An interdisciplinary approach to monitoring the hydroecology of thermokarst lakes in Old Crow Flats, Yukon Territory, Canada

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Science
in
Biology

Waterloo, Ontario, Canada, 2012

AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Lake-rich thermokarst landscapes, such as Old Crow Flats (OCF) in northern Yukon, Canada have been identified as amongst the most vulnerable to climate change. This has raised concerns of the Vuntut Gwitchin First Nation (VGFN) and Parks Canada (Vuntut National Park) about the ecological integrity of this significant wetland. The influence of climate change on the hydroecological conditions of thermokarst lakes are complex and vary across the landscape, thus long-term hydroecological monitoring is essential to adequately assess the ecological integrity of the aquatic ecosystem and how it is changing over time. In a genuine interdisciplinary and collaborative approach, this thesis establishes an integrated approach using isotope hydrology, aquatic ecology, and paleolimnology to develop a robust long-term aquatic monitoring program that has already been adopted by Parks Canada.

In collaboration with Parks Canada, 14 of 58 lakes that were previously studied during the International Polar Year from 2007-09 were selected to represent monitoring lakes. Lakes were sampled in early June and late August/early September 2010-11. Water samples for analysis of hydrogen and oxygen isotope composition and chemistry (i.e., ions and nutrients) were collected to track hydrological and limnological conditions. Artificial substrates were deployed in June and accrued algae were collected at the end of the ice-free season to assess community composition and abundance. Sediment coring was conducted in a culturally-significant lake (Zelma Lake – OCF06) to reconstruct long-term baseline hydroecological conditions over the past three centuries. Radiometric dating techniques (^{137}Cs, ^{210}Pb) were used to develop a sediment core chronology. Baseline hydroecological conditions were reconstructed through analyses of loss-on-ignition, bulk organic carbon and nitrogen elemental and isotope compositions, and pigments.

Meteorological data and a multi-year evaporation pan experiment were used to develop a robust isotope framework, which provides the basis for interpreting five years (2007-11) of lake water isotope measurements and deriving knowledge of hydrological conditions for the monitoring lakes. Using this framework and the coupled-isotope tracer method, isotopic compositions of input water (δ_I) and evaporation-to-inflow (E/I) ratios were calculated and provide key hydrological information for each sampling interval. δ_I values distinguish snowmelt- and rainfall-sourced lakes, with δ_P representing a threshold between the two isotopic-based hydrologic regimes. A Mann-Kendall test showed that three lakes (OCF11, 26, and 49) displayed significant increasing trends in δ_I values indicating a potential transition from snowmelt-sourced to rainfall-sourced isotope-based hydrologic-regimes. E/I ratios >0.5 signifies lakes that are evaporation-dominated with positive water balances and E/I ratios >1 indicates lakes that are evaporation-dominated with negative water balances. Six lakes in OCF (OCF06, 19, 37, 46, 49, and 58) surpass the 0.5 threshold and three of these lakes (OCF06, 19, and 46) crossed the significant evaporation threshold (E/I > 1) during dry climatic conditions.

Multi-proxy paleolimnology analysis conducted on Zelma Lake reveals different hydroecological transitions during the past ~330 years that include: phase 1 (~1678-1900) characterized by stable hydroecological conditions; thermokarst expansion (~1900-1943) marked by decreases in productivity; phase 2 (~1943-2007) distinguished by increasing productivity; and a post drainage phase following rapid drainage in 2007 characterized by further increases in productivity. The stratigraphy of Zelma Lake shows that hydroecological conditions in dynamic landscapes such as OCF are complex and require multi-proxy paleolimnological analysis. In particular, organic matter, $\delta^{13}C_{org}$, and pigment concentrations are important parameters to consider when interpreting past hydroecological conditions, thermokarst expansion, and lake drainage events.

Acknowledgements

"Wherever you fly, you'll be the best.
Wherever you go, you will top all the rest.
Except when you don't, because sometimes you won't.
You can get all hung up, you can get so confused.
But on you will go, because that is not for you.
And will you succeed? Yes! You will indeed!"

- Dr. Seuss

I would like to thank my supervisors, Brent Wolfe and Roland Hall, for your continued support in all my endeavors, your constant encouragement, your enduring enthusiasm, your positive reinforcement, and buying beer at the Grad House. Brent, thank-you for always being excited about new accomplishments and reading them promptly, for never telling me exactly what to do (much to my dismay) and allowing me to figure things out, for reminding me that I can accomplish tasks when I feel they are unattainable, and for challenging me. Roland, thank-you for your positive attitude, for always answering my random questions, and for listening when I just needed to talk about data to understand it. I would also like to thank my committee member and neighbour, Tom Edwards, for your boundless entertainment, conversations at the Grad House, and throwing down the odd roll of toilet paper when needed. I would like to thank Bill Taylor for being on my committee, for letting me borrow lab equipment, and for always having an open-door. Thanks to Jon Sweetman for also being on my committee and providing feedback.

I would like to thank Ian McDonald for being involved with this thesis and providing feedback, participating in all my milestones, providing resources and funding, and supporting my NSERC Northern Research Internship. I am grateful to Parks Canada staff (Leila Sumi, David Frost, Esau Schafer, and Jeffrey Peter) for helping me conduct field work and your unbelievable support when field logistics became exceedingly complicated. Thank-you for expanding the scope of the spring boat trip into Old Crow Flats to include sampling some of the monitoring lakes, organizing everything, and accommodating me. A special thanks to Joel Peter for your keen interest in this research project and guiding the trip, and to Sam Darling for coordinating the return of my precious samples, thesis-vent sessions, and all of your encouragement.

I would like to thank the Vuntut Gwitchin Government (VGG) for supporting this research project and providing key resources. In particular, I would like to thank Shel Graupe, Lance Nagwon, James Itsi, Megan Williams, Edna Kyikavichik, Dick Mahoney, Danny Kassi, and Mary-Jane Mossess for all your help and support with field work and logistics. Thanks to Steve Climie for always letting me transform the school kitchen into a laboratory. Thanks to Florence Netro for lending me your canoe and allowing me to sample Mary Netro Lake. I would also like to thank the VGG for inviting me to participate in Science Camp and purchasing my flight from Whitehorse to Old Crow. A special thanks to Jessica Peter for opening your home and letting me stay with you. I would also like to thank the community of Old Crow for being tremendously hospitable and generously filling my belly with too much food!

I would like to thank all members of the Wolfe and Hall lab groups for your help to complete this research by providing critical feedback and sharing laughs. I have appreciated being part of a large, diverse research group that is always willing to help each other out. A special thanks to Ann Balasubramaniam, Kevin Turner, Katie Thomas, and Nick Sidhu for traveling to Old Crow with me, helping me collect samples, and transporting them to Waterloo. In particular, thanks to Ann Balasubramaniam and Kevin Turner for guiding me through field work and integrating me into the IPY project. Ann - I am indebted to your continuous support and countless conversations about Old Crow. Kevin – I appreciate all your help with water isotopes, answering my badgering emails, and making maps. I would also like to thank Lauren MacDonald for teaching me how to construct periphyton samplers, your technical guidance in the lab, and always delivering my water samples to NLET. Thanks to Johan Wiklund for developing sediment core chronologies and your input on lab methodologies. I would like to extend a big thank-you to Pete Thompson for all your help with statistics.

I would like to especially thank the many friends that I have made in Waterloo, who have made Ontario not so terrible. Thank-you to Ann Balasubramaniam, Madeline Rosamond, Jennifer Hood, Pete Thompson, Jennifer Fresque-Baxter, Andrea Bartram, Brent Lazenby, Justin Harbin, Jessica Leung, and Marcelo Sousa for great memories and giving me heaps of moral support when I needed it. Thanks to the Grad House crew for always being there with a smile of your face; and to the Grad House for never increasing the price of Fireball!

Lastly, I would like to thank my parents. I am grateful for your unwavering love and support in everything that I do. Thank-you for listening to me go on, and on, and on, and on about how the Harper government is systematically impeding the flow of scientific knowledge, the importance of the Experimental Lakes Area, and for sharing information about World Water Day and helping me create awareness. Thanks for always answering the phone whatever time of day and for loving me to infinity and beyond (all the way to trinity)!

Financial support for this research was provided by the Natural Sciences and Engineering Council of Canada Northern Research Chair Program, the International Polar Year, the Polar Continental Shelf Program, the Northern Scientific Training Program, Parks Canada, and the Vuntut Gwitchin Government. I would also like to thank the NSERC Canadian Graduate Scholarship, the University of Waterloo President Scholarship, the Davis Memorial Scholarship, and the Golder and Associates Scholarship for additional funding. I would also like to thank the NSERC Northern Research Internship program, Parks Canada, and Yukon College for enabling a northern internship in Whitehorse during the summer of 2010.

Table of Contents

AUTHOR'S DECLARATION ii

Abstract iii

Acknowledgements v

Table of Contents viii

List of Figures xi

List of Tables xiii

Chapter 1 Introduction 1

1.1 Arctic climate change 1

1.2 Arctic lakes in transition 2

1.3 International Polar Year 4

1.4 Old Crow Flats 5

1.5 Ecological integrity 6

1.6 Long-term aquatic monitoring 9

1.6.1 Water isotope tracers to monitor hydrology 12

1.6.2 Periphyton (diatoms and pigments) to monitor aquatic ecology 13

1.6.3 Multi-proxy paleolimnology to assess natural variability 15

1.7 Research objectives and thesis overview 16

Chapter 2 Developing a long-term hydrological monitoring program for a northern lake-rich landscape using water isotope tracers 18

2.1 Abstract 18

2.2 Introduction 19

2.3 Study area 24

2.3.1 Monitoring lakes 26

2.4 Methods 28

2.4.1 Meteorological data 28

2.4.2 Water isotope sampling and analysis 28

2.4.3 Trend analysis 31

2.5 Results 31

2.5.1 Meteorological conditions 31

2.5.2 Developing an isotopic framework 32
2.5.3 Monitoring lake hydrological conditions with water isotopes 33
2.6 Discussion 36
2.6.1 An isotopic framework for long-term monitoring 38
2.6.2 Monitoring lake hydrological conditions with water isotopes 39
2.7 Conclusion 42
2.8 Calculations I 44
2.8.1 Meteorological calculations 44
2.8.2 Isotopic framework calculations 45
2.8.3 Calculations for E/I ratios 46
2.9 Calculations II 47
Chapter 3 Effects of climate change on the hydroecology of a shallow thermokarst lake in northwestern Canada: a paleolimnological perspective 61
3.1 Introduction 61
3.2 Site Description 64
3.3 Methods 66
3.3.1 Sediment core collection and physical characteristics 66
3.3.2 Sediment core chronology 66
3.3.3 Geochemical analysis 67
3.3.4 Pigment analysis 67
3.4 Results and interpretation 68
3.4.1 Sediment core chronology 68
3.4.2 Physical and geochemical analysis 69
3.4.3 Pigment analysis 71
3.5 Discussion 72
3.6 Conclusion 77
3.7 Appendix 3A - Additional sediment cores 78
Chapter 4 Summary and Recommendations 90
4.1 Summary 90
4.2 Recommendations 92

4.2.1 Water isotope tracers to monitor hydrology 93
4.2.2 Periphyton (diatoms and pigments) to monitor aquatic ecology 94
4.2.3 Multi-proxy paleolimnology to assess natural variability 96
4.3 Future research 98
Appendix A Northern hydroecological monitoring in Old Crow Flats, YT (Vuntut National Park): a guide to field methods 100
Appendix B From student to researcher: lessons learned from an NSERC northern research internship 135
Appendix C Letter of agreement 148
Appendix D Water isotopic values (δ_L,δ_I,and E/I) 151
Appendix E Limnology data 155
Appendix F Paleolimnological data 163
References 184

List of Figures

Figure 1-1. Old Crow Special Management Area and Vuntut National Park (Parks Canada, 2009). 6

Figure 1-2. Conceptual model of the hydroecological monitoring program. 12

Figure 2-1. Map showing the location of 14 lakes selected for the hydroecological monitoring program in Old Crow Flats, Yukon Territory. Catchment areas are outlined (see Turner *et al.* In review). 48

Figure 2-2. Photographs of selected monitoring lakes in OCF. 49

Figure 2-3. Schematic $\delta^{18}O$-δ^2H diagram illustrating two hypothetical lakes (Lake 1 and Lake 2) with typical δ_L values that have been extended to the Global Meteoric Water Line (GMWL) to provide an estimate of δ_I. Key isotopic framework labeling features in relation to the Local Evaporation Line (LEL) include amount-weighted mean annual precipitation (δ_P), the limiting steady-state isotope composition where evaporation is equal to inflow (δ_{SSL}), and the limiting isotopic enrichment (δ^*) of a desiccating basin under thaw season conditions. Parameters that are used in isotope mass-balance models to derive evaporation-to-inflow (E/I) ratios include the lake water isotope composition (δ_L), input water isotope composition (δ_I), and the isotopic composition of evaporated vapour from the lake (δ_E). 52

Figure 2-4. Mean (1971-2000) monthly air temperature (°C) and total monthly precipitation (mm) recorded at the Old Crow weather station (Station ID: 2100800 and 2100805) from 2007 to 2011 (Environment Canada, 2012). 53

Figure 2-5. a) Isotopic evolution of $\delta^{18}O$ of water sampled from an evaporation pan maintained at the Old Crow airport from June to September, 2007-10. b) Evaporation pan evolution is consistent among years and cluster around an average δ_{SSL} (-11.8‰ for $\delta^{18}O$ and -126‰ for δ^2H). c) A four-year mean LEL ($\delta^2H = 4.7\delta^{18}O - 71.7$) was extended through the isotopic composition of pan input water ($\delta_{I\text{-}Pan}$) to the Global Meteoric Water Line (GMWL). 54

Figure 2-6. Isotopic composition of monitoring lakes (δ_L) superimposed on the four-year mean monitoring isotopic framework for each sampling year: a) 2007, b) 2008, c) 2009, d) 2010, e) 2011 and f) the five-year mean for each hydrologic category as designated by Turner et al. (2010). 56

Figure 2-7. Calculated isotopic input water composition (δ_I) for each monitoring lake from 2007-11. 57

Figure 2-8. Temporal distribution of the isotopic input water composition (δ_I) for each monitoring lake from 2007-11. Solid line represents the four-year average amount-weighted mean annual precipitation (δ_P) and the dashed lines represents mean δ_I value 58

Figure 2-9. Temporal distribution of evaporation-to-inflow (E/I) ratios during 2007-11. An E/I ratio > 0.5 represents the threshold for evaporation-dominated lakes (Turner *et al.* In review) and is designated by a dotted line. The dotted line at E/I = 1 represents δ_{SSL}. 60

Figure 3-1. Map of Old Crow Flats (OCF), Yukon Territory, Canada and location of the monitoring lakes from which sediment cores were collected. 82
Figure 3-2. Schematic stratigraphic profiles of organic matter content predicted to be associated with a) rapid drainage and b) evaporative drawdown (MacDonald *et al.* 2012b, pg 127). 83
Figure 3-3. Aerial photographs showing the historical extent of Zelma Lake (OCF6) from 1951, 1972, 2007, and June 2011. Aerial images from 1951 and 1972 were scanned at the Energy, Mines, and Resources library in Whitehorse, Yukon, the 2001 photograph is from SPOT image, and the 2011 image was taken during a helicopter flight. 84
Figure 3-4. Isotopic composition of water samples collected from Zelma Lake during 2007-11 superimposed on a four-year mean isotopic framework (see Chapter 2). The isotopic composition of global precipitation is defined by the Global Meteoric Water Line (GMWL) such that $\delta^2H = 8\delta^{18}O + 10‰$ and local surface water that has been influenced by evaporation is delineated by the Local Evaporation Line (LEL)(Craig 1961). Key isotopic labeling features used to quantify lake water balance are shown and include: the limiting steady-state isotope composition where evaporation is equal to inflow (δ_{SSL}), the limiting isotopic composition of a basin approaching desiccation (δ^*), ambient atmospheric moisture composition (δ_{AS}) and the amount-weighted mean annual precipitation (δ_P). 86
Figure 3-5. a) ^{210}Pb, ^{214}Bi and ^{137}Cs activity profiles for Zelma Lake. b) Zelma Lake sediment core chronology based on the Constant Rate of Supply (CRS) model and linear extrapolated dates. The ^{137}Cs peak activity occurs between 5.5 and 7.5 cm depth, consistent with peak nuclear fall-out ~1963. 87
Figure 3-6. Physical and geochemical measurements for the Zelma Lake sediment core showing organic matter, mineral matter, calcium carbonate, sedimentation rate, percent dry weight organic carbon, nitrogen content as percent of dry mass, percent weight carbon-to-nitrogen (C/N) ratios, isotopic composition of organic carbon, and isotopic composition of nitrogen. Tree ring-width index from spruce trees located across OCF is also shown (see Porter & Pisaric 2011). 87
Figure 3-7. Fossil pigment stratigraphy displaying the concentration (nMol g^{-1} organic matter) of the most abundant chlorophyll and carotenoid pigments in the Zelma Lake core. 88
Figure 3-8. Physical and geochemical stratigraphic profiles for a) OCF48, b) OCF35, c) OCF29, and d) OCF11 as well as tree ring-width data from OCF (black circles) and trees collected from across northwestern North America (grey circles) (see Porter & Pisaric 2011). Also shown are aerial images for each lake with relict shorelines outlined in white dashed lines. 89

List of Tables

Table 2-1. Selected hydrological and catchment characteristics for monitoring lakes. Hydrological categories are based on Turner et al. (2010) and vegetation cover is based on Landsat imagery (Turner et al. In press). 50

Table 2-2. The mean and standard deviation of selected limnological characteristics of monitoring lakes, grouped into hydrological categories. Values represent the average of samples collected in June and August during the 2010 and 2011 sampling campaigns. 51

Table 2-3. Flux-weighted thaw season temperature and relative humidity based on WLU meteorological station set up at Old Crow airport and parameters used to construct an average isotopic framework for long-term monitoring based on 2007-11 evaporation pan data 55

Table 2-4. General statistics and summary statistics of the Mann-Kendall and Seasonal Kendall trend tests for a) $\delta^{18}O_I$ values and b) E/I ratios..59

Table 3-1. Selected limnological characteristics of Zelma Lake (OCF6). Values represent the average early ice-free season (June) and late ice-free season (late August/early September) conditions and standard deviation of samples collected in 2010 and 2011. 85

Chapter 1

Introduction

National parks and protected areas are becoming increasingly important for the conservation of biodiversity and physical landscapes in light of climate change. This is especially true for northern wetlands like Old Crow Flats (OCF) that have been identified as vulnerable to climate change. Traditional knowledge from indigenous circum-Arctic communities, such as the Vuntut Gwitchin First Nation of Old Crow, Yukon, has echoed that the landscape is changing rapidly, leading to widespread community concern regarding the ecological integrity of their traditional territory and its vulnerability to climate change. However, while this vulnerability is recognized, knowledge is lacking regarding how and at what rate these landscapes are changing. In an effort to address these anxieties and understand the complexity of changes that are occurring in OCF, the Government of Canada funded a multi-disciplinary research project to study the physical and biological components of the ecosystem as part of the International Polar Year (IPY) program. Extending beyond the IPY program, this thesis focuses on establishing a legacy of long-term agency-and community-based hydroecological monitoring, in partnership with Parks Canada, that will increase broad understanding of ecosystem change and will serve to inform future policy and land-use management decisions while enabling the capacity for local stewardship.

1.1 Arctic climate change

The Arctic supports a vast array of biodiversity and is homeland to many indigenous cultures that are under growing pressure from climate change. The Arctic Biodiversity Assessment (Hohn & Jaakkola 2010) described climate change as the most significant stressor on Arctic biodiversity, and the United Nations Environment Program (2008) expressed 'extreme concern' over the significant consequences of the rapid alterations occurring throughout the circumpolar North. Polar amplification of anthropogenic climate change through positive feedback mechanisms of cryospheric processes (e.g., ice-albedo, ice-insulation, cloud cover, vegetation, and permafrost feedbacks) increases the sensitivity of northern ecosystems, leaving landscapes, species, and individuals in a state of vulnerability (Serreze *et al.* 2000; Hinzman *et al.* 2005; Hohn & Jaakkola 2010; Miller *et al.* 2010). These changes also affect regions outside the Arctic due to the planetary energy balance and global atmospheric and oceanic circulation systems.

Multi-proxy paleoenvironmental studies of lacustrine and marine sediments, glacier ice, and tree rings have shown a wide variety of changes in circum-Arctic conditions during the Quaternary and reveal progressive warming during the past 400 years (Overpeck *et al.* 1997; Prowse *et al.* 2009a; Miller *et al.* 2010). Paleolimnological evidence has shown unprecedented warming in the past approximately 150 years, which has caused dramatic and unidirectional regime shifts in northern freshwater ecosystems (Smol *et al.* 2005). During the 20th century, four of the five warmest decades of a 2000-year-long composite record occurred between 1950 and 2000 despite a reduction of summer insolation across the Arctic (Kaufman *et al.* 2009; Miller *et al.* 2010). In the past 50 years, northern temperatures have increased up to 2-3°C and are projected to increase another 2.5°C by the mid-21st century and up to 5-7°C by the end of the 21st Century (ACIA 2005).

1.2 Arctic lakes in transition

In recent years, the rate of climate warming has resulted in profound hydrological transitions and regime shifts in the biological communities of many high-latitude lakes (Schindler & Smol 2006; Carroll *et al.* 2011; Karlsson *et al.* 2011). Thermokarst lakes naturally form, expand, and drain in ice-rich sediments and are the most abundant aquatic ecosystems across the Arctic (Vincent *et al.* 2011; Grosse *et al.* 2012). Thawing of near-surface permafrost, ground that has remained below 0°C for more than two years, increases permeability and thickens the active layer, causing widespread changes in the distribution of surface water across the landscape (Rowland *et al.* 2010). Ground-ice distributions, thermokarst lake water balances, and geomorphic responses to warming temperatures display marked heterogeneity. Although climate warming is universally and rapidly altering the hydroecology of northern lakes, remote sensing analysis and field observations have revealed divergent pathways of water-level increases due to lake expansion (Payette 2004; Smith *et al.* 2005) and water-level declines through partial or complete drainage events (Yoshikawa & Hinzman 2003; Riordan *et al.* 2006; Hinkel *et al.* 2007; Wolfe & Turner 2008) as well as increases in evaporation (Smol & Douglas 2007).

The degradation of near-surface permafrost can alter the structure and function of aquatic ecosystems in a variety of ways. Thawing of permafrost leads to extensive shoreline erosion and thaw slumps that introduce inorganic suspended sediments, which increases turbidity and decreases light penetration through the water column thereby reducing photosynthetic activity and inhibiting primary production (MacDonald *et al.* 2012b). In the Mackenzie Delta, lakes affected by thaw slumping exhibited elevated ion concentrations due to the erosion and transport of ancient glacial deposits that are ion-rich (Kokelj *et al.* 2005; 2009b). On the other hand, Hobbie *et al.* (1999) found that thawing permafrost released stored nutrients to an Arctic lake ecosystem in Alaska, particularly phosphorus. Nutrient enrichment may be due to slumping of nutrient-rich allochthonous material into the lake or from supra-permafrost groundwater flow through the active layer. As temperatures become progressively warmer, the active layer thickens, increasing the interaction of input water with organic-rich soils (Frey & McClelland 2009). In a manipulated experiment, Hobbie *et al.* (1999) revealed that Arctic aquatic ecosystems displayed a similar eutrophication response to nutrient enrichment as temperate lakes, such as increased phytoplankton productivity and biomass, as well as cyanobacteria blooms.

In many areas of the Arctic, evaporation and evapotranspiration exceed precipitation. Warmer temperatures amplifies the ratio of evaporation to precipitation, leading to declines in water levels and elevated concentrations of ions and nutrients in shallow lakes (Schindler & Smol 2006; Smol & Douglas 2007). Warmer temperatures also enhance evaporation by extending the length of the ice-free season.

During the past 50 years, earlier breakup and delayed freeze-up of lake-ice across the Arctic have been observed (Prowse & Brown 2010), as well as substantial declines in snow-cover duration (Brown & Mote 2009). Arctic lakes are characterized by extended periods of ice-cover, and longer growing seasons will profoundly affect limnological characteristics. Shorter intervals of snow and ice-cover permit greater light penetration, which enhances photosynthetic activity and leads to increasing primary production and macrophyte growth (Douglas & Smol 1999). Decreased ice-cover also increases wind-induced mixing and nutrient inputs from catchments, further stimulating primary production. Conversely, thinner ice cover may reduce the amount of solutes and nutrients that precipitate out from freezing water. This sub-ice layer of nutrients is important for phytoplankton and zooplankton communities, an effect that will diminish with higher temperatures that promote thinner and shorter ice cover (Schindler & Smol 2006). Climate change will affect hydrological and ecological conditions directly (loss of water) and indirectly (changes in water clarity and water chemistry, including nutrient supply and nutrient cycling) that will have cascading effects on aquatic biological communities (e.g., zooplankton, aquatic invertebrates, fish, and waterfowl).

1.3 International Polar Year

In an effort to address the complexities of climate change, an ambitious, collaborative, international research effort, the International Polar Year, was coordinated by the International Council for Science and the World Meteorological Organization to quantify and understand past and present environmental and human changes within the Polar Regions. As part of this project, the Government of Canada funded a multidisciplinary research effort to study the physical and biological components of a northern wetland – Old Crow Flats, Yukon Territory. The research project "Environmental change and traditional use of the Old Crow Flats in northern Canada (*Yeendoo Nanh Nakhweenjit K'atr'ahanahtyaa*)" began in 2007 and included a broad scope of disciplines including dendrochronology, community health, hydroecology, permafrost science, terrestrial ecology, traditional knowledge, wildlife biology, and Quaternary paleontology. This research project integrated traditional and scientific approaches to: i) document this history of environmental change from the last interglacial to the present; ii) assess the distribution and abundance of wildlife; iii) evaluate the impact of change on traditional food sources; and iv) develop a long-term environmental monitoring program to be conducted by the local community into the future (Wolfe *et al.* 2011a).

1.4 Old Crow Flats

Old Crow Flats (OCF), northern Yukon, is a large (5600 km^2) thermokarst landscape with approximately 2700 shallow lakes that provide a unique breeding, moulting, and staging habitat for half a million waterfowl and is a highly productive environment for moose, grizzly bear, muskrat, mink, caribou (Porcupine Caribou Herd), and other wildlife. Old Crow Flats, known as *Van Tat* (many lakes) in the Gwitchin language, is a central part of the Vuntut Gwitchin First Nation (VGFN) traditional lifestyle and is vital for cultural practices and subsistence use. Internationally recognized for its valuable habitat and cultural significance (Ramsar, 1982), OCF is cooperatively managed by VGFN, Parks Canada (Vuntut National Park) and the North Yukon Renewable Resource Council (Figure 1-1). The jurisdictional boundaries of Vuntut National Park and Old Crow Flats Special Management Area (shown in Figure 1-1) were established in 1995 as part of the Vuntut Gwitchin First Nation Final Land Claims Agreement and are managed by Parks Canada and VGFN, respectively. As part of the Umbrella Final Agreement (1993), the North Yukon Renewable Resources Council was also established to represent the voice of local community members when managing renewable resources. Together, these three organizations are committed to co-managing and preserving the ecological integrity of this pristine landscape, and together they are concerned about rapidly changing lake levels and the impact climate change will have on the future conditions of OCF.

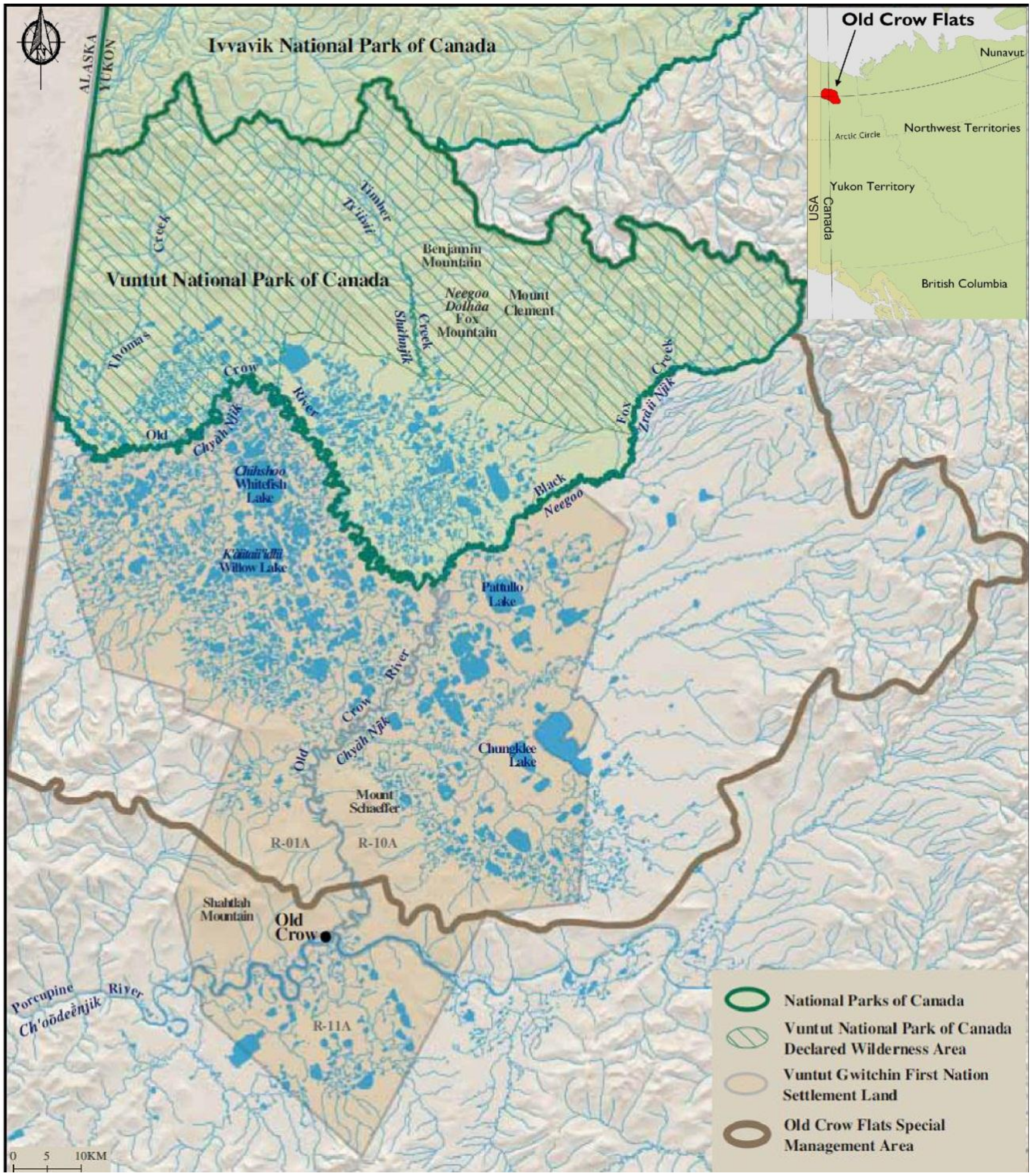

Figure 1-1. Old Crow Special Management Area and Vuntut National Park (Parks Canada, 2009).

1.5 Ecological integrity

Maintaining the ecological integrity of ecosystems has become a common objective for park managers, conservation authorities, monitoring programs, government projects, and sustainability initiatives throughout Canada, USA, and European Union. The concept of (biological) integrity entered

North American environmental policy and law in the late 1960s. Parks Canada introduced ecological integrity into national parks policy in 1979, and in 2001 revised the *National Parks Act* legislating that restoring and maintaining ecological integrity through the protection of natural resources and natural processes shall be the first priority of the agency. Despite the use of the term "ecological integrity" within policy, legislation, and law, the concept remains challenging to define because it incorporates complex and controversial scientific and philosophical issues. In a general sense, ecological integrity relates to the 'natural' conditions of an ecosystem, which is vague, qualitative, and challenging to define, especially in dynamic landscapes such as OCF. Ecological integrity can be viewed as an umbrella concept built on a foundation of values deeply rooted in Aldo Leopold's land ethic such that: "a thing is right when it tends to preserve the integrity, stability, and beauty of the biotic community. It is wrong when it tends otherwise" (Leopold 1949, pg 91).

Key elements that embody the concept of ecological integrity are native species, natural processes, biodiversity, resistance and resilience to natural stresses, ecosystem heath, and minimal human activity (Turner & Beazley 2004 and references therein). Each of these concepts is complex, yet many of the controversial issues within each idea are resolved when they are incorporated under the umbrella of ecological integrity. For example, biodiversity refers to the variety of life on genetic, species, and ecosystem levels within a particular geographic area; yet, it does not differentiate between naturally evolved and artificial biodiversity. However, when looking at biodiversity through the lens of ecological integrity one would consider the variation of local species across space and time, thus adding a native criterion. Ecosystem health is considered a separate concept under the umbrella of ecological integrity, although it is sometimes, incorrectly, considered an analogous term. Ecosystem health is not sufficient to define integrity given that an ecosystem, like a person, can be healthy without containing all its natural components, for example, a person may be healthy with a single kidney (Westra 1994 as cited in Turner & Beazley 2004). Yet, under the holistic notion of ecological integrity, a distinction is made between healthy and incomplete ecosystems, which the concept of ecosystem health alone does not necessarily express. Ecological integrity is further distinguished from ecosystem health in that a system has integrity if it can reorganize in the face of environmental change (resiliency) and the ability to continue to self-organize in its normal environment (Kay & Regier 2000). The largest debate surrounding ecological integrity relates to the place of humans in nature and the notion that an ecosystem with integrity will have been minimally altered by human activities. The Global Ecological Integrity Group (www.globalecointegrity.net) advocates that ecological integrity can only be preserved if it is untouched by humans, while others view that the preservation of ecological integrity is contingent on the belief that human and ecological interests can co-exist. Since literature remains divided on the perception of the human-nature dualism, Fluker (2010) splits these viewpoints into natural ecological integrity and socio-ecological integrity, respectively.

Discussions surrounding the meaning of ecological integrity is mixed in science and ethics, with science identifying indicators of ecological integrity and ethics justifying the obligation to maintain ecological integrity (Fluker 2010). Thus, ecological integrity is an umbrella concept derived from biological, ecological, and environmental science and incorporates beliefs, values, and ethics as properties of ecosystems (Lackey 2001). Indeed, landscapes vary across space and time in response to changing environmental conditions, rendering ecological integrity a challenging concept to define. Yet, its ambiguity should not undermine the importance of this useful concept to underpin legal and political frameworks. Parks Canada has defined ecological integrity as “a condition that is determined to be characteristic of its natural region and likely to persist including abiotic components, the composition and abundance of native species and biologic communities, rates of change, and supporting processes” (Parks Canada 2007). Many different variations of this definition exist throughout literature (Turner & Beazley 2004; Kelly *et al.* 2008; Monk *et al.* 2012). Given this definition, the current state of ecological integrity can be identified by using ecological indicators and trend analysis to determine if ecological integrity is improving, stable, or in decline. Care must be taken, however, to ensure that measures of ecological integrity do not represent a static view of nature, but allow for evolution, dispersal, natural regime shifts, and other spatial and temporal variables. Thus, long-term monitoring is essential to properly identify, and continuously re-evaluate, ecological integrity.

1.6 Long-term aquatic monitoring

The paucity of long-term northern monitoring data inhibits our ability to clearly identify ongoing hydroecological responses to climate change and other factors. The establishment of working groups such as the Circumpolar Biodiversity Monitoring Program, the Ecological Monitoring and Assessment Network, and committees within the Arctic Council illustrate the critical need to implement long-term monitoring programs and develop a pan-Arctic monitoring strategy. Karlsson *et al.* (2011) recently reviewed hydroecological monitoring of inland Arctic ecosystems and revealed that substantial gaps exist, including the fact that coupled hydrological and ecological monitoring rarely occur. Increasingly, however, governments and land managers implement directives focused on restoring the ecological integrity of freshwater habitats that require long-term monitoring plans (Gilvear & Bradley 2000; Vaughan *et al.* 2001; Parks Canada 2007; Bennion *et al.* 2011; Gillett *et al.* 2011).

Monitoring plans are based on the systematic gathering of data and information from a set of indicator variables with the purpose of establishing baseline conditions and detecting changes over time (Vaughan *et al.* 2001; Mezquida *et al.* 2005). Mezquida et al. (2005) suggest that most monitoring programs have generally involved acquisitions of data rather than well-defined plans with specific objectives. This can lead to haphazard monitoring that collects data that are never used (Lovett *et al.* 2007), are inadequate to address important objectives, and fail to provide insight to any future concerns that may emerge. For example, the Commissioner of the Environment and Sustainable Development (2010) reported to the House of Commons that Environment Canada's Fresh Water Quality Monitoring Program is not adequately examining freshwater resources, suggesting that the responsibilities and objectives of the monitoring program need to be re-defined and adjusted to address new concerns regarding effects of industry, climate change, and population growth. Similarly, Schindler (2010) faulted the Regional Aquatic Monitoring Program (RAMP), created to monitor the environmental impacts of Alberta's oil-sands industry, as being poorly designed and sporadic with inconsistent sampling and methodology.

To ensure that monitoring programs actually achieve their objectives, numerous conceptual frameworks have been developed to guide the design and implementation of monitoring strategies (Ramsar 1999; Hocking *et al.* 2000; Vaughan *et al.* 2001; Mezquida *et al.* 2005; Lovett *et al.* 2007; Parks Canada 2007). While various monitoring models exist to meet the specific needs of different areas, they all sequentially start with a diagnosis of the problem, followed by the definition of objectives and scope of the program. Ecological monitoring within national parks is a response to a broad objective, mandated by federal law, to "provide clear and scientifically-defensible assessments of the ongoing ecological integrity condition of national parks" (Parks Canada 2007, pg 2). The fundamental question driving ecological monitoring in national parks is "what is the state of the park ecological integrity, and how is it changing?" (Parks Canada 2007, pg 2).

To address the question proposed by Parks Canada, key ecological processes that are important elements of different ecosystems within the park need to be identified and individually monitored. For example, Vuntut National Park has four main types of ecosystems: Old Crow Flats; Tundra; Forests; and Freshwater (rivers and streams). Within each ecosystem are key aquatic and terrestrial ecological processes (e.g., hydrology, aquatic ecology, permafrost dynamics, tundra vegetation cover; Parks Canada 2009). A key component of a monitoring program is to determine a small but informative collection of indicators that report on the structure and function of the selected ecological process of a particular ecosystem. Ecosystem indicators, as suggested by the wetland risk assessment (Ramsar 1999), should be anticipatory and sensitive in detecting early stages of physical, chemical, or biological responses to a particular stress. An ideal indicator variable is diagnostic, broadly applicable, correlated to actual environmental effects and ecological relevance, and uncomplicated to measure with sufficient accuracy and repeatability. It is also important that an indicator variable can be measured in a timely, non-destructive, cost-effective manner, and is easy to communicate (Ramsar 1999; Vaughan *et al.* 2001; Parks Canada 2007).

To develop a hydroecological monitoring program, I used a combination of different monitoring frameworks (Ramsar 1999; Vaughan *et al.* 2001; Mezquida *et al.* 2005; Parks Canada 2007) to create a conceptual model that identifies key ecosystem processes and indicator variables (Figure 1-2). For northern landscapes, such as OCF, that lack pressure from industrial development, point-source pollution, and population growth, the main driver is climate change. OCF is a Ramsar Wetland of International Importance (1982) and comprises approximately 29% of Vuntut National Park, yet there is an overall lack of data and methods to determine the ecological integrity of the aquatic ecosystem within this landscape. Thus, this research focuses on developing a program to monitor the ecological integrity of the aquatic ecosystem, also a key objective of the IPY program. Recognizing the interaction between hydrology and ecology, and the need for a genuinely interdisciplinary approach, the hydrology and aquatic ecology are identified as key ecological processes (Figure 1-2). Considering the attributes of indicator variables described above, and previous research conducted on 58 lakes within OCF during the first three years (2007-09) of the IPY project, water isotope tracers and periphyton (diatoms and pigments) were selected as key indicators of hydroecological processes that control lake water balances, nutrient levels, and biological communities. For each indicator variable, it is necessary to define baseline conditions, particularly in a dynamic landscape such as OCF. Long-term datasets are important to understand temporal fluctuations and have a critical role to play in determining the range of natural variability within an ecosystem. The integration of contemporary and paleolimnological perspectives into the monitoring program will enhance temporal context and generate the necessary tools to provide ongoing assessment of the ecological integrity of the aquatic ecosystem.

Scientific knowledge generated by the analysis and assessment of ecological integrity for each national park is conveyed to the Canadian public every ten years in State of the Park Reports and is important for developing and informing park management plans. In 2009, the State of the Park Report for Vuntut National Park was released, which assigned a high value of ecological integrity of the entire landscape, yet listed a number of environmental stressors affecting the park ecosystem (Parks Canada 2004).

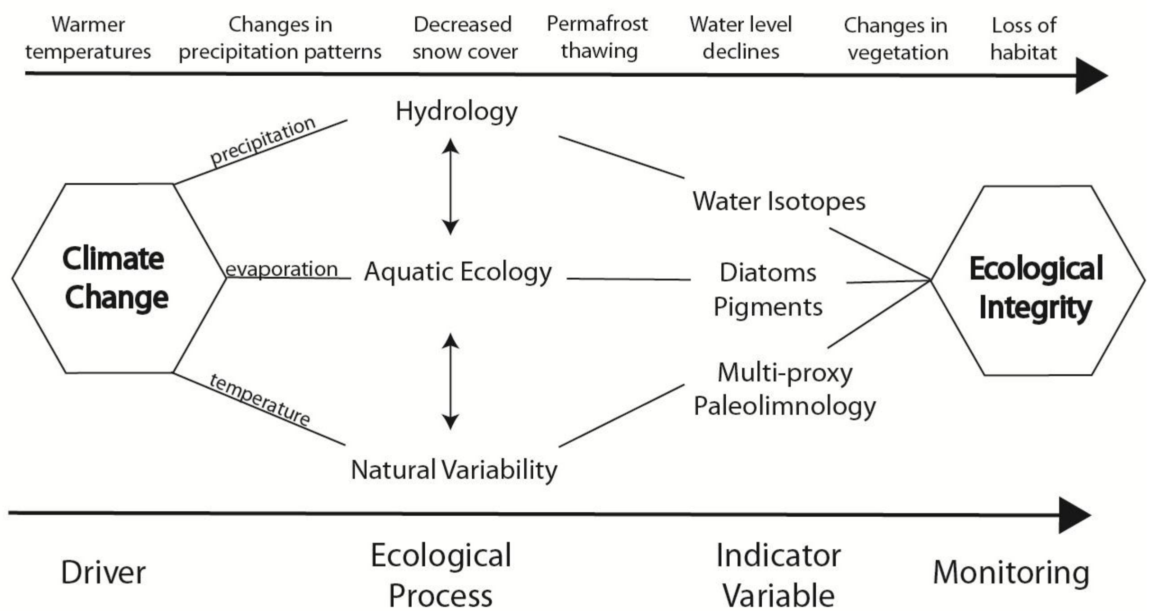

Figure 1-2. Conceptual model of the hydroecological monitoring program.

1.6.1 Water isotope tracers to monitor hydrology

The hydrogen and oxygen isotope composition of water as it passes through the atmosphere, aquatic, and terrestrial ecosystems is well understood (Rozanski 1993; Clark & Fritz 1997; Edwards *et al.* 2004). When water passes through the hydrologic cycle, the isotopic composition changes in predictable ways based on mass-dependent differences. These mass-dependent differences allow for sufficient partitioning (fractionation) among the heavy ($^{1}H^{2}H^{16}O$ and $^{1}H^{1}H^{18}O$) and light ($^{1}H^{1}H^{16}O$) isotopes of water. Water containing the heavy isotope of oxygen or hydrogen preferentially partitions to the more condensed phase (Clark & Fritz 1997), thus evaporated water is preferentially enriched with heavy isotopes and the evaporative moisture flux is depleted in ^{2}H and ^{18}O (Gibson & Edwards 2002).

There are two distinct linear trends in $\delta^{2}H$-$\delta^{18}O$ space that are used to characterize local precipitation and surface water over broad spatial and temporal ranges. The $\delta^{2}H$ and $\delta^{18}O$ of precipitation correlates on a global scale that is defined by the Global Meteoric Water Line (GMWL) where $\delta^{2}H = 8\delta^{18}O + 10‰$ (Craig 1961). This relationship arises from temperature-dependent fractionation during condensation from the vapour mass (Clark & Fritz 1997) and Rayleigh distillation that results in systematic shifts of $\delta^{2}H$ and $\delta^{18}O$ along the GMWL from cold to warm regions (Rozanski 1993). Local surface water that has been influenced by kinetic and equilibrium fractionation during evaporation diverge from the GMWL in a linear trend (Craig & Gordon 1965). This linear trend, known as the Local Evaporation Line (LEL), reflects a heavy-isotope build-up and typically has a slope of 4-6, depending on local meteorological conditions including relative humidity, temperature, and ambient atmospheric moisture isotopic composition (Edwards *et al.* 2004; Wolfe *et al.* 2007).

Displacement of water samples along the LEL and distribution in relation to key reference points can provide a quantitative assessment of a lake's water balance. Using the coupled-isotope tracer method (Yi *et al.* 2008), the relative importance of rainfall and snowmelt on lake hydrological conditions can be quantitatively assessed by calculating the isotopic composition of lake-specific input water (δ_I). Likewise, calculated evaporation-to-inflow (E/I) ratios can evaluate the influence of evaporation on lake water balances. Combined, these metrics offer a promising method to determine lake hydrological responses to climate over a large northern landscape (e.g., Turner *et al.* 2010; Turner *et al.* In review).

1.6.2 Periphyton (diatoms and pigments) to monitor aquatic ecology

Periphyton refers to algae that grow in water bodies on substrates including rocks (epilithion), sand (epipsammon), sediments (epipelon) and biota such as plant stems and leaves (epiphyton) (Wetzel

2001). Algae are useful biota for bio-monitoring because they continuously monitor their environment and represent an integration of many limnological conditions (Dixit *et al.* 1992; Dixit & Smol 1994). These organisms tend to have narrow optima and tolerances for many environmental variables and can therefore be used as indicators to obtain quantitative data on ecological characteristics, water chemistry, and climatic conditions (Dixit *et al.* 1992; Smol 2002). Because periphyton communities are abundant and diverse, sampling procedures can rapidly obtain sufficient information-rich material for analysis. Furthermore, algae are abundant, diverse, and respond rapidly to hydroclimactic changes due their fast growth rates and dispersal abilities, and play an important role in the transfer of nutrients and energy within the ecosystem, making them powerful indicators of environmental change (Battarbee 2000).

Since periphyton grow on many different surfaces, artificial substrates provide an easy method to collect periphyton while controlling for potential confounding influences of colonization time, material, texture, and size (Cattaneo & Amireault 1992). It has been debated in literature whether artificial substrates distort natural periphyton assemblages (Siver 1977; Cattaneo & Amireault 1992); however, Wiklund *et al.* (2010) found very little discrepancy between artificial substrates and natural plants when comparisons were made within lakes. Moreover, the use of artificial substrates controls for effects that lake depth and macrophyte species may have on periphytic communities, making them a preferred substrate when conducting studies of multiple lakes at a landscape scale. A study conducted by MacDonald *et al.* (2012a) showed that composition of periphyton communities sampled on artificial substrates did not differ significantly between sites in pelagic and littoral zones of a shallow thermokarst lake (Mary Netro; OCF 58). Thus, a single sampler placed anywhere in the lake can be used to obtain a representative sample and provide key ecological information.

The complex mixture of algae accruing on artificial substrates can be analyzed for diatom algae, as well as the compositions and abundance of the entire periphyton community from quantification of their photosynthetic pigments, to provide an overall indication of the aquatic conditions of the lake. Diatoms, single-celled microscopic plants belonging to the algal class Bacillariophyceae, are particularly useful biomonitors because they respond to changes in microhabitat as well as physical, chemical, and biological conditions (Dixit *et al.* 1992; Dixit & Smol 1994; Anderson 2000). Likewise, pigments are useful indicators of algal and bacterial community composition and the overall aquatic primary productivity and phototrophic status. Photosynthetic pigments (chlorophylls, carotenoids, and biliprotiens) are a primary characteristic of algae (Wetzel 2001). Chlorophyll-*a* (chl-*a*) is the principal photosynthetic pigment for primary production present in all algae, and carotenoid pigments are accessory pigments that transfer light energy to the chl-*a* protein complex, thereby allowing algae to harvest a wide range of wavelengths of light (Wetzel 2001). Measurements of chl-*a* can be used to approximate plant biomass since it is common to all plants. Carotenoids and other accessory pigments, on the other hand, are specific to certain groups of algae and measurements can be used to determine algal community composition.

1.6.3 Multi-proxy paleolimnology to assess natural variability

Effects of climate change on the hydroecology of dynamic northern landscapes such as OCF are complex and poorly understood. To improve ecosystem management and to adequately determine and understand ecological integrity, knowledge of baseline conditions and natural variability is required. However, logistical constraints, short field seasons, lack of resources, and high cost make long-term monitoring in the Canadian Arctic a difficult task (Keatley *et al.* 2006). As an alternative to conventional long-term monitoring, paleolimnological techniques can be used to rapidly generate information about past hydroecological conditions and how they have evolved over time (Smol 1992). Multi-proxy paleolimnological studies have been widely used in Arctic lakes to determine the response of hydrology and limnology of northern lakes to past changes in climate by analyzing physical, geochemical, and biological information preserved in lake sediments (Joynt III & Wolfe 2001; Wolfe *et al.* 2006; Brock *et al.* 2010; Sinnatamby *et al.* 2010; MacDonald *et al.* 2012b).

