CHARACTERISING TURBIDITY AND IDENTIFYING SEDIMENT SOURCES IN NORWAY HOUSE CREE NATION DRINKING WATER USING SEDIMENT FINGERPRINTING

BY

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A Thesis Submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT: Theroux, Johanna. M.Sc., The University of Manitoba, 2017. Characterising Turbidity and Identifying Sediment Sources in Norway House Cree Nation Drinking Water Using Sediment Fingerprinting. Co-Advisors: Dr. David Lobb and Dr. Annemieke Farenhorst.

The Jack River, located along the Nelson River system in north-central Manitoba, Canada, is the drinking water source for the Norway House Cree Nation (NHCN). The Jack River lies downstream of the 2-Mile Channel which was built by Manitoba Hydro to increase the outflow capacity of Lake Winnipeg. The erosion of the 2-Mile Channel and the subsequent sedimentation downstream has been an on-going environmental concern for NHCN. This study characterizes the source water quality in NHCN with respect to sediments and turbidity, and uses a sediment fingerprinting technique to investigate the sources of sediment at the Jack River drinking water intake. The historic data show that turbidity has been gradually increasing over time ($p<0.05$) and is weakly positively correlated with the previous-day mean wind ($p<0.05$) and the previous 10-day accumulated precipitation ($p<0.05$). The gradual increase of turbidity over time indicates that environmental factors in the Lake Winnipeg Basin including precipitation, land use changes, and multi-decadal climate oscillations are the major influencing factors. To determine the origins of sediments at the Jack River intake, sediment fingerprinting was used and identified four discriminable source areas using three sediment colour properties. Modelling results using MixSIAR showed that 79.3 % (SD 31.2 %) of sediment was reflective of upstream sources while 9.3 % (SD 18.8 %) was reflective of the 2-Mile Channel erosion. These results show that NHCN drinking water was not significantly impacted by the 2-Mile Channel erosion throughout the summer of 2014 and the spring of 2015.

ACKNOWLEDGEMENTS

This research was made possible by funding provided by the Natural Science and Engineering Research Council of Canada (NSERC) as part of the CREATE H2O program for First Nations Water and Sanitation and Security.

I wish to express my appreciation for my co-advisors, Dr. Annemieke Farenhorst and Dr. David Lobb, who provided me with this opportunity to further my education and knowledge in this valuable field. I would like to thank Dr. Farenhorst for introducing me to the environmental coordinators of Norway House Cree Nation and helping establish a good working relationship with the community. I would like to thank Dr. Lobb for his knowledge and expertise in the area of sediment fingerprinting and for guiding me in the right direction when I faced roadblocks in the project. I would also like to thank the CREATE H2O coordinators, Wendy Ross and Pepper Pritty, who provided me with support and guidance throughout the project to successfully build my knowledge of First Nation culture and protocols.

I would like to thank those in the Department of Soil Science including Eva Slavichek for her help with the laboratory analyses and helping organize fieldwork equipment and Brendan Brooks for his assistance in the field, from organizing and locating equipment, to software help, electrical help with the centrifuge and water pumps, and most importantly, his positive attitude and good humour during our trips. I would also like to thank Kui Lui, who was an incredible resource to overcome statistical, modelling, and software roadblocks throughout my project and who gladly made time to answer my questions and provide tutorials to ensure I was on the right track.

I am also incredibly grateful for all the help I received from the Norway House Cree Nation, who without their support, this project would never have been possible. I had many

positive experiences working with the people of Norway House, including James Dixon, Loretta Mowatt, Jaymie Balfour, Alex Balfour, Ken Budd, John Anderson, Jennifer Anderson, and Carmen Anderson, who were always helpful, positive, and in good spirits. Many good laughs were shared and I am thankful to have built some great relationships with people in a place I will never forget. I am so thankful for the Chief and Council of NHCN, including Councillor Gilbert Fredette, for welcoming me to Treaty 5 territory and for supporting this project to unfold.

Finally, I would like to thank my mom and dad for supporting and encouraging my education and my ambitions, and for providing me assistance in times of great stress. I would also like to thank my boyfriend John, who has believed in me, encouraged me, supported me, and pushed me to accomplish this goal.

Table of Contents

ABSTRACT i
ACKNOWLEDGEMENTS ii
List of Figures vii
List of Tables ix
1. INTRODUCTION 1
1.1 Lake Winnipeg Watershed 1
1.2 Hydropower Development on the Nelson River 2
1.3 The 2-Mile Channel and Norway House Cree Nation 3
1.4 NHCN Source Water 4
1.5 Suspended Sediments 5
1.6 Sediment Fingerprinting 6
1.7 Thesis Overview 9
1.8 References 10
2. CHARACTERIZING TURBIDITY IN NORWAY HOUSE CREE NATION SOURCE WATER 14
Abstract 14
2.1 Introduction 15
2.2 Study Area 17
2.3 Methods 19
  2.3.1 Sediment and Water Quality Data 19
  2.3.2 Flow and Water Level Data 20
  2.3.3 Weather Data 20
  2.3.4 Statistical Analysis 22
2.4 Results 23
  2.4.1 Turbidity Analysis 23
  2.4.2 Dissolved Oxygen Analysis 28
  2.4.3 Water Flow and Level Analysis 30
2.5 Discussion 32
  2.5.1 Turbidity Dynamics and the Effects of the 2-Mile Channel 32
  2.5.2 Precipitation Influences on Turbidity 33
  2.5.3 Water Flow Influences on Turbidity 34
  2.5.4 Land Use Changes 36

