Assessing recovery in storm surge impacted lakes of the outer Mackenzie Delta, NT, Canada

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Abstract

Low-lying ecosystems within Canada's Arctic regions have experienced an increased frequency and intensity of storm surge events in recent decades, due to the impacts of anthropogenic climate changes. Following a severe storm surge that took place in September 1999, lakes in the northwest Mackenzie Delta (NT, Canada) were fundamentally altered. Lake sediment cores were collected a decade after the event for paleolimnological analysis, revealing that some lakes had undergone complete or partial transition to brackish environments. However, the condition of the lakes had not been assessed in the last 15 years, and it is unknown if the lakes have recovered, remain highly disturbed, or have been impacted by subsequent storm surge events. The purpose of this study was to assess recent ecosystem trajectories in storm surge-impacted lakes of the outer Mackenzie Delta using contemporary water chemistry and paleolimnological analyses of sedimentary diatom assemblages.

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Chapter 1: General Introduction

1.1 Background Information

Coastal freshwater systems of the outer Mackenzie Delta, Northwest Territories, Canada are increasingly being influenced by storm surge activity that has intensified under the effects of anthropogenic climate change [Smol et al., 2005; Sepp and Jaagus, 2011; Thienpont et al., 2012]. These changes have driven notable ecological transformations in recent decades, largely associated with saline incursions linked to more frequent and severe storm events [Pisaric et al., 2011; Lantz et al., 2015]. An unprecedented event occurred in September 1999, when a significant storm surge transported saline waters up to 30 km inland from the Beaufort Sea coast, flooding the outer delta for multiple days [Kokelj et al., 2012; Lantz et al, 2015]. Remote sensing and hydrometric analyses indicate that nearly all terrestrial surfaces in the region (more than 10,000 ha) were submerged during this event [Kokelj et al., 2012.] The consequences of this disturbance have proven to be persistent, with studies reporting limited ecological recovery in isolated lake systems more than a decade later [Thienpont et al., 2012, 2015].

Sediment core analyses conducted in 2010 from lakes affected by the 1999 surge revealed little evidence of ecological recovery, underscoring the long-term impacts of this event [Thienpont et al., 2012; 2015]. However, the 11-year interval between the 1999 surge and the 2010 sediment sampling provides a relatively short period to assess recovery from a large-scale disturbance, particularly in Arctic lake ecosystems where recovery processes may occur gradually over decadal timescales. The additional 15 years that have elapsed between the 2010 analyses and the present study therefore provide an opportunity to evaluate recovery over a

26year period since the 1999 storm surge, offering a more accurate perspective on the longer-term disturbance and recovery trajectories of these lakes. The acquisition of new sediment cores provides an opportunity to evaluate ecosystem trajectories over the past 25 years, and to assess the range of possible recovery pathways. Understanding these dynamics is of particular importance for Inuvialuit land users [Kokelj et al., 2012; Lantz et al., 2015], and offers broader insight into ecosystem responses to the emerging disturbance regimes that are expected to become more frequent across the Arctic [Jaagus and Sepp, 2011; Pisaric et al., 2011; Wood et al., 2013].

1.2 Research Question and Objectives

Storm surges represent a major episodic disturbance in Arctic coastal environments, particularly in the low-lying outer Mackenzie Delta, where coastal lakes have been previously inundated with saline, sediment-rich marine waters [Pisaric et al., 2011; Kokelj et al., 2015; Thienpont et al., 2012, 2015]. Such events can fundamentally alter lake chemistry, sediment composition, and biological communities, often pushing freshwater systems beyond ecological thresholds [Pisaric et al., 2011; Deasley et al., 2012; Thienpont et al., 2012, 2015]. The objective of this research was to utilize lake sediments from lakes in the outer Mackenzie Delta, in order to evaluate the impacts of recent storm surges and the associated saltwater inundation on local aquatic ecosystems. Using contemporary water chemistry analyses and paleolimnological analysis of sedimentary diatoms, a well-developed indicator of storm surge impacts and changing salinity [Battarbee, 2000; Douglas et al., 2004], this study explores the potential for several competing hypotheses for the change in outer Delta lakes since the 1999 storm surge: a) the lakes have undergone chemical / biological recovery and returned to primarily freshwater conditions, b) recovery is ongoing, but very slow, c) lakes have not recovered and remain impacted, or d)

subsequent, more recent storm surge events have occurred and stalled recovery, indicating these lakes are in a new disturbance regime characterized by disturbance return intervals that are shorter than the time required for recovery [Pisaric et al., 2011; Thienpont et al., 2012]. This leads to the research question: Are storm surge-impacted lakes in the outer Mackenzie Delta exhibiting chemical and physical recovery from the 1999 storm surge, compared to conditions observed in 2010 when no recovery had taken place?

Given the spatial scale and heterogeneous nature of the region it is possible that different lakes may have experienced different environmental trajectories over the past 25 years. Previous observations following the 1999 storm surge indicated persistent changes in lake water chemistry and sediment characteristics, with little evidence of recovery by 2010 [Thienpont et al., 2012, 2015]. However, the extent to which these storm surge-impacted lakes may have undergone chemical and physical recovery in the years since remains unclear [Pisaric et al., 2011; Thienpont et al., 2012, 2015]. This research will build upon existing studies by specifically focusing on the long-term impacts of the 1999 storm surge on lakes in the outer Mackenzie Delta [Pisaric et al., 2011; Kokelj et al., 2012; Thienpont et al., 2012, 2015; Lantz et al., 2015]. Paleolimnological analyses of more recent sediment deposits provide an opportunity to assess whether recovery trajectories have emerged over longer timescales, as reflected by shifts in diatom assemblages [Battarbee, 2000; Douglas et al., 2004; Smol et al., 2005]. To strengthen interpretations of recovery trajectories, diatom assemblage analyses will be integrated with contemporary water chemistry data, to allow for a more comprehensive assessment of presentday lake conditions. By documenting the extent and nature of recovery in these relatively wellstudied storm surge-impacted lakes, this research aims to shed light on the nature of recovery processes taking place, if any, on a decadal scale in the rapidly changing coastal region of the western Canadian Arctic.

Chapter 2: Literature Review

2.1 Climate Warming and Arctic Coasts

The Arctic is experiencing some of the most rapid warming observed globally, with particularly pronounced temperature increases across Canada's polar regions [Douglas et al., 2004; Rantanen et al., 2022; Shipman et al., 2024]. In their 2022 study, Rantanen et al. referred to this phenomenon as Arctic amplification, proposing that the Arctic has warmed at a rate nearly four times faster than the rest of the globe over the past several decades. Several mechanisms have been identified as contributors to Arctic amplification, with their relative importance varying across climate models [Screen et al., 2026]. Proposed processes include increased oceanic heat input, reduced oceanic ice cover and the associated ice–albedo feedback, as well as changes in the atmospheric lapse rate [Jenkins and Dai, 2021; Rantanen et al., 2022; Screen et al., 2026]. Recent modelling experiments by Screen et al. [2026] demonstrated that Arctic amplification occurs even when changes in oceanic ice cover are excluded, though the resulting amplification was weaker. The 2026 analysis by Screen et al. further indicated that the lapse-rate feedback, reflective of changes in the vertical distribution of temperature within the atmosphere, makes the largest individual contribution to polar amplification across all climate models examined [Screen et al., 2026]. The ecological impacts of this amplified warming are particularly evident in Arctic freshwater ecosystems, where minor temperature increases can shorten the duration of seasonal ice cover, consequently altering the biological communities within these affected lakes [Griffiths et al., 2017]. Long-term paleolimnological research in the Canadian Arctic has documented pronounced changes in diatom assemblages consistent with reductions in ice cover, demonstrating that recent climate warming has already produced measurable

ecological changes in Arctic freshwater ecosystems [Douglas et al., 1994; Smol and Douglas, 2007; Griffiths et al., 2017].

As a result of Arctic amplification, climate models and observational studies have indicated an increase in the frequency and intensity of marine storm events over recent decades [Sepp and Jaagus, 2011; Vermaire et al., 2013; Wood et al., 2013]. Declining sea-level pressure over the Arctic Ocean and the Beaufort Sea has promoted more persistent cyclonic conditions over time, reflecting broader shifts in large-scale atmospheric circulation [Cosimo et al., 2008; Sepp and Jaagus, 2011]. These cyclones play a key role in transporting heat and moisture into the Arctic, thereby increasing the likelihood of storm surges along Arctic coastlines [Sepp and Jaagus, 2011]. As a result, storm surges are becoming more frequent, and their impacts on Arctic coastal ecosystems are more pronounced [Pisaric et al., 2011; Sepp and Jaagus, 2011; Small et al., 2011; Vermaire et al., 2013]. Throughout recent decades, substantial changes have been documented in Arctic sea ice and cyclonic behavior in the Beaufort Sea region, with significantly reduced late-summer to early-autumn ice cover recorded over the last 45 years [Simmonds and Keay, 2009; Small et al., 2011; Vermaire et al., 2013]. As sea ice coverage declines, the resulting increase in open-water fetch facilitates greater wave generation during storms, potentially increasing the magnitude of wave-driven coastal impacts [Overeem et al., 2011; Thomson and Rogers, 2014; Squire, 2020]. In the context of wave development, fetch refers to the uninterrupted distance over open water where wind blows over the ocean surface to generate waves [Thomas and Rogers, 2014]. Longer fetch generally allows waves to grow larger and gain more energy [Thomson and Rogers, 2014; Squire, 2020]. Simmonds and Keay [2009] found that the decline in September sea-ice extent was associated with changes in cyclone characteristics across the Arctic, with cyclone intensity, rather than cyclone frequency, emerging as an

important contributor to the observed changes. They proposed that reduced sea-ice cover may enhance the development of existing cyclones by increasing the exchange of heat and moisture between the ocean and atmosphere, while stronger cyclones in turn apply greater mechanical force on the remaining sea ice, further reducing the extent of Arctic sea ice cover [Simmonds and Keay, 2009].

The Mackenzie Delta (Northwest Territories, Canada) is a region where the impacts of increased cyclonic activity and reduced ice cover are being acutely felt, with saltwater intrusion into freshwater systems from storm surge events as an example [Vermaire et al., 2013]. These changes are particularly relevant to storm surge impacts in the Beaufort Sea and outer Mackenzie Delta since sea ice restricts the extent of open water over which winds can generate and develop surface waves [Thomson and Rogers, 2014; Squire, 2020]. In the outer Mackenzie Delta, these changes have direct implications for coastal flooding because strong cyclones and the associated northwesterly winds can generate storm surges capable of pushing seawater inland across the low-lying, sloped delta [Thienpont et al., 2012; Vermaire et al., 2013; Squire, 2020]. These events affect coastal communities [Kokelj et al., 2012; Shipman et al., 2024], sea-ice conditions, and the physical processes shaping the outer delta coastline [Small et al., 2011; Wood et al., 2013]. As sea ice declines and the open-water season lengthens, Arctic coastlines are exposed to stronger wave action and storm-driven water level fluctuations for longer periods each year [Vermaire et al., 2013; Wood et al., 2013]. Vermaire et al. [2013] demonstrated that storm surge activity in the outer Mackenzie Delta has increased alongside regional warming and declining Arctic sea ice extent, with a well-documented 1999 storm surge representing an extreme event which inundated approximately 13,000 hectares of the outer delta. The existing literature suggests that declining sea ice and changes in cyclonic behaviour in the Beaufort Sea are not

simply coincident environmental trends, and in conjunction, may increase the potential for intense storm surges and marine inundation of low-lying Arctic freshwater ecosystems [Simmonds and Keay, 2009; Vermaire et al., 2013; Squire, 2020].

Reoccurring saltwater intrusion events triggered by increasing storm surge activity in the Mackenzie Delta may propel coastal lakes beyond critical ecological thresholds, leading to abrupt and persistent shifts in water chemistry, including elevated conductivity and altered ion composition [Pisaric et al., 2011; Vermaire et al., 2013; Thienpont et al., 2015]. Chemical changes such as these could in turn restructure biological communities by providing more favourable conditions for halophilic (i.e., salt-loving) and brackish species of primary producers, while suppressing freshwater taxa that lack the capacity to adapt to rapid fluctuations in salinity [Pisaric et al., 2011; Deasley et al., 2012; Kokelj et al., 2012; Thienpont et al., 2012, 2015; Lantz et al., 2015]. Collectively, these findings indicate that storm-surge-driven saltwater intrusion represents a significant mechanism of ecological change in Arctic freshwater systems, with the potential to influence community dynamics long after individual intrusion events have occurred [Pisaric et al., 2011; Deasley et al., 2012; Kokelj et al., 2012; Thienpont et al., 2012, 2015; Lantz et al., 2015].

2.2 The 1999 Storm Surge in the Mackenzie Delta

During late September of 1999, lakes of the outer, northwest Mackenzie Delta were fundamentally altered by a severe storm surge [Pisaric et al., 2011; Kokelj et al., 2012; Thienpont et al., 2012, 2015; Lantz et al., 2015]. The September 1999 storm resulted in such intense ecosystem disturbance for the outer Mackenzie Delta due a combination of factors including the low-lying nature of the region, preceding offshore winds that blew the normal freshwater cap of

water in the coastal Beaufort Sea out to sea, followed by a wind shift that resulted in a significant and persistent storm surge with an unusually intense, late season storm prior to sea-ice formation that year [Kokelj et al., 2012].The impacts from the event included landscape-scale vegetation mortality, salinization of surface waters in impacted lakes, altered aquatic biological communities at multiple trophic levels, and reduced oxygen levels in lakes and associated substrates [Pisaric et al., 2011; Deasley et al., 2012; Kokelj et al., 2012; Thienpont et al., 2012, 2015; Lantz et al., 2015]. Severe inundation and flooding of saline marine waters into the normally fresh outer Mackenzie Delta occurred following the event, which reached as far as 30 kilometers inland, altering ecosystems in a manner unparalleled within the last millennium [Pisaric et al., 2011; Lantz et al., 2015].

In this thesis, the recovery dynamics of these coastal Arctic ecosystems will be explored by assessing the recovery of storm surge impacted lakes in the outer Mackenzie Delta since the event took place in 1999 [Pisaric et al., 2011; Thienpont et al., 2012]. The last sampling of the lakes assessed in this study occurred in the summer of 2010, approximately ten years after the initial saline intrusion event took place [Pisaric et al., 2011; Thienpont et al., 2012, 2015; Lantz et al., 2015]. During the 2010 assessments, vegetation recovery was evident across many affected areas, though some sites remained sparsely vegetated or completely barren, indicating limited plant recolonization [Thienpont et al., 2012; Lantz et al., 2015]. The long-term recovery trajectory of these persistently disturbed areas remains uncertain, largely because comparable saline flooding events have not been systematically monitored over extended periods [Kokelj et al., 2012; Lantz et al., 2015; Shipman et al., 2024]. Consequently, there is insufficient historical information to determine how long complete ecological recovery may require following such disturbances, if indeed it is ever possible [Deasley et al., 2012; Lantz et al., 2015]. Current

evidence suggests that storm surge driven salinization represents a significant mechanism of ecological change in Arctic freshwater systems, with the potential to influence community dynamics long after individual intrusion events have occurred [Pisaric et al., 2011; Thienpont et al., 2012, 2015; Deasley et al., 2015; Shipman et al., 2024].