1.7 Research objectives and thesis overview

The IPY project in Old Crow aimed to leave a legacy of community- and agency-based monitoring through the development of a long-term environmental monitoring program to be conducted by the VGFN and other primary stakeholders. In response to this goal, the overarching theme of this thesis has been to meet the challenge set by the Government of Canada IPY program by designing and implementing a scientifically-based hydroecological monitoring program. A key part of this, and for successful monitoring programs in general (Lovett *et al.* 2007), has been building, strengthening, and maintaining collaborative partnerships. This has been augmented by a Northern Research Internship, awarded to myself, funded by the Natural Sciences and Engineering Research Council of Canada (NSERC) to spend additional time in the North to work alongside key personnel at Parks Canada to ensure that the monitoring program would be feasible, meet the specific needs of local stakeholders, and tangibly transfer knowledge of proper sampling techniques (Tondu 2011; see Appendix A and B). Our collaborative efforts have led to a Letter of Agreement between Parks Canada, Wilfrid Laurier University, and the University of Waterloo outlining a commitment to continue long-term hydroecological monitoring of selected lakes to understand, detect, describe, and report on the condition of the aquatic ecosystem and how it is changing over time (Appendix C).

This thesis outlines two of the three components of the hydroecological monitoring program in two separate papers (chapter 2 and 3), followed by a concluding chapter (chapter 4). Chapter 2, entitled "Developing a long-term hydrological monitoring program for a northern lake-rich landscape using water isotope tracers," focuses on using water isotope tracers to structure a lake monitoring program to track changes in hydrological conditions. Calculated lake-specific input water isotope composition (δ_I) values can be used to indicate transitions from snowmelt-sourced to rainfall-sourced isotope-based hydrologic regimes and vice versa depending on future changes in climatic conditions. Sensitivity to evaporation is monitored by calculated E/I ratios and a Mann-Kendall trend test is used to illustrate how long-term trends can be statistically identified over time. Data presented in this chapter build on water isotope data collected by Turner *et al.* (2010; In review) and incorporates a five-year data set. This chapter has been written in a manuscript format for submission to a journal.

Chapter 3, entitled "Effects of climate change on the hydroecology of shallow thermokarst lakes in northern Canada: a paleolimnological perspective" presents a multi-proxy paleolimnological reconstruction of hydroecological conditions of Zelma Lake (OCF06) from analysis of loss-on-ignition, elemental carbon and nitrogen content, stable isotopes ($\delta^{13}C$ and $\delta^{15}N$), and fossil pigments. Results from this sediment core are compared to data from other sediment cores collected from other lakes (OCF11, 29, 35, and 48) to explore the range of natural hydroecological variation in OCF. Multi-proxy evidence from five sediment cores in OCF indicate that past hydroecological conditions in OCF have varied markedly, suggesting that lakes in OCF may be experiencing both accelerated natural thermokarst expansion-drainage cycles as well as gradual water-level declines and increases in primary productivity owing to increasing temperatures. This chapter has been written in a manuscript format for potential submission to a journal.

Chapter 2

Developing a long-term hydrological monitoring program for a northern lake-rich landscape using water isotope tracers

Key Words: isotope hydrology, monitoring, northern freshwater ecosystem, national parks, ecological integrity, climate change, Old Crow Flats

2.1 Abstract

Arctic lake-rich landscapes are vulnerable to climate change but their remote locations present a challenge to develop effective and feasible approaches for monitoring ecosystem status and trends. Here, I use water isotope tracers to structure a lake hydrological monitoring program that addresses the needs of a federal agency responsible for managing some of these landscapes in northern Canada. Our geographic foci are shallow thermokarst lakes of Old Crow Flats (OCF), Yukon Territory, which is the traditional homeland of the Vuntut Gwitchin First Nation, and is recognized nationally (Vuntut National Park) and internationally (Ramsar Wetland of International Importance) for its ecological, historical, and cultural significance. In partnership with Parks Canada, and based on our prior research (Turner *et al.* 2010; Turner *et al.* In review), 14 lakes situated in catchments that are representative of the land-cover and hydrological diversity of OCF were identified. Meteorological data and a multi-year evaporation pan experiment are used to develop a robust isotope framework, which provides the basis for interpreting five years (2007-2011) of lake water isotope measurements and deriving knowledge of hydrological conditions for the monitoring lakes. Using this framework and an isotope-mass balance model, isotopic compositions of input water (δ_I) and evaporation-to-inflow (E/I) ratios were calculated and provide key hydrological information for each sampling interval. From these time-series, 'hydrological thresholds' were established that will identify changes in lake-specific input water isotope composition (snowmelt versus rainfall) and evaporation from ongoing monitoring. The use of a Mann-Kendall trend test for

determining long-term statistically-significant trends is demonstrated. Results from the monitoring program will contribute directly to assessments of ecosystem integrity, which Parks Canada release in 'State of the Park' reports every ten years. The approach we describe could readily be adopted for other northern lake-rich landscapes that are within the jurisdiction of Parks Canada and other agencies.

2.2 Introduction

Shallow thermokarst lakes contribute significantly to Arctic biodiversity with abundant aquatic habitat that supports microbial, planktonic and benthic communities, aquatic plants, and fish (Schindler & Smol 2006; ABEK 2008; Vincent *et al.* 2008; Rautio *et al.* 2011). These freshwater ecosystems also provide important refuges for migratory birds and other wildlife and are integral to the traditional lifestyle and cultural heritage of Indigenous circum-Arctic communities (Wrona *et al.* 2006; White *et al.* 2007). Arctic landscapes are particularly sensitive to accelerating climatic change and are undergoing pronounced ecosystem alterations (Smol *et al.* 2005; Schindler & Smol 2006; Prowse *et al.* 2009b). Remote sensing techniques and field observations have documented widespread hydrological changes during recent decades, including decreases in the abundance and size of lakes in northern Alaska, Siberia, and northwestern Canada (Hinzman *et al.* 2005; Smith *et al.* 2005; Riordan *et al.* 2006; Labrecque *et al.* 2009; Carroll *et al.* 2011), likely driven by increases in susceptibility of thermokarst lakes to sudden drainage events and evaporation (Frohn *et al.* 2005; Hinkel *et al.* 2007; Wolfe & Turner 2008; Grosse *et al.* 2010). Increases in surface water area have also been observed in regions of Alaska (Jorgenson *et al.* 2006), Siberia (Hinzman *et al.* 2005) and northern Quebec (Payette 2004). Although climate models predict further declines in the areal extent of pan-Arctic wetlands (Avis *et al.* 2011), accelerated rates of permafrost thaw within the continuous permafrost zone and increases in precipitation may also lead to increases in total surface area of lakes in some regions. Thus, shallow lakes in circumpolar regions exhibit, and will likely continue to display, variability in their hydrological responses to climate change (Wolfe *et al.* 2011b; Turner *et al.* In review). Since multiple hydrological responses of shallow Arctic lakes are anticipated, there is a growing need for improved comprehensive science-based monitoring programs to adequately assess spatial patterns and rates of change of the hydrological regime in these northern landscapes. Such knowledge will provide decision-makers and self-governing First Nation communities with vital information to support management of northern freshwater resources.

Effective management of aquatic resources requires long-term data, yet long-term monitoring of lakes in northern regions has generally not been conducted because of many unique challenges. Most northern lakes are remotely located and are only accessible via boat, float plane, or helicopter. Thus, they are not easy to sample repeatedly at sufficient frequency, especially given the high costs of northern field work. Limited budgets, availability and capacity of staff, and challenging logistics (travel time, equipment and resources, weather delays, etc.) often deter efforts to implement short-term monitoring programs, let alone long-term initiatives. Yet, long-term data are critical for understanding complex ecosystem processes, quantifying hydrological responses to changes in climate, and determining the trajectories of lake water balances.

The Vuntut Gwitchin First Nation (VGFN) and Parks Canada are concerned about rapidly changing lake levels occurring in their traditional territory and management area, respectively - Old Crow Flats (OCF), Yukon. OCF is the largest, most significant wetland in Yukon and is recognized as a Wetland of International Importance by the Ramsar Convention on Wetlands (1982) for its valuable wildlife habitat and cultural significance. OCF is cooperatively managed by the VGFN, Parks Canada (Vuntut National Park, established in 1995), and the North Yukon Renewable Resources Council. Each organization is committed to co-managing OCF and sharing joint authority to preserve the ecological integrity of this landscape. Given these shared goals and the mounting concerns regarding the impact climate change will have on the ecological integrity of this landscape, a multidisciplinary research project "Environmental change and traditional use of the Old Crow Flats in northern Canada (Yeendoo Nanh

Nakhweenjit K'atr'ahanahtyaa)" was initiated in 2007 to study the physical and biological components of the ecosystem as part of the International Polar Year (IPY) program. The main objectives of this research program were to: (i) document the history of environmental change from the last interglacial to the present; (ii) assess the distribution and abundance of wildlife; (iii) evaluate the impact of change on traditional food sources; and (iv) develop long-term environmental monitoring programs to be conducted by the local community and stewardship agencies into the future (Wolfe *et al.* 2011a).

The IPY project aimed to leave a legacy for the northern community of Old Crow by implementing long-term monitoring programs to detect and quantify ecosystem change, increase understanding of the mechanisms driving changes, and inform decisions and policies underpinning effective ecosystem stewardship. Informed decisions are expected to lead to better conservation, management, and strategic action plans in the face of ongoing climate change and other stressors. In recognition of the need for long-term monitoring, the Canada National Parks Act (2001) stated that clear and scientifically-defensible assessments of the ecological integrity of all parks and comprehensive reports on the whole ecosystem are needed. Thus, scientifically-based monitoring and reporting programs are required to effectively measure the state of ecosystems and determine how they are changing over time. Information capturing an assessment of park ecological integrity is conveyed to the Canadian public every ten years in State of the Park Reports (SoPR). In 2009, the first SoPR for Vuntut National Park was released, which rated the ecological integrity of Vuntut National Park as "good". The report used a wide range of ecosystem indicators, yet there is currently no method to adequately assess the conditions of the aquatic ecosystem within OCF, despite the fact that surface water (mainly shallow thermokarst lakes) in OCF covers 23% of the landscape and OCF itself comprises 29% of Vuntut National Park area (Parks Canada 2009; Turner *et al.* In review). Since shallow thermokarst lakes are an important feature of the OCF landscape, a science-based monitoring program is essential to improve understanding and quantification of the hydrological conditions within OCF and to effectively identify how they are changing over time.

Monitoring plans are based on the systematic gathering of data and information from a set of indicator variables with the purpose of establishing baseline conditions and detecting changes over time (Vaughan *et al.* 2001; Mezquida *et al.* 2005). Mezquida et al. (2005) suggested that most monitoring programs are limited because they are generally acquisitions of data rather than well-defined plans with specific objectives. This can lead to haphazard monitoring that collects data that are never used (Lovett *et al.* 2007), are inadequate to address important objectives, and fail to provide insight to any future concerns that may emerge. To ensure that monitoring programs actually achieve their objectives, numerous conceptual frameworks have been developed to guide the design and implementation of monitoring strategies (Ramsar 1999; Hocking *et al.* 2000; Vaughan *et al.* 2001; Mezquida *et al.* 2005; Lovett *et al.* 2007; Parks Canada 2007). While various monitoring models exist to meet the specific needs of different areas, they all sequentially start with a diagnosis of the problem, followed by the definition of objectives and scope of the program. For northern landscapes, such as OCF, that lack pressure from industrial development and population growth, the main stressor is climate change. Ecological monitoring in national parks is a response to the fundamental question: “what is the state of the park ecological integrity, and how is it changing?” (Parks Canada 2007). To address this question requires the development of a comprehensive monitoring plan to report on all (or at least many) ecosystem processes comprising the terrestrial and aquatic elements of national parks.

Ecosystem indicators, as suggested by the wetland risk assessment (Ramsar 1999), should be anticipatory and sensitive in detecting early stages of physical, chemical, or biological responses to a particular stress. An ideal indicator variable is diagnostic, broadly applicable, correlated to actual environmental effects and ecological relevance, and uncomplicated to measure with sufficient accuracy and repeatability. It is also important that an indicator variable can be measured in a timely, non-destructive, cost-effective manner, and is easy to communicate (Ramsar 1999; Vaughan *et al.* 2001; Parks Canada 2007). In consideration of these attributes and detailed studies that have characterized lake hydrological conditions and their drivers in OCF as part of the IPY project (Turner *et al.* 2010; Turner *et al.* In review), this paper advocates the use of water isotope tracers as a viable monitoring variable to track hydrological changes. Although the hydrogen and oxygen isotope composition of water is well understood as it passes through the hydrological cycle (Clark & Fritz 1997; Edwards *et al.* 2004), it has been underutilized as an indicator variable for hydrological monitoring programs. While wetland hydrological monitoring programs are lacking in general, long-term investigation on lentic systems tend to rely on instrumentation techniques (e.g., lysimeters) that are time-consuming and expensive (Gilvear & Bradley 2000) and are generally not feasible to implement at a large spatial scale in remote northern landscapes.

To effectively detect, describe, and report on ecological integrity in national parks in a broad ecosystem context, multiple indicator variables are essential. A genuine interdisciplinary and collaborative monitoring program to determine the ecological integrity of the aquatic ecosystem is currently being developed, and this paper focuses on determining and applying a method for monitoring hydrological changes using water isotope data collected from 2007 to 2011. Water isotopes are cost-effective and provide key information that effectively characterizes lake water balances of northern freshwater landscapes (e.g., Brock *et al.* 2007; Wolfe *et al.* 2007; Turner *et al.* 2010). We provide five-year time series of calculated lake-specific input water isotope compositions (δ_I) and evaporation-to-inflow (E/I) ratios, key metrics that will serve as the foundation of the hydrological monitoring program. Despite the aforementioned challenges associated with northern long-term monitoring, we also show how researchers, a northern community, and a government agency can effectively collaborate to develop a long-term monitoring program that will continue to evaluate the status and trends of the aquatic ecosystem in response to climate change.

2.3 Study area

Old Crow Flats (68°N 140°W) is a large (5600 km^2) thermokarst landscape with approximately 2700 shallow lakes (Figure 2-1). OCF is a flat, low-lying area with little topographic relief that is bounded by the British and Barn Mountains to the north, the Richardson Mountains to the east, the David Lord Range and Ogilvie Mountains to the south and the Old Crow Range to the west. These surrounding mountains act as a barrier to the inland movement of Pacific air masses resulting in winters that are prolonged and cold (Oswald & Senyk 1977). According to 1971-2000 climate normals at Old Crow airport (Weather Station ID 2100800; Environment Canada 2012), average annual air temperature is -9.0°C and fluctuates substantially between summer and winter months. The average temperature from June to August is 12.6°C, with maximum temperatures occurring in July. Average annual total precipitation is 265.5 mm, ~60% of which falls as rain (165.5 mm) from May to September.

OCF represents a prominent region of Beringia that remained unglaciated during the last glacial maximum. During this time, OCF was inundated by Glacial Lake Old Crow that left a thick (up to 1,200 m) deposit of fluvial and glaciolacustrine sediments, with the exception of an exposure of Carboniferous shale at Timber Hill (Hughes 1972; Lauriol *et al.* 2002; Zazula *et al.* 2004). The shallow-water wetland is dissected by the deeply incising, broadly meandering Old Crow River, leaving the river valley 40-50 m below a plateau of 'perched' lakes that are primarily thermokarst in origin and underlain by continuous permafrost (Yukon Ecoregions Working Group 2004; Labrecque *et al.* 2009; Roy-Leveillee & Burn 2011). Average surface area of lakes in OCF is 44 ha and ranges from 1-3700 ha, although 92% of the lakes have a surface area of 100 ha or less (Labrecque *et al.* 2009). Surface water in OCF occupies 23% of the landscape, based on Landsat imagery analyzed by Turner et al. (In review).

Vegetation in OCF has spatially complex patterns owing to changes in topography, drainage patterns, and ongoing thermokarst cycles (lake formation, growth, and drainage) (Hawking *et al.* 2005).

Land cover in OCF has been broadly categorized by Turner *et al.* (In review) using Landsat imagery. A total of 37% of OCF is covered by dwarf shrub tundra and herbaceous vegetation. This terrain is characterized by ericaceous shrubs (e.g. Labrador tea, blueberry), herbaceous plants (e.g., *Arctophila fulva, Calamagrostis* sp.*, Carex aquatilis, Equisetum*), and non-vascular plants (e.g., sphagnum mosses and lichens) that are commonly found in drained lake beds and low-centre polygons (Ovenden 1982; Ovenden & Brassard 1989). Coniferous and deciduous forests (e.g., black spruce, white spruce), located in well-drained areas account for 13% of the landscape and tall shrub tundra (e.g., shrub birch, willows) covers 25% of the landscape. The southern and western areas of OCF are typically dominated by deciduous and coniferous trees as well as tall shrubs, while the central, northern, and eastern regions generally support communities of herbaceous plants, non-vascular plants, and dwarf shrubs. Shallow lakes located across OCF provide habitat for communities of pond weed (*Potamageton* sp.), yellow pond lily (*Nuphar* sp.), common duck weed (*Lemna minor*), hornwart (*Ceratophyllum* sp.), watermilfoil (*Myriophyllum* sp.), muskgrass (*Chara* sp.), and bur-reed (*Sparganium* sp.) (Ovenden & Brassard 1989; Yukon Ecoregions Working Group 2004; Hawking *et al.* 2005).

Water isotope tracers (^{2}H, ^{18}O) have been used to classify lakes in OCF into hydrologic categories: snowmelt-sourced (formerly snowmelt-dominated), rainfall-sourced (formerly rainfall-dominated), and evaporation-dominated (Turner *et al.* 2010; Turner *et al.* In review). These hydrological differences are driven by physiographic location and catchment characteristics including vegetation type (Turner *et al.* In review). Lakes that are located in the southwestern area of OCF are primarily snowmelt-sourced owing to the dominance of coniferous and deciduous woodland that intercepts and accumulates snow. Lakes classified as rainfall-sourced are typically found in central and northeastern areas of OCF and their catchments have a greater proportion of herbaceous plants, non-vascular plants, and dwarf shrubs. The physiography of snowmelt- and rainfall-sourced lakes located in more peripheral areas of OCF tends to provide adequate runoff from surrounding upland areas to offset evaporation. On the other hand, rainfall-sourced lakes located in more central low-lying areas have smaller catchments, high proportions of surface water, and smaller vegetation land cover, are more susceptible to becoming evaporation-dominated during prolonged dry periods.

2.3.1 Monitoring lakes

During 2007-09, 58 lakes in OCF were repeatedly sampled for water isotope composition (^{2}H, ^{18}O), water chemistry, and algal community composition and abundance. In collaboration with Parks Canada, 14 of these 58 lakes that are representative of OCF, spanning a wide range of hydrological, limnological, and catchment characteristics, were selected for the monitoring program (Figure 2-2; Table 2-1; Table 2-2). Special attention was also given to jurisdictional location to ensure that lakes were distributed between Vuntut National Park (38%) and the VGFN Special Management Area (62%; Figure 2-1). The remote location and difficult terrain of OCF renders most of these lakes inaccessible during the summer months without the use of a helicopter. In an attempt to mitigate future logistical challenges (primarily associated with cost of a helicopter charter), five of the monitoring lakes were also selected based on their proximity to the Old Crow River so they could potentially be accessed by boat in the early spring. This was an important selection criterion because Parks Canada normally conducts a spring boat trip into Vuntut National Park; thus, a high proportion of lakes can still be monitored if helicopter-based sampling is not possible. A helicopter is necessary to sample all monitoring lakes in late summer/early fall as the Old Crow River is not navigable by boat due to low water levels. Initially, 13 lakes were chosen for the monitoring program; however, as a result of a spring boat trip conducted in 2011 to assess the feasibility of accessing lakes from Old Crow River, another lake (OCF37) was added to the monitoring program. Although not part of the dataset reported by Turner et al. (2010; In review), we also included Mary Netro Lake (OCF58) as a monitoring lake because it is close to the community of Old Crow, has cultural significance to the community, and is easily accessible.

Monitoring lakes represent the three major hydrological categories described by Turner *et al.* (2010) and subsequently re-termed (Turner *et al.* In review): snowmelt-sourced (three lakes), rainfall-sourced (eight lakes), and evaporation-dominated (three lakes) (Table 2-1). The lakes span OCF (see Figure 2-1), have varying catchment sizes (0.28 to 395.19 km^2) and surface areas (0.02 to 12.67 km^2; Table 2-1). All monitoring lakes are less than 2.0 m in depth, with the exception of OCF55 which has a depth >5.0 m because it is an oxbow lake. Lakes that are snowmelt-sourced have large drainage ratios (catchment area/lake area), broadly ranging from 12 to 5566, and are dominated by tall shrubs (mean 63.6% of catchment area) and have small proportions of dwarfed shrubs, herbs, and non-vascular plants (mean = 19.7%; Table 2-1). In contrast, the catchments of rainfall-sourced and evaporation-dominated lakes have lower proportions of tall shrubs (mean = 19.1% and 14.0%, respectively) and higher proportions of shrubs, herbs, and non-vascular plants (mean = 34.7% and 34.0%, respectively). Rainfall-sourced and evaporation-dominated lakes also have lower drainage ratios (ranging from 1.7 to 11) (Table 2-1). Barren areas of exposed rock, sand, and fire scar make up a small proportion of land-cover within lake catchment areas with the exception of OCF06 where barren lands total 43.6% of the catchment area (based on a SPOT image from July, 2007). This high proportion of barren land around OCF06 is due to the drainage event that occurred in June 2007 as well as the drainage of two neighbouring lakes (Wolfe & Turner 2008; Turner *et al.* 2010). Since then, a large proportion of barren land has been re-vegetated by grasses and sedges.

Monitoring lakes span a wide range of limnological conditions that are associated with hydrological categories (Table 2-2). Snowmelt-sourced lakes tend to be cirum-neutral (mean pH = 7.00; alkalinity = 17.13 meq/L), whereas rainfall-sourced and evaporation-dominated lakes are more alkaline (mean pH = 8. 07and 8.71; alkalinity = 82.93 meq/L and 100.55 meq/L, respectively). Snowmelt-sourced lakes have relatively low conductivity (mean specific conductance = 44.78 µS/cm) and low concentrations of major ions (Ca, K, Mg, Na, SiO_2), rainfall-sourced lakes have intermediate ion content (mean = 175.03 μS/cm), and evaporation-dominated lakes have high values (mean = 258.00 μS/cm). Dissolved inorganic carbon (DIC) concentration displays a similar pattern among the hydrological categories and is relatively low in snowmelt-sourced lakes (4.30 mg/L) and high in evaporation-dominated lakes (21.48 mg/L). Although lakes in OCF are covered by ice for up to nine months of the year, they contain elevated mean total phosphorus (TP) concentrations (33.21 μg/L – 42.83 μg/L) in the summer. Lakes are mesotrophic to eutrophic based on TP, but have low chlorophyll-*a* and total nitrogen concentrations.

2.4 Methods

2.4.1 Meteorological data

Data from meteorological stations maintained by Environment Canada at the Old Crow airport (Station ID 2100800 and 2100805; www.climate.weatheroffice.gc.ca/climateData/canada_e.html) were used to report monthly mean temperature and monthly total precipitation during the five-year study (2007-2011). Data from a meteorological station erected by Wilfrid Laurier University at Old Crow airport were used to determine average ice-free season temperature and relative humidity, which were flux-weighted, based on potential evapotranspiration (Thornthwaite 1948; see Calculations I), as recommended by Gibson and Edwards (2002) for use in isotopic-mass balance calculations.

2.4.2 Water isotope sampling and analysis

Monitoring lakes were sampled for the analysis of water isotope tracers in June, July, and September from 2007 to 2009, as reported in Turner et al. (2010; In review) and June 10 and August 25, 2010 and June 5-17 and September 12, 2011. The initial three years of sampling included mid-season sampling in July to more fully characterize the hydrological behaviour of lakes within OCF, which was used as a basis for establishing the monitoring program. During 2010, 12 lakes within OCF were sampled with the aid of a helicopter. Mary Netro Lake (OCF58) was sampled from a canoe following river travel by motorboat and a short hike to the lake. In spring 2011, a feasibility assessment was conducted to ascertain the level of accessibility to lakes within close proximity of the Old Crow River. This sampling trip was conducted in conjunction with Parks Canada's annual river trip into Vuntut National Park. Five lakes were sampled during this trip (OCF29, 35, 37, 49, and 55); the remaining nine were sampled as previously described. In September 2011, 13 lakes within OCF were sampled with a helicopter, and Mary Netro Lake was again accessed via boat. Water samples were collected from 10 to 15 cm below the surface at the approximate centre of each lake. A hand-held GPS system was used to ensure that samples were collected at the same location in each lake (within a maximum 150 m) during subsequent sampling trips.

Samples for water isotope analysis were collected in 30-ml high-density polyethylene bottles and transported to the University of Waterloo Environmental Isotope Laboratory for evaluation of oxygen and hydrogen isotope composition. Isotopic concentrations are expressed as variations in the relative abundance of the rare (heavy) isotope species of water with respect to the common (light) isotope species. These ratios are conventionally expressed as a delta (δ) value, reported as per mil (‰). Reported isotopic concentrations are the difference between the ratio of the sample and the ratio of a known standard, such that δ^2H or $\delta^{18}O = 1000 ((R_{sample}/R_{standard})-1)$, where R is the ratio of $^2H/^1H$ or $^{18}O/^{16}O$ in the sample and standard. The international standard for water is the Vienna Standard Mean Ocean Water (VSMOW) and results are normalized to -55.5‰ and -428‰, respectively, for Standard Light Antarctic Precipitation (Coplen 1996), with maximum analytical uncertainties for $\delta^{18}O$ and δ^2H of ±0.2‰ and ±2‰, respectively.

A constant volume Class-A evaporation pan was deployed at the Old Crow airport from 2007-09, as reported by Turner et al. (2010; In review). We continued to monitor the evaporation pan at the Old Crow airport again from June to August, 2010. The evaporation pan was carefully maintained over four years to simulate a terminal basin (i.e., closed-drainage) at isotopic and hydrologic steady-state where inflow is equal to evaporation (δ_{SSL}). Water levels within the pan were maintained at a constant volume and water samples were collected weekly for isotopic analysis.

Lake hydrological conditions were evaluated using a reference isotopic framework in $\delta^{18}O$-$\delta^{2}H$ space (Figure 2-3) using the linear resistance model of Craig and Gordon (1965) (see Calculation I). A key feature on the isotopic framework is the Global Meteoric Water Line (GMWL), which describes the correlation of precipitation on a global scale, such that $\delta^{2}H = 8\delta^{18}O + 10$ (Craig 1961). Surface water that has undergone evaporation deviates away from the GMWL, due to mass-dependent fractionation, in a linear trend characterized as the Local Evaporation Line (LEL), which typically has a slope of 4-6. Key reference points along the LEL include the amount-weighted mean annual precipitation (δ_P, at the GMWL-LEL intersection), the limiting steady-state isotope composition (δ_{SSL}), and the theoretical limiting isotopic enrichment (δ^{*}) of a desiccating basin under thaw season conditions.

The isotopic composition of lake water (δ_L) clusters along the LEL, either below or above, depending on the relative influence that source water (snowmelt and rainfall, respectively) have on lake hydrological conditions. Using the coupled-isotope tracer method, (explained in detail by Yi *et al.* 2008), we quantitatively assessed these hydrological influences on lake water balances by calculating the isotopic composition of lake-specific input water (δ_I) and evaporation-to-inflow (E/I) ratios. δ_I for each lake was estimated by calculating lake-specific LELs and extending δ_L to the intersection of the GMWL (Figure 2-3). According to mass conservation, the isotopic composition of evaporated vapour from a lake (δ_E) will lie on the extension of the LEL, to the left of the GMWL. Using these key water isotope budget components (δ_L, δ_I, δ_E), lake hydrological conditions can be quantified in terms of evaporation-to-inflow (E/I) ratios that consider the mass-balanced ratio between the isotopic composition of lake-specific input water and the evaporative flux from the lake (see equation in Figure 2-3). δ_I and E/I values reported by Turner et al. (2010; In review) were re-calculated to reflect the four-year average monitoring framework, described below.

2.4.3 Trend analysis

A Mann-Kendall non-parametric test originally derived by Mann (1945), developed by Kendall (1975), and modified by Hirsch et al. (1982) and Hirsch and Slack (1984), was used to detect monotonic trends in δ_I and E/I ratios over time (see Calculations II). The Mann-Kendall test is one of the most commonly applied tests to detect trends in hydrologic time series data because it is highly robust to departures from normality, missing values, and seasonal cycles. It is not, however, robust against serial dependence, although a modified test to estimate the covariance between the Seasonal Kendall (S) statistics on sample sizes greater than 10 years can adjust p-values for serial correlation (Hirsch & Slack 1984; Yue & Wang 2004). We apply both the Mann-Kendall and the Seasonal Kendall trend test, which performs the Mann-Kendall trend test for individual seasons separately and then combines the results, to the five-year dataset of δ_I values and E/I ratios. The seasons were defined as early (June) and late (September) based on the proposed frequency of future monitoring. Thus, results from July 2007-09 are not included in the Seasonal Kendall test. Trend analysis was completed using software developed by the U.S. Geological Survey (2005; http://pubs.usgs.gov/sir/2005/5275/downloads/).

2.5 Results

2.5.1 Meteorological conditions

Mean monthly temperature measured at Environment Canada's meteorological station recorded during 2007-2011 were comparable to the 1971-2000 climate normals (Figure 2-4). Total annual precipitation between 2007 and 2011 was variable and was high in the latter two years (417 mm and 625 mm in 2010 and 2011, respectively; Figure 2-4). Total precipitation during the ice-free months (May-September) in 2007 was below average (134 mm; 1951-2000 mean = 166 mm; Environment Canada 2012). The 2007-08 ice-covered months experienced extremely low snowfall and below-average winter cumulative precipitation (snow water equivalent (SWE) = 28 mm; 1951-2000 mean SWE = 100 mm; Environment Canada 2012) and near-average cumulative rainfall during the 2008 ice-free season

(178 mm). Winter snowfall in 2008-09 was above-average (SWE = 134 mm), followed by high ice-free season cumulative rainfall (212 mm). The ice-covered months during 2009-10 experienced below-average snowfall (SWE = 75 mm) and the 2010 ice-free season had above-average cumulative rainfall (276 mm). Heavy snowfall during the fall of 2010 coupled with uncharacteristically high snowfall events in February 2011 contributed to very high winter precipitation amount in 2010-11 (SWE = 359 mm). Cumulative ice-free season rainfall reached 347 mm by September 2011, which is ~200% greater than the long-term mean. Meteorological data for the five years indicate that the ice-free season experienced increasingly wet conditions relative to the long-term mean while precipitation amounts during the ice-covered season fluctuated between below-average (2007-08, 2009-10) and above-average (2008-09, 2010-11). Below-average rainfall during the 2007 ice-free season and extremely low snowfall in 2007-08 led to relatively dry conditions in 2008, while heavy snowfall in 2010-11 and well above-average precipitation during the thaw season generated very wet conditions in 2011, compared to the long-term mean.

2.5.2 Developing an isotopic framework

Results from the evaporation pan in 2010 follow a similar pattern as isotopic data collected during 2007-09 (Turner *et al.* In review; Figure 2-5a). In all four years of deployment, rapid isotopic enrichment occurred during the first four weeks as cumulative evaporation increased and the pan equilibrated with atmospheric conditions. After the 5th week of deployment during each year, $\delta^{18}O$ values remained relatively constant and are used to define δ_{SSL}. The evaporation-pan-derived δ_{SSL} values are similar over four years and the four year-average is $\delta^{18}O_{SSL}$ = -11.8‰ and $\delta^{2}H_{SSL}$ = -126‰ (standard deviation (s) = 0.5 and 3.2, respectively; Table 3). The isotopic composition of evaporation pan input water was very consistent each year (mean $\delta_{I\text{-}pan}$ = -22.1‰ for $\delta^{18}O$ and -173‰ for $\delta^{2}H$; s = 0.3 and 0.3, respectively) and plotted close to the GMWL (Figure 2-5b). Based on the four-year mean δ_{SSL} and $\delta_{I\text{-}Pan}$ values, the LEL ($\delta^{2}H = 4.6\ \delta^{18}O - 71.7$) was extended to the GMWL to provide an estimate of δ_P ($\delta^{18}O_P$ = -

24.2‰ and δ^2H = -184‰; s = 0.1 and 0.8, respectively). The equation provided by Gonfiantini (1986) was used to calculate δ^* for each year (mean δ^* = -5.0‰ for $\delta^{18}O$ and -91‰ for δ^2H; s = 0.6 and 3.2, respectively) and the non-steady state portion of the LEL, defined by the $\delta_{SSL} - \delta^*$ segment (Figure 2-5c). Although an evaporation pan was not maintained in 2011, framework results would likely not deviate substantially since the flux-weighted temperature and relative humidity for 2011 (T = 287.1K, h = 67.1%) were similar to values calculated from 2007 to 2010 (mean T = 286.8 K and mean h = 65.9%; s = 0.8 and 3.0, respectively; Table 2-3).

2.5.3 Monitoring lake hydrological conditions with water isotopes

Lake water isotope compositions (δ_L) obtained from the monitoring lakes during the 2007-11 field campaigns are superimposed on the four-year average isotopic framework developed from the evaporation pan data (Figure 2-6). In general, the lake water isotope composition spans a broad range ($\delta^{18}O_L$=-25.8‰ to -8.7‰ and δ^2H_L=-200‰ to -100‰) among the monitoring lakes and between the sampling periods; however, distinct trends are present. Values that are positioned below the LEL reflect a stronger influence from snowmelt and generally plot closer to the GMWL, whereas lakes that are more influenced by summer rainfall have higher values and deviate above the LEL. δ_L values are lower in June and become higher by the end of the ice-free season, reflecting the seasonal isotopic evolution that is typical of high-latitude lakes as they receive isotopically-depleted snowmelt in spring and subsequently undergo evaporative isotopic enrichment through the summer. This general intra-annual cycle is evident in all five years, although the evolution is unique to each year because of the difference in the flux and isotopic composition of inputs (snowmelt and rainfall) and outputs (evaporation). For example, lakes in 2008 are much more isotopically enriched in July and September, with some lakes plotting beyond δ_{SSL} compared to other sampling years (Figure 2-6). This is because there was very low precipitation during the preceding ten months (Figure 2-4).

The influence of summer rainfall is most clearly revealed in 2010 and 2011 (Figure 2-6d and e) as lake water isotope compositions for August and September, respectively, deviate above the LEL in response to substantial rainfall events in July and August of both years (Figure 2-4). The influence of snowmelt, rainfall, and evaporation on lake water balances is summarized in Figure 2-6f, which shows the 5-year mean δ_L for each monitoring lake according to hydrological lake categories defined by Turner et al. (2010). Lakes that are classified as snowmelt-sourced are located below the LEL close to the GMWL whereas rainfall-sourced lakes plot above the LEL and are closer to δ_{SSL}. An exception to this is one rainfall-sourced lake (OCF48) that plots within the isotopic range of snowmelt-sourced lakes. Turner *et al.* (2010; In review) and MacDonald *et al.* (2012b) note that this lake in particular oscillates between snowmelt- and rainfall-sourced owing to its proximity to Timber Hill, and receives shallow groundwater seepage from snowmelt through the active layer. Evaporation-dominated lakes are situated further along the LEL and the five-year average of one lake (OCF06) plots beyond δ_{SSL}.

The relative role of snowmelt versus rainfall on lake water balances was quantitatively assessed by calculating lake-specific input water isotope compositions (δ_I). As displayed in Figure 2-7, calculated δ_I values over the five-year period show considerable variation within and between lakes. Turner et al. (2010) distinguished snowmelt- versus rainfall-sourced lakes based on the position of δ_I relative to δ_P, such that snowmelt-sourced lakes are defined by $\delta^{18}O_I \leq \delta_P$ and rainfall-sourced lakes are delineated by $\delta^{18}O_I > \delta_P$. Using this metric, rainfall is the main contributor to most monitoring lakes (OCF06, 19, 29, 34, 35, 37, 38, 46, 49, and 58) and snowmelt is a main contributor to only OCF11 and 55. A few lakes oscillate between rainfall and snowmelt categories (OCF26 and 48), and therefore we re-categorize these lakes as snow-rain-sourced lakes. Turner et al. (2010, In review) revealed similar patterns, such that most lakes were rainfall-sourced, only a few remained snowmelt-sourced throughout the entire ice-free season, and lakes that had δ_I values close to δ_P tended to oscillate between snowmelt- and rainfall-sourced categories.

δ_I values were plotted versus time to explore temporal trends in lake-specific input water for each monitoring lake (Figure 2-8). The five-year δ_I mean of each lake was calculated and compared to the four-year mean δ_P (-24.2‰), which delineates the threshold between snowfall- and rainfall-sourced isotopic-based hydrologic regimes (Figure 2-8). Seasonally, δ_I values in June are typically lower than in July and September owing to the decreasing supply of snowmelt and increasing influence of rainfall. Standard deviations (reported in Table 4a) are useful to characterize the degree of variation in δ_I values and reveal lakes that have relatively low, moderate, and high variability in δ_I values during the five-year data set. OCF29, 38, 48, 55, and 58 show very little variability in δ_I values, with standard deviations that narrowly range from 0.6 – 0.7. Most of the monitoring lakes (OCF11, 26, 34, 35, 37, and 49) display moderate variation in δ_I values (0.9 – 1.1). Other lakes including OCF06, 19, and 46 exhibit pronounced seasonal and inter-annual variation in δ_I values and have standard deviations >1.5.

A Mann-Kendall test showed statistically significant increasing monotonic trends at OCF11, 26, and 49 (OCF11: S=48, p=0.004; OCF26: S=44, p=0.003; OCF49: S=38, p=0.011) and an emerging trend in OCF29 (S=-8, p=0.088). A Seasonal Kendall test also showed an emergent trend in OCF29 (S=11 p=0.079), but no significant trends in any of the monitoring lakes (Table 2-4a). From 2007 to 2009, both OCF11 and 26 have depleted δ_I signatures that are below δ_P (-24.2‰) and shift to δ_I values that are above δ_P in 2010 and 2011. An independent sample t-test of δ_I values from 2007-09 and 2010-11 shows a statistically significant difference between the means of 2007-09 and 2010-11 (OCF11: t=-3.034, p=0.013 and OCF26: t=4.699, p=0.001).

The importance of evaporation to lake water balances was quantitatively assessed by calculating evaporation-to-inflow (E/I) ratios using lake-specific input water (δ_I) and the evaporative flux (δ_E) determined for each lake (see Calculations I). An E/I ratio of 0.5, theoretically, represents 50% evaporated vapour loss from a basin and thus an E/I ratio >0.5 signifies evaporation-dominated lakes. An E/I value of 1 is equal to the theoretical terminal basin steady-state limiting composition (δ_{SSL}) in which evaporation is equal to inflow. Thus, E/I ratios that exceed 1 indicate a threshold in which lakes have a negative water balance and are experiencing net evaporative drawdown. Temporal trends for E/I were assessed and five-year mean E/I values were used to determine lakes that are evaporation-dominated (Figure 2-9). Overall, E/I ratios vary substantially among the lakes, ranging from 0.03 in June (mean E/I June = 0.34), due to high spring input of snowmelt and rainfall, to 1.55 by the late ice-free season (mean August/September E/I = 0.53) because of the influence of evaporation. According to the threshold conventions described above, OCF06, 19, 37, 46, 49, and 58 are evaporation-dominated lakes (mean E/I ≥ 0.5) and OCF29 is close to the 0.5 threshold boundary (mean E/I = 0.49). OCF46 and 19 had E/I ratios that exceeded 1 in July and September 2008, respectively. OCF06 had E/I ratios that exceeded 1 in July and September of 2007 and 2008 as well as July 2009.

Monitoring lakes exhibit pronounced differences in both intra- and inter-annual variation that can be described by standard deviations (Table 4b). Similar to δ_I values, we group monitoring lakes into three categories based on mean E/I values and the amount of variation in E/I ratios: low, moderate, and high. OCF26, 48, and 55 display very low E/I values (mean ≤ 0.25) and low variation in E/I ratios (< 0.10). Other lakes, including OCF29, 34, 35, and 38, have moderate mean E/I values (0.35-0.50) and display moderate variation about the mean (0.10-0.14). OCF11 has a low mean E/I value (0.30), yet a large standard deviation (0.20). Lakes that are classified as evaporation-dominated (OCF06, 19, 37, 46, 49 and 58) have high mean E/I values (> 0.5) and large standard deviations (0.12-0.34). A Mann-Kendall test showed no significant increasing or decreasing trends in E/I ratios over time.

2.6 Discussion

Landscapes under the stewardship of northern agencies and communities are logistically challenging to monitor, yet land managers and scientists recognize that long-term, scientifically-based monitoring is necessary to effectively evaluate how northern ecosystems are responding to climate change. Implementation of successful and sustainable long-term monitoring approaches involves coordination among multiple authorities and other stakeholders to systematically gather information. Effective monitoring strategies also need to be included as a routine activity and viewed as an integral part of everyday management and not an extra endeavour (Mezquida *et al.* 2005; Lovett *et al.* 2007). To achieve this, we developed and implemented a hydrological monitoring program in partnership with Parks Canada, with support from the Vuntut Gwitchin First Nation and the North Yukon Renewable Resource Council. A key component of these efforts includes ensuring that future water isotope monitoring (to be conducted by Parks Canada) will be conducted successfully to provide vital hydrologic information for Vuntut National Park State of the Park Reports.

Climate warming is already pronounced in the Arctic (Vincent *et al.* 2011) and has the potential to cause major regime shifts in high-latitude inland ecosystems (Karlsson *et al.* 2011), the most critical threshold being the integrity of lake basins and the presence or absence of water (Vincent *et al.* 2008). In response to climate change, Arctic hydrology appears to show clusters of local variability over space and time (Avis *et al.* 2011; Carroll *et al.* 2011; Karlsson *et al.* 2011; Turner *et al.* In review). Thus, ongoing monitoring that is capable of capturing the diversity of hydrological pathways is needed to adequately assess the ecological integrity of high-latitude aquatic ecosystems. The approach presented here utilizes leading-edge water isotope tracer techniques as an effective monitoring tool to evaluate landscape-scale hydrological change in a northern thermokarst landscape. Water isotopes are sufficiently affordable and logistically feasible to incorporate into a sustainable long-term hydrological monitoring program. Key information from this work includes baseline characterization of lake hydrological conditions, which will be compared to results of future sampling campaigns to evaluate multiple potential hydrological pathways in response to changes in climate.

We used a survey monitoring strategy and selected 14 lakes across a large geographical area, each representing an individual “monitoring station.” The δ_L data collected from 2007-2011 show that the selected monitoring lakes encompass a broad range of isotopic signatures and thus capture the diverse hydrological conditions in OCF (Figure 2-6). This highlights the range of hydrological variation in OCF and reinforces the notion that lakes will likely undergo multifaceted hydrological changes over time. Since hydrological fluxes from groundwater are generally negligible in continuous permafrost landscapes (Woo *et al.* 2000), the main components of thermokarst lake water balances can be characterized using the isotopic metrics δ_I and E/I, which evaluate the relative importance of input source water type (snowmelt and rainfall) and evaporation, respectively. There are a few notable exceptions to this such as OCF48 (located near Timber Hill) and OCF55 (an oxbow lake), which likely receive inputs of groundwater (Turner *et al.* 2010). Ideally, samples for water isotope analysis should be collected during early, mid, and late ice-free season, yet given the logistical constraints of northern monitoring this is not necessarily feasible. δ_I values and E/I ratios collected in July and September are statistically different from each other based on a Wilcoxon signed-rank test (δ_I: n=28, p=<0.001; n=56, p=<0.001, n=58, p=0.002 and E/I: n=28, p=<0.001; n=56, p=0.12; n=58 p=<0.001, respectively); however, collecting samples during the early and late ice-free season captures the full scope of seasonal isotopic evolution and we therefore consider this sample frequency adequate to assess changes in hydrological conditions. Furthermore, lakes that experience high E/I ratios in July generally maintain elevated E/I ratios when sampled again in September, thus the importance of vapour loss can still be determined by collecting samples at beginning and end of the ice-free season.

2.6.1 An isotopic framework for long-term monitoring

A framework to evaluate the isotopic evolution and water balance of monitoring lakes was based on four years of evaporation pan data and flux-weighted temperature and relative humidity. The similarity of flux-weighted temperature and relative humidity during the five-year sampling period and the agreement between isotopic frameworks developed from evaporation pan data for each year (Figure 2-5c; Table 2-3) clearly demonstrates that our approach is robust and repeatable. A meteorological station deployed within OCF at John Charlie Lake (OCF29), located approximately 50 km north of Old Crow airport, revealed that temperature and relative humidity recorded at the Old Crow airport and within OCF were very similar over a three-year period (Turner *et al.* In review). Moreover, temperature and relative humidity recorded by the installed meteorological stations were similar to data recorded by the meteorological station maintained by Environment Canada at Old Crow airport. Thus, temperature and relative humidity recorded by Environment Canada are suitable for interpreting water isotope results for future monitoring. Although we have shown that the four-year average isotope framework is appropriate for characterizing lake water balances during 2007-11, we recommend that an evaporation pan experiment be repeated every five years to ensure that the framework is reflective of hydroclimatic conditions.

2.6.2 Monitoring lake hydrological conditions with water isotopes

We present data collected over five years of varying meteorological conditions (Figure 2-4) and show that lakes within OCF vary substantially in temporal patterns of dominant source-water types (δ_I). δ_I values can be used to identify lakes that are sensitive to changes in snowmelt versus rainfall. Despite experiencing both 'dry' and 'wet' conditions, some lakes in OCF (OCF29, 38, 48, 55, and 58) displayed very narrow ranges in δ_I values over the five-year time period. This suggests that these lakes may remain resilient with respect to lake-specific input water compositions under changing meteorological conditions. In contrast, lakes that display considerable variation in δ_I values will be more sensitive to changes in snowmelt and rainfall (OCF06, 19, and 46), which may result in altered lake hydrological conditions. Increases in summer rainfall, winter rain events, and decreases in winter snowpack thickness influence the input water composition of lakes, and potentially shift the water balance of snowmelt-sourced lakes toward rainfall-sourced lakes. Turner et al. (In review) revealed a strong association between individual lake input values and catchment characteristics such as vegetation, hence monitoring trends in δ_I values over time may reveal changes associated with transformations in land cover. The catchments of snowmelt-sourced lakes have greater proportions of coniferous and deciduous trees and tall shrubs that promote thick snowpack development, which provides substantial snowmelt input during the spring. High-latitude warming has led to the expansion of treeline tree species into tundra ecosystems (Lloyd & Fastie 2003; Lloyd *et al.* 2003), an increase in shrub abundance (Sturm *et al.* 2001), and the overall "greening of the Arctic" (Jia 2003), which may shift lake water balances from rainfall-sourced to snowmelt-sourced, owing to an increased capacity to entrap snow. Complete and partial lake drainage events due to increased rates of thermokarst erosion and lateral expansion as temperatures (Pohl *et al.* 2009) and precipitation rise (Wolfe & Turner 2008) will also influence vegetation dynamics. Mackay and Burn (2002) showed that vegetation grows rapidly on the exposed organic-rich sediments of recently drained lake basins in a successional pattern from grasses and sedges to willow and other shrubs to alder trees and tall willows >2.0m. For example, the margins of OCF06, a lake that drained in 2007, have been re-vegetated by grasses, sedges, and other water tolerant plants. Thus, the margins of partially drained and completely drained lake beds will eventually be colonized by tall shrubs that will enhance winter snowpack thickness. Though not all areas in the Arctic are experiencing increases in tree growth (Osterkamp *et al.* 2000), local land users have observed increases in shrub size and coverage in OCF (ABEK 2008).

Lakes in OCF have low water volume and high surface-area-to-depth ratios, making them susceptible to climate-induced losses in lake area due to increased evaporation rates. In this study, we used calculated E/I ratios to evaluate the importance of evaporation and temporal trends. Lakes that possess low E/I values and low standard deviations are the least sensitive to vapour loss, whereas lakes with high E/I values and larger standard deviations are more responsive to evaporation. OCF26, 48, and 55 represent lakes that are not sensitive to vapour loss whereas OCF06, 19, 37, 46, 49, and 58 have mean E/I ratios that surpass 0.5, indicating that evaporative-water-loss exceeds 50% of the lake volume. This is not to suggest that these lakes are drying up as they still maintain positive water balances. Rather they will be more sensitive to evaporative drawdown under meteorological conditions that enhance rates of evaporation. Rainfall-sourced lakes are most susceptible to becoming evaporation-dominated and they are typically shallow, have small lake surface areas, small catchment areas, or have recently experienced a drainage event. Furthermore, the land cover of catchments of evaporation-dominated lakes typically includes high proportions of low-lying tundra vegetation that appear to generate less spring snowmelt (Turner *et al.* In review). Snowmelt-sourced lakes are less vulnerable to water vapour loss as demonstrated during the dry 2008 ice-free season. On the other hand, three lakes exceeded an E/I ratio of 1 (OCF06, 19, and 46) during the 2008 ice-free season, signifying that these lakes lost total water volume in response to meteorological conditions experienced during this time. If prolonged dry conditions such as these become more frequent, lakes may cross the evaporation-dominated threshold. Several shallow lakes in the high Arctic have completely desiccated, while others have experienced reduced water levels attributed to increased evaporation/precipitation ratios associated with climatic warming (Smol & Douglas 2007). This underscores the importance of continued monitoring of E/I ratios, which identify lakes and regions in OCF that are sensitive to water-level changes due to evaporation.