2.5.5 Temperature Influences in the LWB 36
2.5.6 Environmental Influences on the Variation in Turbidity 37
2.5.7 Dissolved Oxygen 40
2.6 Conclusion 41
2.7 References 43
3. IDENTIFYING SEDIMENT SOURCES IN NORWAY HOUSE CREE NATION DRINKING WATER USING SEDIMENT FINGERPRINTING 47
Abstract 47
3.1 Introduction 49
3.2 Materials and Methods 53
3.2.1 Suspended Sediment Collection 53
3.2.2 Source samples 56
3.2.3 Analysis: Diffuse Reflectance Spectrometry 58
3.2.4 Analysis: Cs-137 61
3.2.5 Statistical Analysis 62
3.3 Description of Statistical Tests 66
3.3.1 Canonical Discriminant Function Analysis 66
3.3.2 Shapiro-Wilk Test 67
3.3.3 Biplot Analysis 67
3.3.4 Kruskal-Wallis H-Test 68
3.3.5 Discriminant Function Analysis 68
3.3.6 MixSIAR 69
3.4 Results 71
3.4.1 Source Discrimination 71
3.4.2 Shapiro-Wilk 73
3.4.3 Biplot Analysis 73
3.4.4 Kruskal-Wallis H-test 75
3.4.5 Quadratic Discriminant Function Analysis 76
3.4.6 MixSIAR modelling 78
3.5 Discussion 80
3.5.1 Sediment Contributions to NHCN Source Water 80
3.5.2 Water Levels and Jenpeg 80
3.5.3 Landscape Characteristics 81
3.5.4 Sources of Error in MixSIAR 83
3.5.5 Rejection of Cs-137 86

3.5.6 Model Verification and Validation 87
3.6 Conclusion 89
3.7 References 90
4. REFLECTIONS ON SEDIMENT FINGERPRINTING IN NORWAY HOUSE CREE NATION .. 98
4.1 Challenges in the Sampling Design 100
4.2 Implications for NHCN 102
4.3 Recommendations for Future Research 103
4.4 References 106
APPENDICES 109
Appendix A: Incoming source water turbidity data 109
Appendix B: Relationship Building 110
Appendix C: Spreadsheet of source sample data used in the Kruskal-Wallis H-Test and the quadratic discriminant function analysis 112
Appendix D: Spreadsheet design for biplot analysis in MixSIAR using 15 colour coefficients 113
Appendix E: MixSIAR spreadsheet design for sediment apportionment in the Jack River and the 2-Mile Channel using a three-tracer combination 114
Appendix F: MixSIAR spreadsheet design for sediment apportionment in the Jack River and the 2-Mile Channel using an eight-tracer combination 116

List of Figures

Figure 1.1 Map of the Lake Winnipeg Basin, retrieved from LWSB (2006) 1
Figure 1.2 Lake Winnipeg regulations projects, retrieved from MB Hydro (2014a) 2
Figure 1.3 Map of Norway House Cree Nation and the surrounding area, retrieved from Statistics Canada (2012) 3
Figure 1.4 Erosion of the 2-Mile Channel Inlet, September 2014 4
Figure 2. 1 Photograph of driftwood debris along the shoreline of 2-Mile Channel inlet, September 2014. 18
Figure 2.2 Photograph of the vegetation along the shoreline of the Jack River, September 2014. 19
Figure 2.3 Map of the monitoring stations for historical data collected near NHCN. 21
Figure 2.4 Linear regression of turbidity over time in the Nelson River at Norway House (1972-2014). 24
Figure 2.5 Linear relationship between turbidity and TSS in the Nelson River at Norway House (1972-2014). 25
Figure 2.6 Linear regression of TSS over time in the Nelson River at Norway House (1972-2014). 25
Figure 2.7 Linear regression of DO over time in the Nelson River at Norway House (1975-2014). 29
Figure 2.8 Linear regression of water flow in the Nelson River below Sea River Falls before channel construction (1967-1975). 31
Figure 2.9 Linear regression of water flow in the Nelson River below Sea River Falls after channel construction (1976-2014). 31
Figure 3.1 Map of sample locations for the 12 Phillips samplers deployed in duplicate in the Summer of 2014 near NHCN. 55
Figure 3.2 Map of the Spring 2015 sampling locations using the continuous-flow centrifuge in NHCN. 56
Figure 3.3 Flowchart of the statistical classification of source areas and selection of tracers utilized in sediment fingerprinting. Source: Boudreault, 2016. 63
Figure 3.4 Scatterplot of canonical scores of the source samples generated from radionuclide Cs-137 and spectral reflectance in the discriminant function analysis and classified into four main source groups including 1) Clays, 2) Organics, 3) Warren's and 4) 2-Mile Suspended 73
Figure 3.5 Three biplots generated from MixSIAR using all remaining sediment properties to verify that the four suspended sediment mixtures lie within the standard error bars of the sources 75

Figure 3.6 Bar graph of sediment source apportionment for the Jack River drinking water intake and 2-Mile Channel suspended sediment mixtures using the optimum sediment property combination Z, G, B as the sediment fingerprint. 79
Figure 3.7 Bar graph of sediment source apportionment for the Jack River drinking water intake and 2-Mile Channel suspended sediment mixtures using the eight tracers X, Z, Y, l, h, R, G, B as the sediment fingerprint. 79
Figure 3.8 Map of the main tributary rivers to the Jack River including the Gunisao River, Opatinow Channel, and the Feeder Channel. 83
Figure 3.9 Photograph evidence of sediment deposition and the formation of a delta at the outlet of the 2-Mile Channel near NHCN, May 2014. 83
Figure 3.10 Photograph of the 2-Mile Channel outlet, displaying slumping and signs of subsurface soil contamination from falling organic material, August 2014. 88
Figure 3.11 Photograph of sediment deposition contributing to surface soils along the shoreline of the 2-Mile Channel, August, 2014. 88

