et al. 2025), but that the scale of slumping needed to do so might be very large. Even though we see very clear turbidity patterns in the slump- impacted lakes, when we see deviations in the pattern as we do in ML-S_CH_9, it is difficult to attribute that change directly to slump activity, as there are other factors that could cause this change. Comparison to other lakes in the region can help allow us to make a better assessment. For example, the spike in turbidity in ML-S_CH_9 did not occur around the same time as observed in other lakes. This shows the complexity of slump response to stressors, and how impacts can differ with changes in flow patterns, catchment size, and location of the slump. These results give insight into how slump lake dynamics may change as temperatures in permafrost regions continue to increase, and thaw slump activity increases.

This analysis demonstrates the usefulness of remote sensing techniques to assess turbidity patterns in permafrost thaw slump-impacted lakes. In the six slump lakes, five showed very similar patterns. They all had low NDTI values close to 0, indicating clear, non turbid waters. In these five lakes, we see that the clearest and non turbid waters are between June and October, aligning with the mid summer to early fall season. The clearest conditions in these months could be expected, aligning with the late spring/early summer season, which would be impacted by inputs of terrestrial material as snow melts, likely increasing early-season turbidity (Sommaruga 2015). These results align with the findings that slump-impacted lakes were less turbid that lakes unimpacted by slump activity, increasing productivity in slump lakes due to the ability for light to penetrate more effectively, resulting in increased photosynthesis and algae production

(Sommaruga 2015). Slump lakes may have lower turbidity for many reasons, such as due to organic and mineral material that is quickly deposited to the lake bottom, and lower water column nutrient levels due to increased benthic productivity (Thienpont et al. 2013). Lakes impacted by thaw slumps also have higher specific conductivity and higher concentrations of dissolved ions (Kokelj et al. 2009a), which can be related to water turbidity levels.

The reference lakes demonstrated a somewhat more variable pattern. In general reference lakes appeared to be more turbid than slump-impacted lakes, though with greater variation in this trend across the sample. For example, in Reference 3, there is only one point in which the NDTI is over 0.2 indicating that most of the time the lake is relatively clear and non turbid. Reference 2 has more inferred values over the 0.2 threshold when compared to Reference 3, except for in 2021, where the greatest NDTI value observed was approximately 0.09 indicating that 2021 was a year in which the lakes were clear and non turbid, more in alignment with what was observed in the slump-impacted lakes. Reference 1 had multiple values over the 0.2 and even the 0.25 threshold in each year, with an increasing number of points passing the 0.2 threshold from 2019 to 2022. This demonstrates the system is more turbid that the slump-impacted lakes and is generally the most turbid of the reference lakes. We also saw a general increase in turbidity each year in Reference 1, an interesting finding that was also found to some degree in Reference 2.

These satellite-based turbidity inferences are important as they allow for an understanding of seasonal turbidity patterns in slump-impacted lakes with comparison to reference lakes unimpacted by slump activity. What these findings suggest is that lakes impacted by slump activity are clear and relatively non-turbid when compared to reference lakes, and that the clearest conditions occur in mid summer to early fall in most of the lakes. These findings are demonstrated in the water chemistry data taken from the reference lakes, demonstrating that the lakes have low turbidity ranging between 0.9 and 6 NTU (Chapter 2). Slump lakes also have higher specific conductivity, driven by the concentration of dissolved ions in the lake, possibly impacting turbidity. In the six study lakes, the average specific conductivity was 358 μS/cm, whereas the mean specific conductivity found in undisturbed lakes by Kokelj et al. (2005) was 89.3 μS/cm. In contrast, reference lakes are generally more turbid, but they do experience more fluctuations and variation in their pattern, at times exhibiting clear, non turbid conditions. The differences in the patterns between slump-impacted and unimpacted lakes only become apparent when examined over multiple years, and with knowledge of the status of the lake. NDTI results alone would be insufficient to track the development of a new slump (at least on a lake with previous slump history) or slump activity, but it does give us insight into how lakes impacted by thaw slumps vary over intra-seasonal patterns and over time where the catchment disturbance regime of the lake is already known.