To determine if hydrological conditions (i.e., δ_I values and E/I ratios) are changing over time, the Mann-Kendall trend tend was applied to detect statistically-significant increasing or decreasing trends. The Mann-Kendall trend test revealed that three lakes (OCF11, 26, and 49) display a statistically-significant increasing trend in δ_I values, although this trend is not significant when the Seasonal Kendall trend test is applied. This may be a result of a small sample size (≤ 5 years of data) or the strong influence of July data. Despite the lack of significant trend according to the Seasonal Kendall test, Figure 2-8 clearly shows that both OCF11 (snowmelt-sourced) and OCF26 (snow-rain-sourced) have δ_I values below the snowmelt/rainfall threshold from 2007-09 and above the threshold in 2010-11 with means that are different. This is likely due to above-average precipitation during the ice-free season of 2010 and 2011. While we are cognizant that this represents a small data set and the trend may be driven by enriched July δ_I values, the test suggests that the water balances of these lakes may transition from snowmelt-sourced to rainfall-sourced isotopic-based hydrologic regimes due to increases in precipitation during the ice-free season. There were no discernible trends in E/I ratios, although prolonged ice-free conditions and warmer temperatures may lead to enhanced evaporative enrichment, which can only be determined by long-term monitoring and future trend tests.

The time-series of δ_I values and E/I ratios presented here provide baseline hydrologic thresholds that can be used to identify and evaluate fluctuations in the hydrological status of lakes in OCF in response to ongoing climate change. The outcome of this work will contribute directly to ecological integrity assessments. Parks Canada uses thresholds as a mechanism to evaluate ecological integrity and determine the 'condition' of the ecosystem (Parks Canada 2007). The condition of the ecosystem is rated as good, fair, or poor based on a "healthy composition and abundance of native species or biological communities, rates of change, and supporting processes" (Parks Canada 2007, 2009). While we do not provide direct assessments of ecosystem health, we do provide a clear and unique tool for hydrological monitoring that can define isotopic-based thresholds and effectively evaluate the status and trends of lake hydrological conditions in OCF. Furthermore, δ_I values and E/I ratios are ecologically-relevant hydrological variables that influence nutrient chemistry (Table 2) and likely aquatic communities (e.g. macrophytes and algae). These metrics will provide Parks Canada, the Vuntut Gwitchin First Nation and the North Yukon Renewable Resource Council with quantitative data that will provide insight to the hydrological responses to changes in climate conditions.

2.7 Conclusion

This paper advocates that long-term hydrological monitoring of high-latitude wetlands is essential to clearly and adequately determine ecological integrity, and that routine surveillance of these landscapes should be incorporated into management activities. There is substantial evidence showing that the Arctic is in a state of hydrological transition (Hinzman *et al.* 2005; Vincent *et al.* 2011), the direction of which is ambiguous. Thus, long-term data sets and monitoring are essential to identify and understand the hydrological status and trends of northern freshwater landscapes. We demonstrate that water isotope tracers are useful monitoring tools that can be used to assess future vulnerabilities of a suite of representative lakes in OCF to changes in input water (snowmelt versus rainfall) and evaporation. δ_I values distinguish snowmelt- and rainfall-sourced lakes, with δ_P representing a threshold between the two isotopic-based hydrologic regimes. Lakes that display considerable variation in δ_I values (OCF06, 11, and 46) are more sensitive to changes in snowmelt and rainfall, which may result in altered lake hydrological conditions. Transitions in δ_I values from snowmelt-sourced to rainfall-sourced hydrology or vice-versa may be a result of increases in summer rainfall, winter rain, and changes in winter snowpack thickness associated with precipitation levels as well as landscape vegetation that entrap snow. A Mann-Kendall test, used to identify monotonic trends over time, revealed that three lakes (OCF11, 26, and 49) display statistically significant increasing trends in δ_I values and that OCF11 and 26 may be transitioning from snowmelt-sourced to rainfall-sourced. Lake sensitivity to vapour loss was monitored using hydrological thresholds established from E/I ratios such that E/I ratios > 0.5 signifies lakes that are evaporation-dominated with positive water balances and E/I ratios > 1 indicates lakes that are evaporation-dominated with negative water balances. Six lakes (OCF06, 19, 37, 46, 49, and 58) surpassed the 0.5 threshold and are evaporation-dominated. Three of these lakes (OCF06, 19, and 46) cross the significant evaporation threshold (E/I > 1), representing lakes that are vulnerable to desiccation. Despite the substantial variability in precipitation during the five-year study period, the water balance of OCF29, 48, and 55 showed marked hydrological resilience to changes in meteorological conditions. While these trends are subject to the limitations inherent to a five-year data set, they highlight the diversity of hydrological conditions in OCF and reinforce the notion that lakes will undergo multiple pathways and trajectories over time that can be captured using water isotope tracers.

Changes in hydrological conditions will likely have implications for water chemistry and aquatic ecology, potentially altering the structure and function of lake ecosystems**.** In recognition of the value and need for coordinated hydrological and ecological monitoring to systematically observe the status and trends of aquatic ecosystems, we recommend (and are working towards) integrating the hydrological monitoring program with an ecological monitoring program, protocols of which were described by MacDonald et al. (2012a). Northern ecosystem monitoring remains challenging. Yet, here we demonstrate how collaboration between researchers, a northern community, and a government agency can successfully develop a long-term monitoring program that will serve to inform future policy and land-use management decisions. Furthermore, these approaches can be readily adopted by other national parks and agencies that have a vested interest in monitoring the hydrological status and trends of northern lake-rich landscapes.

2.8 Calculations I

2.8.1 Meteorological calculations

Average ice-free season temperature and relative humidity were flux-weighted based on potential evapotranspiration (Thornthwaite, 1948):

$$T_{flux} = \sum \frac{(T_a \times E_t)}{(E_t)} \quad (°C) \qquad\qquad h_{flux} = \sum \frac{(h \times E_t)}{(E_t)} \quad (\%)$$

where T_a is the monthly average temperature (°C) and h is the monthly average relative humidity (%) recorded by WLU meteorological station and E_t is given by the equation:

$$E_t = 1.6 \times \frac{L}{12} \times \frac{N}{30} \frac{(10T_a)^a}{I} \quad (\mathrm{cm})$$

where L is the average day length between sunrise and sunset for the month (hours) based on hourly shortwave radiation data recorded at WLU meteorological station such that values > 50W/m^2 were counted as an illumination hour and in the absence of shortwave radiation data, L was estimated by using previous shortwave radiation data and hours of illumination recorded by Environment Canada (http://app.hia-iha.nrc-cnrc.gc.ca/cgi-bin/sun-soleil.pl), *N* is the number of days in the month, *I* is the thaw season heat index and *a* is a calculated coefficient. The thaw season heat index (*I*) is given by:

$$I = \sum \frac{(T_a)^{1.514}}{5} \quad (°C)$$

and the coefficient *a* is calculated by:

$$a = 0.49239 + 0.01792 \times I - 7.7x10^{-5} \times I^2 + 6.75x10^{-7} \times I^3$$

2.8.2 Isotopic framework calculations

The equilibrium liquid-vapour isotope fractionation factor (*α**) is derived from the equation given by Horita and Wesolowski (1994):

$$[\delta^{18}O]: 1000 \ln \alpha^* = -7.685 + 6.7123\left(\frac{10^3}{T}\right) - 1.6664\left(\frac{10^6}{T^2}\right) + 0.35041\left(\frac{10^9}{T^3}\right)$$

$$[\delta^2 H]: 1000 \ln \alpha^* = 1158.8\left(\frac{T^3}{10^9}\right) - 1620.1\left(\frac{T^2}{10^6}\right) + 794.84\left(\frac{T^3}{10^3}\right) + 2.9992\left(\frac{10^9}{T^3}\right) - 161.04$$

where *T* represents the interface temperature (K). The equilibrium (*ε**) and kinetic isotope (ε_K) separation factors between liquid and vapour phases is given by (Gonfiantini, 1986):

$$\varepsilon^* = \alpha^* - 1$$

$$[\delta^{18}O]: \varepsilon_K = 0.0142(1-h)$$

$$[\delta^2 H]: \varepsilon_K = 0.0125(1-h)$$

Isotopic composition of atmospheric moisture over the ice-free season (δ_{AS}) can be calculated by the isotopic composition of a terminal lake at steady-state and input water derived from the evaporation pan data (Gibson & Edwards, 2002):

$$\delta_{AS} = (\delta_{SSL} - \varepsilon^*)/\alpha^* - \varepsilon_K - \delta_P (1 - h + \varepsilon_K)/h$$

The limiting non-steady state composition of a water body approaching complete desiccation (δ*) can be calculated by (Gonfiantini, 1986):

$$\delta^* = \frac{h \cdot \delta_{AS} + \varepsilon_K + \varepsilon^* / \alpha^*}{h - \varepsilon_K - \varepsilon^* / \alpha^*}$$

The slope (*S*) and intercept (*d*) of the local evaporation line can be calculated, in decimal notation, by the approach outlined by Barnes and Allison (1983):

$$S = \frac{\alpha^{*2}\left[\left(\varepsilon_K^2 + \varepsilon^{*2}/\alpha^{*2}\right)\left(1 + \delta_P^2\right) - h\left(\delta_P^2 - \delta_{PS}^2\right)\right]}{\alpha^{*18}\left[\left(\varepsilon_K^{18} + \varepsilon^{*18}/\alpha^{*18}\right)\left(1 + \delta_P^{18}\right) - h\left(\delta_P^{18} - \delta_{AS}^{18}\right)\right]}$$

and

$$d = \delta_P^2 - S \cdot \delta_P^{18}$$

Note that all calculations are expressed in decimal notation.

2.8.3 Calculations for E/I ratios

The isotopic composition of evaporative flux and individual lake input water can be calculated based on isotope mass-balance equations and the coupled isotope tracer method (Yi et al., 2008). This involves balancing the volume of evaporative flux, δ_E, with outflow (δ_L) to yield input water (δ_I). Outflow is isotopically equal to lake water because liquid outflow does not fractionate (Gibson & Edwards, 2002). Thus, considering isotope-mass balance, hydrogen and oxygen isotope data can be quantified in terms of an evaporation-to-inflow (E/I) ratio:

$$E / I = \frac{\left(\delta_I - \delta_L\right)}{\left(\delta_E - \delta_L\right)}$$

where δ_E represents the isotopic composition of the vapour derived from an evaporating lake, defined as (Craig & Gordon, 1965):

$$\delta_E = \frac{\left(\delta_L - \varepsilon^*\right)/\alpha^* - h \cdot \delta_{AS} - \varepsilon_K}{h + \varepsilon_K}$$

2.9 Calculations II

The Mann-Kendall is a rank-based method that compares the relative magnitude between data points to test if values tend to increase or decrease with time with a two-sided test. The presence of an increasing or decreasing trend over time can be calculated by the trend statistic. The Mann-Kendall test statistic is defined by:

$$\boldsymbol{S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(Xj - Xk)}$$

where *Xj* and *Xk* are the sequential data values, n is the number of data points, and

$$\boldsymbol{Sgn(\theta) = \begin{cases} +1 & & \theta > 0 \\ 0 & if & \theta = 0 \\ -1 & & \theta < 0 \end{cases}}$$

The mean variance of *S* given the possibilities of ties is:

$$\boldsymbol{Var(S) = n(n-1)(2n+5) - \sum\nolimits_{t} t(t-1)(2t+5)/18}$$

where *t* is the extent of any given tie and Σ_t is the summation over all ties.

The standard normal variate *Z* is defined by:

$$\boldsymbol{Z = \begin{cases} \dfrac{S-1}{\left(Var(S)\right)^{1/2}} & if\ S > 0 \\ 0 & if\ S = 0 \\ \dfrac{S+1}{(Var(S))^{1/2}} & if\ S < 0 \end{cases}}$$

in which in a two-sided test the H_o (no trend) is accepted if the absolute values of Z is ≤ $Z_{\alpha/2}$.

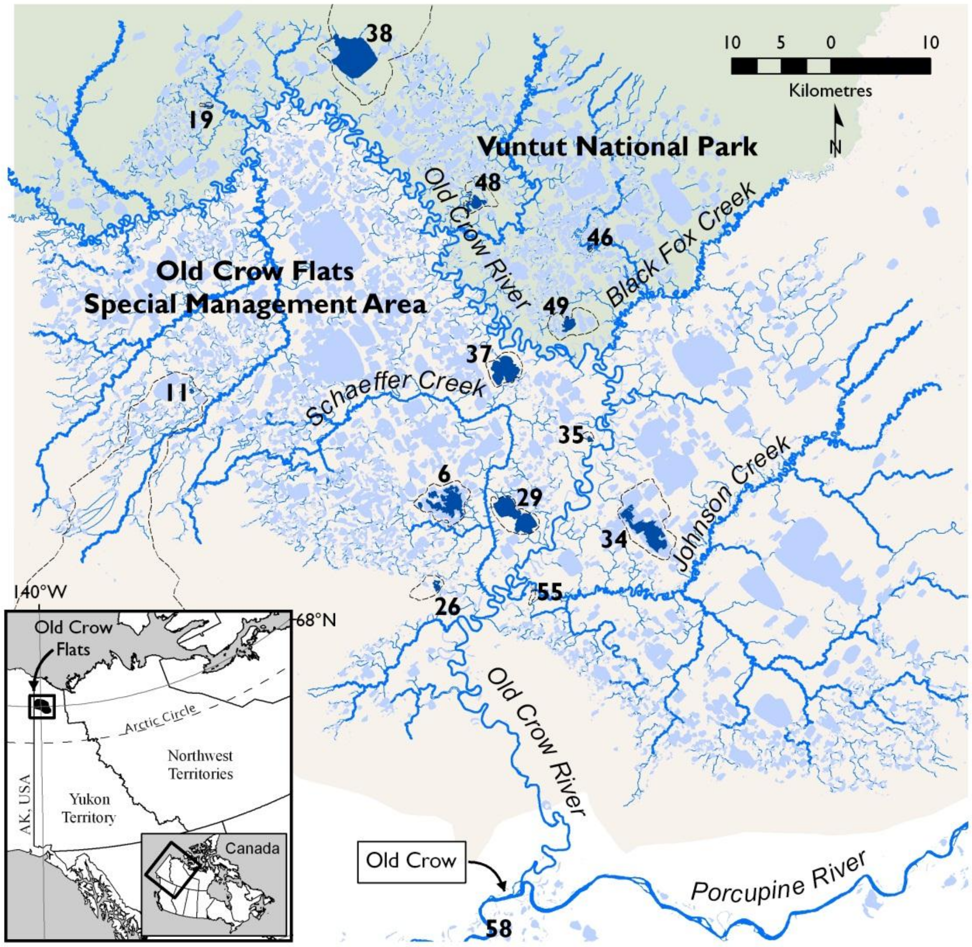

Figure 2-1. Map showing the location of 14 lakes selected for the hydroecological monitoring program in Old Crow Flats, Yukon Territory. Catchment areas are outlined (see Turner *et al.* In review).

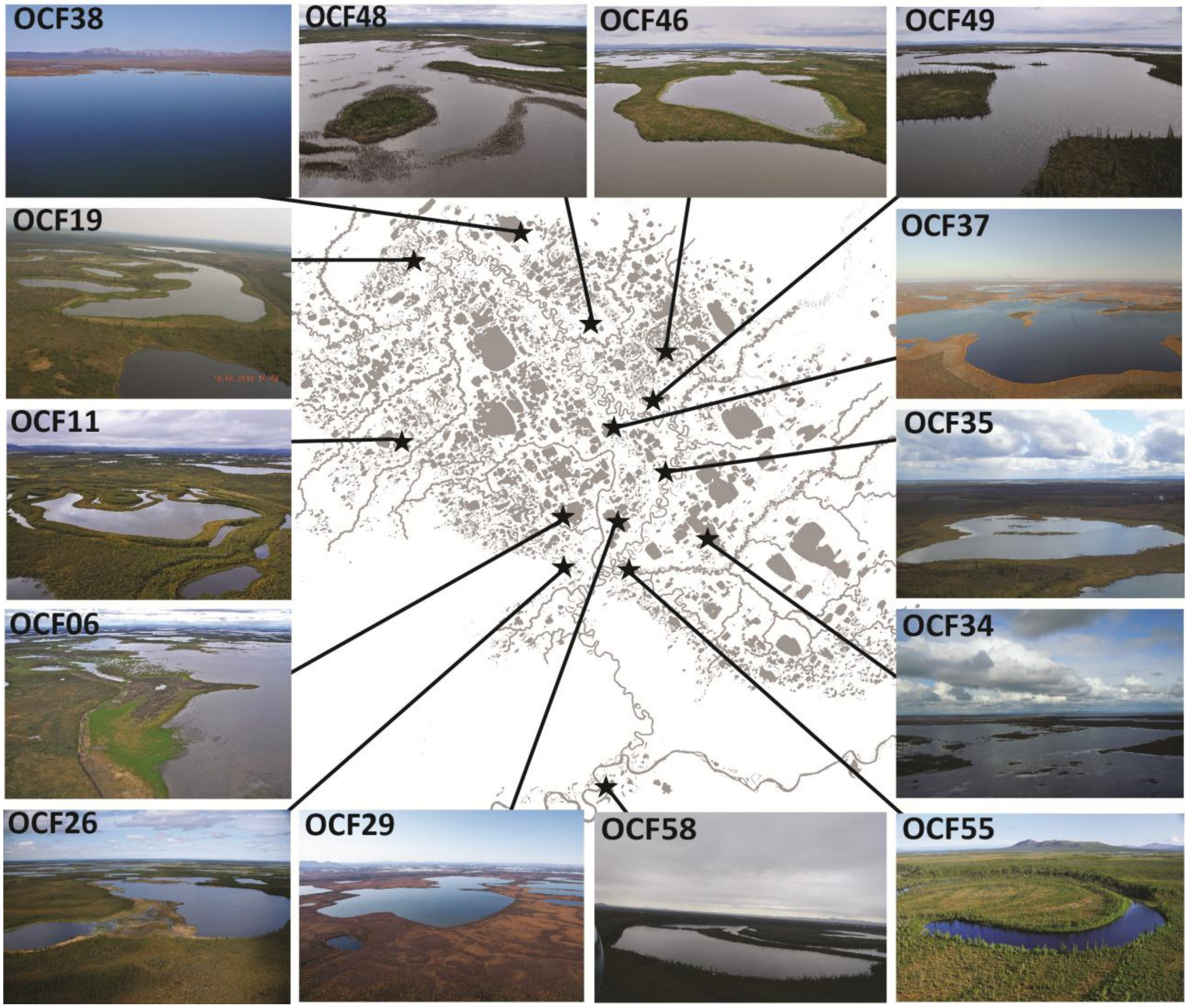

Figure 2-2. Photographs of selected monitoring lakes in OCF.

Table 2-1. Selected hydrological and catchment characteristics for monitoring lakes. Hydrological categories are based on Turner et al. (2010) and vegetation cover is based on Landsat imagery (Turner et al. In press).

Lake ID	Traditional Name	Latitude	Longitude	Hydrology Category	Depth (m)	Lake Surface Area (km^2)	Catchment Area (km^2)	Drainage Ratio (CA:LA)	Woodland (%)	Tall Shrubs (%)	Dwarfed Shrubs (%)	Barren (%)	Surface Water (%)
OCF11		68° 01' N	140° 34' W	Snowmelt	0.8	0.07	395.19	5565.99	10.6	53.8	27.7	1.9	4.3
OCF26		67° 50' N	139° 59' W	Snowmelt	1.7	0.42	5.21	12.31	8.2	73.3	1.9	0.8	15.7
OCF55		67° 50' N	139° 45' W	Snowmelt	> 5.0	0.02	0.59	29.30	3.2	63.6	29.3	0.5	3.4
mean				Snowmelt	2.5	0.17	133.66	1869.20	7.3	63.6	19.7	1.1	7.8
OCF29	John Charlie	67° 54' N	139° 48' W	Rainfall	1.2	6.86	11.71	1.71	0.5	11.2	28.4	1.4	58.6
OCF34	Netro	67° 53' N	139° 27' W	Rainfall	1.5	6.11	29.16	4.77	5.1	25.0	36.5	1.0	32.1
OCF35		67° 58' N	139° 37' W	Rainfall	1.2	0.14	0.80	5.95	6.1	29.3	43.0	1.9	19.7
OCF37	Ts'iivii zhit	68° 05' N	139° 81' W	Rainfall	1.2	5.14	8.84	1.72	3.6	22.7	13.5	2.1	58.2
OCF38	Husky	68° 19' N	140° 08' W	Rainfall	1.0	12.67	137.96	10.89	6.7	3.8	70.5	7.0	12.3
OCF48	Hot Spring	68° 11' N	139° 52' W	Rainfall	0.7	1.31	7.41	5.68	21.4	21.4	26.0	4.8	26.3
OCF49	Marten	68° 04' N	139° 39' W	Rainfall	1.2	1.15	10.75	9.37	6.9	20.3	24.9	3.0	44.6
OCF58	Mary Netro	67° 32' N	139° 51' W	Rainfall*	2.5								
mean				Rainfall	1.3	4.77	29.52	5.73	7.2	19.1	34.7	3.0	36.0
OCF06	Zelma	67° 55' N	139° 56' W	Evaporation	0.3	5.01	15.99	3.20	0.8	14.5	9.9	43.6	31.3
OCF19		68° 17' N	140° 31' W	Evaporation	0.9	0.11	0.58	5.37	1.3	16.6	59.3	2.2	20.5
OCF46		68° 09' N	139° 36' W	Evaporation	0.5	0.12	0.28	2.30	4.6	10.8	32.9	8.0	43.6
mean				Evaporation	0.6	1.74	5.62	3.62	2.3	14.0	34.0	18.0	31.8

* Mary Netro lake is designated a rainfall-sourced lake based on data collected from 2008-2011.

Table 2-2. The mean and standard deviation of selected limnological characteristics of monitoring lakes, grouped into hydrological categories. Values represent the average of samples collected in June and August during the 2010 and 2011 sampling campaigns.

Hydrology category	Snowmelt		Rainfall		Evaporation	
Lake	11, 26, 55		29, 34, 35, 36, 37, 38, 48, 58		06, 19, 46	
Mean/STDV	Mean	STDV	Mean	STDV	Mean	STDV
pH	7.00	0.15	8.07	0.27	8.71	0.07
Specific conductivity (µS/cm)	44.78	5.41	175.03	29.84	258.00	58.65
Alkalinity (meq/L)	17.13	2.41	82.93	17.51	100.55	2.67
Dissolved organic carbon (mg/L)	19.41	2.74	12.64	4.93	17.93	5.34
Dissolved inorganic carbon (mg/L)	4.30	0.68	18.57	3.85	21.48	0.70
Calcium (mg/L)	5.63	0.40	22.00	2.33	32.29	5.08
Magnesium (mg/L)	1.89	0.30	7.44	1.76	11.53	2.87
Potassium (mg/L)	1.08	0.49	1.77	0.82	3.07	0.96
Silica (mg/L)	0.95	0.18	0.86	0.57	0.64	0.29
Total nitrogen (mg/L)	0.65	0.10	0.74	0.18	1.15	0.24
Total dissolved phosphorus (µg/L)	24.65	9.16	11.07	4.59	18.69	3.26
Total phosphorus (µg/L)	42.83	14.39	33.21	12.97	42.62	11.02
Chlorophyll a (µg/L)	4.41	1.37	4.05	1.83	3.50	1.54
Total suspended solids (mg/L)	4.85	3.90	9.83	13.51	9.03	5.72

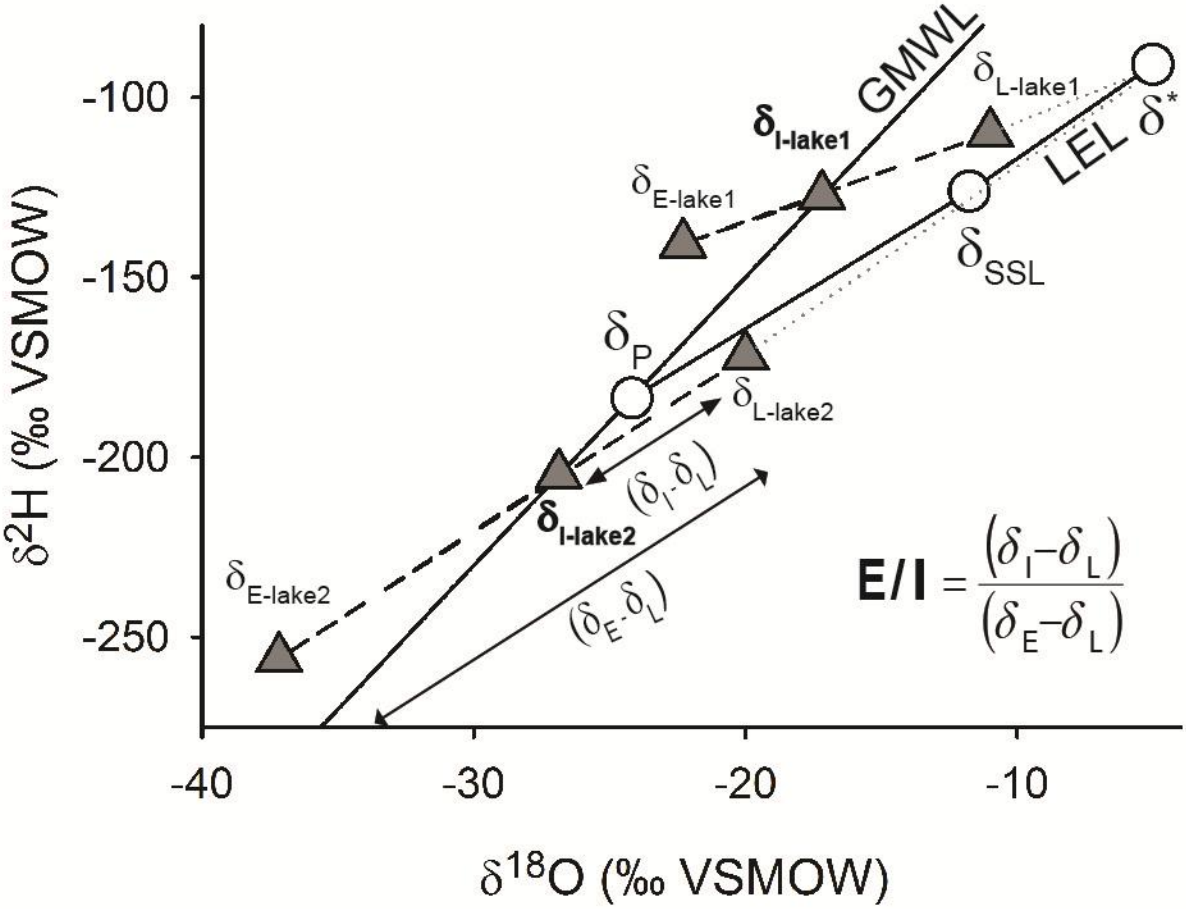

Figure 2-3. Schematic $\delta^{18}O$-$\delta^{2}H$ diagram illustrating two hypothetical lakes (Lake 1 and Lake 2) with typical δ_L values that have been extended to the Global Meteoric Water Line (GMWL) to provide an estimate of δ_I. Key isotopic framework labeling features in relation to the Local Evaporation Line (LEL) include amount-weighted mean annual precipitation (δ_P), the limiting steady-state isotope composition where evaporation is equal to inflow (δ_{SSL}), and the limiting isotopic enrichment (δ^*) of a desiccating basin under thaw season conditions. Parameters that are used in isotope mass-balance models to derive evaporation-to-inflow (E/I) ratios include the lake water isotope composition (δ_L), input water isotope composition (δ_I), and the isotopic composition of evaporated vapour from the lake (δ_E).

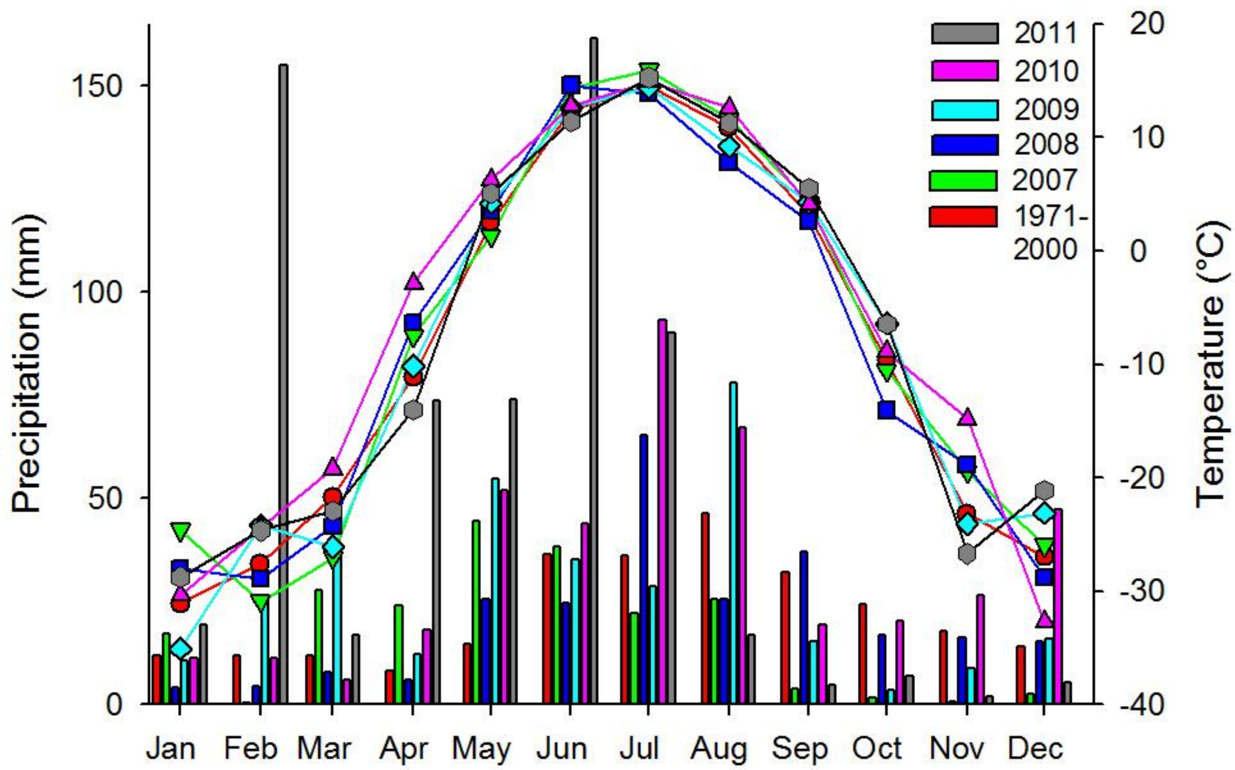

Figure 2-4. Mean (1971-2000) monthly air temperature (°C) and total monthly precipitation (mm) recorded at the Old Crow weather station (Station ID: 2100800 and 2100805) from 2007 to 2011 (Environment Canada, 2012).

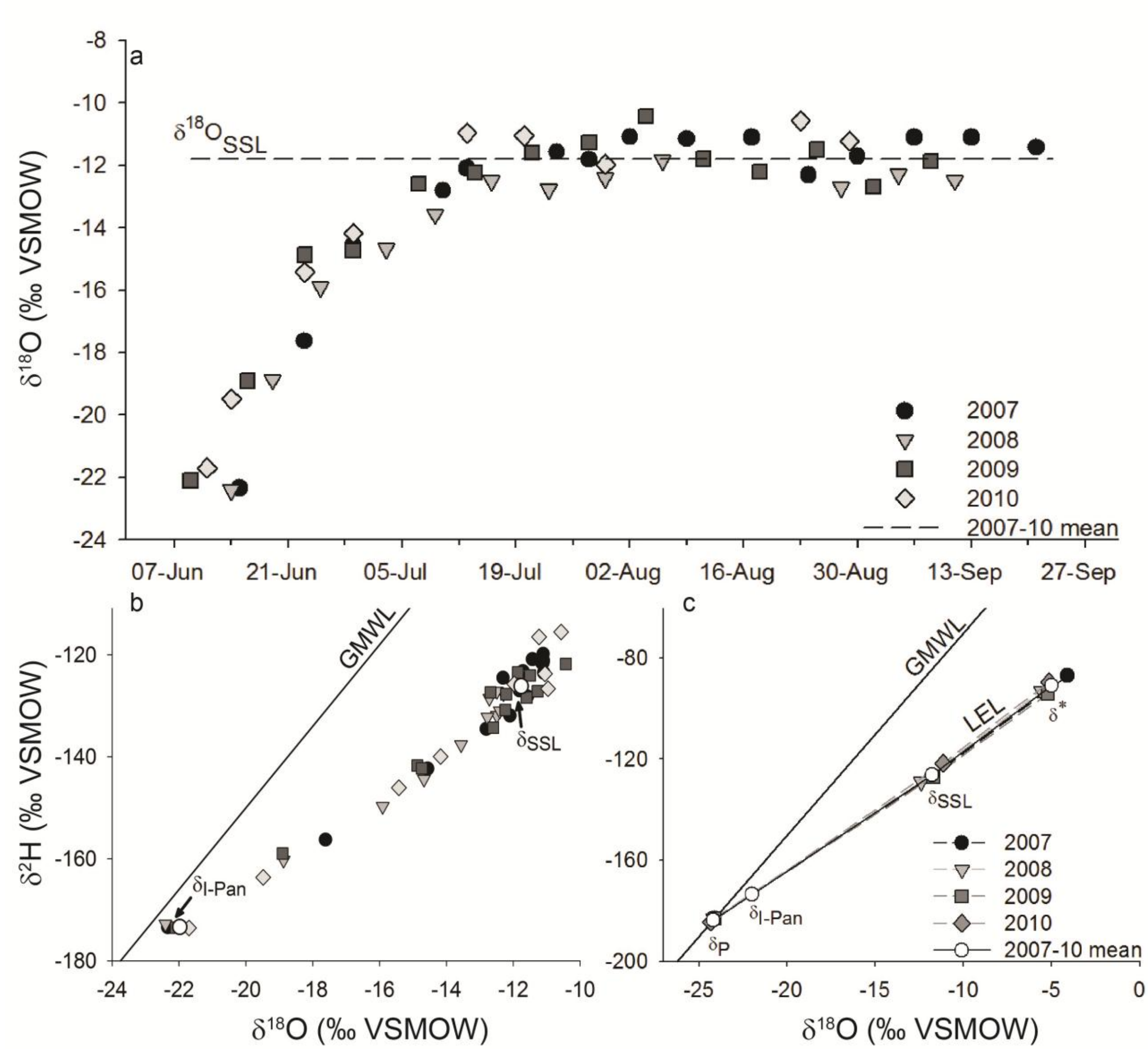

Figure 2-5. a) Isotopic evolution of δ^{18}O of water sampled from an evaporation pan maintained at the Old Crow airport from June to September, 2007-10. b) Evaporation pan evolution is consistent among years and cluster around an average δ_{SSL} (-11.8‰ for δ^{18}O and -126‰ for δ^{2}H). c) A four-year mean LEL ($\delta^{2}H = 4.7\delta^{18}O – 71.7$) was extended through the isotopic composition of pan input water ($\delta_{I\text{-}Pan}$) to the Global Meteoric Water Line (GMWL).

Table 2-3. Flux-weighted thaw season temperature and relative humidity based on WLU meteorological station set up at Old Crow airport and parameters used to construct an average isotopic framework for long-term monitoring based on 2007-11 evaporation pan data

Parameter	2007	2008	2009	2010	2011	Mean	STDV
T(K)	287.7	286.3	285.8	287.1	287.0	286.8	0.8
h (%)	62.6	64	66.5	69.4	67.1	65.9	3.0
α^* (^{18}O, ^{2}H)	1.0103, 1.0910	1.0104, 1.0927	1.0105, 1.0934	1.0103, 1.0917		1.0104, 1.0922	0.0001, 0.0010
ε^* (^{18}O, ^{2}H) ‰	10.3, 91.0	10.4, 92.7	10.5, 93.4	10.3, 91.7		10.4, 92.2	0.09, 1.06
ε_K (^{18}O, ^{2}H) ‰	5.3, 4.7	5.1, 4.5	4.8, 4.2	4.3, 3.8		4.9, 4.3	0.4, 0.4
δ_{AS} (^{18}O,^{2}H) ‰	-28.8, -216	-29.5, -220	-27.8, -216	-26.0, -205		-27.8, -214	1.4, 6.6
δ_{SSL} (^{18}O, ^{2}H) ‰	-11.8, -127	-12.4, -129	-11.7, -127	-11.2, -122		-11.8, -126	0.5, 3.2
δ^* (^{18}O, ^{2}H) ‰	-4.1, -87	-5.6, -93	-5.2, -94	-5.1, -89		-5.0, -91	0.6, 3.2
δ_P (^{18}O, ^{2}H) ‰	-24.1, -183	-24.2, -184	-24.1, -183	-24.3, -185		-24.2, -184	0.1, 0.8
Slope of LEL	4.57	4.65	4.54	4.78		4.63	0.10

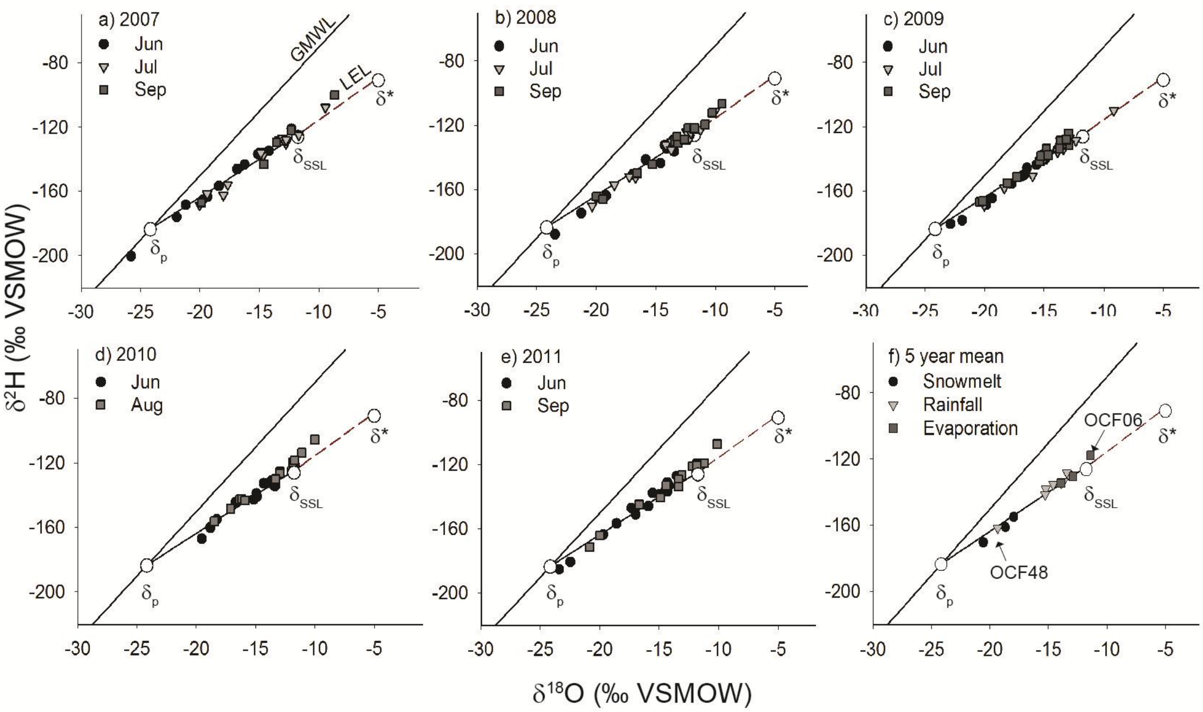

Figure 2-6. Isotopic composition of monitoring lakes (δ_L) superimposed on the four-year mean monitoring isotopic framework for each sampling year: a) 2007, b) 2008, c) 2009, d) 2010, e) 2011 and f) the five-year mean for each hydrologic category as designated by Turner et al. (2010).

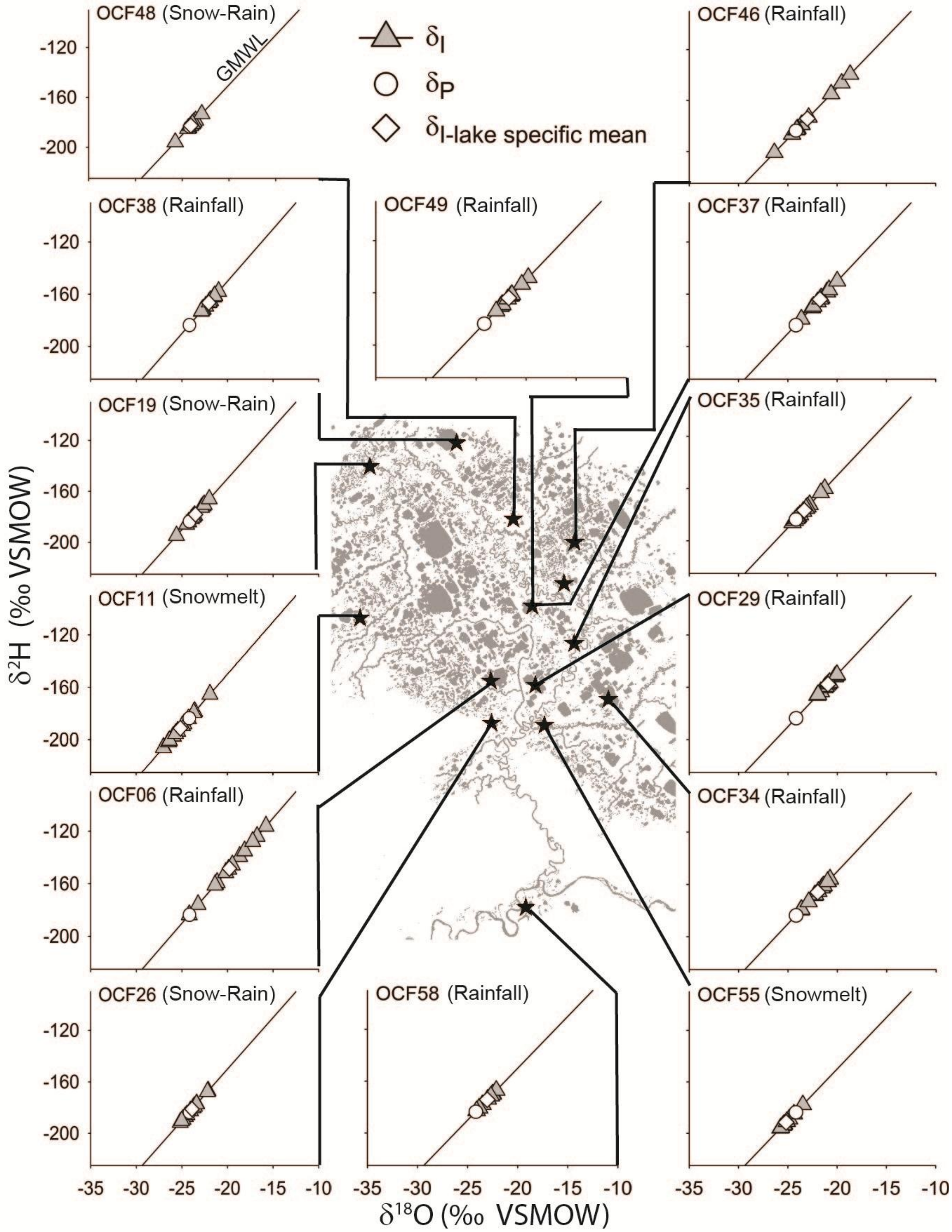

Figure 2-7. Calculated isotopic input water composition (δ_I) for each monitoring lake from 2007-11.

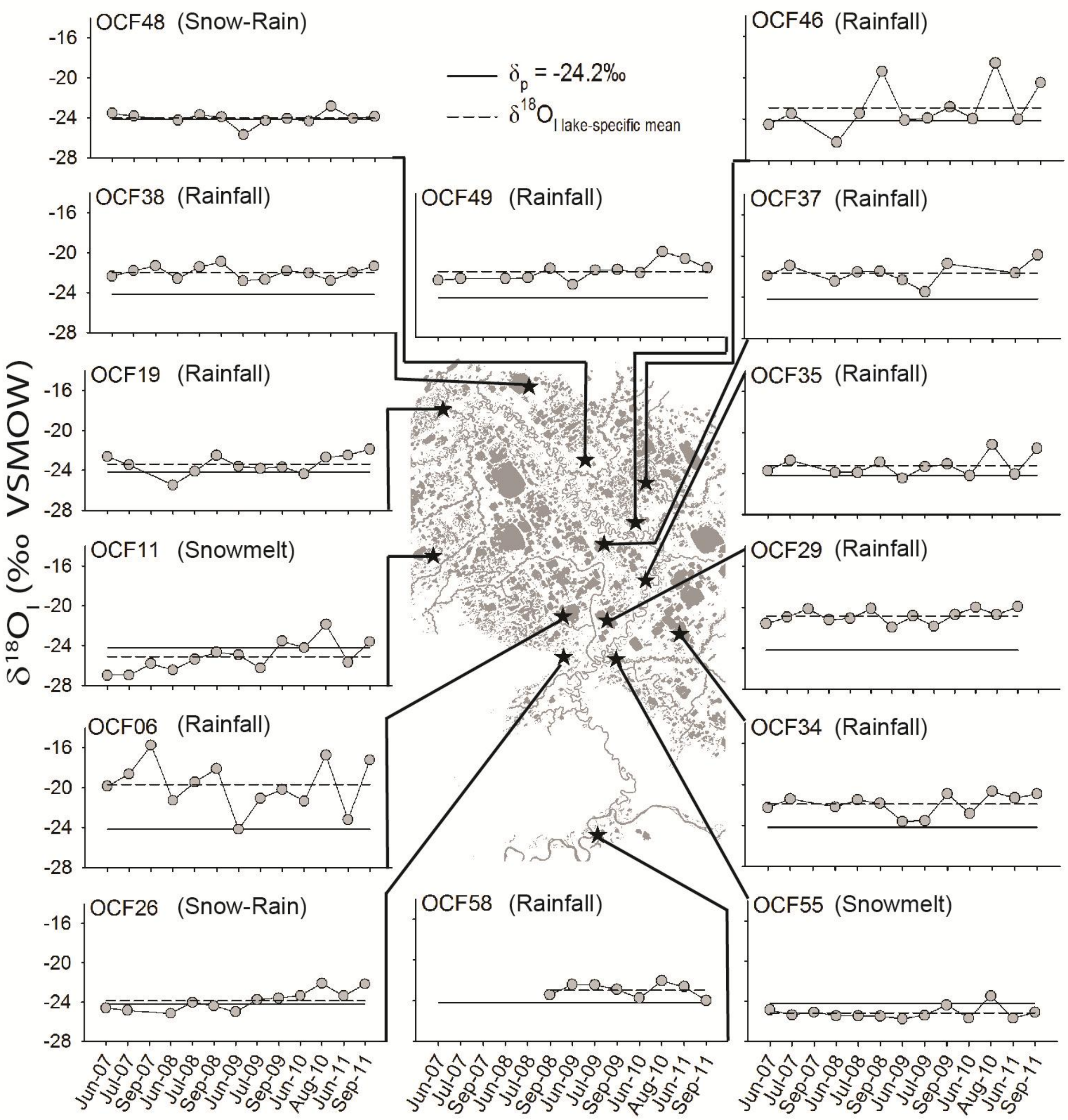

Figure 2-8. Temporal distribution of the isotopic input water composition (δ_I) for each monitoring lake from 2007-11. Solid line represents the four-year average amount-weighted mean annual precipitation (δ_P) and the dashed lines represents mean δ_I value

Table 2-4. General statistics and summary statistics of the Mann-Kendall and Seasonal Kendall trend tests for a) $\delta^{18}O_l$ values and b) E/I ratios

a) $\delta^{18}O_l$ values

Lake	Mean (‰)	Standard Deviation	Mann-Kendall trend test			Seasonal Kendall trend test		
			Mann-Kendall Z	S	p-value	Mann-Kendall Z	S	p-value
OCF06	-19.67	2.50	-0.427	-8	0.665	-1.212	-8	0.225
OCF11	-25.11	1.01	2.867	48	**0.004**	1.905	12	*0.057*
OCF19	-23.40	1.51	1.029	16	0.304	0.596	4	0.551
OCF26	-23.86	1.02	2.949	44	**0.003**	1.391	8	0.164
OCF29	-20.87	0.68	1.708	-8	*0.088*	1.759	11	*0.079*
OCF34	-21.92	1.00	1.303	29	0.193	0.993	6	0.321
OCF35	-23.26	1.03	0.206	20	0.837	-0.199	-2	0.843
OCF37	-21.66	1.01	0.716	4	0.474	1.139	5	0.255
OCF38	-21.99	0.63	-0.183	9	0.573	0.000	0	1.000
OCF46	-22.92	2.26	1.303	20	0.193	0.993	6	0.321
OCF48	-24.05	0.66	-0.480	-4	0.684	0.000	0	1.000
OCF49	-21.64	0.92	2.537	38	**0.011**	1.391	8	0.164
OCF55	-25.15	0.64	-0.671	-12	0.749	-0.520	-4	0.603
OCF58	-22.95	0.70	-0.619	-6	0.732	0.000	-1	1.000

b) E/I ratios

Lake	Mean	Standard Deviation	Mann-Kendall trend test			Seasonal Kendall trend test		
			Mann-Kendall Z	S	p-value	Mann-Kendall Z	S	p-value
OCF06	0.80	0.34	-0.671	-12	0.749	-0.173	-2	0.863
OCF11	0.30	0.20	0.061	2	0.951	0.000	0	1.000
OCF19	0.75	0.20	-0.617	-10	0.731	-0.199	-2	0.843
OCF26	0.25	0.06	-0.480	-8	0.684	-0.596	-4	0.551
OCF29	0.49	0.11	0.488	9	0.625	0.352	3	0.725
OCF34	0.42	0.10	1.029	16	0.304	0.199	2	0.843
OCF35	0.44	0.14	1.029	16	0.304	0.569	4	0.551
OCF37	0.56	0.15	0.179	3	0.858	0.000	1	1.000
OCF38	0.36	0.10	-1.037	-18	0.850	-1.559	-10	0.119
OCF46	0.61	0.25	-0.069	-2	0.527	0.199	2	0.843
OCF48	0.18	0.07	0.891	14	0.373	0.993	6	0.321
OCF49	0.62	0.14	-0.069	-2	0.527	-0.199	-2	0.843
OCF55	0.16	0.05	0.183	4	0.855	-0.520	-4	0.603
OCF58	0.58	0.12	0.000	0	0.500	-0.569	-3	0.613

Significant ($p<0.05$) trends are reported in bold.