List of Tables

Table 2.1 Summary of historical data collected near NHCN 21
Table 2.2 Parameter estimates of the linear regression models of turbidity over time and TSS over time in NHCN (1972-2014) 26
Table 2.3 Correlation of environmental parameters with turbidity in NHCN.. 27
Table 2.4 Stepwise selection of parameters influencing turbidity in NHCN from the multiple linear regression model 28
Table 2.5 Parameter estimates of the linear regression model of DO over time in NHCN (1975-2014)... 29
Table 2.6 Summary results of the student's t-test for water flow and water level in the Nelson River below Sea River Falls pre-channel (1967-1975) and post-channel (1976-2014) construction 32
Table 3.1 Number of source samples and types collected at each sampling location 57
Table 3.2 Fifteen spectral reflectance colour coefficients generated using diffuse reflectance spectrometry and MATLAB adapted from Martinez-Carreras (2010b) Source: Boudreault (2016). 61
Table 3.3 Source sample descriptions and re-classification based on canonical discriminant function analysis.. 72
Table 3.4 Results of the Kruskal-Wallis H-test and the quadratic DFA in R to determine the inter-category contrasts among source groups and the % of sources correctly classified using the remaining eight colour coefficients: X, Z, Y, l, h, R, G, B 76
Table 3.5 Results of the stepwise DFA in R to determine the optimum combination of sediment properties for maximum source discrimination 77

1. INTRODUCTION

1.1 Lake Winnipeg Watershed

Lake Winnipeg is situated between the Interior Plains and the Canadian Shield and extends 436 km from north to south and covers an area of 23,750 km^2 (Brunskill et al., 1980). Its preformation dates back to the formation of Glacial Lake Agassiz, approximately 13,000 years ago, from the meltwater of retreating glaciers (LWSB, 2006). Lake Winnipeg began to form about 8,000 years later, from remnants of Lake Agassiz as it drained into the Hudson Bay in northern Manitoba, Canada. Water in Lake Winnipeg flows south to north into the Nelson River, the single natural outlet from Lake Winnipeg and the Lake Winnipeg Basin (LWB). The LWB drains nearly 953,000 km^2 of land in four provinces including Alberta, Saskatchewan, Manitoba, and Ontario, as well as four US states. While doing so, it receives waters from many tributaries including three major tributaries: The Red River, Saskatchewan River, and Winnipeg River systems (LWSB, 2006) (Figure 1.1). Lake Winnipeg consists of two distinct basins: the north basin and the south basin, which are connected by a 2.5 km wide channel called the Narrows.

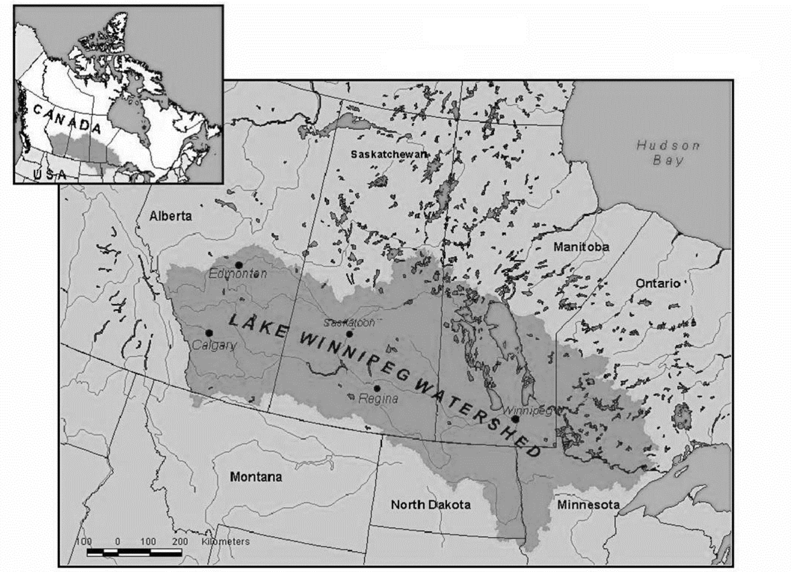

Figure 1.1 Map of the Lake Winnipeg Basin, retrieved from LWSB (2006)

1.2 Hydropower Development on the Nelson River

The Nelson River is approximately 2575 km long with a discharge of 2370 m^3s^{-1} and is the single natural outlet to Lake Winnipeg. In the 1960s, Manitoba Hydro was granted an interim license under the Water Power Act for the regulation of Lake Winnipeg for hydropower development. The series of developments included the construction of three channels by hydraulic dredging from 1971-1975, including the 2-Mile Channel, the 8-Mile Channel, and the Ominawin bypass Channel (Figure 1.2). These channels were built to increase the outflow capability of the lake and to provide more reliable and optimal hydropower production to the upstream generating stations (LWSB, 2006). In addition, the Lake Winnipeg Regulation Projects in the 1960s-1970s also included the construction of five hydroelectric generating stations on the Nelson River, including the Kelsey, Kettle, Long Spruce, Limestone, and Jenpeg generating stations.