These results suggest that while NDTI based on satellite remote-sensing images is not an unambiguous indicator of the formation of new slumps or changing slump activity, it contributes knowledge to developing tools that can be used to track slump development. Using NDTI is one component of a multi-proxy approach where prior knowledge of the lake environment exists and analysis over a multi- year time period is needed. A lack of prior knowledge and ground-based understanding of the landscape is often a shortcoming of remote sensing analyses, especially in the Arctic, and it is a knowledge gap.

### *3.5.2 Comparison to other potential turbidity analyses*

While assessing the NDTI using Google Earth Engine is a rapid and easy method of assessing turbidity, forming the basis of the first attempt to do so that is described in this thesis, there are other methods that should be explored in future analysis, to improve our understanding of the patterns of turbidity in slump-impacted lakes. Binding et al. (2010), assessed lake colour using MODIS wavebands in Lake Erie, a moderately turbid, and optically complex lake. Their model considered inherent optical properties of particulate matter indigenous to Lake Erie. As a result, they derived a great deal of sensitivity in the reflectance algorithms and models, due to variations in particle properties that make applying this model over a large area difficult. For example, type, size, shape, and refractive index are all important factors influencing the turbidity of suspended particles, and thus a model developed for one lake or lake set may not be broadly applicable to other areas. As a result, only regional application of the model was recommended. This model and/or methodology could be adapted to assess water clarity and turbidity in the slump-impacted lakes, with the knowledge of particle properties from the lake systems in the western Arctic.

Hicks et al. (2013), used an automated procedure to examine spatial and temporal variability in water clarity in several shallow lakes in New Zealand. The procedure used Landsat imagery, and looked at estimating total suspended sediment, turbidity, as well as Secchi disk transparency. This work is potentially relevant to the analysis of the slump-impacted lakes as most systems are similarly small. One advantage discussed of using this model was the ability to correspond changes in lake clarity to the causes of these changes, such as land use changes or precipitation, which is particularly relevant in the Mackenzie Delta uplands, as there has been an observed increase in precipitation in the area. The results showed a relationship with precipitation, and this could be explored further in future work on highly- active thaw slump lakes. This research improved the ability to track turbidity in shallow waters, by using a modified normalized difference water index in order to mask areas out as not open water (Hicks et al. 2013). Adapting this model to work for a high-resolution sensor such as Sentinel 2 could provide a complimentary method for assessing turbidity dynamics in these small, slump-impacted lakes.

## 3.6 Conclusions

As temperatures continue to rise throughout the Arctic, and the climate continues to change, the impact of these changes on the landscape is important to assess as it is anticipated that the rate of slump development will increase with continued warming. As such, developing a remote sensing tool that can examine impacted lakes to track thaw slump activity as well as examine new slump growth will allow for large areas of the Arctic to be examined, and mitigate the need for in situ monitoring which can often be difficult in Arctic landscapes.

NDTI analysis was shown to be useful for examining seasonal patterns of turbidity in slump-impacted lakes, though variability in reference systems suggests NDTI alone is insufficient to classify lakes across the landscape as impacted by slumps without another form of confirmation of slump presence, either remotely sensed or field based. However, this work provides important information and a starting point for developing integrative, multi-proxy tools that can be used to track slump growth and activity, and their impacts of receiving waterbodies. In the Mackenzie Delta region, where the temperature is warming especially rapidly, resulting in rapid changes to the environment, these tools will be especially useful for providing insights into how the landscape will continue to change under the continued impacts of rapid climate change.

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# Chapter 4: Discussion and Conclusions

## 4.1 Thesis Summary and Conclusions

The Western Canadian Arctic has been warming at a rate much more rapid than the global average. This has resulted in increased rates of permafrost thaw, impacting the landscape and ecosystem dynamics. The thawing of permafrost results in the development of thermokarst features including one of the most spectacular and catastrophic manifestations: retrogressive thaw slumps. Thaw slumps are landslide features, that develop along the shoreline of lakes and other waterbodies in regions of ice-rich permafrost (Kokelj et al. 2009a). They impact the physical, chemical, and biological nature of downstream aquatic ecosystems.