In their 2024 publication, Shipman et al. provided empirical evidence of the ecological consequences of habitat alteration for Arctic bird communities in the Mackenzie Delta, due to increased storm surge activity. Through the comparison of avian assemblages across revegetated, unvegetated, and unaffected sites following the major 1999 storm surge, the study demonstrated that long-term vegetation changes resulting from saline intrusion have significantly influenced patterns of community composition and biodiversity among Arctic avifauna [Shipman et al., 2024]. The absence of vegetation cover, serving as nesting or perching substrates, was found to reduce the suitability of impacted sites for several species of interest, including the savannah sparrow (*Passerculus sandwichensis*) and the red-necked phalarope (*Phalaropus lobatus*) [Shipman et al., 2024]. In addition to these findings, Shipman et al. [2024] argue that anticipated increases in storm surge activity associated with climate change [Simmonds and Keay, 2009; Vermaire et al., 2013] may accelerate habitat transformation in the Mackenzie Delta, through saltwater intrusion and terrestrial salinization of coastal environments [Lantz et al., 2015].

Varying recovery trajectories among storm surge impacted lakes reflect the influence of local hydrology, landscape position, and lake-specific characteristics in determining ecosystem resilience [Dyke and Brooks, 2000; Håkanson, 2005; Small et al., 2025]. Local hydrological conditions may influence both the magnitude of saltwater intrusion as well as the subsequent removal of marine-derived solutes, with differences in water inputs, drainage, and exchange with surrounding surface waters affecting the rate at which conductivity and major ion concentrations

return toward pre-disturbance conditions [Dyke and Brooks, 2000; Kokelj et al., 2012; Thienpont et al., 2012]. Landscape position may also influence exposure to storm surges, as lakes located closer to the coast or within low-lying portions of the delta are more likely to experience direct marine inundation and receive greater volumes of saline water [Pisaric et al., 2011]. Conversely, lakes situated farther inland or at slightly higher elevations may experience less severe initial impacts and therefore face a shorter pathway to chemical and biological recovery [Dyke and Brooks, 2000; Pisaric et al., 2011; Thienpont et al., 2012]. Lake-specific characteristics such as morphology, surface area, and water residence time, may further influence recovery by affecting the retention of saline water and dissolved ions [Håkanson, 2005; Thienpont et al., 2012; Small et al., 2025]. For example, lakes with greater water volumes or longer residence times may retain marine derived solutes for longer periods, whereas smaller or more rapidly flushed lakes may experience more rapid declines in conductivity following a saline incursion event [Small et al., 2025]. These physical differences can interact with the biological characteristics of individual lake communities to produce divergent ecological responses among lakes exposed to the same regional disturbance [Thienpont et al., 2012; Pisaric et al., 2011]. Therefore, recovery from a storm surge event should not be expected to follow a uniform trajectory across an impacted region, and rather, the magnitude and persistence of ecological change are likely determined by the interaction between disturbance severity and the unique characteristics of individual lakes [Thienpont et al., 2012].

2.3 Assessing Recovery Using the Paleolimnological Approach

Paleolimnology, the study of environmental and ecological information preserved in lake sediments [Douglas et al., 2004; Paterson, 2020], provides a valuable approach for the

examination of how Arctic lakes have responded to environmental change over the years [Smol, 2023]. Since lake sediments accumulate over time, they provide a record of environmental conditions that predates direct observations, allowing contemporary changes to be interpreted within a historical context [Michelutti et al., 2001; Douglas et al., 2004; Paterson, 2020; Neil and Gajewski, 2018]. This long-term perspective is particularly valuable in the Arctic, where climate warming is altering lake ecosystems and environmental conditions at rates that may be difficult to assess using short-term observations alone [Birks and Birks, 2006; Pisaric et al., 2011; Smol, 2023]. Paleolimnological records may therefore be utilized to investigate changes associated with climate warming as well as other environmental disturbances, including storm surges, while providing a means of distinguishing recent changes from the natural variability that may have occurred before contemporary observations [Douglas et al., 2004; Pisaric et al., 2011; Thienpont et al., 2015]. Sedimentary records contain biological, physical, and geochemical indicators that can collectively provide insight into changes taking place in lake conditions over time [Smol and Douglas, 2007; Thienpont et al., 2012, 2015]. By integrating these lines of evidence, the paleolimnological approach can be used to characterize the extent, timing, and persistence of ecological change, as well as determine whether lakes affected by storm surges are moving back toward pre-disturbance conditions or shifting toward different ecological states [Battarbee, 2000; Thienpont et al., 2012, 2015; Neil and Gajewski, 2018].

2.3.1 Methods of collecting sediment cores

To track ecological changes in lakes, sediment cores must be extruded and divided into stratigraphic increments, often in 0.25–1.0 centimetre (cm) slices, to capture subtle shifts in sediment composition over time [Battarbee, 2000; Michelutti et al., 2001]. Individual slices may

correspond to time periods ranging from less than a year to over a decade, depending on the local climatic conditions influencing sedimentation rates [Battarbee, 2000; Thienpont et al., 2012]. To determine when sediment was deposited, paleolimnologists assign approximate ages to the different depth intervals within a sediment core, and use these points to reconstruct its chronology [Birks and Birks, 2006; Brenner and Kenney, 2013]. Recent sediments deposited over the past century or so can be dated using naturally occurring ^{210}Pb, while ^{137}Cs may be used to identify sediments deposited during the period of atmospheric nuclear weapons testing in the mid-twentieth century [Brenner and Kenney, 2013; Smol, 2023]. When material suitable for radiocarbon analysis is preserved in older sediments spanning back thousands of years, ^{14}C dating can provide age estimates beyond the range of ^{210}Pb, due to the radioisotope's longer halflife [Brenner and Kenney, 2013; Smol, 2023].

Several coring techniques are available for recovering lake sediments, with the type of corer depending on water depth, sediment characteristics, and the desired temporal extent of the record [Smol, 2023]. For example, push corers are particularly useful for sampling shallow ponds, generally less than 1 metre in depth, where deeper coring systems may be difficult to deploy effectively [Glew and Smol, 2016; Smol, 2023]. Their simple design allows the corer to be manually pushed into soft surface sediments, making them well suited for recovering short sediment cores [Glew and Smol, 2016]. In contrast, piston corers are generally better suited to obtaining longer sediment cores, and therefore provide greater temporal coverage while slightly sacrificing resolution [Pisaric et al., 2011], making them useful when recent observations need to be placed within a longer-term palaeoenvironmental context [Smol, 2023].

For studies focused specifically on recent disturbance and recovery, gravity coring is the most appropriate method, since maintaining the integrity of the uppermost sediment is essential

for capturing changes occurring over annual to decadal timescales [Pisaric et al., 2011; Smol, 2023]. Gravity corers are particularly useful for investigating recent environmental changes, as they are designed to penetrate the high-water-content upper sediments and can recover relatively short sediment cores while preserving the most recently deposited surface layers [Glew, 1988; Smol, 2023]. The corer is lowered through the water column and allowed to penetrate the lakebed under its own weight, providing an efficient means of collecting relatively undisturbed sediment sequences from deeper water environments [Glew, 1988]. Due to the uppermost sediments being less compacted and containing the most recently deposited material, maintaining the integrity of these layers is important when reconstructing environmental conditions over recent decades to centuries [Smol, 2023]. Gravity cores can also be sectioned at fine intervals following collection, allowing changes in sediment characteristics and other environmental indicators to be examined at a higher temporal resolution [Smol, 2023]. This makes gravity corers particularly appropriate for studies seeking to identify recent environmental disturbances and subsequent ecological responses recorded in lake sediments [Pisaric et al., 2011].

2.3.2 Proxies for reconstructing environmental change from lake sediments

A wide range of proxies can be extracted from sediment archives, with each providing information about different components of a lake or its surrounding environment. [Birks and Birks, 2006; Smol 2023]. Physical proxy data can reveal variations in sediment composition and delivery [Vermaire et al., 2013], while chemical proxy data may provide evidence of changes in nutrient cycling, water chemistry, and the sources of material entering a lake [Birks and Birks,

2006]. Sediment properties such as grain size, organic matter content, and magnetic characteristics can therefore offer valuable information regarding processes occurring within sampled lakes [Birks and Birks, 2006; Vermaire et al., 2013].

Biological proxies provide another major group of paleoecological indicators, as organisms respond to environmental conditions during their lifetimes, which may be reflected in the sediment profile [Battarbee, 2000; Smol, 2023]. Pollen and plant macrofossils can be used to reveal information about changes in terrestrial vegetation surrounding a lake, linking lake sediment records to how local climates and land-use practices have transformed [Birks and Birks, 2006; Chevalier et al., 2020; Smol, 2023]. The remains of aquatic organisms, including chironomids, cladocerans, and diatoms, can instead provide information about conditions within the lake itself [Battarbee, 2000; Deasley et al., 2012; Thienpont et al., 2015]. The specific characteristics and ecological preferences of these organisms allow changes in their fossil assemblages to be interpreted in relation to fluctuating environmental variables such as temperature, salinity, nutrient availability, and habitat conditions [Battarbee, 2000; Michelutti et al., 2001; Smol, 2023].

The remains of chironomids (non-biting midges) preserved in lake sediments can be examined to assess how aquatic environments may have changed over time [Battarbee, 2000; Thienpont et al., 2015; Smol, 2023]. Due to different chironomid taxa possessing distinct environmental optima, changing chironomid assemblages may reflect shifts in variables such as temperature, oxygen availability, nutrient conditions, and contamination within a lake [Birks & Birks, 2006; Nicacio and Juen, 2015]. These optima allow for changes in chironomid communities to provide evidence pertaining to both naturally occurring environmental variation as well as anthropogenic impacts on lake ecosystems [Battarbee, 2000; Nicacio and Juen, 2015;

Thienpont et al., 2015]. In Arctic lakes, chironomid assemblages have also been used to examine ecological responses to disturbances and environmental change, demonstrating their value for reconstructing past conditions in northern environments [Thienpont et al., 2015].

Cladocerans can be particularly informative when reconstructing changes in lake ecosystem dynamics because they occupy an important position within aquatic food webs [Deasley et al., 2015; Smol, 2023]. Their interactions with primary producers and their role as prey for larger organisms mean that shifts in cladoceran communities can reflect changes in relationships among different levels of the food web [Deasley et al., 2015]. This makes cladocerans useful alongside chironomids when paleolimnologists seek to distinguish changes affecting different parts of an aquatic ecosystem, since the two groups occupy different ecological niches and may respond differently to the same environmental change [Birks and Birks, 2006; Smol, 2023].

2.3.3 Diatoms as paleoecological indicators

Diatoms are siliceous algae of the class Bacillariophyceae, which are single-celled and invisible to the naked eye [Dixit et al., 1992]. They are vital constituents of both marine and freshwater ecosystems, serving as an essential food source for many aquatic organisms [Dixit et al., 1992]. Despite their small biomass, diatoms are highly efficient primary producers responsible for approximately 20% of global oxygen production [Karthick and Kale, 2015]. They are distinguished by their intricate glass cell walls, called valves, which are formed by the uptake of environmental silicic acid ($Si(OH)_4$) [Dixit et al., 1992; Smol and Stoermer, 2010; Karthick and Kale, 2015]. In paleolimnological analyses, diatoms are classified based on their distinctive valves, which are identified and counted to reconstruct diatom populations and assemblages

[Dixit et al., 1992]. Diatoms serve as effective bioindicators of environmental change since they are widespread aquatic organisms that respond rapidly and predictably to changes in environmental conditions, including nutrient availability, pH, temperature, and pollution [Antoniades et al., 2009; Smol and Stoermer, 2010]. Since different diatom species exhibit distinct ecological preferences and tolerances, shifts in the composition and abundance of diatom communities across the paleolimnological record may indicate shifts in water quality and ecosystem conditions [Rühland et al., 2015; Costa and Schneck, 2022]. Due to their short life cycles, populations respond relatively quickly to environmental disturbances, making them useful for detecting environmental changes affecting remote locations that are not frequently sampled [Smol and Stoermer, 2010; Pandey et al., 2017]. In addition, their silica-based cell walls preserve well in sediment deposits, allowing for the reconstruction of climatic conditions and the identification of long-term environmental changes such as warming, eutrophication, and acidification [Smol and Stoermer, 2010; Rühland et al., 2008; Smol, 2023].

Thienpont et al. [2012] used diatom analysis to assess how saltwater intrusion affected freshwater ecosystems at a landscape scale across the outer Mackenzie Delta and observed that predominantly freshwater species were replaced by brackish water-adapted taxa following the 1999 storm surge. Since many species of diatoms have well-defined optima and tolerances for salinity across a wide gradient, they serve as useful indicators of saltwater intrusion events in lake ecosystems such as the ones assessed in this study [Battarbee, 2000; Michelutti et al., 2001; Thienpont et al., 2012, 2015]. A paleolimnological approach is well-suited for understanding the long-term impacts of saltwater intrusion in the outer Mackenzie Delta, as it provides a historical perspective on ecosystem changes in lakes that are not regularly monitored for chemical or biological conditions due to their remote locations [Douglas et al., 2004; Kokelj et al., 2012;

Thienpont et al., 2015] and will provide the basis for the research in this thesis examining the trajectory of ecosystem change over the past several decades.

Chapter 3: Site Description

3.1 The Mackenzie Delta

The Mackenzie Delta is located in Canada's Northwest Territories where the Mackenzie River meets the Arctic Ocean, emptying into the Beaufort Sea [Figure 3.1; Dyke and Brooks, 2000]. It is the second-largest Arctic delta on the planet and facilitates the largest single annual discharge of freshwater from North America to the Arctic Ocean [Burn and Kokelj, 2009]. The Delta is a low-lying ecosystem characterized by its many islands, lakes, and ponds [Kokelj et al., 2012]. Moving from the interior toward the coast, the landscape transitions from a boreal taiga into a low-growing tundra [Dyke and Brooks, 2000; Burn and Kokelj, 2009]. The outer Delta is a wide-spread alluvial plain characterized by low shrub vegetation, north of the treeline [Thienpont et al., 2012]. The region's Low Arctic climate is marked by cold winters lasting up to 8 months, accompanied by summers that are brief and cool, which are when most biological activity takes place [Dyke and Brooks, 2000; Burn and Kokelj, 2012; Thienpont et al., 2015]. Climate conditions also vary across the Delta, with colder and generally drier conditions toward the Beaufort Sea and somewhat warmer conditions farther inland [Dyke and Brooks, 2000; Burn and Kokelj, 2009].

