Spatial variability and controls on surface water chemistry and quality in a heterogeneous landscape: the Western Boreal Forest

by

Alexander Jonathan Frederick Mertens

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

in

Land Reclamation and Remediation

Department of Renewable Resources
University of Alberta

Abstract

Shallow lakes are highly abundant in the Canadian Western Boreal Forest (WBF) and provide essential ecosystem functions, water resources, sources of biodiversity and anthropogenic values. Increasing exposure to resource development and climate change are putting these lakes at risk, raising the need for baseline data and an understanding of the controls on lake hydrochemistry to facilitate adaptive management. Understanding the natural variability of, and controls on lake connectivity and water quality is essential to help guide future land use decisions and management strategies intended to mitigate these complex environmental problems. Very few monitoring programs have been performed in the WBF region. This thesis therefore aims to provide insight in the natural variability of lake chemistry and provide reference material for managers to assess potential lake disturbances. This thesis studies the relationship of lake ion and nutrient chemistry with landscape characteristics to infer the processes driving the variability in lake hydrology. A first study investigates the influence of regional-scale landscape characteristics across four Canadian ecozones of the WBF, while a second study focuses on the influence of local-scale landscape characteristics within the Boreal Plains (BP). This first study illustrates that the WBF is more spatially variable in lake ion and nutrient chemistry than previously assumed. Water types delineated by multivariate regression trees (MRTs) were capable of addressing 38% of the variability in lake ion chemistry across the WBF, using the regional characteristics of depth of glacial overburden, bedrock geology types and permafrost. Graphical plots of end-members indicated that the processes of groundwater dissolution, hydrologic isolation and difference in continental-scale precipitation interact to produce distinct lake ion chemistries. Permafrost, peatland abundance, depth of glacial overburden and topographic position delineated water types explaining 31% of the variability in lake nutrient chemistry across the WBF. These identified water types did not adhere to individual Canadian ecozones or sampling areas, and policy makers must therefore consider the complex interactions occurring across the WBF nor assume that hydrologic processes acted uniformly across each of the ecozones. Using MRT analyses, the second study showed that different lake and catchment characteristics give rise to distinct shallow lake hydrochemistry signatures (both ion and nutrient) across the BP. Water types delineated by MRT analysis showed relative wetland connectivity and relative topographic position addressing 45% of the variability in shallow lake ion concentrations. 48% of the variability in lake water quality was explained using water types delineated by the regional hydrologic regime (i.e. recharge vs discharge) and the geologic setting the shallow lakes were situated in. Results of this study showed that comparing natural variability in BP shallow lake hydrochemistry requires a careful consideration of the hydrological landscape shallow lakes are located in. Both studies also assessed the correlations between variability in ion and nutrient chemistry, and found the two chemistry sets to be influenced by distinct processes. Research and surveys assessing lake ion chemistry therefore provide little insight in lake nutrient loadings, and vice versa. This thesis provides the natural range in lake chemistry variability for well-defined hydrologic landforms across the WBF as reference for managers to determine whether lakes have experienced disturbance or not. Additionally, this thesis shows managers and stakeholders that determining future land use practices in the WBF and its individual ecozones requires specific consideration of landforms in policy, regulation and/or adaptive practices to ensure pre-disturbance lake water quality and connectivity and to sustain the lakes' ecosystem functions in the region.

Preface

This thesis is an original work of Alexander Mertens. Chapter 1 provides an introduction into the Western Boreal Forest and a general overview on the influence of all landscape characteristics on lake ion and nutrient chemistry and an overview of each thesis chapter. Both Chapter 2 and 3 are currently in preparation for submission to Freshwater Biology. Chapter 4 summarizes and synthesizes the finding from this work. Supervisors and committee members K. Devito, D. Olefeldt and J. Morissette made important contributions to each chapter.

Some of the data collected for this thesis forms part of a collaboration, led by Dr. Kevin Devito at the University of Alberta and Ducks Unlimited Canada (DUC). Sampling of survey lakes and field measurements for both chapter 2 and 3 were led by Dr. Devito and assisted by Wayne Bell for chapter 2 and Jenny Ferone, Kelly Menchenton and Wayne Bell for chapter 3. Water sample analyses were submitted to the University of Alberta Biogeochemical Analytical Services Laboratory. Original work came from the data management of all collected samples, quality control of lake chemistry, the collection of environmental data and subsequent data analyses. Data on environmental controls was collected from open sources, specifically: GeoScan, the Geological Survey of Canada, and their parent agency Natural Resources Canada, as well as the individual provinces' and territories' geological surveys.

Funding and support for this research was provided by the DUC Boreal Program, the Natural Sciences and Engineering Research Council-Collaborative Research and Development grant (NSERC-CRDPJ477235-14) of Canada, and industry partners Syncrude Canada Ltd and Canadian Natural Resources Ltd.

Acknowledgments

I would like to thank my advisors Dr. David Olefeldt and Dr. Kevin Devito for their guidance and support, and encouragement throughout my research. I would also like to thank my thesis committee member, Julienne Morissette, whose insightful comments on adaptive management and the Western Boreal Forest at large improved my conceptual models and written thesis. I also give thanks to Wayne Bell for all his work preceding this thesis, including his effort in sampling all survey lakes.

I also give thanks to my friends and colleagues at university, Kelly Hokanson, Mika Little-Devito, Emily Pugh, Lindsay James, Maxwell Lukenbach and Michael Bayans. I thank all of you for your support, insights, expertise and help in pouring through endless work documents.

I would like to thank those funding agencies who supported this research, Ducks Unlimited Canada (DUC) and the Natural Sciences and Engineering Research Council (NSERC), without whom this work would not have been possible.

Finally, I would also like to extend my most sincere gratitude to my family, friends and loved ones, not all of whom were able to see me complete this research. I am especially thankful for my mom and dad who were always there to support me no matter what. Without your constant love, support and encouragement, this research would not have been possible.

While it is always best to believe in oneself, a little help from others can be a great blessing.

Table of Contents

List of Tables

List of Figures

Chapter 1: Introduction

1.1 Background

Understanding the variability in hydrochemistry of open water wetlands, ponds, lakes, and other shallow aquatic ecosystems remains a key aspect of water resource research, by providing greater insight into water sources and ecosystem functions. Shallow aquatic ecosystems are abundant in the Canadian Western Boreal Forest (WBF), covering up to 20% of the landscape (Kuhry et al., 1994; Vitt et al., 1995). These ecosystems provide water for communities and industrial use (Foote & Krogman, 2006; AEP, 1998), serve as key biodiversity habitats (Carlson & Brown, 2015; Petrone et al., 2007), and influence nutrient cycling across the landscape (Kortelainen et al., 2006; Tranvik et al., 2009). The WBF is currently experiencing an increase in anthropogenic activities, such as forestry, and oil and gas extraction (Schneider et al., 2003; AEP, 1998), while also experiencing changes in climate at rates greater than the global average (Withey & van Kooten, 2011). The combination of these pressures may lead to the loss of water resources (Sommerfeld, 2012) and habitat degradation. With this research, the goal is to determine the baseline variability in lake chemistry of well-defined hydrological landscapes to provide reference for monitoring programs assessing potential lake disturbances. Additionally, this research tries to address how well landscape characteristics explain variability in lake hydrochemistry and whether these characteristics can be used to infer the hydrologic mechanisms controlling this variability.

Variability in lake ion chemistry in regions as diverse as the WBF is an integration of local to regional scale mechanisms that influence the hydrologic connectivity, length of flow path and residence time of source waters, surface water hydrology and evaporation (Gibbs, 1970; Tóth, 1999; Winter, 2001). Increasing length of flow path is expected to increase salinity and cause a transition in ionic composition from $CaCO_3$ (local flow), to $MgSO_4$ (intermediate), to NaCl (regional; Tóth, 1999). The WBF's diverse bedrock geology may influence scale of flow as well (Moser et al., 1998; Rawson, 1960). In areas of thick overburden, the composition of surficial geology is expected to play a pivotal role on lake hydrologic connectivity (Devito et al., 2005). Direction of flow and water residence time are also influenced by the relative elevation of the individual lakes, as the lakes' relative topographic position influences their function in the regional groundwater system (Winter, 2001; D'Arcy & Carignan, 1997). Permafrost, however, may act as an impermeable barrier, isolating surface waters from the regional groundwater movement (Walvoord et al., 2016; McCauley et al., 2001). Typical for the boreal, overland flow contributes to the inflow of ions into ponds. With increasing overland inflow, lakes are expected to possess ion concentrations more similar to precipitation (Gibbs, 1970; Bache, 1984). By exploring the influence of these controls on lake hydrologic connectivity and water quality, this study aims to provide a framework for managers and stakeholders to assess lakes' susceptibility to landscape disturbances and ecosystem productivity (Kreutzweiser et al., 2008; Nip, 1991; Nürnberg & Shaw, 1999).

Lake nutrient concentrations and water quality are influenced by both internal lake mechanisms, and external mechanisms generating nutrient inflow from the surrounding landscape (Zhang et al., 2012). The focus in this research lies in the influence external controls have on nutrient inflow into lakes. These controls include mean annual temperature (MAT) and precipitation (MAP), known to control landscape primary productivity and soil organic matter decomposition rate (Kirschbaum, 1995). The geology of the flow system also influences the inflow of nutrients into lakes. For example, lakes in areas of sedimentary bedrock have been shown to possess higher nutrient concentrations compared to lakes in areas of granite bedrock (Dillon & Kirchner, 1974; Kalff, 2002). Surficial geology has also been shown to influence lake nutrient concentrations, by affecting water storage and transmission characteristics (Plach et al., 2016). Additionally, research has shown peatlands often serve as nutrient sources to lakes (Ferone & Devito, 2004; Creed et al., 2008). Lake topographic position also influences the inflow of external nutrients, as lakes located higher in the landscape may be more hydrologically isolated and precipitation-fed (Webster et al., 1996; Kratz et al., 1997). Working at the regional scale of the WBF also brings variability in permafrost formations. An increase in the abundance of permafrost is associated with a reduction in MAT, causing a reduction in decomposition and thus available nutrients. Alternatively, increased permafrost abundance may cause an increase overland flow and water movement through organic wetlands, increasing the inflow of nutrients into surface waters. By assessing lake nutrient variability, this research aims to provide a baseline for managers and stakeholders to assess lake and ecosystem productivity across the WBF and infer potential water use for communities.

Most research on lake hydrochemistry focuses on local variability in lakes and the influence of local landscape characteristics. This is particularly true in the WBF where the drier climate, deeper surficial glacial deposits and larger groundwater flow systems make generalizations on hydrologic functioning difficult (Devito et al., 2000). This lack of larger scale research has led to a notable gap in research concerning how much of this variability in lake ion and nutrient chemistry can be addressed using regional landscape characteristics at the scale of the WBF. The first data chapter investigates the extent to which these regional-scale landscape characteristics can be used to infer hydrologic processes and controls on lake hydrochemistry identified by local-scale research. By doing so, further understanding on how lake chemistry varies across the WBF may be obtained, and an identification of which processes influence this variability over the different regions of the boreal is possible. Additionally, working at this regional scale across the WBF facilitates the investigation of which processes are multiscaled, or interact across scales. As a result of these multiscaled processes, similar hydrologic mechanisms could therefore produce different trends in hydrochemistry. The potential role of CSIs on lake hydrochemistry has not yet been investigated in western Canada, due to the difficulty of acquiring data at sufficiently broad spatial extents. By understanding the mechanisms behinds these potential CSIs and the differences in regional controls across the WBF, researchers and managers can determine in what contexts hydrologic relationships can be transferred from one region to another.

Following the results of the regional analyses across the WBF, the second study examines one of the identified water types in greater detail. Specifically, it investigates if the large variability in hydrochemistry of lakes located on the low-relief, thick overburden in the Boreal Plains can be better explained using local-scale landscape characteristics. Again, this study investigates which landscape characteristics can be used to infer hydrologic processes and controls on lake hydrochemistry and how well these explain the observed variability in hydrochemistry. Additionally, the difference in explanatory power among scales by extracting data on landscape characteristics from three different scales is investigated: 1) a 100 m buffer around each lake, 2) a 500 m buffer area around each lake, and 3) a topographical watershed catchment. These results may guide future research and management monitoring strategies by investigating how well arbitrary buffers perform relative to individual lake watersheds.

Finally, the results of local-level conceptual models are integrated with the results of the initial research at the regional level of the WBF. This facilitates a greater insight into the relative role and order of control of regional scale groundwater flow and bedrock geology, local scale surficial geology and ground water connectivity, and wetland connectivity on the spatial variability of lake hydrochemistry. Furthermore, this understanding of landscape controls can be used to explain spatial variability in hydrologic function and assess susceptibility to disturbances, and lake and ecosystem productivity. More importantly, these results will provide a baseline on the natural variability in lake ion and nutrient concentrations in well-defined landscape envelopes as reference for monitoring programs in the assessment of potential hydrologic disturbances.

1.2 Thesis objectives and outline

This thesis follows a paper format style and has been organized into four chapters. The overall objective of this thesis was to investigate the variability in hydrochemistry of lakes of the WBF, and how variability and scale in the environmental controls influences this.

Chapter 2 examines the range in variability in lake hydrochemistry (ions and nutrients) across the WBF, and looks into how well this variability can be accounted for using regional-scale environmental data gathered from open sources available to management agencies. The research objectives of this chapter are to:

1. Provide a baseline inventory of the natural variability in lake salinity, ion composition and nutrient concentrations encountered across the WBF.
2. Identify which regional-scale environmental controls best explain this variability in lake chemistry.
3. Assess how much of this variability in lake chemistry can be explained from regional landscape characteristics.
4. Investigate if cross-scale interactions between environmental controls can be inferred by working at the regional scale across the WBF.

Chapter 3 focuses on lake hydrochemistry variability within a single water type identified in chapter 2, and examines the extent to which this variability can be explained using local-scale environmental data by comparing three different measures of adjacent landscape contributions to shallow lake water chemistry. The research objectives of this chapter are to:

1. Provide a baseline inventory of the natural variability in salinity, ion composition and nutrient concentrations in typical shallow lakes of the Boreal Plains.
2. Identify which local-scale environmental controls and catchment scale best explain the variability encountered in shallow lake chemistry.
3. Assess how much of this variability in shallow lake chemistry can be explained from these local landscape characteristics.

Chapter 4 presents a general summary and conclusions of the previous two chapters and management and implications of the research conducted.

Chapter 2: Contrasting regional landscape controls on lake ion and nutrient water chemistry across the Western Boreal Forest, Canada

2.1 Abstract

Shallow lakes form a key aspect of the Canadian Western Boreal Forest (WBF) through their ecosystem functions and anthropogenic value. Increasing exposure to resource development and climate change are putting these habitats at risk, raising the need for baseline data and an understanding of the controls on lake hydrochemistry to facilitate lake and landscape management. This study examines the relationship of lake ion and nutrient chemistry with regional landscape characteristics of 881 lakes across four Canadian ecozones of the WBF to assess the relative role of ecozones in distinguishing different lake water types and infer the processes driving the variability in lake hydrology. The regional controls influencing variability in ion chemistry assess the source and scale at which waters feed into lakes and were examined to determine the lakes' susceptibility to disturbances. The variability in nutrient chemistry was also assessed to determine water quality and ecosystem productivity. This study illustrates that the WBF is more spatially variable in lake ion and nutrient chemistry than previously assumed. Regional characteristics were capable of identifying broad differences in lake hydrochemistry and identified the dominance of different hydrologic processes influencing lake chemistry at the regional scale of the WBF. Lake ion chemistry shows that depth of glacial overburden, bedrock geology and permafrost cover delineated water types that explain 38% of the variability in lake ion chemistry across the WBF. Graphical plots of end-members indicated that the processes of groundwater dissolution, hydrologic isolation and difference in continental-scale precipitation interact to produce distinct lake ion chemistries that span across ecozones. Lake water quality was best explained (31%) by permafrost, peatland abundance, depth of glacial overburden and topographic position. Higher nutrient concentrations were associated with surface-dominated

flow from organic-rich soils. Cross scale interactions also occurred, where lake ion composition was highly influenced by the composition of the local meteoric waters that varied across sample areas and ecozones. In addition, the influence of certain landscape characteristics (e.g. Bedrock Type and Thick Overburden) could be masked by the presence of other characteristics (e.g. Thick Overburden and Continuous Permafrost). Managers and stakeholders can therefore not assume that hydrologic processes act uniformly across the nationally defined ecozones. Rather, hydrologic management would benefit more from using the water types delineated by this research, as hydrologic processes do act more uniformly within these well-defined landscape envelopes. Additionally, good management should assess potential hydrologic disturbances based on the deviation of monitoring sites from the baseline variability within these delineated hydrologic landscapes, rather than by using ecozone baselines.

2.2 Introduction

Shallow aquatic ecosystems, including open water wetlands, ponds and lakes, are abundant in the Canadian Western Boreal Forest (WBF) and represent key habitats for fish, amphibians and waterfowl (Carlson & Brown, 2015; Petrone et al., 2007). Beyond their value for biodiversity, these ecosystems also influence nutrient cycling and carbon balance at the landscape scale (Kortelainen et al., 2006; Tranvik et al., 2009), provide water for communities and industrial use (AEP, 1998) and offer opportunities for recreational activities and traditional land use (Marles et al., 2000; Boxall & Macnab, 2000). These functions of individual lakes are strongly influenced by their water chemistry, which both indicates dominant water sources and within-lake biogeochemistry. This research focuses on lake ion chemistry, which is highly dependent on the lakes' hydrologic connectivity (local vs regional; Winter, 2001), as well as lake nutrients, which serve as indicators of lake productivity (Nürnberg & Shaw, 1999). Monitoring the spatial variability in lake connectivity and water quality are essential in determining the potential disturbance of hydrologic sites and serve as important indicators of lake sensitivity to disturbances, and ecosystem function and quality, respectively (Seigal, 1988; Soranno et al., 2014). Most work on lake hydrochemistry focuses on local variability and controls (Soranno et al., 2010). There is therefore a notable gap in monitoring the natural variability in lake ion and nutrient chemistry at the regional scale and research on how much of this variability may be attributed to regional landscape characteristics and extrapolated at the scale of the WBF.

The WBF covers a third of Canada and is a mosaic of forests, wetlands and abundant shallow aquatic ecosystems, with lakes covering up to 20% of the landscape (Kuhry et al., 1994; Vitt et al., 1995; Petrone et al., 2007). The WBF encompasses several distinct Canadian ecozones, including the Boreal and Taiga Plains, the Boreal and Taiga Cordilleras and western parts of the

Boreal and Taiga Shield. This region has a dry (sub-humid) climate with spatially variable landscape characteristics, specifically bedrock and surficial geology, permafrost and topography (Fig. 2.1b-f). In addition to this variation, the WBF is experiencing increasing changes in land use such as hydro dams, agriculture, forestry, oil and gas extraction and mining (Schneider et al., 2003; AEP, 1998; Foote & Krogman, 2006) and changes in climate at a greater rate than the global average (Withey & van Kooten, 2011). These pressures may lead to habitat degradation or loss of water resources (Sommerfeld, 2012) and recreational values, but the vulnerability of individual lakes likely depends on the lakes' sources of water (Seigal, 1988) and effective assessment of disturbances requires an understanding of the natural range (baseline) in lake water chemistry.

Variability in lake ion concentrations and composition may be explained at the continental scale by the three main processes of precipitation, water-rock interactions and evaporation-crystallization, (Gibbs, 1970; Wetzel, 1983, Jorgensen and Vollenweider, 1989). These three processes influence the lakes' hydrologic connectivity, residence time of source waters, groundwater dissolution and surface water hydrology (Gibbs, 1970; Tóth, 1999; Winter, 2001). Due to the WBF's sub-humid climate, lakes are not expected to be influenced by the process of evaporation-crystallization. Therefore, high salinity when it occurs is most likely caused by deep, continental-scale groundwater discharge (Chebotarev, 1955). Increases in flow path length are expected to cause a conversion from $CaCO_3$ dominated water (local flow), to $MgSO_4$ (intermediate), to NaCl (regional; Tóth, 1999). The WBF's diverse bedrock may also influence the residence time and scale of flow of groundwater supplied to lakes (Winter, 2001; Moser et al., 1998; Rawson, 1960), while increasing depth of quaternary overburden may reduce the direct influence of bedrock characteristics on lake chemistry (Devito et al., 2005). In northern regions, groundwater flow may be redirected by permafrost acting as an impermeable barrier and isolating lakes from regional groundwater (Walvoord & Kurylyk, 2016; McCauley et al., 2001). Finally, the direction of groundwater flow and residence time of water can be influenced by lake topographic position, which influences the lakes' recharge-discharge function in the flow system (Winter, 2001; Kratz et al., 1997). Understanding the source and scale at which waters feed into lakes provides a framework for managers and stakeholders to assess the relative susceptibility of lakes to land use changes and disturbances on hydrology (Kreutzweiser et al., 2008; Nip, 1991; Winter, 2001). Specifically, lakes limited to local groundwater flow paths for water sources are most sensitive to disturbances and landscape changes (Devito et al., 2000; Seigal 1988).

Lake productivity, water quality and greenhouse gas exchanges are strongly influenced by concentrations of carbon (C), nitrogen (N) and phosphorus (P) (Prairie, 2008; Olefeldt et al., 2013a; Vitousek et al. 1997; Yang et al., 2015; Huttunen et al., 2003). P is most often the limiting nutrient in boreal lakes (Prepas et al., 2001) and is therefore a key element in determining gross primary production (GPP). C, on the other hand, serves as an energy source for lake heterotrophic bacteria and enhances community respiration (R), and high C levels indicate higher lake heterotrophy (R > GPP; Staehr et al., 2010). Two principal regional characteristics influencing surface water nutrients are mean annual temperature (MAT) and precipitation (MAP), because they control primary productivity and soil organic matter decomposition rate (Kirschbaum, 1995). Additionally, peatlands often serve as sources of P, N and C to lakes. Previous research has shown that, relative to water flowing through mineral soils, water flowing through organic soils show increased nutrient concentrations (Devito et al., 2000; Olefeldt et al., 2013b; Ferone & Devito, 2004; Creed et al., 2008). Devito et al. (2000) showed that 50% of differences in P among lakes within a region on the Boreal Plains could be explained by landscape characteristics influencing the scale of lake-groundwater interactions, and the connectivity of lakes to wetlands. The surficial geology of flow systems also influences the inflow of nutrients into lakes, by influencing water storage and transmission characteristics. Plach et al. (2016) showed that lakes atop coarse deposits in low topographic positions received groundwater from nutrient-poor, larger scale groundwater flow systems. Lake topographic position may also influence the inflow of external nutrients, with lakes located higher in the landscape being more hydrologically isolated and precipitation-fed (Webster et al., 1996; Kratz et al., 1997). The presence of lakes and their location in the landscape can therefore play an important role in determining the biosphere's response to enhanced nutrient loadings, both at local and regional scales (Harrison et al., 2009). Additionally, by assessing lake nutrient variability at the regional scale, this study will provide a baseline for managers and stakeholders to assess lake and ecosystem productivity across the WBF.

Working at this regional scale across the WBF makes it difficult to determine the main controls and the possibility exists that certain processes are multi-scaled in space and time, or interact across scales. Traditional hierarchy theory suggests that broad-scale processes act uniformly on ecological response variables (Turner & Gardner, 2015). However, processes operating at different scales may interact and result in context-specific patterns (Peters et al. 2007). Cross-scale interactions (CSIs) occur when there is an interaction among driver variables at different spatial scales, which influences a response variable; or when there is an interaction between processes that link fine- and broad-scaled processes (Soranno et al., 2014). At the regional scale of the WBF, there is strong landscape heterogeneity, transitioning from Cordilleras to Plains, across permafrost, geologies and varying peatland abundance (Fig.2.1b-f). It can therefore be expected that similar hydrologic mechanisms could produce different trends in hydrochemistry.

Possible candidates for CSIs include the effects of wetlands on lake nutrients. Research has shown both positive and negative correlations exist between P concentrations and wetland connectivity (Soranno et al., 2014; Devito et al., 2000; Diebel et al., 2009). In addition, the influence of relative elevation may vary with surficial geology due to their variability in water storage and transmission characteristics. There thus exists a need to develop management units, identified at this regional scale across the WBF, that allow for the extrapolation of management strategies between regions of similar mechanisms and trends in hydrochemistry. The influence of CSIs has not been investigated properly in western Canada because of the challenges of acquiring data at sufficiently broad spatial extents. By understanding the mechanisms behind potential CSIs and the differences in regional controls across the WBF, researchers and managers can determine whether hydrologic relationships can be transferred appropriately from one region to another. CSIs may serve as a basis for efforts to understand a wide variety of multi-scaled problems such as climate change, land-use change and to aid in developing sound policy and management strategies (Carpenter and Turner, 2000; Peters et al., 2007; Soranno et al., 2014).

The objective of this chapter is to describe the natural variability in lake chemistry in the WBF using the chemical and regional physical characteristics of 881 lakes sampled across six study areas within the WBF (Fig.2.1). This analysis attempts to provide a better representation on how lake chemistry varies across the WBF and infer processes that influence this variability over the different regions of the boreal, due to the large heterogeneity in landscape characteristics (e.g. geology, topography, peatland abundance, etc.). Additionally, by combining hydrologic processes and controls identified by local-scale research into a single framework, this study will potentially improve our understanding on how these processes function and influence the variability of ions and nutrients at the regional scale of the WBF. To this end, the following four questions are addressed: (1) What is the baseline and natural variability of lake salinity, ion composition and nutrient concentrations across the WBF? (2) Which landscape controls best explain the variability in lake chemistry? (3) How much of this variability can be explained from regional landscape characteristics? and (4) Can a WBF-wide regional scale assessment be used to infer cross-scale interactions? In answering these questions, this study attempts to guide adaptive management across the region. By providing a range in the natural variability of water chemistry and how this variability is influenced across regions, this can serve as reference for management practices, help guide land use and reclamation and assess human disturbances. The potential hydrologic disturbance of monitoring sites may be determined from these sites' deviation from the baseline variability in lake ion and nutrient concentrations in well-defined hydrologic landscape envelopes.

2.3 Methods

2.3.1 Study Areas

A total of 881 shallow (< 5 m deep) open water wetlands, ponds, and lakes; hereafter referred to as lakes; were sampled across the WBF between 1999 and 2003 (Fig.2.1). Lakes varied in size between 0.05 and 11,000 ha, however 90% of the lakes were less than 120 ha. Lakes were sampled in six areas, selected to maximize and represent landscape and climatic variability across the WBF (Fig.2.1).

The Lower Mackenzie (LM) area (Fig.2.1b – LM) is located in the low-relief Taiga Plains ecozone (Fig.2.1 – BP) and includes lakes both within the Mackenzie River Delta and in the adjacent uplands. A total of 151 lakes were sampled in August, 2003. The sampled lakes are situated in discontinuous (delta) or continuous permafrost (non-delta). The region has thick (>10 m) overburden that overlays sandstone or shale bedrock. Lake elevations range from 3 m to 376 m asl and local peatland abundance varied from 0 to 61% (Fig.2.1d).

The Norman Wells (NW) area (Fig.2.1b – NW) is located in the Taiga Plains ecozone between Great Bear Lake and the Mackenzie Mountains. A total of 95 lakes were sampled in August, 2001. The area has extensive discontinuous permafrost and a range of lake elevations between 60 and 392 m asl. The area is underlain by sandstone, shale and limestone bedrock, with 84 sampled lakes located on thick overburden, while a subset of 11 lakes were located on top of thin overburden (2 to 10 m). Peatland abundance was variable, ranging from 2 to 61%.

The Fort Nelson (FN) study area (Fig.2.1b – FN) is the most southern sampling area within the Taiga Plains. Lakes were sampled in July, 1999 (n=109) and July, 2001 (n=89). This area has sporadic permafrost, with permafrost largely confined to peatland, with local peatland coverage ranging between 0 and 90%. All lakes in the FN area were located on thick overburden, with the majority lakes (163) located on shale deposits and 35 lakes located on sandstone bedrock. Lake elevations in the FN region ranged from 306 m asl on the plains to 701 m asl in the foothills of the Rocky Mountains.

The Southern Lakes (SL) area (Fig.2.1b – SL) is located in the Boreal Cordillera ecozone (Fig.2.1 – BC) and extends from the mountains of the Boundary Range to the valleys of the Miners Range, with 99 lakes sampled in July, 2001. Lake elevations range from 640 to 1650 m asl and were located on varying bedrock: shale, sandstone, limestone, basalt and granite. The area has extensive, sporadic or isolated permafrost depending on elevation and snow cover. Overburden ranges in thickness from 0 to over 10 m (surficial, thin, or thick). No significant peatland formations are present in the SL area.

The Utikuma (UTL) study area (Fig.2.1b – UTL) is located in the Boreal Plains ecozone (Fig.2.1 – BP). A total of 128 lakes were sampled in August, 2001. The majority of lakes were located on shale bedrock, but 12 were located on sandstone. All lakes were located on thick overburden and permafrost is absent in the region. The UTL has low relief, with a range in lake elevations between 520 and 760 m asl and peat cover ranged between 16 and 50%.

The Pasquia (PSQ) area (Fig.2.1b – PSQ) is very diverse and situated at the eastern edge of the Boreal Plains ecozone and transitioning to the westernmost parts of the Boreal Shield (Fig.2.1 – BS). A total of 192 lakes were sampled during July and August, 2003. Because the study area spans plains and shield ecozones, lakes cover highly varied bedrock geology, including shale, sandstone, limestone and granite bedrock. Similarly, the region has variable quaternary deposits, ranging from thick overburden (>10 m), to absent. Lakes are located in zones of sporadic, isolated or absent permafrost. Lake elevations range from to 200 to 780 m asl, while local peatland abundance ranges from 0 to 64%. Additionally, continental aquifers become exposed to the surface in this area (Bachu & Hitchon, 1996). A subset of 44 lakes is located in the Saskatchewan River Delta (SRD), one of the largest active inland deltas in North America (9,500 km^2), which where several of continental scale aquifers discharge regional groundwater. The northeast portion of the PSQ area is situated on the Boreal Shield and includes a subset of 18 lakes, sampled in July, 2004. This part of the area is dominated by Precambrian intrusive rocks (granite) and is covered by a thin layer (2 – 10 m) of lacustrine clay (Corkery, 1987). This subset of lakes was sampled to provide a comparison in lake chemistry between the plains and shield ecozones within the study area.

2.3.2 Lake Sampling and Water Sample Analysis

All lake water samples were collected during the summer months (July-August), either by helicopter or from the shore by sampling with a 4 m rod. All water samples were collected approximately 0.2 to 0.3 m below the surface. Water samples were filtered through a membrane filter (pore size 0.45 μm) and frozen within 8 hours of sampling until analysis. The pH and electrical conductivity (EC) of the water samples were measured in the field using a Fischer Scientific Accumet 925 pH meter and an Oakton Con 300 conductivity meter.

All water chemistry analyses were performed by the University of Alberta Biogeochemical Analytical Services Laboratory (BASL). Water samples from 781 lakes were analyzed for a suite of anion and cation concentrations to determine the ion charge balance. Major cations included sodium (Na^+), potassium (K^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), and were measured using a Perkin Elmer 3300 Atomic Absorption Spectrometer using the methods presented by Stainton et al. (1977). Anions, including sulfate (SO_4^{2-}), chloride (Cl^-) and bicarbonate (HCO_3^-), were measured using a Dionex DX600 Ion Chromatograph using methods presented by Pfaff (1993).

Total dissolved solids (TDS) concentrations were calculated by summing the major anions (Cl^-, SO_4^{2-}, HCO_3^-) and cations (Ca^{2+}, Mg^{2+}, Na^+, K^+). Charge balances for all samples were calculated, with the inclusion of dissolved organic carbon (DOC) to include the contribution of humic substances to the total anionic charge (Oliver et al., 1983). Given the greater chance of error with the inclusion of DOC, water samples with a charge balance ratio of less than 25% were included in further analyses on lake ions. A total of nineteen lakes were removed from further analyses as their ionic charge balances fell outside the acceptable range.