Emerging ($p<0.1$) trends are reported in italics.

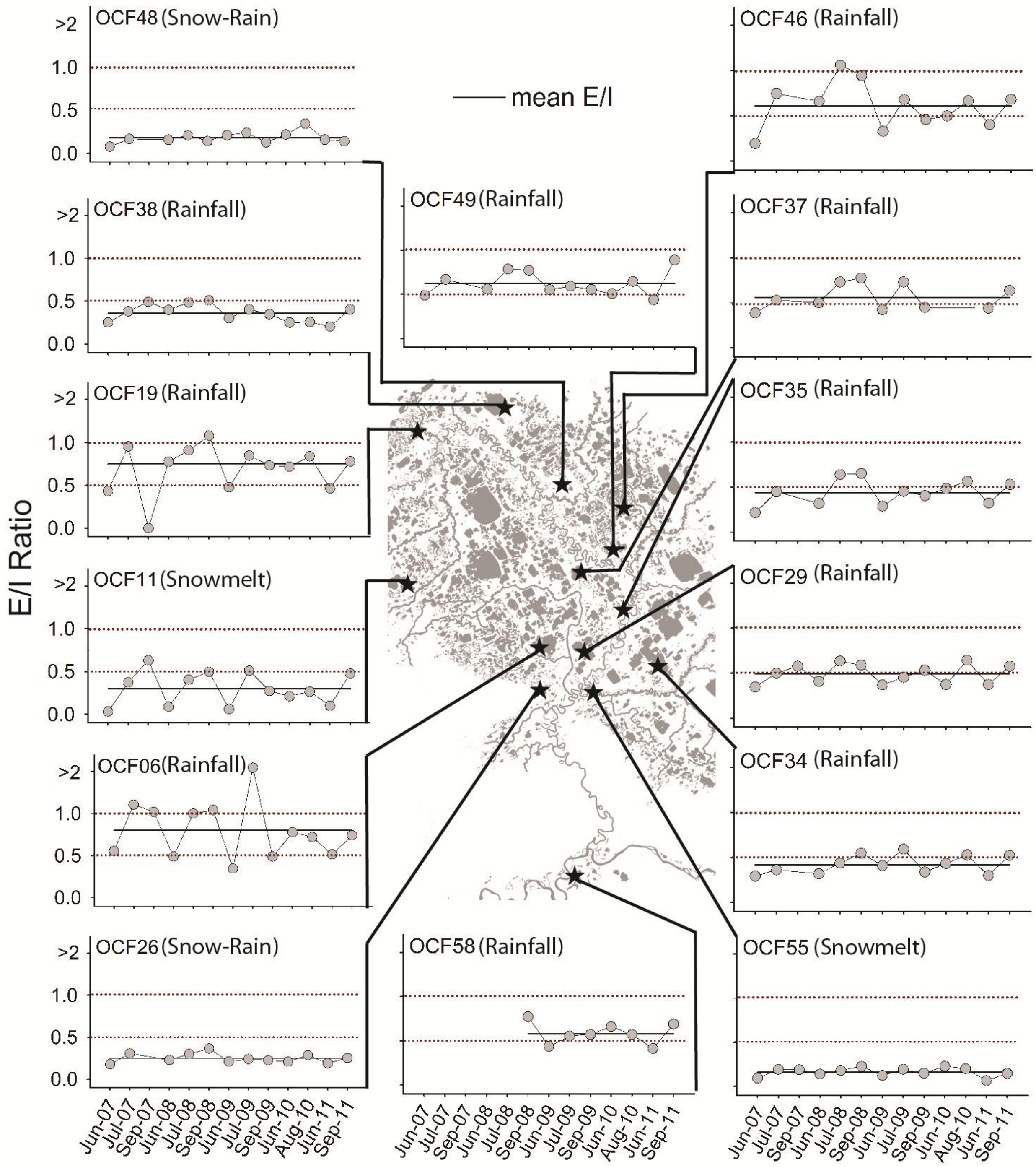

Figure 2-9. Temporal distribution of evaporation-to-inflow (E/I) ratios during 2007-11. An E/I ratio > 0.5 represents the threshold for evaporation-dominated lakes (Turner *et al.* In review) and is designated by a dotted line. The dotted line at E/I = 1 represents δ_{SSL}.

Chapter 3

Effects of climate change on the hydroecology of a shallow thermokarst lake in northwestern Canada: a paleolimnological perspective

Key Words: paleolimnology, Old Crow Flats, drainage, lake expansion, thermokarst, northern freshwater ecosystem, climate change

3.1 Introduction

Thermokarst lakes are abundant and naturally productive ecosystems in many areas of the Arctic, but are often transitional systems that are particularly vulnerable to climate change (Schindler & Smol 2006; Miller *et al.* 2010; Karlsson *et al.* 2011; Vincent *et al.* 2011). In recent decades, northern temperatures have increased up to 2-3°C and are projected to increase another 2.5°C by the mid-21st century (ACIA 2005). Profound hydrological transitions and regime shifts in the biological communities of many high-latitude lakes, attributed to warmer temperatures, have already been documented (Smol *et al.* 2005; Schindler & Smol 2006; Carroll *et al.* 2011; Karlsson *et al.* 2011). In some cases, Arctic lakes have completely desiccated owing to warmer temperatures and an associated increase in evaporation/precipitation ratios, while others have experienced reduced water levels (Smol & Douglas 2007). In northern landscapes underlain by permafrost, geomorphic changes due to thermokarst activity also influences the hydroecology of pan-Arctic wetlands. Recent studies suggest that these changes are amplified by climate warming, which can lead to water-level declines through accelerated lake drainage events due to increases in precipitation (Hinkel *et al.* 2007; Wolfe & Turner 2008), and permafrost thaw (Karlsson *et al.* 2012 in press), as well as lake expansion through accelerated thermokarst activity and permafrost thaw (Payette 2004). Remote sensing studies have provided key information regarding changes in lake surface area over large spatial extents; however, temporal investigations of thermokarst lake dynamics are limited by the availability of images that only span the last few decades (Yoshikawa &

Hinzman 2003; Smith *et al.* 2005; Riordan *et al.* 2006). While remote sensing studies can provide quantitative data on increases or decreases in lake surface area, these approaches are often unable to provide details on the processes responsible for water-level changes. For example, decreases in lake surface area may be due to complete or partial drainage events as well as evaporation, and increases in lake surface area may be attributed to thermokarst expansion, thawing permafrost, or increases in precipitation.

Long-term hydroecological monitoring of lakes in northern landscapes is scarce, inhibiting our ability to clearly identify how lake hydroecological conditions have evolved over time and how they might respond to changes in climate. Yet, understanding long-term hydroecological changes is of great concern to circum-Arctic agencies and communities responsible for the management and stewardship of northern landscapes. For example, the Vuntut Gwitchin First Nation (VGFN) and Parks Canada (Vuntut National Park), responsible for co-managing Old Crow Flats (OCF), Yukon Territory (Figure 3-1), are concerned about how declining water-levels will affect the ecological integrity of their management area, and the impacts climate change will have on the health and future of OCF. In response to these concerns, these organizations are working towards implementing a long-term hydroecological monitoring program (see Chapter 2), yet historical data are essential to determine natural variability and ongoing responses to climate change. Labrecque *et al.* (2009) indicated that lake surface area in OCF has declined since 1972, but the mechanisms driving changes in hydrology are poorly understood and it remains unclear whether these changes are a unique response to warming of the past 50 years or are common on longer time-scales (i.e., within the past 300 years). In the absence of long-term environmental monitoring data, paleolimnological techniques can be used to provide a long-term perspective on hydroecological transitions.

High-latitude paleolimnological research has been widely conducted to investigate the influence of climate change on the hydroecology of northern freshwater landscapes (Douglas *et al.* 1994; Pienitz 1995; Keatley *et al.* 2006; Wolfe *et al.* 2006; Brock *et al.* 2010). Recently, MacDonald *et al.* (2012b) combined paleolimnological techniques with aerial images to track hydrological changes and identify their causes in one thermokarst lake (OCF48) in OCF. Hydrological transitions in thermokarst landscapes, such as OCF, are complex and involve three main processes: i) lake expansion and development through degradation of permafrost enhanced by increases in precipitation and temperature; ii) accelerated vertical and lateral lake drainage events heightened by talik formation and thermo-erosion from increasing temperature, precipitation, and/or permafrost degradation; and iii) lake desiccation due to increasing temperature, duration of the ice-free season, and/or decreasing precipitation.

The paleolimnological analysis of OCF48 revealed that past hydroecological transitions involving multiple pathways (i.e., lake expansion, lake drainage, and gradual water-level declines) can be determined. MacDonald *et al.* (2012b) produced a conceptual model outlining the expected stratigraphic profile of a lake undergoing thermokarst-drainage cycles and evaporative drawdown by linking paleolimnological techniques with historical images (Figure 3-2). In their predicted schematic, organic matter rapidly decreases during the onset of thermokarst expansion owing to an increased supply of minerogenic sediment. This results in an increase in turbidity that reduces lake productivity. Thawing permafrost and high precipitation can often lead to rapid drainage events in thermokarst landscapes (Wolfe & Turner 2008; Marsh *et al.* 2009; Pohl *et al.* 2009). As suggested by MacDonald *et al.* (2012b), this transition would be captured stratigraphically by a sharp increase in organic matter as the water column becomes clear and primary productivity increases, assuming water remains in the basin. After drainage, water-levels in OCF48 increased, suggesting that lakes may re-fill and return to stable state post-drainage. In a different scenario, such as an increase in temperature without pronounced increases in precipitation, MacDonald *et al.* (2012b) suggested that organic matter content would gradually increase owing to an increase in productivity due to evaporative concentration of nutrients and water-level declines. MacDonald *et al.* (2012b) acknowledge that the proposed stratigraphic profiles are based on one sediment core in a landscape with approximately 2700 lakes and suggest that additional paleolimnological research is needed to further evaluate water-level declines in OCF.

The aim of this paper is to expand paleolimnological research in OCF and augment the hydroecological monitoring program in OCF by exploring past hydroecological transitions associated with thermokarst activity and changes in climate. Physical, geochemical, and biological analyses, of a sediment core collected from Zelma Lake (OCF06) are incorporated with historical aerial images to investigate past hydroecological conditions. Zelma Lake is a culturally-significant lake that rapidly drained in June 2007 due to elevated precipitation levels during the preceding winter and spring (Wolfe and Turner 2008). Thus, Zelma Lake will also provide an opportunity to reconstruct hydroecological conditions prior to and post drainage to improve understanding of the hydroecological conditions associated with thermokarst processes, particularly drainage events.

3.2 Site Description

Old Crow Flats (OCF) (68°N 140°W) is a flat, low-lying area at an average elevation of 327 m that is encircled by six different mountain ranges in Yukon and Alaska (Figure 3-1). These mountain ranges act as a barrier to the inland movement of Pacific air masses resulting in winters that are prolonged and cold. According to 1971-2000 climate normals at Old Crow airport, Yukon (Weather Station ID 2100800; Environment Canada 2012), average annual air temperature is -9°C and fluctuates substantially between summer and winter months. The coldest (warmest) month occurs in January (July), which has a mean temperature of -31°C (15°C). Average total annual precipitation is 265.5 mm, ~60% of which falls as rain (165.5 mm) during the months of May to September.

OCF is underlain by continuous permafrost. The landscape is a relic of ancient Glacial Lake Old Crow that inundated the basin from 35,000 yr BP until it drained between 16,400 $\pm$ 110 and 14,860 $\pm$ 120 yr BP (Hughes 1972; Zazula *et al.* 2004). Downcutting of river channels through the thick fluvial and glaciolacustrine sediments deposited from the ancient lake have left lakes, that are primarily thermokarst in origin, perched 40-50 m above rivers (Lauriol *et al.* 2002; Yukon Ecoregions Working

Group 2004). Ice-rich fine-grained Quaternary sediments are easily degraded by thermal abrasion and erosion promoting shoreline recession and bank slumping in lakes in OCF (Roy-Leveillee & Burn 2011).

Surface areas of lakes in OCF vary considerably (0.01-37 km^2), although 92% of these lakes have a surface area of 0.01 km^2 or less, and are generally shallow (0.2-2.0 m), with the exception of oxbow lakes that can be >5.0 m (Labrecque *et al.* 2009). Turner *et al.* (2010; In review) identified three main hydrological lake types using water isotope tracers: snowmelt-sourced, rainfall-sourced, and evaporation-dominated.

The study site, Zelma Lake (OCF06), is a large (~12km^2) centrally located lake (67° 55'N, 139° 56'W; see Figure 3-1). Aerial photographs from 1951 and 1972 show a similar extent of lake surface area (Figure 3-3). In June 2007, Zelma Lake rapidly drained likely due to above-average winter precipitation during October-April, 2006-07 (148 mm, mean 1951-2000 = 100 mm) and above-average precipitation in May (44.4 mm; Wolfe & Turner 2008). The resulting high water levels breached the bank and consequently triggered rapid drained. An upstream lake drained the previous year, which might have also played a key role in catalyzing the drainage of Zelma Lake. The discharge of water from Zelma Lake was substantial (5.8 million m^3) and exposed ~5.2 km^2 of lake bed (Wolfe & Turner 2008). This large volume of water was exported from Zelma Lake via an incised channel connected to Wild Creek; a tributary of Schaeffer Creek that drains into the Old Crow River. Thus, the drainage event represents an overall loss of water from the system as water eventually flowed into the Old Crow River, which drains into the Bearing Sea via the Yukon River. Currently, the average depth of Zelma Lake is 0.3 m.

Water isotope monitoring during 2007-11 indicates that Zelma Lake is a rainfall-sourced lake that becomes evaporation-dominated as the ice-free season progresses (mean $\delta^{18}O_L$ =-11.4‰ and mean δ^2H_L =-118‰; Figure 3-4). Calculated evaporation-to-inflow (E/I) ratios exceeded 1 in 2007-09 indicating sensitivity to evaporation and potential susceptibility to future desiccation (mean E/I = 0.8; see Chapter 2). Zelma Lake is alkaline and pH increases from 8.1 to 9.5 as photosynthesis increases during the ice-free season (Table 1). The lake is meso-eutrophic based on total phosphorus concentration (mean early season = 36.35 µg/l; mean late season = 67.15 µg/l), and has a high concentration of dissolved inorganic carbon and major ions (Ca, K, Mg, Na, and SiO_2). Abundant macrophyte assemblages of pond weed (*Potamogeton sp*.), watermilfoil (*Myriophyllum sp.*), and sedges (*Carex sp*) are also present. Terrestrial vegetation within the 16 km^2 catchment area consists of tall shrubs (14.5%) and dwarfed shrubs, herbs and non-vascular plants (9.9%) (Turner *et al.* In review; Chapter 2). Barren land occupies 44% of the catchment area due to exposure of lake bed area following drainage in 2007. Since then, a large proportion of barren land has been re-vegetated by grasses, sedges, and other plants.

3.3 Methods

3.3.1 Sediment core collection and physical characteristics

A 34.0-cm long sediment core was retrieved from the approximate centre of Zelma Lake in August, 2010 by deploying a Glew (1989) gravity corer from the pontoon of a helicopter. The sediment core was extruded and sectioned into 0.5-cm intervals using a close-sectioning upright extruder (Glew 1988) in the community of Old Crow. Sediments were stored in Whirlpak® bags at 4°C until analysis. Water content, weight percent of organic matter and carbonate content were determined on contiguous 0.5-cm intervals by sequential heating of 0.5 $\pm$ 0.05 g of well-mixed, wet sediment at 90°C for 24 hours, 550°C for 1 h, and 950°C for 1 h, respectively (Dean 1974; Heiri *et al.* 2001).

3.3.2 Sediment core chronology

Sediment core chronology was developed by measuring the activities of ^{210}Pb, ^{214}Bi, and ^{137}Cs on every 2nd 0.5-cm thick sediment sample from 0-20 cm and every 4th 0.5-cm thick sediment sample from 20-32 cm. Activities for ^{210}Pb and ^{214}Bi were used to calculate sedimentation rates and ages using the Constant Rate of Supply (CRS) model, which allows the sedimentation rate to vary through time (Appleby 2001). Activities of ^{137}Cs were used as a complementary radioisotope dating technique to the ^{210}Pb-based chronology by providing an independent marker for the 1963 peak fallout of this radionuclide. Approximately 2.0-3.0 g of freeze-dried sediment was weighed and packed (tightly) into

DSPEC tubes to a height of 35 mm. Sediments were sealed with 1 cm^3 of epoxy resin to establish equilibrium between ^{226}Ra and daughter isotopes (^{210}Pb, ^{137}Cs, and ^{214}Bi). Prepared samples were analyzed with an Ortec co-axial HPGe Digital Gamma Ray Spectrometer (Ortec #) and Maestro 32 software (version 5.32).

3.3.3 Geochemical analysis

Elemental carbon and nitrogen content and isotope compositions were measured on contiguous 0.5-cm sections. All samples were prepared for analysis following methods outlined by Wolfe et al. (2001). Samples were treated with 10% (by volume) HCl in a 60°C water bath to remove carbonate minerals and shells. After 24 hours, samples were rinsed with de-ionized water repeatedly until the pH approximated neutral, placed in a freeze-dryer to remove moisture, and sieved (500 µm) to remove coarse organic debris. The fine fraction (<500 µm) was weighed, submitted to the University of Waterloo Environmental Isotope Laboratory, and analyzed for organic carbon and nitrogen elemental and isotopic composition using an elemental analyzer interfaced with a Continuous Flow Isotope Ratio Mass Spectrometer (CF-IRMS). Data are reported in the conventional δ notation and given as per mil (‰) relative to Vienna Pee-Dee Belemnite (VPDB) for carbon isotope composition and atmospheric nitrogen for nitrogen isotope composition. Analytical uncertainties, based on repeat samples, for elemental carbon and nitrogen are $\pm$ 0.10‰ and $\pm$ 0.02‰, respectively, while uncertainties for $\delta^{13}C$ are $\pm$ 0.08‰ and $\delta^{15}N$ are $\pm$ 0.11‰. The percent dry weight of carbon and nitrogen were used to calculate carbon-to-nitrogen ratios.

3.3.4 Pigment analysis

Lake sediment samples from every second 0.5-cm interval were analyzed for pigment concentrations using the reverse phase high performance liquid chromatography (HPLC) method described by Mantoura and Llewellyn (1983), modified by Leavitt et al. (1989). Approximately 0.4 $\pm$ 0.05 g of freeze-dried sediments were submerged in 5 mL of extraction solvent (80:15 (v/v), acetone:MeOH) and placed in a freezer for 24 hours. Once the pigments were extracted, the solution was filtered through a 0.2-µm Millex-FG syringe-driven hydrophobic PTFE filter to remove fine particles from the organic solvent, and poured into amber vials. The filtrate was dried with N_2 gas to prevent oxidation and degradation of pigments. Once dry, 300 µL of calibration solution (Sudan II) was added to the sample vial, pipetted into inserts, and analyzed with a WATERS 2695 HPLC system. Pigment concentrations, expressed as nMol pigment g^{-1} organic matter, were identified using retention times and chromatograms compared to known standards (Jeffrey *et al.* 1997). Pigments identified included carotenoids characteristic of total algae (β-carotene), green algae (lutein), siliceous algae and dinoflagellates (fucoxanthin), mainly diatoms (diatoxanthin), cyanobacteria (echinenone), colonial cyanobacteria (canthaxanthin), and purple-sulfur bacteria (okenone). Chlorophyll-*a* and-*b* pigments were also identified and are representative of total algal concentrations and green algae, respectively.

3.4 Results and interpretation

3.4.1 Sediment core chronology

The ^{210}Pb activity in Zelma Lake sediments declines rapidly with depth in an exponential fashion (Figure 3-5a). ^{210}Pb activities in the upper 5 cm decline from 0.132 Bq g^{-1} to 0.075 Bq g^{-1} and from 0.081 Bq g^{-1} to 0.041 Bq g^{-1} between 5 cm and 10 cm. Activities reach near-background levels (supported ^{210}Pb estimated from the mean of all measured values of ^{214}Bi and ^{214}Pb = 0.040 ± 0.004 Bq g^{-1}) at 10 cm (0.041 Bq g^{-1}). However, ^{210}Pb activity increases at 11 cm (0.048 Bq g^{-1}) and remains above background ^{210}Pb levels until 18 cm (0.043 Bq g^{-1}). It is likely that increases in sedimentation rates during this time have a diluting effect on the ^{210}Pb activity levels. This suggests that sediment accumulation rates were not constant, thus the Constant Rate of Supply (CRS) model was applied to determine sediment chronology (Oldfield & Appleby 1984; Appleby 2001). As unsupported ^{210}Pb activity asymptotically approaches zero with depth, a small value of unsupported ^{210}Pb activity below 18 cm depth remains that cannot be directly measured. This value was estimated to be 0.198 Bq cm^{-2} or 1.4% of the total unsupported ^{210}Pb inventory. Incorporating this "missing" portion of the ^{210}Pb inventory in the CRS age model improves the accuracy of dates near background depth (Appleby 2001). The resulting CRS model for Zelma Lake gave a basal date of approximately 1877 (18 cm) with mean sampling resolution of 3.8 years from 0 cm to 18 cm. Error in the CRS modelled chronology range from ±2.1 to ±18.2 years (average = ±11.9 years). Dates below the level of unsupported ^{210}Pb activity are extrapolated based on linear regression of the CRS modelled dates versus cumulative sediment dry mass from ~1924 to 1877, before changes in modelled ages are influenced by non-uniform sedimentation rates. Estimated dates after 1877 assume a sedimentation rate that is equivalent to the ~1924-1877 period and approximated the basal date of the bottom-most sediments to be ~1678 (Figure 3-5b).

^{137}Cs was also measured as a complementary radioisotope dating technique and supports the ^{210}Pb-based chronology. Results indicate a peak in ^{137}Cs activity (0.026 Bq g^{-1k}) at 6.5 cm (1964 according to the CRS model) in the core, which is in good agreement with the well-established maximum ^{137}Cs fallout that occurred in 1963-64 as a result of nuclear weapons testing (Appleby 2001).

3.4.2 Physical and geochemical analysis

The percentage of organic and mineral matter, carbonate content, bulk organic carbon (C_{org}) and nitrogen (N), carbon-to-nitrogen (C/N) ratios, carbon ($\delta^{13}C_{org}$), and nitrogen ($\delta^{15}N$) isotopic signatures show systematic and coupled trends throughout the sediment profile (Figure 3-6). Overall, there are four distinct intervals of variation that are interpreted to reflect hydroecological changes over the past ~330 years. During the first ~220 years (~1678-1900) of the sediment record, all geochemical measures show small oscillations and slight trends, but overall reflect a relatively stable period. Throughout this interval, the relative proportions of organic matter (16-21%), mineral matter (76-81%), and carbonate content (5-16%) display a modest oscillatory pattern with no apparent overall trend. Values for C_{org} (9.5-12.4%), N (0.8-1.1%), and C/N ratios (10.9 to 12.6) remain relatively constant. $\delta^{13}C$ values (-20.7 to -19.6‰) and $\delta^{15}N$ values (2.0-2.7‰) also show little variation. Overall, the early part of the sediment record reflects a relatively stable period (termed phase 1) in which all geochemical parameters remain near-constant.

Most geochemical measures show pronounced changes after ~1900 and clear trends that continue until ~1943 (Figure 3-6). During this interval, organic matter (15-11%) sharply declines and mineral matter concomitantly increases (83-87%), while carbonate content (4.8-6.0%) remains nearly constant. Elevated sedimentation rates occur between ~1920-1929 (0.19-0.78 $g/cm^2/yr$) and ~1938-1943 (0.21-1.40 $g/cm^2/yr$). Both C_{org} (9.9-5.5%) and N (0.9-0.4%) abruptly decrease, resulting in a steep increase in C/N ratios (10.9-12.6). Values for $\delta^{13}C_{org}$ (-21.4 to -25.0‰) decrease in a similar fashion as the other parameters, while $\delta^{15}N$ (2.4-3.1‰) increases.

The increase in C/N ratios, which can be used to distinguish the input of allochthonous versus autochthonous material, suggests that organic matter is increasingly derived from terrestrial matter rather than aquatic sources (Meyers & Teranes 2001).These changes are characteristic of increased minerogenic turbidity associated with the introduction of sediments and terrestrial material from shoreline erosion due to thermokarst activity. The carbon isotope composition of organic matter ($\delta^{13}C_{org}$) is useful for reconstructing past productivity in lake sediments because phytoplankton preferentially remove CO_2 containing ^{12}C during photosynthesis to produce organic matter (Meyers & Teranes 2001; Wolfe *et al.* 2001). This leaves the remaining $CO_{2(aq)}$ enriched with the heavier isotope of carbon (^{13}C) and generates an increase in the $\delta^{13}C$ of organic matter produced in the lake (Battarbee 2000). The decline in $\delta^{13}C_{org}$ values during this lake expansion period signifies a reduction in productivity, likely a result of reduced light availability due to the highly turbid conditions. Most of the geochemical proxies indicate highly turbid conditions, an increase in terrestrial input, and a decrease in aquatic productivity typical of a lake undergoing thermokarst expansion, with the exception of $\delta^{15}N$. Organic matter that is produced autochthonously using dissolved nitrate results in ^{15}N-enrichment due to algal discrimination in favour of ^{14}N, thus higher $\delta^{15}N$ values would suggest an increase in aquatic primary production (Meyers & Teranes 2001). However, MacDonald et al (2012b) point out that increases in

$\delta^{15}N$ values may be a result of the leaching of soils from shoreline erosion introducing ^{15}N-enriched nitrate.

After ~1943, each parameter displays reverse trends, with the exception of $\delta^{15}N$. Organic matter (12.4-18.5%), C_{org} (6.9-8.8%), N (0.6-0.8%), $\delta^{13}C_{org}$ (-24.5 to -23.1‰), and $\delta^{15}N$ (2.3-3.3‰) all display a gradual increasing trend. In contrast, mineral matter (85-79%) and C/N ratios (14.0-10.6) gradually decline and sedimentation rates remain constant.

The decrease in mineral matter suggests that active thermokarst expansion has either ceased or decelerated. The increase in organic carbon, nitrogen, $\delta^{13}C_{org}$, and $\delta^{15}N$ values insinuates an increase in productivity. C/N ratios begin to decline ~1961, which suggests a trend towards the production of autochthonous organic matter. The delay in the decline of C/N ratios could be attributed to the addition of shoreline trees due to previous bank instability. Overall, this period reflects different hydroecological conditions (labeled phase 2) in which thermokarst activities may have decreased enough to allow suspended sediments to settle to the bottom of the lake thereby enhancing light penetration and aquatic productivity. In 2007, Zelma Lake experienced a rapid drainage event in which an estimated 5.8 million m^3 of water was lost via an eroded outlet channel (Wolfe & Turner 2008) . Within the upper 2 cm of the sediment profile, organic matter increased by 3.8% and mineral matter decreased by 3.4%.

3.4.3 Pigment analysis

Fossil algal pigments provided information on the relative abundance of major algal groups in Zelma Lake over the past ~330 years (Figure 3-7). Pigment concentrations vary throughout the sediment profile and stratigraphic changes occur at the same horizons as the geochemistry data (Figure 3-6). Lutein and chlorophyll-*a* are consistently recorded in the sediment profile from ~1678-1900 and maintain relatively constant concentrations (mean = 214.4 nMol g^{-1} and 64.6 nMol g^{-1}, respectively). β-carotene (4.7 nMol g^{-1}), canthaxanthian (13.2 nMol g^{-1}), echinenone (14.1 nMol g^{-1}), and fucoxanthin (3.4 nMol g^{-1}) are also present during this interval, however, their concentrations display a decreasing trend and fucoxanthin is recorded sporadically. Phase 1 is characterized as a moderately productive aquatic period owing to the substantial presence of green algae (lutein) and cyanobacteria (canthaxanthian) and modest concentrations of chlorophyll-*a* from total algae.

Echinenone and β-carotene disappear from the sediment record after ~1900 and the mean concentration of canthaxanthian (5.5 nMol g^{-1}) and fucoxanthin (6.0 nMol g^{-1}) remain low and occur intermittently until ~1943. During this time period, lutein occurs intermittently and mean concentrations generally decrease (64.3 nMol g^{-1}) while mean chlorophyll-*a* concentrations slightly increase (78.9 nMol g^{-1}). This interval (~1900-1943) is marked by an overall decrease in primary productivity owing to the decrease in mean concentrations of fucoxanthin, lutein, and canthaxanthian as well as the disappearance of β-carotene and echinenone.

After ~1943, large increases in mean pigment concentrations of fucoxanthin (36.4 nMol g^{-1}), lutein (260.3 nMol g^{-1}), chlorophyll-*a* (323.4 nMol g^{-1}), and canthaxanthian (36.3 nMol g^{-1}) occur. Unique to this interval is the occurrence of chlorophyll-*b* (mean = 154.1 nMol g^{-1}), with the exception of one sample at the base of the sediment core. β-carotene re-emerges during this phase (~1984), phase 2, which is characterized by an increase in primary productivity.

The upper 2 cm of the sediment core exhibit a pronounced transition towards greater rates of primary productivity with the re-emergence of echinenone (mean = 11.1 nMol g^{-1}) and the appearance of okenone (16.0 nMol g^{-1}) and diatoxanthin (91.4 nMol g^{-1}). The presence of these algal groups is likely a result of the changing limnological conditions associated with the 2007 drainage event. Okenone is produced by purple sulphur bacteria which are strict anaerobes.

3.5 Discussion

The effects of climate change on the hydroecology of dynamic northern landscapes such as OCF are complex and poorly understood. Northern high-latitude regions contain tens of thousands of thermokarst lakes that continually develop, expand, and drain through degradation of surface permafrost (Grosse *et al.* 2012). There is debate within literature as to whether eventual re-initiation and re-filling of thermokarst lakes occurs after drainage (Grosse *et al.* 2012) or whether differential ice aggradation leads to the formation of secondary thaw lakes or eventual paludification (Jorgenson & Shur 2007). Thermokarst lakes initially form through the thawing of polygonal ice veins and wedges or the broad subsidence of ice-rich ground that forms a depression in which water can accumulate (Czudek & Demek 1970). Fundamental to thermokarst lake development is the formation of the talik (area of unfrozen ground between the active layer and permafrost) beneath the lake that creates positive winter-time heat fluxes and aids in the warming and degradation of adjacent permafrost (Grosse *et al.* 2012). Lakes continue to expand laterally by thermal erosion due to the high specific heat capacity of water and mechanical erosion through wave action and ice-shove during lake-ice break-up. Erosion from thermal energy and the conversion of potential to kinetic energy form steep banks along the margins of thermokarst lakes that can result in thaw slumps that introduce trees and other vegetation, soil and peat layers, and sediments into lakes (Osterkamp *et al.* 2000; Kokelj *et al.* 2009a). Thermokarst lakes may eventually drain, either partially or completely, and mechanisms that drive lake drainage are multifaceted and include: increases in water levels from large precipitation events that promote water to breach the edge of the lake (Marsh & Neumann 2001; Wolfe & Turner 2008); retrogressive thaw slumps along the shoreline (Lantz & Kokelj 2008); sub-surface pipe flow through interconnected ice wedge cracks (Marsh *et al.* 2009); penetration of the talik into sub-permafrost groundwater and establishment of vertical hydraulic gradients (Yoshikawa & Hinzman 2003); and deeper-than-normal active layers in combination with moderately high lake levels and high soil moisture resulting in increased ground water leaking from the lake through the active layer (Pohl *et al.* 2009). This constant thermokarst evolution causes water-levels to fluctuate, which are expected to influence the limnology and aquatic ecology.

Long-term data generated by a multi-proxy paleolimnological analysis from sediments of Zelma Lake indicate distinct phases of hydroecological conditions over the past ~330 years associated with thermokarst activity. All paleolimnological indicators during phase 1 (~1678-1900) remain constant and indicate that the lake was not experiencing any major hydroecological change. After ~1900, there is a sharp decline in organic matter content, organic carbon, and nitrogen content, $\delta^{13}C_{org}$, and pigment concentrations and a concomitant increase in mineral matter, $\delta^{15}N$, and C/N ratios. These changes are likely associated with thermokarst lake expansion that lasted approximately 40 years.

In ~1943, a hydroecological transition from active thermokarst expansion towards phase 2 occurs. It appears that the shorelines of Zelma Lake either stabilized or active thermokarst activity decelerated, indicated by a decrease in mineral matter content (and corresponding increases in organic matter content) and constant sedimentation rates. Historic aerial images of Zelma Lake suggest that lake surface area between 1951 and 1972 remained constant. From ~1943-2007, the hydroecological conditions of Zelma Lake are marked by an increase in organic matter and primary productivity indicated by $\delta^{13}C_{org}$, $\delta^{15}N$, and elevated pigment concentrations. The decline in C/N ratios indicates a trend towards increasing autochthonous production of organic matter. This change in hydroecological conditions may be attributed to a decrease in active thermokarst expansion, which may have led to clear water conditions allowing for more light to penetrate the water column and enhance primary productivity. The addition of terrestrial material during the previous thermokarst expansion phase may have introduced nutrient rich bioavailable organic material, suggested by the increase in $\delta^{15}N$ during this interval, further promoting primary production in phase 2. Within phase 2, pigment concentrations increase markedly beginning in ~1975, particularly dinoflagellates (fucoxanthin), green algae (lutein and Chl-*b*), and total algae (chl-*a*), and β-carotene re-emerges in ~1984. This change occurs simultaneously with ring-width index, a proxy for July temperatures, determined from spruce trees in OCF (Figure 3-6; Porter & Pisaric 2011), which indicate July temperatures have become progressively warmer in the last several decades. Thus, increases in primary productivity during phase 2 may also be influenced by warmer summer temperatures.

In June 2007, Zelma Lake rapidly drained due to above-average winter snowfall and precipitation in early spring (Wolfe & Turner 2008). The discharge of water from Zelma Lake was forceful and easily eroded an incised channel through the soft clay resulting in a ~43% reduction in lake area and over ~80% loss of water volume (Wolfe & Turner 2008). Undoubtedly, such a rapid and extreme hydrological change will have direct ecological consequences. The upper sediments show an abrupt increase in organic matter and the emergence of cyanobacteria, purple sulphur bacteria, and diatoms that have taxonomic affinities to the pigments echinenone, okenone, and diatoxanthin, respectively. Although the upper sediments represent freshly deposited material, these pigment concentrations are unique to the stratigraphy and their chemical stability and preservation are ranked high (Leavitt & Hodgson 2001). The presence of these algal groups suggests that highly productive conditions developed in the remnant shallow ponds that remained after the drainage event. The presence of purple sulphur bacteria implies that Zelma Lake now experiences extended periods of anoxia, possibly due to increased growth of lake biota and very shallow water levels during ice-cover. Current nutrient concentrations in Zelma Lake are high (see Table 2), which could be attributed to the release of phosphorous under anaerobic conditions by phosphorus-mobilizing bacteria or iron sulfide formation (Wetzel 2001). High nutrient concentrations of exposed lake bottom sediments may also supply nutrients into the remaining water column. Due to decreases lake depth, nutrient enhancement may also be a result of evaporative concentration. Water samples collected from Zelma Lake reveal strong seasonal isotopic enrichment of δ_L values and high E/I ratios that exceed 1 from 2007-09, confirming the enhanced influence of evaporation on lake water balance (Figure 3-3; see also chapter 2).

The stratigraphic profile of Zelma Lake is similar to the sediment record of OCF48, reported by MacDonald *et al.* (2012b), and the expected sedimentary profile of accelerated thermokarst expansion-drainage cycles (Figure 3-2); but, there are some key differences. Both sediment cores showed a stable period early in the stratigraphic profile, when all paleolimnological variables remained relatively consistent (Figure 3-6; Figure 3-8a). Thermokarst expansion in Zelma Lake commenced ~1900 and persisted for approximately 40 years, while thermokarst expansion at OCF48 was initiated in ~1967 and lasted for 22 years. After ~1943, Zelma Lake experienced an increase in organic matter and primary productivity indicated by $\delta^{13}C_{org}$, $\delta^{15}N$, and elevated pigment concentrations as the shoreline became more stable and active thermokarst erosion slowed down. This same shift transpired in OCF48 in ~1989; however, this hydroecological transition was caused by a rapid drainage event. Rapid drainage events, as hypothesized by MacDonald *et al.* (2012b; Figure 3-2), would lead to increases in organic matter as the water column becomes clearer, although this is contingent on water remaining within the basin and conditions that promote re-filling. Both stratigraphic profiles show an increase in water clarity and productivity, yet the mechanisms causing these phases are different. While parameters such as LOI were able to depict shifts in hydroecological conditions of OCF48, the interpretation of Zelma Lake required additional measures to portray hydroecological transitions. For example, both Zelma Lake and OCF48 experienced an increase in primary productivity succeeding lake drainage, indicated by increases in carbon content, $\delta^{13}C_{org}$, and pigment concentrations, suggesting they are also key indicators of lake drainage. In particular, Zelma Lake exhibited eutrophic conditions after drainage, which may be a key consequence of rapid and complete drainage events (not necessarily partial drainage events) that can be used to identify historic drainage events in stratigraphic profiles. Paleolimnological analysis can detect past hydroecological conditions in thermokarst lakes, yet separating drainage events from increases in primary productivity due to bank stability and increases in temperature remains complex and requires multi-proxy analysis.

Following a drainage event, there are multiple hydroecological responses that may happen, such as eventual re-filling, secondary thermokarst lake development, adaption to current water-levels, or eventual paludification. Water-levels in OCF48 recovered between 2001 and 2007, which may be attributed to groundwater flow from Timber Hill, precipitation, and/or a beaver dam located near a channel outlet. After five years, Zelma Lake water levels do not appear to be recovering. It is possible that the remnant ponds of Zelma Lake may go through paludification, or infilling, from accumulations of benthic algae at the bottom in conjunction with ice aggradation causing surface uplift, creating conditions favorable for plant growth and development (Jorgenson & Shur 2007). The succession of aquatic wetlands towards terrestrial environments has already been documented across the Arctic (Karlsson *et al.* 2011). Water isotope analysis suggests that Zelma Lake is sensitive to evaporation which could potentially lead to overall desiccation, a phenomenon not uncommon to high Arctic lakes (Smol & Douglas 2007). On the other hand, Zelma Lake may adjust to its new water balance. Continued monitoring is required to determine how the hydroecological conditions of Zelma Lake will evolve following lake drainage.

3.6 Conclusion

Climate change will affect the presence or absence, abundance, depth, hydrology, and ecology of thermokarst lakes. Zelma Lake experiences different hydroecological transitions during the past ~330 years that include: phase 1 (~1678-1900) characterized by stable hydroecological conditions; thermokarst expansion (~1900-1943); phase 2 (~1943-2007) distinguished by increasing primary productivity; and a post drainage phase following rapid drainage in 2007. The stratigraphy of Zelma Lake shows that: i) active thermokarst expansion does not necessarily culminate with a drainage event; ii) inputs of terrestrial material during thermokarst expansion likely increases the availability of organic material generating nutrient-rich conditions that enhance aquatic primary productivity when turbidity subsides; and iii) drained lakes are susceptible to evaporative drawdown and eutrophic conditions.

Zelma Lake was very similar to the expected stratigraphic profile of a lake undergoing thermokarst expansion-drainage cycles proposed by MacDonald *et al.* (2012b), although the onset of the hydroecological phase succeeding active thermokarst expansion were caused by different mechanisms. Hydroecological conditions in dynamic landscapes such as OCF are complex and require multi-proxy paleolimnological analysis. In particular, organic matter, $\delta^{13}C_{org}$, and pigment concentrations are important parameters to consider when interpreting past hydroecological conditions, thermokarst expansion, and lake drainage events. Lakes within OCF display hydroecological heterogeneity and variability in their hydrological responses to climate change (Chapter 2), thus to fundamentally understand thermokarst processes, and how the hydroecological conditions of lakes in OCF are responding to ongoing changes in climate, long-term datasets from lakes with different hydrological and limnological characteristics are essential (Appendix 3-A).

3.7 Appendix 3A - Additional sediment cores

To further enhance knowledge and improve understanding of past hydrological conditions associated with thermokarst processes and changes in climate in lakes with different hydrological and limnologial conditions (see Chapter 2), I explored paleolimnological measures from three additional sediment cores (OCF11, 29, and 35) collected from OCF in 2008 and 2010 (Figure 3-1). OCF11 is a snowmelt-sourced lake, OCF29 is a large rainfall-sourced lake, and OCF35 is a small rainfall-sourced lake. The stratigraphic profiles of organic matter, organic carbon, $\delta^{13}C_{org}$, and ring-width index from Porter and Pisaric (2011) as well as aerial images for each lake are presented in Figure 3-8.

OCF35 displays a similar stratigraphic profile to Zelma Lake and OCF48 (Figure 3-8b). The early portion of the sediment core is relatively stable and there is a sharp decrease in organic matter (25.3-18.6‰), organic carbon (11.7-9.5%), and $\delta^{13}C_{org}$ (-24.7 to -25.6‰) from ~1945-1960. The decline in overall productivity during this interval is likely due to thermokarst expansion. This expansion phase possibly caused the coalescence of two adjacent lakes that are hydrologically connected in the 1951 and 1972 aerial images, and is separated in the 2007 aerial image. After ~1960, organic matter, organic carbon, and $\delta^{13}C_{org}$ values become relatively stable until ~1989 in which organic matter (20.9-25.7%), organic carbon (9.8-13.8%) increased markedly until the top of the sediment core, while $\delta^{13}C_{org}$ remained relatively constant (-25.5 to -25.9‰).

Similar to Zelma Lake, OCF35 displays active thermokarst expansion that either ceases or decelerates, owing to the near constancy of the parameters from ~1960 to 1989. In ~1989, organic matter and organic carbon increased, yet $\delta^{13}C_{org}$ remained relatively stable, suggesting that this hydroecological transition is more likely attributed to gradual water-level declines rather than a rapid drainage event. An aerial image from 2007 confirms that OCF35 is experiencing a reduction in water-levels and overall lake surface area. It is possible that OCF35 is losing water via an outlet channel as well as evaporative drawdown. Enhanced evaporative drawdown due to warmer temperatures is consistent with the onset of increasing July temperatures in OCF, indicated by ring-width index data. Contemporary isotopic analysis conducted from 2007-11 reveals that OCF35 is sensitive to evaporation and has E/I ratios that exceed 0.5, particularly during dry conditions and near the end of the ice-free season (mean E/I = 0.44; see Chapter 2). The aerial images show a deeply incised channel, likely formed by a rapid drainage event, extending from the Old Crow River to a small drained (or evaporated) lake adjacent to OCF35. OCF35 is connected to this lake, although the channel is not deeply incised (field observations in 2011). The presence of the deeply incised channel connected to Old Crow River in 1951 suggests that neither water loss from the small lake nor OCF35 were responsible for its formation. The 1972 aerial image shows OCF35 as well as the surrounding catchment area in which a relict shoreline is visible (outlined in a white dashed line). This large lake likely drained prior to the basal date of the sediment record (1886), thus OCF35 represents a remnant pond of a much larger thermokarst lake. Interestingly, $\delta^{13}C_{org}$ values remain constant, which is uncharacteristic of water level decreases. It is possible that low water levels are enhancing macrophyte production, explaining the increase in organic matter content and the lack of change in $\delta^{13}C_{org}$ values.

The stratigraphic profile of OCF29 (Figure 3-8c) begins with evidence of thermokarst expansion from ~1200-1300, a period of approximately 100 years, as indicated by decreasing organic matter (22.7-13.2%), organic carbon (11.6-6.3%) and $\delta^{13}C_{org}$ values (-22.2 to -22.8‰). It is possible that OCF29 experienced a drainage event ~1300 denoted by the major increase in organic matter (16.2-23.9%) and organic carbon (8.5-12.6%), although $\delta^{13}C_{org}$ values (-22.7 to -22.1‰) only increase slightly. The slight increase in $\delta^{13}C_{org}$ may reflect a partial drainage event, corroborated by the accompanying aerial image that shows a relict shoreline suggesting a historic partial drainage event (Figure 3-8). Alternatively, this could represent a more complete drainage event followed by a period of lake re-filling. From ~1350-1950 (phase 1), organic matter, organic carbon, $\delta^{13}C_{org}$ values fluctuate but do not show any pronounced changes. Hydroecological conditions appear to shift in ~1985 towards an increase in productivity denoted by increases in organic matter (18.4-22.0%), organic carbon (8.5-10.0%), and $\delta^{13}C_{org}$ (-21.1 to -20.6‰). This shift is also consistent with increases in tree-ring data, which may suggest that increasing temperatures are causing a gradual increase in productivity due to evaporative concentration of nutrients and declining water volume. Contemporary water isotope data collected from OCF29 indicates that this lake can be sensitive to evaporation and has E/I ratios that exceed 0.5 during dry conditions and at the end of the ice-free season (mean E/I = 0.49; see Chapter 2). It is possible that the linear increase in parameters near the top of the sediment core reflect warmer temperatures, although these values are not outside the range of natural variability.

The sediment profile of OCF11 (Figure 3-8d) does not show evidence of thermokarst activity and is stable for approximately 500 years (~1490-1985; phase 1). Near the top of the sediment core, a dramatic shift occurs ~1985 leading to phase 2, characterized by an increase in organic matter (15.6-23.7%) and organic carbon content (8.1-12.8%), and a decrease in $\delta^{13}C_{org}$ values (-27.3 to -28.0‰). These changes are harmonious with increases in ring-width index, further suggesting that recent increases in temperature are influencing the hydroecology of thermokarst lakes in OCF. The decrease in $\delta^{13}C_{org}$ values are not consistent with increases in productivity; however, OCF11 is a highly productive lake (mean TP = 53.28 μg/L) that accrues thick biofilm on artificial substrates (field observations). The $\delta^{13}C_{org}$ values of highly productive lakes may decline due to net respiration and/or chemically enhanced CO_2 invasion (enhanced fractionation), that is influenced by pH and the thickness of the stagnant boundary layer (Herczeg & Fairbanks 1987).

Interestingly, lakes in OCF appear to exhibit non-synchronous changes reflecting geomorphic effects due to thermokarst activity as well as synchronous changes likely influenced by climate. Four out of the five lakes (OCF06, 29, 35, and 48) undergo thermokarst expansion at some point during the sediment profile. One lake (OCF29) underwent thermokarst expansion from approximately ~1200-1300, while three lakes (OCF06, 35, and 48) experienced thermokarst expansion during the 20th century. Two out of the five lakes (OCF06 and 48) experienced drainage events within the past 30 years, and OCF29 possibly underwent a drainage event ~1300.

There seems to be harmonious shifts in hydroecological conditions towards enhanced aquatic productivity within the late 1980s. These changes occur simultaneously with increases in ring-width indices (a proxy for July temperature) collected from spruce stands across OCF, which are unprecedented within the last 300 years (Porter & Pisaric 2011). Studies from many shallow Arctic lakes have revealed transitions in aquatic ecology towards greater primary productivity and diversity of algal assemblages in the mid- to late- 19th century due to increasing temperatures (Smol *et al.* 2005). By contrast, lakes in OCF suggest a recent response to environmental fluctuations, which may simply be because lakes in OCF are at lower latitude as well as regional differences associated with warming temperatures. Yet, the recent acceleration of aquatic primary productivity post-1980 agrees with observations from sediment cores collected from northern Ellesmere Island, (Antoniades *et al.* 2005) and Cornwallis Island (Michelutti *et al.* 2003), associated with recent climatic changes.