The physiography of the Delta is dominated by a broad, gently sloping depositional plain that extends toward the Beaufort Sea [Burn and Kokelj, 2009]. The Delta is encompassed by rolling uplands to the east and the Cordillera to the west, while the central and outer portions are characterized by low elevations (<10 metres above sea level) [Dyke and Brooks, 2000; Thienpont et al., 2012] and extensive fluvial deposits [Burn and Kokelj, 2009]. The Mackenzie

River divides into numerous channels across this low-lying terrain, producing a complex landscape in which river channels, lakes, wetlands, and terrestrial surfaces are closely connected [Dyke and Brooks, 2000; Burn and Kokelj, 2009]. Due to the Mackenzie Delta's extensive and gently sloping profile, storm surges generated in the Beaufort Sea can travel far inland, flooding broad expanses of low-elevation alluvial land [Thienpont et al., 2015]. The 1999 storm surge provides a particularly well-documented example of this connection between the Beaufort Sea and the inland delta environment [Pisaric et al., 2011]. On September 23rd and 24th, 1999, the event produced a water-level increase exceeding two metres in portions of the delta's distributary system [Pisaric et al., 2011; Kokelj et al., 2012]. Seawater subsequently reached approximately 30 km inland and remained across affected areas for several days [Pisaric et al., 2011; Kokelj et al., 2012]. The resulting increase in soil salinity caused widespread vegetation mortality and produced the area subsequently referred to as the "Dead Zone" [Pisaric et al., 2011; Kokelj et al., 2012; Thienpont et al., 2012, 2015]. Observations from field investigations, remote sensing, and Inuvialuit knowledge have all contributed to documenting the environmental effects and persistence of this disturbance [Kokelj et al., 2012].

All sampling sites referenced in this study are located in the northwest Mackenzie Delta, within 10 km of the Arctic Ocean coast, with the exception of the control site, which is located inland and outside the impact zone of the 1999 storm surge (colloquially called the Dead Zone) [Thienpont et al., 2012]. The surface areas of all sample lakes range from 3.5 to 228.8 hectares [Thienpont et al., 2012]. Lake depth was measured for two of the six sample lakes, noted in a 2015 publication by Thienpont et al. Lake DZO-30 is shallow with a maximum depth of ~1.8 metres, while DZO-29 is slightly deeper due to its maximum depth of ~4.1 metres [Thienpont et al., 2015]. Sites were initially sampled in 2009 and 2010 and were re-visited in the summer of

2025 for sampling of water and sediments. During the July 2025 sampling period, persistence of the Dead Zone was observed, although with some shifts noted in relation to vegetation recovery.

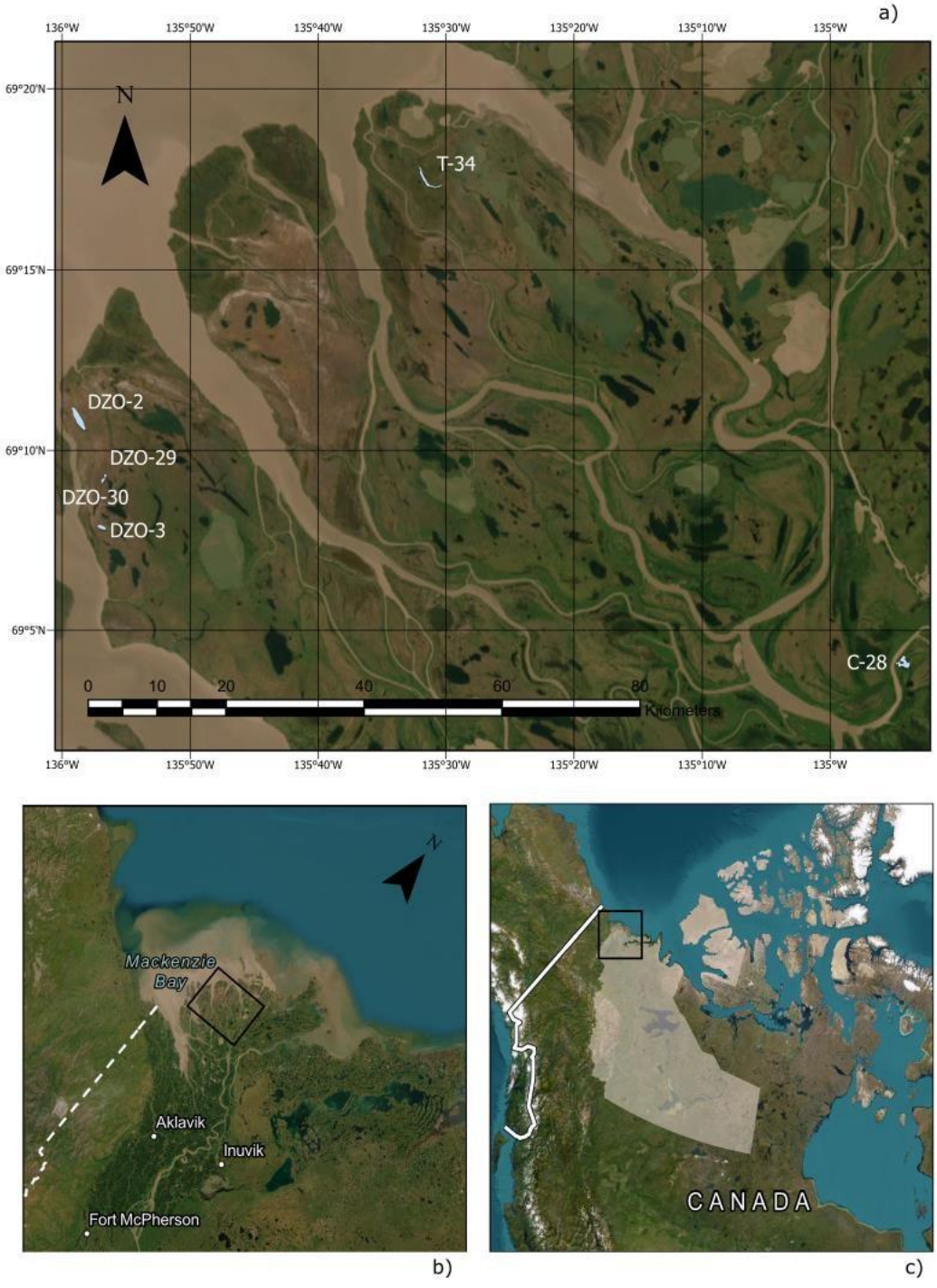


Figure 3.1. a) Locations of study lakes DZO-2. DZO-29, DZO-30, DZO-3, T-34, and C-28; b) The study area in relation to the rest of the Mackenzie Delta; c) The outer Mackenzie Delta in relation to the rest of Canada. This figure was produced using ArcGIS Pro version 3.6.

3.2 The Dead Zone

Sediment cores were collected from six sites in the outer Mackenzie Delta in July 2025, to investigate spatial variability in the effects of the 1999 storm surge on coastal Arctic lakes [Pisaric et al., 2011]. Four of these locations, which are designated with the code "DZO" to indicate their position within the so-called "dead zone" [Figure 3.2], identified in 2010 are situated on Ellice Island along the outer margin of the delta, directly within the primary zone of saltwater intrusion during the 1999 storm surge [Figure 3.1; Pisaric et al., 2011; Kokelj et al, 2012; Thienpont et al., 2012]. The term "dead zone" refers to the severity of vegetation mortality and soil salinization in the region following the 1999 event, which was made evident through aerial observations, remote sensing analyses, and traditional ecological knowledge imparted by Inuvialuit [Figure 3.2; Pisaric et al., 2011; Kokelj et al, 2012; Thienpont et al., 2012]. Regarding the dead zone's spatial orientation in relation to the other study zones, it is located south-west of the transitional zone and north-west of the control zone [Figure 3.1].

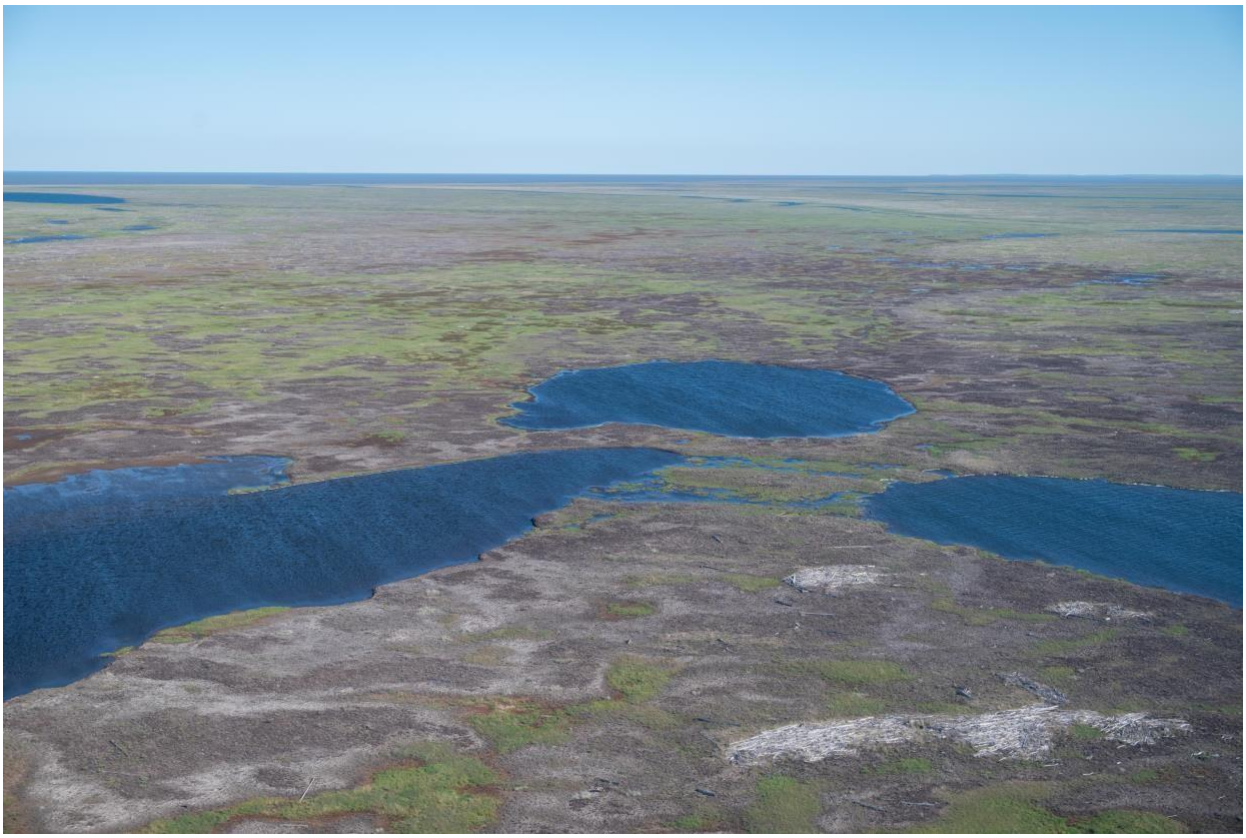


Figure 3.2. Aerial view of DZO-29 (middle) and DZO-30 (left), surrounding by storm surgeimpacted vegetation in the dead zone (July 2025).

3.3 The Transitional Zone

Site T-34 initially exhibited moderately elevated ionic concentrations relative to control conditions and was therefore categorized as a transitional (“T”) site based on its 2010 assessment [Pisaric et al., 2011; Thienpont et al., 2012]. Various lakes sampled within the transitional zone have displayed a similar pattern, with T-34 being broadly representative of conditions across the area [Thienpont et al., 2012]. It is the northernmost study site and is located 7.58 kilometres from the coast, with a surface area of approximately 75 hectares [Figure 3.1]. The transitional zone is located north-east of the dead zone and north-west of the control zone [Figure 3.1]. Upon our

reassessment of the transitional zone in July 2025 for the purposes of this study, much of the vegetation appeared patchy and withered [Figure 3.3], with several sections of barren land. Several indications of woody debris were also present. Based on these observations, the transitional zone may have been impacted by an additional storm surge event, occurring after the last assessment took place in 2010.



Figure 3.3. Aerial view of the transitional zone, where vegetation has notably deteriorated since 2010. Riparian vegetation persists along the river.

3.4 The Control Zone

The sixth site, named C-28, serves as the control (“C”) for this study. The lake is located within a designated control zone for this study, which was determined based on previous control

sites from the 2010 assessment [Pisaric et al., 2011; Thienpont et al., 2012]. It is the largest of all the study lakes assessed in this study, with a surface area of approximately 230 hectares [Figure 3.1]. C-28 is located 43 kilometres inland and sits 7 metres above sea level, making it unlikely to have experienced saltwater intrusion from the 1999 event [Thienpont et al., 2012]. In comparison, all other study lakes have an average elevation of ~1 metre above sea level, making them more susceptible to storm surge impacts. The vegetation surrounding C-28 was observed to be lush, with an abundance of graminoids, shrubs and grasses [Figure 3.4]. In terms of spatial orientation, the control zone is located south-east of both the dead zone and the transitional zone [Figure 3.1].

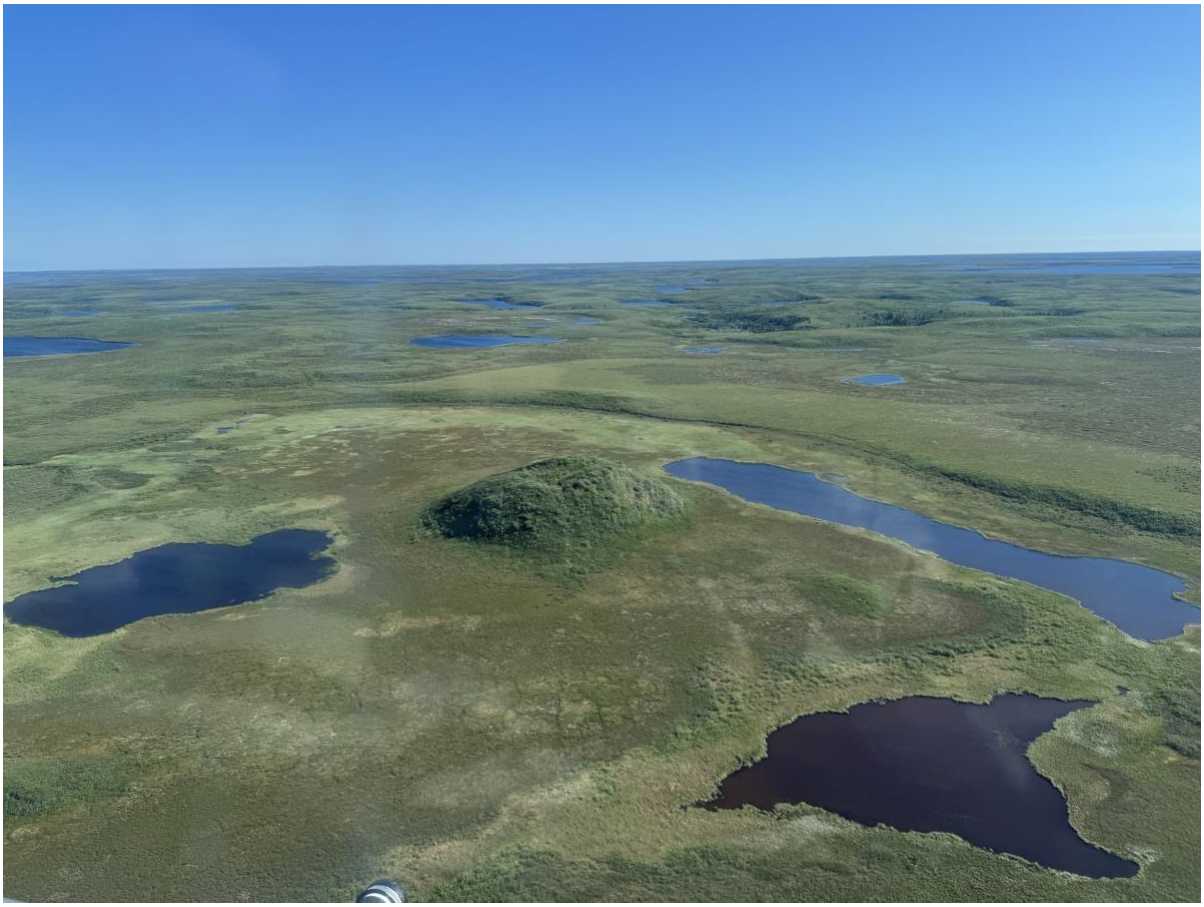


Figure 3.4. Aerial view of a pingo located in the control zone, where vegetation has remained unaffected by storm surge-induced saltwater intrusion.