Samples were analyzed for nutrient concentrations, but specific parameters varied between regions. Most lake water samples (718) were analyzed for concentrations of DOC, total dissolved nitrogen (TDN) and total dissolved phosphorous (TDP). For DOC analysis, water samples were filtered using a membrane filter (pore size 0.45 µm) and analyzed using an Ionics Model 1505 Programmable Carbon Analyzer following Greenberg et al. (1992). Samples for TDN and total nitrogen (TN) analysis were filtered in the lab using Gelman glass fiber filter (pore size 1.0 µm) and analyzed using a Technicon Autoanalyzer II following Stainton et al (1977). Samples for TDP and total phosphorus (TP) were filtered in the lab using Gelman glass fiber filter (pore size 1.0 µm) and analyzed using a Cary 50 UV/Visible Spectrophotometer following Prepas and Rigler (1982). Water for Chlorophyll a (Chl-a) analysis was filtered through a Gelman type A/E 47 mm filter, and soluble reactive phosphorus (SRP), ammonium (NH_4^+) and nitrate (NO_3^-) were all filtered through a 0.45 µm syringe filter within 24 hours of sampling and then frozen for analyses at a later date.

2.3.3 Regional Characteristics

Eleven regional characteristics were selected that were considered most likely to influence lake ion and nutrient chemistry through processes identified by previous local-scale research (Table

2.1). All landscape variables were extracted from open data sources with consistent regional-scale spatial data covering the entire WBF. These data sources were chosen because they represent data available to management agencies across Canada.

Multiple features of climate variability were gathered to assess the control of climate on lake chemistry variability (Table 2.1). Mean annual precipitation (MAP) and potential evaporation (MAPET) were extracted at the level of ecodistricts for each lake (Government of Canada's National Ecological Framework, sis.agr.gc.ca, 2016). The contribution of snowfall (Snow%) to MAP was determined from:

$$Eq. 1\ Snow\% = \frac{SNWFL}{MAP} \times 100$$

The Climate Moisture Index (CMI; Hogg et al.,1997) was calculated from:

$$Eq. 2\ CMI = MAP - MAPET$$

Mean annual temperature (MAT) for each lake was extracted from the WorldClim 1.4 (http:// worldclim.org/current, accessed on April 6, 2017). Permafrost zonation of each lake was classified as absent, isolated, sporadic, discontinuous, or continuous permafrost and was gathered from the Canadian Permafrost map (Heginbottom et al., 1995).

Bedrock type surrounding each lake was determined using publications based on each province and territory's geological surveys. A total of 51 different bedrock types used in the geological surveys were categorized into five general bedrock type classes of increasing weathering rate: granite, sandstone, basalt, shale and limestone (Table S2.2).

Regional surficial geology for each lake was determined using "Surficial materials of Canada" (Fulton et al., 1995). Mapped deposits were classified into five Hydrologic Response Areas (HRAs; Devito et al., 2017), based on texture and landscape structure: 1) Bedrock, including all lithified rock left uncovered by surficial material; 2) Till veneer, including all till deposits less than 2 m thick; 3) Coarse, including coarse-textured glacio-fluvial and glacio-lacustrine deposits; 4) Fine plain, including fine-textured clay-rich glacio-lacustrine deposits; 5) Fine hummocky, including all fine-textured clay-rich hummocky moraines and thick rolling tills (Table S2.3).

Thickness of the surficial deposits overlying the bedrock was estimated using geological survey reports obtained from the respective provincial and territorial geological surveys (Klassen, 1979; Betcher et al., 1995; Hume, 1954; Fulton, 1970; Hickin & Kerr, 2005; Seguin et al., 1999; Paulen et al., 2004a & 2004b). These maps contained the general depth of the different surficial deposits. Thickness of overburden material for all individual lakes was classified as: 1) Surficial, <2 m thick; 2) Thin, 2-10 m; 3) Thick, >10 m.

Regional peatland abundance surrounding each lake was determined from "Peatlands of Canada" (Tarnocai et al., 2011), where peatland abundance is expressed as landscape % coverage for individual ecodistricts.

Elevation of each lake was obtained from the Canadian Digital Elevation Model (CDEM; NRC, 2016). Relative elevation of each lake was determined based on its elevation within its larger topographic catchment:

$$\text{Eq. 3 Relative Elevation} = \frac{\text{Elevation} - \text{Elevation}_{\min}}{\text{Elevation}_{max} - \text{Elevation}_{\min}}$$

where $\mathrm{Elevation}_{\mathrm{min}}$ and $\mathrm{Elevation}_{\mathrm{max}}$ are the lowest and highest elevations within the lake catchment. Catchments were determined by conceptualizing the regional-scale overland flow within each study area, using 1:50,000 scale streamflow (CanVec; NRC, 2017) and contour maps (CDEM).

2.3.4 Data Analyses

Multivariate Regression Trees (MRT)

Multivariate Regression Trees (MRTs) were used to classify lake water types and assess the influence of lake regional landscape characteristics on lake water chemistry. MRT analysis is suitable as it allows for the determination of interactive effects of different regional characteristics on water chemistry. At split in the MRT, a specific landscape characteristic and a division point along that variable are selected to minimize "impurity" – the variation within the groups. Impurity is estimated as the sum of squared Euclidean distances from individual samples to the centroid of each grouping's space (De'ath, 2002; McCune & Urban, 2002; Jongman et al., 1995).

The MRTs were created using the 'greedy algorithm' provided by the R package 'mvpart' (Therneau & Atkinson, 2004). All chemistry data were normalized using the 'standard score', given the different units of measurement and range in data of the chemistry variables (McCune & Urban, 2002; Jongman et al., 1995). Independent MRTs were created for lake ion and nutrient chemistry. The ion chemistry variables included in the MRT were: conductivity (EC), pH, major ions (Na^+, K^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, Cl^- and HCO_3^-), as well as the ion ratios Na/(Na+Ca), $Cl/(Cl+HCO_3)$ and $SO_4/(SO_4+HCO_3)$. The nutrient chemistry variables included were DOC, TDN and TDP. TDN and TDP were used, rather than TN and TP, as dissolved nutrients provide a better estimate of nutrients available to phytoplankton to stimulate eutrophication (Caffrey et al., 2007). The final MRTs were created after initial MRTs were pruned by selecting those with the smallest cross-validated relative error.

Following the outcome of the final MRTs, Multi-Response Permutation Procedures (MRPPs) were performed to test if there was a significant difference between MRT branches. MRPP is a nonparametric procedure that compares dissimilarities within and among groups using Euclidian distances. If two groups (i.e. water types) are different, then the average of the within-group dissimilarities is less than the average of the dissimilarities between two groups (McCune & Urban, 2002; Mielke & Berry, 2001).

End-member Analysis (EMA)

Following the results of the MRT analysis on lake ion variability, a graphical plot of the lakes' ratio of Na/(Na+Ca) and Cl/(Cl+HCO_3) in relation to TDS was created. This plot also included a selection of end-members to identify the main mechanisms controlling the lakes' chemical composition of the major dissolved salts and to highlight the origin of water (Gibbs, 1970). These end-members included meteoric water signatures of distinct geographical locations, groundwater signatures of different bedrock geologies and groundwater signatures of different lengths of flow path. Using this EMA, the goal was to infer the main mechanisms and processes linked to the landscape characteristics identified in the MRT analysis on lake ion variability.

Principal Component Analysis (PCA)

A principal components analysis (PCA) was performed to examine relatedness among all lake ion and nutrient chemistry variables, and regional characteristics. In total, 11 ion chemistry variables, 3 nutrient chemistry variables and 26 regional characteristics were included in the PCA. Since not all lake samples were analyzed for a complete ion and nutrient chemistry suite, the PCA analysis was limited to a total of 620 lakes, with the inclusion of lakes from all study areas.

The PCA was created using the ‘prcomp’ function in R, generating a Pearson-type PCA. No data were transformed, but to capture the effects of each distinct non-numerical landscape characteristic, categorical variables (i.e. permafrost, bedrock geology, surficial geology and depth to bedrock) were entered as binary dummy variables – ‘0’ representing a negative and ‘1’ a positive. Arrows of variables that are positively correlated are plotted such that the angle between the arrows is small and variables that are negatively correlated are plotted pointing in opposite directions (Martins, 2013).

2.4 Results

2.4.1 Influence of regional characteristics on lake ion chemistry

Six water types (I_A-I_F) were identified by the MRT that assessed the correlation between lake regional characteristics and lake ion chemistry (Table 2.2, Fig.2.2a). The six water types were not primarily associated with the individual study areas (Fig.2.3) and MRPPs found that all water types were significantly different. The MRT explained 38% of the variability in ion chemistry and identified overburden thickness, combined with bedrock type and permafrost conditions, as primary controls on lake ion chemistry.

Water type I_A encompassed all lakes located in regions with thick overburden (>10 m) and continuous permafrost. Water type I_A had the lowest EC and overall low ion concentrations, but relatively high Na^+ and Cl^- concentrations (Table 2.2). Only lakes in the LM study area were included in water type I_A (Fig.2.3a,c). Water type I_D also encompassed lakes in regions with thick overburden, but located outside the continuous permafrost zone. These lakes were located across the Taiga and Boreal Plains of the WBF: ranging from the Mackenzie River Delta, across the plains of NW, FN and UTL, to the glacial plains of PSQ (Fig.2.3a). Lakes with ion water type I_D had intermediate EC and ion concentrations, albeit with elevated SO_4^{2-} concentrations (Table 2.2).

Lakes in regions with surficial or thin overburden (<10 m) were classified into four water types. Water type I_B encompassed lakes located in regions with granite bedrock and had low EC and ion concentrations. Lakes of water type I_B were located in the SL and PSQ study areas, despite contrasting topography (Fig.2.3a,b). Water types I_C, I_E and I_F encompassed lakes located in regions with sedimentary bedrock types, which were further distinguished by absence of permafrost (I_E), extensive permafrost and thin overburden (I_C), or extensive permafrost and surficial overburden (I_F). Lakes of water type I_E exhibited high salinity and ion concentrations, especially in Na^+ (Table 2.2) and were located in valleys of the SL study area and in the southeastern edge of the PSQ study area, at the transition to the Boreal Shield where sharp breaks in the lithology of carbonate bedrock and Precambrian Shield are encountered (Fig.2.3a,b,d). Lakes of water type I_C had low EC and ion concentrations, with relatively high concentrations of Ca^{2+} and HCO_3^- and were located in the NW study area and in valleys of the SL study area. Lakes of water type I_F had the highest salinity and ion concentrations, especially in Ca^{2+} and HCO_3^-. Water type I_F encompassed lakes located in valleys of the SL study area (Fig.2.3a,b).

2.4.2 Processes responsible for variability within and among ion water types

The TDS and Na/(Na+Ca) ratio of all ion-balanced lakes were graphically plotted in order to identify the hydrologic processes controlling the variability within and between the ion chemistry water types (Fig.2.4a). The six ion chemistry water types (I_A-I_F) separated reasonably well in the mixing space defined by TDS and the Na/(Na+Ca) ratio (Fig.2.4b). Distinct end-member waters, including surface waters, precipitation, artesian wells and deep groundwater samples, supported this interpretation of dominant processes in different regions of the mixing space.

The largest group of lakes (n=446 lakes) was associated with rock-water interactions (defined by Gibbs as the process of geology), with a large range in lake TDS (80 to 1,000 mg L^{-1}) and relatively low sodium ratios (<0.5) (Calcium dominated lakes). These rock-dominated lakes come from all parts of the WBF and constitute all water types, but are largely lakes from regions with deeper surficial deposits in the permafrost LM area (I_A), across the glaciated Taiga and Boreal Plains (I_C and I_D), and clay-rich areas on the Boreal Shield (I_B). They are similar in composition to lake waters located on a range of bedrock types (basalt, granite, limestone, shale), which likely reflects the parent material of the surficial glacial deposits.

With dilution, likely due to the predominance of precipitation, the lake chemistry spread into different types of waters compared to rock-water dominated lakes, corresponding to local precipitation chemistry (Fig 2.4). A group of lakes (n=121) with I_C and I_D type water are dilute (TDS < 80 mg L^{-1}) with low sodium ratios (<0.2) and are dominated by sodium-poor precipitation. In contrast, dilute lakes from the permafrost-rich LM sampling area with I_A type water show an increase in the Na and Cl ratio (>0.3), reflecting maritime influences. The distribution of I_D water type at the LM is restricted to the delta, which receives waters from the Taiga and Boreal Plain via the Athabasca and Mackenzie River (Fig 2.3c). Lakes located on granitic bedrock regions (I_B) were intermediate between low and high sodium precipitation, and reflect dilute lakes on granite as well as the precipitation composition on the Boreal Cordillera.

The lakes classified as I_E overlap in chemistry only slightly with rock-dominated I_D lakes and generally have higher Na ratios (>0.3), but remain within the bounds for rock-dominated waters initially described by Gibbs (1970). These lakes are located in areas with limestone and shale bedrock (Fig. 2.3b,d), with no or thin overburden. These lakes have a similar Na ratio as artesian water from Saskatchewan, albeit more dilute. A group of lakes (n=14) classified as water type I_E occurred in the geographically diverse SL and PSQ areas. They had the highest salinity, with TDS > 1,000 mg L^{-1} and high sodium ratios (>0.6). This group of lakes also shared a composition similar to deep continental groundwater, indicating that they were associated with dissolution processes (Fig. 2.3b,d). 31 lakes classified as I_E water type had moderately saline freshwaters (TDS: 100-1,000 mg L^{-1}) with high sodium ratios (>0.5) that fall outside the boundaries for surface water types (Gibbs 1970) and were located solely in the PSQ area. These lakes were located on the Saskatchewan River Delta and an interface of continental groundwater discharge (Fig 2.3d). This water therefore represents a mix of groundwater dominated by dissolution and subsequent dilution from surface waters.

The final group (n=3) of lakes had brackish water, with TDS > 1,000 mg L^{-1} and low sodium ratios (<0.2), and was considered dominated by the dissolution of carbonate bedrock. These lakes in the SL sampling area are similar to marl rich artesian groundwater from the Boreal Plain of Alberta (UTL site).

The influence of lake relative elevation on ion salinity was assessed through an ad-hoc analysis on a subset of lakes classified as dominated either by precipitation (both sodium-rich and -poor) or geology. The hypothesis that lakes at higher relative elevation are more likely to be dominated by precipitation was tested by creating lake density plots (Kernel-type; Fig.2.5). Comparing density plots shows that more dilute lakes (TDS < 80 mg L^{-1}) had a tendency to be located at relatively higher elevation than rock-dominated lakes. This difference was most pronounced when lakes from different ion water types were considered individually. Lakes with water types I_A and I_B, located on continuous permafrost and granite bedrock respectively, had a significant split ($p < 0.001$) in relative elevation between lakes dominated by precipitation and geology processes. Lakes of water type I_D showed a defined bimodal distribution, with more dilute lakes located at relatively higher elevation than rock-dominated lakes, but without a significant split ($p = 0.029$) between the two processes.

2.4.3 Influence of regional characteristics on lake nutrient chemistry

Five nutrient water types (N_A-N_E) were identified by the MRT that assessed the correlation between lake regional characteristics and lake nutrient chemistry (TDN, TDP and DOC; Table

2.3). The MRT analysis explained 31% of the variability in nutrient concentrations and identified permafrost conditions, peatland abundance, thickness of overburden and topographic position as primary controls on lake nutrient chemistry (Fig. 2.2b). The MRPPs found all nutrient water types to be significantly different, except for water types N_C and N_D ($p = 0.218$). Total Phosphorus (TP) and Chl-a concentrations were not measured for all lakes and therefore not included in the MRT, but were measured in a sufficient number of lakes to yield median and ranges for each nutrient water type and was used to determine the trophic status of each nutrient water type (Table 2.3).

Nutrient water types N_A and N_B included all lakes located in regions with discontinuous or continuous permafrost. Separation between lakes with N_A and N_B water types was dependent on the regional absence or presence of peatlands, respectively. Lakes with nutrient water type N_A were all located in the SL study area (Fig.2.6), had the lowest nutrient concentrations (Table 2.3) and were identified as oligotrophic and carbon-poor (CCME, 2004). Lakes with nutrient water type N_B were located across the Taiga Plains (LM, NW and FN study areas) and on the northern permafrost-affected edge of the PSQ study area and had moderate nutrient concentrations, classified as mesotrophic and carbon-rich.

Nutrient water types N_C, N_D, and N_E consisted of all lakes located in regions where permafrost was absent. These water types had generally higher nutrient concentrations than lakes with water type N_A and N_B and were further separated based on whether lakes were located in regions with surficial or thin overburden (N_C), in regions with thick overburden and high relative elevation (N_D), or in regions with thick overburden and low relative elevation (N_E). Lakes with water type N_C were all located in the PSQ study area, including locations in both the Boreal Plains and Shield ecozones, while lakes with water type N_D were all situated in the glacial deposition regions of the Boreal Plains (UTL and PSQ). Both water types N_C and N_D were classified as meso-eutrophic with intermediate carbon concentrations. Lakes with water type N_E were located in the UTL study area along with a few lakes in PSQ and had the highest nutrient concentrations, classified as eutrophic, carbon-rich waters.

An ad-hoc analysis was conducted to examine the influence of precipitation vs rock-water dominance on lake water quality across different ion water type classifications to indicate the influence of lake topographic position, isolation and dominance of overland flow. Figure 2.7 shows a boxplot analysis on a subset of lakes classified as dominated either by precipitation or geology for water types I_A, I_B and I_D. Comparing boxplots shows that in regions with continuous permafrost (I_A) and granite bedrock (I_B), lakes dominated by precipitation are significantly ($p < 0.001$) more dilute in nutrient concentrations than geology-dominated lakes. In contrast, lakes dominated by precipitation had significantly greater nutrient concentrations than geology-dominated lakes ($p < 0.001$) in the Taiga and Boreal Plains with waters classified as type I_D.

2.4.4 General chemistry and landscape variability

A PCA was carried out using data from 647 lakes that had complete data coverage of all ion and nutrient variables and all regional landscape characteristics (Fig.2.8). The first four principal components of the PCA explained 54.6% of the data variance, with each of the four first components explaining 20.5%, 15.8%, 9.6% and 8.7%, respectively. The biplot of the two first principal components showed that nutrient concentrations (TDN, TDP and DOC) were associated with the first component while ion concentrations and ion ratios were associated with the second component. The perpendicular loadings of ion and nutrient variables in the PCA indicate a lack of correlation among these groups of variables, which in turn suggest that ion and nutrient chemistry have independent and different correlations with the regional landscape characteristics. Ion variables had positive correlation (> +0.15) with thin overburden and negative correlation (< -0.15) with thick overburden, granite bedrock, continuous permafrost and relative elevation. Conversely, nutrient variables had positive correlation with regional peatland cover, thick overburden, shale bedrock, climate variables MAP, MAT and CMI, and absence of permafrost, while a negative correlation with regional Snow%, presence of continuous permafrost and relative elevation was observed (Table 2.4). It is also noted that several regional landscape characteristics were poorly correlated to either ion or nutrient variables, including several surficial geology deposits (SG-Coarse, -Fine Plain, -Fine Hummocky, -Bedrock and –Till veneer), bedrock deposits (BR-Limestone and -Basalt) and absolute elevation.

2.5 Discussion

This study illustrates the large variability that exists in the hydrochemistry (ions and nutrients) of lakes across the WBF, both between and within the six study areas. While boreal lakes also exhibit variability in hydrochemistry in eastern Canada (Dupont, 1992) and the European Boreal (Henriksen et al., 1998), these regions do not possess the same range in variability as the WBF. Moreover, lakes in the WBF have relatively high ion and nutrient concentrations compared to the ion-dilute, nutrient-poor lakes of these other boreal regions. This difference is most pronounced when compared with the lakes situated on the Canadian Shield. While regional variability in lake hydrochemistry has been assessed in the WBF (Halsey et al., 1997; Pienitz et al., 1997; Kokelj et al., 2009), no previous study has explored the influence of regional landscape characteristics on lake chemistry across the different ecozones. Approximately a third of the variability in lake ion (38%) and nutrient (31%) concentrations could be explained using regional landscape characteristics. It should also be noted that the hydrologic mechanisms controlling lake ion and nutrient chemistry differ strongly and little correlation exists between the two set of chemistry.

2.5.1 Regional controls on lake ion chemistry

Previous research at the local scale has illustrated the influence of geology on lake ion chemistry (Moser et al., 1998; Devito et al., 2005; Brinson, 1993; Bedford, 1999). Results from this study show that this influence extends to the regional scale, as almost all lakes located in the Boreal and Taiga Plains were collected into a single water type (I_D), characterized by thick overburden. Lakes with water type I_D exhibited intermediate EC and ion concentrations, albeit with elevated SO_4^{2-} concentrations compared to the rest of the WBF (Table 2.2). This may be attributed to the lakes location atop thick overburden consisting predominantly of shale deposits, adding to the

SO_4^{2-} concentrations in the local groundwater (Fenton et al. 2003; Paulin et al. 2004; Meybeck et. al, 1989) as well as relatively high SO_4^{2-} concentrations in local meteoric waters (Devito Lab).

This control exerted by thick overburden becomes masked in the presence of continuous permafrost. Lakes located in regions of continuous permafrost had the lowest ion concentrations across the WBF (I_A; Table 2.2). This is because permafrost acts as an impermeable barrier, isolating the lakes from regional groundwater (Walvoord & Kurylyk, 2016; McCauley et al., 2001). Instead, these lakes are likely limited to local, lateral flow in the active surface layers and precipitation as their water sources. Lakes of this water type did possess relatively high Na^+ and Cl^- concentrations. This was due to their location near the coast, attributing to greater NaCl concentrations in local meteoric waters (Reeder et al., 1972). Although almost all of the northernmost lakes were of water type I_A, those situated in the Mackenzie River Delta were of water type I_D. This may be largely due to the contributions of source waters from the Mackenzie River, which provide waters originating from the Taiga and Boreal Plains, and the absence of continuous permafrost in the delta, allowing the lakes to receive regional groundwater inputs. These hydrologic processes give the lakes situated in the delta a water type similar to that of lakes situated further south in the plains. This also supports previous research in the Mackenzie River that low-elevation lakes in the delta are hydrologically well-connected (Tank et al., 2011).

Lakes of water type I_B had dilute ion concentrations as well due to their location in regions with little overburden and granite bedrock. Similar to continuous permafrost, granite bedrock acts as an impermeable barrier, isolating the lakes from regional groundwater (Devito et al., 2005). Lakes of water type I_B therefore possess an ion chemistry composition similar to the local meteoric waters (Li, 2013), as their water sources are local, lateral flow and precipitation-dominated.

Lakes located in regions with little overburden have higher ion concentrations, but also showed greater variability if not located on granite bedrock (I_C, I_E and I_F), reflecting the differences in weathering rates and composition of individual bedrock types. Lakes of water type I_C had dilute ion concentrations due to their location in regions of extensive permafrost with low-weatherable carbonate bedrock (i.e. sandstone and basalt). This can be observed in the low EC of I_C lakes and relatively high $CaCO_3$ concentrations, typical of local groundwater flow (Tóth, 1999; Chebotarev, 1955). While also located in regions of extensive permafrost, lakes of water type I_F possess high ion concentrations, as these lakes were located in regions of high-weatherable carbonate bedrock (i.e. marl; Turner et al., 1982; Sheath et al., 1982; Street-Perrott et al., 1993).

Lakes of water type I_E had high ion concentrations, but exhibited the greatest variability in both ion chemistry and in hydrologic processes influencing the chemistry. These lakes were located in the PSQ area, in a river valley that transitions from the Boreal Plains to the Canadian Shield, and in the SL area, in a valley of carbonate bedrock. The EMA indicated the process of dissolution dominated several lakes within this water type. These lakes were located in both the PSQ and SL areas. In both areas, the dissolution process was caused by large-scale groundwater discharge. In PSQ, these lakes were located in a deep basin-scale discharge area, as sedimentary deposits of the Williston basin expose aquifers to the surface along the Shield's edge, discharging regional-scale groundwater originating from Montana and South Dakota (Bachu & Hitchon, 1996). Similarly, lakes in SL receive groundwater discharge from deep geological formations as a result of bedrock aquifers and aquitards being fractured, faulted and folded, resulting in variable hydraulic properties and creating large-scale groundwater systems (Forster & Smith, 1988; Lopez & Smith, 1995). Unique to PSQ area were waters experiencing both dissolution and subsequent dilution from surface waters. This unique process was due to the location of lakes in the Saskatchewan River Delta. While receiving deep basin-scale discharge, these lakes were likely diluted by surface waters from the Saskatchewan River (Fig.2.3d).

While not identified as a regional control in the MRT analysis on lake ion variability, the influence of lake topographic position was indicated by the difference in ion concentrations between lakes controlled by the processes of precipitation and geology, respectively. The analysis (Fig.2.5) showed that less dilute lakes dominated by the process of water-rock interactions (geology) were located lower in the local landscape than the more dilute lakes dominated by the precipitation process. Specifically, the influence of relative topographic position was most pronounced in areas limited to local flow and precipitation as their water sources, such as I_A and I_B water types. This supports previous research performed on the Canadian Shield (D'Arcy & Carignan, 1997; Hinton et al., 1993), where lake topographic position is a significant control on lake hydrochemistry. Lake topographic position was less influential on lake ion chemistry for lakes located in the low-relief, thick overburden deposits of the Taiga and Boreal Plains (Fig.2.5d). Rather than topographic position, peatland abundance appears to influences lake ion chemistry in these landscapes. The ad-hoc analysis (Fig.2.7, I_D) suggests the dilute ion chemistry of precipitation-dominated lakes is the result of the nutrient-rich, ion-poor inputs from the surrounding peatlands.

In all water types and their correlated landforms, climate was never identified as a significant control on lake ion concentrations. Working at this scale, it was hypothesized that variability in climatic controls (i.e. MAT, MAP, CMI and Snow%) would influence runoff rates. Specifically, it was expected that with increasing runoff rates, water residence time would drop and as a result evaporative concentrations would fall as well, reducing the inflow of ion-rich water (Table 2.1).

Analyses (MRT and PCA) showed regional climatic controls did not influence lake ion concentrations.

2.5.2 Regional controls on lake nutrient chemistry

Not all of the landscape controls on lake nutrient concentrations identified at the regional scale were intuitive to earlier predictions. An example of this was the negative correlation of permafrost with lake nutrient concentrations. This result is contradictory to results of previous research at local and meso scales (Walvoord & Striegl, 2007; Kokelj et al., 2009) which suggest that the presence of permafrost reduces groundwater contributions, leading flow paths to be located predominantly in near-surface soil layers, rich in organics. At the regional scale, increasing permafrost reduces lake nutrient concentrations, because permafrost serves as a proxy for overall landscape productivity. With increasing permafrost formation, there is a simultaneous decrease in temperature (MAT) and increase in relative snowfall (Snow%), reducing the microbial activity, nutrient turnover rate of nutrients and summer runoff, limiting the inflow of nutrient-rich waters into lakes (Schuur et al., 2007 & 2009; Routh et al., 2014, Vitt et al, 1999).

In areas of permafrost, peatland abundance served as an additional control on lake nutrient concentrations. These results fall in line with previous local-scale research (Prepas et al., 2001; Pienitz et al., 1996; Moser et al., 1998), suggesting peatlands serve as nutrient-sources to lakes. The lack of a relationship between peatland abundance and lake nutrient concentrations in areas absent of permafrost may be due to the relatively high abundance of peatlands in these areas. Since most lakes in these areas have a large regional abundance of peatlands, it is the connectivity of lakes to these peatlands that determines their water quality. Lake topographic position therefore influenced nutrient concentrations, due to lakes located higher in the landscape becoming more isolated or limited to local flow and precipitation as water sources and receiving only limited inflow from surrounding peatlands (Plach et al., 2016; Tóth, 1999; Winter, 2001).

While lake topographic position was an important control in areas of thick overburden, this was not the case in areas of thin overburden. Rather, lakes on thin overburden (N_C) exhibited nutrient concentrations similar to lakes located at high position on thick overburden (N_D). This thin overburden limits lakes' water sources to precipitation, local lateral flow and regional bedrock groundwater discharge. As a result, N_C lakes atop thin overburden also lack an integrated peatland-flow network, similar to N_D lakes, resulting in relatively limited contributions from the surrounding peatlands to the lakes' nutrient loadings.

Although the depth of overburden appeared to be related lake nutrient concentration, contrary to local-scale research (Plach et al., 2016; Moser et al., 1998), the specific type of surficial geology was expected not correlated to lake nutrient concentrations of water types. This lack of influence from surficial geology may be a result of the coarse scale at which these data were collected. Since the surficial geology dataset provided little internal variability within study areas, this dataset may have provided insufficient resolution to capture the effects of the different deposits' permeability, flow rate and residence time.

2.5.3 Cross-scale interactions and regional vs local controls

Working at the scale of the WBF provided the opportunity to assess the possibility of cross-scale interactions (CSIs) between regional controls for the first time. In doing so, this study highlighted the influence of precipitation on the ion composition of lakes, as lakes located in the vicinity of the coastline had relatively higher NaCl concentrations (I_A, Table 2.2). Moving deeper into the continent, into the Taiga and Boreal Plains, precipitation becomes poor in NaCl and has relatively higher $MgSO_4$ concentrations. This pattern of ion composition is reflected in the lakes that were precipitation-dominated as well, possessing relatively lower concentrations in NaCl, but increasing $MgSO_4$ concentrations for waters of type I_D. Management strategies and future EMAs therefore need to consider the strong spatial variability in precipitation encountered across the WBF when assessing the ion composition of surface waters. While Tóth (1999) presents the transition in lake ion composition as a result of increasing flow path lengths, the EMA shown here demonstrates that spatial variability in the precipitation's ion chemistry needs to be accounted for as well.

A second CSI identified was the influence of lake topographic position between different water types. While previous research has stated the importance of local topography on lake hydrochemistry (D'Arcy & Carignan, 1997; Hinton et al., 1993; Winter, 2000 & 2001), these results suggest this is true only in areas of low hydraulic conductivity (e.g. granite bedrock or continuous permafrost). In the low-relief, thick deposits of the Taiga and Boreal Plains, topographic position does not have a significant influence on lake ion chemistry, however the relative contributions of peatlands play a larger role.

Additionally, surveying the combined effects of local and regional landscape characteristics presented instances where certain characteristics nullified the effects of other characteristics. Bedrock geology had a significant influence in lake ion chemistry when covered by little overburden, but in areas of thick overburden this influence of bedrock on lake ion chemistry becomes heavily reduced. In turn, the effects of thick overburden became reduced in the presence of continuous permafrost, with permafrost acting as an impermeable barrier that isolates lakes from regional groundwater.

2.5.4 Ion controls vs nutrient controls

This study suggests that the regional controls on lake ion concentrations differ strongly from the regional controls influencing lake nutrient loadings. Specifically, while lake ion chemistry is controlled by lake-groundwater connectivity (local vs regional) and the geologic settings (carbonate vs granite bedrock), lake nutrients are controlled by organic soils and any runoff they generate. These controls and processes contributing to higher ion and nutrient concentrations are not only distinct from one another, but on occasions counteract each other (i.e. lakes in areas of thin overburden possess high ion concentrations, but low nutrient concentrations due to groundwater-buffering). Although mechanisms stimulating higher ion or nutrient concentrations may counteract one another, processes promoting low concentrations in ions or nutrients may stimulate one another. Specifically, isolated lakes limited to local flow and precipitation exhibited both low ion and low nutrient concentrations when located in areas of low hydraulic conductivity (i.e. granite bedrock or continuous permafrost).

2.5.5 Management implications

As little regional-scale lake monitoring is performed across the WBF, this research provides an important insight in the baseline natural variability of lake ion and nutrient chemistry. The results of this study show that, rather than relying on Canadian ecozones, good management should assess the regional hydrologic landscape a lake is situated in to determine if it experienced disturbance. Additionally, the potential hydrologic disturbance of a lake may be determined from the lake’s deviation from the regional-scale baseline chemistry of the hydrologic landscape the lake is situated in (Table 2.2 and 2.3).