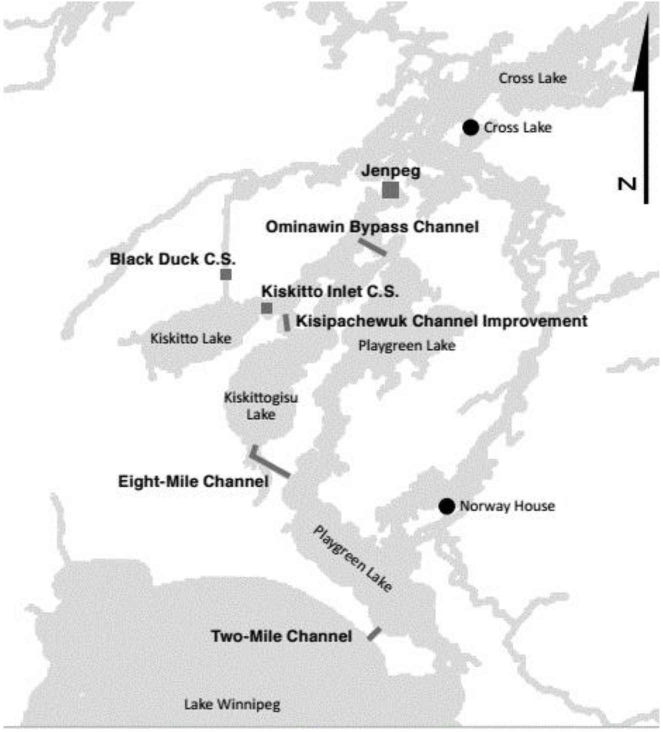

Figure 1.2 Lake Winnipeg regulations projects, retrieved from MB Hydro (2014a)

1.3 The 2-Mile Channel and Norway House Cree Nation

The 2-Mile Channel is located at the confluence of the Nelson River and Lake Winnipeg (53.45’02.00 N 98.24’07.00 W) and was one of the three channels built to overcome natural constrictions in the Nelson River system, namely, the outflow of Lake Winnipeg at Warren’s Landing. It is estimated that the constructed channels increased outflow capacity of Lake Winnipeg by 40-50 % (Lévesque and Page, 2011). The 2-Mile Channel is approximately 3.1 km long and 183-213 m wide, with water depth increasing gradually from 0 meters along the shoreline, to approximately 12.5 meters in the centermost part of the channel (CAMPP, 2014). It is estimated that 80 % of the flow from Lake Winnipeg goes through the 2-Mile Channel (Scott et al., 2011). Approximately 17 km upstream of the channel is the Norway House Cree Nation (NHCN), a First Nation which lies on the territory surrounding the Jack River on the East Channel of the Nelson River (Figure 1.3). The drinking water in NHCN originates from the surface water of the Jack River and is pumped to the drinking water treatment plant, where it is treated, and trucked or piped to the nearly 1,200 homes in the community.

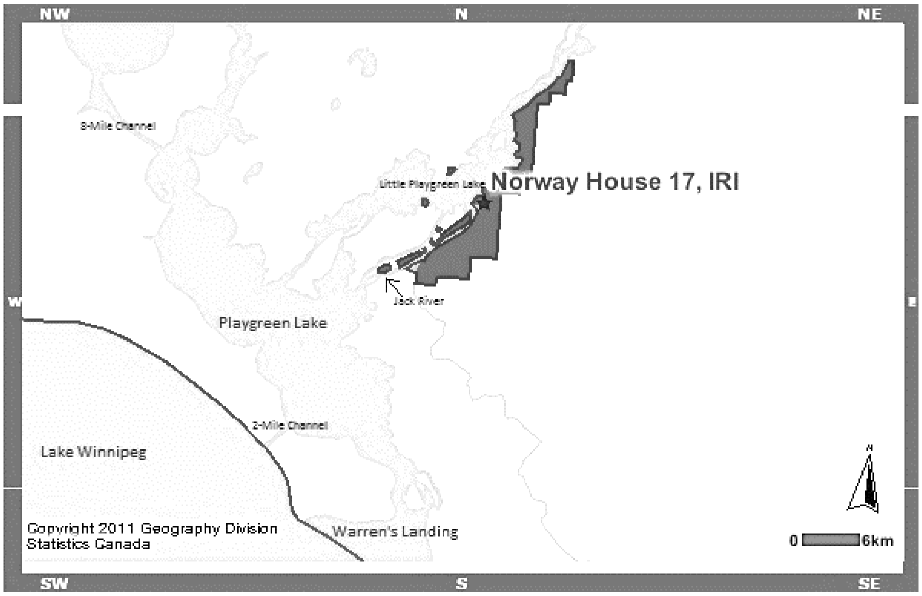

Figure 1.3 Map of Norway House Cree Nation and the surrounding area, retrieved from Statistics Canada (2012)

1.4 NHCN Source Water

Water and sanitation security has long been an issue in many First Nations in Canada. In April 2011, the Department of Indian and Northern Affairs released an assessment report indicating that 314 out of the 807 water systems inspected in First Nations across Canada were classified as high risk (AANDC, 2011a). In January 2017, there were 144 Drinking Water Advisories in effect on 95 First Nations south of the 60th parallel (Health Canada, 2017). NHCN has an on-reserve community of approximately 5,441 members and is one of the most populated First Nations in Manitoba (AANDC, 2011a). The economy relies heavily on commercial fishery, along with providing educational services, health care, food services and retail (Statistics Canada, 2013). Water is part of recreation, spirituality, culture, and the economy in NHCN and is celebrated annually during the Treaty and York Boat Days Festival.

As of January 2011, it was determined that the source water in NHCN was at a high overall risk of causing health impacts to the community due to several risk drivers including: no source water protection plan, deteriorating water quality over time, risk of contamination, and

Figure 1.4 Erosion of the 2-Mile Channel Inlet, September 2014

insufficient capacity to meet future requirements (AANDC, 2011b). Based on discussions with the environmental monitoring agency in NHCN regarding shoreline erosion from the north shore of Lake Winnipeg, as well as in the 2-Mile Channel, and based on previous water quality data from the water treatment plant (Appendix A), it was identified that suspended sediments could be a significant contaminant affecting source water quality. The estimates of bank erosion from the 2-Mile Channel reported by Manitoba Hydro are 1.35 m year^{-1} in some areas, with the largest rates of erosion occurring at the channel inlet and outlet (MB Hydro, 2014b) (Figure 1.4).