Chapter 4: Methods

4.1 Field Sampling

Sediment cores ranging from 18 cm to 34 cm in length were collected from the center of each study lake in July of 2025, using a Uwitec USC0600 gravity corer deployed from the pontoons of a Bell 206L helicopter [Glew, 1989]. The cores were sectioned in the laboratory at the Aurora Research Institute in Inuvik, NT, using a vertical extruder [Glew, 1988]. Sections were divided into 0.50 cm intervals for the first 10 cm, and 1 cm intervals from 10 cm until the bottom of the core. In addition, water sampling for contemporary limnological variables (pH, conductivity, and various ion concentrations) was conducted to compare current water chemistry conditions to the previous conditions based on sampling from 2009 and 2010 [Thienpont et al., 2012]. Water samples were collected from just below the surface of the water column to maintain consistency with the sampling methods employed in previous analyses, kept cold until analysis at the Taiga Environmental Laboratory (Yellowknife, NT), a CALA-accredited facility, and the same location where previous samples were analyzed.

4.2 Laboratory Methods

Dissolved organic carbon (DOC), major ions, and nutrient analyses were conducted on water samples at the Taiga Laboratory, Yellowknife, NT. To establish a chronology of the sediment profiles of each core, freeze-dried sediment samples were sent to the Paleoecological Environmental Assessment and Research Lab (PEARL) at Queen's University in Kingston, Ontario, where the ^{210}Pb dating method by gamma spectrometry was implemented. However, at the time of writing this thesis these analyses are ongoing. However, given the re-analysis of diatom

assemblages found in each core, relative timing of specific events can be determined by comparing previous diatom assemblage shifts to those that occurred in the core assemblages when the lakes were previously sampled in 2009 and 2010. To evaluate ecosystem changes that took place since the 1999 storm surge, the upper-most sediment intervals of the six newly collected cores were sampled. The first 8-10 cm of cores from DZO-2, DZO-29, T-34, and C-28 were assessed to provide further insight into environmental changes that may have occurred prior to the 1999 event, and for the best comparison with the previously analyzed cores. 10 cm was chosen based on previous ^{210}Pb-based chronologies from lakes in this region, which indicate, unsurprisingly, that sedimentation is relatively low in these small, closed-basin Arctic lake environments.

Diatoms were extracted from sediment samples using roughly 0.5 g of wet material from each interval, which were transferred into glass scintillation vials. Using hydrogen peroxide digestion following the method of Battarbee et al. [2001], all organic content was eliminated. To achieve this, each vial was filled with 30% H_2O_2 and placed partially in a 70 °C water bath, followed by additional rinsing with deionized water over a seven-day period until neutral pH was reached. The resulting slurries were applied to coverslips at four dilution levels and allowed to dry at room temperature within a covered slide container to minimize airborne contamination. Finally, the coverslips were mounted on microscope slides using Naphrax® and examined with a Leica DMRB light microscope under oil immersion at 1000× magnification. A minimum of 300 diatom valves were counted per sediment interval [Battarbee et al., 2001], and diatom identification was derived primarily from Krammer and Lange-Bertalot [1991-2000], with reference to additional texts where required.

4.3 Data Analysis

Principal components analysis (PCA) was conducted using 2010 [Thienpont et al., 2012] and 2025 water chemistry data from each study lake with RStudio (version 4.5.2), to quantify chemical change / recovery across a spatial gradient. Values from 2010 were plotted passively in the 2025 data output matrix, to visualize changes over the last ~15 years. Diatom species diversity in each interval was assessed using Hill's N2 index [Hill, 1973], calculated in RStudio (version 4.5.2) with the Rioja and Vegan packages [Juggins, 2024; Oksanen et al., 2025]. A stratigraphically constrained incremental sum of squares (CONISS) cluster analysis was then applied to identify periods of change in diatom assemblages over time, with the number of meaningful clusters determined by comparison to a broken-stick model.

Chapter 5: Results

5.1 Water Chemistry

The clearest pattern across the water chemistry data was an overall decline in ionic concentrations in most of the DZO lakes between 2010 and 2025, as reflected by substantial reductions in conductivity and major ions (Na, Cl, SO_4, Ca) [Table 5.1, Table 5.2]. Lake DZO-2 displayed the largest shift, with conductivity dropping by over 50%, and major ions decreasing sharply. Most notably, the concentration of chloride dropped from 5920 mg/L [Table 5.1] to 1950 mg/L [Table 5.2]. Lake DZO-29 exhibited a similarly pronounced decline, with conductivity reduced from 12,722 µS/cm [Table 5.1] to 5,130 µS/cm [Table 5.2] as well as consistent decreases across all major ions, reinforcing that these two lakes experienced the largest reductions in salinity-related variables. In DZO-30, conductivity decreased from 6,855 µS/cm [Table 5.1] to 5,610 µS/cm [Table 5.2], and reductions in Na, Cl, and SO_4 were also observed. While the magnitude of decrease in ionic strength is minimal compared to other sites, the direction of change in lake DZO-30 is consistent with the broader pattern of declining ionic strength across all study lakes. Lake DZO-3 however showed the smallest magnitude decrease in conductivity out of all DZO lakes, from 3,090 µS/cm [Table 5.1] to 2,800 µS/cm [Table 5.2], and relatively small decreases in ion concentrations. In contrast to the DZO lakes' general trend towards lower conductivity, T-34 stood out as the only lake with a marked increase in salinityrelated chemical variables. Conductivity rose substantially from 568 µS/cm [Table 5.1] to 2,760 µS/cm [Table 5.2], and major ion concentrations all increased accordingly. Finally, the control site of lake C-28 remained consistent with only a minor increase in conductivity and

small changes in ion concentrations, indicating relatively stable conditions compared to the other lakes.

Table 5.1. 2009 and 2010 environmental (physical and chemical) data for the six study lakes [Adapted from Thienpont et al., 2012].

Lake	Surface area (ha)	Distance from coast (km)	Conductivity (µS/cm)	pH	DOC (mg/L)	Ca (mg/L)	Na (mg/L)	Cl (mg/L)	SO4 (mg/L)	TP (mg/L)
DZO-2	126.3	3.57	14655	8.08	8.1	244	2750	5920	716	0.0164
DZO-3	22.6	7.86	3090	8.63	13.1	79.9	475	1000	89	0.0248
DZO-29	3.5	6.49	12722	8.01	9.8	251	2270	5030	496	0.0137
DZO-30	8.7	7.25	6855	8.19	12.9	125	1120	2530	208	0.0209
T-34	75.3	7.58	567.8	8.57	9.5	33.3	57.8	120	44	0.0180
C-28	228.8	43.0	240.1	8.5	9.6	23.9	6.1	7.7	34	0.0148

Table 5.2. 2025 chemical data for the six study lakes.

Lake	Conductivity(µS/cm)	pH	DOC (mg/L)	Ca (mg/L)	Na (mg/L)	Cl (mg/L)	SO4 (mg/L)	TP (mg/L)
DZO-2	6430	6.78	4.9	75.8	1070	1950	262	0.0110
DZO-3	2800	7.27	7.5	54.7	418	752	111	0.0090
DZO-29	5130	7.07	7	82.5	816	1520	178	0.0090
DZO-30	5610	7.24	9.3	97	899	1680	184	0.0140
T-34	2760	7.4	7.4	69.2	403	738	107	0.0200
C-28	324	7.15	6.3	42.2	10.1	11.9	36	0.0170

The Principal component analysis (PCA) highlights a strong primary gradient along Axis

1 (explaining 65.3% of the variance), aligning with measured ionic concentration and conductivity [Figure 5.1]. This is indicated by the clustering of conductivity, Na, Cl, SO_4, and Ca vectors pointed toward the positive end of Axis 1. Samples plotted further to the right are therefore enriched in these constituents. Comparing 2010 (plotted passively in the PCA ordination space determined based on 2025 data) and 2025, two sites shift leftward along this axis, indicating a decline in salinity over time. These changes occur at DZO-2 and DZO-29, which show pronounced shifts from the high-ion strength end of the first PCA axis in 2010 toward much lower values in 2025 [Figure 5.1]. Their elongated vectors on the plot reflect substantial changes in water chemistry, driven by large decreases in dissolved ions.

In contrast, the vectors for lakes DZO-3 and DZO-30 remained in a similar position along Axis 1, suggesting minor changes in ionic strength at both sites [Figure 5.1]. Despite slight reductions in ionic strength at both sites, minimal horizontal transformations of their respective vectors toward the positive end of axis 1 are visible in the PCA diagram [Figure 5.1]. Rather than being driven by an increase in ionic strength, this slight positive shift along axis 1 is likely due to the notable decreases in total phosphorus (TP) in lakes DZO-3 and DZO-30 [Table 5.2]. The TP vector along Axis 1 points toward the negative end of the axis, opposite the clustering of the conductivity, Na, Cl, SO_4, and Ca vectors. Sites DZO-3 and DZO-30 notably had the greatest reductions in TP since 2010 among all sample sites based on the modern water chemistry data [Table 5.1, Table 5.2]. Therefore, any positive shifts along axis 1 for their respective vectors were most likely influenced by decreases in TP rather than changes in ionic strength.

Lake T-34 stood out as the only site moving in the opposite direction, shifting right along Axis 1 toward higher ion variables and conductivity. This shift denotes a strong increase in conductivity and ion concentrations, distinguishing lake T-34 from the broader trend toward

decreasing ion strength observed among the DZO lakes. Lake C-28 showed only a small shift and remains on the low-conductivity end of the gradient in both 2010 and 2025, indicating relatively stable and dilute conditions [Figure 5.1]. Overall, the PCA pattern reflects a general decrease in salinity across the DZO lakes, while T-34 stands out as the main site to have experienced increased salinity over the same 15-year period [Figure 5.1].

Axis 2 of the PCA diagram (explaining 23.9% of the variance) aligns with measured dissolved organic carbon (DOC) and pH, indicated by the pair of DOC and pH vectors pointed toward the positive end of Axis 2 [Figure 5.1]. Samples plotted further to the top of the ordination space were therefore found to contain greater concentrations of DOC as well as higher pH values (though to a lesser extent). Across all sampled sites, decreases in both DOC and pH were observed [Table 5.1, Table 5.2], which is reflected strongly in the PCA diagram [Figure 5.1]. The vectors representing sites DZO-2, DZO-3, and DZO-29 displayed the longest vertical shifts downward along axis 2, indicating greater decreases in both measured values [Figure 5.1]. For sites DZO-30 and T-34, vertical shifts indicating reductions in DOC and pH were also observed, but to a lesser extent. The vector relating to C-28 displayed a negative vertical shift consistent with reduced DOC and pH values as well, similar in magnitude to the vertical shifts seen for DZO-30 and T-34.

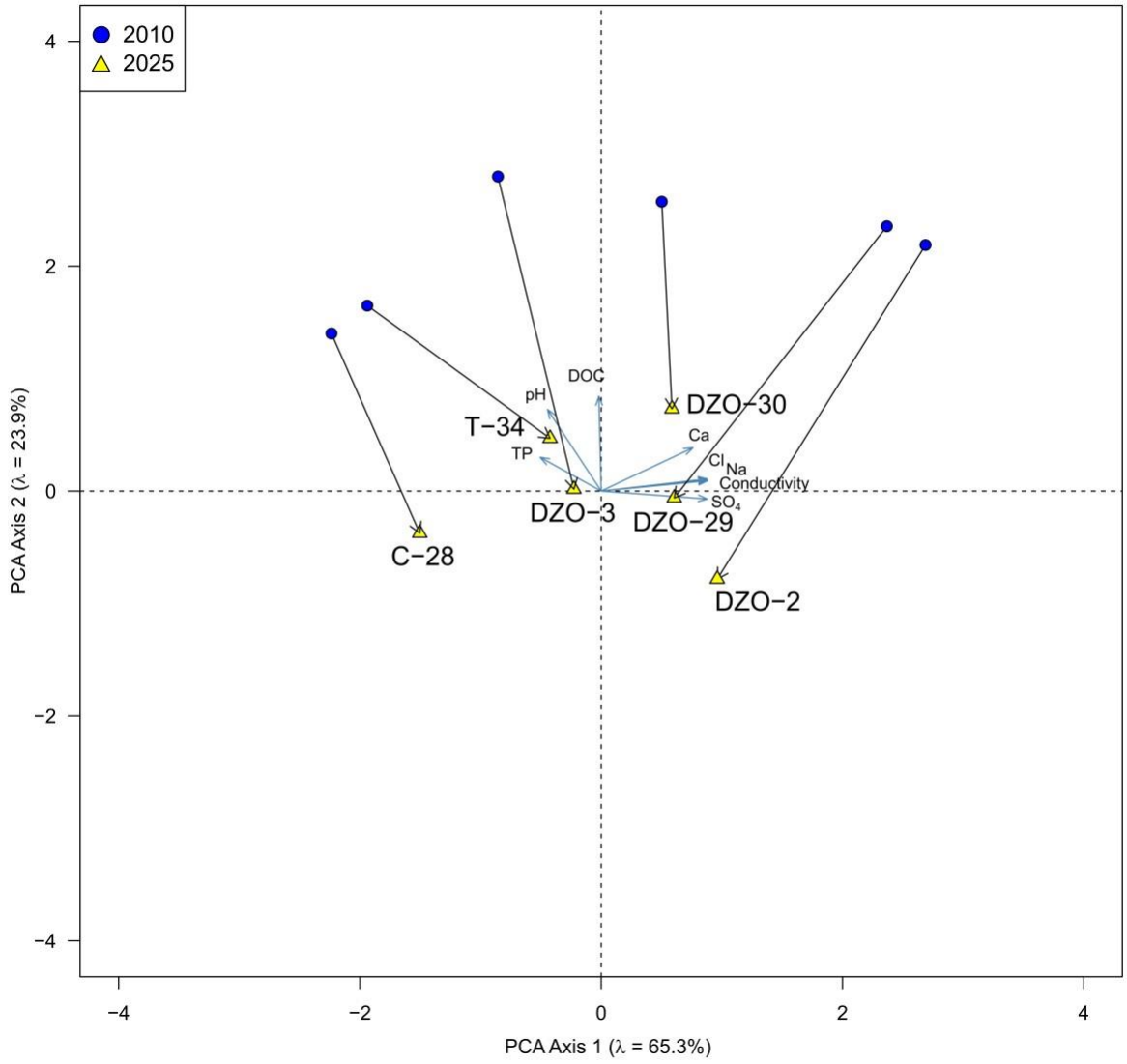


Figure 5.1. Principal component analysis biplot comparing water chemistry data from 2010 and 2025. 2010 data are plotted passively in the ordination space based on the 2025 dataset.