Approximately one third of this variability in lake ion and nutrient concentrations can be explained using regional landscape characteristics. These results illustrate that there are profound differences in the hydrologic processes controlling lake chemistry across the WBF. By assessing the variability in lake hydrochemistry at this scale, this study also illustrates that this variability is much greater than in other boreal regions, such as eastern Canada and northern Europe (Dupont, 1992; Henriksen et al., 1998). The results demonstrate that not all boreal lakes are ion-dilute or nutrient-poor as previously claimed (Henriksen et al., 1998; Yang et al., 2015). Additionally, by working at this scale, the influence of regional-scale processes may not act uniformly on lake hydrochemistry, which provides evidence for the existence of CSIs in the WBF.

Although regional landscape characteristics were insufficient to address all variability in lake hydrochemistry, results show that these characteristics provide a better outline for the natural lake variability than the Canadian ecozones. The identified water types also provide insight into the regional ecosystem function and quality of lakes, as well as their sensitivity to disturbances. The results of the EMA also showed that the spatial variability in the chemistry of source waters (i.e. precipitation, dissolution) also should be considered by management and research assessing potential disturbances in boreal lakes. As climate change is expected to increase permafrost thaw (Mackay, 1995; Wolfeet et al., 2000), lakes in areas of permafrost can be expected to experience greater landscape productivity, expressed by lowering the lakes' water quality and increasing their nutrient concentrations. Additionally, permafrost thaw is expected to increase connectivity of lakes to regional groundwater, reducing sensitivity to local landscape disturbances and resulting in increased ion concentrations (Seigal, 1988; Soranno et al., 2014).

2.6 Conclusion

This study highlights the spatial variability in hydrochemistry of the WBF and demonstrates these lakes have much higher ion and nutrient concentrations than other boreal areas. While regional characteristics do not provide sufficient explanatory power to address local variability in lake hydrochemistry, they are capable of explaining broad differences in lake chemistry and help guide regional-scale management by delineating hydrologic landscapes with distinct chemistry signatures. Due to the complex interactions between geology, peatlands, climate and topography, specific local data are required to guide proper adaptive management of individual lakes.

This study also illustrates that distinct processes influence ion and nutrient chemistry. While lakes limited to local flow and precipitation exhibited both low ion and low nutrient concentrations, results showed that the mechanisms stimulating higher ion or nutrient concentrations strongly differed and often counteracted each other. Research and surveys assessing lake ion chemistry will therefore provide very little insight in lake nutrient loadings, and vice versa.

As a key aspect of adaptive risk management, there is a need for modeling and monitoring studies that assess cross-scale effects of landscape characteristics (Linkov et al., 2006; Walters, 1997). Results showed that decision makers must consider the complex interactions occurring across regions of the WBF and cannot assume hydrologic processes act uniformly across these region. Rather, proper management needs to assess whether lakes deviate from regional hydrochemistry baselines (Table 2.2 and 2.3) before assuming hydrologic processes have been disturbed.

Tables and Figures

Table 2.1: Regional characteristics extracted for lakes at 6 sampling locations across the Western Boreal Forest. Categories and ranges in variability, and predictions and motivations supporting variable selection. Abbreviations within brackets indicate names used for PCA (Fig.2.8).

Regional Characteristics	Categories/Range	Predictions/Motivation
Climate		
Mean Annual Temperature[1] (MAT)	-9.5 – 1.5°C	Lower MAT corresponds with higher permafrost cover, limiting groundwater flow to the active surface layers. Lower MAT also reduces microbial activity, reducing nutrient turnover rates. Low MAT causes lake chemistry to more closely resemble precipitation chemistry (i.e. poor in ions and nutrients).
Mean Annual Precipitation[2] (MAP)	216 – 502 mm	The precipitation's ion composition contributes to the composition of the flow system. Increasing MAP leads to dominance of shallow and faster flow paths, poor in ions but rich in nutrients.
Snowfall Contribution[2,a] (Snow%)	24 – 60%	Higher snowfall contribution corresponds with greater snow melt, giving a higher probability for overland flow, shifting dominant flow from summer to spring. Increasing overland flow leads to decreasing ion inflow but increasing nutrient inflow.
Climate Moisture Index[2,b] (P-PET)	-240 – -40 mm	Increasing moisture levels increase runoff availability. Higher runoff rates correspond with low water residence time and lower evaporative concentrations, decreasing ion inflow but increasing nutrient inflow.
Permafrost[3] (PF)	Continuous (+90%), extensive (90-50%), sporadic (50-10%), isolated (10-0%), absent (0%)	Greater PF presence limits groundwater to local lateral flow in the active surface layers, reducing ion inflow. Additionally, greater PF presence is correlated to decreasing landscape productivity, reducing nutrient inflow. High PF presence causes lakes to resemble precipitation chemistry more.
Landscape		
Bedrock Type[4] (BR)	Granite, Sandstone, Basalt, Shale, Limestone	Increasing permeability and weathering rate correspond with increasing ion inflow. Soluble sedimentary BR contribute to greater nutrient inflows than granite BR.
Overburden Thickness[4] (OT)	Surficial (0 – 2 m), Thin (2-10 m), Thick (>10 m)	Greater OT masks the effects of BR composition on ion concentrations and composition. Greater OT also corresponds with thicker peatland formations, increasing nutrient inflow.
Surficial Geology[5] (SG)	Bedrock, Till veneer, Coarse, Fine hummocky, Fine plain	Groundwater flows through fine deposits more slowly and experiences greater weathering, while coarse deposits experience greater subsurface flow at a larger scale but with low weathering rates. Fine deposits therefore exhibit greater ion concentrations. Peatland abundance is greater atop fine deposits due to low drainage effects, allowing a greater inflow of nutrients.
Peatland Area[6]	0 – 90%	Greater peatland abundance increases inflow of ion-poor, nutrient-rich surface water, due to their interaction with organic layers.
Elevation[4]	60 – 1650 m	Mountainous lakes exhibit similar hydrochemistry to precipitation due steeper landscapes, increasing the rate of runoff and lowering residence time.
Relative Elevation[4]	0.00 – 1.00	Lakes located higher in the landscape are more isolated or limited to local flow, are more precipitation-fed and have more dilute ion inflows.

[1] Hijmans, R. et al., 2005
[2] National Ecological Framework Canada
[3] Heginbottom et al., 1995
[4] Provincial Geological Surveys
[5] Fulton et al., 1995
[6] Tarnocai et al., 2011

[a] Snowfall contribution was calculated as the percentage MAP in form of snowfall

[b] Climate Moisture Index was calculated as the difference between Mean Annual Precipitation and Mean Annual Penman Potential Evaporation

Table 2.2: Ion signatures of each of the six water types identified by the multivariate regression tree regressing regional characteristics (Table 2.1) on lake ion chemistry (Fig.2.2a). Values outside brackets indicate medians, values within brackets the 5-95% range. Subscript letters identify water types in order of increasing median EC for comparison in the graphical plot of the lakes' ion ratios (Fig.2.4).

	I_A	I_B	I_C	I_D	I_E	I_F
EC (µS cm^{-1})	85 (30 – 250)	100 (10 – 110)	110 (35 – 210)	170 (40 – 570)	400 (100 – 10000)	1050 (950 – 2100)
Na (mg L^{-1})	6 (1 – 25)	2 (0 – 15)	2 (1 – 10)	3 (1 – 30)	10 (1 – 13000)	2 (1 – 10)
Cl (mg L^{-1})	4 (1 – 15)	0.3 (0 – 5)	1 (0 – 10)	0.2 (0 – 4)	2 (0 – 200)	0 (0 – 2)
Mg (mg L^{-1})	7 (1 – 20)	4 (0 – 20)	4 (1 – 25)	7 (1 – 25)	20 (3 – 200)	50 (5 – 80)
SO_4 (mg L^{-1})	5 (1 – 45)	2 (0 – 75)	5 (1 – 100)	10 (1 – 140)	5 (0 – 800)	80 (30 – 95)
K (mg L^{-1})	0 (0 – 1)	1 (0 – 3)	0 (0 – 5)	1 (0 – 8)	3 (0 – 55)	2 (1 – 10)
Ca (mg L^{-1})	10 (2 – 40)	14 (1 – 45)	15 (2 – 65)	25 (5 – 60)	20 (9 – 170)	50 (25 – 600)
HCO_3 (mg L^{-1})	35 (5 – 100)	50 (5 – 110)	75 (15 – 190)	85 (15 – 220)	150 (40 – 300)	2300 (700 – 4300)
pH	7.3 (5.6 – 8.4)	7.9 (6.3 – 8.6)	7.8 (6.6 – 9.2)	7.9 (6.6 – 9.6)	8.4 (7.5 – 9.7)	8.2 (7.5 – 8.8)
Na/ (Na+Ca)	0.38 (0.13 – 0.70)	0.21 (0.03 – 0.36)	0.07 (0.01 – 0.27)	0.11 (0.01 – 0.29)	0.43 (0.14 – 0.92)	0.08 (0.04 – 0.14)
Cl/ (Cl+HCO_3)	0.12 (0.05 – 0.31)	0.01 (0.00 – 0.04)	0.00 (0.00 – 0.03)	0.00 (0.00 – 0.06)	0.01 (0.00 – 0.97)	0.00 (0.00 – 0.03)
SO_4/ (SO_4+HCO_3)	0.04 (0.00 – 0.26)	0.05 (0.01 – 0.31)	0.08 (0.01 – 0.36)	0.15 (0.01 – 0.65)	0.03 (0.00 – 0.77)	0.04 (0.02 – 0.06)
Sample Size	**110**	**69**	**17**	**458**	**104**	**4**

Table 2.3: Nutrient signatures of each of the six water types identified by the multivariate regression tree regressing regional characteristics (Table 2.1) on lake nutrient chemistry (Fig.2.2b). Values outside brackets indicate medians, values within brackets the 5-95% range. Subscript letters identify water types in order of trophic status, determined by median nutrient concentrations. While not sampled for all lakes, additional nutrient signatures of TN, NO_2+NO_3, TP, SRP and Chl-a not implemented in the analyses are included for each water type.

	N_A	N_B	N_C	N_D	N_E
Complete lake coverage					
TDN (µg L^{-1})	370	850	1400	1200	2300
	(120 – 1300)	(470 – 2200)	(480 – 3100)	(470– 5100)	(900 – 7100)
TDP (µg L^{-1})	5	10	15	15	35
	(2 – 25)	(4 – 25)	(5 – 30)	(4 – 45)	(7 – 120)
DOC (mg L^{-1})	10	30	30	25	45
	(3 – 45)	(17 – 90)	(14 – 60)	(9 – 50)	(20 – 110)
Sample Size	**99**	**322**	**112**	**79**	**88**
Incomplete lake coverage					
TN (µg L^{-1})	480	900	1500	1400	2300
	(170 – 840)	(550 – 2100)	(650 – 3900)	(620 – 4500)	(820 – 8600)
NO_2 + NO_3 (µg L^{-1})	2	8	10	7	12
	(1 – 10)	(4 – 40)	(5 – 50)	(4 – 30)	(5 – 50)
TP (µg L^{-1})	10	20	35	35	75
	(3 – 35)	(7 – 87)	(15 – 180)	(15 – 180)	(20– 430)
SRP (µg L^{-1})	2	3	6	5	5
	(0.2 – 4)	(0.4 – 6)	(1 – 15)	(1 – 35)	(2 – 65)
Chl-a (µg L^{-1})	2	4	9	12	30
	(1 – 5)	(1 – 7)	(4 – 15)	(5 – 30)	(2 – 70)

Table 2.4: Summary of the PCA loading values for all statistical variables used in the PCA (Fig.2.8) for the first four principal components comparing landscape characteristics, lake ion and nutrient chemistry.

	PC1 (20.5%)	**PC2 (15.8%)**	**PC3 (9.6%)**	**PC4 (8.7%)**
TDN	0.19900	-0.14657	-0.18941	-0.03368
TDP	0.24311	-0.04769	-0.17238	-0.07943
DOC	0.24930	-0.14278	-0.16944	0.15525
EC	0.15289	0.25674	-0.20051	-0.12417
Na	0.14904	0.22311	-0.14371	-0.03624
Cl	0.09248	0.17913	-0.23618	-0.00367
Mg	0.10783	0.20012	-0.18946	-0.09670
SO_4	0.08726	0.19874	-0.00584	-0.12114
Ca	0.09874	0.19200	-0.16781	-0.01589
HCO_3	0.14994	0.21259	0.01568	-0.04096
K	0.13975	0.22118	-0.12731	-0.07291
Na/(Na+Ca)	0.16274	0.22856	-0.08413	-0.06941
$Cl/(Cl+HCO_3)$	0.14914	0.18955	-0.16885	-0.00127
$SO_4/(SO_4+HCO_3)$	0.10364	0.23159	0.03519	-0.14001
pH	0.14813	0.11634	-0.17412	0.03344
MAT	0.24569	-0.08588	-0.19456	-0.15454
MAP	0.25184	-0.10957	-0.18954	0.04330
P-PET	0.18426	-0.14705	-0.22045	0.19073
Snow%	-0.25671	0.08193	0.09842	-0.05125
PF-Continuous	-0.18956	-0.17894	0.06148	0.07635
PF-Extensive	-0.10456	0.14051	-0.07681	0.24743
PF-Sporadic	-0.06471	0.12580	-0.07711	-0.32844
PF-Isolated	0.01640	0.06127	-0.02355	0.15927
PF-Absent	0.25056	-0.12580	0.05984	-0.05677
BR-Granite	-0.14897	-0.20114	-0.20145	-0.22589
BR-Sandstone	-0.13046	0.01566	0.05411	0.25186
BR-Basalt	-0.02145	0.05700	0.06181	-0.11893
BR-Shale	0.18646	-0.14238	-0.20118	-0.17390
BR-Limestone	0.01945	0.07586	-0.01843	0.23588
SG-Bedrock	-0.01567	0.03519	-0.01994	0.01094
SG-TillVeneer	-0.05461	0.06119	0.16781	0.11302
SG-FinePlain	0.06189	-0.01023	0.11540	-0.14901
SG-FineHummocky	-0.00454	-0.08431	-0.04187	0.01950
SG-Coarse	-0.01346	0.08941	-0.06483	0.06865
OT-Surficial	0.03687	-0.04589	0.10894	-0.15021
OT-Thin	0.09716	0.22357	-0.00458	0.22099
OT-Thick	0.19054	-0.20581	-0.10245	-0.12503
Peatland	0.26117	-0.14218	-0.23987	0.30415
Elevation	0.05046	-0.04984	0.05183	-0.48188
Relative Elevation	-0.17087	-0.15607	-0.35187	-0.24807

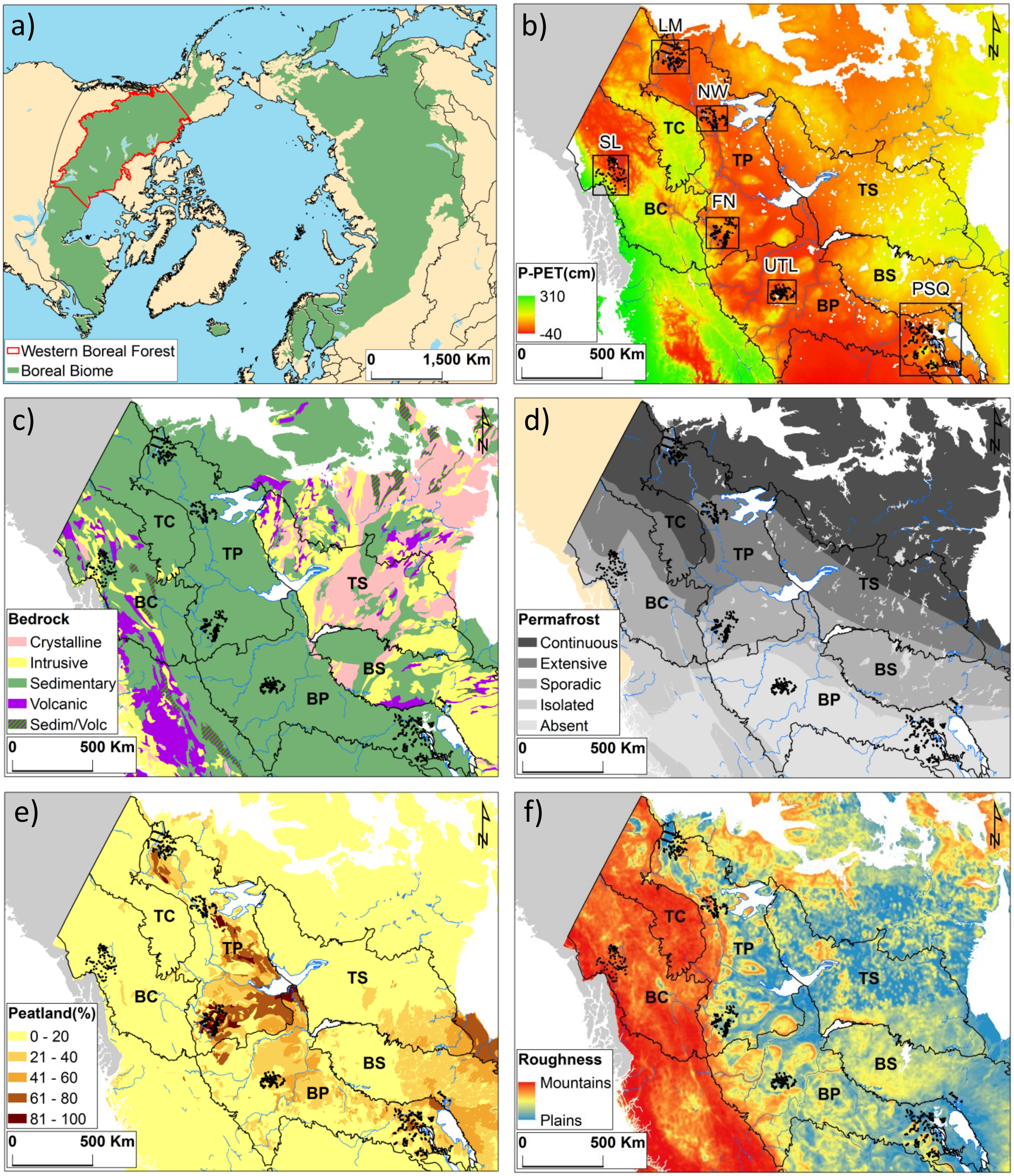

Fig.2.1: Distribution of key regional characteristics on the Western Boreal Forest (WBF) and location of lakes from the 6 sampling locations. Panel a) illustrates the WBF's location within the Northern Boreal region (Brandt et al., 2013). Remaining panels show locations of sampled lakes, with respect to the WBF's variability in b) Moisture (Hogg et al., 1997), c) Bedrock geology (Chorlton, 2007), d) Permafrost (Heginbottom et al., 1995), e) Peatland Abundance (Tarnocai et al., 2011), and f) Roughness (Gruber, 2012). Panels b-f illustrate Canadian ecozones (TC=Taiga Cordillera, TP=Taiga Plains, TS=Taiga Shield, BC= Boreal Cordillera, BP=Boreal Plain & BS=Boreal Shield). Panel b also presents the distribution of the sample areas (LM=Lower Mackenzie, NW=Norman Wells, SL=Southern Lakes, FN=Fort Nelson, UTL=Utikuma, PSQ=Pasquia).

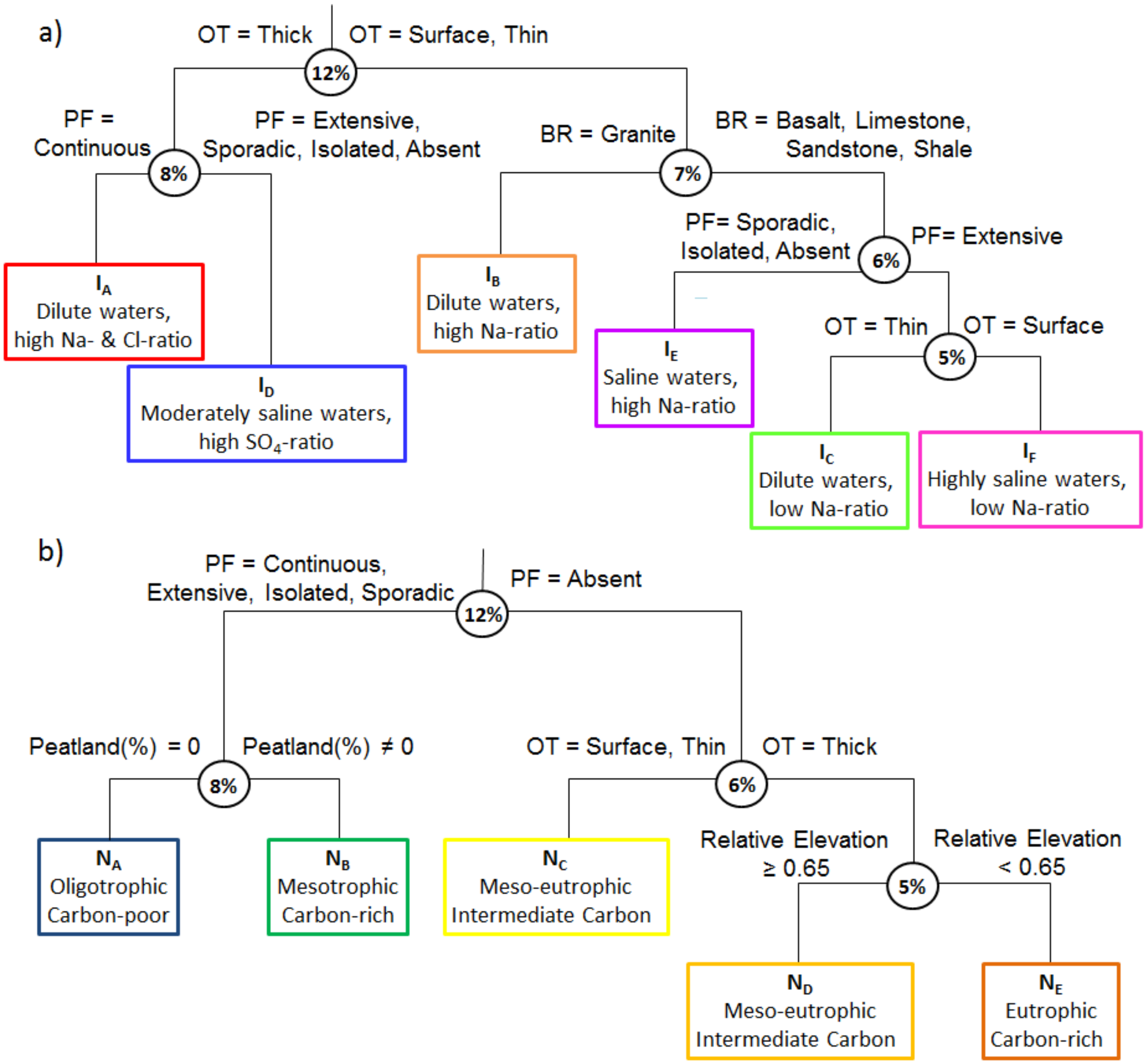

Fig.2.2: Multivariate Regression Tree (MRT) results regressing regional landscape characteristics and the variability in the lakes' a) ion concentrations and ratios, and b) nutrient concentrations. Values in circles indicate the percentage variability explained by each branch of the MRT. Saline waters indicate median EC above 150 $\mu S\ cm^{-1}$, dilute waters below 150 $\mu S\ cm^{-1}$. Trophic statuses were determined using guidelines of the Canadian Council of Ministers of the Environment, (2004). Carbon-rich waters have median DOC concentrations of 30 $mg\ L^{-1}$ or higher, carbon-poor of 10 $mg\ L^{-1}$ or below.

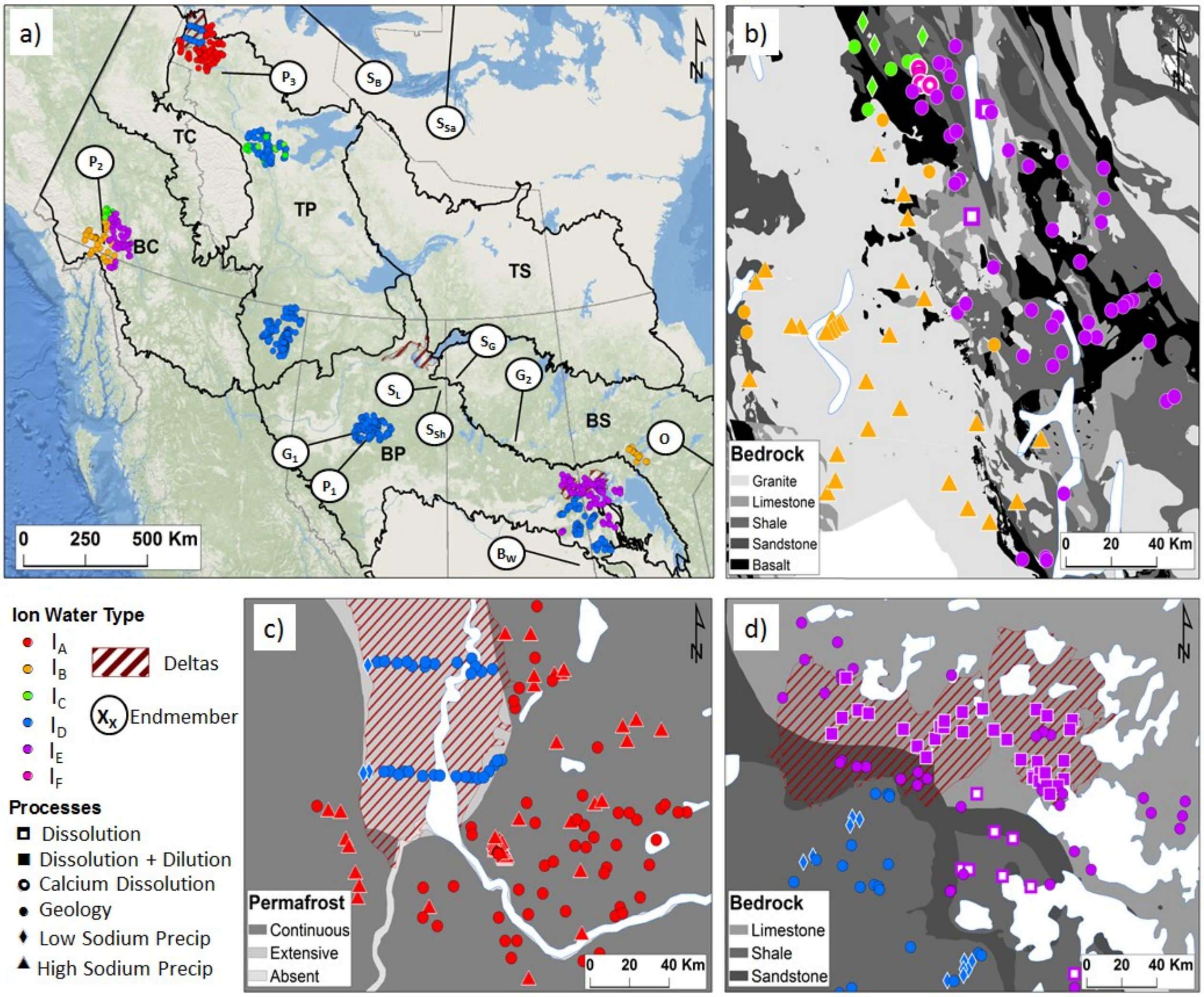

Fig.2.3: Spatial extent and ion lake water types as classified by the MRT (Fig.2.2a) and processes illustrated in the EMA (Fig.2.4). Black borders indicate the national classification of ecozones, and dashed brown borders the extent of the three major delta's in the WBF: Mackenzie, Peace-Athabasca, and Saskatchewan rivers. The location of all end members used in the EMA is presented in panel a). Additional panels show the unique processes occurring at: b) Southern Lakes (SL), c) Mackenzie River Delta (LM), and d) Saskatchewan River Delta (PSQ) sample areas.

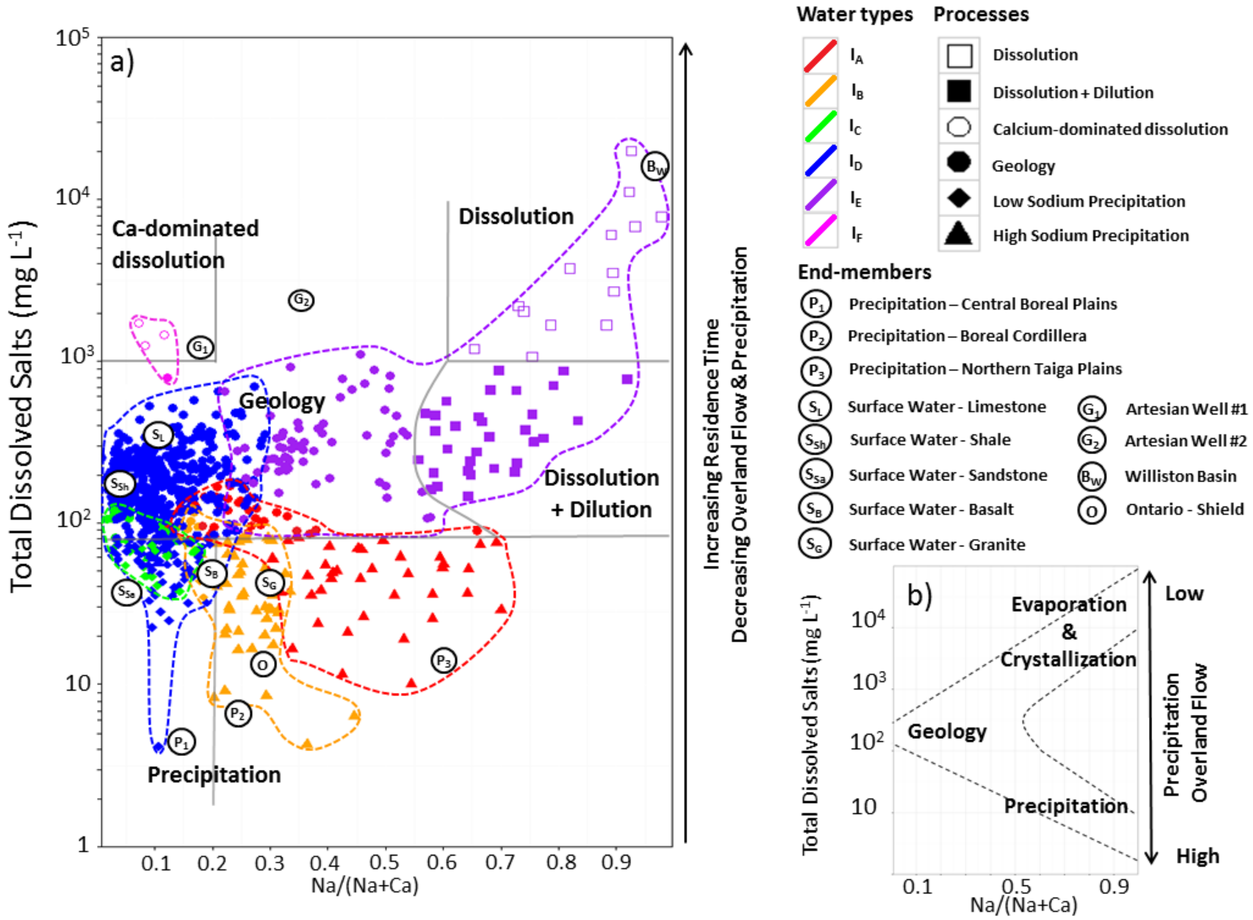

Fig.2.4: Graphical plot of variation in lake water ratio of Na/(Na + Ca) concentrations as a function of TDS to infer the driving processes of the ion water types identified by MRT (Fig.2.2a) based on Gibbs (1970). a) Lake symbols are colored based on ion water types (Table 2.2), and grey lines indicate the transition between processes controlling ion concentration and composition. Example end-members were added to highlight the origin of water, including: groundwater from artesian wells in the UTL sample area, Alberta (G$_1$; Devito et al., 2016) and Saskatchewan (G$_2$; Fortin et al., 1991), deep groundwater from the Williston Basin (B$_W$; Iampen & Rostron, 2000), surface water located atop the Canadian Shield, Ontario (O; Palmer et al., 2011), surface waters located on different geological deposits: Limestone, Shale and Granite (S$_L$, S$_{Sh}$ and S$_G$; Moser et al., 1998), Basalt (S$_B$; Antoniades et al., 2003), and Sandstone (S$_{Sa}$; Lim et al., 2001), precipitation data from the central Boreal Plains (P$_1$; Devito Lab), the Boreal Cordillera (P$_2$; Li, 2013), and the northern Taiga Plains (P$_3$; Reeder et al., 1972). b) Graphical plot of Gibbs' original outline and processes (1970).