This research focused on aquatic ecosystems in the Mackenzie Delta uplands, an area with a long history of thaw slump activity, and an area that has been the subject of many studies relating to thaw slump development, activity, and impacts to water bodies (Lantz and Kokelj, 2008). While there has been significant research done on the impacts of stable, polycyclic slumps in the region, as temperatures continue to increase and permafrost continues to thaw it is anticipated that there will be an increase in large, highly active thaw slump development. These highly active “enhanced slumps” have not been studied in significant detail in the region to date (Thienpont et al. 2025). This research looked at six lakes in the Mackenzie Delta uplands identified as being impacted by large, highly active thaw slumps, utilizing a combination of paleolimnological and remote sensing approaches to assess the impacts of these highly active thaw slumps on downstream lake ecosystems.

#### *4.1.1. How do large, highly active thaw slumps impact the lake environment differently than other slump lakes in the area?*

In previous studies conducted on thaw slumps in the Mackenzie Delta uplands region, it was found that lakes impacted by thaw slumps have lower total organic carbon (TOC) concentrations in sediments when compared to reference lakes (Deison et al. 2012). This is driven by the highly siliciclastic slump material being deposited into the lake-bottom environment. As TOC is lower in thaw slump environments, mercury is also generally lower in slump-impacted lakes. As mercury has an affinity for organic carbon, changes in TOC impact the delivery of mercury to the sediment.

In this study, the six slump-impacted lakes, all had lower total organic carbon when compared to previously published reference lakes (Deison et al. 2012). TOC was <10% in all six of the slump lakes and mercury was <135 ng/g, dw in all six lakes, compared to reference lakes where the TOC was generally >10% and mercury often was >150 ng/g, dw. The C:N ratio also showed mixed sources of carbon to the system in most of the study lakes and at most intervals. Five of the six study lakes showed similar, consistent profiles in TOC and total mercury throughout the periods represented by the sediment cores studied (last 2-300 years), but an exception was noted for one lake, ML-S_CH_9. At the top of this core, there was an observed substantial decrease in carbon and mercury, with values near the lower limits of detection for both analytes. This was inferred to be in response to a pulse of significant input of siliciclastic terrestrial material to the system, likely from the recent highly active, enhanced thaw slumping. While it was expected that all six lakes would behave in a similar manner (i.e., recording periods of enhanced slumping in sediment cores), the findings from Lake ML-S_CH_9 shows that with significant enough slump activity contributing materials to the system, lake sediments can track pulses of allochthonous material, but that many highly active slumps record quiescent sediment profiles of TOC and total mercury.

### *4.1.2 How do seasonal trends in turbidity differ from reference lakes?*

Using Sentinel 2 imagery within Google Earth Engine, remote sensing analysis was performed on each of the same six lakes impacted by highly active thaw slumps, as well as three reference lakes. This research computed a normalized difference turbidity index (NDTI) between 2015-2022, to examine seasonal trends over a multi- year period in lake water turbidity, which is hypothesized to be related to thaw slump activity.

Much of the work done on thaw slump-impacted lakes in the Mackenzie Delta region have demonstrated that generally, slump-impacted lakes have lower turbidity when compared to reference lakes (Thienpont et al. 2013). I hypothesized that lakes with larger, highly active slumps would have higher turbidity compared to reference lakes because of the input of terrigenous materials, similar to how lakes with stable slumps may have looked with the initial slump formation, perhaps centuries or millennia ago. The results of my analyses show that despite the six study lakes being impacted by large and highly active slumps, they had lower turbidity that reference lakes. Surface waters in slump-impacted lakes were generally inferred by NDTI to be clear, especially in the early summer to late fall. An important exception from this trend was again Lake ML-S_CH_9, where several periods of high turbidity were inferred throughout the time series. This demonstrates that under some enhanced slumping conditions (Lake ML-S_CH_9 has the largest and most active slump in the present dataset), it is possible for highly active slump lakes to exhibit elevated turbidity. This is important to understand as temperatures continue to increase in the region, which is expected to result in an increase in the number of lakes impacted by highly active thaw slumping. High turbidity conditions can have implications for the aquatic environment, and understanding changes in water clarity at a landscape scale is important for evaluating aquatic ecosystem change under continued and accelerated permafrost thaw.