5.2 Diatom Analyses

5.2.1 Lake DZO-2

In lake DZO-2, the diatom assemblage shows a clear ecological transition consistent with disturbance by saltwater inundation and rapidly warming temperatures, followed by gradual freshwater recovery [Figure 5.2; Campeau et al., (1999); Karst-Riddoch et al., 2009; Kamae, 2015; Neil and Gajewski, 2018]. Below the transition horizon (red line), the community was found to be dominated by benthic Fragilariaceae species. These taxa are characteristic of eutrophic to mesotrophic freshwater systems in Arctic and subarctic environments, well-known to be tolerant of a range of environmental conditions [Smol et al., 2005; Karst-Riddoch et al., 2009]. At a core depth of 2.5 cm [Figure 5.2], the relative abundance of brackish indicators increased sharply, marking the timing of the 1999 storm surge or the point at which its influence peaked and then receded [Pisaric et al., 2011]. Species include *Craticula halophila, Diploneis elliptica*, *Mastogloia smithii*, and a continued high relative abundance of benthic Fragilariaceae [Figure 5.2]. *C. halophila*, *D. elliptica*, and *M. smithii* are commonly associated with brackish to saline waters, characterized by moderate conductivity conditions [Watermann et al., 2004; KarstRiddoch et al., 2009; Kamae, 2015]. Above the 2.5 cm depth interval, the assemblage appeared more diverse and was increasingly dominated by benthic and periphytic freshwater taxa, including *Diploneis elliptica* and *Mastogloia smithii* [Figure 5.2].

An increased presence of *Fragilaria tenera* and *Nitzschia perminuta* were found in the surface sediments, which appeared to have occurred at the expense of the *D. elliptica* population [Figure 5.2]. *D. elliptica* is an epipelic, oligohalobous (optimal in freshwater to slightly brackish conditions) species, found on the water-sediment interface of slightly brackish water bodies [Watermann et al., 2004]. Therefore, the trends observed between *F. tenera* and *D. elliptica* may

suggest that lake DZO-2 has begun to recover from the effects of previous saltwater intrusion, but may be exhibiting the onset of new changes resulting from warming regional temperatures [Watermann et al., 2004; Neil and Gajewski, 2018]

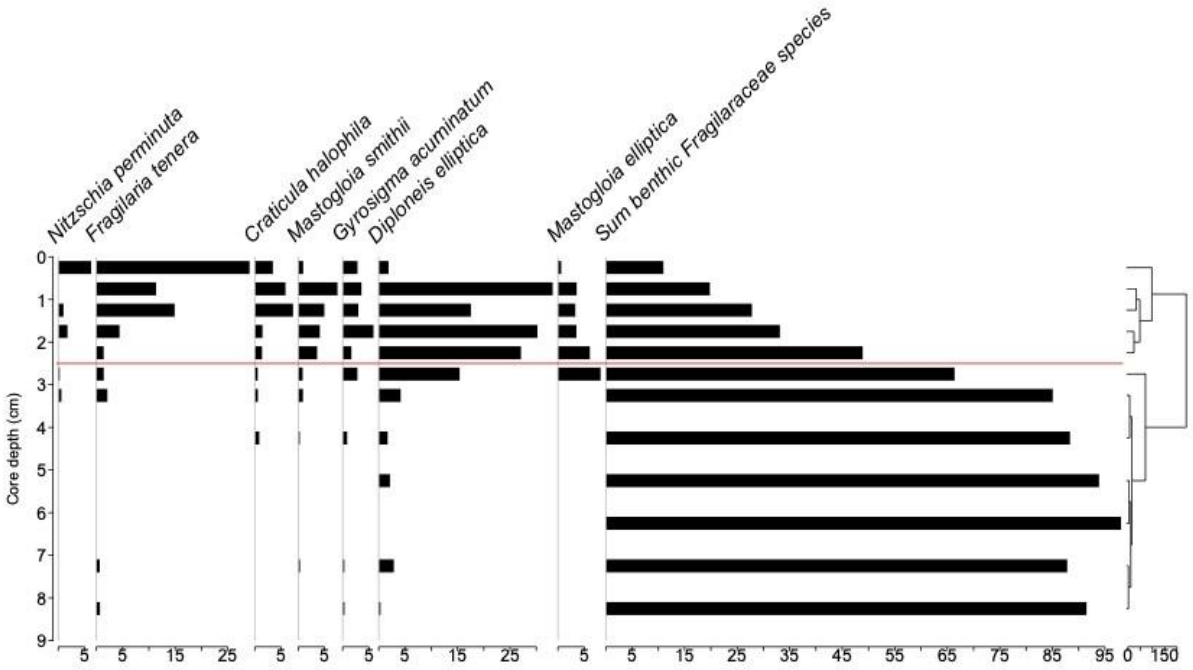


Figure 5.2. Stratigraphy diagram of the diatom taxa found at greater than 5% relative abundance from impacted lake DZO-2.

5.2.2 Lake DZO-29

The diatom assemblage recovered from lake DZO-29 records a pronounced shift consistent with saltwater disturbance followed by recovery, with brackish-water diatom taxa accounting for approximately 10% of all diatoms found in the sediment core [Figure 5.3; Campeau et al., 1999]. The assemblage suggests a slightly prolonged recovery trajectory compared to Lake DZO-2 [Figure 5.2]. Within the deeper sediment intervals, the assemblage was

overwhelmingly dominated by benthic Fragilariaceae, reaching relative abundances as high as 90% [Figure 5.3]. At the transition horizon located above the 4 cm depth interval, there is a clear compositional break in the assemblage [Figure 5.3]. Directly above this boundary, the assemblage appears more taxonomically diverse, with the presence and increasing contribution of several taxa associated with brackish to moderately saline environments, including *C. halophila*, *Navicula salinarum*, and *Nitzschia palea* [Figure 5.3; Campeau et al., 1999]. Towards the surface, diversity increases relative to the deeper sediment intervals, though the continued presence of brackish and disturbance-tolerant taxa suggests that saline conditions persisted long after the 1999 event took place [Campeau et al., 1999; Watermann et al., 2004]. The taxa observed in the uppermost sediment intervals imply a mixed or transitional state, likely indicating incomplete recovery or lingering salinity effects [Campeau et al., 1999; Smol et al., 2005; Karst-Riddoch et al., 2009; Thienpont et al., 2012]. However, an increased abundance of *Diatoma monoiliformis* (freshwater species) combined with decreased sodium ion concentration [Table 5.2] suggests early-stage recovery. Increased species richness alongside the continued presence of salt-tolerant species [Campeau et al., 1999; Watermann et al., 2004] also implies gradual and incomplete return to freshwater conditions. Compared to a fully recovered system, lake DZO-29 appears to retain a longer legacy of saltwater influence, with ecological recovery still ongoing or constrained [Douglas et al., 2004; Smol et al., 2005; Thienpont et al., 2012].

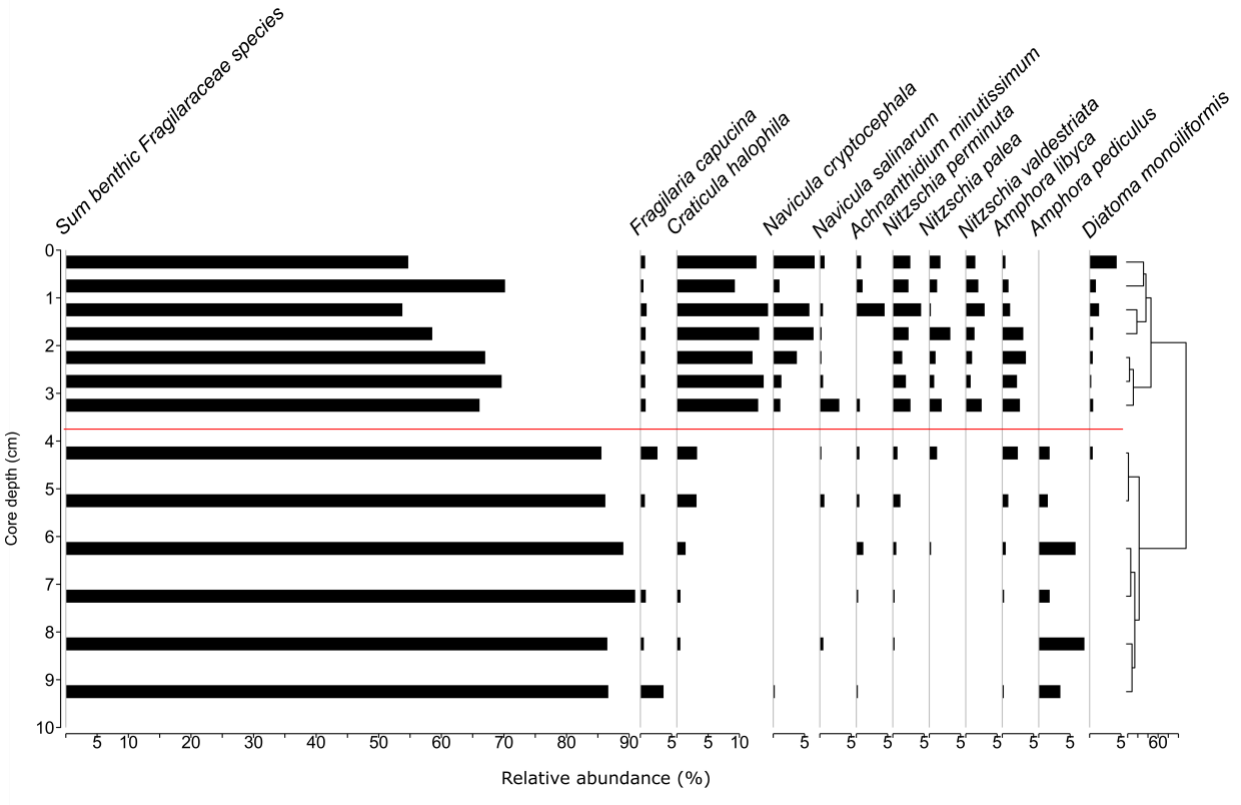


Figure 5.3. Stratigraphy diagram of the diatom taxa found at greater than 5% relative abundance from impacted lake DZO-29 [Pisaric et al., 2011; Thienpont et al., 2012].

5.2.3 Lake T-34

The diatom assemblage for lake T-34 suggests a shift toward increasing salinity over time, rather than a clear recovery trajectory [Figure 5.4; Thienpont et al., 2012]. This trend aligns with the modern water chemistry data which revealed elevated sodium ion concentration [Figure 5.1], establishing that lake T-34 is saltier today than it was in 2010 [Thienpont et al., 2012]. Below the transition horizon, the assemblage is mixed, though it includes several freshwater to slightly brackish taxa such as *Pinnularia borealis*, *Navicula salsa*, *Gyrosigma acuminatum*

[Campeau et al., 1999; Potapova and Leppik, 2026]. While some halophilous species such as *C. halophila* are present, they are not dominant, suggesting moderately fresh to only weakly brackish conditions [Campeau et al., 1999; Pisaric et al., 2011; Thienpont et al., 2012]. At the transition horizon (1 cm), there was a noticeable turnover in species composition [Figure 5.4]. Above the transition horizon, shallower sediment intervals displayed a clear increase in species associated with elevated salinity and environmental stress [Campeau et al., 1999; Watermann et al., 2004]. Species including *C. halophila, N. salinarum*, and *N. salsa*, were more consistently represented, alongside a continued presence of benthic Fragilariaceae [Potapova and Leppik, 2026]. The persistence of these brackish and salt-tolerant diatoms [Campeau et al., 1999; Watermann et al., 2004] suggests that saline influence is not only ongoing but likely intensifying in the transitional zone. The absence of a significant return to freshwater-indicator taxa [Smol et al., 2005; Karst-Riddoch et al., 2009] strongly suggests that lake T-34 has not recovered from salinization and instead appears to be transitioning further into a brackish state [Thienpont et al., 2012].

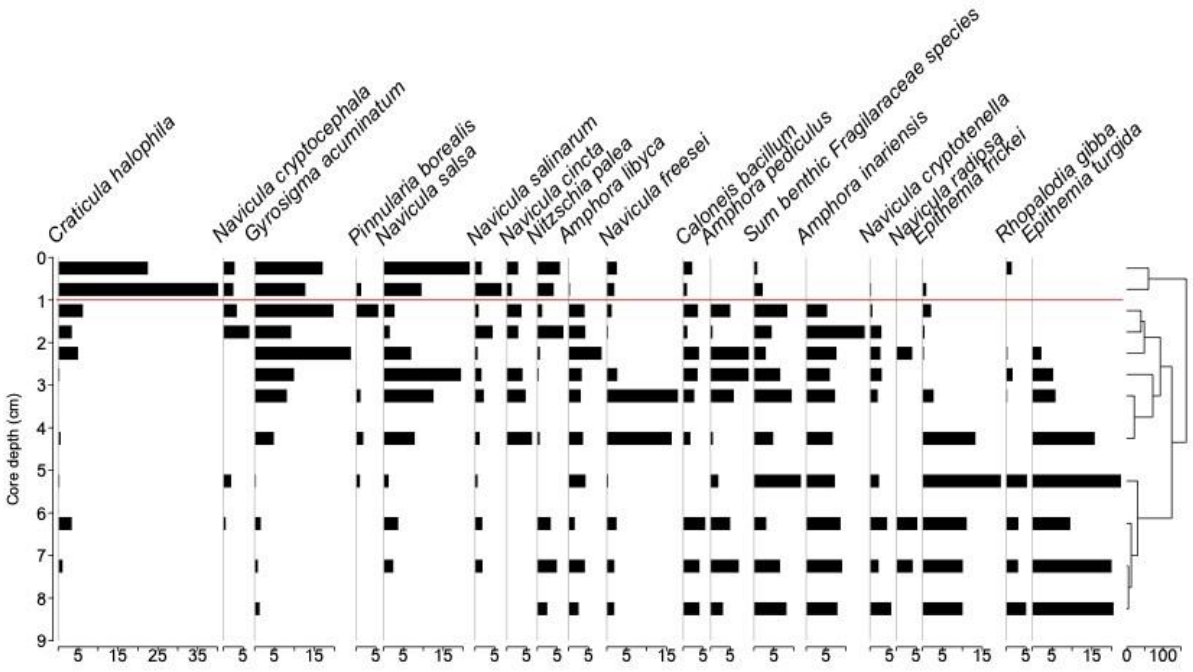


Figure 5.4. Stratigraphy diagram of the diatom taxa found at greater than 5% relative abundance from 'transition' lake T34 [Thienpont et al, 2012].