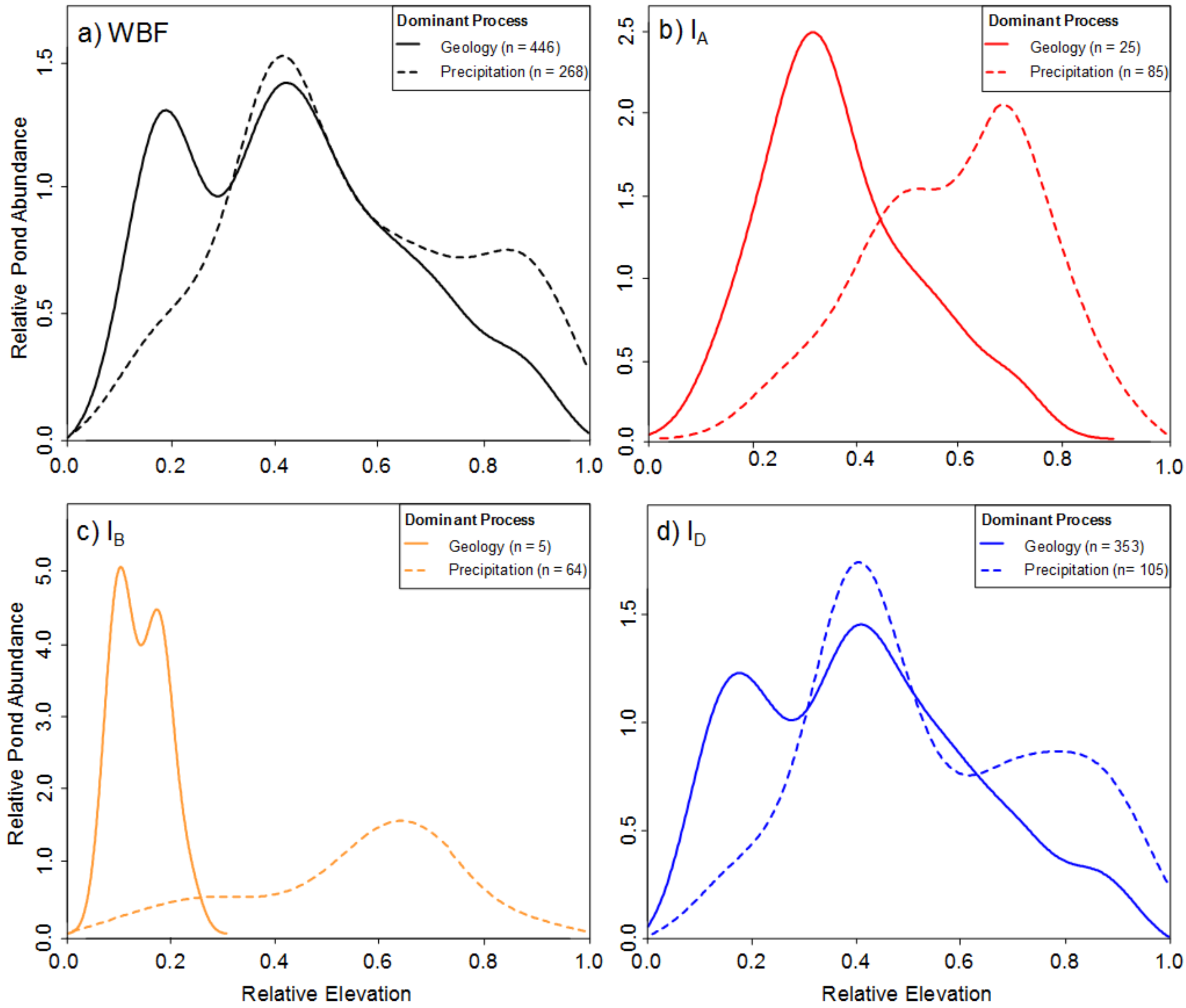

Fig.2.5: Relative abundance (Kernel-density) of lakes across relative elevation, identified by lake TDS to indicate the predominance of precipitation vs rock-water interactions as source waters (Fig.2.4). Relative abundance was determined for a) all lakes sampled across the WBF, and the separate ion water types: b) I_A (Continuous Permafrost), c) I_B (Granite Bedrock) and d) I_D (Boreal and Taiga Plains) (Fig.2.2a).

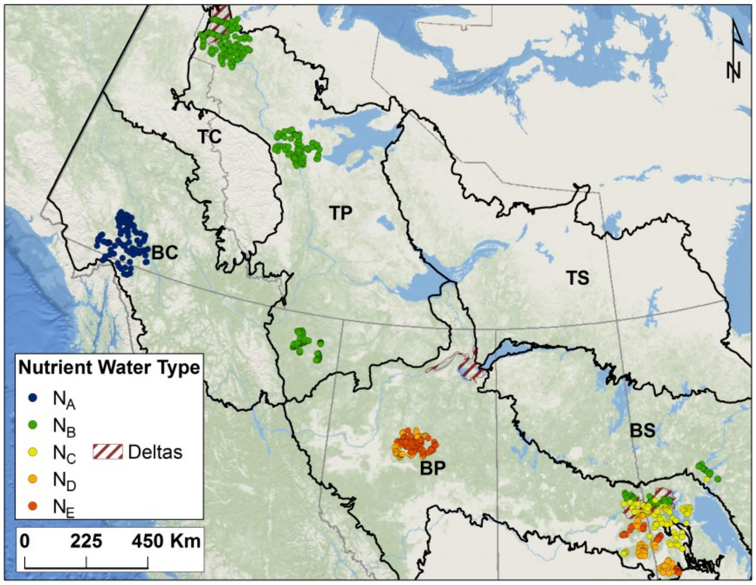

Fig.2.6: Spatial extent and nutrient lake water types as classified by the MRT (Fig.2.2b). Black borders indicate the national classification of ecozones, and dashed brown borders the extent of the three major delta's in the WBF: Mackenzie, Peace-Athabasca, and Saskatchewan rivers.

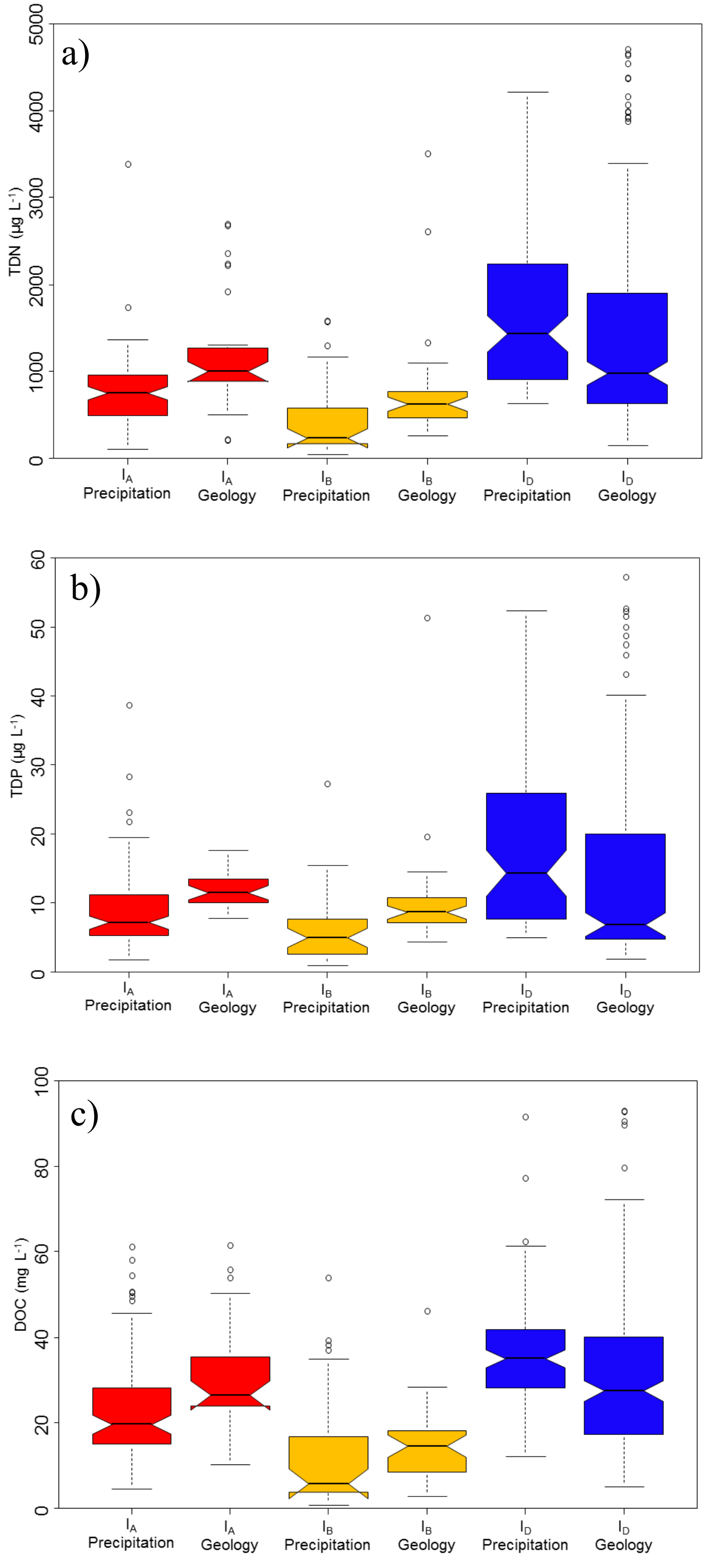

Fig.2.7: Boxplots of nutrient concentrations of a) TDN, b) TDP, and c) DOC on a subset of lakes classified as dominated either by precipitation or geology (Fig.2.4) for lakes classified by ion water types I_A (Continuous Permafrost), I_B (Granite Bedrock) and I_D (Boreal and Taiga Plains).

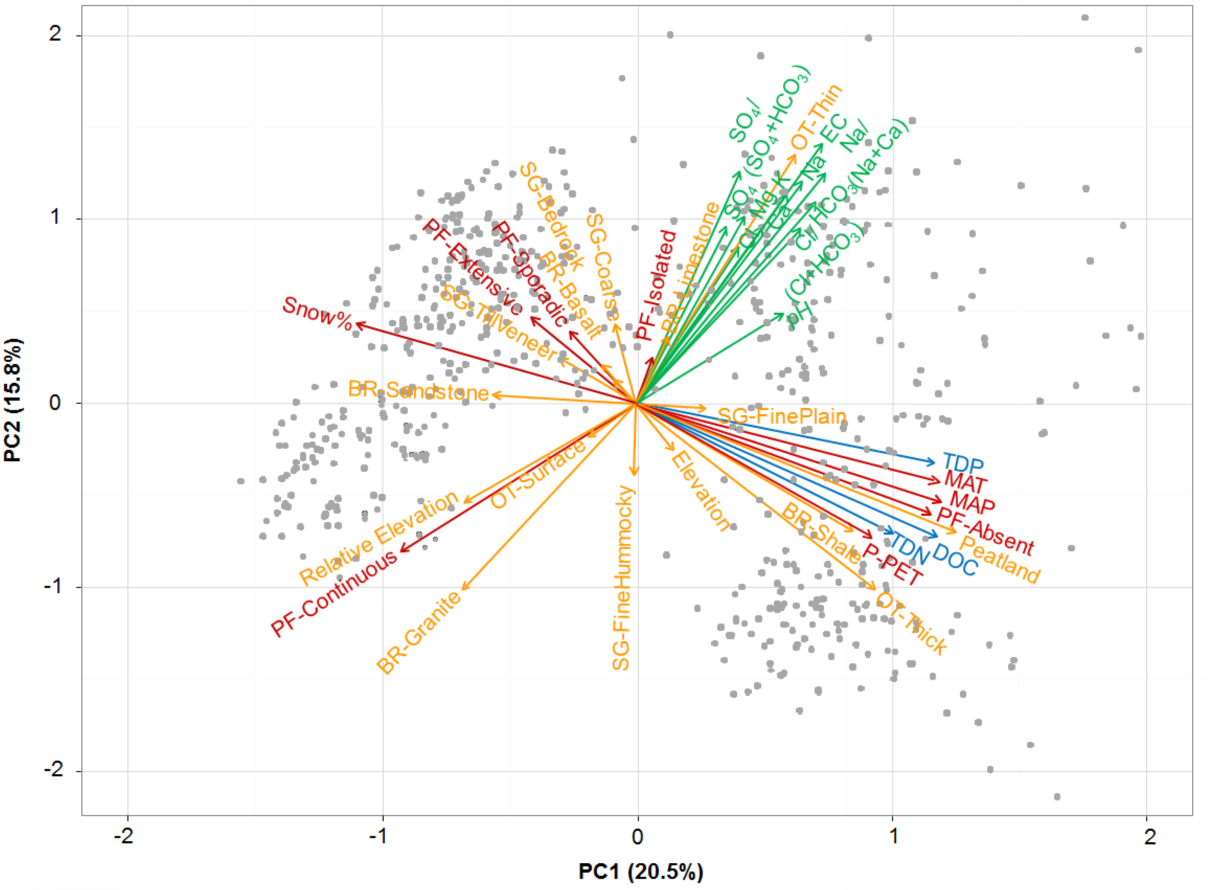

Fig.2.8: The biplot of the scores and arrows for the first two principal components (PC1 20.5% and PC2 15.8%) of all sampled lakes' hydrochemistry (ions in green, nutrients in blue) and their correlation with landscape characteristics (climate in red, landscape in orange). The length of their respective arrows illustrates the component loadings of the indices. Abbreviations are as presented in Table 2.1: MAT=Mean Annual Temperature, MAP=Mean Annual Precipitation, Snow%=Snowfall Contribution, P–PET=Climate Moisture Index (CMI), PF=Permafrost, BR=Bedrock Geology, OT=Overburden Thickness, SG=Surficial Geology.

Supplemental Appendix

Table S2.1: Mean, minimum and maximum of all hydrochemistry variables captured by the WBF lake sampling.

Hydrochemistry variable	Units	N	Average	Min	Max
Conductivity	$\mu S\ cm^{-1}$	817	374	4	34900
Ca	$mg\ L^{-1}$	814	27	1	526
Mg	$mg\ L^{-1}$	814	15	0	880
Cl	$mg\ L^{-1}$	807	50	0	10965
SO_4	$mg\ L^{-1}$	781	45	0	4916
Na	$mg\ L^{-1}$	814	34	0	6544
K	$mg\ L^{-1}$	814	3	0	190
HCO_3	$mg\ L^{-1}$	814	101	2	483
pH		814	8.0	4.8	10.1
TDN	$\mu g\ L^{-1}$	718	1394	43	10629
TDP	$\mu g\ L^{-1}$	768	15	1	284
DOC	$mg\ L^{-1}$	814	33	1	160

Table S2.2: Collection of the bedrock formations captured by the lake sampling across the WBF and their conversion to Bedrock Types.

Formation Name	**Unit Code and Time of Deposition**	**Lithology**	**Bedrock Type**	**Source**
Unspecified Fort St. John Group	(lK) lower Cretaceous	Siltstone, mudstone, shale fine clastic sedimentary rocks	Shale	Cui et al., 2016
Riding Mountain Formation	(2uK) upper Cretaceous	Soft greenish bentonitic shale	Shale	Viljoen et al., 2016
Undifferentiated Pleistocene and Holocene deposits	(Q) Quaternary	Silt, minor sand and gravel	Shale	Cui et al., 2016
Second White Specks Formation	(uK) upper Cretaceous	Shale and siltstone	Shale	Prior et al., 2013
Badheart Formation	(lK) lower Cretaceous	Siltstone, mudstone, shale fine clastic sedimentary rocks	Shale	Cui et al., 2016
Fish Scales and Belle Fourche Formations	(uK) upper Cretaceous	Shale, siltstone, and bioclastic sandstone	Shale	Prior et al., 2013
Richthofen Formation	(lJ) lower Jurassic	Shale, sandstone	Shale	Gordey & Makepeace, 2003
Slater River Formation	(uK) upper Cretaceous	Sandstone, shale, mudstone	Shale	Fallas, 2011b
Puskwaskau Formation	(uK) upper Cretaceous	Shale and siltstone	Shale	Prior et al., 2013
East Fork Formation	(KT) Cretacious and Tertiary	Mudstone, shale, sandstone	Shale	Fallas, 2011b
Dawson Bay Formation	(mD) middle Devonian	Basal red shale, Bitumous dolomite and high calcium micrimitic limestone	Shale	Viljoen et al., 2016
Lea Park Formation	(uK) upper Cretaceous	Shale and mudstone	Shale	Prior et al., 2013
Souris River Formation	(uD) upper Devonian	Basal red shale, Bitumous dolomite and high calcium micrimitic limestone	Shale	Viljoen et al., 2016
Horton River Formation	(lK) lower Cretaceous	Shale, minor bentonite	Shale	Cui et al., 2016
Shaftesbury Formation (upper)	(uK) upper Cretaceous	Shale and mudstone	Shale	Cui et al., 2016
Westgate Formation	(lK) lower Cretaceous	Shale and mudstone	Shale	MacDonald & Slimmon, 1999
Cache Creek Formation	(Tr) Triassic	Clastic shale and sandstone	Shale	Gordey & Makepeace, 2003
Favel Formation	(1uK) upper Cretaceous	Calcareous speckled shale, minor limestone, oil shale. Carbonaceous shale	Shale	Viljoen et al., 2016
Unspecified Colorado Group	(1uK) upper Cretaceous	Siltstone, shale, sandstone, conglomerate	Shale	MacDonald & Slimmon, 1999
Horn River Formation	(lmD) lower and middle Devonian	Shale, limestone (marine)	Shale	Fallas et al., 2011
Sully Formation	(lK) lower Cretaceous	Siltstone, mudstone, shale fine clastic sedimentary rocks	Shale	MacDonald & Slimmon, 1999
Shaftesbury Formation (lower)	(uK) upper Cretaceous	Shale and mudstone	Shale	Prior et al., 2013

Formation Name	Unit Code and Time of Deposition	Lithology	Bedrock Type	Source
Kaskapau Formation	(uK) upper Cretaceous	Shale and siltstone	Shale	Prior et al., 2013
Imperial Formation	(uD) upper Devonian	Sandstone, minor shale and siltsone	Sandstone	Cook & Aiken, 1974
Summit Creek Formation	(KT) Cretacious and Tertiary	Sandstone, shale, coal, tuff	Sandstone	Fallas, 2011b
Mahony Lake Formation	(lK) lower Cretaceous	Sandstone, shale	Sandstone	Fallas, 2011b
Sikanni Formation	(lK) lower Cretaceous	Fine-grained grey sandstone, siltstone, shale	Sandstone	Cui et al., 2016
Unspecified Manville Group	(1uK) upper Cretaceous	Marine quartzose sandstone, shale, siltstone	Sandstone	MacDonald & Slimmon, 1999
Dunvegan Formation	(uK) upper Cretaceous	Sandstone and shale	Sandstone	Cui et al., 2016
Winnipegosis Formation	(uO) upper Ordovician	Basal sandstone overlain by complex sequence of quartzose sandstone and shale	Sandstone	Viljoen et al., 2016
Rat River Formation	(lK) lower Cretaceous	Sandstone, minor siltsone	Sandstone	Norris, 1974
Tanglefoot Formation	(lJ) lower Jurassic	Shale, sandstone	Sandstone	Gordey & Makepeace, 2003
Inklin Formation	(lJ) lower Jurassic	Shale, sandstone	Sandstone	Cui et al., 2016
Swan River Formation	(lK) lower Cretaceous	Quartzose sandstone, in places glauconitoc shale and minor lignite	Sandstone	Viljoen et al., 2016
Little Bear Formation	(lK) lower Cretaceous	Sandstone, mudstone, shale, coal	Sandstone	Fallas, 2011b
Peace River Formation	(lK) lower Cretaceous	Sandstone, siltstone, shale and mudstone	Sandstone	MacDonald & Slimmon, 1999
Undifferentiated Proterozoic rocks	(X) Proterozoic	Quartzite, argillite, minor dolomite	Sandstone	Viljoen et al., 2016
Tantalus Formation	(lJ) lower Jurassic	Shale, sandstone, siltstone, coal, argillite	Sandstone	Gordey & Makepeace, 2003
Spirit River Formation	(lK) lower Cretaceous	Shale, mudstone, siltstone, and sandstone	Sandstone	MacDonald & Slimmon, 1999
East Arm Formation	(lS) lower Silurian	Micritic, fossiliferous, stromatolitic and biostromal dolomites with several sandy/argillaceous marker beds	Limestone	MacDonald & Slimmon, 1999
Franklin Mountain Formation	(ES) Cambrian to Silurian	Dolostone, shale, sandstone	Limestone	Fallas, 2011a
Aksala Formation	(uTr) upper Triassic	Shale, limestone	Limestone	Gordey & Makepeace, 2003
Interlake Formation	(lS) lower Silurian	Micritic, fossiliferous, stromatolitic and biostromal dolomites with several sandy/argillaceous marker beds	Limestone	Gordey & Makepeace, 2003
Stony Mountain Formation	(uO) upper Ordovician	Dolostone and dolomitic limestone	Limestone	Gordey & Makepeace, 2003
Stonewall Formation	(uO) upper Ordovician	Dolomite, fine grained, sparsely fossiliferous	Limestone	Viljoen et al., 2016

Formation Name	Unit Code and Time of Deposition	Lithology	Bedrock Type	Source
Vunta Formation	(S) Silurian	Limestone, dolostone	Limestone	Gordey & Makepeace, 2003
Bear Rock Formation	(lmD) lower and middle Devonian	Limestone, dolostone, minor breccia	Limestone	Fallas, 2011a
Ashern Formation	(lS) lower Silurian	Argillaceous dolostone and dolomitic shale	Limestone	Viljoen et al., 2016
Horsefeed Formation	(DP) Devonian to Permian	Limestone, dolostone marble, calcareous sedimentary rocks	Limestone	Gordey & Makepeace, 2003
Unspecified Ruby Range Group	(pT) Paleogene	Granodiorite, quartz monzonite, quartz diorite and diorite	Granite	Gordey & Makepeace, 2003
Nordenskiold Formation	(lJ) lower Jurassic	Tuff, sandstone, dacite	Granite	Gordey & Makepeace, 2003
Snowcap Formation	(TrJ) Triassic-Jurassic	Quartzite and schist	Granite	Gordey & Makepeace, 2003
Long Lake Formation	(TrJ) Triassic-Jurassic	Granodiorite, diorite, monzodiorite	Granite	Gordey & Makepeace, 2003
Whitehorse Formation	(ZTr) Neoproterozoic-Triassic	Granodiorite, diorite, monzodiorite	Granite	Gordey & Makepeace, 2003
Povoas Formation	(uTr) upper Triassic	Andesite-dacite and fragmental volcanic rock	Granite	Gordey & Makepeace, 2003
Prospector Mountain Formation	(uK) upper Cretaceous	Granodiorite, quartz monzonite, quartz diorite and diorite	Granite	Gordey & Makepeace, 2003
Unspecified Teslin Group	(Mki) Mid-Cretaceous	Granodiorite, quartz monzonite, quartz diorite and diorite	Granite	Gordey & Makepeace, 2003
Unspecified Archean Group	(WT) Archean	Granite, granodiorite	Granite	Viljoen et al., 2016
Nakina Formation	(MJ) Mississippian-Jurassic	Basalt, gabbro, peridotite, andesite, porphyry	Basalt	Gordey & Makepeace, 2003
Casino Formation	(2uK) upper upper Createaceous	Basalt, andesite, porphyry, dacite	Basalt	Gordey & Makepeace, 2003
Open Creek Formation	(uK) upper Cretaceous	Basalt flows, basal sedimentary epiclastic rocks	Basalt	Gordey & Makepeace, 2003

Table S2.3: Collection of the surficial geology deposits (Fulton et al., 1995) captured by the lake sampling across the WBF and their conversion to HRAs.

Deposit Name	Description	HRA
Ra	**Apline complexes:** rock, colluvium and till, rock and Quaternary deposits complex in area, characterized by alpine and glacial landforms	Bedrock
R	**Undivided:** rock with minor Quaternary deposits	Bedrock
A	**Alluvial deposits:** stratified silt, sand, clay and gravel; floodplain, delta and fan deposits; in places overlies and includes glaciofluvial deposits	Coarse
E	**Eolian deposits**: sand and minor silt; dunes, blowouts and undulating plains; in most places overlies deltaic sediments, coarse lacustrine sediments, or glaciofluvial deposits	Coarse
sL	**Lacustrine sand:** sand and locally gravel; deposited as sheet sands, lags and beaches	Coarse
bC	**Colluvial blocks:** blocks and rubble with sand and silt; derived from crystalline bedrock, medium grade metamorphic substrate and cemented sandstone	Coarse
sC	**Colluvial sand:** sand and gravel; derived from poorly lithified sandstone and conglomerate substrate	Coarse
cL	**Coarse grained glaciolacustrine and lacustrine deposits:** sand, silt and gravel; deposited as deltas, sheet sands and lag deposits	Coarse
Gp	**Plain glaciofluvial deposits:** sand and gravel; deposited as outwash sheets, valley trains and terrace deposits	Coarse
Gx	**Complex glaciofluvial deposits:** sand and gravel and locally diamicton; undifferentiated ice contact stratified drift and outwash; locally includes till and rock	Coarse
V	**Quaternary volcanic rock:** consolidated lava, breccia and tephra; dominantly basaltic and adesitic in composition; includes flow, volcanic piles and cinder cones	Coarse
rC	**Colluvial rubble:** rubble and silt; derived from carbonate and consolidated fine clastic sedimentary rock substrate	Fine hummocky
fC	**Colluvial fines:** silt, clay and fine sand; derived from weakly consolidated shale and siltstone substrate	Fine hummocky
Tb	**Till blanket:** thick and continuous till	Fine hummocky
mL	**Lacustrine mud:** fluid silty clay and clayey silt; deposited as quiet water sediment	Fine plain
fL	**Fine grained glaciolacustrine and lacustrine deposits:** silt and clay, locally containing stones; deposited as quiet water sediments	Fine plain
O	**Organic deposits:** peat, muck and minor inorganic sediments, large bog, fen and swamp areas where organic fill masks underlying surficial materials; generally >2m thick	Fine plain
Tv	**Till veneer:** thin and discontinuous till; may include extensive areas of rock outcrop	Till veneer

Chapter 3: Differences in shallow lake ion and nutrient water chemistry within the Boreal Plains related to local landscape characteristics

3.1 Abstract

The Boreal Plains is a unique Canadian ecozone, due to its low-relief, heterogeneous glacial landforms and sub-humid but cold climate that result in complex surface and groundwater interactions. It is also home to an abundance of open water-wetlands and shallow lakes (hereafter all called shallow lakes), which provide essential water resources and are an important source of biodiversity. These shallow lakes are increasingly at risk from intensifying natural resource development in combination with a rapidly changing climate. Determining the natural variability in shallow lake hydrochemistry in well-defined hydrologic landforms is essential for monitoring programs to assess the potential disturbance of monitoring sites. Additionally, identifying the controls on shallow lake connectivity to the surrounding landscape and water quality is essential to understand the susceptibility of shallow lakes to disturbances and help guide future land use decisions and management strategies intended to mitigate these complex environmental problems. The relationship of landscape characteristics of lakes and their contributing catchment areas with the variability in ion and nutrient concentrations was investigated in 184 Boreal Plains shallow lakes to infer the role of different scales of topographic position on shallow lake hydrologic connectivity and water quality. Characteristics of shallow lakes and of the contributing areas adjacent to lakes was extracted from three separate scales (a 100 m lake-buffer, a 500 m lake-buffer, and a topographically defined lake-catchment), to assess the efficacy and practical application of landscape analyses for management practices. Multivariate regression tree (MRT) analyses indicate different lake and catchment characteristics give rise to distinct hydrochemistry signatures (both ion and nutrient) across the Boreal Plains. The MRT analyses classified five unique ion water types, and lake relative elevation (topographic position)

and area of wetland connected to shallow lakes, relative to lake area, explained 45% of the variability in lake ion concentrations. Five unique nutrient water types were classified by MRT analyses, and 48% of the variability in lake water quality was explained using the regional groundwater function (i.e. recharge vs discharge), topographic position, and dominant surficial geology the shallow lakes were situated in. For both nutrients and ion concentrations, landscape controls collected at the topographically defined catchment scale provided the greatest explanatory power. The results of this study show that, from a management perspective, comparing the natural variability in boreal lake ion and nutrient chemistry requires a careful consideration of the hydrological landscape lakes are located in. Good management will benefit from the results of monitoring research such as these to determine potential hydrologic disturbances based on deviations from the baseline variability within the hydrologic landscapes defined by these water types.

3.2 Introduction

Shallow lakes and open water wetlands provide important habitats for wildlife (e.g. fish, amphibians and waterfowl) and water resource in the Boreal Plains (BP) ecozone of Canada (Carlson & Brown, 2015; Petrone et al., 2007) and are vulnerable to increasing natural resource development (e.g. forestry and energy), combined with ongoing climate change (Withey & van Kooten, 2011; Foote & Krogman, 2006). The BP ecozone also forms a unique component of the Western Boreal Forest due to a distinct combination of landscape characteristics which set it apart from the adjacent Shield and Cordillera ecozones, and give rise to complex hydrologic conditions (Devito et al., 2005; Ireson et al. 2015; Winter 2001). The BP is a complex of open water, peatland-swamps, and forests ecosystems (Devito et al., 2012 & 2017; Ireson et al., 2015), were wetlands, including aquatic or open water and terrestrial peatlands or swamps, comprise up to 50% of the landscape (Kuhry et al., 1994; Vitt et al., 1995). On the BP, the interaction and exchange of energy, water and biogeochemistry between these shallow lakes and adjacent peatland-swamp wetlands and upland forests are complex, and often differ with surrounding topography and surficial geology (Devito et al., 2000; Hokanson et al., submitted; Smerdon et al., 2005; Fig. 3.1). Management strategies intended to mitigate these complex environmental problems thus require an understanding of the cause–effect relationships that exist between landscape characteristics and the open water-wetland complexes typical of the BP (Kreutzweiser et al., 2008; Soranno et al., 2014). This study attempts to provide well-defined envelopes of baseline variability in shallow lake chemistry to provide reference material to monitoring programs assessing potential lake disturbances. Additionally, this research tries to gain greater insight in the influence of boreal landscape characteristics (e.g. surficial geology, topographic position, land cover composition, etc.) on the variability in shallow lake hydrochemistry (dissolved salts and nutrients) and to identify the main processes controlling this variability.

The BP is characterized by glacial landforms, varying from fine-textured disintegration moraines, glacio-lacustrine plains and near-flat undifferentiated moraines, to coarse-textured glacial-fluvial deposits (Vogwill, 1978; Ceroici, 1979). These landforms are overlain with shallow lakes (this includes open water wetlands, ponds and large lakes, which often have a mean depths of less than 2 m), most often in complexes with abundant and large peatland-swamp wetland complexes composed of thick organic deposits (NWWG, 1988). This combination of thick glacial deposits and numerous lakes and wetlands has led to the formation of complex groundwater-surface water interactions (Ferone & Devito, 2004). In sub-humid low-relief landscapes such as the BP, minor variations in topography can drive complex local to regional groundwater flow systems and spatial patterns of groundwater recharge and discharge (Tóth, 1963; Winter & Woo, 1990). Shallow lake position within the landscape can therefore strongly influence the form and magnitude of hydrologic connections, and result in different responses to disturbance in the local landscape (Bedford, 1999; Devito et al., 2000; Winter et al., 2001). Moreover, vertical and subsurface connections tend to dominate in these landscapes, causing variability in geology and land cover to potentially have a strong influence in groundwater-surface interactions with shallow lakes (Devito et al., 2005 & 2017; Tetzlaff, et al., 2009; Kratz et al., 1997).