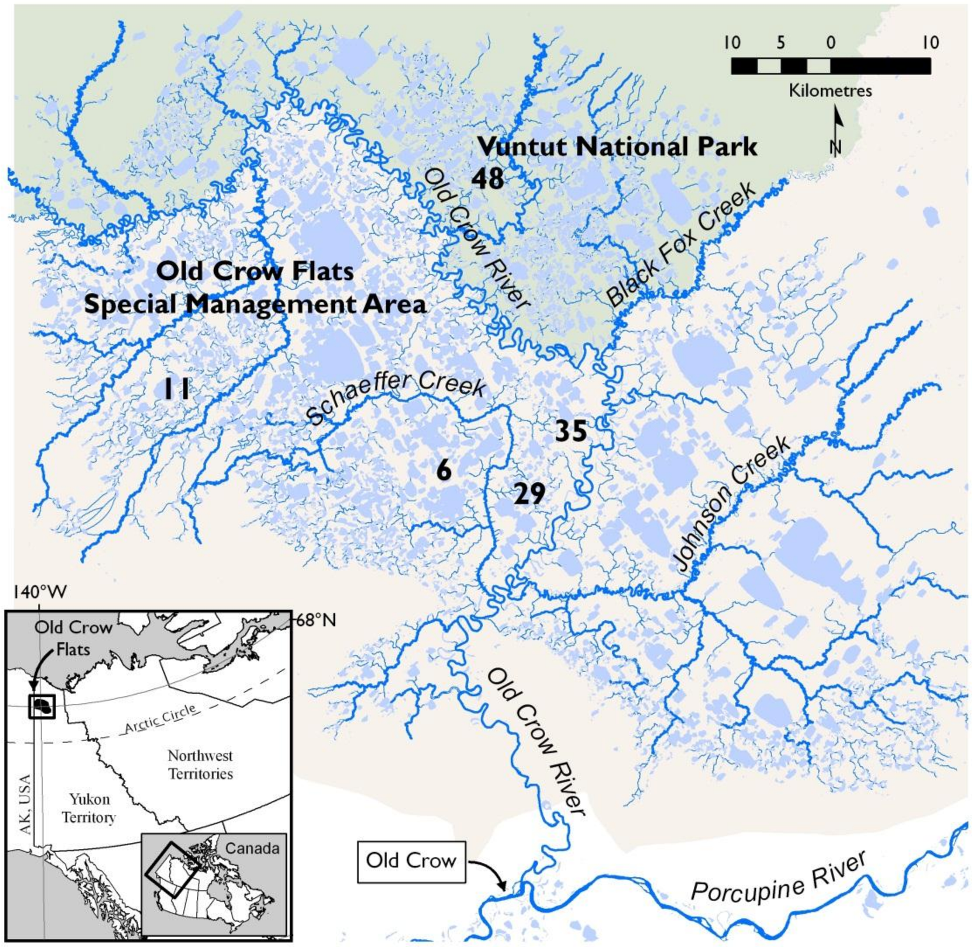

Figure 3-1. Map of Old Crow Flats (OCF), Yukon Territory, Canada and location of the monitoring lakes from which sediment cores were collected.

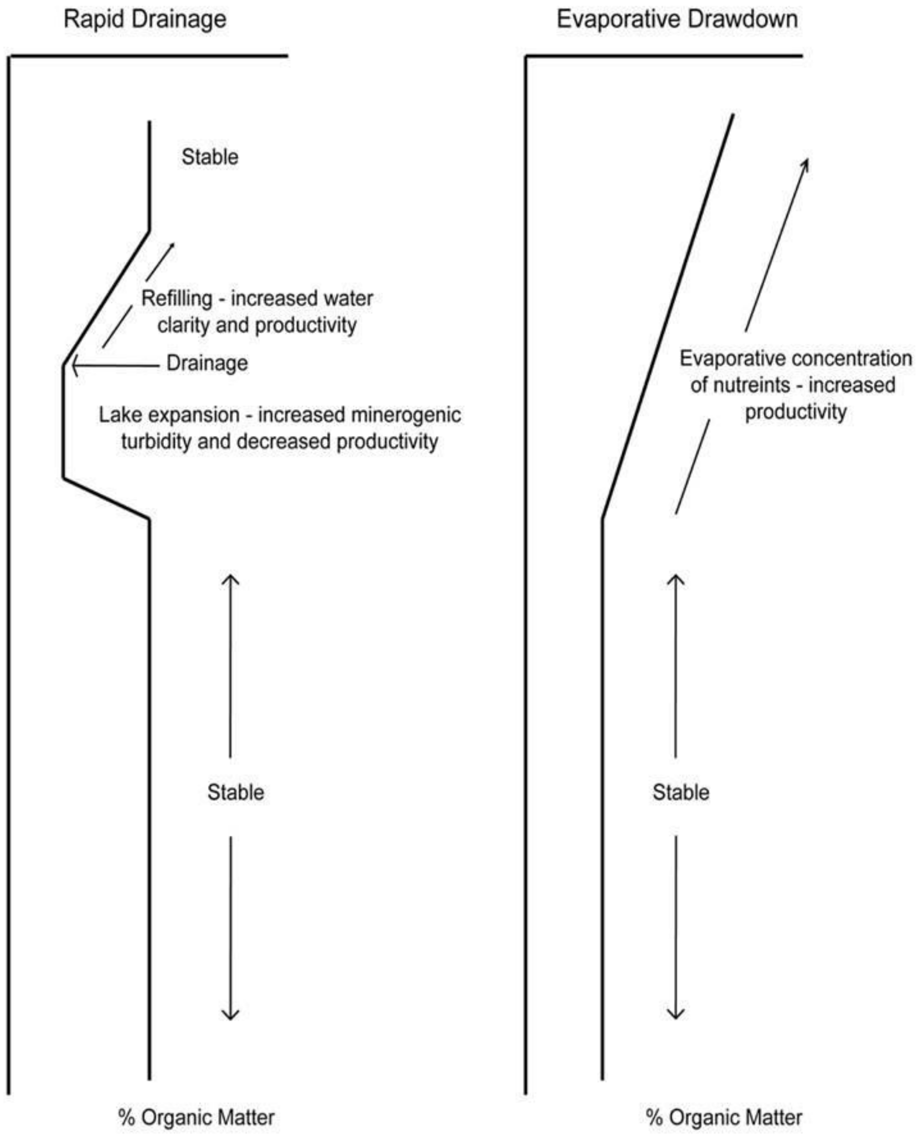

Figure 3-2. Schematic stratigraphic profiles of organic matter content predicted to be associated with a) rapid drainage and b) evaporative drawdown (MacDonald *et al.* 2012b, pg 127).

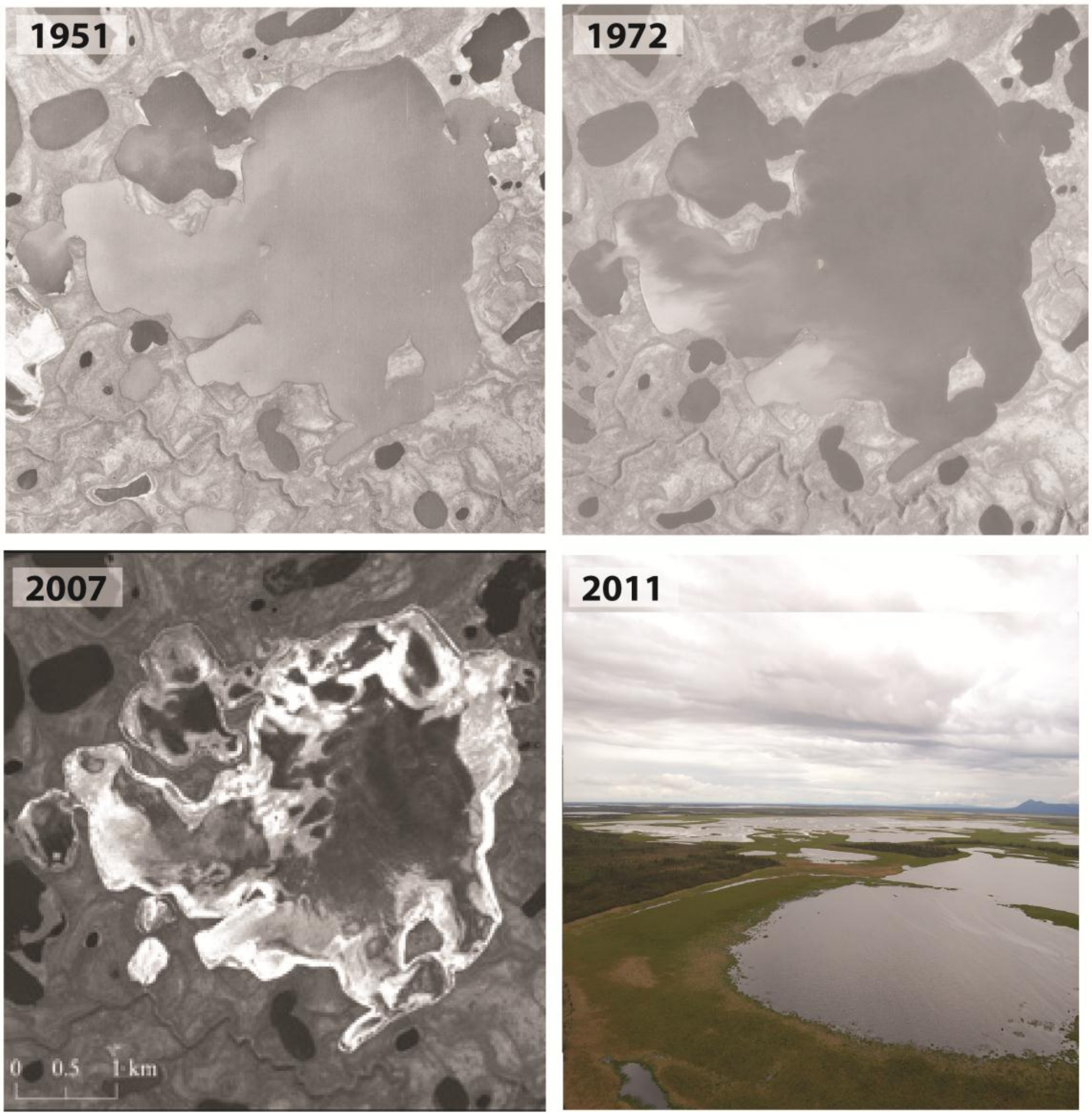

Figure 3-3. Aerial photographs showing the historical extent of Zelma Lake (OCF6) from 1951, 1972, 2007, and June 2011. Aerial images from 1951 and 1972 were scanned at the Energy, Mines, and Resources library in Whitehorse, Yukon, the 2001 photograph is from SPOT image, and the 2011 image was taken during a helicopter flight.

Table 3-1. Selected limnological characteristics of Zelma Lake (OCF6). Values represent the average early ice-free season (June) and late ice-free season (late August/early September) conditions and standard deviation of samples collected in 2010 and 2011.

	Early ice-free season		Late ice-free season	
	mean	stnd dev	mean	stnd dev
pH	8.08	0.06	9.50	0.52
Specific conductivity (µS/cm)	313.00	85.56	252.50	156.27
Alkalinity (meq/l)	130.00	9.90	65.20	2.55
Dissolved organic carbon (mg/l)	13.05	1.77	18.00	1.77
Dissolved inorganic carbon (mg/l)	30.95	2.62	10.50	2.12
Calcium (mg/l)	45.75	2.33	28.95	16.90
Magnesium (mg/l)	16.50	1.84	13.13	7.60
Potassium (mg/l)	5.62	1.48	1.31	1.00
Silica (mg/l)	0.23	0.13	1.37	0.25
Sodium (mg/l)	2.86	0.04	3.52	1.51
Total nitrogen (mg/l)	1.08	0.32	1.56	0.01
Total dissolved phosphorus (µg/l)	14.75	11.17	26.20	14.64
Total phosphorus (µg/l)	36.35	21.00	67.15	4.172
Chlorophyll *a* (µg/l)	4.94	5.65	5.54	1.37
Total suspended solids (mg/L)	6.65	7.06	23.85	18.00

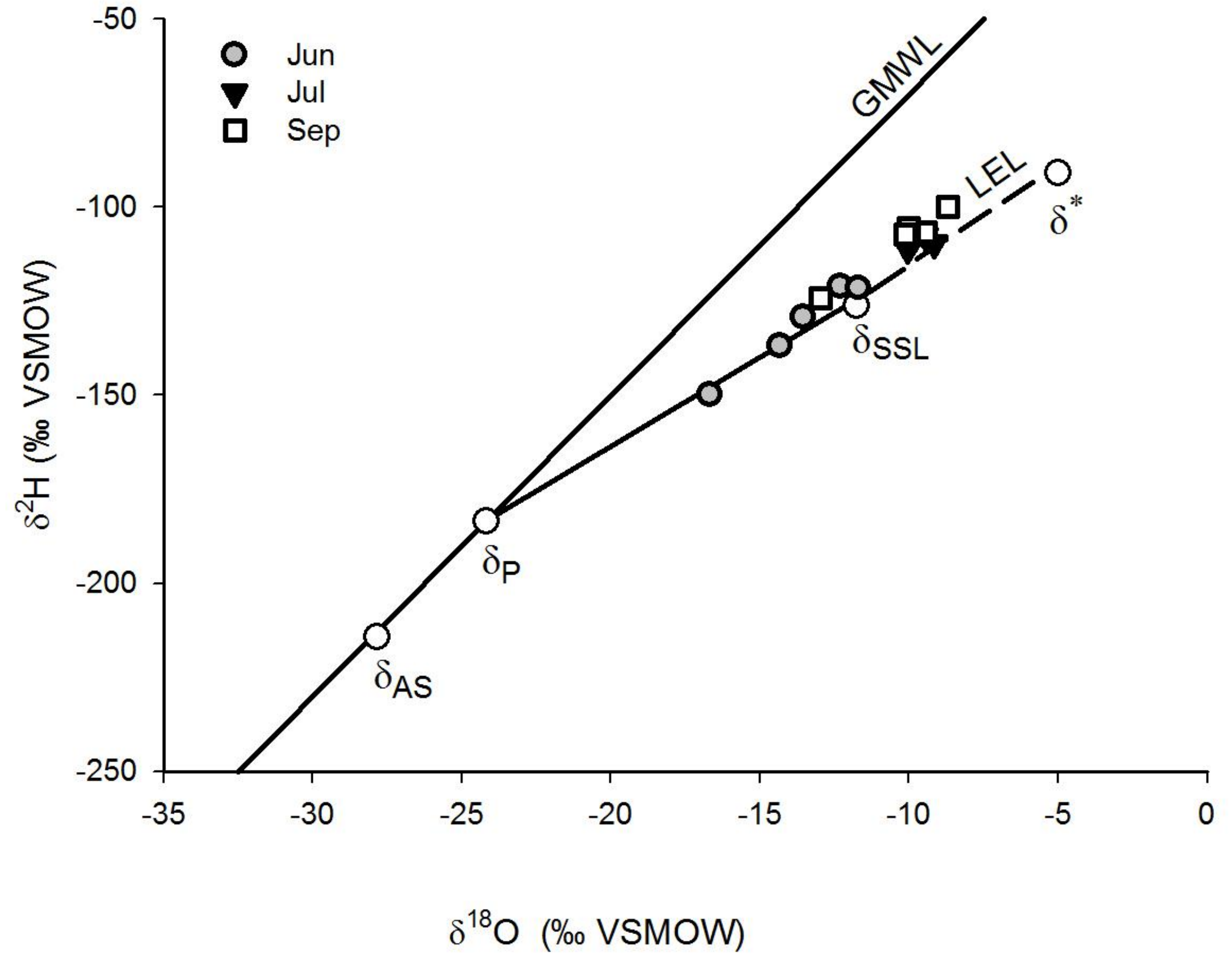

Figure 3-4. Isotopic composition of water samples collected from Zelma Lake during 2007-11 superimposed on a four-year mean isotopic framework (see Chapter 2). The isotopic composition of global precipitation is defined by the Global Meteoric Water Line (GMWL) such that $\delta^2H = 8\delta^{18}O + 10‰$ and local surface water that has been influenced by evaporation is delineated by the Local Evaporation Line (LEL)(Craig 1961). Key isotopic labeling features used to quantify lake water balance are shown and include: the limiting steady-state isotope composition where evaporation is equal to inflow (δ_{SSL}), the limiting isotopic composition of a basin approaching desiccation (δ^*), ambient atmospheric moisture composition (δ_{AS}) and the amount-weighted mean annual precipitation (δ_P).

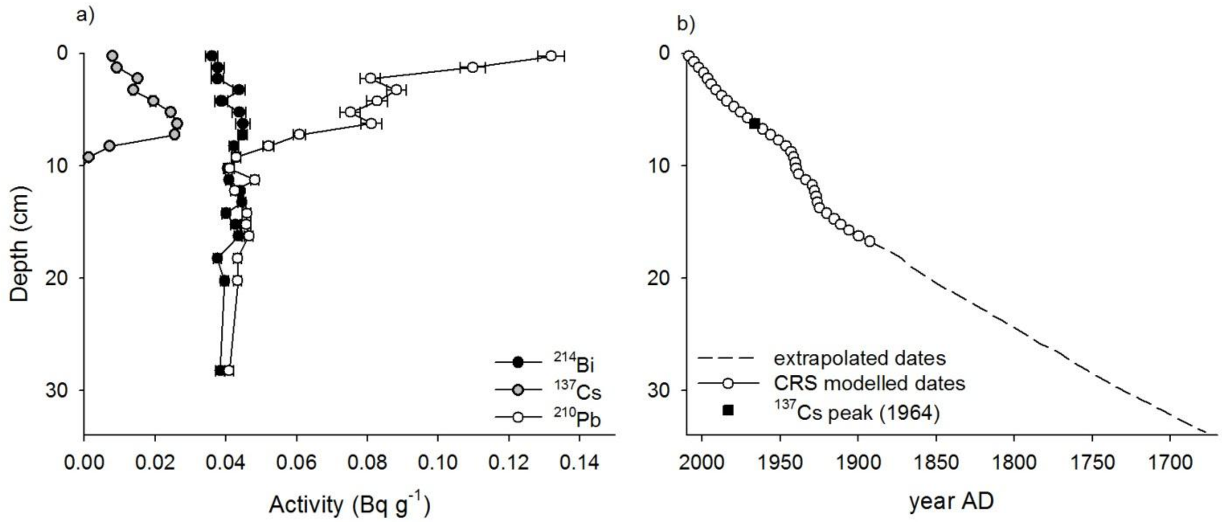

Figure 3-5. a) ^{210}Pb, ^{214}Bi and ^{137}Cs activity profiles for Zelma Lake. b) Zelma Lake sediment core chronology based on the Constant Rate of Supply (CRS) model and linear extrapolated dates. The ^{137}Cs peak activity occurs between 5.5 and 7.5 cm depth, consistent with peak nuclear fall-out ~1963.

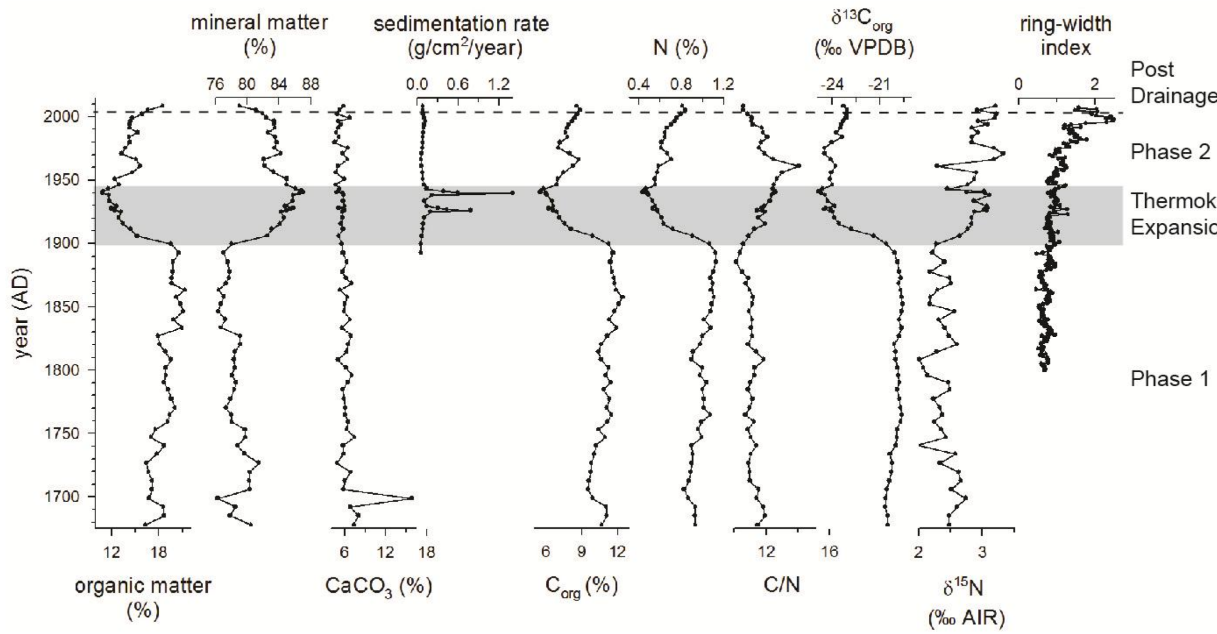

Figure 3-6. Physical and geochemical measurements for the Zelma Lake sediment core showing organic matter, mineral matter, calcium carbonate, sedimentation rate, percent dry weight organic carbon, nitrogen content as percent of dry mass, percent weight carbon-to-nitrogen (C/N) ratios, isotopic composition of organic carbon, and isotopic composition of nitrogen. Tree ring-width index from spruce trees located across OCF is also shown (see Porter & Pisaric 2011).

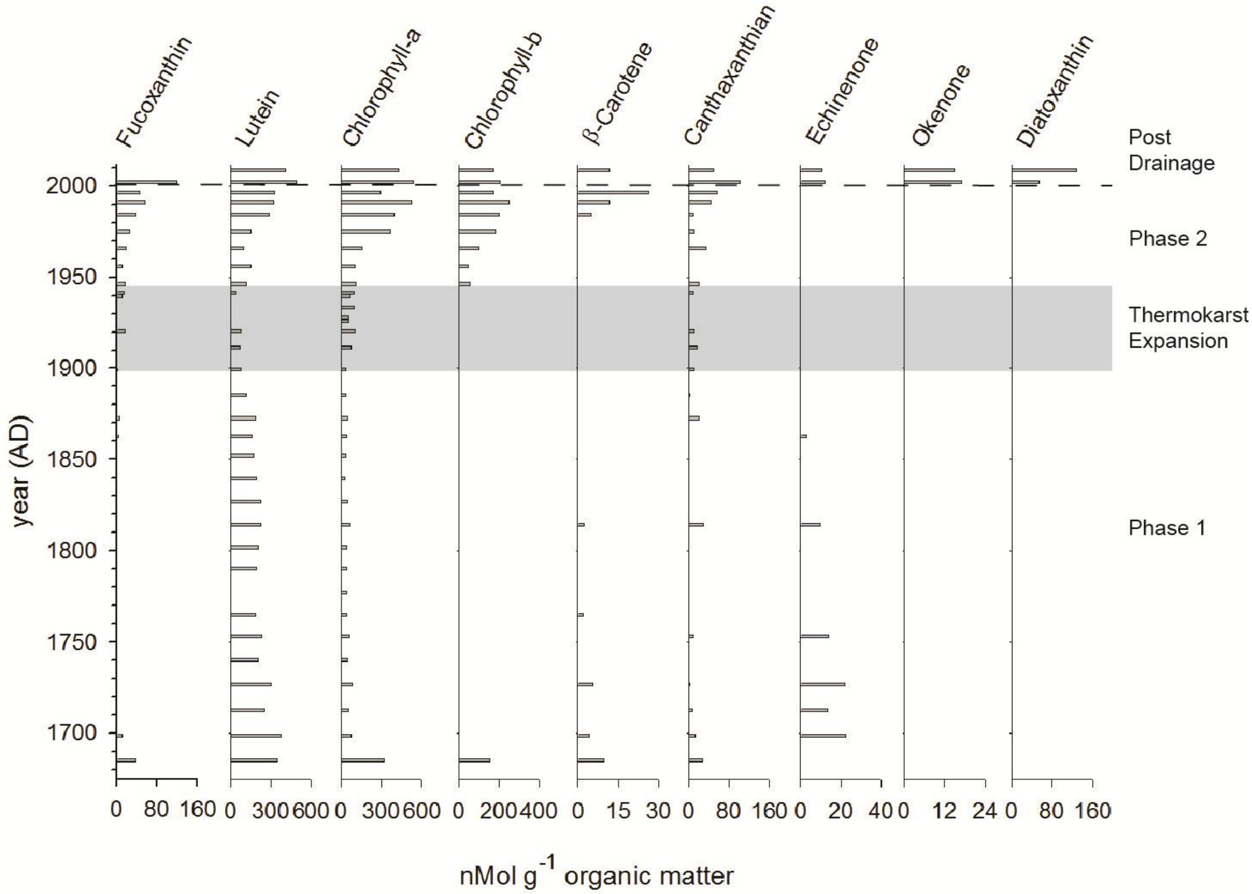

Figure 3-7. Fossil pigment stratigraphy displaying the concentration (nMol g^{-1} organic matter) of the most abundant chlorophyll and carotenoid pigments in the Zelma Lake core.

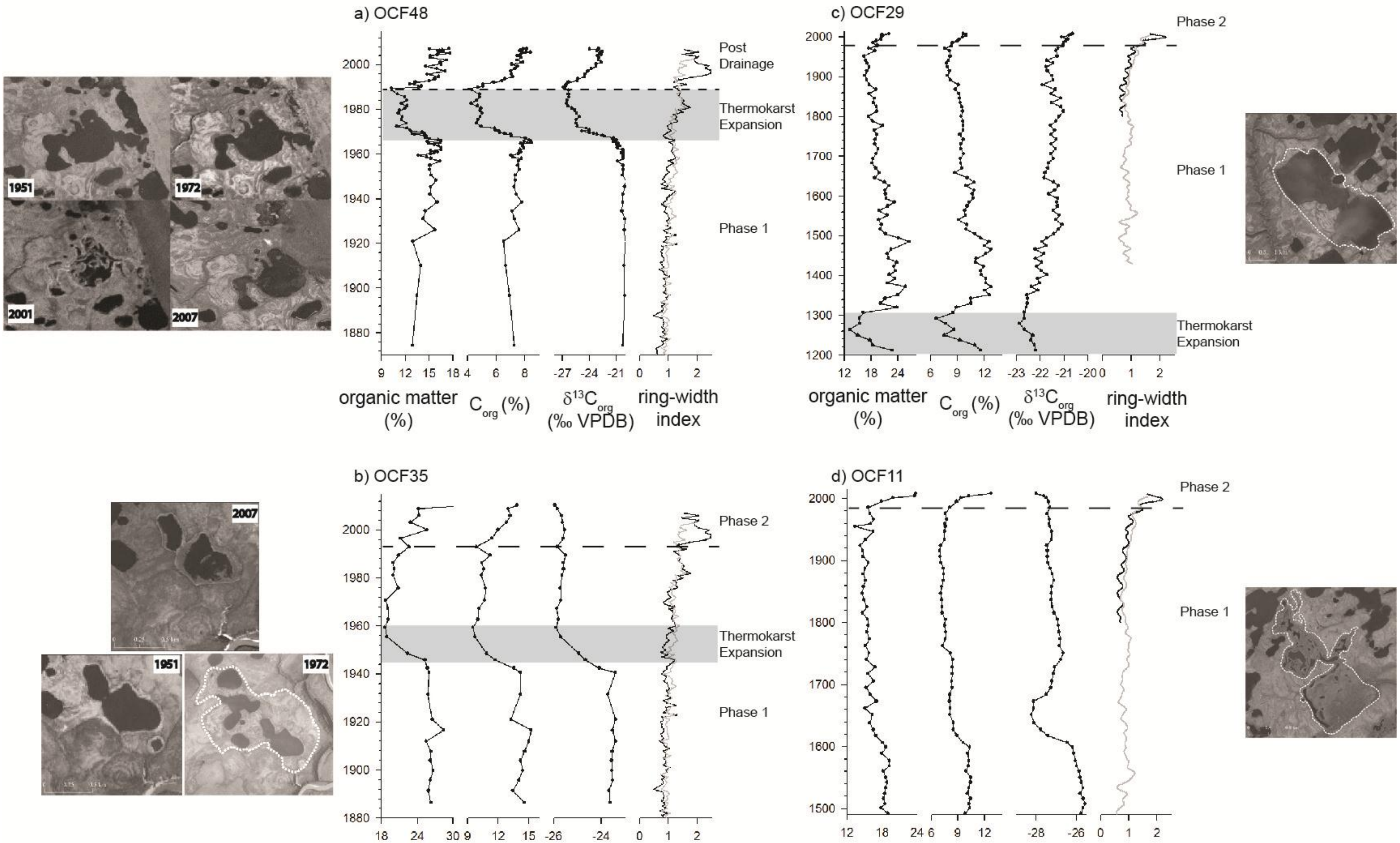

Figure 3-8. Physical and geochemical stratigraphic profiles for a) OCF48, b) OCF35, c) OCF29, and d) OCF11 as well as tree ring-width data from OCF (black circles) and trees collected from across northwestern North America (grey circles) (see Porter & Pisaric 2011). Also shown are aerial images for each lake with relict shorelines outlined in white dashed lines.

Chapter 4

Summary and Recommendations

4.1 Summary

Polar amplification of climate warming is dramatically transforming Arctic ecosystems and continued warming will likely produce large hydrological and biological transitions in freshwater ecosystems. This thesis aims to develop and implement a long-term hydroecological monitoring program that will adequately assess spatial and temporal patterns and rates of change of the hydroecology of Old Crow Flats (OCF) by incorporating water isotope tracers and multi-proxy paleolimnological techniques to track hydrological conditions and responses to changes in meteorological conditions. Results from the previous two data chapters reveal that hydroecological transitions in northern lake-rich landscapes are multifaceted, thus long-term monitoring that can detect different trajectories of hydroecological change is necessary.

Results demonstrate that water isotope tracers are useful monitoring tools that can be used to track future changes in input water (snowmelt versus rainfall) and evaporation. Using the coupled-isotope tracer method, isotopic compositions of input water (δ_I) and evaporation-to-inflow (E/I) ratios were calculated and provide key information on hydrological conditions. δ_I values distinguish snowmelt- and rainfall-sourced lakes, with δ_P representing a threshold between the two isotopic-based hydrologic regimes. Lakes that display considerable variation in δ_I values (OCF06, 11, and 46) are more sensitive to changes in snowmelt and rainfall which may result in altered lake hydrological conditions. Transitions in δ_I values from snowmelt-sourced to rainfall-sourced hydrology or vice versa may be a result of increases in summer rainfall, winter rain events, and changes in winter snowpack thickness as well as landscape vegetation that entrap snow.

Lake sensitivity to vapour loss was monitored using hydrological thresholds established from E/I ratios such that E/I ratios > 0.5 signifies lakes that are evaporation-dominated with positive water balances and E/I ratios > 1 indicates lakes that are evaporation-dominated with negative water balances. The five-year mean E/I ratio of six lakes in OCF (OCF06, 19, 37, 46, 49, and 58) surpass the 0.5 threshold and are evaporation-dominated. Three of these lakes (OCF06, 19, and 46) crossed the significant evaporation threshold (E/I > 1) during dry climatic conditions, representing lakes that are vulnerable to desiccation. Lakes that become evaporation-dominated during the ice-free season are all rainfall-sourced lakes, thus snowmelt-sourced lakes are less vulnerable to evaporative drawdown. Despite the substantial variability in precipitation during the study period, the water balance of OCF29, 48, and 55 showed marked hydrological resilience to changes in meteorological conditions. Overall, selected monitoring lakes are reasonably representative of the landscape and reflect similar spatial associations revealed by Turner *et al.* (In review) in that lakes located in the central and eastern area of OCF are typically rainfall-sourced lakes that show a greater response to evaporation. Lakes located in the south-western area of OCF are primarily snowmelt-sourced and are less sensitive to vapour loss.

A Mann-Kendall and a Seasonal-Kendall test were used to explore for monotonic trends over time. The Mann-Kendall test revealed that three lakes (OCF11, 26, and 49) display statistically significant increasing trends in δ_I values, indicating a potential transition from snowmelt-sourced to rainfall-sourced isotope-based hydrologic-regimes. These trends were not significant when a Seasonal-Kendall trend test was applied, likely owing to the short time span of the data. Nonetheless, water isotopes (δ_I values and E/I ratios) and the application of a Mann-Kendall trend test will provide a useful tool to monitor the hydrological status, trends, and conditions in OCF.

Multi-proxy analysis conducted on a sediment core from Zelma Lake revealed hydroecological transitions associated with thermokarst activity and changes in climate. Zelma lake exhibits different shifts in hydroecological conditions during the past ~330 years: phase 1 (~1678-1900) characterized by stable hydroecological conditions; thermokarst expansion (~1900-1943) that showed in increase in terrestrial derived organic matter and a decrease in aquatic productity; phase 2 (~1943-2007) distinguished by increasing primary productivity; and a post drainage phase following rapid drainage in 2007 that displayed a marked increase in productivity. The increase in aquatic productivity during phase 2 is likely due to increased water clarity due to a deceleration in active thermokarst expansion as well as increases in temperature. The stratigraphy of Zelma Lake shows that: i) active thermokarst expansion does not necessarily culminate with a drainage event; ii) inputs of terrestrial material during thermokarst expansion likely increases the availability of organic material generating nutrient-rich conditions that enhance aquatic primary productivity when turbidity subsides; and iii) drained lakes are susceptible to evaporative drawdown and eutrophic conditions. Hydroecological conditions in dynamic landscapes such as OCF are complex and require multi-proxy paleolimnological analysis. In particular, organic matter, $\delta^{13}C_{org}$, and pigment concentrations are important parameters to consider when interpreting past hydroecological conditions, thermokarst expansion, and lake drainage events because thermokarst expansion will lead to a decrease in aquatic productivity and drainage events will likely cause a dramatic increase in aquatic productivity.

Northern ecosystem monitoring remains challenging. Yet, in this thesis I have demonstrated how the collaboration of researchers, a northern community, and a government agency can lead to the development of a successful long-term monitoring program that will serve to inform future policy and land-use management decisions. Furthermore, these approaches can be readily adopted by other national parks and agencies that have a vested interest in monitoring the hydroecological status and trends of northern lake-rich landscapes.

4.2 Recommendations

This thesis outlined two of the three components of a long-term hydroecological monitoring program aimed at determining the status, trends, and conditions of the aquatic ecosystem in OCF. Since this is a long-term monitoring program, future work involves continuing the monitoring program, with specific obligations outlined in a Letter of Agreement between Parks Canada, Wilfrid Laurier University

(WLU), and the University of Waterloo (UW) (Appendix C). Yet there are few considerations to advance the monitoring program, outlined below for each ecosystem process and monitoring variable.

4.2.1 Water isotope tracers to monitor hydrology

In this study, an average isotopic framework was developed to assess past, present, and future hydrological conditions by modeling δ_{SSL} values with an evaporation pan for four years (2007-10). It is highly recommended that an evaporation pan experiment be conducted every five years to ensure that the framework is reflective of hydroclimatic conditions. In the event that temperature and relative humidity recorded at the Old Crow airport begin to substantially deviate from the average values that were used to construct the four-year average framework, a new framework should be developed.

As this research has shown, water isotope tracers provide a useful tool to monitor the hydrological status, trends, and conditions in OCF, which can be identified using a Mann-Kendall test. The Seasonal-Kendall test should be used to determine monotonic trends, since δ_I values and E/I ratios display isotopic evolution throughout the ice-free season. The Mann-Kendall test simply identifies the presence of an increasing or decreasing trend, it does not identify whether or not an isotopically-defined threshold has been crossed. An independent sample t-test can be used to test if the means of δ_I (or E/I) values before or after that transition are statistically different. Once ten years of data are obtained, the dataset can be tested for serial correlation. The p-value for serial correlation is already adjusted within the USGS program, thus using this program and the adjusted p-value once ten years of data are obtained is recommended.

Deuterium-excess from river water samples are currently being explored as a method to determine the approximate amount of river discharge that is contributed by lakes (Turner *et al.* In preparation). This will provide an index of lake-river connectivity and identify areas of OCF that are experiencing greater export of water from lakes. Thus, additional sampling for water isotope tracers at key points along the Old Crow River and its tributaries could potentially detect substantial lake drainage events. Aerial images focusing on the specific area experiencing greater water export from lakes can be analyzed to identify lakes that may have experienced a reduction in surface area. Key tributaries of the Old Crow River to sample include: King Edward Creek, Schaeffer Creek, Johnson Creek, Black Fox Creek, and Timber Creek; and key points along the Old Crow River to sample include: upstream from Johnson Creek; upstream from Black Fox Creek; upstream from Timber Creek; downstream from the creek near Husky Lake; and at the mouth of the Old Crow River (Turner *et al.* In preparation). Ideally, sampling of lentic water should be conducted in June and late August/early September; however, since drainage events are linked to high levels of precipitation, sampling during 'wet' conditions should be sufficient enough to identify substantial drainage events.

4.2.2 Periphyton (diatoms and pigments) to monitor aquatic ecology

A key component to the hydroecological monitoring program is to determine the influence of hydrological and meteorological conditions on aquatic ecology; however, this aspect of the monitoring program remains to be developed. Given the strong linkages between hydrology and aquatic ecology, a coordinated monitoring strategy is needed to adequately assess the ecological integrity of the aquatic ecosystem. Thus, a key recommendation is to develop a method that can characterize the state of ecological conditions and how they are changing over time that can be combined with water isotope analysis to provide a complete assessment of ecological integrity within the aquatic ecosystem. This includes:

- Complete diatom and photosynthetic pigment analysis on biofilm accrued on artificial substrates from 2008-2011;
- Identify relationships between hydrological and limnological conditions associated with diatoms and pigments accrued on artificial substrates (see Sokal *et al.* 2008, 2010; Wiklund *et al.* 2010; Wiklund *et al.* 2012 for methods and ideas); and

- Develop a method to monitor the status, trends, and conditions of aquatic ecology to determine ecological integrity. A modified reference condition approach could be used to create predictive models for each hydrological category to see if changes in algal abundance and community composition are occurring over time (i.e., using time as a reference instead of a set of reference lakes). The abundance and community composition of algae (given by diatom and pigment data) collected in 2008-09 can be compared to the abundance and community composition of algae collected in subsequent years to determine if there are differences between the communities (see Reece & Richardson 2000; Bennion *et al.* 2004; Bennion *et al.* 2011). An alternative approach, or method to use in conjunction with the modified reference condition, is to develop a hydroecological diatom index (HDI) by allocating diatoms into one of three groups according to hydrology (i.e., diatoms that are reflective of snowmelt-sourced, rainfall-sourced, and evaporation-dominated lakes). Following methods of Kelly *et al.* (2008; 2009) an 'expected' HDI can be determined and used to determine if ecological conditions within each monitoring lake are changing over time (i.e., is the abundance and community composition reflective or what is 'expected' or is there a significant difference).

Logistically, I would recommended to always place two periphyton samplers in each lake to ensure enough biofilm is collected in the event that a sampler is lost from a lake (see Appendix A for more details). I would also recommend moving the periphyton sampler location of OCF38 to the northeast side of the lake near 68°20'21.91 N and 140°9'55.34 W. Periphyton samplers are often lost from this lake, likely due to the fact that the current location is near a channel outlet and banks that are eroding. Thus, losses of samplers are likely due to enhanced turbulent flow within this area of the lake. The northeast end of the lake (away from the outlet channel located on the northwest shore) does not show signs of eroding banks and may therefore experience less wave action. A study conducted on Mary

Netro Lake (OCF58) by MacDonald *et al.* (2012a) revealed that there is no statistical difference between periphyton sampled on artificial substrates in pelagic and littoral zones, thus moving the location of the periphyton sampler should not confound results.

4.2.3 Multi-proxy paleolimnology to assess natural variability

In total, nine sediment cores were collected in 2008 (OCF11, 29, 46, and 48) and 2010 (OCF06, 19, 35, 49, and 58) from the monitoring lakes to explore past hydroecological conditions to determine natural variability. Loss-on-ignition has been performed on all sediment cores, geochemical analysis and ^{210}Pb analysis has been conducted on six sediment cores (OCF06, 11, 29, 35, 46, and 48), and pigment analysis has been completed on two sediment cores (OCF06 and 48).

OCF is a dynamic landscape and lakes within this region display hydroecological heterogeneity and variability in their hydrological responses to climate change. To fundamentally understand how the hydroecological conditions of lakes in OCF are responding to ongoing changes in climate, long-term datasets from lakes with different hydrological and limnological characteristics are essential. Since fossil pigments have provided important, sensitive records of hydroecological change, it is highly recommended to complete pigment analysis on all sediment cores that have already been collected (with the exception of OCF49), particularly OCF11, 29, and 35. Completing pigment analysis on these three sediment cores would contribute to long-term understanding of hydroecological changes in a snowmelt-sourced lake (OCF11) and two rainfall-sourced lakes (OCF29 and 35) that can be compared to a snow-rain-sourced lake (OCF48) and an evaporation-dominated lake (OCF06). Furthermore, these three lakes show interesting past hydroecological transitions associated with thermokarst activity and increases in temperature that would be enhanced by pigment data (see Figure 3-8). Loss-on-ignition data from both sediment cores collected from OCF49 are variable, thus it is recommended to re-core this lake rather than proceed with further analysis. Re-coring and performing multi-proxy analysis would provide further details on past hydroecological transitions and natural variability within OCF.

Furthermore, this lake is located within the boundaries of Vuntut National Park and near the traditional camp of an Old Crow resident who has a vested interest in the monitoring program.

Ideally, a sediment core should be retrieved and analyzed for physical, geochemical, and biological parameters from each monitoring lake since each lake represents an individual "monitoring station." Thus, each monitoring station should have a long-term dataset to effectively determine the hydroecological status, trends, and conditions of lakes in OCF. Five monitoring lakes have not been cored (OCF26, 34, 37, 38, and 55). In particular, I would suggest collecting a sediment core from OCF34 (Netro Lake) because it experienced a previous drainage event (Labrecque *et al.* 2009). Thus, information gained by reconstructing the hydroecology of OCF34 would improve understanding of the hydroecological conditions associated with thermokarst processes, particularly conditions before and after a drainage event.

The overall lifespan of thermokarst processes (initiation, expansion, and drainage) is poorly understood and idea of a thermokarst lake "cycle" involving the eventual re-filling or re-initiation of lakes after they drain has been contested within literature (Jorgenson & Shur 2007). It has been postulated that warmer temperatures may accelerate thermokarst lake dynamics and increase the frequency of lake drainage events (Jorgenson & Shur 2007; Pohl *et al.* 2009; MacDonald *et al.* 2012b). Yet, long-term data is essential to understand natural thermokarst processes, the frequency of drainage events, and the trajectory of hydroecological conditions succeeding a lake drainage event. OCF represents a prominent region of Beringia that remained unglaciated during the last glacial maximum and was inundated by Glacial Lake Old Crow from 35,000 yr BP until it completely drained approximately 15,000 years later (Zazula *et al.* 2004). Thus, a detailed paleolimnological analysis of a sediment core in OCF may provide a record of hydroecological transitions throughout the Holocene and part of the Pleistocene. This expanded timescale will be able to capture the full evolution of thermokarst lakes in OCF and the hydroecological responses to changes in meteorological conditions to strengthen current understanding of hydroecological responses to climate change. To achieve this, a longer sediment core is required, which could be collected using a rod-drive piston corer or vibracorer. Since a great deal of effort is needed to collect a long sediment core, choosing an appropriate lake is essential. I would recommend a remnant lake of a much larger thermokarst lake, such as OCF19 (located in Vuntut National Park). Aerial and satellite imagery from OCF reveals many relict shorelines belonging to ancient lakes that have likely drained in the past. Paleolimnological reconstruction of a long sediment core collected from a remnant lake may provide insight to initial thermokarst development, lake drainage, and the influence of climate change on hydroecological conditions.

4.3 Future research

While this thesis has presented an innovative and effective hydroecological monitoring program to monitor the effects of ongoing climate change on the hydroecological conditions of thermokarst lakes within OCF, the program could benefit from additional types of measurements. For example, groundwater likely plays a key role in lake water balance and limnological conditions in OCF. Lakes that exhibit low values and low ranges in E/I ratios may be influenced by supra-permafrost and/or sub-permafrost groundwater flow, yet little is known about groundwater flow in OCF. The influence of groundwater on lake water balances could be studied be installing piezometers in the catchment of each monitoring lake or deploying data loggers that measure changes in water volume into each monitoring lake and calculating net groundwater flow in each lake (see Tondu 2008). An extensive 3-D groundwater modeling project could also reveal groundwater patterns through OCF. Permafrost dynamics throughout OCF are largely unknown and likely influences the hydrology and limnology of lakes in OCF, thus knowledge of permafrost throughout the landscape would benefit the hydroecological program. Macrophytes likely play a large role in the transfer of nutrients within the aquatic ecosystem because they occupy a large proportion of total biomass within lakes (field observations). Macrophyte coverage and community composition could also be included to enhance the hydroecological monitoring program. Traditional macrophyte (accounting for abundance and community composition on a plot by plot basis) is labour intensive and time-consuming, however, analysis of aerial images that shows macrophyte coverage may provide a simple method for acquiring information regarding macrophyte conditions. Photographs of vegetation within the catchment area taken from the same reference point each year could also be incorporated into the sampling campaign to evaluate temporal changes in terrestrial vegetation.

Appendix A

Northern hydroecological monitoring in Old Crow Flats, YT (Vuntut National Park): a guide to field methods

Preface

This work was completed during an NSERC Northern Research Internship and is in support of an MSc project co-supervised by the University of Waterloo and Wilfrid Laurier University. This document will serve to guide Parks Canada and Vuntut Gwitchin Government staff members to gather data in a consistent and systematic manner to monitor the lakes within the Old Crow Flats. The design and outline of this monitoring program is in recognition of the strong partnership that exists between Parks Canada-Yukon Field Unit, Vuntut Gwitchin Government, Wilfrid Laurier University and the University of Waterloo.

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Acknowledgements

This work is the result of an NSERC Northern Internship Program that was sponsored by the Northern Research Institute. I would like to thank Clint Sawicki for providing and arranging in-kind support (office and living space) during the internship, Ian MacDonald (Parks Canada) and Brent Wolfe (Wilfrid Laurier University) for identifying the need for a field methods manual and providing valuable comments and insights and Roland Hall (University of Waterloo) for reviewing and providing support. I am grateful to Lauren MacDonald and Ann Balasubramaniam (University of Waterloo) for teaching me how to construct the periphyton samplers. I am thankful to all field assistants who helped deploy and collect the samplers and were subject to photographs: Ann Balasubramaniam (UW), David Frost (Parks Canada), James Itsi (Vuntut Gwitchin Government), Jeffrey Peter (Parks Canada), Esau Schafer (Parks Canada), Nick Sidhu (WLU), Leila Sumi (Parks Canada)and Kevin Turner (WLU).

Table of Contents

1.0 Introduction to Hydroecological Monitoring
1.1 What is Hydroecology?
1.2 Ecological Integrity, Baseline Conditions and the Role of Paleolimnology
1.3 Environmental Monitoring in the North

2.0 Field Sampling Preparation
2.1 Field Trip Preparation
2.2 Locating Sites in the Field
2.3 Field Notes and Observations
2.4 Constructing Periphyton Samplers

3.0 Field Sampling Techniques
3.1 Deploying Periphyton Samplers
3.1.1 Deploying from a Helicopter
3.1.2 Deploying from a Boat
3.2 Collecting Periphyton Samplers
3.2.1 Collecting from a Helicopter
3.2.2 Collecting from a Boat
3.3 Collecting Water Samples for Isotopic (H, O) Analysis
3.4 Field Measurements
3.4.1 Lake Water Depth
3.4.2 Water Temperature
3.4.3 Conductivity
3.4.4 pH
3.4.5 Dissolved Oxygen

4.0 Sample Storage and Shipping

1.0 INTRODUCTION TO HYDROECOLOGICAL MONITORING

1.1 What is Hydroecology?

Hydroecology is a term used to simply reflect the scientific overlap between hydrology and ecology. It is the study of how hydrology affects the physical and chemical conditions of freshwater systems and the impacts on plants and animals over space and time. In this monitoring program, we are studying the water balance of the lakes using water isotope tracers (H, O) and how changes in the water balance influence aquatic conditions and biology. The water balances of lakes in the Old Crow Flats are influenced by the **hydrologic cycle**. The hydrologic cycle describes the continuous movement of water from the oceans and land to the atmosphere and back again (Figure 1.1). The hydrologic cycle is driven by climate, and therefore climate change will alter the water balance and aquatic ecology of lakes.