5.2.4 Lake C-28

In the designated control lake C-28, no brackish-water diatom taxa were recorded throughout the assemblage [Figure 5.5]. The community is composed of a highly varied assemblage of benthic and periphytic diatoms [Smol et al., 2005; Thienpont et al., 2012]. Among the six lakes examined in this study, lake C-28 boasted the greatest variety of diatoms, featuring taxa such as *Amphora, Epithemia, Gomphonema*, and *Nitzschia* [Figure 5.5; Pisaric et al., 2011; Thienpont et al., 2012].

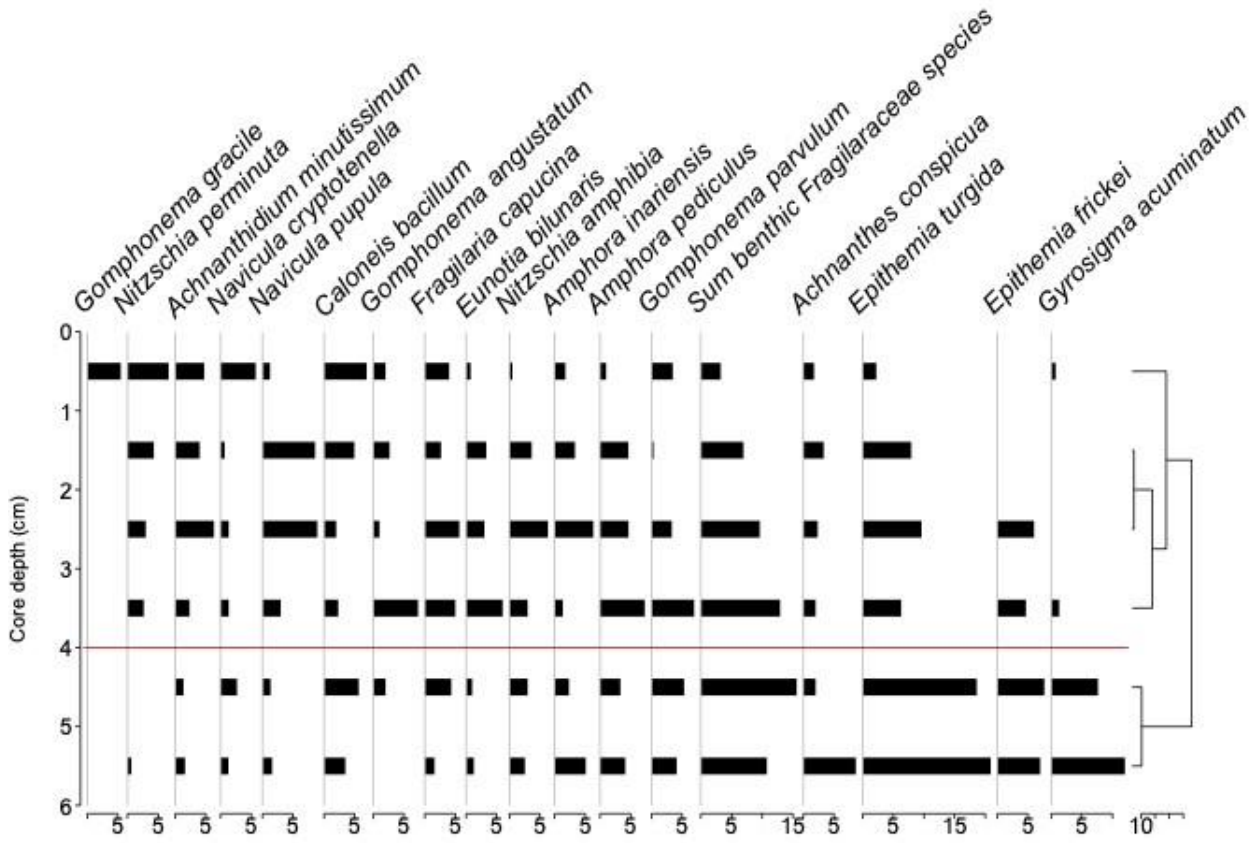


Figure 5.5. Stratigraphy diagram of the diatom taxa found at greater than 5% relative abundance from control lake C-28 [Pisaric et al., 2011; Thienpont et al., 2012].

Chapter 6: Discussion

6.1 Evidence of Chemical Recovery

The chemistry data and supporting PCA suggest that most lakes are undergoing a longterm recovery from the 1999 storm surge, indicated by progressive freshening and declining ionic strength [Figure 5.1]. This is especially evident in the DZO lakes, which were originally classified as “dead zones” due to the severity of saltwater intrusion and ecological damage [Pisaric et al., 2011; Kokelj et al., 2012; Thienpont et al., 2012; Lantz et al., 2015]. The strong reductions in conductivity and major ions at sites DZO-2 and DZO-29 suggest that these systems are gradually re-establishing more dilute chemical conditions [Table 5.1, Table 5.2, Figure 5.1]. Such changes are consistent with recovery trajectories driven by precipitation inputs in these small, closed-basin lake systems [Volik et al., 2017]. The degree of change observed in these lakes implies that, despite their initial classification as heavily impacted [Thienpont et al., 2012], they are among the most responsive in terms of chemical recovery.

Lakes DZO-30 and DZO-3 showed minor decreases in conductivity in comparison to lakes DZO-2 and DZO-29, suggesting partial but incomplete recovery. These slight changes suggest that the lakes’ ionic conditions have remained comparatively stable over time, showing minimal signs of recovery. While both lakes exhibited decreases in conductivity and major ion concentrations, they remained more saline than DZO-2 and DZO-29 [Table 5.2, Figure 5.1]. These varying recovery trajectories may reflect differences in precipitation inputs, lake morphology, or residence time, which may prolong the removal of marine-derived solutes [Dyke and Brooks, 2000; Håkanson, 2005; Thienpont et al., 2015; Small et al., 2025]. Basin size and depth determine the volume of water that must be replaced, while basin shape can influence

circulation and mixing within the lake [Håkanson, 2005]. Consequently, lakes with larger volumes relative to their water inputs generally have longer residence times and slower rates of water turnover [Small et al., 2025]. Lakes with longer residence times may therefore retain marine-derived solutes for longer periods, resulting in slower declines in conductivity and majorion concentrations, while shorter residence times may promote more rapid chemical recovery [Small et al., 2025]. For example, DZO-30 has a greater surface area [Table 5.1], is more elongate, and is shallower than DZO-29 [Thienpont et al., 2015]. These characteristics may have reduced the magnitude of the initial saltwater impact [Vermaire et al., 2013], and possibly influenced subsequent dilution of marine-derived solutes. DZO-3 is also substantially larger than DZO-29 and DZO-30 [Table 5.1; Thienpont et al., 2012], which may similarly affect the dilution and retention of marine-derived solutes. Differences in morphology among the DZO lakes may therefore contribute to the contrasting recovery rates observed among them [Figure 5.1]. However, direct measurements of residence time are not available for these lakes, so the relationship between morphology, water residence time, and recovery rate cannot be quantified officially. Following the 1999 storm surge, recovery would partially depend on the rate at which saline water and ions are exchanged with surrounding surface waters, groundwater, and the outer Mackenzie Delta floodplain [Kokelj et al., 2012; Thienpont et al., 2015]. In their 2012 publication, Thienpont et al. suggested that ions may be progressively diluted from these impacted lakes through annual freshets, though the process is constrained as spring flooding occurs while the lakes remain frozen, limiting effective dilution of stored salts [Thienpont et al., 2012; 2015]. Therefore, the continued elevated conductivity and major-ion concentrations in DZO-30 and DZO-3 likely reflect the prolonged persistence of marine-derived solutes within the lake catchment system rather than the absence of recovery altogether [Thienpont et al., 2012; 2015;

Small et al., 2025]. Despite the modern conductivity levels in DZO-3 and DZO-30, the consistent direction of change still points toward gradual recovery, even if at a slower pace.

In contrast to the general recovery trend observed in the four dead zone lakes, lake T-34 provides an example of delayed or increasing salinization. Originally considered "transitional," this lake now shows a substantial increase in conductivity and major ions, placing it firmly within the range of the original dead zone lakes [Pisaric et al., 2011; Kokelj et al., 2012; Thienpont et al., 2012; Lantz et al., 2015]. These findings are indicative of a shift toward more saline conditions and suggest that T-34 may be influenced by different hydrological processes than the DZO lakes. Its shift towards increasing axis-1 scores in the PCA highlights a movement toward higher ionic strength, opposite to the recovery trajectories observed elsewhere, especially in the originally most impacted lakes. This suggests that T-34 may have been impacted by a more recent severe salinization event, which would have taken place between 2010 and 2025. Impacts of a secondary salinization event were evident in aerial surveys of the transitional zone, where vegetation was observed to have deteriorated considerably since 2010 [Figure 3.2]. As a result, T-34 appears to have chemically transitioned into a true dead zone state. The control site C-28 appeared to have remained stable throughout the 15-year span between assessments [Table 5.1, Table 5.2, Figure 5.1], reflecting its location inland and at a somewhat perched elevation for lakes in the outer Mackenzie Delta.

Overall, the chemistry data indicate that the legacy effects of the 1999 storm surge are not uniform across the study lakes but instead reflect divergent trajectories of chemical change. While the DZO lakes generally show progressive freshening and declining ionic strength, the rate and extent of recovery vary among individual sites. The contrasting trajectory of T-34

further demonstrates that recovery is not necessarily unidirectional, and that some lakes may remain vulnerable to reoccurring saline incursion events. In contrast, the stability of C-28 provides evidence that lakes outside the primary zone of storm-surge influence can maintain relatively consistent chemical conditions over time. Together, these results highlight the spatially variable and dynamic nature of post-storm-surge recovery across the Mackenzie Delta, with lake-specific characteristics playing an important role in determining whether systems continue toward freshening, remain relatively stable, or shift toward increased salinity.

6.2 Evidence of Biological Recovery

The diatom assemblages collected from each sediment core provided compelling evidence of biological responses to storm surge-induced saline incursion, as well as subsequent ecological recovery in several of the impacted lakes [Campeau et al., 1999; Karst-Riddoch et al., 2009]. Changes in species composition through time reflected shifts in conductivity [Table 5.1; Table 5.2], habitat stability, and environmental conditions following the 1999 storm surge, allowing reconstruction of post-disturbance ecological trajectories and potential recovery to be determined across the Outer Mackenzie Delta. Lake DZO-2 exhibited the clearest evidence of biological recovery among the lakes examined [Figure 5.2]. This evidence is consistent with the chemical analysis findings, which revealed lake DZO-2 to have had the greatest decreases in ionic concentration among all ions tested. Within the deeper, older sediment intervals, the assemblage was dominated by benthic Fragilariaceae diatoms commonly associated with nutrient-rich freshwater environments [Smol et al., 2005; Karst-Riddoch et al., 2009]. Approaching the 3 cm depth interval, a marked increase in brackish-water indicators (*Craticula halophila, Diploneis elliptica, and Mastogloia smithii)* was observed, signaling the onset and peak influence of saline inundation associated with the 1999 storm surge [Campeau et al., 1999;

Lange-Bertalot, 2001]. The observed indicator taxa are characteristic of environments with elevated conductivity and moderate salinity, signifying a substantial ecological disturbance within subarctic freshwater environments [Lange-Bertalot, 2001; Watermann et al., 2004]**.** Within the surface sediments, the assemblage appeared increasingly diverse and was characterized by a greater abundance of benthic and periphytic freshwater taxa, such as *Fragilaria tenera* and *Nitzschia perminuta*. The decline of brackish species and expansion of freshwater indicators suggested progressive declines in lake salinity, stabilization of littoral substrates, as well as re-establishment of freshwater habitat conditions [Thienpont et al., 2012] The reduction of brackish species, coupled with the rise in freshwater indicators, reflects improving conditions consistent with lower conductivity levels, stabilization of substrates, and the re-establishment of typical littoral habitats [Pisaric et al., 2011; Thienpont et al., 2012]. The increased presence of *F. tenera* found in the surface sediments serves as an indication of recent climate warming, as the species is linked to warming temperatures in higher latitudes [Rühland et al., 2015; Neil and Gajewski, 2018]. As a pelagic species, *F. tenera* is associated with lower DOC conditions where reduced organic carbon concentrations increase light availability in the water column, supporting greater photosynthetic activity [Fonseca et al., 2022]. This preference is consistent with the lake's recently measured DOC concentration of 4.9 mg/L [Table 5.2]. *N. perminuta* also exhibited greater abundance in the surface sediments. This increase corresponds with the decline in DOC from 8.1 mg/L to 4.9 mg/L indicated by the chemical analyses [Tables 5.1, 5.2]. This relationship is consistent with *N. perminuta's* reported DOC optimum of 3.19 mg/L and tolerance range of 1.50–6.81 mg/L [Antonaides et al., 2008]. The degree of recovery from saltwater intrusion in DZO-2 appears substantial, as the upper assemblage resembles a stable, freshwater-dominated system, despite the small population of *C. halophila* still present in

the surface sediments [Figure 5.2]. Furthermore, the appearance of *F. tenera* in the surface sediments likely reflects recent regional warming, consistent with observations that this species has increased in abundance in northern lakes under warming climatic conditions [Neil and Gajewski, 2018]. Together, these findings indicate that lake DZO-2 has undergone substantial biological recovery following storm surge disturbance.

Evidence for recovery is also present in lake DZO-29, although the trajectory appears slower and less complete than that observed in DZO-2 [Figure 5.2, Figure 5.3]. This trajectory aligns with the chemical recovery pattern observed in DZO-29, which showed the lake to have had the second-greatest decreases in ionic concentrations among all study lakes. The lower portion (inferred to be pre-1999) of the sediment record is characterized by overwhelming dominance of benthic Fragilariaceae, reaching relative abundances of approximately 90% [Figure 5.3]. Low-diversity assemblages dominated by benthic Fragilariaceae are sometimes colloquially associated with environmental stress and instability, due to the taxon's generalist nature, and likely reflect conditions prior to saline disturbance [Karst-Riddoch et al., 2009; Goeyers et al., 2006]. Such dominance is typical of subarctic lakes, considering the taxon's tolerance of cold temperatures and prolonged ice cover [Smol et al., 2005; Karst-Riddoch et al., 2009]. Within the surface sediment intervals, species richness increased and several brackishwater diatoms became more prominent, including *C. halophila, N. salinarum,* and *N. palea* [Campeau et al., 1999; Lange-Bertalot, 2001]. While increased diversity generally suggests improving ecological conditions, the continued abundance of salt-tolerant and disturbanceassociated taxa indicates that elevated salinity persisted after the initial storm surge event [Campeau et al., 1999; Lange-Bertalot, 2001; Pisaric et al., 2011; Thienpont et al., 2012]. The uppermost sediments contained a greater abundance of the freshwater species *D.*

moniliformis, exhibiting a biological trend which coincides with declining sodium concentrations in the surface water chemistry record. Together, these observations suggest that freshwater conditions have recently and gradually begun to re-establish in lake DZO-29. However, the persistence of brackish taxa indicates that recovery remains incomplete, and the lake continues to exhibit a biological legacy of past saltwater intrusion [Pisaric et al., 2011; Thienpont et al., 2012].