Syntheses of research from across the BP and the rest of the boreal (Devito et al., 2012; Tóth, 1999; Winter, 2001; Bell, 2010) form the basis for conceptual models of water movement on the BP (Devito et al., 2005 & 2012; Ireson et al., 2015). However, to date conceptualization of the contributions of surface and groundwater connectivity, and geologic and soil characteristics encountered in the flow paths to the variability in boreal shallow lake ion chemistry (i.e. salinity and ion composition) and nutrient chemistry have not been studied. This study addresses this need and presents the hypothesized role of landscape characteristics on shallow lake ion and nutrient chemistry (Fig.3.1). Major differences in surface and subsurface hydrologic connectivity in the BP can be attributed to the variability in surficial geology. The composition of surficial deposits can play a pivotal role in groundwater movement, residence time and scale of flow (Winter, 2001; Plach et al., 2016). The rate of groundwater flow is slow in fine, highly weathered deposits and is often limited to local flow, while there is more subsurface flow at larger scales in coarse-textured deposits (Devito et al., 2000 & 2005; Brinson, 1993; Bedford, 1999; Winter, 2001). Groundwater residence time and scale of flow are influenced by the relative elevation of individual aquatic systems as well, as topographic position influences their recharge-discharge function and the scale (local, intermediate, and regional) of interaction with the surface within the groundwater flow system (Winter, 2001; D'Arcy & Carignan, 1997; Devito et al., 2005). Shallow lakes in groundwater discharge zones are hypothesized to experience a greater inflow of ion-rich groundwater than shallow lakes located in recharge areas, which have greater water sources from dilute precipitation. Shallow lakes and wetlands have demonstrated dynamic groundwater-surface water interactions across the BP (Meyboom, 1966; Hayashi et al., 1998; Winter & Rosenberry, 1995) and may influence flow path connections between surface waters and surrounding uplands. In addition to the inflow of allochthonous materials and weathering from contributing areas surrounding the shallow lakes, the conceptual model (Fig.3.1) also incorporates the potential inflow of weathering products (i.e. ions) from upstream lakes (Soranno et al., 1999; Martin & Soranno, 2006), as an increase in upstream lakes may increase the inflow of these products. The difference in surface and subsurface contributions from adjacent land covers (peatland-swamps, forests), as well as upstream lotic systems, can influence shallow lake ion chemistry. A better understanding of the above relationships can provide estimates of the relative interaction and connectivity of shallow lakes to their surroundings and their susceptibility to land use practices that may interact with these connections to shallow lakes (Devito et al., 2000; Kreutzweiser et al., 2008; Winter, 2000).

Contributions of surface and groundwater from different land covers (peatlands vs forests) or adjacent glacial deposits can influence the source of nutrients and thus the variability in BP shallow lake nutrient concentrations (Devito et al., 2000; Kreutzweiser et al., 2008; Plach et al., 2016). Surface waters are a key aspect of both the carbon (C) and nitrogen (N) balance of the BP ecozone, receiving increasing inputs from terrestrial (forests and wetlands) ecosystems (Prairie, 2008; Olefeldt et al., 2013a; Vitousek et al. 1997; Galloway et al. 2004) and upstream ponds and lakes (Soranno et al., 2008). Boreal lakes tend to be nutrient rich (Sass et al., 2008), because within-lake processes remove a large fraction of terrestrially exported C and N (Algesten et al., 2004; Weyhenmeyer et al., 2012; Saunders & Kalff, 2001). Phosphorus (P), however, is often a limiting nutrient in these waters (Prepas et al., 2001), and as such is often the key element in boreal lakes' trophic status and eutrophication. Devito et al. (2000) showed that 50% of differences in P among shallow lakes within the BP ecozone could be explained by landscape factors, such as wetland connectivity and lake relative elevation. The lakes' topographic position is also assumed to influence the relative nutrient contributions from adjacent wetlands and forests, since lakes located higher in the landscape may be more hydrologically isolated from regional groundwater and limited to inputs from local flow. Lake chemistry in local flow systems can reflect precipitation signatures and may be more nutrient-poor in some landscapes. However, on fine-textured glacial deposits and flat, plateau areas on topographic highs typically have organic rich wetlands (peatlands-swamps) that are a sources of P, N and DOC in local flow systems to shallow lakes (Plach et al., 2016.) Further, longer residence times of lakes in contact to clays in regional highs (recharge locations) may result in shallow lakes with higher nutrient concentrations. Lakes in lower topographic positions may be in zones of groundwater discharge, and the effects of nutrient-rich wetland sources may be diminished due to 'groundwater buffering' ─ the inflow of nutrient-poor groundwater diluting the contributions of nutrient inflow from wetland (sub)surface flow (Plach et al., 2016). This inflow of nutrient-poor groundwater is further affected by the lakes' location atop glacial deposits. Plach et al. (2016) showed that lakes located on coarse deposits in low topographic positions received nutrient-poor groundwater from larger scale flow system. This study also intends to assess how contributions of surface water and groundwater connectivity, inferred by the conceptual model and landscape characteristics, influence BP shallow lake nutrient variability. Using the identified shallow lake (including open water wetlands), terrestrial wetland (peatland-swamp), and forest ecosystems, the conceptual model considers the abundance, connectivity and type of wetland to be determining factors in lake nutrient variability. Therefore, the second objective of this research is to assess which landscape characteristics best explain the variability encountered in shallow lake C, N and P concentrations across the BP.

Research looking at inter-catchment comparisons has increased our understanding of the potential roles and interactions of landscape characteristics in developing multi-scaled hydrological pathways and spatial variations in surface water chemistry (Devito et al., 2017; Julian & Gardner, 2014; D'Arcy & Carignan, 1997; Buttle, 2006). This study's objective was to determine how well variability in hydrochemistry of 184 shallow lakes sampled in the BP could be explained using landscape characteristics by inferring the contributions of surface and groundwater to the shallow lakes. To this end, this study addresses the following three questions: (1) What are the baseline salinity, ion composition and nutrient concentrations in typical shallow lakes of the BP? (2) What regional and local landscape controls influence the observed variability in shallow lake hydrochemistry? (3) How much of this variability can be explained using landscape characteristics? In addressing these questions, this research will aid landscape management in the BP ecozone, since establishing geochemical and water quality baselines characterizing the natural variability in surface water ion and nutrient concentrations form an important prerequisite in both pre- and post-disturbance landscapes (Edmunds et al., 2003). Specifically, this research will attempt to provide the baseline variability in hydrochemistry for well-defined hydrologic landscapes to aid monitoring programs in the assessment of potential hydrologic disturbances across the Boreal Plains. Additionally, this study attempts to increase understanding of the relative role of regional drivers (recharge vs discharge, relative elevation) and variability in the local landscape (surficial geology, wetland connectivity). Improved understanding of the role of potentially key drivers is essential in providing reference material for adaptive management practices, to help guide land use decisions pre- and post- disturbance (e.g road placement, reclamation, etc.) at both local and regional scales.

3.3 Methods

3.3.1 Study Areas

This study was conducted within the Central Mixedwood Natural Subregion of Alberta, located in the Boreal Plains ecozone (Downing & Pettapiece, 2006). A total of 184 shallow (approx. 1 to 5 m deep) open water ecosystems (including open-water wetlands, ponds and shallow lakes; all hereafter referred to as shallow lakes (L)) were sampled in two distinct study areas (Fig.3.2). These two study areas are identified as: 1) the Mistehae area (56°N, 114°W), and 2) the Utikuma Region Study Area (URSA; 56°N, 115°W), home to a number of long term (>10 years) studies on hydrogeology (Devito et al., 2016). Hydrogeological investigation by the Alberta Geologic Survey has identified that the selected shallow lakes of URSA occur in a region with significant groundwater discharge (high frequency of -flowing wells) and the shallow lakes of Mistehae are located in an intermediate topographic high with groundwater recharge (Vogwill, 1978; Fig.3.2).

Both study regions have Quaternary glacial deposits that vary 25 to 250 m in thickness, overlaying shale deposits of the Upper Cretaceous period (Vogwill, 1978; Ceroici, 1979). The surficial geology of both study regions is roughly equal portions of fine-textured glacio-lacustrine deposits, hummocky clay-rich glacial till moraines, and coarse-textured glacio-fluvial and aeolian deposits (Fenton et al., 2013; Vogwill, 1978; Paulen et al., 2004). Low relief and poorly integrated drainage has promoted peatland formation across the region. In poorly drained sites, organic soils – consisting predominantly of peatlands – reach depths to over 4 m and cover up to 50% of the land area in the region (Kuhry et al., 1993, Vitt et al., 1995; Tarnocai et al., 2011).

Shallow lake elevation ranges from 580 to 700 m and 630 to 670 m asl in Mistehae and URSA, respectively (Fig.3.2). The two study regions share a continental climate, with summer (July) and winter (January) long-term mean temperatures of 15.7°C and -14.6°C, respectively. The annual precipitation (P) average is slightly less than the potential evapotranspiration (PET) (483 and 513mm, respectively). On average 50–60% of annual P occurs between June and August, followed by dry autumn months. Winter snow generally comprises less than 30% of the total annual P (Devito et al., 2005). Long-term climate data indicate a moisture-deficit, with PET greater than P for most years, albeit with infrequent wet years occurring with an approximate twenty-year frequency (Mwale et al., 2009; Carrera-Hernandez et al., 2011). Long-term average annual runoff is less than 100 mm yr^{-1} and varies annually from <5 to 300 mm yr^{-1} (Devito et al., 2005 & 2017; Redding and Devito, 2008).

In both study regions, forests located on coarse-textured landforms are predominantly composed of pine (*Pinus banksiana*). Well drained fine-textured landforms are largely comprised of aspen (*Populus tremuloides*) and birch (*Betula papyrifera*) during early successional stages, but are succeeded by white spruce (*Piceaglauca*) and balsam fir (*Abies balsemea*) with age. The canopy cover of organic soils is primarily comprised of black spruce (*Picea mariana*) and tamarack (*Larix sp.*), with ground cover mostly composed of peatland mosses (Downing & Pettapiece, 2006).

3.3.2 Lake Sampling and Water Sample Analysis

All 184 shallow lakes were sampled during the summer (July-August), either by helicopter (1998), or on land by sampling near the shore with a 4 m rod (1999). A total of 78 shallow lakes were sampled in Mistehae, while the remaining 106 shallow lakes were sampled in URSA. For all water samples, water was collected approximately 0.2 to 0.3 m below the surface. Perishable parameters were filtered through a membrane filter (pore size 0.45 μm) and frozen within 8 hours of sampling until analysis. The pH and electrical conductivity (EC) of the shallow lakes were measured within 8 hours of sampling using a Fischer Scientific Accumet 925 pH meter and an Oakton Con 300 conductivity meter, respectively. Water samples were packed in ice filled coolers and shipped to the University of Alberta Biogeochemical Analytical Service Laboratory (BASL) for chemistry analysis within 72 hours.

A suite of anion and cation concentrations was analyzed to determine the ion charge balance. Major cations included sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}), and were measured using a Perkin Elmer 3300 Atomic Absorption Spectrometer using the methods presented by Stainton et al. (1977). For anions, sulfate (SO_4^-), chloride (Cl^-) and bicarbonate (HCO_3^-) were measured using a Dionex DX600 Ion Chromatograph using methods presented by Pfaff (1993). Total dissolved solids (TDS) concentrations were calculated by summing the major anions (Cl, SO_4, HCO_3) and cations (Ca, Mg, Na, K). Charge balances for all samples were calculated, with the inclusion of DOC to include the contribution of humic substances to the total anionic charge (Oliver et al., 1983). Given the greater chance of error with the inclusion of DOC, water samples with a charge balance ratio of less than 25% were utilized. Three shallow lake samples were removed from this analysis as their ionic charge balances fell outside the acceptable range.

Samples were also analyzed for nutrient concentrations. For Dissolved Organic (DOC) analysis, water samples were filtered using a membrane filter (pore size-0.45 μm) and processed using an Ionics Model 1505 Programmable Carbon Analyzer following Greenberg et al. (1992). Samples for total dissolved nitrogen (TDN) were filtered in the lab using a Gelman glass fiber filter (pore size of 1.0 μm) and processed using a Technicon Autoanalyzer II following Stainton et al (1977). Samples for total phosphorus and total dissolved phosphorus (TP & TDP, respectively) were filtered in the lab using a Gelman glass fiber filter (pore size of 1.0 μm) and processed using a

Cary 50 UV/Visible Spectrophotometer, following Prepas and Rigler (1982). Water for Chlorophyll a (Chl-a) analyses was filtered through a Gelman type A/E 47 mm filter.

3.3.3 Landscape Characteristics

A total of 16 landscape characteristics, including 9 lake-scale characteristics and 7 catchment-scale characteristics, were identified in the conceptual model as potentially the most significant in controlling scale of flow and flow path, and in regulating the variability in shallow lake hydrochemistry (Table 3.1). To represent the general data made available to management agencies across Canada, all variables were gathered from open sources (NRC and AGS), except the detailed wetland vegetation classes (Ducks Unlimited Canada (DUC)) used to derive hydrologic response units (HUs; Devito et al. 2017).

Lake characteristics

Surficial geology was classified into three categories of Hydrologic Response Areas (HRAs): coarse-textured deposits (CO), fine-textured hummocky moraines (HM), and fine-textured clay-plains (CP). The shallow lakes' HRA (L_{HRA}) was determined following the methods presented in Devito et al. (2017), using the Alberta Geological Survey's (AGS) surficial geology maps (Paulen et al., 2004a & 2004b). Fine-textured deposits were divided between HM (comprising all non-sandy stagnant ice moraines and moraines with a hummocky geomorphic class) and CP (consisting of lacustrine, distal glacio-lacustrine, and thrust moraine landforms). The CO category consisted of all fluvial, glacial-fluvial, aeolian and littoral glacio-lacustrine deposits. Organic soils were assumed to overlay CP, but were categorized as CO if >75% of the perimeters of the organic deposits were surrounded by coarse-textured landforms. Shallow lake water bodies were identified using AGS's lake boundary data (Alberta Environment, 2008). In most cases, shallow lakes were situated atop a single HRA category, but when shallow lakes were found on the border between two or more HRA's the dominant HRA was used to classify.

Shallow lake elevation was obtained from the Canadian Digital Elevation Model (CDEM; NRC, 2015), at a scale of 1:50,000. Relative elevation of the sampled shallow lakes (LRE) was determined at three different scales. For each scale, relative elevation was determined by the highest and lowest point and subsequently assigning an elevation to each shallow lake in relation to these extremes:

$$\text{Eq. 1 LRE} = \frac{\text{Elevation} - \text{Elevation}_{\text{min}}}{\text{Elevation}_{max} - \text{Elevation}_{\text{min}}}$$

The local relative elevation of each shallow lake (Loc-LRE) was delineated within the individual HRA units (i.e. CO, HM and CP) the lake was located in. Each HRA unit typically had a high point in elevation (e.g. hill tops, ridge lines, saddles) surrounded by lower elevation breaks (slopes, streams), defined as two fundamental hydrologic landscape units by Winter (2000). The boundaries were defined using the 1:50,000 scale CanVec 'Water Flow' data layer (NRC, 2017) and contour maps (CDEM).

Intermediate relative elevation (Int-LRE) was defined by the larger boundaries of the sampling universe of all lakes for the study area, URSA and Mistehae separately, similar to the methods used by Plach et al. (2016). These study regions were defined by the coordinates (56.181°N, 115.793°W), (56.174°N, 115.059°W), (55.874°N, 115.799°W) and (55.868°N, 115.070°W) for URSA, and (55.981°N, 114.536°W), (55.968°N, 113.945°W), (55.713°N, 114.555°W) and (55.699°N, 113.971°W) for Mistehae.

Each shallow lake's regional relative elevation (Reg-LRE) was determined based on their location in the regional-scale topographic watersheds. Similar to the local-scale watershed, boundaries were delineated using streamflow (CanVec) and contour maps (CDEM), but expanded beyond the individual HRA units. Rather, regional-scale topographic watersheds were aimed at capturing the potential groundwater connectivity and cumulative surface flow of each study area (Fig.3.2). Following the regional high points of elevation towards regional low points (i.e. streams), a total of three regional watersheds were identified for URSA, and two for Mistehae. These watersheds were then combined into a single catchment for each respective study region and shallow lake relative elevation was determined using the highest and lowest point of elevation within this catchment.

The inflow of weathering products (i.e. ions) into shallow lakes was expected to increase with rising magnitude of stream order. Shallow lakes were therefore categorized by their connection to streams, using streamflow (CanVec). Shallow lakes were assigned an order (LO) based on the Strahler stream order (Strahler, 1957) of the shallow lakes' outflow stream. Shallow lakes not connected to an inflow stream were categorized as order 0.

As an additional measurement, the number of upstream lakes feeding into the survey lakes was also inventoried. The conceptual model assumed that an increase in the number of lakes contributing to survey lakes would increase the inflow of weathering products, but possibly also increase the retention of nutrients upstream. The number of upstream lakes (NoUL) feeding into the survey lakes was determined using streamflow (CanVec) to identify lakes connected by streamflow. In addition, Ducks Unlimited's EWC was used to identify lakes connected by wetlands, feeding into the survey lakes via (sub)surface flow.

Shallow lakes were also categorized in a binary method on the absence (0) or presence (1) of an outflow stream (LOS) using streamflow (CanVec). This was done to determine if the presence of an outflow channel contributed to the removal of weathering products from the shallow lakes.

As the effects of local shoreline impacts are dependent on the lake shoreline length (L_S) relative to the lake's area size (A_L), the shallow lakes' Shoreline Development Index (SDI) was calculated to determine the "roundness" of the shallow lakes. The SDI is calculated as:

$$Eq. 2\ SDI = \frac{L_S}{2(\pi A_L)^{0.5}}$$

where the closer this ratio is to 1, the more circular the lake is (Osgood, 2005). Increasing SDI (i.e. more convoluted lake shapes) corresponds with increasing lake productivity, as a larger SDI means a larger zone through which terrestrially-derived nutrients may enter the shallow lake (Cole, 1975; Wetzel, 1976).

The two study areas were selected for sampling due to the a-priori knowledge that URSA and Mistehae have been identified as a hydrological discharge and recharge zone, respectively (Vogwill, 1978). Shallow lakes were therefore also classified by their regional groundwater function (RGF). All shallow lakes located in URSA were therefore labeled as 'discharge', while all Mistehae shallow lakes were labeled 'recharge' to assess the potential influences of regional-scale groundwater regimes on lake hydrochemistry.

Catchment characteristics

An additional goal of this study was to examine how the contributing effects of the landscape characteristics differed when extracted from different scales. In doing so, three different catchment scales were utilized: (a) a 100 m buffer area (CB1) extending from the lake shoreline,

(b) a 500 m buffer area (CB5) extending from the lake shoreline, and (c) the topographical watershed catchment (CT). Topographic catchments CT were defined using streamflow (CanVec) and contour maps (CDEM), following the local high points of elevation (hill tops, ridge lines, saddles), feeding into the drainage point (local low point).

The relative contributing area of each HRA category in relation to shallow lake area was calculated. This was done using the total area of each individual HRA category ($A_{C\text{-}HRA}$) within the CB1, CB5 and CT catchment separately, and calculating it as a ratio relative to lake area:

$$Eq. 3\ \frac{A_{C-HRAi}}{A_L}\quad with\ \ C = CB1, CB5, or\ CT\quad and\quad i = CO, HM, or\ CP$$

In addition to the effects of geology, the influence of the vegetation land-cover groups or Hydrologic Units (HUs) along the lakes' shoreline perimeters were also assessed. HUs were categorized into five main categories (S3.1), using the 24 vegetation classes provided by Ducks Unlimited Canada's Enhanced Wetland Classification (DUC, 2011). HUs were categorized based on their a-priori hypothesized contribution to runoff and nutrient mobilization: (a) HU_1 contained 'open water & aquatic wetlands' (open waters, aquatic beds, mudflats, emergent & meadow marshes, and graminoid poor & rich fens), (b) HU_2 captured 'conveyor wetlands' (open bogs, shrubby poor & rich fens, shrubby bogs & swamps, and treed rich fens), (c) HU_3 categorized the 'source wetlands' (treed bogs, treed poor fens, and treed swamps), (d) HU_4 captured 'forested uplands' (upland deciduous, conifer and mixedwood), and (e) HU_5 contained 'anthropogenic uplands' (anthropogenic and burnt). Similar to the HRAs, the relative contributing area of each HU category was calculated within the CB1, CB5 and CT catchment separately, and calculated as a ratio relative to A_L:

$$Eq.4\ \frac{A_{C-HUi}}{A_L}\quad with\ C = CB1, CB5, or\ CT\quad and\quad i = CO, HM, or\ CP$$

Within all of the shallow lake catchments, the total wetland area ($A_{W_{All}}$) and the connected wetland area ($A_{W_{Con}}$) were calculated to determine the effects of the surrounding wetlands on shallow lake hydrochemistry. $A_{W_{All}}$ was determined by extracting the total area of all wetland HUs ($HU_{1,2\&3}$) located in the CB1, CB5 and CT catchments, respectively. $A_{W_{Con}}$ was calculated from all wetland HUs connected to the shallow lake; either connected directly to the lake shoreline, or connected by streamflow (CanVec). Both wetland measurements were included in the modelling as a ratio to the shallow lake area (A_L) to determine their effects on hydrochemistry relative to the size of the individual shallow lakes.

$$Eq.5\ \frac{A_{C-W_{All}}}{A_L}\quad with\ A_{W_{All}} = A_{HU_1} + A_{HU_2} + A_{HU_3}\ and\ C = CB1, CB5, or\ CT$$

$$Eq.6\ \frac{A_{C-W_{Con}}}{A_L}\quad with\ W_{Con}\ determined\ by\ 'Water\ Flow'\ \&\ 'EWC'\ and\ C = CB1, CB5, or\ CT$$

As an additional environmental driver, the catchment to lake area ratio was included also. The goal of this was to capture the relative contribution of runoff and precipitation to lakes. The conceptual model assumed that greater catchment to lake area ratios contributed to an increase in the production of runoff, decreasing the relative contribution of precipitation. This in turn would affect the lake hydrochemistry (both ions and nutrients).

$$Eq.7\ \frac{A_C}{A_L}\quad with\ C = CB1, CB5, or\ CT$$

The total wetland (W_{All}) to total upland (U_{All}) area ratio was calculated within each catchment designation to capture the contribution of overland flow into shallow lakes, assuming that with increasing wetland-upland ratios, catchments generate greater overland flow, in form of ion-poor, nutrient-rich surface water.

$$Eq. 8\ \frac{A_{C-W_{All}}}{A_{C-U_{All}}} = \frac{A_{HU_1} + A_{HU_2} + A_{HU_3}}{A_{HU_4} + A_{HU_5}} \quad with\ C = CB1, CB5, or\ CT$$

As a final ratio, the total wetland to catchment area ratio was calculated to using the equation:

$$Eq. 9\ \frac{A_{C-W_{All}}}{A_C} \quad with\ C = CB1, CB5, or\ CT$$

This ratio was included as it is a landscape characteristic commonly used in research assessing the hydrologic mechanisms for topographically controlled hydrologic systems.

3.3.4 Data Analyses

Scatterplot Matrices

Scatterplot matrices were created to visualize the variability hydrochemistry among shallow lakes and to highlight the correlation between the chemistry variables used in the regression tree analyses. Scatterplots visualize the pairwise correlation between variables and provides a coefficient of determination (R^2) for each comparison. The matrices were created using the R package ‘pairs’. A single matrix was created which included a selection of ion chemistry variables that exhibited strong variability across the lakes (EC, Na, SO_4 and HCO_3) and nutrient variables (TDN, TDP and DOC). No data was transformed or normalized for this analysis.

Multivariate Regression Trees (MRT)

Multivariate Regression Trees (MRTs) were created to assess the correlation between the chemistry data and landscape drivers. MRT is a hierarchical method for forming groups and analyzes the relationship between two matrices – hydrochemistry and landscape drivers. MRT emphasizes local structure and interactions between the environmental effects and the chemistry data and assumes no particular relationship between the two. At each division of sample units (i.e. shallow lakes), a specific environmental variable and a division point along that variable are selected to minimize "impurity" – the variation within the groups. Impurity is measured as the sum of squared Euclidean distances from individual samples to the centroid of each grouping's space (De'ath, 2002; McCune & Grace, 2002; Jongman et al., 1995).

The MRTs were created using the 'greedy algorithm' provided by the R package 'mvpart' (Therneau & Atkinson, 2004). All chemistry data was normalized using the 'standard score', due to the different units of measurement and range in data of the chemistry variables (McCune & Grace, 2002; Jongman et al., 1995), and MRTs were created independently for the shallow lakes' ion and nutrient concentrations. The ion chemistry MRT included EC, pH and all major ions (Na, K, Ca, Mg, SO_4, Cl and HCO_3). The MRT analysis on shallow lake nutrient concentrations included DOC, TDN and TDP. TDN and TDP were used, rather than TN and TP, as dissolved nutrients provide a better estimate of nutrients available to phytoplankton and potential to stimulate eutrophication (Caffrey et al., 2007). For both ion and nutrient chemistry, nine separate MRTs were produced. The first series of MRTs consisted of all the gathered landscape characteristics, while the second series was produced using a limited selection of landscape variables (L_{HRA}, Int-LRE, $A_{C\text{-}WCon}/A_L$ and RGF). A third series of MRTs was also constructed using landscape variables commonly used for topographically controlled hydrologic systems ($A_{C\text{-}WAll}/A_C$ and A_C/A_L). For each of these selections in landscape characteristics, an individual MRT was produced at each of the catchment scales (CB1, CB5 & CT). Created trees were pruned by selecting those with the smallest cross-validated relative error.

Following the outcome of the final MRTs, Multi-Response Permutation Procedures (MRPPs) were performed to test if there was a significant difference between MRT branches. MRPP is a nonparametric procedure that compares dissimilarities within and among groups using Euclidian distances. If two groups (i.e. water types) are different, then the average of the within-group dissimilarities is less than the average of the dissimilarities between two groups (McCune & Urban, 2002; Mielke & Berry, 2001).

Correspondence between ion and nutrient water types

Following the results of the MRTs, a Sankey diagram (SankeyMATIC, http://sankeymatic.com/build/, accessed on July 23, 2018) was produced to assess the correspondence between the individual lakes' water types derived from the MRT analyses on shallow lake ion and nutrient concentrations. This analysis visualizes correspondence of shallow lakes from their respective ion to nutrient water types. The width of the arrows is proportional to the number of shallow lakes transferred between water types.

3.4 Results

3.4.1 Correlations and variability in ion and nutrient shallow lake chemistry

The pairwise comparison of ion and nutrient variables showed shallow lake EC to have a strong positive correlation with all selected ion concentrations ($R^2 > 0.5$, $p < 0.001$; Fig.3.3). While the selected ion concentrations also exhibited strong correlation with each other ($p < 0.05$), this correlation was not as pronounced as with EC ($R^2 < 0.55$). Additionally, comparison of variability in EC and ion concentrations across study areas showed the majority of more saline shallow lakes to be located in URSA, while the most ion-dilute shallow lakes were located in Mistehae. However, both study areas did exhibit a large range in variability in ion concentrations and there existed a considerable overlap in this range between the two areas. The assessment on the correlation between different nutrient variables showed TDN and DOC to be strongly correlated with one another ($R^2 > 0.72$, $p < 0.001$). TDP on the other hand did not exhibit a significant correlation with either TDN or DOC ($R^2 \geq 0.3$, $p > 0.05$). Comparison of nutrient signatures between the study regions highlighted the presence of considerably higher nutrient concentrations in URSA shallow lakes, compared to shallow lakes located in Mistehae, specifically in TDN and DOC concentrations. While there also existed an overlap in shallow lake nutrient concentrations between the two regions, this overlap was less pronounced than with the ion concentrations. The comparison between the ion and nutrient variables showed that, overall the two chemistry sets were not strongly correlated with each other ($R^2 > 0.5$, $p > 0.05$).

3.4.2 Influence of landscape characteristics on shallow lake chemistry

For shallow lake ion and nutrient chemistry, the MRTs using all landscape variables (lake and catchment) provided slightly greater explanatory power (approximately 3%) than the MRTs using the four main variables, but in all cases the explanatory power in MRTs using just two commonly used variables was poor (Table 3.2 and 3.3). Comparing the different definitions for quantifying catchment contributions, defining contributions to lakes using CT provided the greatest explanatory in each variable scenario, with a loss in explanation of variation in lake chemistry ranging from 2 to 8% using CB1 and CB5 compared to CT. We focus on the results of the MRT produced using the selection of the four main landscape controls, collected at the CT-scale. We do so, as this reduction in explanatory variables provided more intuitive effects of landscape controls on shallow lake ion and nutrient variability, at little cost in explanatory power.

For shallow lake ion chemistry, the MRT using the four main variables (L_{HRA}, Int-LRE, $A_{CT\text{-}WCon}/A_L$ and RGF) accounted for 45% of the variability encountered (Table 3.2). A total of seven water types were identified in this regression tree, but MRPPs identified two sets of water types as not significantly different ─ I_{1a} & I_{1b}, and I_{3a} & I_{3b} respectively (Fig.3.4a).

The main controls in the MRT on shallow lake ion chemistry were relative wetland connectivity ($A_{CT\text{-}WCon}/A_L$), combined with the shallow lakes' topographic position at the intermediate scale (Int-LRE). The first split in this MRT was based on relative wetland connectivity, at a $A_{CT\text{-}WCon}/A_L$ ratio of 0.415. Overall, shallow lakes with a high $A_{CT\text{-}WCon}/A_L$ exhibited lower salinity than shallow lakes with a lower $A_{CT\text{-}WCon}/A_L$. Within the group of shallow lakes with a high $A_{CT\text{-}WCon}/A_L$, three distinct water types (I_{1a}, I_2, and I_{3a}) were identified based on their topographic position, displaying lower salinity with higher relative positions (Table 3.4).

In similar fashion, four water types were identified in the group of shallow lakes with a low $A_{CT\text{-}WCon}/A_L$ (I_{1b}, I_{3b}, I_4 and I_5). Within this group, shallow lakes exhibited higher salinity with lower topographic positions as well. Shallow lakes located at a Int-LRE below 0.491 (i.e. I_4 and

I_5) were classified further based on their relative wetland connectivity, with shallow lakes possessing a lower connectivity (< 0.11; I_5) exhibiting a higher salinity (Table 3.2).

For shallow lake nutrient chemistry, the MRT using the four main variables accounted for 48% of the variability encountered. Using these four landscape controls, five nutrient water types were identified, but further analyses by MRPPs reduced this to four (Fig.3.4b).

The first split in this MRT was based on the shallow lakes' location in a discharge or recharge zone, with lakes located in a recharge region exhibiting lower nutrient concentrations overall (Table 3.5). Lakes located in a regional recharge were further classified based on their topographic position, with higher nutrient concentrations observed in shallow lakes located lower in the landscape (Int-LRE < 0.796; N_{2b}) and were identified as hyper-eutrophic and carbon-poor. An interaction with topographic position and surficial geology is evident. Shallow lakes located on CP deposits (N_{2a}) are also identified as hyper-eutrophic and carbon-poor, regardless of lake topographic position. At the Mistehae sample area (regional recharge) CO or HM deposits located higher in the landscape (Int-LRE ≥ 0.796; N_1) had relatively low nutrient concentration and were defined with a eutrophic, carbon-poor signature.