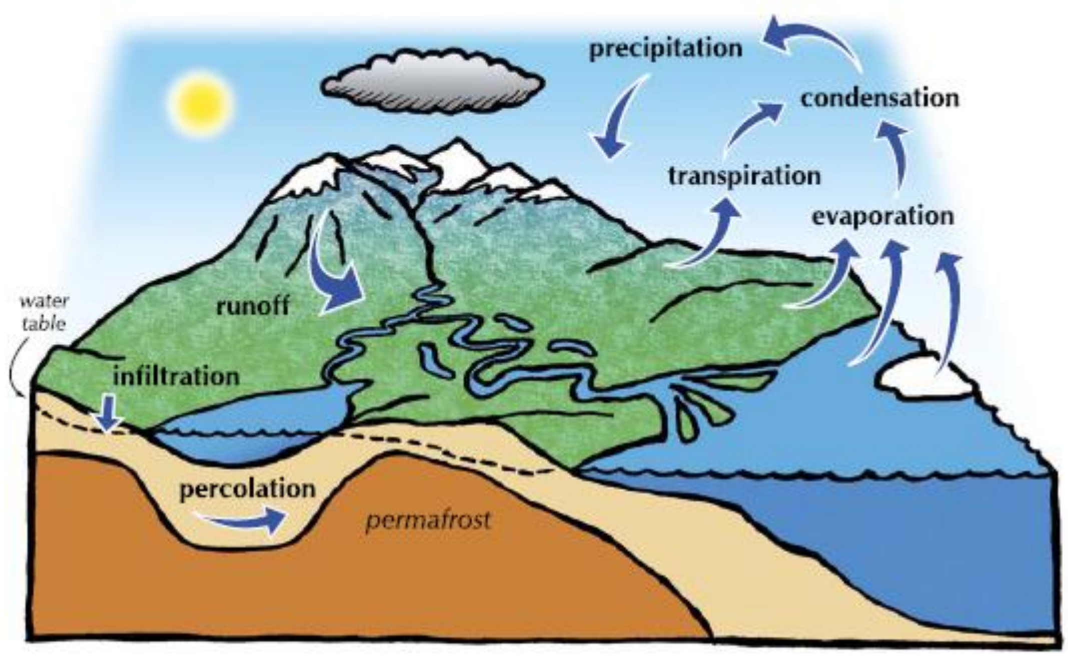


Figure 1.1. The hydrological cycle involves many different processes. Each process is influenced by climate and in turn influences the water balance of lakes. Figure from EMAN-North, 2005.

The **water balance** of a lake is a simple budget of water gains and losses. In lakes of the Old Crow Flats, the main source of water gain is rainfall and snowmelt and the main source of water loss is evaporation (Figure 1.2). In a simple way, the water balance (ΔS) can be calculated by:

$$\Delta S = \text{Rainfall} + \text{Snowmelt} - \text{Evaporation}$$

This is a very simplified equation for a water balance and there are many other factors like streams and groundwater that also influence the water balance of lakes. For this hydroecological monitoring program, water isotope tracers will be used as a tool to monitor lake water balances.

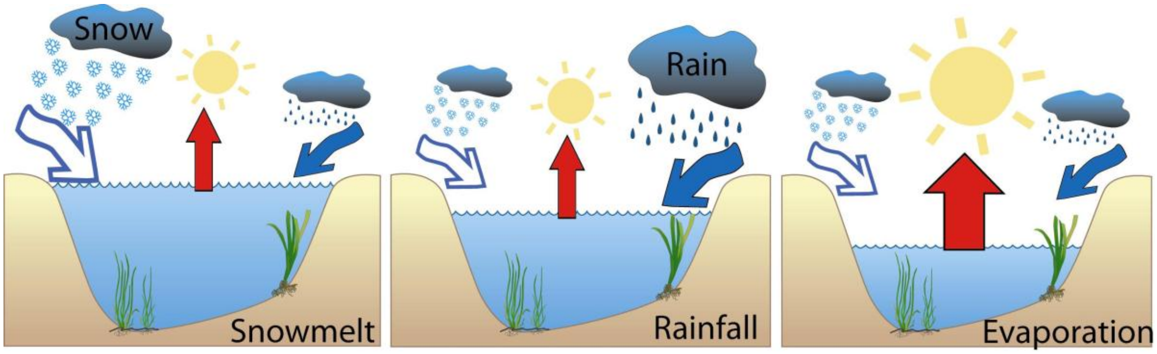


Figure 1.2. There are three main lake types found in the Old Crow Flats, based on their water balance. The lake on the left is mainly influenced by snowmelt, the lake in the middle is mainly influenced by rain, and for the lake on the right the dominant hydrological process is evaporation. Notice that each lake has a different water level. Each of these lakes will have a different ratio of heavy to light isotopes of hydrogen and oxygen in the water.

An **isotope** is an atom that has the same number of electrons and protons, but differs in the number of neutrons. Isotopes are like identical twins, the same in every way, except that one is heavier (has more neutrons) and one is lighter (has less neutrons). As water passes through the hydrological cycle, the hydrogen and oxygen isotope composition of water (the ratio of heavy to light hydrogen and oxygen isotopes) changes. For example, water that has undergone evaporation becomes enriched in the heavier isotopes of hydrogen and oxygen because the lighter isotopes will evaporate first. Also, snowmelt and rainfall differ in their hydrogen and oxygen isotope composition. The ratio of the heavy and light isotopes in lake water reflects the lake's water balance and the primary source of water that is supplied to the lake.

Each lake will have a different water balance; some will receive more snowmelt and some will evaporate more than others. Differing amounts of snowmelt, rainfall and evaporation affect the aquatic ecosystem. To measure changes to the aquatic ecosystem, the hydroecological monitoring program will focus on periphyton. **Periphyton** refers to algae that grow on substrates. Substrates that algae can grow on include rocks, sand, sediments, and biota such as plant stems and leaves. Scientists deploy artificial substrates such as glass slides or plastic sheets to obtain a sample of periphyton (this hydroecological monitoring program will deploy plastic sheets). Algae are good indicators of ecosystem change because they are very small, grow rapidly and respond quickly to environmental changes. Also, their communities consist of large numbers of species, and so small samples can provide considerable ecological information. In contrast, fish are large organisms that respond to ecosystem changes much more slowly and they are absent in many shallow lakes or there are not many species present. The advantage of using algae to monitor the aquatic ecology is that they continually monitor the environment 24/7 and reflect the environmental conditions in which they live. Many species of algae can only tolerate a certain range of conditions. For example, if the water temperature becomes too warm or the pH becomes too high, the population of a species may not be able to tolerate the new conditions and start to die out. On the other hand, a new species may prefer the new conditions and start to accumulate in the lakes (Figure 1.3). A change in the composition of algae in a lake will indicate changing environmental conditions, likely due to changes in climate.

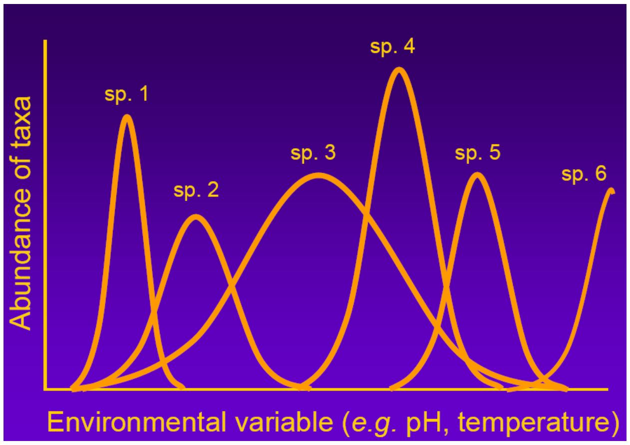


Figure 1.3. Species responses to environmental variables can be very specific. As shown in this figure, different species tolerate different ranges of conditions. The amount and type of algal species found in a lake reflects the environmental conditions (i.e. water chemistry) of the lake.

1.2 Ecological Integrity, Baseline Conditions and the Role of Paleolimnology

The hydroecological monitoring program is designed to assess the ecological integrity of the aquatic ecosystem and how it is changing over time in response to a changing climate. **Ecological integrity** is a "condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biologic communities, rates of change and supporting processes" (Parks Canada, 2009). The condition of the aquatic ecosystem in its natural state before any human or human-induced activity has occurred is known as **baseline conditions**, or the pre-impact state. Ecosystems are always changing and it can be difficult to tell the difference between natural changes and human-induced change. Although Vuntut National Park is remote in location and has one of the highest ecological integrity ratings in Canada, the region has undergone substantial warming over the past two to three decades (Parks Canada, 2004). According to tree-ring records (Porter, 2010), this warming period is substantially higher than any other period in the past 300 years. So, while there is little direct human-induced development or change within the region, the area is still indirectly influenced by human-induced climate change.

Determining baseline conditions requires a long-term data set to gain perspective on how the environment has varied naturally over time. It is often difficult to find long-term data sets, especially in the North. However, hydroecological research in Old Crow Flats has studied past lake conditions by gathering information preserved in sediment cores from the lakes. This is known as **paleolimnology** - a science that uses physical, chemical and biological information that is preserved in the sediments of lakes to reconstruct past environmental conditions (Figure 1.4). Understanding baseline conditions is very important. These conditions will be used as a reference point in which present conditions can be compared to determine if any change or stress has been imposed on the ecosystem.

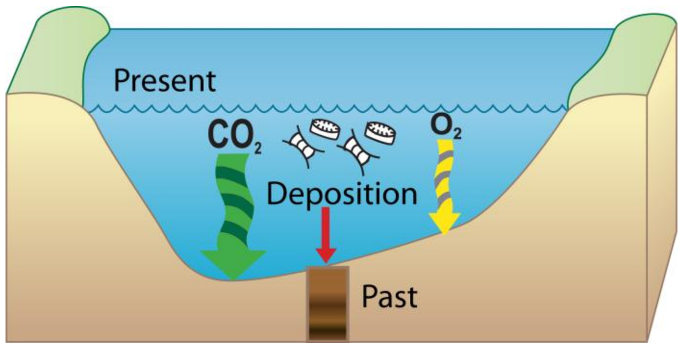


Figure 1.4. Paleolimnology uses physical, chemical and biological information stored in lake sediment profiles to reconstruct past conditions. Materials fall to the bottom of the lake where they are preserved for hundreds, even thousands, of years. Scientists can take a core from the bottom of a lake and analyze the different layers of sediment for properties such as algae and chemical composition. This can determine what the water balance and aquatic ecology was like many years ago and can identify baseline conditions.

1.3 Environmental Monitoring in the North

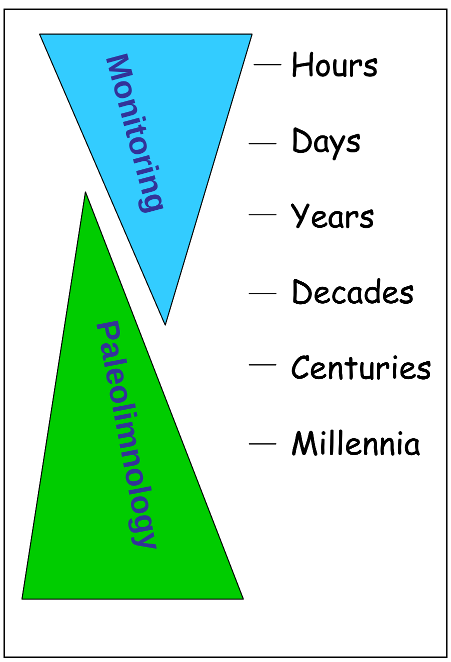


Figure 1.5. Environmental monitoring is a matter of timescales. By combining paleolimnology (looking at the past) with current monitoring programs, environmental managers can develop useful and powerful datasets for determining ecological integrity and to inform stewardship and management decisions. Adapted from Smol, 2008.

Monitoring programs consist of repeated collection of samples using the same method over a period of time. Monitoring programs can span a range of timescales, depending on the purpose of the program. Figure 1.5 shows the different time scales of monitoring programs and paleolimnological studies. This northern hydroecological monitoring is intended to be a long-term monitoring program designed to answer the general question "what is the state of the aquatic ecosystem and how is it changing over years to many decades?" It will use data generated by the paleolimnology study and build the data set forward in time with ongoing monitoring. Long-term hydroecological monitoring will detect trends and changes associated with variations in climate. This is often known as **trend monitoring**.

Trend monitoring is a long-term commitment and, in a northern context, can be very expensive and challenging. It will require a major commitment from staff to repeatedly collect the samples, from university partners to assist with sample analyses, analyze the data and describe the results, and from administrators to continually fund the program. Although this type of monitoring can be costly, it will provide useful and valuable information that will be essential for periodic reporting (e.g., State of the Park Reports) and informed decision-making.

2.0 FIELD SAMPLING PREPARATION

2.1 Field Trip Preparation

In preparation for the fieldwork, a list of the types of samples that are going to be collected should be made. In the case of this hydroecological monitoring program, we will be collecting water isotope and periphyton (algae) samples. The next thing to do is make a list of all the required equipment, supplies and material that are needed to collect these samples. Table 2.1 shows the necessary equipment needed to collect samples for the hydroecological monitoring program.

Prepare the parts of the periphyton samplers (2 per lake) and partially assemble them before the sampling starts; see section *2.4 Constructing Periphyton Samplers* for instructions. To help keep the field trip organized and reduce the amount of work needed to be done in the field, sample bottles can be pre-labeled with tape and organized in whirlpack or ziplock bags. It is a good idea to prepare a check list of all the items that must be taken on the trip. This can include a map of the area, necessary permits, field observation sheets, GPS, camera, personal safety equipment and proper gear, first aid kit, tool kit, food, etc. The checklist will vary depending on whether the sampling will be done via helicopter or boat.

Table 2.1. Detailed list of equipment and material required

Variable Collected	Material Required
Water Isotopes 	• 30ml Nalgene high-density polyethylene bottles (2 per lake) • Labeling tape (coloured electrical tape) • Fine Sharpie marker to label bottles • (2) Large ziplock bags
Periphyton 	• Wooden floats (2 per lake) • Artificial substrates (4 per lake) • Anchor (2 per lake) • Easy off cable ties (10 per lake) • Black film containers (20 per lake) • Large ziplock bag (2 per lake) • Labeling tape (coloured electrical tape) • Sharpie marker for labeling • Spare parts for periphyton samplers (additional rope, substrates, nylons, etc)

2.2 Locating Sites in the Field

Preliminary site selection has already been completed for the hydroecological program in Vuntut National Park, yet more lakes can be added to the program in the future. During the years 2007-2009, 57 lakes in the Old Crow Flats were intensely studied during the International Polar Year (IPY) Project "Yeendoo Nanh Nakhweenjit K'atr'ahanahtyaa – Environmental Change and Traditional Use of the Old Crow Flats in Northern Canada". A smaller group of these lakes were carefully chosen by researchers and Parks Canada staff to be part of the hydroecological monitoring program. A total of 14 lakes were selected that represent a range of hydroecological conditions, catchment and spatial characteristics (Turner et al., 2010). These decisions were also influenced by jurisdictional location and accessibility; the selected lakes are summarized in Table 2.2 and can be viewed in Figure 2.1. Note that OCF 37 was added to the monitoring program in 2011 owing to its easy access from the Old Crow River and is actively used by local community members.

Table 2.2. Summary of hydrologic and catchment characteristics of selected Old Crow Flats monitoring lakes.

Lake ID	Local Name	Jurisdiction	Hydrological class	Surface Area (km^2)	Average July Depth (m)	Easting	Northing
OCF06	Zelma	VGFN	Evaporation	4.46	0.15	542310	7534197
OCF11		VGFN	Snowmelt	0.07	0.5	517935	7546028
OCF 19		VNP	Evaporation	0.11	1.1	519752	7574535
OCF 26		VGFN	Snowmelt	0.42	1.5	542429	7536271
OCF 29	John Charlie	VGFN	Rainfall	6.86	1.3	550592	7533401
OCF 34	Netro	VGFN	Rainfall	5.71	1.6	564208	7530710
OCF 35		VGFN	Rainfall	0.13	1.2	557752	7541127
OCF 37		VGFN	Rainfall	5.03	0.6	549542	7548839
OCF 38	Husky	VNP	Rainfall	12.60	0.5	535923	7578985
OCF 46		VNP	Evaporation	0.12	0.6	557881	7560258
OCF 48	Hot Spring	VNP	Rainfall	1.27	0.45	546491	7564657
OCF 49		VNP	Rainfall	1.14	1.75	555720	7552606
OCF 55		VGFN	Snowmelt	0.02	3.85	552282	7525870
OCF 58	Mary Netro		Rainfall		2.15	548663	7491580

VGFN = Vuntut First Nation Special Management Area

VNP = Vuntut National Park

The exact site location can be found using a Global Positioning System (GPS) and a map. Coordinates, provided in Table 2.2, can be entered by hand into a GPS system or synced using GPS mapping software such as MapSource or OziExplorer. Detailed instructions on how to use a GPS and GPS mapping software are provided in their user manuals. A map of the area marking the lake sites has been created by Kevin Turner (PhD student, Wilfrid Laurier University) using ArcMap. This map has been printed and is available to Parks Canada and VGG staff to help locate the monitoring lakes. It is a good idea to study the area before the sampling begins and create a flight plan (if the intended transportation is a helicopter). Creating two flight trips will ensure that there is enough gas to reach all lakes and give staff and the pilot a chance to take a break for lunch. A suggested flight plan is provided in Figure 2.2. Note that OCF 37 can be added to flight trip 1.

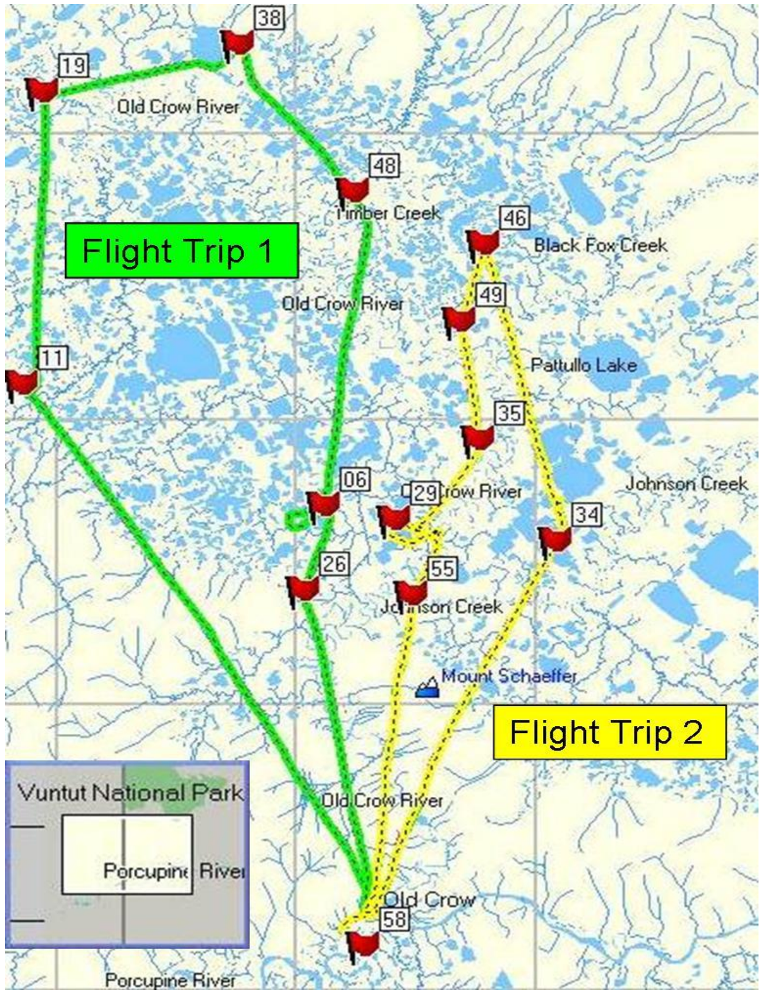


Figure 2.2. Suggested flight plan for the monitoring lakes.
Flight Trip 1: Old Crow →11 → 19 → 38 → 48 → 37 → 06 → 26
Flight Trip 2: Old Crow →34 → 46 → 49 →35 → 29 → 55

It is a good idea to become familiar with the flight plan and the characteristics of each lake before the sampling begins. Take some time and look at the photographs of each lake and pick out some key features. This will make locating the correct lake a lot easier. For example, OCF 49 is the only lake in the vicinity that has an island of trees in the middle which makes it very easy to identify from the helicopter. See Appendix A for photos of each lake.

In 2011, five of these lakes were accessed by boat off the Old Crow River. Access by boat will serve as a back up in case funding for the helicopter trips are not available. Figure 2.3 shows the lakes and access points for the boat trip and the GPS coordinates are summarized in Table 2.3.1.

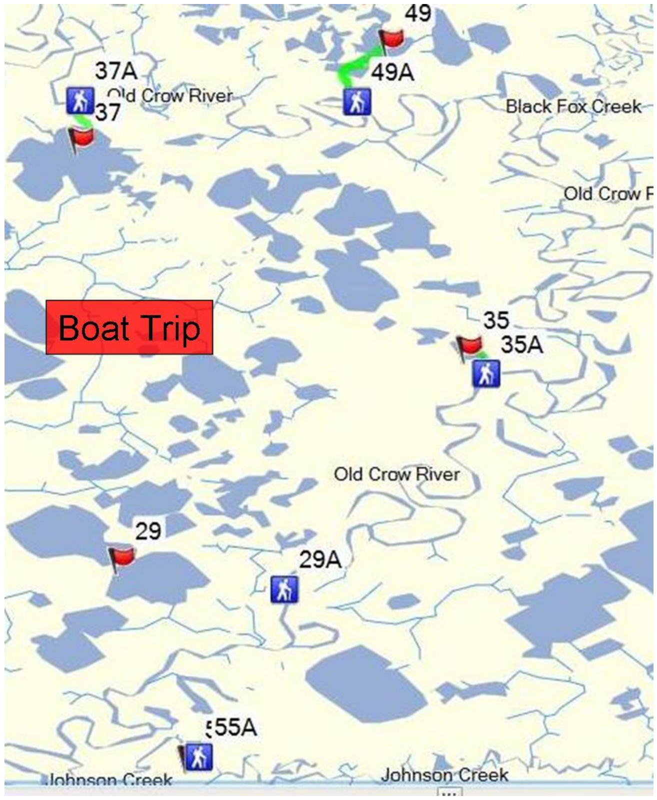


Figure 2.3. Monitoring lakes that are accessible by boat off the Old Crow River. Red flags indicate the sample location for the lake and the hiker symbol represents access points from the river.

Table 2.2.1. Description of lake access from boat off the Old Crow River

Lake	Easting	Northing	Access Notes
OCF 29	554174	7532215	Camp at access point and well established trail to lake. Canoe and paddles present. Randall Tetlichi camp.
OCF 35	558259	7540358	Access on east side of stream channel. Access is steep, but hauling a light canoe up the bank is possible. No marked trail, but easy terrain. Walk around the northeast side of the drained lake that has thick willows and look for flagging tape.
OCF 37	549519	7550360	Camp at access point and well established trail to lake. No canoe present, but frequently used camp near lake – Erwin Linklater Camp.
OCF 49	555325	7550437	Camp at access point and well established trail part way that leads to “Canoe Lake.” Canoe was stashed by Joel Peter during the preceding winter. Might be difficult to portage a canoe from river. Canoe across “Canoe Lake” and short portage (>100m) to OCF 49.
OCF 55	552501	7525925	Bank is a bit steep, but relatively easy to haul a canoe. Portage is >100m.

2.3 Field Notes and Observations

Detailed field notes are an asset to any type of field work. Useful things to note are the date, field crew, weather, water depth, hydrology, vegetation, wildlife in the area, aquatic organisms, turbidity or colour of the lake, photos, etc. It is also very important to record any measurements that are being taken. If your field team is going to use a multi-parameter Water Quality Meter (e.g., YSI 660) you will want to record the water temperature, pH, specific conductivity and dissolved oxygen content. To make things easier in the field and help with organization, observation sheets can be made and printed before the field trip. Appendix B shows an example of a field-note sheet that can be used.

2.4 Constructing Periphyton Samplers

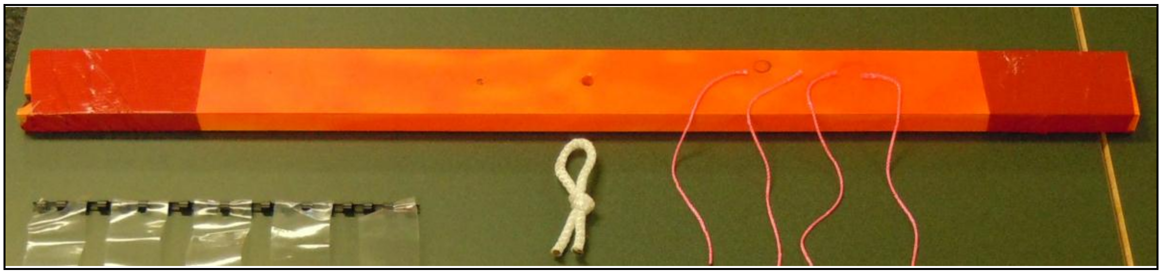
Periphyton samplers should be partially prepared before the field trip begins so they can be rapidly assembled at the lake site using easy off cable ties, either in the helicopter or boat. There are three parts to the periphyton sampler: the wooden float, the artificial substrate and the anchor. Table 2.4 provides a complete list of all the material required to construct the periphyton samplers.

Table 2.4. Detailed list of equipment and material required to build a periphyton sampler

Material Required
• 3”x 1”x 32” pieces of wood with a hole (diameter = 3/8”) drilled in the middle (2 per lake)
• Fluorescent spray-paint (~1 can for 6 samplers)
• Varathane finishing (spray can ~ 1 can for 6 samplers)
• Red duct tape
• Roll of sill seal foam
• Rope for top knot (1/4” braided rope)
• Rope to hang sampler unit (Nylon Masonline)
• Rope for anchor (Nylon Masonline)
• Trouser sock or heavy-duty nylon (2 per lake)
• Surlock binder coils (8 per lake)
• 4x14 cm polypropylene sheets (20 per lake)
• Anchor rocks (2 per lake)

The Wooden Float

The wooden float is made out of untreated lumber that is 1”x 3”x 32”. Lumber yards will wood that has 1”x3”x 8’ dimensions that can be cut into three equal pieces. The next step is to drill a hole in the middle of the sampler. This hole should be large enough to fit a piece of rope through; in the past a 3/8” drill bit has been used. The stick needs to be painted a fluorescent colour so it can be easily identified from the helicopter. Spray paint is the easiest way to paint the sticks and they can either be painted red or yellow. Once the paint dries, the stick should be coated with Varathane to protect the wood and paint from water and fading. Make sure that extra Varathane is applied to any knots in the wood and the ends where the wood has been cut.



To help aid in buoyancy, wrap sill seal foam around the ends of the stick and cover with red duct tape. The red duct tape will keep the added foam in place and also aids in identification of the sampler stick. This is not entirely necessary, but is thought to aid in buoyancy. The last part of the wooden float is the top knot. Tie pieces of the rope into a noose knot (the thicker white rope in the above photo). If you have used a 3/8" drill bit to drill the whole, it is best to use braided rope that is ¼ inch thick. It is beneficial to burn the ends of the top knot to avoid any fraying that may occur. The top knot is the knot that will be fed through the hole in the centre of the stick, with the loop side facing downward to connect to the anchor rope.

The Artificial Substrate

The artificial substrate is the part that the algae will grow on. It is easily constructed out of polypropylene sheets and Surlock binder coils. Polypropylene sheets are large sheets that need to be cut into rectangles that are 4 x 14 cm. This is easily done with a rotary cutter (commonly used to cut material for sewing). Try not to use marker to measure the sheets, instead just use a ruler and use the rotary cutter to mark the dimensions. It is best to try to minimize contaminants on the sheets as this may affect the algae. Once the sheets have been cut in proper dimensions, take a small pile and hole-punch the top and bottom (length-wise). The hole will be the attachment point to the binder coils. Once the polypropylene sheets have been cut and hole-punched (top and bottom), 5 pieces can be attached to each binder coil. Space the sheets so that all of the sheets fit evenly on the binder coil.

The artificial substrates are attached to the sampler stick with string. The artificial substrate should hang down 30 cm from the stick. Before cutting the string, 30 cm should be marked out with a marker and excess should be left on each side (10 cm and 25 cm). The marked part of the string will be an indicator of where to tie the knots to ensure that the length of the string is 30 cm. Melt each end of the string with a lighter, this will stop the ends from fraying. With the 10 cm end, tie a noose knot. This end will attach to the artificial substrate. With the 25 cm end also tie a noose knot. Wrap the string around the wooden float and feed it through the noose knot. Wrap the string through the knot of few times and tie it off with a double knot. This should make a secure knot that will withstand a summer in the water.

The Anchor

The anchor is the part of the periphyton sampler that will hold the sampler in place so that it does not get washed to shore. The anchor is simply made out of heavy duty nylons (women's knee high trouser socks are best) and rocks. The rocks can be collected in the town of Old Crow. For example, the two boat launch areas in Old Crow have many rocks that can be used as an anchor. When selecting an anchor rock, look for a rock that is sufficiently heavy and has smooth edges. More than one rock can be used as an anchor if a large enough rock is not found. Place the rocks inside the nylon. If the nylon tears, double wrap the rock with another.

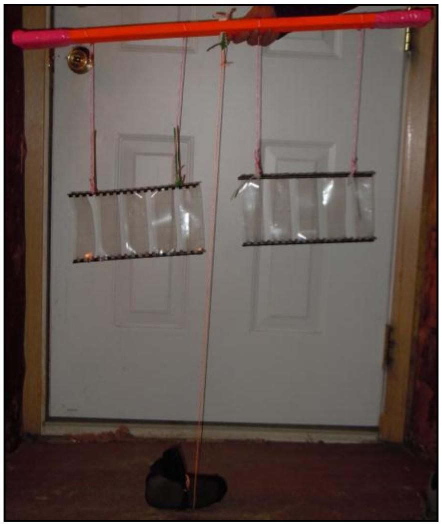
The anchor needs to be connected to a long string that will be connected to the top knot on the sampler stick. Anchor strings should be pre-measured according to the depth of the monitoring lakes, see Table 2.4.1 for 2010 anchor rope lengths. These may change in the future depending on the water balance of the lakes. The length of the anchor line does not need to be exact and it is best to allow for some excess length in case there is a lot of rain. Tie the anchor rope to the nylon and make a noose knot at the top end (to connect to the top knot of the stick). Make sure to keep the different depths separate in a labeled bag.

Table 2.4.1 Depth categories and total amount of anchor ropes required

Depth Category	0.5 m	1.0 m	1.5 m	2.0 m	3.0 m	>6.0 m
Lake ID	OCF06	OCF11, 38, 46, 48	OCF19, 35, 37	OCF26, 29, 34, 49	OCF58	OCF55
Total Anchor Rope	2	8	6	8	2	2

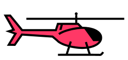
3.0 FIELD SAMPLING TECHNIQUES

3.1 Deploying Periphyton Samplers



The periphyton samplers should be deployed sometime in June so that they can collect algae throughout the summer. Deploying the samplers is very easy and straight-forward. Before the sampler is to be deployed, final assembly is required. There are three parts that need to be connected. First, connect two artificial substrates (sheets of polypropylene) to the strings that are hanging down from the wooden float using easy off cable ties. Each artificial substrate should be connected with two strings. So, on each stick there will be four strings and two sample substrates. Next, attach the anchor to the knotted rope that has been placed in the middle of the wooden float. The anchor will have a rope with a loop on it. Simply connect the anchor loop to the loop on the sampler stick with a cable tie. Make sure that you are connecting an anchor that has an appropriately measured length of rope for the lake that you are deploying in.

For each lake, two periphyton samplers will be deployed for quality control. It will provide a duplicate set of data that can be used to assess analytical uncertainties. Also, deploying two samplers will increase the chances of recovering at least one sampler later in the summer. For large lakes, like Husky Lake (OCF 38), it might be a good idea to deploy three periphyton samplers to increase the chance of recovery. Sometimes curious animals chew on the samplers, winds are so strong that they blow the sampler away, or water levels rise higher than the anchor rope.



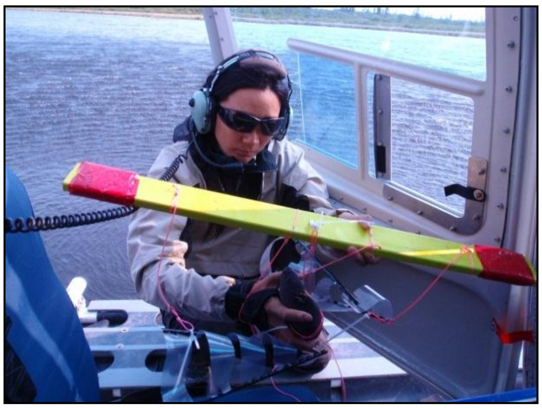
3.1.1 Deploying from a Helicopter

Most of the sites are located in remote locations and sampling will involve the use of a helicopter. The field technician who is in the front of the helicopter will be responsible for finding the correct location on the map using a GPS, marking a way-point and recording the GPS coordinates (NAD 83) of deployment (so you can easily locate the sampler later), taking photographs, and writing down any observations.

The field technician sitting in the back of the helicopter will be responsible for deploying the periphyton samplers and collecting the water samples. While the helicopter is traveling to the site location, the technician in the back of the helicopter can assemble the periphyton sampler. Once the helicopter has landed at the appropriate site, the technician in the back can open the door and carefully exit the helicopter, step on the pontoon, turn to face the helicopter and assume a comfortable and stable position either squatting or kneeling on the float. Once in place, reach for the sampler and take the wooden float in one hand and the anchor in the other hand. Then, hold the stick of the sampler in one hand and drop the anchor rock into the water. Do not slowly lower the rock with the anchor rope; let it fall to the bottom under its own weight so that stress is not added to the nylon (which may cause it to tear). Once the rock has landed, place the stick in the water. If the artificial substrates become tangled, untangle and orient them properly while they are submerged under water. Repeat this and deploy both periphyton samplers at the same location (3-10 m apart). There will be slack on the anchor rope allowing the samplers to move around a bit. A previous study (MacDonald, 2009) at Mary Netro Lake determined that there is little difference in results among samplers, even if they are placed at different regions of the lake. So, placing samplers beside each other, with enough distance to prevent them from tangling, is fine.

All persons in the helicopter will be required to wear headphones for communication at all times. The technician who steps onto the pontoon will continue to wear the headphones (to protect against engine noise) and will be able to communicate with the pilot and field crew. It is important to maintain clear communication with the field crew and mention any observations to be recorded. The photographs below illustrate the different steps involved in deploying the periphyton samplers.

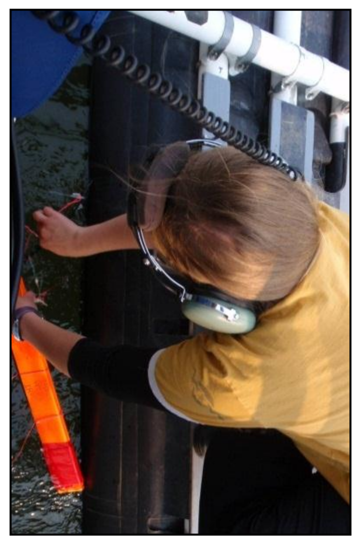
Step 1: Assemble the sampler in the helicopter. This is made easy by propping the sampler stick so that the units can hang down freely and placing the anchor in the foot area.



Step 2: Field technician has assumed a stable and comfortable position and has grabbed the sampler stick with one hand and the anchor with the other.

Step 3: Field technician has released the anchor into the water and is holding onto the sampler stick with the other until the anchor has reached the bottom.

Step 4: The anchor has landed at the bottom of the lake. The field technician is now placing the periphyton sampler in the water**.**

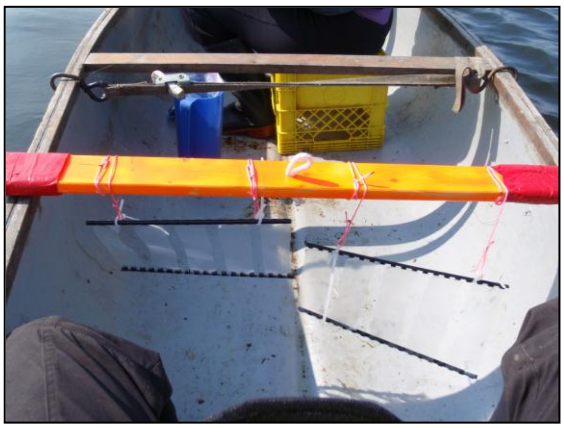


Step 5: Field technician has noticed that the sample units are tangled. With one hand holding onto the stick, the units are easily untangled while submerged under the water.

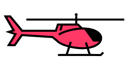
3.2.1 Deploying from a Boat

Periphyton samplers will be deployed from a boat (canoe, rowboat or inflatable raft) at Mary Netro Lake and other sites that are easy to access from the river (OCF 55, 29, 35, 37 and 49). Ensure that when sampling from a boat proper safety procedures are being followed and a life jacket is worn at all times.

The periphyton samplers can be assembled on the shore of the lake and then placed into the boat. Once all the necessary materials are placed in the boat, the field crew can paddle to the middle of the lake to deploy the sampler. One field technician can be designated to deploy the sampler while the other is responsible for taking notes. Once the boat has reached the proper location, the anchor and float can be held over the side of the boat. Drop the anchor and hold the float until the anchor reaches the bottom. Gently place the sampler into the water and untangle the units if they become crossed. Place a sampler from either side of the boat.

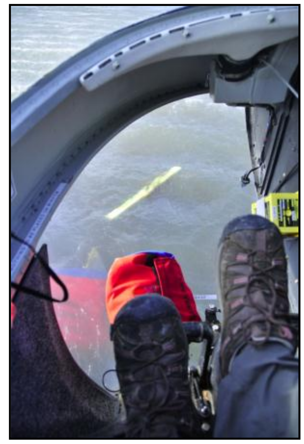


3.2 Collecting Periphyton Samplers



3.1.1 Collecting from a Helicopter

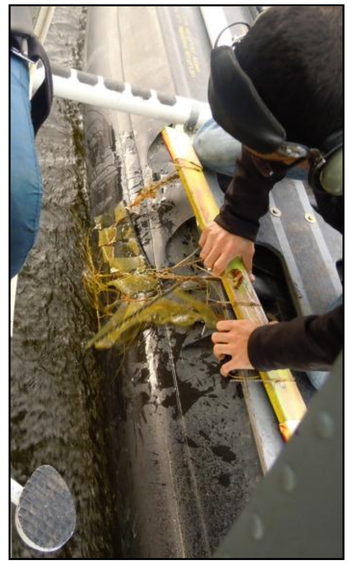
Similar to deployment, the field technician in the front of the helicopter will be responsible for navigating to the monitoring lakes. Prior to departure, it is important that the waypoints taken with the GPS when the periphyton samplers were deployed are programmed into the GPS system. This will allow the helicopter to approach the correct area of the lake that the samplers were deployed and make it easier to find them. Finding the samplers can be tricky, especially in larger lakes. The field technician in the front will search for the wooden floats and instruct the helicopter pilot to the correct location. Once the wooden floats have been spotted from the air, the helicopter will land on the lake close to the samplers.

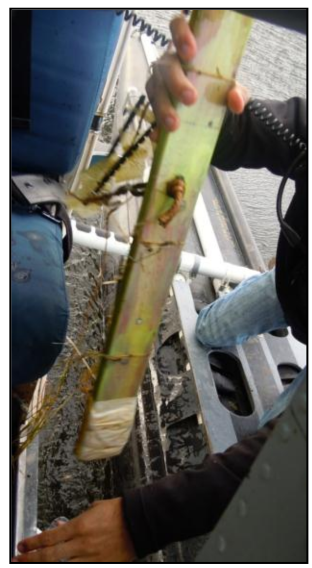
On the lake, the helicopter will navigate over the periphyton samplers. The wooden floats will pass under the front of the helicopter to be picked up by the field technician on the pontoon.

As soon as the helicopter has landed, the field technician in the back will carefully exit the helicopter and assume a comfortable and stable position on the pontoon. The pilot will navigate the helicopter over to the wooden floats, so it is important to hold onto something while the helicopter moves around the lake. A line and a lifejacket should be worn for additional safety. The wooden floats will pass underneath the helicopter. As the helicopter approaches the wooden floats, lean towards the inside of the pontoon and wait for the wooden float to pass by. When the wooden float is near, reach out with one hand and grab the wooden float. Lift the wooden float onto the pontoon and hold it in place with one knee. Locate the anchor rope and proceed to pull the anchor out of the water. Remove any excess weeds that may be attached to the anchor and place the anchor on the floor of the helicopter. Then place the wooden float vertically in the helicopter, making sure that the artificial substrates are not tangled. Once the first periphyton sampler has been retrieved the second one can be collected. Note that the samplers may be located close together and both samplers may be picked up before they are placed in the helicopter. Once the samplers have been placed in the helicopter, carefully climb back into the helicopter.

The photo on the left shows how the field assistant has assumed a stable position on the pontoon and is waiting for the wooden float to pass by under the helicopter. On the right, the field assistant has reached into the water, retrieved the periphyton sampler, placed the sampler on the pontoon and is about to secure the wooden float with his knee.



On the left, the field technician has secured the sampler in place with his knee and is pulling up the anchor line. Once the anchor has been placed on the floor of the helicopter, pick up the wooden float, twist it into a vertical position and place it in the helicopter, as shown in the photo on the right.



Before the artificial substrates are taken off, the thickness and colour of the algae should be noted and recorded. The technician who collects the sample can communicate any observations to the technician in the front to be recorded. Make sure to also report and record any observations about the lake and the condition of the periphyton sampler. For example, sometimes muskrats can be curious about the sampler units and may chew on them. A picture of the polypropylene sheets should also be taken; pictures of the entire unit or a single sheet are fine. Once the information is recorded and pictures are taken, remove each individual periphyton sheet from the unit, roll the sheets up and insert them into a black film container (one sheet per film container). Black film containers are used because they prevent light from hitting the samples. If black containers are unavailable ensure that the sample is not exposed to sunlight by promptly placing them in a dark bag. Previously packed whirlpack or ziplock bags with 5 black film containers, labeled 1-5, should be prepared prior to the fight. Ensure that the middle sheet is placed in the film container #3 and the outermost sheets are placed in containers labeled 1 and 5. Remove the polypropylene sheet from the sampler by simply tugging it away from the binder coil. Once the sheet is in hand, wrap it around the index finger and insert the rolled sheet into a film container.

Once all 5 sheets of the artificial substrate have been placed in the bag, label the bag (Lake ID and date) and toss it into a cooler or larger bag (this will help with organization in the helicopter). A total of 20 sheets will be collected from each lake (sometimes there may be less depending if both samplers are collected and sheets are intact). Once this is complete the left over pieces of the sampler unit and anchor can be placed in a garbage bag to keep things organized. The process of removing and packaging the individual periphyton samples will take place in flight while the helicopter is traveling to the next monitoring lake.

The photos on the left show how the polypropylene sheet is rolled around the index finger and inserted into the black film container. Sometimes the algae on the sheets can be quit thick, as shown in the photo on the right. It is a good idea to take a photo of what the algae looks like at each lake and write down any, and all, observations.

3.2.1 Collecting from a Boat

As previously mentioned, some of the lakes, particularly Mary Netro, will be accessed with a boat. Collecting periphyton samplers from a boat is simple and straight forward. Paddle the boat to the location of the periphyton samplers (using the GPS for navigation). Once the proper location has been reached the samplers will be in view. Approach the samplers with the boat so that the sampler can be easily reached from the side of the boat. Once the boat has reached the periphyton sampler, the field technician can slowly and carefully reach out towards the sampler to retrieve the wooden float. Lift the sampler out of the water and place it on the edge of the boat. Find the anchor rope and pull the anchor out of the water and place it in the boat. Once the anchor is in the boat, hold up the periphyton sampler so that the technician in the back can take a photo. Document the thickness and colour of the algae as well as any other observations about the lake and the condition of the periphyton sampler.

Remove each artificial substrate from the periphyton sampler by tugging the sheet away from the binder coil. Wrap the sheet around your index finger and place the rolled sheet into a black film container, following the same procedures when collecting from a helicopter.

Approach the periphyton sampler with the canoe or boat. Slowly and carefully reach over the side of the boat to retrieve the periphyton sampler.

Place the wooden float on the side of the boat and pull up the anchor. Take a photo of the periphyton sampler and make a note about the thickness and colour of the algae.

3.3 Collecting Water Samples for Isotopic (H, O) Analysis

Water isotope samples will be collected twice during the monitoring program. It is important to collect water isotope samples close to 'ice-off' to capture the initial isotopic signature prior to evaporative influences and once again at the end of the season to monitor the influence of evaporation. Water isotope samples can be collected by using the 'grab sampling' technique (EMAN-North, 2005) because the lakes are well mixed. This hand-held method of sampling is the simplest way of collecting a water sample. The sample should be taken about 15cm below the surface of the lake, which is about mid-forearm deep. The water sample will be collected in a 30 ml Nalgene HDPE plastic bottle. When taking the sample, make sure that the bottle is filled to the top and quickly place the lid on the bottle and tighten fully. Ensure that there are no air spaces in the bottle, this is very important to make sure that no evaporation occurs. If the sample undergoes evaporation before it is analyzed it will give an inaccurate reading of the lake's water balance.

Try to take the water sample from the same location each time the site is monitored. The use of global positioning system (GPS) to find the geographic coordinates will help make sure the precise sampling site is located. Sometimes this can be challenging in a helicopter; aim for maximum range of 250 metres. Note if the location of the sample site has changed by a significant distance (i.e. if a lake has drained the helicopter may have to find a pond with deep enough water, or if it is really windy on a large lake the helicopter pilot may want to stay closer to shore).

3.4 Field Measurements

There are many different field measurements that can be collected; the most common are depth, temperature, conductivity, pH, dissolved oxygen (DO), and water clarity (EMAN-North, 2005). Measurements should be recorded as soon as they are taken on a field observation sheet.

Many field instruments have been specifically designed to record these different parameters. Some instruments, called multi-meters, can measure many parameters at the same time; a YSI 660 has been used in the past. Measurements are generally taken by lowering the instrument probe directly into the lake water to a depth of approximately 30 cm and recording the data off the screen.

If using an instrument to collect field data, it is very important to properly maintain, store and calibrate the instrument. The instrument must be in good condition and properly calibrated in order to get accurate results. The manufacturer of the instrument will provide specific information on how to properly store, handle, calibrate and operate the instrument.

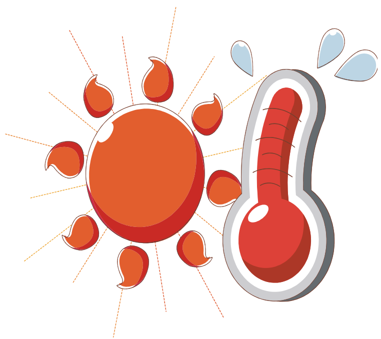
3.4.1 Lake Water Depth

This is a simple and important measurement to take that does not require a sophisticated instrument. A depth metre can easily be constructed with a long rope, heavy weight, permanent marker, and a metre stick.

At the end of the rope tie a heavy weight (a plumb bob for example). Lay the rope out and mark every 50 cm with a coloured marker (e.g., red) and every 10 cm with a black marker. It is better to use marker than tape because tape can shift over time. Wrap the rope around a stick or pipe so that the measuring rope can be easily stored and used.

When positioned on the float of the helicopter or leaning over the side of a boat, drop the weight in the water and record the depth at which the weight hits the bottom. Make sure that the rope is straight and not at an angle so that the measurement is accurate. The weight may have to be dropped a couple of times in order to get a straight line. If the helicopter is generating too much wind or moving around too much, ask the pilot to stabilize the helicopter.

3.4.2 Water Temperature



Water temperature is an important measurement to make and can be recorded by using an YSI multi-meter or a standard thermometer. Water temperature will influence many different physical, chemical and biological variables in the lake. For example, water temperature can influence pH, conductivity and dissolved oxygen concentrations. Water temperature can also affect biologic activity in the lake. The lakes in the Old Crow Flats are well mixed and the temperature-depth profile remains constant (the temperature at the surface and at the bottom of the lake are similar). Therefore, one measurement approximately 30 cm below the surface of the water is adequate.

3.4.3 Conductivity

Conductivity is the measure of water's ability to conduct electrical current per unit distance. It is expressed as units of microsiemens per centimetre (µS/cm). Conductivity is affected by the amount and type of dissolved substances in the water and is mostly influenced by the geology of the area. For example, a lake in an area with granite bedrock will have a lower conductivity than a lake in an area with clay soils because soil has more available ions and particles that can be dissolved into the water. Also, conductivity can increase over time in a lake during periods of net evaporation. Conductance measurements in the monitoring lakes are often very different from each other and typically range between 25 µS/cm and 320 µS/cm.

3.4.4 pH

pH indicates the strength of an acidic or basic solution. It is a dimensionless number that is on a scale between zero and 14, where zero is strongly acidic, 7 is neutral and 14 is strongly basic or alkaline (Figure 3.1). Most natural surface water is slightly alkaline and has a pH greater than 7.0. Groundwater is more acidic than surface water. Rain water is generally acidic with a pH between 5.0 and 6.0 and precipitation with a pH less than 5.0 is classified as acid rain. Many species of algae can only tolerate a certain pH, if the pH of a lake changes then there may be a change in aquatic organisms. The pH of lakes within the Old Crow flats are slightly alkaline, ranging from 7.5 to 8.5.