In contrast, lake T-34 provided no evidence for biological recovery and instead appeared to have experienced a secondary saltwater incursion event [Figure 5.4]. The diatom assemblage below the 1-cm depth interval contains a mixture of freshwater and slightly brackish taxa, including *Pinnularia borealis, Navicula salsa,* and *Gyrosigma acuminatum*, suggesting relatively fresh conditions prior to the observed ecological shift. As described by Pisaric et al. (2011), the presence and abundance of *G. acuminatum* may also provide an important indicator of channel connectivity. This raises the possibility that lake T-34 may have become increasingly isolated from riverine influences prior to the 1999 storm surge, potentially reducing freshwater inputs and further increasing the lake's susceptibility to saltwater intrusion. Although halophilous taxa such as *C. halophila* are present in these deeper sediments, they occur at low abundances and do not dominate the assemblage [Campeau et al., 1999]. A taxon of particular interest in this assemblage is *Epithemia,* the species of which were present in lake T-34 have been found to have a narrow salinity tolerance [Chiba et al., 2023]. The species *Epithemia turgida* was found by Chiba et al. [2023] to be unable to survive salinity levels above 10% in Lake Akan, Japan. This threshold was evident in the sediment core record of T-34, where *E. turgida* disappeared completely from the assemblage around the 2-centimere depth interval [Figure 5.4]. Towards the surface sediments,

there was a clear increase in salt-tolerant and disturbance-associated species, including *C. halophila*, *N. salinarum, and N. palea* [Campeau et al., 1999; Lange-Bertalot, 2001]. The persistence and increasing relative abundance of these taxa indicates ongoing saline influence rather than recovery. This trajectory is supported by modern water chemistry data, which displayed elevated sodium concentrations [Table 5.2, Figure 5.3] demonstrating that lake T-34 is currently more saline than it was in 2010 [Thienpont et al., 2012]. The concomitant decrease in taxa like *G. acuminatum* may indicate the lake has become more isolated from fluvial sources, as this taxa has been associated with low-closure lakes in the Mackenzie Delta region [Michelutti et al. 2001] and was highly dominant in the lower portions of a piston core from DZO-29 [Pisaric et al. 2012]. The decrease in freshwater-indicator taxa reflected by the surface sediments' diatom community suggests that biological recovery has not occurred, and that the lake may have been affected by a separate, likely smaller salinization event which affected the northern sector of the delta where T-34 is located [Pisaric et al., 2011]. The effects of this secondary salinization event were also apparent in aerial surveys of the transitional zone, where vegetation had noticeably degenerated since 2010 [Figure 3.2]."

The control lake, C-28, provided an important reference for evaluating recovery status in the storm surge-impacted lakes of the dead zone and transitional zone [Pisaric et al., 2011; Thienpont et al., 2012]. No brackish-water diatom taxa were identified throughout the sediment record, indicating an absence of saline disturbance [Figure 5.5; Thienpont et al., 2012]. Instead, the assemblage is characterized by high taxonomic diversity and a broad representation of benthic and periphytic taxa, including members of *Amphora, Epithemia, Gomphonema,* and *Nitzschia.* The consistently diverse assemblage of lake C-28 likely reflects stable freshwater conditions and well-developed littoral habitats that support complex food webs and ecosystem

functioning [Pisaric et al., 2011; Thienpont et al., 2012]. The high diversity observed in lake C28 contrasts sharply with the assemblages recorded in the impacted lakes and provides a useful benchmark for assessing biological recovery [Pisaric et al., 2011; Thienpont et al., 2012]. While the diatom assemblage assessed in DZO-2's surface sediment begins to reflect more dilute conditions [Figure 5.2], lake DZO-29 was found to remain in a transitional state [Figure 5.3], while lake T-34 continues to exhibit signs of increasing salinity [Figure 5.4].

Overall, the diatom records demonstrate that biological recovery following storm surge disturbance is occurring across some lakes in the Outer Mackenzie Delta, but recovery trajectories vary considerably among sites [Pisaric et al., 2011; Thienpont et al., 2012]. These patterns highlight that chemical recovery from large-scale saltwater intrusion can be spatially heterogeneous and non-linear. Differences in the persistence of salt-tolerant taxa, rates of freshwater species re-establishment, and overall community diversity suggest that recovery may be influenced by differing precipitation inputs, lake morphology, and the duration of postdisturbance saline conditions [Dyke and Brooks, 2000; Thienpont et al., 2015]. The nearcomplete return to freshwater conditions observed in DZO-2, the partial recovery evident in DZO-29, and the continued salinization of T-34 highlight the heterogeneous nature of ecological responses to storm surge events in Arctic coastal lake systems.

The results of the diatom analyses reveal that ecological recovery following saline disturbance does not necessarily represent a return to the pre-disturbance state. Lakes such as DZO-2 and DZO-29 appear to be undergoing shifts toward new ecological configurations, characterized by increased representation of taxa such as *F. tenera, N. perminuta*, and *D. moniliformis*, rather than a re-establishment of the benthic Fragilariaceae dominated assemblages observed in older sediments [Figure 5.1, Figure 5.2]. This pattern suggests that recovery is not

necessarily a process of returning to a previous ecological baseline but may instead involve the development of a new assemblage under altered environmental conditions. The widespread decline in DOC observed across all study sites may be one factor contributing to these changing assemblages, particularly given the association of several assemblage-dominating taxa with lower DOC conditions [Antonaides et al., 2018; Fonseca et al., 2022]. Reduced DOC increases water-column transparency and light availability, potentially favouring pelagic taxa as well as other taxa adapted to greater photosynthetic opportunities [Fonseca et al., 2022]. Consequently, the re-establishment of freshwater conditions following saltwater incursion may have occurred under a different light condition than that represented by the pre-disturbance sediments. The resulting assemblages may therefore represent not a return to the historical ecological state, but the development of novel freshwater communities shaped by the combined effects of declining salinity, reduced DOC resulting in increased light availability, and ongoing climatic warming [Table 5.1, Table 5.2]. Even where biological recovery is evident, the diatom records suggest that these lakes are not simply returning to their former states but are instead transitioning toward new ecological conditions, reflective of both the legacy of saline disturbance and broader environmental changes across the outer Mackenzie Delta.

6.3 General Conclusions

6.3.1 Summary of Main Findings

This study examined the long-term recovery of storm surge-impacted lakes in the Outer Mackenzie Delta, using contemporary water chemistry and sedimentary diatom assemblages to assess both chemical and biological responses more than two decades after the 1999 storm surge event [Pisaric et al., 2011; Thienpont et al., 2012, 2015; Vermaire et al., 2013; Lantz et al., 2015].

The results demonstrate that recovery from large-scale saltwater intrusion is highly variable among lakes and likely influenced by local environmental conditions, as well as the lake's conditions prior to disturbance. Several lakes showed clear evidence of chemical recovery, characterized by declining sodium concentrations and a return toward freshwater conditions [Table 5.2; Figure 5.1]. In contrast, other lakes (such as T-34) remained strongly influenced by salinity or exhibited signs of continued salinization, indicating that the ecological effects of the 1999 storm surge persist in parts of the delta. These contrasting chemical trajectories suggest that recovery is neither uniform nor predictable across the landscape.

Biological responses inferred from diatom assemblages generally followed observed chemical differences over the two sampling points. Lake DZO-2 displayed substantial recovery, with freshwater taxa re-establishing dominance following an interval characterized by increased abundance of brackish-water species. Lake DZO-29 showed evidence of recovery as well, although the continued presence of salt-tolerant taxa indicates that ecological recovery remains incomplete. In contrast, lake T-34 exhibited a shift toward increasingly saline conditions, with no clear biological evidence of recovery. These findings demonstrate that biological recovery may lag behind chemical improvements and that ecological responses to disturbance can persist long after salinity levels begin to decline.

Overall, the results highlight the spatially heterogeneous and non-linear nature of recovery from storm surge disturbance in Arctic coastal lake systems. Lakes exposed to the same regional event followed significantly different recovery trajectories, ranging from near-complete freshwater recovery to ongoing transformation toward brackish conditions. These contrasting outcomes emphasize the importance of local hydrological connectivity, landscape position, and climate variability in regulating resilience and long-term ecosystem response. As climate change

is expected to increase the frequency and intensity of storm surge events in the Arctic, understanding the factors that influence recovery will be critical for predicting future ecological change across northern deltaic environments.

6.3.2 Future Directions

The contrasting recovery trajectories identified in this study highlight several areas that warrant further investigation. Future research should first examine the role of local hydrological conditions in controlling recovery from saltwater intrusion. Although the lakes examined in this study were affected by the same 1999 storm surge event, their subsequent chemical and biological responses differed considerably. Differences in landscape position, lake morphology, and groundwater exchange may help explain these contrasting trajectories. A broader assessment of these characteristics across storm surge impacted lakes could help determine which environmental conditions promote recovery toward freshwater conditions and which may contribute to persistent salinization.

A second priority is to continue long term monitoring of both water chemistry and biological indicators. The results from DZO-2 and DZO-29 suggest that biological recovery may not occur at the same rate as chemical recovery. In contrast, the continued saline conditions observed at T-34 likely reflect the impacts of a secondary salinization event rather than a continued response to the 1999 storm surge, highlighting the need to distinguish between the legacy of the original disturbance and subsequent environmental changes. Repeated measurements of conductivity and major ion concentrations combined with diatom assemblage analysis could help identify whether changes in lake conditions result from continued recovery, subsequent saltwater intrusion, or other hydrological changes.

Finally, future research should consider how changes in Arctic climate and coastal processes may influence the frequency and ecological consequences of future storm surge events. The 1999 event provides an important example of how a single large disturbance can produce effects that persist for decades, while the apparent secondary salinization of T-34 demonstrates that lakes may also experience additional disturbances during their recovery. Examining lakes across gradients of disturbance intensity and recovery history could help identify conditions under which freshwater systems are likely to remain resilient and those under which repeated saltwater intrusion may result in more lasting ecological change. Addressing these questions will be important for understanding how the recovery patterns observed following the 1999 event may inform predictions of future responses in the Outer Mackenzie Delta.

6.4 References

Antoniades, D., Hamilton, P. B., Douglas, M. S. V., and Smol, J. P. (2008) Diatoms of North America: The freshwater floras of Prince Petrcik, Ellef Ringnes and northern Ellesmere Islands from the Canadian Arctic Archipelago. *Iconographia Diatomologica 17.*

Antoniades, D., Douglas, M. S. V., and Smol, J. P. (2009). Biogeographic distributions and environmental controls of stream diatoms in the Canadian Arctic Archipelago. Botany, 87(5), 443–454. (https://doi.org/10.1139/B09-001)

Battarbee, R. W. (2000) Palaeolimnological approaches to climate change, with special regard to the biological record. *Quaternary Science Reviews,* 19(1), 107–124. (https://doi.org/10.1016/S0277-3791(99)00057-8)

Birks, H. H., and Birks, H. J. B. (2006) Multi-proxy studies in palaeolimnology. *Vegetation History and Archaeobotany*, 15, 235–251. (https://doi.org/10.1007/s00334-006-0066-6)

Brenner, M. and Kenney, W. F. (2013) Dating Wetland Sediment Cores. *Methods in Biogeochemistry of Wetlands* (eds R.D. DeLaune, K.R. Reddy, C.J. Richardson and J.P. Megonigal). (https://doi.org/10.2136/sssabookser10.c45)

Burn, C. R. and Kokelj, S. V. (2009) The environment and permafrost of the Mackenzie Delta area. *Permafrost and Periglacial Processes*, 20(2), 83-105. (https://doi.org/10.1002/ppp.655)

Campeau. S., Pienitz, R., and Héquette, A. (1999) Diatoms from the Beaufort Sea Coast, Southern Arctic Ocean (Canada). Berlin: Gebrüder Borntraeger.

Chevalier, M., Davis, B. A. S., Heiri, O., Seppä, H., Chase, B. M., Gajewski, K., Lacourse, T.,

Telford, R. J., Finsinger, W., Guiot, J., Kühl, N., Maezumi, S. Y., Tipton, J. R., Carter, V. A., Brussel, T., Phelps, L. N., Dawson, A., Zanon, M., Vallé, F., Nolan, C., Mauri, A., de Vernal, A., Izumi, K., Holmström, L., Marsicek, J., Goring, S., Sommer, P. S., Chaput, M., and Kupriyanov, D. (2020) Pollen-based climate reconstruction techniques for late Quaternary studies, *Earth-Science Reviews*, 210, 103384. (https://doi.org/10.1016/j.earscirev.2020.103384)

Chiba, T., Horie, Y., and Tuji, A. (2023) Seven Epithemia taxa (Bacillariophyta) from Lake Akan (Japan) and their salinity tolerances. *Phytokeys,* 229, 139-155. (https://doi.org/10.3897/phytokeys.229.104449)

Comiso, J. C., Parkinson, C. L., Gersten, R., and Stock, L. (2008) Accelerated decline in the Arctic sea ice cover. *Geophysical Research Letters*, 35(1), L01703. (https://doi.org/10.1029/2007GL031972)

Costa, A. P. T., and Schneck, F. (2022) Diatoms as indicators in running waters: Trends of studies on biological assessment and monitoring. *Environmental Monitoring and Assessment*, 194(10), 695. (https://doi.org/10.1007/s10661-022-10383-3)

Deasley, K., Korosi, J. B., Thienpont, J. R., Kokelj, S. V., Pisaric, M. F. J, and Smol, J. P. (2012) Investigating the response of Cladocera to a major saltwater intrusion event in an Arctic lake from the outer Mackenzie Delta (NT, Canada). *Journal of Paleolimnology*, 48, 287-296. (https://doi.org/10.1007/s10933-012-9577-6)

Dixit, S. S., Smol, J. P., Kingston, J. C, and Charles, D. F. (1992) Diatoms: powerful indicators of environmental change. *Environmental Science and Technology*, 26(1), 22-33. (https://doi.org/10.1021/es00025a002)

Douglas, M. S., Smol, J. P., and Blake, W., Jr. (1994) Marked post-18th century environmental change in high-arctic ecosystems. *Science (New York, N.Y.)*, 266(5184), 416–419. (https://doi.org/10.1126/science.266.5184.416)