### *4.1.3. Modelling thaw slump dynamics and the impact of continued warming on thaw slump dynamics*

The findings from this research show that enhanced thaw slump activity can change the sediment and water environments of impacted lakes. While five of the six slump lakes studied had characteristics of stable slumps like what has been found in other analysis of thaw slump activity in the region, ML-S_CH_9 behaved differently. This lake demonstrated characteristics of enhanced slumping, as demonstrated by the high turbidity conditions and decreases in carbon and mercury in the sediments, likely from dilution by terrigenous material (Figure 4.1). While isolated to one lake, this aligns with the theorized impacts of enhanced slumping, though the barrier to these limnological changes may be higher than previously hypothesized. Nonetheless these results contribute important understanding of the impacts of continued climate warming on permafrost thaw slump dynamics.

In future research, I plan to examine the response of thaw slump-impacted lakes in previous periods of warming. In the early Holocene there was a period of warming defined as the Holocene Climate Optimum (Gajewski 2015), that exhibited extreme warm temperatures within the Western Canadian Arctic similar to the warming that is currently being experienced. The

Holocene Climate Optimum may also represent the time period of the formation of many lakes in the Mackenzie Delta uplands, as well as the time of initial thaw slump development in the catchments of lakes. As a result, looking at how slump-impacted lakes responded to the permafrost thawing and impacts to receiving waterbodies will provide important insights into millennial-scale ecosystem and permafrost dynamics and ultimately allow us to better understand how we can expect lakes to respond to ongoing human-driven warming and associated environmental changes.

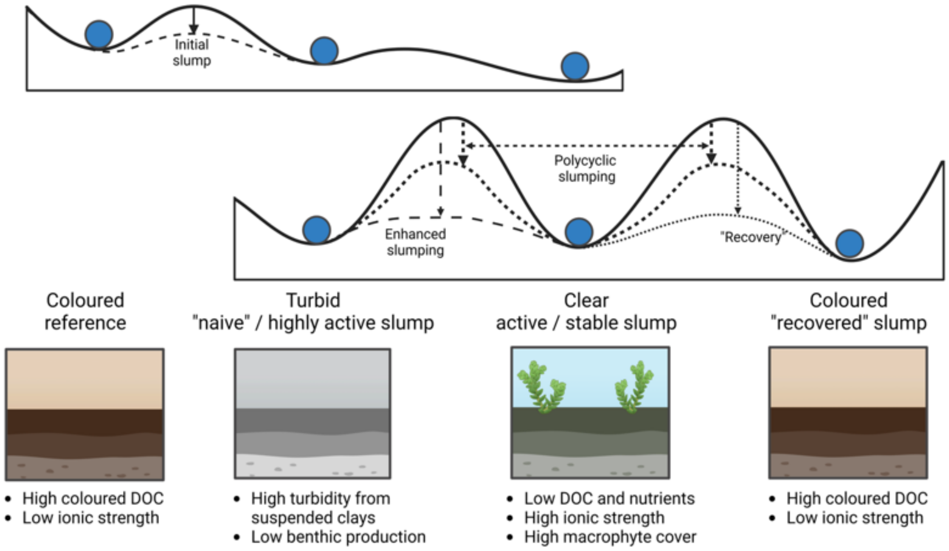

*Figure 4.1: Conceptual Model (Published under CC BY-NC-4.0 in Thienpont et al. 2025 ) proposing how the lake environment is impacted at different stages of thaw slump development and polycyclic slumping*

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