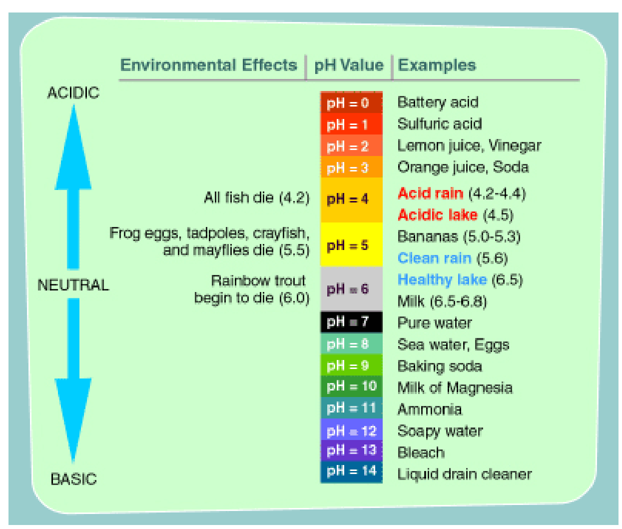


Figure 3.1 The pH Scale

3.4.5 Dissolved Oxygen

This is the measure of the amount of oxygen that is dissolved in the water and can be recorded as a concentration (mg/L) or percent oxygen saturation (%). Adequate amounts of oxygen are required for the survival of fish and other aquatic organisms. Dissolved oxygen levels in northern lakes are generally high because there is a low demand. Lakes within the Old Crow Flats are typically saturated to supersaturated and dissolved oxygen measurements are generally over 100 percent saturation (> 10.31 mg/L).

4.0 SAMPLE STORAGE AND SHIPPING

Water isotope samples can be stored in a refrigerator or at room temperature and they should not be put in direct sunlight. The polypropylene sheet of the periphyton samplers with algae must be frozen and avoid exposing the samples to light. The samples should be frozen as soon as possible.

Samples should be shipped as soon as possible after collection. Isotope samples collected in June can remain in storage and shipped with the periphyton samples and isotope samples collected in August. Samples can be packed and shipped in a small cooler, make sure there is enough room in the cooler for ice packs. The samples should be well sealed and packed, using bubble wrap or newspaper to protect the samples from damage. Be sure to include copies of a field sheet indicating what samples are in the cooler and any forms that are required. Place these forms in a plastic bag inside the shipping container to protect them from spills or damage.

Label all shipping containers with the address of the destination. This will most likely be the address of the university that is going to be doing the analysis. For example:

Ship to: Prof. Roland Hall
Department of Biology
University of Waterloo
200 University Avenue
Waterloo, Ontario N2L 3G1

Address labels should be taped over with clear packing tape to protect the address from tearing. Coolers should also be taped to make sure that the lid does not open while being shipped. The latch and spigot should also be taped over to prevent spillage and breakage. It is a good idea to contact the university beforehand so that they are aware the samples are being shipped. Containers can be transported by Air North to Whitehorse and then either ground or air transport to the university destination.

Good Sources

EMAN-North. 2005. Northern Waters: A guide to designing and conducting water quality monitoring in Northern Canada. Northern Ecological Monitoring and Assessment Network (EMAN-North).

Parks Canada. March 2007. Monitoring and Reporting Ecological Integrity in Canada's Nation Parks. Volume 2: A park-level guide to establishing EI monitoring.

Smol, JP. 2008. Pollution of Lakes and Rivers: A Paleoenvironmental Perspective (2nd Edition). Blackwell Publishing, Malden MA, USA. 383 p.

Flight Trip 1

OCF 11

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 517857 E 7545969	N 68 01 38.3 W 140 34 20.4	N 68.02729 W 140.52621

Facing South

Facing South

OCF 19

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 519564 E 7574560	N 68 17 01.0 W 140 31 34.3	N 68.28361 W140.52621

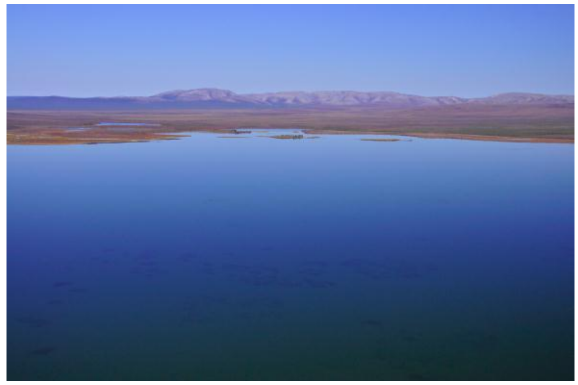
Facing North

Facing Northeast

OCF 38

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 535235 E7578773	N 68 19 11.6 W 140 08 43.1	N 68.31988 W140.14532

Facing North



Facing North

OCF 48

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 546573 E 7564585	N 68 11 27.7 W 139 52 35.8	N 68.19102 W 139.87662

Facing West

Facing North

OCF 06

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 544509 E 7534581	N 67 55 20.2 W 139 56 19.8	N 67.92228 W 139.93883

Facing North

Facing South

OCF 26

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 542575 W 7526179	N 67 50 50.0 W 139 59 17.5	N 67.84722 W 139.98821

Facing North

Facing North

Flight Trip 2

OCF 34

UTM	Lat/Long mm’ss.s”	Lat/Long ddddd
N 564706 E 7531350	N 67 53 22.2 W 139 27 33.8	N 67.88949 W 139.45940

OCF 46

UTM	Lat/Long mm’ss.s”	Lat/Long ddddd
N 557960 W 7560331	N 68 09 02.8 W 139 36 15.7	N 68.15079 W139.60437

Facing South

Facing North

OCF 49

UTM	Lat/Long mm’ss.s”	Lat/Long ddddd
N 555912 W 7552421	N 68 04 49.0 W 139 39 28.1	N 68.08027 W 139.65781

Facing North

OCF 35

UTM	Lat/Long mm’ss.s”	Lat/Long ddddd
N 557837 W 7541257	N 67 58 47.2 W 139 37 03.4	N 67.97978 W 139.61761

Facing East

Facing Southwest

OCF 29

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 55108 W 7533791	N 67 54 51.4 W 139 48 20.7	N 67.91428 W 139.80574

Facing East

Facing West

OCF 55

UTM	Lat/Long mm'ss.s"	Lat/Long ddddd
N 552288 W 7525879	N 67 50 34.6 W 139 45 27.3	N 67.84294 W 139.75758

Facing North

Facing South

Vuntut National Park Hydroecological Monitoring Field Notes

Lake ID:_____________________________ Date and Time:______________________

Sampling Crew:____

Weather: (light, rain etc.) ____

Water depth (m): _______________________________

GPS Location: _________________________________

YSI: Temp (°C):__________	SCond (μg/cm) _________	pH: ________
DO (mg/L): ___________	DO %: _________	

Hydrology :

(make a note of drunken trees, submerged vegetation, slumped banks, if water levels are high or low, etc)

Turbidity/Colour:

Vegetation:

(list any veg. that can be identified. Common types include: [Pondweed, Water Lily, Duckweed, Hornwart, Milfoil] in water [Muskgrass, Bur-reed, Sedges, Horsetail] along the shore)

Additional Notes:

(note any wildlife, aquatic organisms, photos taken, difficulty accessing site, etc.)

Periphyton Sampler Collection

Samplers Retrieved: __________ Number of Intact Sheets:___________

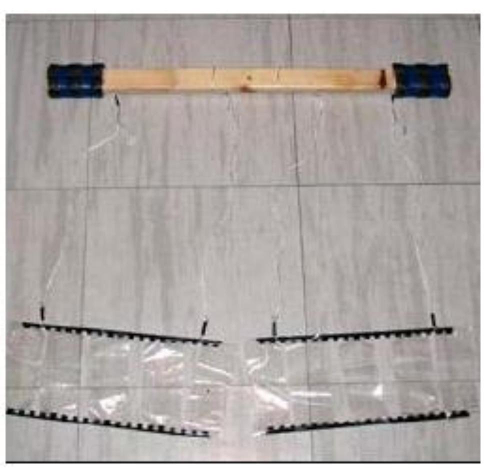
Algae/Sampler Notes:

(note the colour and thickness of algae, if a curious animal has chewed the sheets, etc.)

Detailed List of Equipment, Supplies and Materials Needed for the Hydroecological Monitoring Program.

Variable Collected	Material Required
Water isotopes	• (26) 30ml plastic Nalgene bottles • Labeling tape (coloured electrical tape) • Thin sharpie to label bottles • (1) Large ziplock bag
Periphyton	• (26) 2"x1" pieces of wood with a hole drilled in the middle • (4 cans) Fluorescent spray-paint • (4 cans) Varathane finishing (spray can) • Red duct tape • Roll of sill seal foam • Rope for top knot • Rope to hang sampler unit • Rope for anchor • (26) Heavy duty nylons • (104) Binder coils • (260) 4x14 cm polypropylene sheets • Anchor rocks • (260) black film containers • (26) whirlpack bags • Labeling tape (coloured electrical tape) • Sharpie for labeling

* This table lists the minimum amount of each material. It is a good idea to bring extra supplies into the field in case some are lost or broken along the way.



Appendix B

From student to researcher: lessons learned from an NSERC northern research internship

Published in Meridian (newsletter of the Canadian Polar Commission), spring/summer issue, 2011, pg 17-25.

Although I am a new northern researcher, I am not a newcomer to the north, and I know how important it is for researchers to develop strong relationships with northern communities. Long stays in the north are essential to building trust, developing collaborative partnerships, and creating opportunities for knowledge exchange.

Paul Nadasdy illustrates in his book *Hunters and Bureaucrats,* how difficulties and struggles arise when trust is not established between researchers and local First Nation members, ultimately leading to failed knowledge integration and lost confidence. The success of the new northern research paradigm, which emphasizes collaborative research and reflects northern priorities, will depend on the level of trust established between researchers and local communities. Wolfe et al. (2011) elaborates on how a northern, multi-disciplinary research project funded by the Government of Canada International Polar Year (IPY) program – "Environmental Change and Traditional Use of the Old Crow Flats in Northern Canada" -- has worked with the community of Old Crow, Yukon to establish trust and incorporate northern priorities into research design.

Time and cost, however, make it difficult to spend long periods in the north. The Natural Sciences and Engineering Research Council of Canada (NSERC) created the Northern Research Internship (NRINT) program to enable new northern researchers to stay for several months in northern communities. Several years ago Ann Balasubramaniam, a member of my lab group, held an NRINT award in Old Crow. Her experience, which she described in a *Meridian* article

(Balasubramaniam, 2009) strengthened community-researcher relationships and has had long-lasting positive effects on both her academic progress and relationships with the community. Inspired by her example, I applied to the program and subsequently held a NRINT award in Whitehorse from May to September 2010. The award involved collaboration with Parks Canada, partnership with Yukon College and knowledge exchange with the community of Old Crow.

Collaboration with Parks Canada

My project, part of the IPY project mentioned above, involves implementing a northern hydroecological monitoring program in the Old Crow Flats (part of Vuntut National Park) to be sustained by Parks Canada and the Vuntut Gwitchin Government (VGG) in the future. Like most northern communities, the Vuntut Gwitchin First Nation is concerned about the ecological integrity of their traditional territory and the impacts climate change will have on their health and future. Central to these concerns are recent observations of declining lake levels and the rate of change that is occurring in the Old Crow Flats. For Parks Canada, notable gaps in their current monitoring programs are unable to effectively determine the state of the aquatic ecosystem and assess how it is changing over time. The monitoring program uses a three-pronged approach to address these questions by analyzing: (1) water isotopes to measure lake water balance; (2) algae to monitor limnological conditions; and (3) paleolimnology to determine how hydrological and ecological conditions have changed over time.

Staff from Parks Canada (the primary stakeholder) and VGG had expressed the need for a monitoring program that would meet the specific needs of both organizations, while overcoming the logistical challenges of northern monitoring. In remote areas like the Old Crow Flats, site access is limited to helicopter and boat (provided the water levels are high enough). The majority of the approximately 2700 small thermokarst lakes are only accessible by helicopter, which is costly.

Having researchers travel from southern institutions to the north is also time-consuming and expensive, especially in the context of an annual monitoring program; however, partnerships between universities, northern agencies, and communities can overcome these challenges. Empowering northern agencies and communities to implement their own simple and scientifically informative monitoring programs further enables the capacity for local stewardship over the land. My first field season -- two short trips to Old Crow in June and August, 2010 to collect samples -- hardly offered enough time to collaborate effectively with my local partners, primarily Parks Canada staff. Implementing a successful long-term monitoring program would take more time and commitment. I hoped to leave a true "legacy of knowledge" -- to help northerners gain a better understanding of ecosystem change and to develop an effective ecosystem stewardship strategy of that could provide information needed for wise policy decisions. At the same time, I hoped to expand my network of northern colleagues, renew past relationships and learn more about the community of Old Crow. To achieve these goals, I decided to spend additional time in the north working with the Vuntut National Park Monitoring Ecologist, Ian McDonald, towards implementing the monitoring program.

Ian is based out of the main office in Whitehorse and despite our very different schedules for the field season in Old Crow – they were in fact polar opposites -- we were able connect and plan strategies for implementing the monitoring program, especially in terms of being prepared for the potential challenge of fluctuating budgets. Over the summer I developed a framework for an analysis that outlined the major stakeholders, goals, logistical alternatives to sampling, and associated costs and benefits of the hydroecological monitoring program. This framework will help ensure that managers have the knowledge they need to make informed decisions should changing government priorities affect their funding.

Our meetings with Parsk Canada and the Vuntut Gwichin Government also revealed a strong need to transfer knowledge from the researchers to the staff who will be doing the sampling. We invited Parks staff out into the field to gain firsthand experience with the monitoring program. We used a Parks boat to travel to Mary Netro Lake and invited staff on our June and August helicopter trips to the Old Crow Flats, to learn sampling methods (Figure 1). These trips were very successful in transferring knowledge to current Parks Canada personnel, but a high staff turnover rate means knowledge is often lost when employees leave. A more tangible source of information was required to help new staff learn proper field sampling methods and maintain continuity. I developed a field methods manual in collaboration with the monitoring ecologist who made sure that it met the needs of its intended audience. The manual, *Northern hydroecological monitoring in the Old Crow Flats (Vuntut National Park): A guide to field methods*, has been published in the Parks Canada Information Centre on Ecosystems (ICE) internal database. Working with the monitoring ecologist on this manual greatly improved my ability to create a document that conveyed scientific field methods in a language that was easy to understand. The end result was a document that will be useful to Parks staff, not only in Vuntut National Park, but also in other northern parks.

Figure 1**.** Graduate students from the University of Waterloo (Jana Tondu and Ann Balasubramaniam) and Parks Canada staff (David Frost) at Mary Netro Lake preparing to deploy algal samplers. The mosquitoes were also out for the day, but we were prepared for them, – although David did not seem to be bothered. Photo Credit: Leila Sumi (Parks Canada). Photo: Leila Sumi, Parks Canada.

Developing a Partnership with Yukon College

One of the requirements of the NRINT program is a northern partner to provide in-kind support. The Northern Research Institute (NRI), a division of Yukon College, agreed to act as my northern partner, facilitating and supporting the internship. As a Yukon College Alumni, establishing a link between a northern research project and the NRI -- a mutually beneficial partnership that will likely continue -- was personally enriching. When results from the research project are available I will present a guest lecture to classes in the college's School of Science, Trades and Technology, and give a public presentation to the Yukon Science Institute.

Staying and working at Yukon College during the internship gave me a broader perspective on research in the north. A professor and two graduate students from my home institution - Wilfrid Laurier University - who are conducting research in the Kluane area invited me on a road trip along the Alaska Highway to learn about their research, as well as other projects. I was fortunate to visit the community-based archeology camp (Little John) to learn about ethnographic and archeological research in the Upper Tanana watershed. Located at the Alaska-Yukon boarder just outside the village of Beaver Creek, Yukon College anthropologist Norm Easton has worked and collaborated effectively with the White River First Nation to document the culture and history of the area. It was clear to me that the strong relationship between researchers and the local community has not developed overnight – rather, it has grown over 20 years of persistent research, consultation with the community and participation by researchers in local events.

Knowledge Exchange with the Community of Old Crow

Of all of the enriching experiences I had during my internship, the most memorable was working with the science camp for children in Old Crow. Science camp aims to create linkages between traditional ways of knowing and science using land-based and hands-on learning. Students are engaged in relevant ways of learning so that they can become future leaders in the community and stewards of the land. For the past four years, the VGG has funded and coordinated this camp for Old Crow children between the ages of 9-14. The camp is held outside the village of Old Crow to provide the students with the opportunity to learn that science is not as hard as they think, and that it can be applied to things they already know.

Since I was staying in Whitehorse, the science camp coordinator asked if I would be interested helping coordinate the camp – and handle the 'science' portion. I eagerly agreed, however I had never participated in a science camp before and I had no idea what to do. Fortunately, Yukon College's Science Quest camp was going on and Google helped me find the US Environmental Protection Agency's *Water Source Books* that gave me some great ideas. I developed a science workshop as well as small activities – such as making lava lamps and solar ovens, and engineering structures with marshmallows and spaghetti -- that would entertain and educate. I prepared for all these activities in Whitehorse, as most of what I needed was not available in Old Crow, and somehow managed to get it all on the plane (thanks Air North). I also involved Yukon College as a sponsor: the School of Sciences, Trades and Technology lent field equipment, and the Technology Innovation Centre, the College Bookstore, and the College Relations and International Development donated prizes.

This year, the science camp was held on the Porcupine River at the 'School Cabin,' otherwise known as Caribou Lookout. The boys and girls are divided into separate groups and stay at the camp for four days and three nights. The children all camp together in the cabin with a camp counsellor (an older youth who helps out with the camp) and the camp coordinators, camp cook and camp steward curl up in sleeping bags in tents. The boys and girls participate in the same science activities but learn different forms of traditional knowledge during the camp. For example, the girls learned about berries and how to cut fish and the boys learned how to collect poles on the river and set up canvas tents.

The integration of traditional knowledge from local community members with the scientific activities that I provided was a true sign of knowledge sharing. For example, one day with the girls we travelled up the Porcupine River to Mary-Jane and George Moses' camp to learn how to cut fish, cook bannock, learn about medicinal plants, and pick berries (salmon [cloud] berries are now, by far, my favorite berry). The next day we talked about alternate forms of energy, which the children already knew a lot about. We made solar ovens out of empty pizza boxes and made pita pizzas to place in the box and let the sun do the rest. Most were skeptical of the idea and would have rather had an actual pizza, but surprisingly enough, it was a success and the cheese melted.

While we waited for the pizzas to cook, we began a bio-monitoring workshop that I designed, and discussed how benthic invertebrates and other organisms, such as the algae I collect for my MSc research, can be used to gauge the health of aquatic ecosystems. Originally, we were going to assess the health of the Porcupine River by sampling the different types of macro-invertebrates; however, unusually high water levels from heavy precipitation flooded the shore and made sampling impossible. With a bit of luck and some contingency planning, we found a pond just behind the camp that we could sample to identify what types of benthic invertebrates inhabit the Old Crow area.

The students had a great time learning how to use a dip-net to collect specimens for analysis (Figure 2). The boys were very excited to witness predator-prey relationships and loudly proclaimed “how cool” it was as they watched a very large predaceous diving beetle larva chase and capture dragon fly nymphs. Once we collected our samples, we headed back to the camp lab where we learned how to identify the invertebrates we found (Figure 3). This activity went over really well with the students and they were very surprised to learn that the huge predaceous diving beetle larvae they found would grow up to be very small and different looking adults. I had vials and preservative so that each student could keep one invertebrate that they found and I also gave a sample of each invertebrate to the community science teacher to be displayed at the school.

Figure2. Collecting freshwater invertebrates from a pond near camp. Students learned how to use a dip-net to collect samples and used tweezers to capture specimens to take back to the camp lab and analyze. Photo: Jana Tondu

Figure 3. Identifying aquatic invertebrates at the camp lab. We used plastic egg cartons and ice cube trays as insect holders and hand-held magnifying glasses to observe the structure of individual specimens. The students found 6 different families: dragon fly nymphs (*Aeshnidae, Libellulidae*?), predaceous water beetle larvae and adults (*Dytiscidae*), phantom midges (*Chaoboridae*), water striders, and damselfly larvae. Photo: Jana Tondu

Throughout Science Camp, people from Old Crow would visit and share some of their knowledge with the students or just stop by for dinner and tea. I fondly remember the interaction between one of the youngest children at camp and a camp visitor. The boy was struggling to make a bow, like the older boys, until he was shown how to find a proper stick and how to carve it. Being at the camp was a great way to get to know different people from the community and set the stage for knowledge sharing. In particular, I learned a lot about the history of the Old Crow area. I even found some archeological artifacts on the bluff near camp and a community member discovered an arrow head. One of the most instrumental things I learned at science camp was the community's perspective on researchers and how much they value the knowledge they can transfer to the community. It surprised me that the community viewed me as a "researcher" -- a term I generally reserve for my supervisor.

As a new graduate student, I had labelled myself as a "student" and had not given much thought to the idea that, really, I am a researcher. This concept crept up on me when a few members from the Renewable Resource Council (RRC) came to the camp. One member explained how the Old Crow Flats are important to the Vuntut Gwitchin, the "People of the Lakes". He commented on how researchers are truly welcome on their land, and in the community, to help them understand how the Flats are changing. He stressed to the young students how important education is so that they could learn about the land and one day be a researcher - like me. Prior to this talk I almost felt out of place, but afterwards I realized that I had been invited to Old Crow because I had knowledge that I could pass on to the students. I came to science camp feeling like a student, and left feeling like a researcher.

Staying for an extended period in the north and spending time with local people outside of my own research demonstrated to the community that I was dedicated and committed to the project. In turn, community members have been very welcoming and receptive to my project. When I went to chat with one of the RRC members who came out to the science camp because his cabin is near one the lakes that I sampled, he informed me that the lake -- which I knew as OCF 49 -- was actually called Marten Lake, and he generously offered to store his canoe nearby over the winter so that I could use it next summer.

I strongly believe that extended stays in the North are vital for researchers. In the north, interpersonal connections are a fundamentally important part of the cultural fabric -- and can only be developed in person. Spending time in a community and collaborating with northerners who have a vested interest in northern research will leave an invaluable legacy for future northern researchers and citizens. The NRINT program is one of the only resources available to students to help support extended stays in the north – but it is scheduled to end in March 2011. This will only make it more challenging to accomplish collaborative research that truly reflects northern priorities. The need to train highly qualified northern researchers (students) has been clearly demonstrated by IPY -- one of the main IPY goals was to train a new generation of polar researchers -- and Canada's Northern Strategy, released in 2009, emphasizes leadership in science and technology. We are an Arctic nation and resources such as the NRINT program are needed to ensure world-class northern research continues.

Figure 4. Left to right: Researchers Jana Tondu and Ann Balasubramaniam, with Parks Canada employee Leila Sumi, at a stop to collect climate data from a weather station during June field work in the Old Crow Flats. Photo: Jana Tondu

Figure 5. Discussing proper sampling methods and how to assemble algal samplers at Mary Netro Lake. Left to right: researchers David Frost (Parks Canada), researchers Jana Tondu and Ann Balasubramaniam, Jeffrey Peter (Parks Canada). Photo: Leila Sumi, Parks Canada.

Acknowledgments

On every level, I am grateful to NSERC for providing funding for the Northern Research Internship and thankful to Clint Sawicki of the Northern Research Institute for providing in-kind support. I would also like to thank Ian McDonald of Parks Canada for supporting the internship and setting time aside to meet with me. I would like to give a big thanks to Jessica Peters for inviting me to participate in Science Camp and letting me stay at her house. Thank you to the VGG for supporting my involvement with Science Camp and purchasing my July flight to Old Crow. A big thank you to Yukon College for welcoming me back, lending me equipment and donating prizes. An extended thanks goes to Scott Slocombe for taking me to Beaver Creek and the Arctic Research Institute. Lastly, but not least, thank you to my supervisors, Brent Wolfe and Roland Hall for encouraging me to do a northern research internship.

References

Balasubramaniam, AM. 2009. Community-based research, youth outdoor education and other highlights of a Northern Research Internship experience in Old Crow, YT. *Meridian.* Spring/Summer issue: 16-19.

Nadasdy, P. 2003. Hunters and bureaucrats: Power, knowledge, and aboriginal state relationships in the southwest Yukon. Vancouver, UBC Press.

Wolfe, BB., MM., Humphries, MFJ., Pisaric, AM., Balasubramaniam, CR., Burn, L., Chan, D., Cooley, DG., Froese, S., Graupe, RI., Hall, T., Lantz, TJ., Porter, P., Roy-Leveillee, KW., Turner, SD., Wesche and M. Williams. 2011. Environmental change and traditional use of the Old Crow Flats in northern Canada: An IPY opportunity to meet the challenges of the new northern research paradigm. *Arctic* (in press).

Appendix C

Letter of agreement

Letter of Agreement

Between: Parks Canada, Yukon Field Unit
205-300 Main Street
Whitehorse, YT
Y1A 2B5

And Wilfrid Laurier University
75 University Avenue West
Waterloo, Ontario
N2L 3C5

And University of Waterloo
200 University Avenue West
Waterloo, Ontario
N2L 3G1

Parks Canada, Wilfrid Laurier University and the University of Waterloo recognize shared objectives between Parks Canada's ecological integrity monitoring initiative and the Old Crow Flats, Yukon Territory hydroecological monitoring program ("the program") developed by Dr. Brent Wolfe of Wilfrid Laurier University and Dr. Roland Hall of the University of Waterloo. This work will help Wilfrid Laurier University, the University of Waterloo and Parks Canada to understand aspects of the limnology, hydroecology and hydrology of selected lakes in the Old Crow Flats and how they change over time. Subject to the terms and conditions described below, Wilfrid Laurier University, the University of Waterloo and Parks Canada ("the parties") hereby agree to work in partnership to continue the program.

Parks Canada agrees to:

1. Conduct and pay for fieldwork needed to deploy and retrieve periphyton samplers and to collect water samples for isotope analysis.
2. Pay for the analysis of periphyton and water samples. Approximately 15 periphyton samples/year will be analysed for the community composition and abundance of diatom algae and photosynthetic pigments. Costs of analysis will be calculated based on the University of Waterloo's standard rate of pay for a Graduate Student Assistantship ($27.70/hour in 2011) and for 8 hours of work/sample. Approximately 30 water isotope samples/year will be analyzed at a cost of $45/sample.

Dr. Brent Wolfe and Dr. Roland Hall agree to:

1. Analyze periphyton and water samples collected through the program.
2. Provide Parks Canada with expertise on how to monitor the limnology, hydroecology and hydrology of selected lakes in the Old Crow Flats.

Canada

3. Provide Parks Canada with expertise on how to report on the status of lakes in the Old Crow Flats for Parks Canada State of the Park reports.
4. Provide Parks Canada with existing and new data collected through the program.

Support outside the scope of this agreement can be provided if mutually agreed to by the parties.

Barry Troke
A/Park-Sites Manager, Vuntut National Park, Chilkoot Trail & S.S. Klondike National Historic Sites
Yukon Field Unit

[signature] Nov 23, 2011
Signature Date

Dr. Brent Wolfe
Associate Professor and NSERC Northern Research Chair
Wilfrid Laurier University

[signature] 25 Nov 2011
Signature Date

Dr. Roland Hall
Professor, Department of Biology
University of Waterloo

[signature] 29 Nov. 2011
Signature Date

Appendix D

Water isotopic values (δ_L,δ_I,and E/I)

Table C1. Isotopic values for monitoring lakes collected from 2007-11

Date	Lake ID	$\delta^{18}O_L$	δ^2H_L	$\delta^{18}O_I$	δ^2H_I	E/I
Jun 2007	OCF06	-12.32	-121.02	-19.78	-148.26	0.55
Jun 2007	OCF11	-25.79	-200.32	-26.99	-205.93	0.03
Jun 2007	OCF19	-14.81	-137.82	-22.63	-171.06	0.43
Jun 2007	OCF26	-19.77	-165.21	-24.60	-186.78	0.18
Jun 2007	OCF29	-15.14	-136.88	-21.62	-162.95	0.35
Jun 2007	OCF34	-16.24	-143.24	-22.27	-168.20	0.29
Jun 2007	OCF35	-18.42	-156.72	-23.73	-179.84	0.22
Jun 2007	OCF37	-14.88	-136.52	-21.92	-165.40	0.39
Jun 2007	OCF38	-16.87	-146.17	-22.36	-168.84	0.25
Jun 2007	OCF46	-19.40	-163.35	-24.54	-186.32	0.19
Jun 2007	OCF48	-21.20	-168.45	-23.56	-178.48	0.08
Jun 2007	OCF49	-14.22	-134.88	-22.48	-169.88	0.49
Jun 2007	OCF55	-21.96	-175.94	-24.85	-188.76	0.09
Jul 2007	OCF06	-9.46	-107.69	-18.50	-137.97	1.11
Jul 2007	OCF11	-18.06	-162.43	-26.96	-205.71	0.37
Jul 2007	OCF19	-11.71	-124.86	-23.46	-177.67	0.95
Jul 2007	OCF26	-17.68	-156.04	-24.84	-188.72	0.31
Jul 2007	OCF29	-13.33	-127.76	-20.97	-157.77	0.50
Jul 2007	OCF34	-14.85	-135.12	-21.40	-161.23	0.36
Jul 2007	OCF35	-14.71	-137.58	-22.72	-171.77	0.45
Jul 2007	OCF37	-13.10	-126.76	-20.95	-157.63	0.53
Jul 2007	OCF38	-14.89	-136.28	-21.80	-164.43	0.38
Jul 2007	OCF46	-12.80	-130.15	-23.49	-177.91	0.75
Jul 2007	OCF48	-19.41	-161.50	-23.85	-180.81	0.17
Jul 2007	OCF49	-12.78	-128.08	-22.32	-168.56	0.67
Jul 2007	OCF55	-20.04	-168.47	-25.34	-192.73	0.19
Sep 2007	OCF06	-8.70	-99.94	-15.62	-114.98	1.02
Sep 2007	OCF11	-14.65	-143.02	-25.82	-196.59	0.63
Sep 2007	OCF19					
Sep 2007	OCF26					
Sep 2007	OCF29	-12.35	-121.98	-20.16	-151.31	0.58
Sep 2007	OCF34					
Sep 2007	OCF35					
Sep 2007	OCF37					
Sep 2007	OCF38	-13.58	-129.55	-21.31	-160.52	0.49
Sep 2007	OCF39					
Sep 2007	OCF46					
Sep 2007	OCF48					
Sep 2007	OCF55	-19.89	-167.04	-25.07	-190.55	0.19
Jun 2008	OCF06	-13.55	-129.27	-21.24	-159.88	0.49

Date	Lake ID	$\delta^{18}O_L$	$\delta^{2}H_L$	$\delta^{18}O_I$	$\delta^{2}H_I$	E/I
Jun 2008	OCF11	-23.47	-187.77	-26.45	-201.63	0.09
Jun 2008	OCF19	-13.45	-136.35	-25.48	-193.84	0.78
Jun 2008	OCF26	-19.17	-163.88	-25.15	-191.20	0.23
Jun 2008	OCF29	-14.28	-132.33	-21.24	-159.95	0.41
Jun 2008	OCF34	-15.86	-141.43	-22.20	-167.60	0.32
Jun 2008	OCF35	-16.93	-150.37	-23.90	-181.23	0.32
Jun 2008	OCF37	-14.09	-134.27	-22.47	-169.77	0.50
Jun 2008	OCF38	-15.18	-139.43	-22.61	-170.88	0.40
Jun 2008	OCF39	-13.41	-129.63	-21.69	-163.53	0.54
Jun 2008	OCF46	-14.59	-143.39	-26.26	-200.08	0.66
Jun 2008	OCF48	-19.91	-164.98	-24.28	-184.21	0.16
Jun 2008	OCF49	-13.56	-131.61	-22.33	-168.65	0.56
Jun 2008	OCF55	-21.28	-174.54	-25.43	-193.46	0.14
Jul 2008	OCF06	-10.04	-111.27	-19.31	-144.51	1.00
Jul 2008	OCF11	-16.72	-152.58	-25.38	-193.05	0.40
Jul 2008	OCF19	-12.16	-127.98	-24.12	-182.95	0.91
Jul 2008	OCF26	-17.23	-152.05	-24.02	-182.16	0.30
Jul 2008	OCF29	-12.43	-124.24	-21.09	-158.74	0.63
Jul 2008	OCF34	-14.16	-132.47	-21.52	-162.13	0.44
Jul 2008	OCF35	-13.71	-135.23	-23.92	-181.40	0.64
Jul 2008	OCF37	-12.06	-123.48	-21.55	-162.39	0.73
Jul 2008	OCF38	-13.68	-130.27	-21.43	-161.47	0.49
Jul 2008	OCF39	-12.45	-121.68	-19.86	-148.89	0.54
Jul 2008	OCF46	-11.27	-122.70	-23.46	-177.67	1.06
Jul 2008	OCF48	-18.50	-157.06	-23.72	-179.76	0.21
Jul 2008	OCF49	-12.06	-124.71	-22.25	-167.99	0.79
Jul 2008	OCF55	-20.36	-170.25	-25.44	-193.52	0.18
Sep 2008	OCF06	-9.45	-106.79	-17.97	-133.79	1.04
Sep 2008	OCF11	-15.28	-144.20	-24.68	-187.45	0.50
Sep 2008	OCF19	-10.88	-119.62	-22.51	-170.08	1.08
Sep 2008	OCF26	-16.59	-149.87	-24.39	-185.11	0.37
Sep 2008	OCF34	-13.39	-129.88	-21.84	-164.71	0.55
Sep 2008	OCF35	-13.15	-130.84	-22.91	-173.29	0.65
Sep 2008	OCF38	-13.23	-127.19	-20.90	-157.22	0.51
Sep 2008	OCF39	-12.19	-122.56	-20.75	-155.97	0.65
Sep 2008	OCF46	-10.27	-112.29	-19.40	-145.23	0.95
Sep 2008	OCF48	-19.99	-164.35	-23.94	-181.48	0.14
Sep 2008	OCF49	-11.75	-121.71	-21.31	-160.48	0.77
Sep 2008	OCF55	-19.45	-165.97	-25.47	-193.73	0.23
Sep 2008	OCF56	-17.81	-153.86	-23.68	-179.47	0.25
Sep 2008	OCF58	-12.60	-129.04	-23.40	-177.21	0.77
Jun 2009	OCF06	-16.70	-149.85	-24.14	-183.15	0.35
Jun 2009	OCF11	-22.90	-180.41	-24.92	-189.39	0.06
Jun 2009	OCF19	-14.93	-140.47	-23.63	-179.07	0.48
Jun 2009	OCF26	-19.41	-164.60	-25.00	-189.98	0.21
Jun 2009	OCF29	-15.10	-137.55	-21.96	-165.68	0.37

Date	Lake ID	$\delta^{18}O_L$	$\delta^{2}H_L$	$\delta^{18}O_I$	$\delta^{2}H_I$	E/I
Jun 2009	OCF34	-15.63	-143.75	-23.63	-179.03	0.41
Jun 2009	OCF35	-17.76	-155.56	-24.47	-185.78	0.29
Jun 2009	OCF36	-14.59	-137.72	-23.05	-174.43	0.48
Jun 2009	OCF38	-16.48	-145.71	-22.83	-172.66	0.30
Jun 2009	OCF46	-16.88	-150.61	-24.11	-182.86	0.33
Jun 2009	OCF48	-19.88	-168.67	-25.71	-195.67	0.21
Jun 2009	OCF49	-13.88	-134.19	-22.91	-173.26	0.55
Jun 2009	OCF55	-21.88	-178.21	-25.74	-195.88	0.12
Jun 2009	OCF58	-14.67	-136.75	-22.42	-169.37	0.44
Jul 2009	OCF06	-9.15	-109.74	-20.89	-157.16	1.55
Jul 2009	OCF11	-15.99	-150.57	-26.26	-200.11	0.51
Jul 2009	OCF19	-12.36	-128.56	-23.83	-180.60	0.85
Jul 2009	OCF26	-17.98	-154.77	-23.73	-179.87	0.24
Jul 2009	OCF29	-13.64	-128.76	-20.85	-156.80	0.45
Jul 2009	OCF34	-13.88	-135.39	-23.54	-178.35	0.59
Jul 2009	OCF35	-15.03	-140.39	-23.37	-176.94	0.45
Jul 2009	OCF37	-12.90	-130.67	-23.52	-178.15	0.73
Jul 2009	OCF38	-15.16	-139.56	-22.70	-171.56	0.40
Jul 2009	OCF46	-13.41	-133.75	-23.91	-181.30	0.68
Jul 2009	OCF48	-18.38	-158.07	-24.30	-184.43	0.24
Jul 2009	OCF49	-12.90	-127.01	-21.48	-161.88	0.59
Jul 2009	OCF55	-20.06	-168.72	-25.40	-193.18	0.19
Jul 2009	OCF58	-13.64	-132.22	-22.44	-169.54	0.55
Sep 2009	OCF06	-12.97	-124.34	-20.12	-150.96	0.49
Sep 2009	OCF11	-17.33	-151.33	-23.54	-178.30	0.27
Sep 2009	OCF19	-12.97	-131.27	-23.69	-179.52	0.73
Sep 2009	OCF26	-18.13	-155.06	-23.59	-178.74	0.23
Sep 2009	OCF29	-13.53	-130.54	-21.87	-164.95	0.53
Sep 2009	OCF34	-14.81	-133.71	-20.92	-157.35	0.34
Sep 2009	OCF35	-15.38	-141.40	-23.09	-174.72	0.40
Sep 2009	OCF37	-13.64	-128.54	-20.76	-156.05	0.45
Sep 2009	OCF38	-15.28	-137.99	-21.82	-164.59	0.35
Sep 2009	OCF46	-14.67	-137.61	-22.82	-172.60	0.46
Sep 2009	OCF48	-20.41	-166.68	-24.09	-182.72	0.13
Sep 2009	OCF55	-20.18	-166.42	-24.36	-184.87	0.15
Sep 2009	OCF58	-13.72	-133.48	-22.91	-173.25	0.57
Jun 2010	OCF06	-11.70	-121.41	-21.26	-160.04	0.78
Jun 2010	OCF11	-18.86	-160.04	-24.23	-183.83	0.21
Jun 2010	OCF19	-13.36	-134.26	-24.38	-185.03	0.72
Jun 2010	OCF26	-18.26	-154.97	-23.35	-176.80	0.21
Jun 2010	OCF29	-14.30	-132.61	-21.31	-160.51	0.41
Jun 2010	OCF34	-14.95	-138.91	-22.84	-172.72	0.43
Jun 2010	OCF35	-15.17	-142.76	-24.21	-183.71	0.48
Jun 2010	OCF37					
Jun 2010	OCF38	-16.68	-144.49	-22.03	-166.24	0.25
Jun 2010	OCF46	-14.88	-140.89	-23.96	-181.71	0.50

Date	Lake ID	$\delta^{18}O_L$	$\delta^{2}H_L$	$\delta^{18}O_I$	$\delta^{2}H_I$	E/I
Jun 2010	OCF48	-18.81	-160.21	-24.37	-184.95	0.22
Jun 2010	OCF49	-13.68	-130.96	-21.76	-164.10	0.51
Jun 2010	OCF55	-19.56	-167.01	-25.67	-195.39	0.23
Jun 2010	OCF58	-13.48	-133.82	-23.75	-179.99	0.66
Aug 2010	OCF06	-10.01	-105.72	-16.65	-123.17	0.72
Aug 2010	OCF11	-16.34	-142.57	-21.87	-164.94	0.27
Aug 2010	OCF19	-11.96	-124.98	-22.71	-171.70	0.84
Aug 2010	OCF26	-16.19	-142.54	-22.09	-166.70	0.29
Aug 2010	OCF29	-11.88	-119.82	-20.02	-150.15	0.64
Aug 2010	OCF34	-12.95	-125.50	-20.66	-155.26	0.53
Aug 2010	OCF35	-12.95	-126.59	-21.17	-159.40	0.56
Aug 2010	OCF37					
Aug 2010	OCF38	-17.11	-148.45	-22.81	-172.51	0.26
Aug 2010	OCF46	-11.11	-113.79	-18.58	-138.64	0.67
Aug 2010	OCF48	-15.92	-143.29	-22.85	-172.83	0.35
Aug 2010	OCF49	-11.72	-118.49	-19.69	-147.50	0.65
Aug 2010	OCF55	-18.49	-156.30	-23.45	-177.61	0.20
Aug 2010	OCF58	-13.32	-129.99	-22.05	-166.38	0.57
Jun 2011	OCF06	-14.34	-136.77	-23.15	-175.23	0.51
Jun 2011	OCF11	-22.48	-180.76	-25.66	-195.29	0.10
Jun 2011	OCF19	-14.44	-135.87	-22.48	-169.85	0.46
Jun 2011	OCF26	-18.61	-156.59	-23.37	-176.98	0.19
Jun 2011	OCF29	-14.32	-131.26	-20.74	-155.89	0.37
Jun 2011	OCF34	-15.54	-137.78	-21.33	-160.67	0.30
Jun 2011	OCF35	-16.98	-151.02	-24.08	-182.65	0.32
Jun 2011	OCF37	-14.21	-133.02	-21.65	-163.20	0.44
Jun 2011	OCF38	-17.34	-147.02	-21.96	-165.68	0.20
Jun 2011	OCF46	-15.91	-145.92	-24.03	-182.25	0.41
Jun 2011	OCF48	-19.73	-163.58	-24.07	-182.59	0.16
Jun 2011	OCF49	-13.52	-127.12	-20.37	-152.95	0.44
Jun 2011	OCF55	-23.43	-185.20	-25.68	-195.42	0.07
Jun 2011	OCF58	-15.02	-138.72	-22.62	-170.95	0.41
Sep 2011	OCF06	-10.14	-107.24	-17.12	-126.99	0.74
Sep 2011	OCF11	-14.93	-140.44	-23.61	-178.87	0.48
Sep 2011	OCF19	-11.94	-123.54	-21.88	-165.07	0.78
Sep 2011	OCF26	-16.70	-144.90	-22.16	-167.28	0.25
Sep 2011	OCF29	-12.26	-121.14	-19.95	-149.60	0.58
Sep 2011	OCF34	-13.11	-126.70	-20.92	-157.33	0.52
Sep 2011	OCF35	-13.41	-129.39	-21.57	-162.58	0.53
Sep 2011	OCF37	-11.86	-119.47	-19.90	-149.17	0.64
Sep 2011	OCF38	-14.40	-133.08	-21.35	-160.78	0.40
Sep 2011	OCF46	-11.88	-120.75	-20.50	-153.98	0.68
Sep 2011	OCF48	-19.99	-164.16	-23.88	-181.05	0.14
Sep 2011	OCF49	-11.19	-119.22	-21.28	-160.25	0.89
Sep 2011	OCF55	-20.83	-171.49	-25.09	-190.72	0.15
Sep 2011	OCF58	-13.38	-133.77	-24.00	-181.99	0.69

Appendix E

Limnology data

Table D1. Raw limnology data from monitoring lakes sampled in June 2010

Lake ID	Sample Date	pH	Cond (µS/cm)	Alkalinity (mg/L)	NO_3-NO_2 (mg/L)	Ammonia (mg/L)	SO_4^- (mg/L)	Cl^- (mg/L)	DOC (mg/L)	DIC (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)
OCF06	10-Jun-2010	8.03	338	137.00	0.010	0.174	36.70	1.72	14.30	32.80	44.10	15.2	4.57
OCF11	10-Jun-2010	7.27	48	18.20	0.014	0.090	0.73	0.27	17.10	4.70	5.60	1.84	1.55
OCF19	10-Jun-2010	8.07	287	135.00	0.007	0.076	14.20	0.79	13.00	32.00	40.50	10.9	4.84
OCF26	10-Jun-2010	7.15	38	13.80	0.006	0.028	0.16	0.16	17.60	3.60	5.27	1.56	0.62
OCF29	10-Jun-2010	8.07	196	97.70	0.008	0.051	2.75	0.52	6.90	23.50	27.10	7.78	0.82
OCF34	10-Jun-2010	8.04	208	96.40	0.009	0.111	7.55	1.04	9.70	23.60	29.60	6.78	3.64
OCF35	10-Jun-2010	7.91	144	62.60	0.012	0.071	7.38	0.36	16.00	14.40	19.50	6.03	2.1
OCF37													
OCF38	10-Jun-2010	7.74	119	49.40	0.008	0.032	7.93	0.57	5.40	11.60	17.90	3.41	1.35
OCF46	10-Jun-2010	8.19	327	153.00	0.009	0.089	17.40	1.25	23.00	36.20	49.50	12.4	3.13
OCF48	10-Jun-2010	8.15	205	105.00	0.046	0.138	1.12	0.38	6.60	24.90	23.40	6.88	1.98
OCF49	10-Jun-2010	8.15	272	131.00	0.009	0.082	11.00	0.81	12.40	31.70	39.60	10.9	2.09
OCF55	10-Jun-2010	6.96	44	18.20	0.009	0.067	0.23	0.22	24.80	3.60	5.83	2.1	1.2
OCF58	10-Jun-2010	7.90	164	80.80	0.010	0.098	0.28	1.02	18.60	18.80	20.60	7.84	2.51

Lake ID	Sample Date	NA^{2+} (mg/L)	SIO_2 (mg/L)	TN (mg/L)	TDP (µg/L)	TP (µg/L)	TSS (mg/L)	Chl-*a* (mg/L)	Water Temp (°C)	DO (mg/L)
OCF06	10-Jun-2010	2.83	0.32	1.31	16.10	51.20	11.64	8.94	19.42	12.11
OCF11	10-Jun-2010	1.18	0.51	0.81	31.90	58.00	3.86	4.05	19.56	10.14
OCF19	10-Jun-2010	2.11	0.35	0.78	10.60	24.70	4.20	1.91	18.23	10.14
OCF26	10-Jun-2010	0.39	0.94	0.51	13.90	24.10	1.71	1.75	17.34	9.63
OCF29	10-Jun-2010	1.37	0.21	0.44	5.40	15.90	3.43	2.18	16.41	10.22
OCF34	10-Jun-2010	0.94	0.36	0.67	11.30	29.30	3.90	3.01	15.63	11.1
OCF35	10-Jun-2010	0.82	0.09	0.81	11.00	27.30	1.00	0.73	16.92	10.47
OCF37										
OCF38	10-Jun-2010	0.64	0.26	0.22	4.40	38.10	30.80	0.64	13.54	10.86
OCF46	10-Jun-2010	2.11	0.17	0.95	15.10	36.70	4.12	1.94	17.14	10.46
OCF48	10-Jun-2010	9.92	0.8	0.78	17.90	56.40		6.21	19.77	14.02
OCF49	10-Jun-2010	1.81	0.63	0.27	6.70	24.50	3.70	2.78	16.54	11.63
OCF55	10-Jun-2010	0.35	1.85	0.34	15.30	30.70	2.93	4.52	15.74	9.22
OCF58	10-Jun-2010	1.42	1.21	0.40	15.10	26.60	2.70	1.72	15.89	11.25

Table D2. Raw limnology data from monitoring lakes sampled in August 2010

Lake ID	Sample Date	pH	Cond (µS/cm)	Alkalinity (mg/L)	NO_3-NO_2 (mg/L)	Ammonia (mg/L)	SO_4^- (mg/L)	Cl^- (mg/L)	DOC (mg/L)	DIC (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)
OCF06	25-Aug-2010	9.87	142	63.40	0.016	0.086	8.80	0.21	19.80	9.00	17.00	7.75	0.6
OCF11	25-Aug-2010	7.21	53	20.70	0.018	0.084	0.76	0.12	21.60	5.90	6.61	2.22	0.71
OCF19	25-Aug-2010	9.43	171	73.10	0.020	0.054	14.60	0.24	15.80	13.60	16.90	10.8	2.55
OCF26	25-Aug-2010	7.00	40	14.70	0.017	0.060	0.30	0.11	19.80	3.70	5.30	1.76	0.46
OCF29	25-Aug-2010	9.45	111	56.70	0.015	0.067	2.25	0.2	12.20	11.50	11.10	7.09	0.13
OCF34	25-Aug-2010	8.83	140	65.30	0.016	0.085	5.59	0.32	12.60	12.80	14.70	7.6	2.58
OCF35	25-Aug-2010	7.89	181	80.40	0.017	0.107	9.00	0.15	24.00	17.60	23.20	8.5	1.65
OCF37													
OCF38	25-Aug-2010	7.63	107	50.50	0.016	0.045	2.89	0.41	12.10	11.60	15.60	3.14	1
OCF46	25-Aug-2010	9.35	155	70.70	0.017	0.187	8.37	0.22	31.90	11.00	19.10	8.77	0.69
OCF48	25-Aug-2010	9.22	169	89.10	0.067	0.085	0.58	0.26	10.80	17.10	12.30	7.51	1.15
OCF49	25-Aug-2010	8.80	162	71.90	0.017	0.107	11.40	0.27	15.80	14.10	15.40	10.3	0.94
OCF55	25-Aug-2010	6.89	49	20.70	0.017	0.098	0.24	0.18	28.20	4.60	6.03	2.5	1.04
OCF58	21-Aug-2010	7.75	160	78.50	0.016	0.097	0.25	0.77	21.40	17.80	20.50	8.08	2.06