Douglas, M. S. V., Smol, J. P., Pienitz, R., and Hamilton, P. (2004) Algal indicators of environmental change in arctic and antarctic lakes and ponds. In: Smol, J. P., Pienitz, R., and Douglas, M. S. V. (eds) *Long-term Environmental Change in Arctic and Antarctic Lakes. Developments in Paleoenvironmental Research*, 8, 117-157. Springer, Dordrecht. (https://doi.org/10.1007/978-1-4020-2126-8_5)

Dyke, L. D., and Brooks, G. R. (2000) The physical environment of the Mackenzie Valley, Northwest Territories: A base line for the assessment of environmental change (Bulletin 547). *Geological Survey of Canada.* (https://publications.gc.ca/site/eng/9.615312/publication.html)

Fonseca, B. M., Levi, E. E., Jensen, L. W., Graeber, D., Søndergaard, M., Lauridsen, T. L., Jeppesen, E., and Davidson, T. A. (2022) Effects of DOC addition from different sources on phytoplankton community in a temperate eutrophic lake: An experimental study exploring lake compartments. *The Science of the total environment*, 803, 150049. (https://doi.org/10.1016/j.scitotenv.2021.150049)

Glew, J. R. (1988) A portable extruding device for close interval sectioning of unconsolidated core samples. *Journal of Paleolimnology*, 1, 235-239. (https://doi.org/10.1007/BF00177769)

Glew, J. R. (1989) A new trigger mechanism for sediment samplers. *Journal of Paleolimnology,*

2, 241–243. (https://doi.org/10.1007/BF00195474)

Glew, J. R., and Smol, J. P. (2016) A push corer developed for retrieving high-resolution sediment cores from shallow waters. *Journal of Paleolimnology*, 56, 67–71. (https://doi.org/10.1007/s10933-015-9873-z)

Goeyers, C., Verleyen, E., Vijver, B. V. D., Kohler, T. J., Klímová, P., Gradstein, S. R. and Sabbe, K. (2026) Moss diatoms show regional structuring, high potential endemism, and an inverse latitudinal diversity gradient in the Arctic. *Ecography*, 2026(3), e08362. (https://doi.org/10.1002/ecog.08362)

Griffiths, K., Michelutti, N., Sugar, M., Douglas, M. S., and Smol, J. P. (2017) Ice-cover is the principal driver of ecological change in High Arctic lakes and ponds. *PloS one*, 12(3), e0172989. (https://doi.org/10.1371/journal.pone.0172989)

Håkanson, L. (2005) The Importance of Lake Morphometry for the Structure and Function of Lakes. *International Review of Hydrobiology*, 90, 433–461. (https://doi.org/10.1002/iroh.200410775)

Hill, M. O. (1973) Diversity and Evenness: A Unifying Notation and Its Consequences. *Ecology*, 54, 427–432. (https://doi.org/10.2307/1934352)

Jenkins, M., and Dai, A. (2021) The impact of sea-ice loss on Arctic climate feedbacks and their role for Arctic amplification. *Geophysical Research Letters*, 48, e2021GL094599. https://doi.org/10.1029/2021GL094599

Juggins, S. (2024) rioja: Analysis of Quaternary Science Data, R package version (1.0-7).

(https://cran.r-project.org/package=rioja).

Kamae, B. (2015). Diploneis elliptica. *Diatoms of North America*. (https://diatoms.org/species/50682/diploneis_elliptica)

Karst-Riddoch, T., Malmquist, H., and Smol, J. P. (2009) Relationships between freshwater sedimentary diatoms and environmental variables in Subarctic Icelandic lakes. *Fundamental and Applied Limnology / Archiv für Hydrobiologie,* 175(1), 1–28. (https://doi.org/10.1127/1863-9135/2009/0175-0001)

Kokelj, S. V., Lantz, T. C., Solomon, S., Pisaric, M. F. J., Keith, D., Morse, P., Thienpont, J. R., Smol, J. P., and Esagok, D. (2012) Using Multiple Sources of Knowledge to Investigate Northern Environmental Change: Regional Ecological Impacts of a Storm Surge in the Outer Mackenzie Delta, N.W.T. *The Arctic Institute of North America,* 65(3), 245–366. (https://doi.org/10.14430/arctic4214)

Kale, A., and Karthick, B. (2015) The diatoms: Big significance of tiny glass houses. *Resonance*, 20, 919-930. (https://doi.org/10.1007/s12045-015-0256-6)

Krammer, K., and Lange-Bertalot, H. (1991) Bacillariophyceae 4. Teil: Achnanthaceae, Kritische Ergänzungen zu Navicula (Lineolatae) und Gomphonema Gesamtliteraturverzeichnis Teil 1-4. In: Ettel H, Gerloff J, Heynig H, et al. (eds) *Süßwasserflora von Mitteleuropa 2/4*. Berlin: Spektrum Akademischer Verlag.

Krammer, K., and Lange-Bertalot, H. (1997) Bacillariophyceae 2. Teil: Bacillariaceae, Epithemiacaeae, Surirellaceae. In: Ettel H, Gerloff J, Heynig H, et al. (eds) *Süßwasserflora von Mitteleuropa 2/2*. Berlin: Spektrum Akademischer Verlag.

Krammer, K., and Lange-Bertalot, H. (1999) Bacillariophyceae 1. Teil: Naviculaceae. In: Ettel H, Gerloff J, Heynig H, et al. (eds) *Süßwasserflora von Mitteleuropa 2/1*. Berlin: Spektrum Akademischer Verlag.

Krammer, K., and Lange-Bertalot, H. (2000) Bacillariophyceae 3. Teil: Centrales, Fragilariaceae, Eunotiaceae. In: Ettel H, Gerloff J, Heynig H, et al. (eds) Süßwasserflora von Mitteleuropa 2/3. Berlin: Spektrum Akademischer Verlag.

Lange-Bertalot, H. (2001) Navicula sensu stricto, 10 Genera separated from Navicula sensu lato. *Frustulia Diatoms of Europe,* 2, 1–526.

Lantz, T. C., Kokelj, S. V., and Fraser, R. H. (2015) Ecological recovery in an Arctic delta following widespread saline incursion. *Ecological Applications*, 25(1), 172–185. (https://doi.org/10.1890/14-0239.1)

Michelutti, N., Hay, M. B., Marsh, P., Lesack, L., and Smol, J. P. (2001) Diatom Changes in Lake Sediments from the Mackenzie Delta, N.W.T., Canada. *Paleohydrological Applications, Arctic, Antarctic, and Alpine Research*, 33(1), 1–12. (https://doi.org/10.1080/15230430.2001.12003398)

Neil, K., and Gajewski, K. (2018) An 11,000-yr record of diatom assemblage responses to climate and terrestrial vegetation changes, southwestern Québec. *Ecosphere*, 9(11), e02505. (https://doi.org/10.1002/ecs2.2505)

Nicacio, G. and Juen, L. (2015) Chironomids as indicators in freshwater ecosystems: an assessment of the literature. *Insect Conservation and Diversity*, 8, 393–403. (https://doi.org/10.1111/icad.12123)

Oksanen, J., Simpson, G. L., Blanchet, F. G., Kindt, R., Legendre, P., Minchin, P. R., ... & Weedon, J. (2025). vegan: community ecology package. 10.32614. *CRAN. package. Vegan*.

Overeem, I., R. S. Anderson, C. W. Wobus, G. D. Clow, F. E. Urban, and N. Matell. (2011) Sea ice loss enhances wave action at the Arctic coast, *Geophysical Research Letters*, 38, L17503. (https://doi.org/10.1029/2011GL048681)

Pandey, L. K., Bergey, E. A., Lyu, J., Park, J., Choi, S., Lee, H., Depuydt, S., Oh, Y. T., Lee, S. M., and Han, T. (2017) The use of diatoms in ecotoxicology and bioassessment: Insights, advances and challenges. *Water Research*, 118, 39–58. (https://doi.org/10.1016/j.watres.2017.01.062)

Patterson, A. M., Köster, D., Reavie, E. D., and Whitmore, T. J. (2020). Preface: paleolimnology and lake management. *Lake and Reservoir Management*, 36(3), 205–209. (https://doi.org/10.1080/10402381.2020.1805998)

Pisaric, M. F. J., Thienpont, J. R., Kokelj, S. V., Nesbitt, H., Lantz, T. C., Solomon, S., and Smol, J. P. (2011) Impacts of a recent storm surge on an Arctic delta ecosystem examined in the context of the last millennium. *PNAS,* 108(22), 8960–8965. (https://doi.org/10.1073/pnas.1018527108)

Potapova, M., and Leppik, S. (2026) Diatoms of the Alaskan Arctic Coastal Plain prior to recent climate change: a reexamination of Leonard Freese's collections. *Proceedings of the Academy of Natural Sciences of Philadelphia*, 169(1), 125–184. (https://doi.org/10.1635/053.169.0110)

Rantanen, M., Karpechko, A. Y., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., and Laaksonen, A. (2022) The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment,* 3, 168. (https://doi.org/10.1038/s43247-022-00498-3

Rühland, K. M., Paterson, A. M., and Smol, J. P. (2008) Hemispheric-scale patterns of climaterelated shifts in planktonic diatoms from North American and European lakes. *Global Change*
Biology, 14, 2740–2754. (https://doi.org/10.1111/j.1365-2486.2008.01670.x

Rühland, K. M., Paterson, A. M., and Smol, J. P. (2015) Lake diatom responses to warming: reviewing the evidence. *Journal of Paleolimnology*, 54, 1–35. (https://doi.org/10.1007/s10933015-9837-3)

Screen, J. A., Audette, A., Blackport, R., Deser, C., England, M., Feldl, N., Gervais, M., Hay, S., Kushner, P. J., Liang, Y. C., Msadek, R., Mudhar, R., Sigmond, M., Smith, D., Sun, L., and Yu, H. (2026) Causes and consequences of Arctic amplification elucidated by coordinated multimodel experiments. *Communications earth & environment*, 7(1), 23. (https://doi.org/10.1038/s43247-025-03052-z)

Sepp, M., and Jaagus, J. (2011) Changes in the activity and tracks of Arctic cyclones. *Climatic Change,* 205, 577–595. (https://doi.org/10.1007/s10584-010-9893-7)

Shipman, F. N. A., Lantz, T. C., and Blight, L. K. (2024) Assessing ecological effects of storm surges on Arctic bird populations in the outer Mackenzie Delta, Northwest Territories. *Arctic Science*, 10(4), 630-642. (https://doi.org/10.1139/as-2023-0064)

Simmonds, I., and Keay, K. (2009) Extraordinary September Arctic sea ice reductions and their relationships with storm behavior over 1979–2008. *Geophysical Research Letters*, 36, L19715. (https://doi.org/10.1029/2009GL039810)

Small, D., Atallah, E., and Gyakum, J. (2011) Wind Regimes along the Beaufort Sea Coast Favorable for Strong Wind Events at Tuktoyaktuk. *Journal of Applied Meteorology and Climatology*, 50(6), 1291-1306. (https://doi.org/10.1175/2010JAMC2606.1)

Small, G. E., Bass, C., Forgrave, R., Janke, B. D., Wendorff, A., and Finlay, J. C. (2025) Lake morphometry controls chloride retention and modulates impacts of road salt on stratification in urban lakes. *Water Resources Research*, 61, e2025WR040095. (https://doi.org/10.1029/2025WR040095)

Smol, J.P., Wolfe, A.P., Birks, H.J.B. , Douglas, M.S.V. , Jones, V.J. , Korhola, A. , Pienitz, R., Rühland, K. , Sorvari, S., Antoniades, D., Brooks, S.J., Fallu, M., Hughes, M., Keatley, B.E., Laing, T.E., Michelutti, N., Nazarova, L., Nyman, M., Paterson, A.M., Perren, B., Quinlan, R., Rautio, M., Saulnier-Talbot, É., Siitonen, S., Solovieva, N., and Weckström, J. (2005) Climatedriven regime shifts in the biological communities of arctic lakes. *Proc. Natl. Acad. Sci. U.S.A.*,
102(12), 4397-4402. (https://doi.org/10.1073/pnas.0500245102)

Smol, J. P. and Douglas, M. S. (2007) From controversy to consensus: making the case for recent climate change in the Arctic using lake sediments. *Frontiers in Ecology and the Environment*, 5, 466–474. (https://doi.org/10.1890/060162)

Smol, J. P., and Stoermer, E. F. (2010) The Diatoms: Applications for the Environmental and Earth Sciences, Second Edition. Cambridge University Press, 8-14.

Smol, J. P. (2023) Lakes in the Anthropocene: Reflections on tracking ecosystem change in the Arctic. *Excellence in Ecology Book Series*, International Ecology Institute (ECI), Oldendorf/Luhe, Germany. 13 chapters. 425 pp.

Squire, V. A. (2020) Ocean Wave Interactions with Sea Ice: A Reappraisal. *Annual Review of Fluid Mechanics,* 52, 37–60. (https://doi.org/10.1146/annurev-fluid-010719-060301)

Thienpont, J. R., Johnson, D., Nesbitt, H., Kokelj, S. V., Pisaric, M. F. J., and Smol. J. P. (2012) Arctic coastal freshwater ecosystem responses to a major saltwater intrusion: A landscape-scale palaeolimnological analysis. *The Holocene*, 22(12), 1451–1460. (https://doi.org/10.1177/0959683612455538)

Thienpont, J. R., Steele, C., Vermaire, J. C., Pisaric, M. F. J, Kokelj, S. V., and Smol, J. P. (2015) Synchronous changes in chironomid assemblages in two Arctic delta lake ecosystems after a major saltwater intrusion event. *Journal of Paleolimnology*, 53, 177–189. (https://doi.org/10.1007/s10933-014-9815-1)

Thomson, J., and W. E. Rogers (2014) Swell and sea in the emerging Arctic Ocean. *Geophysical Research Letters*, 41, 3136–3140. (https://doi.org/10.1002/2014GL059983)

Vermaire, J. C, Pisaric, M. F. J., Thienpont, J. R., Mustaphi, C. J. C, Kokelj, S. V, and Smol, J. P. (2013) Arctic climate warming and sea ice declines lead to increased storm surge activity. *Geophysical Research Letters*, 40(7), 1386-1390. (https://doi.org/10.1002/grl.50191)

Volik, O., Petrone, R. M., Hall, R. I., Macrae M. L., Wells, C. M., Elmes, M. C., and Price, J. S. (2017) Long-term precipitation-driven salinity change in a saline, peat-forming wetland in the Athabasca Oil Sands Region, Canada: a diatom-based paleolimnological study. *Journal of Paleolimnology*, 58, 533–550. (https://doi.org/10.1007/s10933-017-9989-4)

Watermann, F., Freund, H., and Gerdes, G. (2004) Distribution and palaeoecological indicator value of diatoms in Holocene coastal deposits of the southern North Sea (Lower Saxony, Germany). *E&G Quaternary Science Journal*, 54(1), 48–70. (https://doi.org/10.3285/eg.54.1.04)

Wood, K. R., Overland, J. E., Salo, S. A., Bond, N. A., Williams, W. J., and Dong, X. (2013) Is there a “new normal” climate in the Beaufort Sea? Polar Research, 32(1), 19552. (https://doi.org/10.3402/polar.v32i0.19552)