1.5 Suspended Sediments

Sediments in water are identified as suspended or deposited. Suspended sediment is held in suspension in the water column from the water turbulence, and consists largely of fine-grained particles classified as <0.062 mm. Elevated levels of suspended sediment in a waterbody increases turbidity, restricts light penetration, reduces photosynthesis, and consequently, can impair primary production (Davies-Colley et al., 1992; Woodridge and Armitage, 1997; Bilotta and Brazier, 2008). Suspended sediments can also negatively impact commercial fisheries by reducing disease tolerance in fish (Bruton, 1985) as well as impairing spawning habitat and larvae development (Chapman, 1988; Robertson, 2006). In addition, suspended sediments can act as contaminant vectors which contributes to the transportation and deposition of organic and inorganic contaminants, bacteria and pathogens (Sibbesen and Sharpley 1997; Meharg et al., 1999; Warren et al., 2003; Jamieson et al., 2005; Sormunen et al., 2008). The presence of such contaminants at high levels are problematic for water treatment operators, who must apply chemical flocculants such as aluminum and ferric salts to remove sediments and provide other water treatment in an effort to supply safe and acceptable drinking water to homes and minimize risks to the exposures of human to water-born pathogens and harmful chemicals. More specifically, high levels of suspended sediments causing high turbidity can elevate the cost of drinking water treatment (Dearmont et al., 1998). This can be a significant problem for remote First Nations, who have limited infrastructural resources available for extensive water treatment.

1.6 Sediment Fingerprinting

Historically, retreating glaciers deposited large amounts of highly erodible materials in the LWB (ECCC, 2016). Clays and silts from Glacial Lake Agassiz now constitute the agricultural soils throughout the Canadian Prairies (Tamplin, 1967). These materials are now a common non-point source pollutant in lakes and rivers tributary to Lake Winnipeg, namely the Red River, and the Winnipeg River (Brunskill et al., 1979). Suspended sediments often originate from non-point sources and the origin of these sediments can be difficult to attribute to a specific location or source material in the watershed. Identifying areas on the landscape which are contributing to suspended sediments and hence turbidity can be useful for water managers in order to employ monitoring and mitigation measures for the ongoing provision of safe and reliable drinking water throughout the year.

Sediment fingerprinting is a technique which is based on the assumption that sediments which are entering the waterbody have similar characteristics as the soils or sources from which they originated (Collins et al., 1997; 1998; 2010; Walling et al., 2005). By analyzing for a single or a suite of diagnostic properties in a sediment mixture, researchers can trace the sediment back to its upstream origins. A variety of sediment properties exist which have the ability to discriminate between sources and hence can be used in sediment fingerprinting. These properties can be grouped into three main properties types including geochemical, biochemical, and physical (Koiter et al., 2013a). Biochemical properties which have been used in sediment fingerprinting include plant pollen content and enzyme activity (Brown, 1985; Nosrati et al., 2011). Several geochemical properties have also been used, namely radiochemical (Foster and Walling, 1994; Collins et al., 1997), isotopic (Douglas et al., 1995) and magnetic properties (Yu and Oldfield, 1993; Walden et al., 1997; Walling et al., 1999) while physical properties used include particle size (Petticrew, 2005) and spectral reflectance or sediment colour (Martinez-Carreras et al., 2010; Barthod et al., 2015).

Soil colour is traditionally described using colour chips that follow the Munsell System of colour notation; however; this method does not describe colour as a continuous variable and therefore, cannot be used in sediment colour fingerprinting. Colour analysis using diffuse reflectance spectrometry allows the reflectance of light to be measured as it is reflected from a sample surface which can be measured on a continuous gradient. Sediment colour fingerprinting using spectral reflectance has been shown to be a straightforward, cost-effective method to determine changes in predominant sediment sources in the South Tobacco Creek Watershed, a small sub-watershed in the Red River Basin in Manitoba, Canada (Barthod et al., 2015). Colour fingerprints have also been used successfully as a tracer to identify and quantify sediment sources in medium sized catchments and during runoff events (Martinez-Carreras et al., 2010; Legout et al., 2013).

Fallout radionuclides have also been used successfully in identifying sediment sources in the South Tobacco Creek Watershed (Koiter et al., 2013b). The radionuclide Cs-137 is useful in sediment fingerprinting studies because it is readily absorbed to clay and organic soils, and its concentration declines with soil depth (Ritchie and McHenry, 1990; Horowitz, 1991). This information gives researchers insight about the erodibility of surface versus subsurface soils on the landscape. Additionally, radionuclides can discriminate between cultivated and non-cultivated land, and between erosional or depositional areas, as the fallout signal becomes redistributed across the landscape (Koiter et al., 2013a). Cs-137 is also particularly useful as a tracer because it was generated solely from anthropogenic thermonuclear reactions during nuclear bomb testing in the 1950s and 1960s and the subsequent deposition onto soil during atmospheric fallout and precipitation.

Early sediment fingerprinting studies employed a single sediment property as a tracer to distinguish between sediment sources, however; the discriminatory power of one tracer is diminished as sediment mobilization processes throughout the watershed become increasingly complex (Collins et al., 1998). Composite fingerprinting techniques, which employ multiple sediment properties to distinguish the sediment fingerprint, have been shown to greatly improve sediment source discrimination (Collins, 1998; Walling, 1999), as well as reduce error and improve the consistency and robustness of results (Collins and Walling, 2002). Once the sediment properties are analyzed in the suspended sediment mixture and in the source materials, data can be entered into a statistical unmixing model such as MixSIAR in order to determine the contribution of each source to the sediment mixture.