Lake ID	Sample Date	NA^{2+} (mg/L)	SIO_2 (mg/L)	TN (mg/L)	TDP (µg/L)	TP (µg/L)	TSS (mg/L)	Chl-*a* (mg/L)	Water Temp (°C)	DO (mg/L)
OCF06	10-Jun-2010	2.45	1.19	1.55	34.10	64.20	11.12	4.58	9.72	9.87
OCF11	10-Jun-2010	1.32	3.39	0.69	36.80	57.00	2.50	2.48	11.38	10.7
OCF19	10-Jun-2010	2.18	1.55	0.88	18.50	31.60	4.00	1.25	11.87	9.51
OCF26	10-Jun-2010	0.58	0.61	0.60	15.30	27.00	2.13	3.21	11.96	12.08
OCF29	10-Jun-2010	1.43	0.57	0.73	9.40	27.00	3.02	4.01	10.80	12.9
OCF34	10-Jun-2010	1.12	0.7	0.79	14.60	27.10	1.60	3.09	11.23	9.26
OCF35	10-Jun-2010	1.08	0.41	0.97	11.60	20.00	1.55	5.43	11.22	11.87
OCF37										
OCF38	10-Jun-2010	0.83	1.37	0.56	7.20	29.30	11.71	1.68	10.04	13.4
OCF46	10-Jun-2010	2.13	0.41	1.79	30.70	72.00	16.67		11.45	11.08
OCF48	10-Jun-2010	14.1	4.76	1.06	35.10	57.40	8.88		10.17	11.46
OCF49	10-Jun-2010	1.97	1.36	1.00	8.40	26.20	2.20	4.45	11.49	11.76
OCF55	10-Jun-2010	0.42	1.53	0.69	15.20	25.70	2.00	4.29	12.44	5.69
OCF58	10-Jun-2010	1.38	1.44	0.88	8.00	26.20	3.07	4.34	14.71	9.11

Table D3. Raw limnology data from monitoring lakes sampled in June 2011

Lake ID	Sample Date	pH	Cond (µS/cm)	Alkalinity (mg/L)	NO_3-NO_2 (mg/L)	Ammonia (mg/L)	SO_4^- (mg/L)	Cl^- (mg/L)	DOC (mg/L)	DIC (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)
OCF06	17-Jun-2011	8.12	459	123.00	0.008	0.054	109.00	1.87	11.80	29.10	47.40	17.8	6.67
OCF11	17-Jun-2011	6.87	44	16.50	0.008	0.107	0.81	0.43	17.70	4.20	5.15	1.53	2
OCF19	17-Jun-2011	7.90	261	124.00	0.007	0.125	11.20	0.88	12.50	29.40	36.30	9.72	4.87
OCF26	17-Jun-2011	6.99	39	16.00	0.007	0.035	0.26	0.36	16.80	3.40	5.59	1.57	0.73
OCF29	17-Jun-2011	7.94	184	92.80	0.007	0.056	2.77	0.54	6.50	21.90	25.80	7.11	0.86
OCF34	17-Jun-2011	7.87	209	96.40	0.007	0.096	8.22	1.14	9.50	22.40	29.80	7.07	3.9
OCF35	06-Jun-2011	7.37	110	45.80	0.012	0.140	5.06	0.45	15.60	10.50	14.60	4.3	2.2
OCF37	17-Jun-2011	7.94	205	98.00	0.007	0.085	7.61	0.64	11.70	21.80	29.50	7.49	2.04
OCF38	17-Jun-2011	7.78	122	51.80	0.008	0.040	6.79	0.6	6.90	11.80	18.40	3.36	1.4
OCF46	17-Jun-2011	7.89	268	124.00	0.007	0.116	13.80	1.23	17.50	29.10	41.10	8.33	3.32
OCF48	17-Jun-2011	8.07	249	127.00	0.006	0.111	2.46	0.86	6.20	29.30	32.30	7.25	2.62
OCF49	07-Jun-2011	7.96	240	119.00	0.007	0.108	5.33	0.81	10.70	28.80	33.40	9.83	1.86
OCF55	05-Jun-2011	6.57	48	16.80	0.008	0.197	2.09	0.58	19.60	5.60	5.88	1.94	1.98
OCF58	14-Jun-2011	7.79	157	77.50	0.007	0.076	0.22	1.02	19.60	17.90	20.60	7.46	2.25

Lake ID	Sample Date	NA^{2+} (mg/L)	SIO_2 (mg/L)	TN (mg/L)	TDP (µg/L)	TP (µg/L)	TSS (mg/L)	Chl-*a* (mg/L)	Water Temp (°C)	DO (mg/L)
OCF06	10-Jun-2010	2.88	0.14	0.85	13.40	21.50	1.66	0.95	15.80	0.54
OCF11	10-Jun-2010	0.96	0.21	0.76	37.00	56.70	5.00	7.96	15.70	11.40
OCF19	10-Jun-2010	2.08	0.35	0.76	12.50	31.10	3.60	3.68	15.49	3.34
OCF26	10-Jun-2010	0.46	1.16	0.53	17.00	30.60	2.92	3.62	14.24	2.99
OCF29	10-Jun-2010	1.34	0.39	0.45	12.90	17.70	4.32	1.98	14.76	10.34
OCF34	10-Jun-2010	1.04	0.49	0.69	11.50	27.90	3.18	3.33	14.50	10.99
OCF35	10-Jun-2010	0.66	0.59	0.79	15.50	33.50	2.18	6.22	12.60	8.06
OCF37		1.56	0.77	0.75	8.30	26.00	3.60	4.58	15.35	0.38
OCF38	10-Jun-2010	0.65	0.51	0.36	4.90	16.90	9.71	1.50	12.16	8.80
OCF46	10-Jun-2010	1.78	0.44	0.96	17.20	39.60	4.00	2.59	16.40	2.73
OCF48	10-Jun-2010	9.15	0.2	0.58	11.90	33.30	3.12	4.18	16.65	7.05
OCF49	10-Jun-2010	1.72	1.8	0.75	13.30	21.20	3.26		10.77	8.15
OCF55	10-Jun-2010	0.4	< 0.02	0.84	51.40	89.30	26.67		10.00	6.23
OCF58	10-Jun-2010	1.32	1.86	0.83	9.70	19.60	3.37	2.61	12.37	11.51

Table D4. Raw limnology data from monitoring lakes sampled in September 2011

Lake ID	Sample Date	pH	Cond (µS/cm)	Alkalinity (mg/L)	NO_3-NO_2 (mg/L)	Ammonia (mg/L)	SO_4^- (mg/L)	Cl^- (mg/L)	DOC (mg/L)	DIC (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	K^+ (mg/L)
OCF06	12-Sep-2011	9.13	363	67.00	0.077	0.014	113.00	0.95	16.20	12.00	40.90	18.5	2.02
OCF11	12-Sep-2011	7.15	42	14.00	0.005	0.055	1.70	0.07	15.20	3.60	4.83	1.81	0.39
OCF19	12-Sep-2011	9.20	159	72.90	0.006	0.107	9.03	0.41	15.60	13.40	15.10	9.77	2.85
OCF26	12-Sep-2011	7.05	37	14.00	0.005	0.058	0.18	0.08	16.80	3.40	4.92	1.56	0.39
OCF29	12-Sep-2011	8.12	136	66.60	0.005	0.078	3.95	0.22	8.80	14.50	14.70	7.65	0.19
OCF34	12-Sep-2011	7.95	167	74.70	0.011	0.109	8.53	0.6	13.20	16.50	18.50	8.32	3.08
OCF35	12-Sep-2011	7.79	188	82.20	0.019	0.108	10.50	0.27	20.80	18.30	23.60	8.41	2.32
OCF37	12-Sep-2011	7.93	142	61.50	0.016	0.141	8.20	0.17	15.40	12.80	15.30	7.68	0.39
OCF38	12-Sep-2011	7.97	203	90.20	0.024	0.039	12.50	0.69	8.00	20.10	30.20	5.84	2.02
OCF46	12-Sep-2011	9.37	166	63.50	0.035	0.054	18.80	0.12	23.80	10.10	19.60	8.47	0.77
OCF48	12-Sep-2011	7.99	270	142.00	0.158	0.061	0.93	0.9	5.20	31.10	24.50	11	2.46
OCF49	12-Sep-2011	8.41	181	76.90	0.018	0.059	14.50	0.33	13.10	15.80	18.10	10.3	0.93
OCF55	12-Sep-2011	6.92	55	22.00	0.007	0.130	1.20	0.52	17.70	5.30	6.51	2.29	1.84
OCF58	17-Aug-2011	8.11	153	76.50	0.009	0.087	0.22	0.56	21.60	15.00	19.30	7.91	1.57

Lake ID	Sample Date	NA^{2+} (mg/L)	SIO_2 (mg/L)	TN (mg/L)	TDP (µg/L)	TP (µg/L)	TSS (mg/L)	Chl-*a* (mg/L)	Water Temp (°C)	DO (mg/L)
OCF06	10-Jun-2010	4.59	1.54	1.57	18.30	70.10	36.58	6.51	9.68	
OCF11	10-Jun-2010	1.01	0.3	0.77	25.00	41.40	1.50	2.38	8.30	
OCF19	10-Jun-2010	2.41	1.02	1.08	18.10	34.10	4.14	5.05	8.02	
OCF26	10-Jun-2010	0.45	0.32	0.60	12.50	24.00	1.38	3.99	8.80	
OCF29	10-Jun-2010	1.44	0.29	0.62	7.90	24.60	3.17	3.72	8.85	
OCF34	10-Jun-2010	1.29	0.16	0.92	13.50	35.20	2.65	4.06	8.47	
OCF35	10-Jun-2010	1.12	0.21	1.05	10.90	24.50	2.52	5.25	8.82	
OCF37		1.54	0.7	1.20	9.50	58.70	7.17	9.66	8.23	
OCF38	10-Jun-2010	0.93	0.55	0.55	4.60	87.90	108.78	3.46	7.18	
OCF46	10-Jun-2010	2.2	0.18	1.37	19.70	34.60	6.67	2.36	10.07	
OCF48	10-Jun-2010	14.2	1.92	0.91	18.60	81.90	45.00	8.84	8.84	
OCF49	10-Jun-2010	1.97	0.16	0.87	8.30	15.40	2.00	2.00	8.65	
OCF55	10-Jun-2010	0.4	0.6	0.71	24.50	49.50	5.62	8.80	9.72	
OCF58	10-Jun-2010	1.27	1.35	0.89	9.00	22.50	3.36	4.17		

Appendix F

Paleolimnological data

Table E1. Sediment core chronology for Zelma Lake

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation ($g/cm^2/yr$)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
0.25	7.92	2.17	0.48	0.32	0.08	0.13	2008.53	
0.75	7.23			0.49	0.08	0.22	2005.24	
1.25	6.59	2.26	0.55	0.80	0.09	0.14	2002.20	
1.75	5.68			1.04	0.10	0.20	1999.02	
2.25	4.85	2.26	0.90	1.33	0.12	0.21	1996.46	
2.75	5.07			1.54	0.10	0.24	1994.13	
3.25	5.29	2.63	0.83	1.87	0.09	0.13	1991.08	
3.75	5.13			2.12	0.08	0.16	1987.49	
4.25	4.97	2.33	1.17	2.41	0.08	0.14	1983.93	
4.75	4.73			2.74	0.08	0.12	1979.69	
5.25	4.51	2.63	1.47	3.04	0.07	0.13	1975.27	
5.75	4.69			3.28	0.06	0.12	1970.99	
6.25	4.87	2.69	1.57	3.51	0.05	0.10	1966.26	
6.75	4.23			3.76	0.06	0.11	1961.27	
7.25	3.65	2.69	1.53	4.12	0.07	0.10	1956.15	
7.75	3.38			4.47	0.08	0.11	1950.99	
8.25	3.12	2.54	0.43	4.85	0.09	0.12	1946.32	
8.75	2.84			5.13	0.13	0.24	1943.02	
9.25	2.57	2.58	0.08	5.53	0.35	0.45	1941.35	
9.75	2.52			6.01	0.54	0.57	1940.33	

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
10.25	2.46	2.43	-0.05	6.27	1.28	2.45	1939.78	
10.75	2.67			6.81	0.19	0.18	1938.22	
11.25	2.89	2.46	-0.03	7.35	0.09	0.09	1933.63	
11.75	2.72			7.58	0.12	0.26	1929.51	
12.25	2.55	2.64	-0.06	7.86	0.27	0.48	1928.00	
12.75	2.51			8.29	0.38	0.45	1926.91	
13.25	2.47	2.67	-0.05	8.68	0.69	0.88	1926.06	
13.75	2.61			8.99	0.17	0.27	1924.82	
14.25	2.75	2.40	-0.01	9.56	0.09	0.08	1920.31	
14.75	2.75			9.74	0.07	0.19	1915.42	
15.25	2.75	2.56	-0.06	10.09	0.07	0.10	1911.32	
15.75	2.77			10.35	0.05	0.10	1905.90	
16.25	2.79	2.62	-0.01	10.62	0.04	0.08	1899.67	
16.75	2.74			10.86	0.04	0.08	1892.62	
17.25	2.69			11.11	0.04	0.08	1885.42	
17.75	2.65			11.36	0.04	0.07	1877.82	
18.25	2.60	2.26	-0.02	11.63				1872.69
18.75	2.60			11.88				1868.65
19.25	2.60			12.13				1863.12
19.75	2.60			12.37				1857.73
20.25	2.60	2.38	-0.02	12.63				1852.24
20.75				12.90				1846.37
21.25				13.21				1839.90
21.75				13.48				1833.52
22.25				13.81				1826.90

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
22.75				14.06				1820.47
23.25				14.34				1814.61
23.75				14.62				1808.42
24.25				14.94				1801.81
24.75				15.16				1795.86
25.25				15.44				1790.30
25.75				15.67				1784.63
26.25				16.10				1777.36
26.75				16.32				1770.18
27.25				16.58				1764.92
27.75				16.84				1759.18
28.25	2.45	2.31	-0.02	17.12				1753.23
28.75				17.41				1746.95
29.25				17.71				1740.47
29.75				18.01				1733.87
30.25				18.34				1726.81
30.75				18.67				1719.49
31.25				18.97				1712.63
31.75				19.28				1705.89
32.25				19.61				1698.82
32.75				19.90				1692.02
33.25				20.23				1685.14
33.75				20.56				1677.78

Table E2. Loss-on-ignition data from Zelma Lake

Mid-point depth (cm)	CRS Date	Moisture content (%)	Organic matter (%)	Mineral matter (%)	$CaCO_3$ (%)
0.25	2008.53	62.56	18.46	79.00	5.77
0.75	2005.24	56.93	16.61	81.09	5.23
1.25	2002.20	57.12	15.91	81.94	4.89
1.75	1999.02	57.93	14.64	82.41	6.70
2.25	1996.46	56.16	14.43	83.36	5.04
2.75	1994.13	53.55	14.29	83.34	5.39
3.25	1991.08	52.79	14.29	83.48	5.06
3.75	1987.49	55.25	15.33	82.59	4.73
4.25	1983.93	52.36	14.23	83.50	5.15
4.75	1979.69	54.28	14.34	83.67	4.52
5.25	1975.27	56.49	13.74	83.45	6.39
5.75	1970.99	51.56	13.29	84.20	5.70
6.25	1966.26	59.85	15.14	82.06	6.37
6.75	1961.27	57.11	15.64	82.16	5.01
7.25	1956.15	54.52	14.62	83.32	4.69
7.75	1950.99	50.17	12.42	84.98	5.92
8.25	1946.32	46.00	12.97	84.96	4.69
8.75	1943.02	44.91	11.64	86.07	5.20
9.25	1941.35	43.60	10.97	86.81	5.05
9.75	1940.33	43.14	10.88	87.03	4.75
10.25	1939.78	48.35	10.88	86.61	5.70
10.75	1938.22	47.46	11.71	85.75	5.76
11.25	1933.63	47.55	11.75	85.72	5.74
11.75	1929.51	50.30	12.63	84.73	5.99
12.25	1928.00	48.32	11.96	85.80	5.09
12.75	1926.91	46.42	11.96	85.46	5.87
13.25	1926.06	47.74	12.42	84.95	5.97
13.75	1924.82	47.38	13.27	84.25	5.65
14.25	1920.31	46.75	12.91	84.60	5.66
14.75	1915.42	49.48	13.48	84.11	5.46
15.25	1911.32	52.63	14.43	83.05	5.72
15.75	1905.90	53.49	15.24	82.51	5.12
16.25	1899.67	57.22	19.50	78.05	5.58
16.75	1892.62	61.51	20.50	76.98	5.73
17.25	1885.42	60.63	19.76	77.48	6.26
17.75	1877.82	58.46	19.72	77.80	5.63
18.25	1872.69	59.67	19.61	77.69	6.16
18.75	1868.65	61.25	19.59	77.33	7.02
19.25	1863.12	58.97	21.25	76.42	5.30
19.75	1857.73	61.42	20.16	77.05	6.34
20.25	1852.24	61.41	20.72	76.65	5.98
20.75	1846.37	59.88	21.07	76.33	5.91
21.25	1839.90	47.94	19.81	77.22	6.76
21.75	1833.52	58.15	20.90	76.64	5.60
22.25	1826.90	56.30	17.88	79.08	6.91
22.75	1820.47	50.98	18.03	79.11	6.49
23.25	1814.61	53.56	18.81	78.44	6.25

Mid-point depth (cm)	CRS Date	Moisture content (%)	Organic matter (%)	Mineral matter (%)	$CaCO_3$ (%)
23.75	1808.42	54.04	19.50	78.31	4.98
24.25	1801.81	53.76	18.84	78.44	6.19
24.75	1795.86	54.62	18.86	78.05	7.03
25.25	1790.30	53.95	18.62	78.57	6.40
25.75	1784.63	54.55	19.14	78.36	5.67
26.25	1777.36	54.43	19.57	77.85	5.87
26.75	1770.18	55.54	20.01	77.32	6.08
27.25	1764.92	52.99	19.38	77.97	6.04
27.75	1759.18	52.47	19.10	78.05	6.48
28.25	1753.23	51.27	17.55	79.70	6.25
28.75	1746.95	51.11	17.00	79.74	7.41
29.25	1740.47	48.04	18.68	78.80	5.73
29.75	1733.87	48.81	17.76	79.67	5.84
30.25	1726.81	45.69	16.42	81.46	4.83
30.75	1719.49	47.09	16.67	80.33	6.82
31.25	1712.63	47.74	17.15	80.22	5.97
31.75	1705.89	48.02	17.13	80.31	5.81
32.25	1698.82	48.93	16.74	76.28	15.86
32.75	1692.02	48.18	18.53	78.49	6.79
33.25	1685.14	18.67	77.81	3.52	8.01
33.75	1677.78	16.29	80.48	3.23	7.35

Table E3. Geochemical analysis of the Zelma Lake sediment core

Mid-point depth (cm)	CRS Date	Carbon (%)	Nitrogen (%)	C/N (%)	C/N (Atomic)	$\delta^{13}C$(‰ VPDB)	$\delta^{15}N$ (‰ AIR)
0.25	2008.53	8.57	0.81	10.56	12.33	-23.30	3.21
0.75	2005.24	8.86	0.84	10.56	12.32	-23.08	2.92
1.25	2002.20	8.63	0.80	10.83	12.63	-23.10	3.23
1.75	1999.02	8.41	0.76	11.09	12.95	-23.14	3.20
2.25	1996.46	8.20	0.74	11.08	12.93	-23.32	2.94
2.75	1994.13	7.88	0.71	11.14	13.00	-23.44	3.09
3.25	1991.08	7.77	0.66	11.73	13.68	-23.49	2.84
3.75	1987.49	7.64	0.65	11.80	13.77	-23.75	2.93
4.25	1983.93	7.80	0.65	12.08	14.10	-23.39	2.84
4.75	1979.69	7.17	0.61	11.68	13.63	-24.06	2.84
5.25	1975.27	7.04	0.61	11.54	13.47	-24.50	3.18
5.75	1970.99	7.98	0.67	11.89	13.88	-24.49	3.33
6.25	1966.26	8.77	0.70	12.45	14.53	-24.09	3.18
6.75	1961.27	8.26	0.59	14.07	16.42	-23.80	2.29
7.25	1956.15	7.47	0.57	13.00	15.17	-24.07	2.90
7.75	1950.99	6.97	0.55	12.66	14.77	-24.16	2.87
8.25	1946.32	6.91	0.55	12.48	14.56	-24.01	2.77
8.75	1943.02	5.79	0.47	12.41	14.49	-24.62	2.45
9.25	1941.35	5.56	0.44	12.57	14.66	-24.85	3.03
9.75	1940.33	5.49	0.44	12.60	14.71	-25.04	2.75
10.25	1939.78	5.98	0.48	12.46	14.54	-24.71	3.04
10.75	1938.22	6.05	0.49	12.34	14.40	-24.47	3.11
11.25	1933.63	6.49	0.53	12.24	14.29	-24.29	2.87
11.75	1929.51	6.60	0.56	11.87	13.85	-23.86	3.07
12.25	1928.00	6.22	0.53	11.71	13.67	-24.43	3.08
12.75	1926.91	6.24	0.53	11.77	13.74	-24.52	3.03
13.25	1926.06	6.59	0.58	11.43	13.34	-24.13	3.08
13.75	1924.82	6.92	0.58	11.93	13.93	-23.99	2.88
14.25	1920.31	7.11	0.62	11.51	13.43	-23.90	2.83
14.75	1915.42	7.57	0.63	11.93	13.92	-23.56	2.84
15.25	1911.32	8.10	0.72	11.25	13.13	-22.81	2.77
15.75	1905.90	9.90	0.91	10.90	12.72	-21.39	2.64
16.25	1899.67	11.27	1.07	10.56	12.33	-20.60	2.27
16.75	1892.62	11.62	1.12	10.35	12.08	-20.09	2.22
17.25	1885.42	11.41	1.13	10.11	11.80	-19.89	2.40
17.75	1877.82	11.55	1.10	10.49	12.24	-19.81	2.17
18.25	1872.69	11.71	1.08	10.87	12.69	-19.69	2.49
18.75	1868.65	11.77	1.10	10.72	12.51	-19.83	2.51
19.25	1863.12	11.88	1.08	10.96	12.79	-19.71	2.29
19.75	1857.73	12.43	1.11	11.19	13.06	-19.65	2.18
20.25	1852.24	12.11	1.09	11.11	12.97	-19.59	2.17
20.75	1846.37	11.73	1.08	10.90	12.72	-19.64	2.56
21.25	1839.90	11.30	1.02	11.11	12.97	-19.81	2.31
21.75	1833.52	11.92	1.08	11.06	12.91	-19.65	2.40
22.25	1826.90	11.14	1.00	11.12	12.97	-19.80	2.47

Mid-point depth (cm)	CRS Date	Carbon (%)	Nitrogen (%)	C/N (%)	C/N (Atomic)	$\delta^{13}C$(‰ VPDB)	$\delta^{15}N$ (‰ AIR)
22.75	1820.47	10.61	0.98	10.86	12.67	-20.11	2.60
23.25	1814.61	10.39	0.91	11.38	13.28	-20.03	2.28
23.75	1808.42	10.63	0.90	11.85	13.83	-20.03	2.01
24.25	1801.81	11.28	1.00	11.27	13.15	-19.90	2.07
24.75	1795.86	11.00	0.98	11.26	13.14	-19.85	2.14
25.25	1790.30	11.43	1.04	10.99	12.83	-19.78	2.46
25.75	1784.63	10.86	1.00	10.85	12.66	-19.93	2.49
26.25	1777.36	11.31	1.02	11.14	13.00	-19.80	2.23
26.75	1770.18	11.10	1.01	10.96	12.79	-19.70	2.33
27.25	1764.92	11.47	1.07	10.69	12.48	-19.62	2.37
27.75	1759.18	11.15	0.99	11.24	13.12	-19.70	2.25
28.25	1753.23	10.40	0.96	10.84	12.65	-19.94	2.36
28.75	1746.95	10.95	0.99	11.04	12.88	-19.95	2.42
29.25	1740.47	10.21	0.90	11.38	13.28	-20.01	1.98
29.75	1733.87	10.05	0.91	11.04	12.88	-20.38	2.58
30.25	1726.81	9.79	0.90	10.88	12.69	-20.23	2.33
30.75	1719.49	9.74	0.89	10.97	12.80	-20.29	2.62
31.25	1712.63	9.59	0.87	10.97	12.81	-20.42	2.66
31.75	1705.89	9.53	0.83	11.52	13.44	-20.57	2.51
32.25	1698.82	9.90	0.87	11.40	13.31	-20.65	2.74
32.75	1692.02	11.05	0.93	11.83	13.80	-20.68	2.60
33.25	1685.14	11.12	0.93	11.93	13.92	-20.52	2.47
33.75	1677.78	10.68	0.93	11.46	13.37	-20.51	2.48

Table E4. Fossil pigment data from the Zelma Lake sediment core identified using high phase liquid chromatography (HPLC). Concentrations are in (nMol g^{-1})

Mid-point depth (cm)	Fucoxanthin	Sediment B	Sediment C	Sudan II	Diatoxanthin	Lutein	Canthaxanthian	Chl_b	Okenone	Chl-*a*	Chl-*a'*	Echinenone	Pheophytin *b*	Pheophytin *a*	α-Carotene	β-Carotene
0.25	0.15	0.00	0.00	2591.73	128.78	409.69	50.01	173.32	15.00	429.28	28.52	10.43	211.38	181.61	7.59	11.68
1.25	118.92	3.89	0.00	1626.64	53.94	486.34	100.87	203.25	17.06	536.24	38.29	11.83	198.35	214.81	7.04	0.00
2.25	45.01	7.17	0.00	2157.75	0.00	324.46	55.71	172.63	0.00	290.25	40.21	0.00	270.96	345.08	0.00	26.27
3.25	56.07	10.20	0.00	1680.46	0.00	317.24	43.50	248.87	0.00	523.20	84.41	0.00	218.63	293.68	0.00	11.69
4.25	37.50	5.36	0.00	1724.82	0.00	283.72	9.10	199.03	0.00	394.67	69.41	0.00	187.41	308.95	0.00	5.09
5.25	25.19	8.60	0.00	1730.07	0.00	152.06	12.13	182.97	0.00	366.73	67.03	0.00	382.99	341.99	0.00	0.00
6.25	17.65	8.23	0.00	1700.95	0.00	98.55	35.48	102.19	0.00	159.62	18.58	0.00	197.04	230.84	0.00	0.00
7.25	11.31	8.47	0.00	1663.96	0.00	150.33	0.00	47.55	0.00	101.25	14.37	0.00	128.38	202.67	0.00	0.00
8.25	15.73	14.11	0.00	1764.39	0.00	120.19	19.66	56.61	0.00	109.60	42.21	0.00	209.49	221.88	0.00	0.00
9.25	14.50	13.65	0.00	1645.77	0.00	45.34	9.17	0.00	0.00	96.80	0.00	0.00	109.82	204.38	0.00	0.00
10.25	11.90	8.90	0.00	2052.44	0.00	0.00	0.00	0.00	0.00	69.43	5.02	0.00	110.77	167.06	0.00	0.00
11.25	0.00	15.10	0.00	1504.59	0.00	0.00	0.00	0.00	0.00	98.87	34.68	0.00	230.54	211.45	0.00	0.00
12.25	0.00	0.00	5.69	1550.72	0.00	0.00	0.00	0.00	0.00	55.08	0.00	0.00	191.25	129.94	0.00	0.00
13.25	0.00	14.20	0.00	1584.71	0.00	0.00	0.00	0.00	0.00	52.15	16.02	0.00	138.05	207.61	0.00	0.00
14.25	15.79	10.97	0.00	1609.60	0.00	75.02	12.12	0.00	0.00	103.05	18.44	0.00	168.29	253.82	1.34	0.00
15.25	0.00	0.00	3.85	1779.43	0.00	72.39	16.87	0.00	0.00	77.10	31.49	0.00	162.45	217.99	0.00	0.00
16.25	2.67	4.77	0.00	1985.74	0.00	77.55	10.73	0.00	0.00	32.79	9.96	0.00	91.76	190.05	0.00	0.00
17.25	0.00	6.25	0.00	2281.35	0.00	119.62	1.81	0.00	0.00	38.49	7.88	0.00	89.46	186.22	0.00	0.00
18.25	5.01	3.66	0.00	2456.99	0.00	185.93	19.60	0.00	0.00	47.17	11.97	0.00	137.57	203.42	0.00	0.00
19.25	4.69	6.38	0.00	2462.62	0.00	156.50	0.00	0.00	0.00	40.72	10.57	2.84	158.86	183.63	0.00	0.00
20.25	0.00	0.00	0.00	3010.97	0.00	170.66	0.00	0.00	0.00	37.35	8.37	0.00	79.66	195.22	0.00	0.00
21.25	0.00	5.96	0.00	2766.93	0.00	189.03	0.00	0.00	0.00	31.26	6.73	0.00	74.59	181.82	0.00	0.00
22.25	0.00	0.00	0.00	2373.61	0.00	222.34	0.00	0.00	0.00	51.04	9.95	0.00	119.11	260.31	0.00	0.00
23.25	0.00	0.00	2.81	1786.36	0.00	224.50	28.44	0.00	0.00	69.72	23.94	9.57	224.00	299.96	0.00	2.17
24.25	0.00	0.00	0.00	2797.87	0.00	208.13	0.00	0.00	0.00	40.10	8.58	0.00	95.24	228.04	0.00	0.00
25.25	0.00	0.00	0.00	2458.41	0.00	191.67	0.00	0.00	0.00	42.83	8.96	0.00	105.98	253.33	0.00	0.00
26.25	0.00	0.00	0.00	1491.72	0.00	0.00	0.00	0.00	0.00	43.64	0.00	0.00	182.68	388.80	0.00	0.00
27.25	0.00	0.00	0.00	1380.32	0.00	186.36	0.00	0.00	0.00	43.45	0.00	0.00	423.76	397.50	0.00	1.92

Mid-point depth (cm)	Fucoxanthin	Sediment B	Sediment C	Sudan II	Diatoxanthin	Lutein	Canthaxanthian	Chl_b	Okenone	Chl-*a*	Chl-*a'*	Echinenone	Pheophytin *b*	Pheophytin *a*	α-Carotene	β-Carotene
28.25	0.00	0.00	0.00	2090.55	0.00	230.91	9.02	0.00	0.00	62.21	23.83	13.85	221.66	284.79	0.00	0.00
29.25	0.00	0.00	0.00	2201.26	0.00	205.20	0.00	0.00	0.00	48.16	10.72	0.00	159.15	276.61	5.95	0.00
30.25	0.00	0.00	11.49	2170.33	0.00	300.93	2.04	0.00	0.00	85.14	28.02	0.00	281.44	348.75	0.00	5.56
31.25	0.00	0.00	0.00	2632.87	0.00	252.55	8.25	0.00	0.00	56.16	16.64	13.57	162.31	157.27	0.00	0.00
32.25	10.54	9.50	0.00	1941.92	0.00	375.23	12.65	0.00	0.00	73.20	20.88	22.44	216.64	205.83	0.00	4.46
33.25	38.88	0.00	0.00	1494.36	0.00	346.89	27.29	156.71	0.00	319.07	104.87	0.00	256.10	304.31	0.00	9.60

Table E5. Sediment core chronology for OCF11

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation ($g/cm^2/yr$)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
0.25	8.75	2.57	0.43	0.11	0.03	0.13	2008.68	
0.75	7.35	2.78	0.60	0.20	0.03	0.17	2004.50	
1.25	6.91			0.37	0.03	0.09	2001.33	
1.75	6.50	2.61	0.50	0.60	0.03	0.06	1995.36	
2.25	5.44			0.85	0.03	0.06	1985.97	
2.75	4.51	2.64	0.52	1.09	0.04	0.06	1975.91	
3.25	3.67			1.35	0.08	0.08	1966.80	
3.75	2.94	2.47	0.52	1.64	0.04	0.13	1959.46	
4.25	3.22			1.96	0.02	0.07	1955.43	
4.75	3.52	2.42	0.50	2.21	0.02	0.05	1947.03	
5.25	3.30			2.55	0.01	0.03	1934.13	
5.75	3.08	2.63	0.36	2.87	0.01	0.02		1924.67
6.25	2.68			3.16		0.02		1915.96
6.75	2.32	2.37	0.33	3.46				1906.83
7.25	2.40			3.79				1896.82
7.75	2.48	2.33	0.37	4.09				1887.87
8.25	2.47			4.40				1878.55
8.75	2.47			4.73				1868.35
9.25	2.47			5.08				1857.93
9.75	2.47	2.47		5.43				1847.30
10.25				5.77				1837.05
10.75				6.14				1825.61
11.25				6.47				1815.78
11.75				6.81				1805.33
12.25				7.13				1795.66
12.75				7.49				1784.96

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
13.25				7.86				1773.80
13.75				8.23				1762.53
14.25				8.61				1751.10
14.75				8.95				1740.80
15.25				9.36				1728.26
15.75				9.71				1717.59
16.25				10.11				1705.69
16.75				10.45				1695.35
17.25				10.81				1684.30
17.75				11.17				1673.37
18.25				11.55				1661.86
18.75				11.89				1651.61
19.25				12.32				1638.63
19.75				12.69				1627.47
20.25				13.00				1618.03
20.75				13.37				1606.90
21.25				13.63				1599.12
21.75				13.96				1589.12
22.25				14.34				1577.56
22.75				14.62				1568.97
23.25				14.89				1560.72
23.75				15.24				1550.35
24.25				15.50				1542.49
24.75				15.79				1533.56
25.25				16.09				1524.57
25.75				16.36				1516.45
26.25				16.62				1508.34
26.75				16.87				1500.95

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation ($g/cm^2/yr$)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
27.25				17.14				1492.62

Table E6. Sediment core chronology for OCF29

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
0.25	5.20	1.95	0.63	0.15	0.05	0.17	2008.69	
0.75	4.70	1.63	0.75	0.26	0.05	0.24	2005.56	
1.25	4.74	1.85	0.74	0.42	0.05	0.14	2003.38	
1.75	4.76	1.61	0.83	0.62	0.04	0.11	1999.71	
2.25	4.31	1.99	0.93	0.78	0.04	0.14	1994.72	
2.75	4.33	1.98	1.10	0.98	0.04	0.09	1990.96	
3.25	4.17	1.87	1.39	1.18	0.03	0.09	1985.09	
3.75	3.86	1.76	1.37	1.39	0.03	0.08	1978.73	
4.25	3.20	1.89	1.40	1.62	0.04	0.09	1971.73	
4.75	3.92	2.11	1.59	1.86	0.02	0.04	1965.64	
5.25	2.94	1.74	1.11	2.12	0.03	0.06	1951.89	
5.75	3.03	1.66	0.83	2.35	0.02	0.04	1941.46	
6.25	2.96	2.03	0.31	2.63	0.01	0.02		1934.43
6.75	2.46	2.08	0.20	2.89	0.01	0.02		1924.81
7.25	2.08	1.98	0.09	3.17				1915.00
7.75	2.13	2.06		3.48				1903.70
8.25	2.18	2.13	0.04	3.81				1891.64
8.75	2.18	2.06		4.14				1879.87
9.25	2.18	2.00	0.09	4.45				1868.61
9.75	2.09	1.97		4.77				1857.14
10.25	2.01	1.94	0.01	5.08				1845.74
10.75	2.14	1.92		5.38				1835.10
11.25	2.28	1.90	-0.01	5.67				1824.71
11.75	1.92	1.87		5.97				1813.74
12.25	1.55	1.83	-0.05	6.34				1800.54
12.75	1.59	1.86		6.68				1788.07

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation ($g/cm^2/yr$)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
13.25	1.64	1.89		6.97				1777.61
13.75	1.68	1.92		7.32				1764.89
14.25	1.72	1.95		7.61				1754.59
14.75	1.76	1.97		7.94				1742.55
15.25	1.80	2.00		8.27				1730.77
15.75	1.84	2.03		8.61				1718.59
16.25	1.88	2.06	-0.02	8.93				1706.80
16.75	1.89	1.99		9.27				1694.58
17.25	1.90	1.92		9.59				1683.00
17.75	1.88	2.06		9.94				1670.56
18.25	1.92	1.78	-0.01	10.27				1658.55
18.75	1.94	2.05		10.61				1646.23
19.25	1.88	2.06		10.92				1635.06
19.75	1.99	2.04		11.18				1625.61
20.25	2.11	2.02	-0.03	11.47				1615.02
20.75	2.11	2.02		11.74				1605.59
21.25	2.11	2.02		12.04				1594.44
21.75	2.11	2.02		12.31				1584.86
22.25				12.59				1574.81
22.75				12.91				1563.23
23.25				13.23				1551.54
23.75				13.55				1539.99
24.25				13.87				1528.42
24.75				14.19				1516.85
25.25				14.52				1505.15
25.75				14.81				1494.71
26.25				15.08				1484.83
26.75				15.34				1475.37

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
27.25				15.61				1465.89
27.75				15.91				1454.81
28.25				16.24				1442.87
28.75				16.51				1433.27
29.25				16.80				1422.64
29.75				17.10				1411.85
30.25		2.24	-0.07	17.37				1402.26
30.75				17.64				1392.38
31.25				17.94				1381.47
31.75				18.20				1372.11
32.25				18.45				1363.21
32.75				18.78				1351.36
33.25				19.01				1342.89
33.75				19.36				1330.35
34.25				19.65				1319.98
34.75				20.01				1306.88
35.25				20.41				1292.41
35.75				20.76				1279.65
36.25				21.18				1264.66
36.75				21.59				1249.91
37.25				21.93				1237.56
37.75				22.27				1225.16
38.25				22.64				1212.12

Table E7. Sediment core chronology for OCF35

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
0.25	7.42	2.17	0.82	0.09	0.06	0.37	2010.39	
0.75	6.23			0.16	0.08	0.54	2009.69	
1.25	5.17	2.20	0.92	0.31	0.10	0.33	2008.88	
1.75	4.73			0.50	0.12	0.30	2007.64	
2.25	4.32	2.00	0.88	0.67	0.13	0.41	2006.03	
2.75	4.35			0.83	0.12	0.36	2004.57	
3.25	4.39	2.23	0.83	1.00	0.11	0.33	2003.25	
3.75	4.34			1.19	0.11	0.30	2001.78	
4.25	4.30	1.94	0.68	1.37	0.10	0.29	2000.15	
4.75	4.01			1.59	0.11	0.26	1998.39	
5.25	3.74	2.09	0.76	1.77	0.12	0.33	1996.50	
5.75	3.69			2.00	0.12	0.26	1994.73	
6.25	3.63	2.10	0.70	2.19	0.12	0.32	1992.98	
6.75	3.51			2.41	0.13	0.29	1991.20	
7.25	3.39	2.22	0.70	2.63	0.14	0.31	1989.52	
7.75	3.22			2.82	0.15	0.40	1987.82	
8.25	3.06	2.16	0.60	3.06	0.18	0.39	1986.37	
8.75	3.01			3.29	0.20	0.42	1985.08	
9.25	2.96	2.38	0.58	3.51	0.21	0.47	1983.82	
9.75	3.38			3.75	0.13	0.27	1982.67	
10.25	3.85	2.37	0.58	3.99	0.08	0.17	1981.16	
10.75	3.62			4.22	0.09	0.19	1978.68	
11.25	3.40	2.44	0.59	4.46	0.09	0.20	1975.84	
11.75	3.02			4.71	0.12	0.24	1973.16	
12.25	2.66	2.05	0.57	4.98	0.19	0.36	1970.77	
12.75	2.80			5.24	0.14	0.27	1969.01	

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation (g/cm^2/yr)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
13.25	2.94	2.19	0.42	5.49	0.11	0.21	1967.35	
13.75	2.79			5.75	0.13	0.25	1965.13	
14.25	2.65	2.08	0.42	6.02	0.18	0.34	1962.83	
14.75	2.66			6.30	0.18	0.31	1961.03	
15.25	2.68	2.25	0.36	6.56	0.18	0.33	1959.44	
15.75	2.88			6.86	0.11	0.18	1957.85	
16.25	3.08	2.26	0.18	7.14	0.07	0.12	1955.62	
16.75	2.68			7.42	0.11	0.20	1952.02	
17.25	2.31	2.07	-0.02	7.69	0.40	0.76	1948.57	
17.75	2.42			7.95	0.18	0.34	1946.93	
18.25	2.53	2.15	0.03	8.20	0.12	0.25	1945.84	
18.75	2.35			8.44	0.24	0.51	1944.03	
19.25	2.17	2.27	0.01	8.66	1.20	2.74	1942.49	
19.75	2.48			8.91	0.10	0.21	1941.90	
20.25	2.81	1.92	-0.04	9.13	0.05	0.11	1940.56	
20.75	2.72			9.37	0.05	0.10	1936.84	
21.25	2.63	2.08	-0.01	9.59	0.04	0.10	1931.48	
21.75	2.54			9.82	0.05	0.10	1925.76	
22.25	2.45	2.15	-0.02	10.01	0.05	0.13		1921.12
22.75	2.39			10.17	0.05	0.17		1918.57
23.25	2.32	2.04	-0.02	10.42	0.06	0.13		1916.60
23.75	2.26			10.68				1914.13
24.25	2.20	2.11	-0.02	10.86				1912.00
24.75	2.24			11.10				1909.94
25.25	2.27			11.29				1907.81
25.75	2.31			11.48				1905.99
26.25	2.34	2.03	-0.01	11.70				1904.00
26.75	2.32			11.92				1901.87

Mid-point depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	Cumulative dry mass (g/cm^2)	Dry mass sedimentation ($g/cm^2/yr$)	Depth based sedimentation (cm/yr)	CRS Date	Extrapolated Date
27.25	2.31			12.13				1899.82
27.75	2.29			12.34				1897.78
28.25	2.27	2.17	-0.05	12.53				1895.83
28.75	2.20			12.78				1893.67
29.25	2.13	1.98	-0.03	12.98				1891.47
29.75	2.18			13.25				1889.21
30.25	2.23	2.00	-0.04	13.53				1886.54

Table E9. Physical and geochemical analysis from OCF11, 29, and 35

OCF29				OCF11				OCF35			
CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)
2008.69	21.97	9.67	-20.65	2008.68	23.71	12.78	-28.00	2010.39	33.57	13.86	-25.94
2005.56	20.45	10.00	-20.74	2004.50	23.52	10.25	-27.63	2008.88	24.15	12.93	-25.85
2003.38	20.73	10.01	-20.81	2001.33	19.84	9.37	-27.49	2006.03	24.32	13.16	-25.67
1999.71	20.38	9.60	-21.11	1995.36	17.86	8.86	-27.40	2003.25	22.88	12.81	-25.63
1994.72	20.21	9.27	-20.84	1985.97	15.63	8.07	-27.32	2000.15	25.66	11.97	-25.54
1990.96	19.21	9.04	-20.93	1975.91	15.94	7.56	-27.45	1996.50	21.19	11.38	-25.59
1985.09	18.38	8.46	-21.03	1966.80	16.58	7.70	-27.34	1992.98	22.62	9.85	-25.85
1978.73	19.33	8.40	-21.05	1959.46	16.10	7.53	-27.36	1989.52	20.91	11.21	-25.49
1971.73	17.43	7.60	-21.27	1955.43	13.42	7.60	-27.31	1986.37	19.94	10.38	-25.59
1965.64	18.83	8.13	-21.35	1947.03	16.48	7.49	-27.23	1983.82	20.13	10.59	-25.58
1951.89	16.40	8.19	-21.30	1934.13	15.16	7.48	-27.24	1981.16	19.95	10.34	-25.66
1941.46	16.75	8.00	-21.74	1924.67	14.31	7.06	-27.47	1975.84	20.83	10.77	-25.72
1934.43	17.07	7.81	-21.47	1915.96	14.71	6.92	-27.44	1970.77	18.72	10.68	-25.69
1924.81	17.58	7.89	-21.76	1906.83	14.75	6.99	-27.44	1967.35	19.05	10.12	-25.88
1915.00	17.08	8.15	-21.71	1896.82	15.66	7.06	-27.43	1962.83	19.15	10.03	-25.79
1903.70	16.54	7.91	-21.53	1887.87	15.10	7.34	-27.30	1959.44	18.57	9.52	-25.90
1891.64	17.02	8.22	-21.47	1878.55	14.78	7.37	-27.20	1955.62	18.88	9.72	-25.71
1879.87	17.56	9.12	-21.92	1868.35	15.20	7.33	-27.12	1948.57	22.42	10.86	-24.94
1868.61	19.09	8.80	-21.38	1857.93	14.82	7.13	-27.23	1945.84	25.30	11.71	-24.67
1857.14	17.49	9.18	-21.55	1847.30	14.60	7.02	-27.24	1942.49	25.68	13.54	-24.08
1845.74	18.73	9.24	-21.15	1837.05	14.89	7.15	-27.25	1940.56	25.99	14.16	-23.42
1835.10	18.48	9.32	-21.53	1825.61	15.40	7.19	-27.20	1931.48	25.79	14.15	-23.74
1824.71	19.16	9.50	-21.14	1815.78	14.72	7.22	-27.11	1921.12	26.51	13.22	-23.41
1813.74	19.27	9.57	-21.03	1805.33	15.54	7.59	-26.93	1916.60	28.44	15.23	-23.54
1800.54	17.36	9.43	-21.21	1795.66	15.63	7.49	-26.91	1912.00	25.50	14.98	-23.40
1788.07	18.30	9.62	-21.35	1784.96	15.39	7.62	-26.87	1907.82	26.28	14.58	-23.55
1777.61	20.53	9.63	-21.58	1773.80	15.88	7.58	-26.82	1904.00	26.20	14.19	-23.56
1764.89	18.67	9.63	-21.41	1762.53	15.16	7.28	-26.85	1899.82	26.66	14.36	-23.56
1754.59	19.27	9.29	-21.55	1751.10	15.78	8.14	-26.65	1895.83	26.14	14.01	-23.53
1742.55	18.90	9.67	-21.33	1740.80	15.33	8.42	-26.78	1891.47	25.87	13.44	-23.68
1730.77	18.78	9.39	-21.56	1728.26	16.77	8.33	-27.07	1886.54	26.27	14.55	-23.64
1718.59	19.51	9.39	-21.37	1717.59	15.63	8.37	-27.15				

OCF29				OCF11				OCF35			
CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)
1706.80	19.10	9.71	-21.56	1705.69	16.58	8.28	-27.22				
1694.58	18.36	9.32	-21.47	1695.35	15.28	8.33	-27.28				
1683.00	18.15	9.36	-21.67	1684.30	15.97	8.07	-27.50				
1670.56	19.01	9.54	-21.68	1673.37	17.03	8.04	-28.12				
1658.55	19.79	8.75	-21.81	1661.86	15.07	8.12	-28.12				
1646.23	18.81	10.11	-21.83	1651.61	16.34	8.07	-28.24				
1635.06	20.98	10.88	-21.44	1638.63	15.89	8.49	-28.11				
1625.61	21.92	9.96	-21.24	1627.47	16.53	8.48	-27.77				
1615.02	21.05	10.90	-21.40	1618.03	16.93	8.87	-27.42				
1605.59	21.21	10.69	-21.66	1606.90	18.06	9.58	-26.47				
1594.44	21.33	10.75	-21.28	1599.12	18.66	10.34	-26.20				
1584.86	23.13	10.34	-21.31	1589.12	17.96	10.11	-26.13				
1574.81	21.66	10.10	-21.28	1577.56	19.25	10.23	-26.06				
1563.23	19.78	9.83	-21.48	1568.97	19.28	10.18	-25.98				
1551.54	21.55	9.92	-21.21	1560.72	18.22	9.92	-25.86				
1539.99	19.65	9.08	-21.35	1550.35	18.59	10.44	-25.82				
1528.42	20.31	10.07	-21.08	1542.49	18.84	10.43	-25.74				
1516.85	20.00	9.96	-21.24	1533.56	18.55	10.24	-25.68				
1505.15	21.18	10.96	-21.44	1524.57	18.43	10.10	-25.82				
1494.71	24.14	11.59	-21.73	1516.45	18.30	10.42	-25.67				
1484.83	26.49	12.53	-21.93	1508.34	18.46	10.26	-25.59				
1475.37		12.04	-21.76	1500.95	17.85	10.35	-25.68				
1465.89	22.46	12.76	-22.21	1492.62	18.96	9.81	-25.77				
1454.81	21.56	12.19	-21.85								
1442.87	21.92	11.09	-22.21								
1433.27	23.69	11.03	-21.94								
1422.64	23.08	11.94	-22.16								
1411.85	23.41	11.60	-21.96								
1402.26	22.08	11.70	-21.73								
1392.38	23.30	12.20	-22.12								
1381.47	21.64	12.20	-22.03								
1372.11	25.66	12.76	-22.38								
1363.21		12.06	-22.12								

OCF29				OCF11				OCF35			
CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)	CRS Date	OM (%)	C (%)	$\delta^{13}C$ (‰ VPDB)
1351.36	23.91	12.58	-22.56								
1342.89	21.06	10.50	-22.53								
1330.35	20.13	10.53	-22.54								
1319.98	23.70	8.91	-22.59								
1306.88	16.21	8.53	-22.68								
1292.41	15.37	6.63	-22.67								
1279.65	15.43	7.71	-22.88								
1264.66	13.27	8.63	-22.67								
1249.91	14.99	7.54	-22.32								
1237.56	17.70	9.29	-22.41								
1225.16	18.30	10.95	-22.25								
1212.12	22.70	11.60	-22.21								

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