Shallow lakes situated in the discharge region (i.e. URSA) were further organized based on their location on surficial geology deposits. Specifically, shallow lakes situated on CO or HM deposits (N_3) possessed lower nutrient concentrations than shallow lakes located on top of CP (N_4). Although both water types were of a hyper-eutrophic trophic status, shallow lakes located on CP deposits exhibited very high nutrient concentrations (Table 3.5). Both water types showed an additional level of branching, based on the shallow lakes' $A_{CT\text{-}WCon}/A_L$ ratio (not included in Fig.3.4b). But while shallow lakes with greater $A_{CT\text{-}WCon}/A_L$ possessed higher P concentrations, analysis by MRPP showed the overall difference in nutrient concentrations not to be significant ($p > 0.05$).

3.4.3 Correspondence between ion and nutrient water types

A visualization was created from the correspondences between the ion and nutrient water types identified at the topographical watershed catchment (CT) using the four main landscape variables (L_{HRA}, Int-LRE, $A_{CT\text{-}WCon}/A_L$ and RGF). This diagram (Fig.3.7) showed strong branching in almost all water types, especially in shallow lakes of intermediate salinity (I_3). This strong branching illustrates that there is little similarity in dominant processes between the water types of the two chemistry suites. Shallow lakes of more dilute ion chemistry (I_1 and I_2) only exhibited limited branching however, spreading mostly across more dilute nutrient water types as well (N_1 and N_2). This branching presents that many shallow lakes of dilute ion chemistry possess a dilute nutrient chemistry as well. Little transfer of shallow lakes could be observed between ion rich and nutrient rich water types however, suggesting that few surveyed lakes possess both high ion and nutrient concentrations.

3.5 Discussion

3.5.1 Landscape controls on shallow lake ion chemistry

Comparing the natural variability in shallow lake ion concentrations across the BP ecozone requires a careful consideration of the hydrological landscape the lakes are situated in. While landscape management, either pre- or post-disturbance, requires a proper geochemical 'baseline' with a quantification of an area's natural variability (Edmunds et al., 2003), the results from this study suggest that providing a single baseline for the entirety of the BP ecozone would not serve as a realistic representation of the region. Rather, researchers and managers need to take into account the shallow lakes' topographic position in the landscape and its connectivity to the surrounding wetlands to get an idea on the contribution and scale of flow of surface and groundwater into the shallow lake. Decision makers can therefore not assume BP shallow lakes to have similar response to future scenarios of climate change and natural resource development, but will need to assess the landform a shallow lake is located in to develop proper strategies.

The results of the MRT using the four main landscape variables extracted from the topographical watershed catchment (CT) to explain the variability in shallow lake ion concentrations generally follows the a-priori conceptual model (Fig.3.1). Shallow lake ion chemistry is strongly influenced by the relative wetland connectivity, showing more dilute lakes possessing a greater relative connectivity. Previous studies have frequently indicated a strong difference in ion concentrations between shallow groundwater originating from wetlands and deeper groundwater, with deeper groundwater exhibiting overall greater concentrations due to higher mineralization (Devito et al., 2000; Hill, 1990; Reid et al., 1981; Elwood and Turner, 1989; Dewalle and Swistock, 1994; Plach et al., 2016).

This difference in mineral loadings between wetland (sub)surface flow and deeper groundwater flow can be noted in the difference in ion chemistry between shallow lakes of different relative wetland connectivity. While shallow lakes of water type I_{3a} and I_{3b} share highly similar chemistry concentrations and composition, the two water types take up different topographic positions. Specifically, shallow lakes possessing a greater relative wetland connectivity (I_{3a}) are located at a lower topographic position, but share similar ion chemistry with shallow lakes located higher in the landscape with a lesser wetland connectivity (I_{3b}). When located at a similar topographic position, these lakes with greater wetland connectivity exhibit a more dilute ion chemistry (I_2; Table 3.4). The diluting effects of wetland connectivity on shallow lake ion chemistry are exhibited in water types I_4 and I_5 as well, where shallow lakes with greater wetland connectivity exhibit lower concentrations of dissolved salts (I_4).

Shallow lake ion concentrations were found to be highly controlled by relative elevation as well, with shallow lakes located higher in the landscape possessing more dilute ion concentrations. Concentrations of major ions are primarily controlled by the lakes' hydrologic regime (Eilers et al., 1983; Kenoyer & Anderson, 1989; Webster et al., 1990). As groundwater possesses greater ion concentrations than precipitation, shallow lakes receiving larger inflows of groundwater relative to precipitation have greater ion concentrations (Kratz et al., 1997, Webster et al., 1996). The relative amounts of groundwater and precipitation input depend on the lake's topographic position. Shallow lakes located at a lower topographic position have greater concentrations of major cations due to relatively larger inputs of groundwater compared to shallow lakes of a higher topographic position (Kratz et al., 1997; Tóth, 1970).

The effects of groundwater contributions can be noted in the chemical signatures of the ion water types (Table 3.4). The dilute ion chemistry of water type I_1 shows that shallow lakes located sufficiently high in the landscape become hydrologically isolated, and are limited to precipitation and local-scale lateral flow systems as their water sources ─ regardless of the abundance in surrounding wetlands (I_{1a} vs I_{1b}). The relative amount of precipitation input into shallow lakes diminishes as lakes are located lower in the landscape. This was observed in the ion concentrations of the ion water types (Fig.3.6), where shallow lakes of a lower topographic position consistently exhibit greater ion concentrations, reflecting greater relative inputs of groundwater.

Additionally, the shallow lakes' topographic position and position in the groundwater flow system also influence their response to drought. Research in similar landscapes (Webster et al., 1996; Kratz et al., 1997) has shown lakes situated low in the landscape to increase in concentrations of major ions during times of drought, due the increasing relative contribution of groundwater, while lakes with higher topographic positions experienced no change, or a decrease in ions. As the study areas experienced a severe drought in the period of 1998-2000 (Ferone & Devito, 2004), this may have contributed to the dilute ion concentrations observed in shallow lakes of high topographic position, and the more saline ion chemistry of the shallow lakes situated lower in the landscape.

It may be argued that the higher salinity observed in shallow lakes of water type I_5 is not solely due to larger relative groundwater inputs, but also due to the HRA these lakes are located on. Previous research (Tóth, 1999; Devito et al., 2005; Winter, 2001; Moser et al., 1998) and the a-priori conceptual model assessed surficial geology as having a significant role on lake ion chemistry. Difference in the composition of surficial deposits was predicted to have a strong influence on flow rate, weathering effects and scale of flow (Devito et al., 2005; Brinson, 1993; Bedford, 1999; Devito et al., 2000; Plach et al., 2016; Winter, 2001). It was expected these effects would express themselves by higher ion concentrations in shallow lakes located on fine deposits. Although the lakes' HRA was not supported by the results of the MRT as a significant control on ion concentrations, the most saline shallow lakes were encountered on fine deposits (Fig.3.5). The high ion concentrations in these lakes may be a result of their presence in hummocky moraines (HM). As hummocky glacial landscapes are characterized by isolated depressions and smaller contributing catchment areas (Winter, 2001; Ferone & Devito, 2004), the shallow lakes' catchments form closed basins with little wetland connectivity and low runoff, giving rise to high evapotranspiration rates and increasing concentrations of major salts.

The MRT analyses did not support the a-priori conceptual model in its assessment on the effects of groundwater recharge and discharge zones. Based on earlier research (Tóth, 1963; Winter, 2001; D'Arcy & Carignan, 1997; Devito et al., 2005) it was hypothesized that shallow lakes located in regions of groundwater discharge experience a greater inflow of regional-scale, ion-rich groundwater. While shallow lake location in a recharge or discharge zone was not identified as a significant variable in the ion regression tree, it is worth noting that all of the most dilute lakes (I_1) were located in Mistehae (recharge zone), and almost all of the most saline lakes ($I_{4\&5}$) were found in URSA (discharge zone) (Fig.3.5).

3.5.2 Landscape controls on shallow lake nutrient chemistry

Following the results of the MRT on shallow lake nutrient variability (Fig.3.4b), it can be stated that a single baseline on nutrient concentrations for shallow lakes in the BP would provide little insight, given the strong variability encountered across the study regions. While most shallow lakes encountered in this research were identified as either eutrophic or hyper-eutrophic, there still exists a large range in nutrient variability (Table 3.5). Management assessment of lake productivity or susceptibility to eutrophication from land use in the BP ecozone should therefore take into account the landscape the shallow lakes are situated in, as the main controls on water quality may differ strongly. The MRT analyses on variability in shallow lake nutrient concentrations generally support the a-priori conceptual model on the role of topographic position and surficial geology, however the expected role of wetland connectivity was not supported (Table 3.1, Fig.3.1).

Previous research in the BP has shown the significant influence of regional groundwater flow systems and spatial patterns of groundwater recharge and discharge on lake water quality (Plach et al., 2016; Smerdon et al., 2005; Ferone & Devito, 2004; Devito et al., 2000). The influence of groundwater recharge and discharge on water quality is complex however, as lake nutrient loadings may be reduced by recharge-effects, as wetlands located at higher within landscape units may only serve a groundwater recharge function (Winter, 2001), reducing the levels of ion-poor, nutrient-rich (sub)surface flow from wetlands into the lakes. But lake nutrient concentrations may also be reduced by the inflow of regional-scale, nutrient-poor groundwater discharge. This discharge-effect may be averted however in perched lakes, or lakes situated atop fine deposits, due to the low-permeability of these systems isolating the lakes from regional groundwater flow (Plach et al., 2016; Smerdon et al., 2005; Ferone & Devito, 2004).

The effects of groundwater recharge are visible in the water quality of the survey lakes, as shallow lakes situated in zones of hydrological recharge (N_1 and N_2) exhibit overall lower nutrient concentrations compared to shallow lakes in discharge zones (N_3 and N_4; Table 3.5). This may be due to regional recharge draining surface water from wetlands, reducing the relative input of ion-poor, nutrient-rich (sub)surface flow from wetlands into the shallow lakes. Additionally, these deep drainage effects become more distinguished at higher topographic positions, since shallow lakes located higher in the local landscape exhibit lower nutrient concentrations overall (N_1; Fig.3.6). Alternatively, these shallow lakes situated at higher topographic position may possess more dilute nutrient concentrations due to receiving a greater proportion of their input waters from precipitation than shallow lakes located lower in the landscape (Kratz et al., 1997).

The influence of regional-scale groundwater discharge is visible in lake nutrient concentrations. As shallow lakes associated with CO deposits (N_3) may be well-connected to the larger-scale groundwater flow systems with high flow due to the high hydrological conductivity of the quartz-sand mineral deposits (Smerdon et al., 2005). These lakes will receive a dominance of nutrient-poor mineral groundwater discharge (Plach et al., 2016), this results in lakes with overall lower nutrient concentrations. While shallow lakes located on fine-textured HM deposits exhibited similar dilute nutrient concentrations to shallow lakes associated with CO deposits, this is not likely the result of groundwater discharge, due to the low-permeability of HM deposits and high topographic locations (Smerdon et al., 2005; Ferone & Devito, 2004). Rather, in hummocky moraine landscapes isolated depressions form smaller contributing catchment areas where wetlands are not a major source of water due to lack of an integrated flow network (Winter, 2001; Ferone & Devito, 2004), resulting in limited contributions of the surrounding wetlands to the shallow lake nutrient loadings (Fig.S3.1).

In both recharge and discharge zones, it can be noted that shallow lakes located on fine-textured CP deposits exhibit elevated nutrient concentrations (N_{2a} and N_4, respectively). In part, this is due to the low-permeability of fine-textured deposits isolating shallow lakes from regional groundwater flow, preventing the nutrient-diluting effects of groundwater recharge and discharge. But in addition, the low permeability and porosity of fine-grained materials allow these deposits to maintain higher moisture levels, which reduce infiltration capacities as the upper part of the soil profile becomes saturated more rapidly (Burt & Haycock, 1996). Therefore, catchments dominated by low relief, fine-textured surficial material promote the formation of peatlands, resulting in large sources of nutrients for shallow lakes atop CP deposits.

3.5.3 Ion controls vs nutrient controls

In the visualization of the correspondences between the ion and nutrient water types (Fig.3.7), it is clear that the processes contributing to higher ion and nutrient concentrations ($I_{4\&5}$ and N_4, respectively) are distinct from one another, and on occasions counteract each other. This is in large part due to the hydrologic effects of groundwater, serving as a major source of dissolved salt, but diluting the nutrient contributions of wetland (sub)surface flow.

Whereas the mechanisms stimulating higher ion and nutrient concentrations counteract one another, the processes promoting low concentrations in ions and nutrients may stimulate each other. Shallow lakes dilute in ions ($I_{1\&2}$) exhibited limited branching, branching towards more nutrient-dilute water types as well ($N_{1\&2}$). The visualization technique suggests that many shallow lakes of dilute ion concentrations possess dilute nutrient concentrations as well. This is in large part due to these lakes' topographic position within a recharge zone, making them hydrologically isolated, and limited to precipitation and local-scale lateral flow systems (Kratz et al., 1997; Tóth, 1970).

3.6 Conclusion

It has previously been shown that a combination of water chemistry measurements and inferred hydrologic flow paths are required to identify the hydrologic controls on variability in shallow lake connectivity and water quality (Devito et al., 2005 & 2017; Moser et al., 1998; Plach et al., 2016). The results of this study clearly show that, from a management perspective, comparing natural variability in shallow lake ion and nutrient chemistry also requires careful consideration of hydrological landscape in which the lake is situated. Hydrologic management and monitoring programs would benefit by assessing the deviation of monitoring lakes from the baseline variability within the hydrologic landscapes defined by these water types to determine potential hydrologic disturbances. Connectivity to surrounding wetlands and shallow lake topographic position determine the relative contributions of precipitation, surface water and groundwater, while the regional hydrologic regime (recharge vs discharge) and surficial geology influence shallow lake nutrient concentrations and water quality. However, while shallow lake ion and nutrient chemistry appear to be influence by separate mechanisms, BP shallow lakes exhibited dilute concentrations in both chemistry sets when hydrologically isolated. Furthermore, results of this study indicate that data on a limited number of landscape characteristics (i.e. L_{HRA}, Int-LRE, $A_{C\text{-}WCon}/A_L$ and RGF) are sufficient to assess approximately 50% of natural variability encountered in both ion and nutrient chemistry. These major landscape factors did not include controls typically used (i.e. $A_{C\text{-}WAll}/A_C$ and A_C/A_L) in conventional studies. Additionally, the assessment on the importance of scales (i.e. CB1, CB5 and CT) demonstrates that landscape data collected at the topographically defined catchment scale provides the greatest explanatory power. This study provides evidence to managers and stakeholders that determining future land use practices in the BP ecozone requires delicate consideration of distinct hydrologic landforms in policy, regulation and/or adaptive practices to ensure pre-disturbance shallow lake water quality and connectivity and to sustain the shallow lakes’ ecosystem functions across the BP.

Tables and Figures

Table 3.1: Lake and catchment characteristics extracted for all the study lakes for the Utikuma Region Study Area (URSA) and Mistehae sampling locations, on the Boreal Plains. Categories and ranges in variability, and predictions and motivations supporting variable selection. Abbreviations within brackets indicate names used for MRTs (Fig.3.4).

Landscape Characteristics	Categories/Range	Predictions/Motivation
Lake		
Lake HRA (L_{HRA})	L_{CO} (Coarse), L_{CP} (Clay-plain), L_{HM} (Hummocky moraines)	Groundwater flows through fine deposits more slowly and experiences greater weathering, whereas coarse deposits experience greater subsurface flow at a larger scale but with low weathering rates. Fine deposits will therefore exhibit greater ion concentrations.
Local/Intermediate/ Regional Lake Relative Elevation (Loc-/Int-/Reg-LRE)	0.00 – 1.00	Lakes located higher in the landscape are more isolated or limited to local flow, are more precipitation-fed are predicted to and have more dilute ion concentrations.
Lake Order (LO)	0 – 4	With increasing magnitude of lake order, lakes experience an increase in inflow of weathering products (ions) and in materials originating from allochthonous sources (nutrients)
Number of Upstream Lakes (NoUL)	0 – +10	With increasing number of upstream lakes, lakes experience increased inflow of weathering products (ions) and materials originating from allochthonous sources (nutrients)
Lake Outlet Streams (LOS)	0 (Absent) – 1 (Present)	The presence of an outflow channel contributes to the removal of weathering products (ions) and allochthonous materials (nutrients) from lakes.
Shoreline Development Index (SDI)	1 – 5.3	Increasing SDI is expected to correlate with increasing shoreline-associated impacts (i.e. perimeter HUs)
Regional Groundwater Function (RGF)	Discharge, Recharge	Lakes located in areas of groundwater discharge experience a greater inflow of ion-rich regional groundwater, though this regional flow may be redirected by local flow. While rich in ions, regional groundwater is poor in nutrients.
Catchment (CB1, CB5 and CT)		
Relative HRA area	$\frac{A_{C-HRAi}}{A_L}$ with $\mathrm{C} = \mathrm{CB1, CB5, or\ CT}$ and $\mathrm{i} = \mathrm{CO, HM, or\ CP}$	Greater abundance of coarse deposits corresponds with greater groundwater flow rates, but reduced residence time. Coarse deposits also experience less weathering, reducing the inflow of weathering products through groundwater.
Relative HU area	$\frac{A_{C-HUi}}{A_L}$ with $\mathrm{C} = \mathrm{CB1, CB5, or\ CT}$ and $\mathrm{i} = 1, 2, 3, 4, \mathrm{or}\ 5$	Increasing presence of HU_1 increases the sinks for water flow, reducing the inflow of nutrient-rich waters into lakes. Catchment dominance of HU_2 will increase the inflow of nutrient-dilute water coming from the shrubby wetlands. Dominance of HU_3 increases the inflow of nutrient-rich water from the treed wetlands into the lakes. Dominance of HU_4 will limit the amount of runoff flowing into lakes, reducing lake nutrient and ion concentrations.
Catchment - Lake Area Ratio	$\frac{A_C}{A_L}$ with $\mathrm{C} = \mathrm{CB1, CB5, or\ CT}$	With increasing catchment-lake area ratio, the relative contribution of runoff increases, decreasing the relative contribution of precipitation, increasing lake nutrient concentrations.

Connected Wetland - Lake Area Ratio	$\frac{A_{C-W_{Con}}}{A_L}$ with $\mathrm{C} = \mathrm{CB1}, \mathrm{CB5}, \text{or CT}$	Greater connected wetland-lake area ratios correspond with greater relative contributions of wetlands into lakes by ion-poor, nutrient-rich surface flow.
Total Wetland - Lake Area Ratio	$\frac{A_{C-W_{All}}}{A_L}$ with $A_{W_{All}} = A_{HU_1} + A_{HU_2} + A_{HU_3}$ and $\mathrm{C} = \mathrm{CB1}, \mathrm{CB5}, \text{or CT}$	Greater wetland-lake area ratios correspond with greater relative contributions of wetlands into lakes by ion-poor, nutrient-rich surface flow. If this ratio is more significant than the ‘connected wetland-lake ratio’, it is expected that wetlands may contribute to lake inflows, regardless of connectivity status.
Total Wetland - Total Upland Area Ratio	$\frac{A_{C-HU_1} + A_{C-HU_2} + A_{C-HU_3}}{A_{C-HU_4} + A_{C-HU_5}}$ $with\ C = CB1, CB5, or\ CT$	Greater wetland-upland ratios correspond with greater relative contributions of the catchment to generate overland flow, in form of ion-poor, nutrient-rich surface water into lakes.
Total Wetland – Catchment Area Ratio	$\frac{A_{C-W_{All}}}{A_C}$ with $A_{W_{All}} = A_{HU_1} + A_{HU_2} + A_{HU_3}$ and $\mathrm{C} = \mathrm{CB1}, \mathrm{CB5}, \text{or CT}$	Greater wetland-catchment ratios correspond with greater relative contributions of the catchment to generate overland flow, in form of ion-poor, nutrient-rich surface water into lakes.

Table 3.2: The percentage variability accounted for in shallow lake ion chemistry using landscape characteristics from the lakes' topographic watershed (CT), 100 m (CB1) and 500 m (CB5) buffer around the lake, using: 1) all collected lake and catchment variables (Table 3.1), 2) the subset of four variables (L_{HRA}, Int-LRE, $A_{C\text{-}WCon}/A_L$ and RGF), and 3) the two main landscape characteristics commonly used for topographically controlled hydrologic systems ($A_{C\text{-}WAll}/A_C$ and A_C/A_L).

	All variables	**L_{HRA}, Int-LRE, $A_{C\text{-}WCon}/A_L$ and RGF**	**$A_{C\text{-}WAll}/A_C$ and A_C/A_L**
CB1	43%	38%	18%
CB5	45%	40%	17%
CT	48%	45%	22%

Table 3.3: The percentage variability accounted for in shallow lake nutrient chemistry using landscape characteristics from the lakes' topographic watershed (CT), 100 m (CB1) and 500 m (CB5) buffer around the lake, using: 1) all collected lake and catchment variables (Table 3.1), 2) the subset of four variables (L_{HRA}, Int-LRE, A_{C-WCon}/A_L and RGF), and 3) the two main landscape characteristics commonly used for topographically controlled hydrologic systems (A_{C-WAll} /A_C and A_C/A_L).

	All variables	**L_{HRA}, Int-LRE, A_{C-WCon}/A_L and RGF**	**A_{C-WAll} /A_C and A_C/A_L**
CB1	49%	43%	19%
CB5	48%	40%	17%
CT	51%	48%	23%

Table 3.4: Median and 5-95% range of ion concentrations of shallow lake water types identified by the MRT analysis using the four selected landscape characteristics at the topographic watershed (Fig.3.4a). Values outside brackets indicate medians, values in the brackets the 5-95% range. The subset letters identify the water types in order of increasing median EC.

	I_1	**I_2**	**I_3**	**I_4**	**I_5**
EC (μS cm^{-1})	90	150	200	230	430
	(45 – 165)	(60 – 250)	(70 – 370)	(120 – 440)	(370 – 490)
Na (mg L^{-1})	1	2	4	4	8
	(0.4 – 2)	(0.8 – 5)	(1 – 7)	(1 – 8)	(4 – 12)
Cl (mg L^{-1})	0.2	0.5	2	0.6	3
	(0 – 0.4)	(0.1 – 0.6)	(0.1 – 9)	(0.2 – 1)	(0.4 – 3)
Mg (mg L^{-1})	4	6	10	14	26
	(2 – 6)	(3 – 11)	(3 – 20)	(4 – 25)	(18 – 35)
SO_4 (mg L^{-1})	4	7	13	30	80
	(0.2 – 11)	(0.4 – 20)	(0.7 – 35)	(4 – 55)	(50 – 90)
K (mg L^{-1})	2	3	4	10	20
	(1 – 3)	(1 – 6)	(0.7 – 9)	(6 – 15)	(9 – 30)
Ca (mg L^{-1})	15	25	30	30	40
	(5 – 25)	(9 – 40)	(10 – 55)	(15 – 50)	(30 – 55)
HCO_3 (mg L^{-1})	45	75	100	110	140
	(20 – 95)	(30 – 135)	(35 – 190)	(50 – 180)	(110 – 180)
pH	7.6	8.2	8.3	8.9	8.7
	(6.6 – 8.8)	(7.0 – 9.7)	(6.9 – 9.7)	(8.1 – 9.6)	(8.2 – 9.1)
Sample Size	**23**	**47**	**92**	**8**	**11**

Table 3.5: Median and 5-95% range of nutrient concentrations of shallow lake water types identified by the MRT analysis using the four selected landscape characteristics at the topographic watershed (Fig.3.4b). Values outside brackets indicate medians, values in brackets the 5-95% range. Water types were labelled by order of in order of increasing median nutrient concentrations within each study region. While not sampled for all shallow lakes, additional nutrient signatures of TP and Chl-a not implemented in the analyses are included for each water type.

	N_1	N_2	N_3	N_4
TDN (μg L^{-1})	800 (650 – 1000)	1200 (710 – 2100)	1800 (850 – 3000)	2500 (1600– 3600)
TDP (μg L^{-1})	25 (15 – 50)	80 (15 – 210)	50 (15 – 100)	160 (25 – 380)
DOC (mg L^{-1})	20 (15 – 25)	25 (15 – 35)	30 (20 – 50)	45 (35 – 70)
TP (μg L^{-1})	65 (30 – 90)	130 (30 – 360)	100 (20 – 300)	230 (100 – 420)
Chl a (μg L^{-1})	15 (5 – 25)	40 (2 – 150)	25 (5 – 95)	40 (5 – 100)
Sample Size	**7**	**69**	**86**	**19**

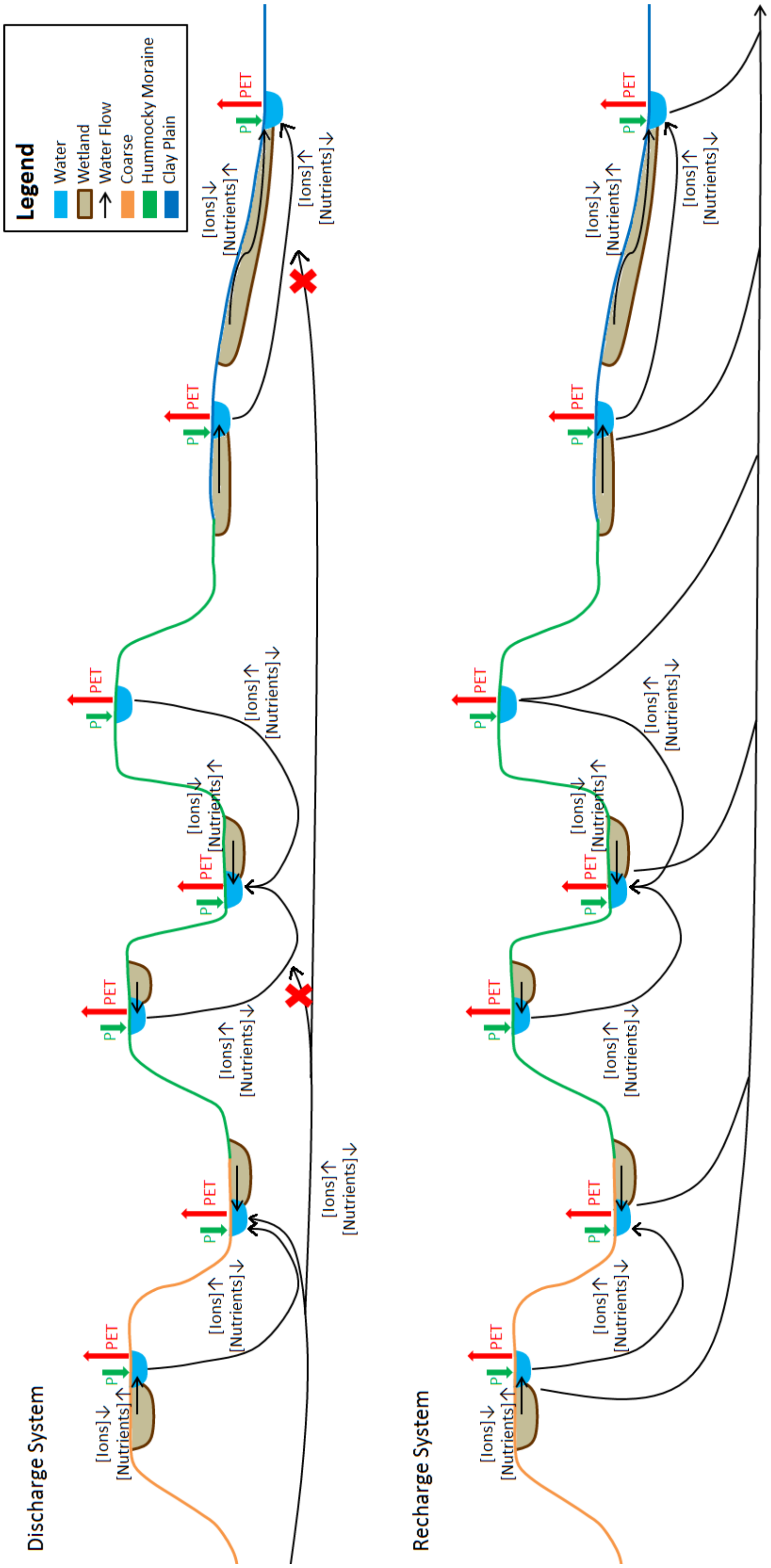

Fig.3.1: Conceptual model of the contributions of surface and groundwater connectivity, and geology and soil characteristics to the variability encountered in boreal shallow lake ion and nutrient chemistry.

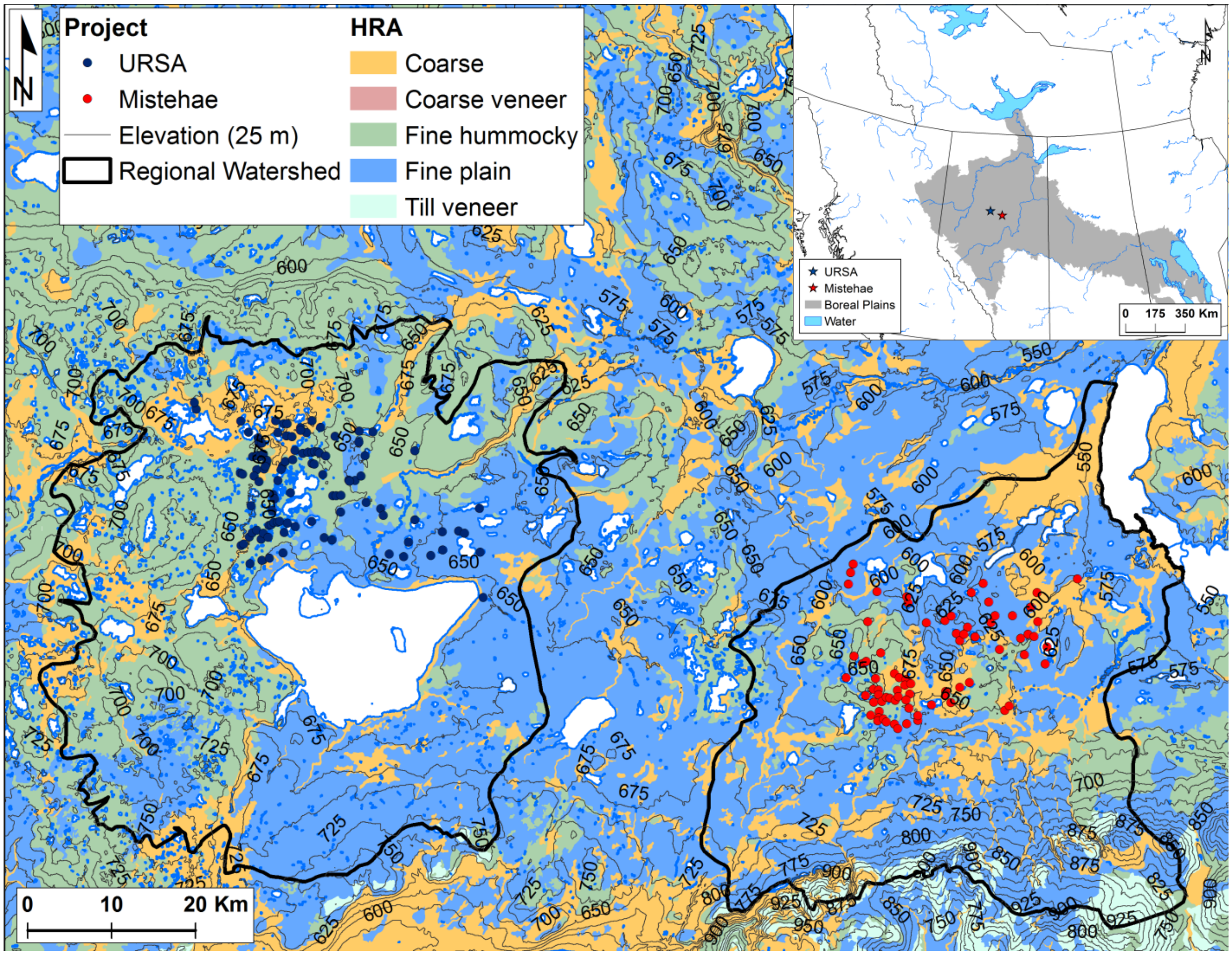

Fig.3.2: Location of the study areas within the Boreal Plains ecozone of Canada (inset), and the location of the sampled shallow lakes within the URSA and Mistehae regional watersheds. Hydrologic response areas (HRA) as in Devito et al. (2017), and modified from surficial geology maps (Paulen et al., 2004a & 2004b).