Given the reported erosion from the 2-Mile Channel near NHCN, and the community concerns regarding the impacts of the channel construction on their source water quality, the objectives of this study were:

a) To characterize the source water quality with respect to suspended sediments and analyze historical trends to understand what factors are contributing to high suspended sediments which could threaten the reliability of the drinking water supply in NHCN.
b) To trace the suspended sediments in the NHCN drinking water supply back to their source using Cs-137 and colour properties in sediment fingerprinting to determine if the 2-Mile Channel is contributing significantly to the total amount of sediments.

1.7 Thesis Overview

This thesis and its research is part of the CREATE H2O Program for First Nations Water and Sanitation Security, and established a collaboration with NHCN, one of the largest First Nations communities in Manitoba, to focus on source water protection, an essential component to securing access to clean, drinking water as a human right. Components of this thesis are:

Chapter 1: An analysis of historical data which describes the trends in water flow and water quality parameters related to observed suspended sediments in the Nelson River East Channel near the Norway House Cree Nation drinking water supply in north-central Manitoba. This study characterizes the changes in historical suspended sediment concentrations and investigates the environmental factors which could be influencing this variation in concentrations.

Chapter 2: A sediment fingerprinting study where source and suspended samples were collected throughout the NHCN study area and analyzed for colour and Cs-137. Source areas were identified and tracers were selected using three tests of statistical strength and discriminatory power. The statistical unmixing model MixSIAR was used to estimate the contribution of sediment from each potential source. This study is important for the community to determine the best management strategies to protect their drinking water during high turbidity events and to implement strategies to manage sources of erosion.

Chapter 3: A discussion of the implications of this research, future research recommendations, study limitations, and an exploration of mitigation measures and strategies which could improve water quality protection in NHCN.

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2. CHARACTERIZING TURBIDITY IN NORWAY HOUSE CREE NATION SOURCE WATER

Abstract

Norway House Cree Nation (NHCN) is situated downstream of the 2-Mile Channel, a channel built in the 1970s by Manitoba Hydro to increase the outflow capacity of Lake Winnipeg. Suspended sediments resulting from erosion of the 2-Mile Channel banks are a significant environmental concern for NHCN source water. This study utilized historical weather and sediment data to examine temporal changes in turbidity near the NHCN drinking water intake. Environmental parameters including 1-day antecedent wind, water flow, and accumulated precipitation were tested for statistical correlation with turbidity and total suspended solids (TSS) to determine how environmental factors could influence changes in water clarity. Temporal analysis showed that turbidity and TSS have been increasing significantly over time, with a high degree of variability. Water flow has shown to be increasing over time in both pre- and post-channel construction periods, with a significant decrease in the mean water flow in the post-channel construction period. Environmental correlations showed that one-day antecedent wind, water flow, and ten-day accumulated precipitation were weakly positively correlated to turbidity while stepwise regression showed that one-day antecedent wind and water flow had an additive effect on influencing turbidity levels. The temporal increase in turbidity and TSS near NHCN is largely explained by the increases in precipitation and land use changes observed over the past century in the Lake Winnipeg Basin, leading to increases in runoff and water flow in several major tributaries to Lake Winnipeg and contributing to the erosion of shorelines and channel banks. The analysis of water flow also indicates that the inflows to Lake Winnipeg are increasing, despite the effects of Lake Winnipeg Regulation. These findings indicate that water

quality in upstream Lake Winnipeg is the major factor influencing sediment concentrations in NHCN source water.

2.1 Introduction

The Norway House Cree Nation (NHCN) is a First Nation situated on the East Channel of the Nelson River, at the confluence of the Nelson River and Lake Winnipeg in central Manitoba, Canada. The community lies at the outlet of the Lake Winnipeg Basin (LWB), a 953,000 km^2 watershed, draining four provinces and four US states. Hydropower development in the area began in the 1970s and included the construction of several channels and generating stations along the Nelson River, and the regulation of water levels in Lake Winnipeg (Figure 1.2). The 2-Mile Channel lies approximately 17 km upstream from NHCN and was one of the three channels built in the mid-1970s to increase the outflow capacity of Lake Winnipeg (Figure 1.2). It is estimated that the series of channels increases outflow capacity by 40-50 % (Lévesque and Page, 2011). Through meetings with the NHCN environmental monitoring agency, along with turbidity readings from the water treatment plant (Appendix A), and reports of channel bank erosion of up to 1.35 m year^{-1} (MB Hydro, 2014a), suspended sediments were identified as a significant contaminant of concern in NHCN source water. Furthermore, NHCN source water has been deemed to be at high overall risk based on several risk factors including deteriorating water quality over time (AANDC, 2011). Suspended sediments impact source water quality by acting as contaminant vectors and their removal through chemical flocculation increases the cost of drinking water treatment (Dearmont et al., 1998; ECCC, 2016). Sediments can also impact source water quality by restricting light penetration into the water column, which can result in lowered photosynthesis rates and reduced oxygen levels, resulting in decreased habitat quality for primary producers and fish (Van Nieuwenhuyse, 1983; Lloyd, 1987). A depletion of dissolved oxygen (DO) is also an indicator that respiration is occurring at a greater rate than photosynthesis, and can be caused by the increase of oxygen demand due to decomposition of organic matter from lake turnover, plant biomass, point, and non-point source pollution (MPCA, 2009). Historically, during the construction of the channels in the 1970s, losses in fish production due to siltation of spawning beds and altered fish migration patterns were identified as potential impacts, although these impacts were predicted to be short-term (LWCNRSB, 1975). Furthermore, Playgreen Lake historically contributed approximately 60 % of fish production in the area, which the community continues to rely on for commercial and subsistence purposes (LWCNRSB, 1975; Saunders and Apetagon, 2015).

Suspended sediments are generated through several erosion processes, including: plant and animal activities (bioturbation), anthropogenic activities, wind and water erosion of surface soils, and shoreline and channel bank erosion caused by wind induced waves, water flow, and ice movement (ECCC, 2016). Fluctuations in suspended sediment in a waterbody result from point and non-point source sediment inputs. Point sources of sediment and the resulting increase in suspended sediment load can be readily identified and quantified, however, the transportation and deposition of non-point source inputs are influenced by hydrological processes including surface runoff, precipitation, drainage, and land cover (Zhang et al., 2011). In the LWB, wind action, water flow, and agricultural land use changes have been identified as potential erosional sources (LWBS, 2006; McCullough et al., 2012; Schindler et al., 2012). Wind can contribute to erosion of surface soils and produces waves, causing weathering of shorelines and channel banks due to hydraulic action and abrasion. Surface water flow can mobilize surface soils over the landscape and contributes to erosion when water flow becomes channelized and increases shear stress forces on channel banks (Visser et al., 2004). Water flow is influenced by the hydrology of the landscape including snowmelt, precipitation, geology, channel morphology, topography, land cover, and land use (STAC, 2007).

Currently, limited data exist on the water quality near NHCN prior to hydropower development. Several water quality assessments began once the license for regulation was issued in 1970 (LWCNRSB, 1975), allowing this study to utilize historical records of total suspended solids (TSS), turbidity and DO. Historical weather and water flow data were also utilized to examine hydrological and climactic influences on water quality. The objective of this chapter was to characterize the temporal variation in turbidity, TSS, and DO near the NHCN drinking water intake and to investigate the influences of multiple environmental parameters on turbidity levels.

2.2 Study Area

The study area is located on the East Channel of the Nelson River in central Manitoba, Canada at the outlet of Lake Winnipeg and the LWB. Water flows northward from Lake Winnipeg, through the 2-Mile Channel and the natural outlet at Warren's Landing, into Playgreen Lake and through the East and West Channels of the Nelson River (Figure 1.2). The Nelson River discharges into the Hudson Bay and is approximately 2,500 km in length.

The climate in this region is part of the Norway House Ecodistrict. This ecodistrict is located in a warmer, more humid subdivision of the High Boreal Ecoclimatic Region in Manitoba, and is associated with short, cool summers and long, cold winters, with a mean annual temperature of -0.8 ^{o}C and mean annual precipitation of 440 mm, of which one third falls as snow (Smith et al., 1998). The dominant soils in the area are poorly to very poorly drained Typic (deep) and Terric (shallow) Mesisols associated with fens and bogs, which overlie calcareous, clayey glaciolacustrine sediments (Smith et al., 1998). The land surrounding the study area is a level to undulating peat-covered clayey glaciolacustrine plain with long, smooth slopes that range from level in peat-filled depressions to 2-5 % (Smith et al., 1998). Irregular hummocky terrain is also present in the forested areas on either side of the 2-Mile Channel with slopes ranging from 10-15 % (Smith et al., 1998). Drainage is northeastward over terrain and falls at about 0.5 m km^{-1} (Smith et al., 1998). Dominant vegetation in the area consists of stunted white and black spruce stands, willow trees, sedge and shrubs. Balsam fir, jack pine, trembling aspen, and white birch are also present. The shoreline along the 2-Mile Channel and Warren's Landing does not support aquatic vegetation due to high water velocity and shoreline sediments consisting mainly of freshly eroded clay and course sand deposits. Driftwood is also prevalent along the shoreline of the 2-Mile Channel (Figure 2.1). The shoreline of the Jack River consists predominantly of cattails, willow trees and shrubs and exposed bedrock (Figure 2.2).

Figure 2. 1 Photograph of driftwood debris along the shoreline of 2-Mile Channel inlet, September 2014.

Figure 2.2 Photograph of the vegetation along the shoreline of the Jack River, September 2014.

2.3 Methods

2.3.1 Sediment and Water Quality Data

In this study, sediment data were retrieved from Manitoba Conservation and Water Stewardship for the station "Nelson River at Norway House" #MB05UBS001 for 1972-1974 and #MB05UBS002 for 1975-2014 (Figure 2.3; Table 2.1) (MBCWS, 2015). TSS was measured by filtration in mg L^{-1} and turbidity was measured by turbidimeter in NTU (Nephelometric Turbidity Units). TSS readings that were below the detection limit of 5 mg L^{-1} (35 % of all records) were excluded from the dataset. Turbidity readings lying outside three times the standard deviation from the mean were classified as outliers and were also eliminated from the dataset (0.8% of all records). Data were also retrieved from MBCWS from 1975-2014 (Station #MB05UBS002) (MBCWS, 2015). Readings during ice cover (December-March) were excluded from all datasets to reduce confounding results associated with seasonal effects. Seasonal effects were not investigated in this study due to the highly infrequent and irregular sampling resolution in the 42-year period.

2.3.2 Flow and Water Level Data

Daily mean water flow data were retrieved from the Water Survey of Canada (WSC) from 1967-2014 from the station “Nelson River (East Channel) below Sea River Falls” (#MB05UB008), downstream of Norway House (Figure 2.3). Daily mean water level data were retrieved from the WSC station “East Channel at Norway House” (#MB05UB001) from 1913-2014 (Figure 2.3).