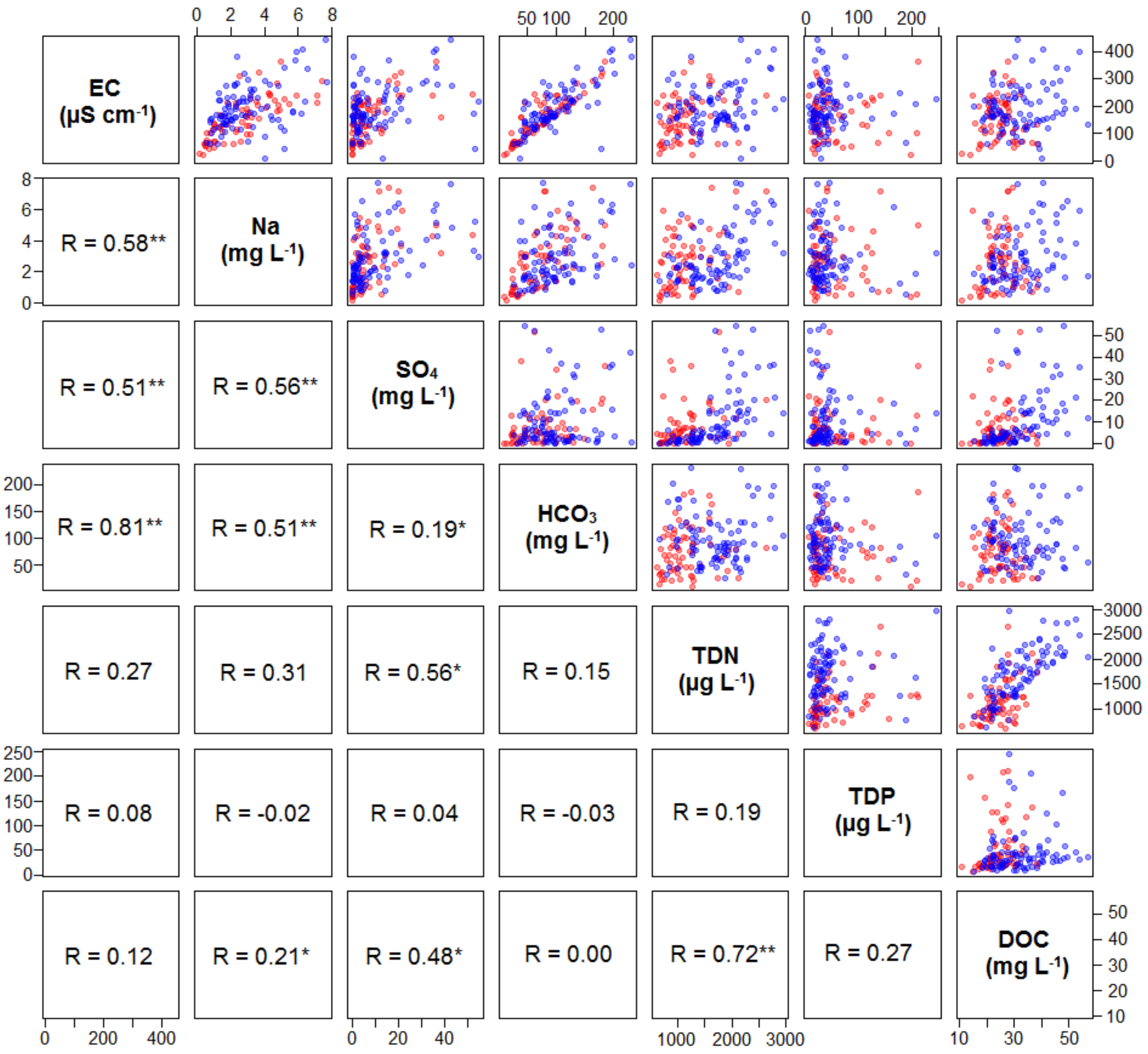

Fig.3.3: Pairwise comparison of a selection of ion variables used in the ion regression tree, and all nutrient variables used in the nutrient regression tree. Samples are colored by study area (URSA=blue, Mistehae=red). R-values indicate the adjusted R^2, and Spearman correlation strength is presented by stars (* = p<0.05, ** = p<0.01, no star = p>0.05). A total of 9 lake samples were excluded from this data matrix to reduce axes scaling.

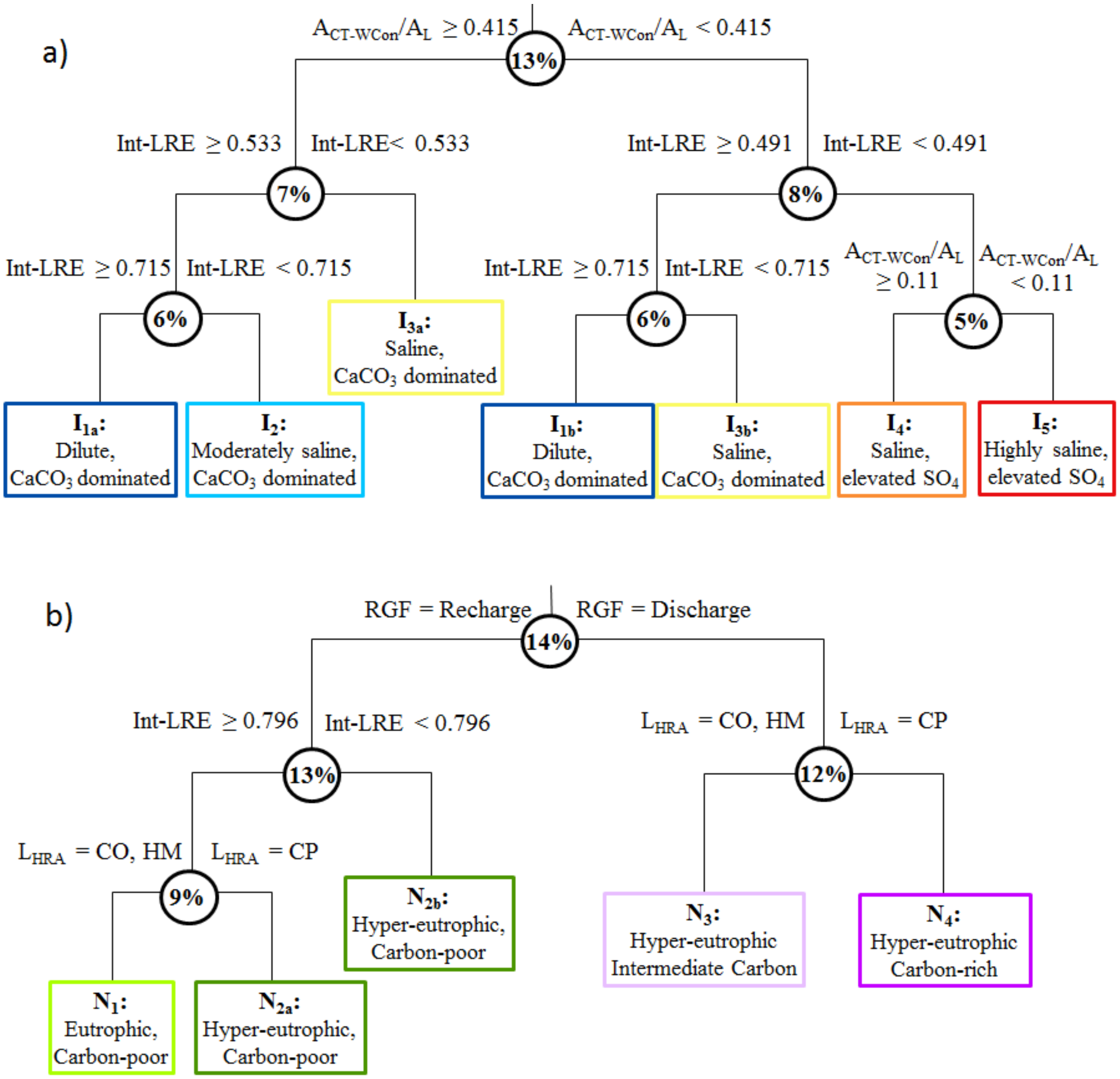

Fig.3.4: Multivariate Regression Trees (MRTs) results regressing three lake- and one topographic catchment-landscape characteristics (L_{HRA}, Int-LRE, $A_{CT\text{-}WCon}/A_L$ and RGF) and the variability in the shallow lakes' a) ion, and b) nutrient concentrations. Values in circles indicate the percentage variability explained by each branch of the MRT. Saline waters indicate median EC above 150 µS cm^{-1}, dilute waters below 150 µS cm^{-1}. Trophic statuses were determined using guidelines of the Canadian Council of Ministers of the Environment, (2004). Carbon-rich waters have median DOC concentrations of 40 mg L^{-1} or higher, carbon-poor of 25 mg L^{-1} or below.

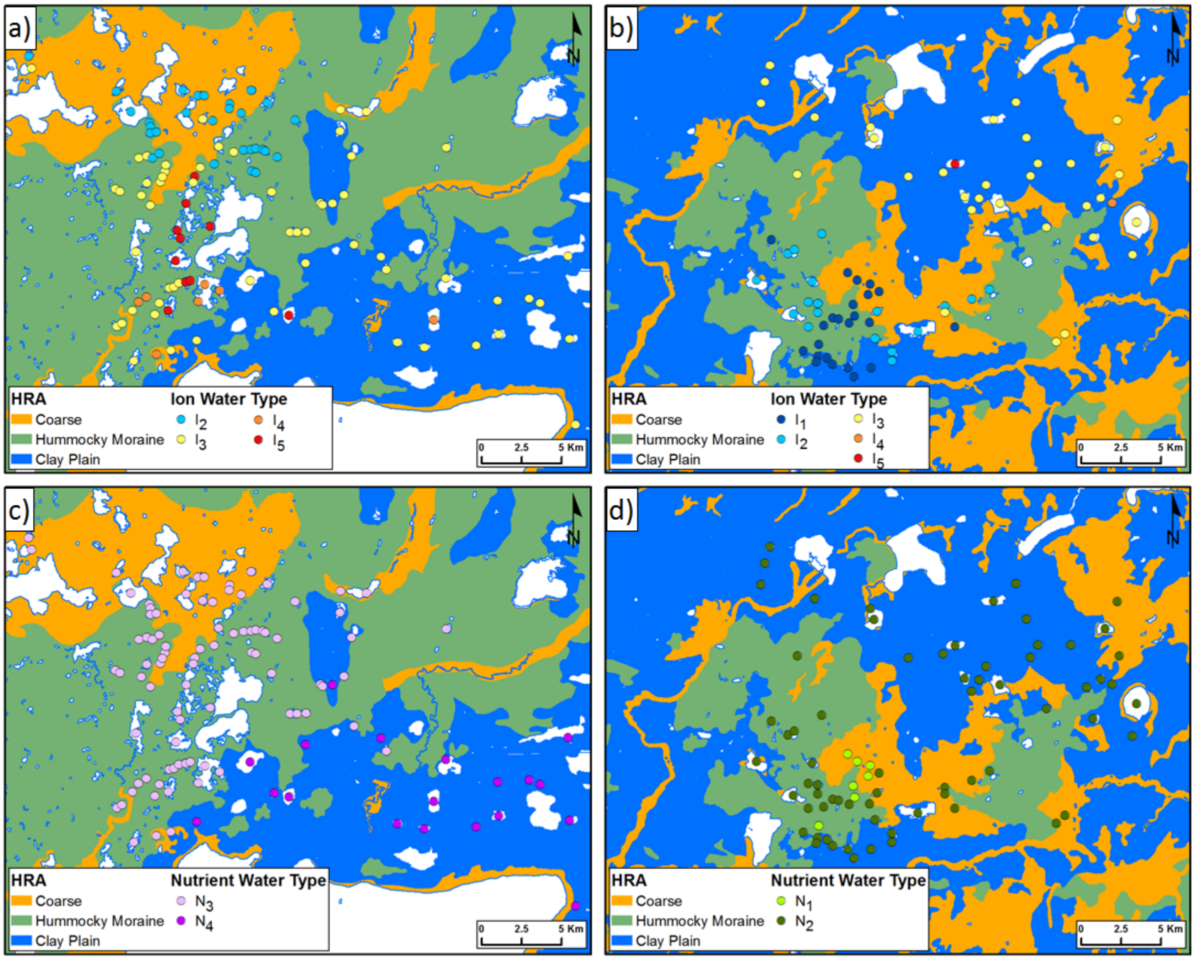

Fig.3.5: Spatial extent of shallow lakes classified by ion and nutrient water types in URSA (a and c) and Mistehae (b and d) relative to the three landscape settings: coarse-textured deposits (CO), fine-textured hummocky moraines (HM), and fine-textured clay-plain deposits (CP). Shallow lakes were classified based on the water types identified by MRTs regressing regional landscape characteristics and the variability in the lakes' ion concentrations (a and b), and nutrient concentrations (c and d), respectively.

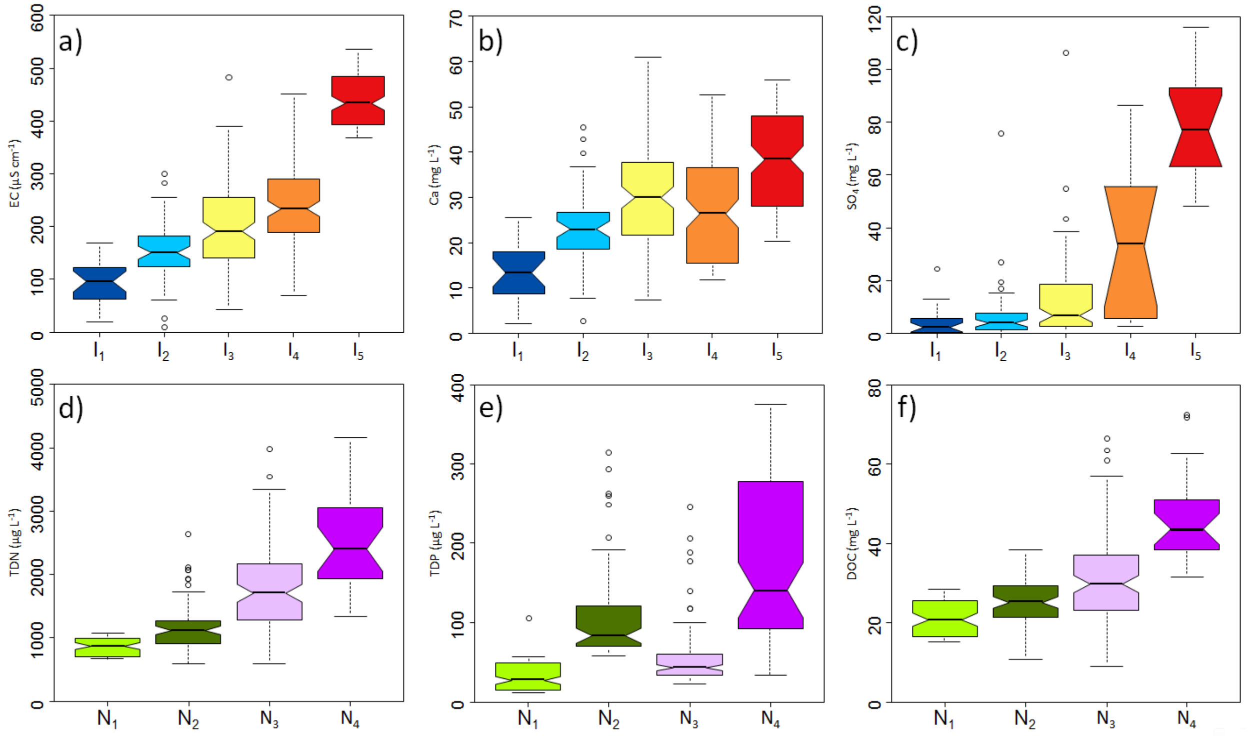

Fig.3.6: Boxplots highlighting the main differences in a) EC, b) Ca^{+}, and c) SO_4^{2-} concentrations of the shallow lake ion water types classified by MRT (Fig 3.4a); as well as the differences in in the concentrations of: d) TDN, e) TDP, and f) DOC of the shallow lake nutrient water types classified by MRT (Fig 3.4b).

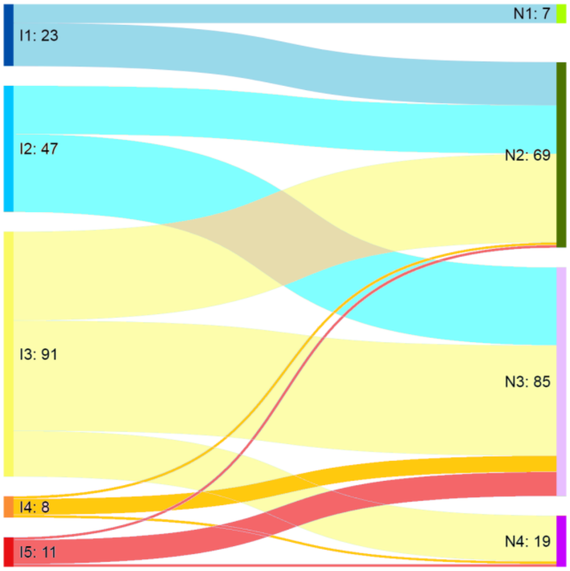

Fig.3.7: Visualization of the correspondence of shallow lakes from their respective ion (left) to nutrient (right) water types. The width of the arrows is proportional to the number of lakes corresponding between water types.

Supplemental Appendix

Table S3.1: Conversion table of the EWC's vegetation land-covers into Hydrologic Units (HUs).

Final Classification	HU	EWC ClassName	Area(%)	Justification
Open water & aquatic wetlands	HU1	Open Water	1.70	Open waters and marshes are conceptualized in our models as sinks for both nutrients and water flow
Open water & aquatic wetlands	HU1	Aquatic Bed	0.92	Open waters and marshes are conceptualized in our models as sinks for both nutrients and water flow
Open water & aquatic wetlands	HU1	Mudflats	0.00	Open waters and marshes are conceptualized in our models as sinks for both nutrients and water flow
Open water & aquatic wetlands	HU1	Emergent Marsh	1.20	Open waters and marshes are conceptualized in our models as sinks for both nutrients and water flow. Marshes may act as sources during wet cycles.
Open water & aquatic wetlands	HU1	Meadow Marsh	0.87	Open waters and marshes are conceptualized in our models as sinks for both nutrients and water flow. Marshes may act as sources during wet cycles.
Open water & aquatic wetlands	HU1	Graminoid Rich Fen	2.16	Graminoid fens are included in "Open waters" as distinguishing graminoid fens from marshes was "one of the main sources of error" in the EWC
Open water & aquatic wetlands	HU1	Graminoid Poor Fen	0.01	Graminoid fens are included in "Open waters" as distinguishing graminoid fens from marshes was "one of the main sources of error" in the EWC
Conveyor/Buffer wetlands	HU2	Open Bog	0.00	Terrigenous wetlands with shrubby vegetation are conceptualized to have consistent standing water present, limiting their contribution to lake nutrient inputs, serving mostly as conveyor systems for "source" wetlands
Conveyor/Buffer wetlands	HU2	Shrubby Rich Fen	4.05	Terrigenous wetlands with shrubby vegetation are conceptualized to have consistent standing water present, limiting their contribution to lake nutrient inputs, serving mostly as conveyor systems for "source" wetlands
Conveyor/Buffer wetlands	HU2	Shrubby Poor Fen	0.76	Terrigenous wetlands with shrubby vegetation are conceptualized to have consistent standing water present, limiting their contribution to lake nutrient inputs, serving mostly as conveyor systems for "source" wetlands
Conveyor/Buffer wetlands	HU2	Shrubby Bog	1.23	Terrigenous wetlands with shrubby vegetation are conceptualized to have consistent standing water present, limiting their contribution to lake nutrient inputs, serving mostly as conveyor systems for "source" wetlands
Conveyor/Buffer wetlands	HU2	Shrub Swamp	3.74	Terrigenous wetlands with shrubby vegetation are conceptualized to have consistent standing water present, limiting their contribution to lake nutrient inputs, serving mostly as conveyor systems for "source" wetlands
Conveyor/Buffer wetlands	HU2	Treed Rich Fen	2.59	Treed rich fens are conceptualized to be conveyors as well, due to general open canopy and short height of trees in this EWC class
Source wetlands	HU3	Treed Poor Fen	4.22	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff

Final Classification	HU	EWC ClassName	Area(%)	Justification
Source wetlands	HU3	Treed Bog	14.08	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff
Source wetlands	HU3	Hardwood Swamp	0.31	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff
Source wetlands	HU3	Mixedwood Swamp	0.18	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff
Source wetlands	HU3	Tamarack Swamp	0.25	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff
Source wetlands	HU3	Conifer Swamp	5.97	Terrigenous wetlands with treed vegetation are conceptualized to have limited standing water present, allowing the mineralization and mobilization of nutrients and their inflow into lakes by runoff
Forested uplands	HU4	Upland Conifer	4.02	Coniferous and deciduous uplands are classified together, due to the relative low abundance of coniferous uplands. Although sinks, they may act as sources during wet cycles.
Forested uplands	HU4	Upland Deciduous	46.75	Coniferous and deciduous uplands are classified together, due to the relative low abundance of coniferous uplands. Although sinks, they may act as sources during wet cycles.
Forested uplands	HU4	Upland Mixedwood	0.71	Coniferous and deciduous uplands are classified together, due to the relative low abundance of coniferous uplands. Although sinks, they may act as sources during wet cycles.
Anthropogenic uplands	HU5	Anthropogenic	4.29	Anthropogenic uplands are (first) classified separately to examine their possible unique contributions
Anthropogenic uplands	HU5	Burnt	0.01	Burned areas are categorized as anthropogenic, due to their low abundance (0.01%, 1 catchment)
N/A		Cloud	0.00	

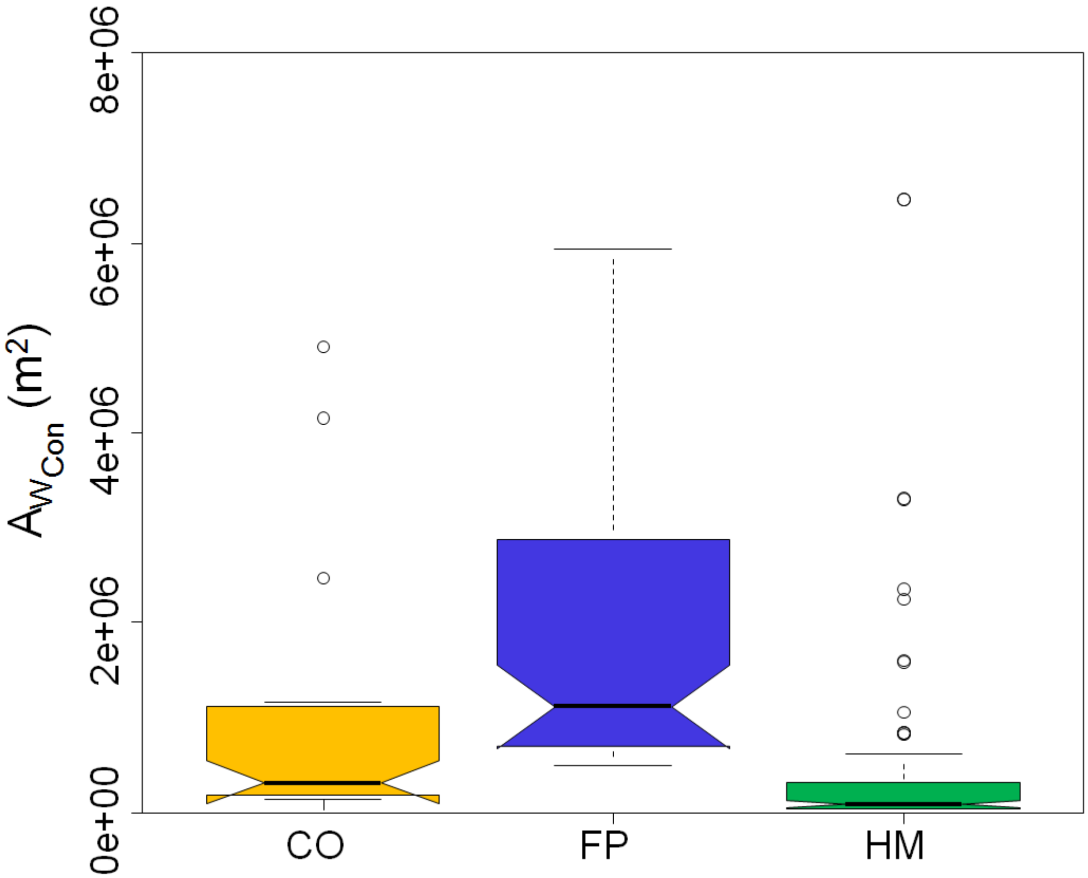

Fig.S3.1: Boxplots highlighting the main differences in connected wetland area ($A_{CT\text{-}WCon}$) for the different HRA categories across URSA and Mistehae.

Chapter 4: Conclusions

The preceding chapters provide data and interpretation to increase our knowledge on processes controlling lake source waters and water quality. Globally, few studies have combined all hydrologic processes and landscape controls identified by local-scale research into a single framework as conducted here. By doing so, this study identified the primary landscape controls and used these to infer hydrologic processes that dominate lake hydrochemistry across the WBF. Additionally, both regional- and local-scale lake monitoring are essential for managers to assess the potential disturbance of lakes. This research provides keen insight in the baseline natural variability of lake ion and nutrient chemistry within specified hydrologic landforms, rather than Canadian ecozones. These baselines may thus serve as reference material for managers to assess if a lake has experienced disturbance, based on the lake's deviation from the baseline chemistry of the distinct regional- and/or local-scale hydrologic landscape the lake is situated in.

This study increases our generally understanding of the landscape control on the spatially variability in lake hydrochemistry across the WBF. The first study (Ch.2) illustrates that the WBF is more spatially variable in lake hydrochemistry than previously thought, and has a much greater concentrations in both ions and nutrients than other boreal areas. Additionally, this study identified regional-scale water types and their corresponding landscapes, where the dominant hydrologic controls act uniformly across the region. These water types are therefore more suitable to guide proper lake adaptive management at the regional scale rather than Canadian ecozones, as well as provide a baseline in natural variability for each of these water types. Working at this regional scale across the WBF allowed for the identification of potential cross-scale interactions (CSIs). These CSIs included the effects of the local precipitation ion chemistry on lake ionic composition, the importance of topographic position depending on the hydraulic conductivity of the landscape and the masking of the influence of certain landscape controls by the presence of others. Managers therefore need to take into account these complex interactions that occur at the regional scale of the WBF and not assume for hydrologic processes to act uniformly across the WBF region. Rather, effective management will require the assessment whether lakes deviate from the regional hydrochemistry baselines provided by the water types before assuming disturbances on hydrology.

Following this, the second study (Ch.3) illustrated that even at the smaller scale of study areas, extrapolating natural variability in ion and nutrient chemistry of BP shallow lakes requires a careful consideration of hydrological landscape they are situated in. Additionally, results of this study indicate that a limited selection of landscape controls can explain a significant amount (~50%) of the natural variability encountered in lake ion and nutrient chemistry. Furthermore, the results also indicate that, while landscape data collected from topographically defined catchment scale provide the greatest explanatory power, only a limited amount of this power is lost by extracting data from buffers instead. Given the difficulty of defining topographical watersheds in low-relief landscapes as the BP, this study thus serves as reference material for future studies, managers and stakeholders. Furthermore, the utilization of buffers may be more logistically practical to employ in future studies assessing the hydrochemistry of large sample populations of shallow lakes.

Both studies illustrate that ion and nutrient chemistry are influenced by distinct processes. Lakes limited to local flow and precipitation exhibited both low ion and low nutrient concentrations. But the mechanisms stimulating higher ion or nutrient concentrations differed strongly and even counteracted each other, regardless of the scale at which these mechanisms were assessed (i.e. Ch.2 vs Ch.3). Therefore, management decisions made using only an assessment of lake ion chemistry will provide little insight in lake nutrient loadings, and vice versa. Both studies also highlight the importance of assessing variability in and controls on lake hydrochemistry at different scales.

First, regional-scale studies such as in the first data chapter show that a considerable amount (~35%) of variability can be addressed at this coarse scale. Results of this study showed that similarities in hydrochemistry do not imply the influence of similar hydrologic processes. Assessment of the impact of land-use on natural lake hydrology will benefit from these regional hydrochemistry baselines. Additionally, this study also demonstrates that the baseline in natural shallow lake hydrochemistry is highly variable across the WBF but modest extrapolation is possible, depending on the landscape characteristics. The results of the second data chapter illustrate that, even in more local-scale studies, there still exists a strong variability in both lake ion and nutrient chemistry. Local-scale landscape characteristics exhibited greater explanatory power compared to the results of the first data chapter. This was in part due to knowledge gained from this previous study allowing for the identification of landscapes where the dominant hydrologic largely act uniformly. Effective lake management policies thus require consideration of the combined efforts of research on both local- and regional-scale landscape characteristics.

As mentioned, boreal shallow water ecosystems and their landscapes are changing as a result of human activities, including oil and gas extraction, mining, and climate change (Schneider et al., 2003; AEP, 1998; Foote & Krogman, 2006; Withey & van Kooten, 2011). Adaptive management in the boreal therefore needs to be forward looking, flexible, responsive to ongoing changes, and attune to local conditions in order to sustain supplies of high-quality water (Williamson et al., 2009). Management activities can potentially sever or enhance hydrological connections across landscapes, but these disturbances can be minimized with knowledge of when and where this connectivity is most vulnerable (Creed et al., 2011). The delineated water types provide keen insight into where these connections are potentially most vulnerable, at both regional and local scales. Additionally, hydrological systems are considerably dynamic due to constantly changing climatic conditions. It is therefore important for managers to understand these shifts over both short (i.e. intra-annual) and longer time periods (i.e. inter-annual timing; Creed et al., 2011). The studies may provide insight into the potential reaction of shallow water ecosystems and their landscapes to climate change. An example of this can be found in chapter 2, on the potential effects of permafrost thawing (section 2.5.5). While this thesis does not provide a specific framework for decision makers on how to direct management activities, it does provide reference material to assess potential lake disturbances within specific hydrologic landscape envelopes, as well as a better understanding of the dynamic interplay amongst landscape characteristics (local and regional), and a useful conceptual approach to address spatial variation in lake hydrochemistry.

Bibliography

Alberta Environment, 2008. Lesser Slave Lake, Alberta - Bathymetry, Digital Elevation Model (Arc ascii grid format). Alberta Geological Survey, Edmonton, AB.

Alberta Environmental Protection (AEP), 1998. The boreal forest natural region of Alberta. Natural Resources Service, Recreation and Protected Areas Division, Edmonton, AB.

Algesten, G., Sobek, S., Bergström, A.K., Ågren, A., Tranvik, L.J. and Jansson, M., 2004. Role of lakes for organic carbon cycling in the boreal zone. Global change biology, 10(1), pp.141-147.

Antoniades, D., Douglas, M.S. and Smol, J.P., 2003. The physical and chemical limnology of 24 ponds and one lake from Isachsen, Ellef Ringnes Island, Canadian High Arctic. International Review of Hydrobiology: A Journal Covering all Aspects of Limnology and Marine Biology, 88(5), pp.519-538.

Bache, B.W., 1984. Soil-water interactions. Philosophical Transactions of the Royal Society B, 305(1124), pp.393-407.

Bedford, B.L., 1999. Cumulative effects on wetland landscapes: links to wetland restoration in the United States and southern Canada. Wetlands, 19(4), pp.775-788.

Bell, W.R.V., 2010. Regional and local controls of surface water chemistry in the Boreal Plain and Shield transition of Canada (Doctoral dissertation, University of Alberta).

Betcher, R.N., Pupp, C. and Grove, G., 1995. Groundwater in Manitoba: hydrogeology, quality concerns, management. Environment Canada, National Hydrology Research Institute.

Boxall, P.C. and Macnab, B., 2000. Exploring the preferences of wildlife recreationists for features of boreal forest management: a choice experiment approach. Canadian Journal of forest research, 30(12), pp.1931-1941.

Brandt, J.P., Flannigan, M.D., Maynard, D.G., Thompson, I.D. and Volney, W.J.A., 2013. An introduction to Canada’s boreal zone: ecosystem processes, health, sustainability, and environmental issues. Environmental Reviews, 21(4), pp.207-226.

Brinson, M.M., 1993. A hydrogeomorphic classification for wetlands. EAST CAROLINA UNIV GREENVILLE NC.

Burt, T.P. and Haycock, N.E., 1996. Linking hillslopes to floodplains. Floodplain Processes, pp.461-492.

Buttle, J., 2006. Mapping first-order controls on streamflow from drainage basins: the T3 template. Hydrological Processes: An International Journal, 20(15), pp.3415-3422.

Caffrey, J., Younos, T., Connor, M.S., Kohlhepp, G., Robertson, D.M., Sharp, J.H. and Whitall, D., 2007. Nutrient Requirements for the National Water Quality Monitoring Network for US Coastal Waters and their Tributaries. National Water Quality Monitoring Network.

Canadian Council of Ministers of the Environment (CCME), Bureau de normalization du Quebec, B., (2006). Canadian water quality guidelines for the protection of aquatic life: Phosphorus, Canadian guidance framework for the management of freshwater systems.

Carlson, M. and Browne, D., (2015). The Future of Wildlife Conservation and Resource Development in the Western Boreal Forest: A technical report on cumulative effects modeling of future land use scenarios.

Carpenter, S.R. and Turner, M., 2000. Opening the black boxes: Ecosystem science and economic valuation. Ecosystems, 3(1), pp.1-3.

Carrera-Hernández, J.J., Mendoza, C.A., Devito, K.J., Petrone, R.M. and Smerdon, B.D., 2011. Effects of aspen harvesting on groundwater recharge and water table dynamics in a subhumid climate. Water Resources Research, 47(5).

Ceroici, W., 1979. Hydrogeology of the Peerless Lake Area, Alberta. Earth sciences report, pp.79-5.

Chebotarev, I.I., 1955. Metamorphism of natural waters in the crust of weathering—1. Geochimica et Cosmochimica Acta, 8(1-2), pp.22-48.

Chorlton, L.B., 2007. Generalized geology of the world: bedrock domains and major faults in GIS format. Geological Survey of Canada, Open File, 5529(1).

Cole, G.A., 1975. Light and the Aquatic Ecosystem. Textbook of Limnology. The C. V. Mosby Company, St. Louis, Missouri, p.11.

Corkery, M., 1987. Geological Highway Map of Manitoba. Geological Survey of Canada, Winnipeg Section; M.D.A Special Publication No.1.

Creed, I.F., Beall, F.D., Clair, T.A., Dillon, P.J. and Hesslein, R.H., 2008. Predicting export of dissolved organic carbon from forested catchments in glaciated landscapes with shallow soils. Global biogeochemical cycles, 22(4).

Cui, Y., Miller, D., Nixon, G. and Nelson, J., 2015. British Columbia digital geology. British Columbia Geological Survey, Open File, 2.

D'Arcy, P. and Carignan, R., 1997. Influence of catchment topography on water chemistry in southeastern Quebec Shield lakes. Canadian Journal of Fisheries and Aquatic Sciences, 54(10), pp.2215-2227.

De'Ath, G., 2002. Multivariate regression trees: a new technique for modeling species–environment relationships. Ecology, 83(4), pp.1105-1117.

Devito, K., Creed, I., Gan, T., Mendoza, C., Petrone, R., Silins, U. and Smerdon, B., 2005. A framework for broad-scale classification of hydrologic response units on the Boreal Plain: is topography the last thing to consider?. Hydrological processes, 19(8), pp.1705-1714.

Devito, K., Mendoza, C. and Qualizza, C., 2012. Conceptualizing water movement in the Boreal Plains, Implications for watershed reconstruction, Synthesis report prepared for the Canadian Oil Sands Network for Research and Development, Environmental and Reclamation Research Group, 164 pp.

Devito, K.J., Creed, I.F., Rothwell, R.L. and Prepas, E.E., 2000. Landscape controls on phosphorus loading to boreal lakes: implications for the potential impacts of forest harvesting. Canadian Journal of Fisheries and Aquatic Sciences, 57(10), pp.1977-1984.

Devito, K.J., Hokanson, K.J., Moore, P.A., Kettridge, N., Anderson, A.E., Chasmer, L., Hopkinson, C., Lukenbach, M.C., Mendoza, C.A., Morissette, J. and Peters, D.L., 2017. Landscape controls on long-term runoff in subhumid heterogeneous Boreal Plains catchments. Hydrological Processes, 31(15), pp.2737-2751.

Devito, K.J., Mendoza, C., Petrone, R.M., Kettridge, N. and Waddington, J.M., 2016. Utikuma Region Study Area (URSA)–part 1: hydrogeological and ecohydrological studies (HEAD). The Forestry Chronicle, 92(1), pp.57-61.

DeWalle, D.R. and Swistock, B.R., 1994. Causes of episodic acidification in five Pennsylvania streams on the northern Appalachian Plateau. Water Resources Research, 30(7), pp.1955-1963.

Diebel, M.W., Maxted, J.T., Robertson, D.M., Han, S. and Vander Zanden, M.J., 2009. Landscape planning for agricultural nonpoint source pollution reduction III: assessing phosphorus and sediment reduction potential. Environmental management, 43(1), pp.69-83.

Dillon, P.J. and Kirchner, W.B., 1975. The effects of geology and land use on the export of phosphorus from watersheds. Water Research, 9(2), pp.135-148.

Downing, D.J. and Pettapiece, W.W., 2006. Natural Regions and Subregions of Alberta. Pub. No. T/852. Natural Regions Committee: Government of Alberta, Alberta, Canada.

Ducks Unlimited Canada, 2011. Enhanced wetland classification inferred products users guide version 1.0.

Dupont, J., 1992. Quebec lake survey: I. Statistical assessment of surface water quality. Water, Air, and Soil Pollution, 61(1-2), pp.107-124.

Edmunds, W.M., Shand, P., Hart, P. and Ward, R.S., 2003. The natural (baseline) quality of groundwater: a UK pilot study. Science of the Total Environment, 310(1-3), pp.25-35.

Elwood, J.W. and Turner, R.R., 1989. Streams: water chemistry and ecology. In Analysis of biogeochemical cycling processes in Walker Branch Watershed. Springer, New York, NY, pp. 301-350.

Fallas, K., 2011a. Canadian Geoscience Map 88 Geology, Mahony Lake (Northwest) (1: 1000000). Geological Survey of Canada, Ottawa, ON.

Fallas, K., 2011b. Canadian Geoscience Map 90 Geology, Mahony Lake (Southeast) (1: 1000000). Geological Survey of Canada, Ottawa, ON.

Fallas, K., MacLean, B. and Hadlari, T. 2011. Canadian Geoscience Map 91 Geology, Mahony Lake (Southwest) (1: 1000000). Geological Survey of Canada, Ottawa, ON.

Fenton, M.M., Paulen, R.C. and Pawlowicz, J.G., 2003. Surficial geology of the Lubicon Lake area, Alberta (NTS 84B/SW). Alberta Energy and Utilities Board.

Fenton, M.M., Waters, E.J., Pawley, S.M., Atkinson, N., Utting, D.J. and Mckay, K., 2013. Surficial geology of Alberta. Alberta Geological Survey, AER/AGS Map, 601.

Fergus, C.E., Soranno, P.A., Cheruvelil, K.S. and Bremigan, M.T., 2011. Multiscale landscape and wetland drivers of lake total phosphorus and water color. Limnology and Oceanography, 56(6), pp.2127-2146.

Ferone, J.M. and Devito, K.J., 2004. Shallow groundwater–surface water interactions in pond–peatland complexes along a Boreal Plains topographic gradient. Journal of Hydrology, 292(1-4), pp.75-95.

Foote, L. and Krogman, N., 2006. Wetlands in Canada's western boreal forest: Agents of change. The Forestry Chronicle, 82(6), pp.825-833.

Forster, C. and Smith, L., 1988. Groundwater flow systems in mountainous terrain: 2. Controlling factors. Water Resources Research, 24(7), pp.1011-1023.

Fortin, G., Van Der Kamp, G. and Cherry, J.A., 1991. Hydrogeology and hydrochemistry of an aquifer-aquitard system within glacial deposits, Saskatchewan, Canada. Journal of Hydrology, 126(3-4), pp.265-292.

Fulton, R., 1970. Open File 21, Surficial Geology and Landforms Maps, NTS 96F (Mahoney Lake), 96G (Fort Franklin), 96E (Norman Wells) (1:250000). Geological Survey of Canada, Ottawa, ON.

Galloway, J.N., Dentener, F.J., Capone, D.G., Boyer, E.W., Howarth, R.W., Seitzinger, S.P., Asner, G.P., Cleveland, C.C., Green, P.A., Holland, E.A. and Karl, D.M., 2004. Nitrogen cycles: past, present, and future. Biogeochemistry, 70(2), pp.153-226.

Gibbs, R.J., 1970. Mechanisms controlling world water chemistry. Science, 170(3962), pp.1088-1090.

Gordey, S.P. and Makepeace, A.J., 2003. Open File 1749, Yukon digital geology (1:1000000). Geological Survey of Canada, Ottawa, ON.

Greenberg, A.; Clesceri, L. & Eaton, A, 1992. Standard methods for the examination of water and wastewater (Vol. 2). American Public Health Association.

Gruber, S., 2012. Derivation and analysis of a high-resolution estimate of global permafrost zonation. The Cryosphere, 6(1), p.221.

Harrison, J.A., Maranger, R.J., Alexander, R.B., Giblin, A.E., Jacinthe, P.A., Mayorga, E., Seitzinger, S.P., Sobota, D.J. and Wollheim, W.M., 2009. The regional and global significance of nitrogen removal in lakes and reservoirs. Biogeochemistry, 93(1-2), pp.143-157.

Hayashi, M., van der Kamp, G. and Rudolph, D.L., 1998. Water and solute transfer between a prairie wetland and adjacent uplands, 1. Water balance. Journal of Hydrology, 207(1-2), pp.42-55.

Heginbottom, J.A., Dubreuil, M.A., and Harker, P.A., 1995. Canada –Permafrost, in National Atlas of Canada. 5th ed. National Atlas Information Service, Natural Resources Canada, Ottawa, Ont., MCR 4177.

Henriksen, A., Skjelvåle, B.L., Mannio, J., Wilander, A., Harriman, R., Curtis, C., Jensen, J.P., Fjeld, E. and Moiseenko, T., 1998. Northern European lake survey, 1995: Finland, Norway, Sweden, Denmark, Russian Kola, Russian Karelia, Scotland and Wales. Ambio, pp.80-91.

Hickin, A.S. and Kerr, B., 2005. Bedrock topography mapping and shallow gas in Northeastern BC. Summary of activities, pp.69-75.

Hinton, M.J., Schiff, S.L. and English, M.C., 1993. Physical properties governing groundwater flow in a glacial till catchment. Journal of Hydrology, 142(1-4), pp.229-249.

Hogg, E.H., 1997. Temporal scaling of moisture and the forest-grassland boundary in western Canada. Agricultural and Forest Meteorology, 84(1-2), pp.115-122.

Hume, G. S., 1954. The Lower Mackenzie River area, Northwest Territories and Yukon. Geological Survey of Canada, Memoir 273. 118 p.

Huttunen, J.T., Alm, J., Liikanen, A., Juutinen, S., Larmola, T., Hammar, T., Silvola, J. and Martikainen, P.J., 2003. Fluxes of methane, carbon dioxide and nitrous oxide in boreal lakes and potential anthropogenic effects on the aquatic greenhouse gas emissions. Chemosphere, 52(3), pp.609-621.

Ireson, A.M., Barr, A.G., Johnstone, J.F., Mamet, S.D., Van der Kamp, G., Whitfield, C.J., Michel, N.L., North, R.L., Westbrook, C.J., DeBeer, C. and Chun, K.P., 2015. The changing water cycle: the Boreal Plains ecozone of Western Canada. Wiley Interdisciplinary Reviews: Water, 2(5), pp.505-521.

Jorgensen, S.E. and Vollenweider, R.A., 1989. Guidelines of lake management–v. 1. Principles of lake management. Otsu, Japan: ILEC–UNEP.

Julian, J.P. and Gardner, R.H., 2014. Land cover effects on runoff patterns in eastern Piedmont (USA) watersheds. Hydrological Processes, 28(3), pp.1525-1538.

Kalff, J., 2002. Limnology: inland water ecosystems. Prentice Hall, New Jersey, NY, pp.202-210.

Kirschbaum, M.U., 1995. The temperature dependence of soil organic matter decomposition, and the effect of global warming on soil organic C storage. Soil Biology and biochemistry, 27(6), pp.753-760.

Kokelj, S.V., Zajdlik, B. and Thompson, M.S., 2009. The impacts of thawing permafrost on the chemistry of lakes across the subarctic boreal-tundra transition, Mackenzie Delta region, Canada. Permafrost and Periglacial Processes, 20(2), pp.185-199.

Kortelainen, P., Rantakari, M., Huttunen, J.T., Mattsson, T., Alm, J., Juutinen, S., Larmola, T., Silvola, J. and Martikainen, P.J., 2006. Sediment respiration and lake trophic state are important predictors of large CO2 evasion from small boreal lakes. Global Change Biology, 12(8), pp.1554-1567.

Kratz, T., Webster, K., Bowser, C., Magnuson, J. and Benson, B., 1997. The influence of landscape position on lakes in northern Wisconsin. Freshwater Biology, 37(1), pp.209-217.

Kreutzweiser, D.P., Hazlett, P.W. and Gunn, J.M., 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: a review. Environmental Reviews, 16(NA), pp.157-179.

Kuhry, P., 1994. The role of fire in the development of Sphagnum-dominated peatlands in western boreal Canada. Journal of Ecology, pp.899-910.

Li, T., 2013. The Geochemistry and Runoff Process in Wolf Creek Research Basin, Whitehorse, Yukon Territory (Doctoral dissertation, Université d'Ottawa/University of Ottawa).

Lim, D.S., Douglas, M.S., Smol, J.P. and Lean, D.R., 2001. Physical and chemical limnological characteristics of 38 lakes and ponds on Bathurst Island, Nunavut, Canadian High Arctic. International Review of Hydrobiology: A Journal Covering all Aspects of Limnology and Marine Biology, 86(1), pp.1-22.

Linkov, I., Satterstrom, F.K., Kiker, G., Batchelor, C., Bridges, T. and Ferguson, E., 2006. From comparative risk assessment to multi-criteria decision analysis and adaptive management: Recent developments and applications. Environment International, 32(8), pp.1072-1093.

López, D.L. and Smith, L., 1995. Fluid flow in fault zones: analysis of the interplay of convective circulation and topographically driven groundwater flow. Water resources research, 31(6), pp.1489-1503.

MacDonald, R. & Slimmon, W. (1999). Geological map of Saskatchewan (1:1000000). Saskatchewan Geological Survey, Saskatchewan Industry and Resources, Regina, SK.

Marles, R.J., Clavelle, C., Monteleone, L., Tays, N. and Burns, D., 2000. Aboriginal plant use in Canada's northwest boreal forest. UBC Press (University of British Columbia).

Martin, S.L. and Soranno, P.A., 2006. Lake landscape position: relationships to hydrologic connectivity and landscape features. Limnology and Oceanography, 51(2), pp.801-814.

Martins, T. (2013). Computing and visualizing PCA in R. Data Analysis & Statistics, R, Tools, Unsupervised techniques & visualization.

McCauley, C.A., White, D.M., Lilly, M.R. and Nyman, D.M., 2002. A comparison of hydraulic conductivities, permeabilities and infiltration rates in frozen and unfrozen soils. Cold Regions Science and Technology, 34(2), pp.117-125.

McCune, B., Grace, J.B. and Urban, D.L., 2002. Analysis of ecological communities (Vol. 28). Gleneden Beach, OR: MjM software design.

Meyboom, P., 1966. Unsteady groundwater flow near a willow ring in hummocky moraine. Journal of Hydrology, 4, pp.38-62.

Mielke, P.W. and Berry, K.J., 2007. Permutation methods: a distance function approach. Springer Science & Business Media.

Moser, K.A., Smol, J.P., Lean, D.R.S. and MacDonald, G.M., 1998. Physical and chemical limnology of northern boreal lakes, Wood Buffalo National Park, northern Alberta and the Northwest Territories, Canada. Hydrobiologia, 377(1-3), pp.25-43.

Mwale, D., Gan, T.Y., Devito, K.J., Silins, U., Mendoza, C. and Petrone, R., 2010. Regionalization of runoff variability of Alberta, Canada, by wavelet, independent component, empirical orthogonal function, and geographical information system analyses. Journal of Hydrologic Engineering, 16(2), pp.93-107.

National Wetlands Working Group (NWWG), 1988. Wetlands of Canada. Ecological land classification series, no. 24. Sustainable Development Branch, Environment Canada, Ottawa, Ontario, and Polyscience Publications Inc., Montreal, Quebec, 452.

Natural Resources Canada (NRC) (2016). Canadian Digital Elevation Model. Government of Canada, Natural Resources Canada, Map Information Branch.

Natural Resources Canada (NRC) (2017). CanVec – Hydro Features. Government of Canada, Natural Resources Canada.

Nip, A.M.K., 1991. The Tri-Creeks experimental watershed-changes in hydrology and water quality following forest harvesting. Alberta Forestry, Lands and Wildlife, Forest Service.

Norris, D.K., 1974. Map 1520A Geology Fort McPherson (1:250000). Geological Survey of Canada.

Nürnberg, G.K. and Shaw, M., 1999. Productivity of clear and humic lakes: nutrients, phytoplankton, bacteria. Hydrobiologia, 382(1-3), pp.97-112.

Olefeldt, D., Devito, K.J. and Turetsky, M.R., 2013a. Sources and fate of terrestrial dissolved organic carbon in lakes of a Boreal Plains region recently affected by wildfire. Biogeosciences, 10(10), pp.6247-6265.

Olefeldt, D., Turetsky, M.R. and Blodau, C., 2013b. Altered composition and microbial versus UV-mediated degradation of dissolved organic matter in boreal soils following wildfire. Ecosystems, 16(8), pp.1396-1412.

Oliver, B.G., Thurman, E.M. and Malcolm, R.L., 1983. The contribution of humic substances to the acidity of colored natural waters. Geochimica et Cosmochimica Acta, 47(11), pp.2031-2035.

Osgood, R.A., 2005. Shoreline density. Lake and Reservoir Management, 21(1), pp.125-126.

Palmer, A.R. and Klassen, R.W., 1981. Pleistocene geology and geomorphology of the Riding Mountain and Duck Mountain areas, Manitoba-Saskatchewan (Vol. 300). Geological Survey of Canada.

Paulen, R.C., Fenton, M.M. and Pawlowicz, J.G., 2004. Map 313 Surficial geology of the Willow River area (NTS 83O/NE) (1:100000). Alberta Geological Survey, Edmonton, AB.

Paulen, R.C., Pawlowicz, J.G. and Fenton, M.M., 2004. Map 312 Surficial geology of the Utikuma area (NTS 83O/NW) (1:100000). Alberta Geological Survey, Edmonton, AB.

Peters, D.P., Bestelmeyer, B.T. and Turner, M.G., 2007. Cross–scale interactions and changing pattern–process relationships: consequences for system dynamics. Ecosystems, 10(5), pp.790-796.

Petrone, R.M., Silins, U. and Devito, K.J., 2007. Dynamics of evapotranspiration from a riparian pond complex in the Western Boreal Forest, Alberta, Canada. Hydrological Processes: An International Journal, 21(11), pp.1391-1401.

Pfaff, J.D., 1993. Method 300.0 Determination of inorganic anions by ion chromatography. US Environmental Protection Agency, Office of Research and Development, Environmental Monitoring Systems Laboratory, 28.

Plach, J.M., Ferone, J.M., Gibbons, Z., Smerdon, B.D., Mertens, A., Mendoza, C.A., Petrone, R.M. and Devito, K.J., 2016. Influence of glacial landform hydrology on phosphorus budgets of shallow lakes on the Boreal Plain, Canada. Journal of Hydrology, 535, pp.191-203.

Prairie, Y.T., 2008. Carbocentric limnology: looking back, looking forward. Canadian Journal of Fisheries and Aquatic Sciences, 65(3), pp.543-548.

Prepas, E.E. and Rigler, F.H., 1982. Improvements in quantifying the phosphorus concentration in lake water. Canadian Journal of Fisheries and Aquatic Sciences, 39(6), pp.822-829.

Prepas, E.E., Planas, D., Gibson, J.J., Vitt, D.H., Prowse, T.D., Dinsmore, W.P., Halsey, L.A., McEachern, P.M., Paquet, S., Scrimgeour, G.J. and Tonn, W.M., 2001. Landscape variables influencing nutrients and phytoplankton communities in Boreal Plain lakes of northern Alberta: a comparison of wetland-and upland-dominated catchments. Canadian Journal of Fisheries and Aquatic Sciences, 58(7), pp.1286-1299.

Prior, G.J., Hathway, B., Glombick, P.M., Pana, D.I., Banks, C.J., Hay, D.C., Scheider, C.L., Grabe, M., Elgr, R. and Weiss, J.A., 2013. Map 600 Bedrock Geology of Alberta (1: 1000000). Alberta Geological Survey and Alberta Energy Regulator, Edmonton, AB.

Rawson, D.S., 1960. A limnological comparison of twelve large lakes in northern Saskatchewan. Limnology and oceanography, 5(2), pp.195-211.

Redding, T.E. and Devito, K.J., 2008. Lateral flow thresholds for aspen forested hillslopes on the Western Boreal Plain, Alberta, Canada. Hydrological Processes, 22(21), pp.4287-4300.

Reeder, S.W., Hitchon, B. and Levinson, A.A., 1972. Hydrogeochemistry of the surface waters of the Mackenzie River drainage basin, Canada—I. Factors controlling inorganic composition. Geochimica et Cosmochimica Acta, 36(8), pp.825-865.

Reid, J.M., MacLeod, D.A. and Cresser, M.S., 1981. Factors affecting the chemistry of precipitation and river water in an upland catchment. Journal of Hydrology, 50, pp.129-145.

Routh, J., Hugelius, G., Kuhry, P., Filley, T., Tillman, P.K., Becher, M. and Crill, P., 2014. Multi-proxy study of soil organic matter dynamics in permafrost peat deposits reveal vulnerability to climate change in the European Russian Arctic. Chemical Geology, 368, pp.104-117.

Sass, G.Z., Creed, I.F., Bayley, S.E. and Devito, K.J., 2008. Interannual variability in trophic status of shallow lakes on the Boreal Plain: Is there a climate signal?. Water resources research, 44(8).

Saunders, D.L. and Kalff, J., 2001. Nitrogen retention in wetlands, lakes and rivers. Hydrobiologia, 443(1-3), pp.205-212.

Schneider, R.R., Stelfox, J.B., Boutin, S. and Wasel, S., 2003. Managing the cumulative impacts of land uses in the Western Canadian Sedimentary Basin: a modeling approach. Conservation Ecology, 7(1).

Schuur, E.A., Crummer, K.G., Vogel, J.G. and Mack, M.C., 2007. Plant species composition and productivity following permafrost thaw and thermokarst in Alaskan tundra. Ecosystems, 10(2), pp.280-292.

Schuur, E.A., Vogel, J.G., Crummer, K.G., Lee, H., Sickman, J.O. and Osterkamp, T.E., 2009. The effect of permafrost thaw on old carbon release and net carbon exchange from tundra. Nature, 459(7246), p.556.

Seguin, M.K., Stein, J., Nilo, O., Jalbert, C., Ding, Y., Pomeroy, J. and Granger, R., 1999. Hydrogeophysical investigation of the Wolf Creek Watershed, Yukon Territory, Canada. Wolf Creek Research Basin: Hydrology, Ecology, Environment. National Water Research Institute, Environment Canada. Saskatoon, SK.

Sheath, R.G., Havas, M., Hellebust, J.A. and Hutchinson, T.C., 1982. Effects of long-term natural acidification on the algal communities of tundra ponds at the Smoking Hills, NWT, Canada. Canadian Journal of Botany, 60(1), pp.58-72.

Smerdon, B.D., Devito, K.J. and Mendoza, C.A., 2005. Interaction of groundwater and shallow lakes on outwash sediments in the sub-humid Boreal Plains of Canada. Journal of Hydrology, 314(1-4), pp.246-262.

Soranno, P.A., Cheruvelil, K.S., Bissell, E.G., Bremigan, M.T., Downing, J.A., Fergus, C.E., Filstrup, C.T., Henry, E.N., Lottig, N.R., Stanley, E.H. and Stow, C.A., 2014. Cross-scale interactions: quantifying multi-scaled cause–effect relationships in macrosystems. Frontiers in Ecology and the Environment, 12(1), pp.65-73.

Soranno, P.A., Cheruvelil, K.S., Webster, K.E., Bremigan, M.T., Wagner, T. and Stow, C.A., 2010. Using landscape limnology to classify freshwater ecosystems for multi-ecosystem management and conservation. BioScience, 60(6), pp.440-454.

Soranno, P.A., Webster, K.E., Riera, J.L., Kratz, T.K., Baron, J.S., Bukaveckas, P.A., Kling, G.W., White, D.S., Caine, N., Lathrop, R.C. and Leavitt, P.R., 1999. Spatial variation among lakes within landscapes: ecological organization along lake chains. Ecosystems, 2(5), pp.395-410.

Staehr, P.A., Sand-Jensen, K., Raun, A.L., Nilsson, B. and Kidmose, J., 2010. Drivers of metabolism and net heterotrophy in contrasting lakes. Limnology and Oceanography, 55(2), pp.817-830.

Stainton, M.P., Capel, M.J. and Armstrong, F.A.J., 1977. The Chemical Analysis of Freshwater, Fisheries and Environment of Canada Miscellaneous Special Publication, 25, pp.147-160.

Strahler, A.N., 1957. Quantitative analysis of watershed geomorphology. Eos, Transactions American Geophysical Union, 38(6), pp.913-920.

Street-Perrott, F.A., Hales, P.E., Perrott, R.A., Fontes, J.C., Switsur, V.R. and Pearson, A., 1993. Late Quaternary palaeolimnology of a tropical marl lake: Wallywash Great Pond, Jamaica. Journal of Paleolimnology, 9(1), pp.3-22.

Tank, S.E., Lesack, L.F., Gareis, J.A., Osburn, C.L. and Hesslein, R.H., 2011. Multiple tracers demonstrate distinct sources of dissolved organic matter to lakes of the Mackenzie Delta, western Canadian Arctic. Limnology and Oceanography, 56(4), pp.1297-1309.

Tarnocai, C., Kettles, I.M. and Lacelle, B., 2011. Peatlands of Canada database. Geological Survey of Canada Open File 6561. Natural Resources Canada, Ottawa, Canada.

Tetzlaff, D., Seibert, J. and Soulsby, C., 2009. Inter-catchment comparison to assess the influence of topography and soils on catchment transit times in a geomorphic province; the Cairngorm mountains, Scotland. Hydrological Processes: An International Journal, 23(13), pp.1874-1886.

Therneau, T. & Atkinson, B. (2005). The mvpart Package.

Thompson, C., Mendoza, C.A. and Devito, K.J., 2017. Potential influence of climate change on ecosystems within the Boreal Plains of Alberta. Hydrological processes, 31(11), pp.2110-2124.

Toth, J., 1963. A theoretical analysis of groundwater flow in small drainage basins. Journal of geophysical research, 68(16), pp.4795-4812.

Tóth, J., 1999. Groundwater as a geologic agent: an overview of the causes, processes, and manifestations. Hydrogeology journal, 7(1), pp.1-14.

Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Finlay, K., Fortino, K., Knoll, L.B., Kortelainen, P.L., Kutser, T., Larsen, S., Laurion, I., Leech, D., McCallister, S., McKnight, D., Melack, J., Overholt, E., Porter, J., Prairie, Y., Renwick, W., Roland, F., Sherman, B., Schindler, D., Sobek, S., Tremblay, A., Vanni, M., Verschoor, A., von Wachenfeldt, E. and Weyhenmeye, G., 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnology and Oceanography, 54(6, part 2), pp.2298-2314.

Turner, J.V., Fritz, P., Karrow, P.F. and Warner, B.G., 1983. Isotopic and geochemical composition of marl lake waters and implications for radiocarbon dating of marl lake sediments. Canadian Journal of Earth Sciences, 20(4), pp.599-615.

Turner, M.G. and Gardner, R.H.,2015. Landscape Ecology in the Theory and Practice: The Critical Concept of Scale. London: Springer, pp.24-45.

Viljoen, D., Chackowsky, L., Lenton, P. and Broome, H.. Geological Map of Manitoba, accessed on 2 August 2016, https://web33.gov.mb.ca/mapgallery/mgg-gmm.html.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H. and Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: sources and consequences. Ecological applications, 7(3), pp.737-750.

Vitt, D.H., Bayley, S.E. and Jin, T.L., 1995. Seasonal variation in water chemistry over a bog-rich fen gradient in continental western Canada. Canadian Journal of Fisheries and Aquatic Sciences, 52(3), pp.587-606.

Vitt, D.H., Halsey, L.A. and Zoltai, S.C., 1999. The changing landscape of Canada's western boreal forest: the current dynamics of permafrost. Canadian Journal of Forest Research, 30(2), pp.283-287.

Vogwill, R.I., 1978. Hydrogeology of the Lesser Slave Lake area, Alberta. Report 77-1 1978. 32 p, 6 fig, 1 tab, 3 map, 28 ref, 2 append.

Walters, C., 1997. Challenges in adaptive management of riparian and coastal ecosystems. Conservation ecology, 1(2).

Walvoord, M.A. and Kurylyk, B.L., 2016. Hydrologic impacts of thawing permafrost—A review. Vadose Zone Journal, 15(6).

Walvoord, M.A. and Striegl, R.G., 2007. Increased groundwater to stream discharge from permafrost thawing in the Yukon River basin: Potential impacts on lateral export of carbon and nitrogen. Geophysical Research Letters, 34(12).

Webster, K.E., Kratz, T.K., Bowser, C.J., Magnuson, J.J. and Rose, W.J., 1996. The influence of landscape position on lake chemical responses to drought in northern Wisconsin. Limnology and Oceanography, 41(5), pp.977-984.

Wetzel, R.G., 1975. Limnology. Philadelphia: WB Saunders Company, pp.180-185, 255, 743.

Weyhenmeyer, G.A., Fröberg, M., Karltun, E., Khalili, M., Kothawala, D., Temnerud, J. and Tranvik, L.J., 2012. Selective decay of terrestrial organic carbon during transport from land to sea. Global Change Biology, 18(1), pp.349-355.

Winter, T. and Woo, M., 1990. Hydrology of lakes and wetlands. Surface Water Hydrology, Geological Society of America, pp.159– 187.

Winter, T.C., 2000. THE VULNERABILITY OF WETLANDS TO CLIMATE CHANGE: A HYDROLOGIC LANDSCAPE PERSPECTIVE 1. JAWRA Journal of the American Water Resources Association, 36(2), pp.305-311.

Winter, T.C., 2001. THE CONCEPT OF HYDROLOGIC LANDSCAPES 1. JAWRA Journal of the American Water Resources Association, 37(2), pp.335-349.

Winter, T.C., Rosenberry, D.O. and LaBaugh, J.W., 2003. Where does the ground water in small watersheds come from?. Groundwater, 41(7), pp.989-1000.

Withey, P. and van Kooten, G.C., 2011. The effect of climate change on optimal wetlands and waterfowl management in Western Canada. Ecological Economics, 70(4), pp.798-805.

Yang, H., Andersen, T., Dörsch, P., Tominaga, K., Thrane, J.E. and Hessen, D.O., 2015. Greenhouse gas metabolism in Nordic boreal lakes. Biogeochemistry, 126(1-2), pp.211-225.