2.3.3 Weather Data

Precipitation data was collected from the Meteorological Survey of Canada (MSC) historical data archive from the weather station “Norway House Forestry” (1972), “Norway House A” (1973-2005), and “Norway House” (2006-2014) to coincide with turbidity measurements. Precipitation data were recorded as total precipitation for a 24-hour day in mm. Days when precipitation was below 0.1 mm were recorded as 0 mm. Accumulated precipitation was recorded as the sum of the precipitation from each day, up to 10 days prior to the turbidity measurement. Wind data recorded by the weather stations “Norway House A” from 1973 to 2005 and by “Norway House” from 2006 to 2014 were also used. Maximum wind level was recorded as the speed in km h^{-1} of the maximum wind gust during the day defined as the peak instantaneous reading (>31 km h^{-1}) from the anemometer during the 24-hour period. The duration of a gust typically corresponds to an elapsed time of 3-5 seconds. Where no gust exceeded 31 km hr^{-1}, the maximum of hourly wind speed recorded during the 24-hour period was used as a proxy. The mean wind speed was calculated by averaging the 24 hourly wind readings throughout the day. A summary of the data retrieved is displayed in Table 2.1.

Table 2.1 Summary of historical data collected near NHCN

Sampling Station	Data Source	Collection Period	Data Type	Location
Norway House Forestry	MSC	1972	Precipitation	54^{0}00'00"N 97^{0}48'00W
Norway House A	MSC	1973-2005	Wind + Precipitation	53^{0}57'00 "N 97^{0}51'00"W
Norway House	MSC	2005-2014	Wind + Precipitation	53^{0}57'30 "N 97^{0}50'39 "W
MB05UB001	WSC	1913-2014	Water Level	53^{0}59'54 "N 97^{0}47'54 "W
MB05UB008	WSC	1967-2014	Water Flow	54^{0}14'23"N 97^{0}35'16"W
MB05UBS001	MCWS	1972-1974	TSS+Turbidity	53^{0}59'13"N 97^{0}50'04"W
MB05UBS002	MCWS	1975-2014	DO +TSS+Turbidity	53^{0}59'13"N 97^{0}50'04"W

Figure 2.3 Map of the monitoring stations for historical data collected near NHCN.

2.3.4 Statistical Analysis

A simple linear regression model was used to investigate the temporal variation in turbidity and TSS over time. Data were log-transformed to meet the assumption of normality in the regression model based on the Shapiro-Wilk test ($p > 0.05$). Water flow was analyzed using simple linear regression to determine temporal variation and a non-paired student's t-test was used to determine the difference in flow for pre- and post-hydropower development periods. Water level was also analyzed using a student's t-test to determine the difference in water level pre- versus post-hydropower development.

Multiple parameters (listed in Table 2.3) were log-transformed to meet the assumption of normality for correlation analysis and were subsequently correlated with turbidity using the Pearson's correlation coefficient. This analysis was used to determine which parameters had a significant influence on turbidity levels. Zero values which cannot be log-transformed were consequently eliminated from the dataset. Four parameters did not meet the normality assumption after log transformation: 1) same-day water flow, 2) TSS, 3) same-day precipitation, and 4) same day+antecedent day mean precipitation. These parameters were correlated using the non-parametric Spearman's correlation coefficient. Parameters resulting in a significant correlation coefficient ($p < 0.05$) were input into the stepwise multiple linear regression model to determine the additive influence on turbidity.

Additionally, turbidity was correlated with one-to 10-day antecedent precipitation to determine the amount of time required for precipitation to generate runoff and significantly influence turbidity levels downstream (Table 2.3). Two-to 15-day accumulated precipitation was also correlated with turbidity to determine the number of days required to saturate surface soils, influencing surface runoff and contributing to increased turbidity (Table 2.3). For these analyses, data largely did not meet the assumption of normality due to many zero values in the dataset and consequently, the non-parametric Spearman correlation coefficient was used.

2.4 Results

2.4.1 Turbidity Analysis

2.4.1.2 Regression

Turbidity levels collected on the East Channel of the Nelson River at NHCN from 1972-2014 are presented in Figure 2.4. The sampling stations MB05UB001 and MB05UB002 are located in the same area and therefore, combining data from these two periods did not have any significant effect on the analysis. From the linear regression model of turbidity over time, it is evident that there has been a significant increase ($p<0.05$) from 1972-2014 with an average turbidity reading of 8.47 NTU. The increase observed (Figure 2.4) corresponds to an increase from approximately 6.3 NTU in 1972 to 7.9 NTU in 2014 (an approximate 25% increase). Turbidity was not monitored in three of the 42 years after the 2-Mile Channel construction (1978-1980), therefore, TSS levels collected at the same location were plotted against turbidity to establish a relationship between the parameters and supplement the findings. Turbidity measurements and TSS concentrations are positively correlated (Figure 2.5) because turbidity represents a measure of water clarity that is directly influenced by suspended solids in the water. Using the average TSS level from 1978-1980 of 9.3 mg L^{-1} in the regression equation, it is predicted that turbidity during that time was 8.9 +/- 1.54 NTU. TSS levels collected at the same location from 1972-2014 were plotted over time and are presented in Figure 2.6. The linear regression indicates that TSS has also been increasing significantly over time ($p<0.05$), with a mean TSS level of 9.23 mg L^{-1}. Given the relatively low predicted turbidity level from the regression equation (Figure 2.5), and the absence of a significant peak in both TSS and turbidity during the years proceeding channel construction, it is unlikely that channel construction directly impacted long term turbidity levels in the community drinking water supply. Parameter estimates of the linear regression models are summarized in Table 2.2. Significant variation in turbidity is evident during the 42-year period, as indicated by the relatively low r^2 value of 0.12 (Figure 2.4) and 0.06 (Figure 2.6). The low r^2 values may be reflective of the irregular and infrequent sampling resolution of turbidity and TSS. Additionally, large variations in turbidity may be explained by environmental influences such as variations in rainfall, runoff, and water flow entering the East Channel from major tributaries, as well as variations in wind and erosion within the East Channel.

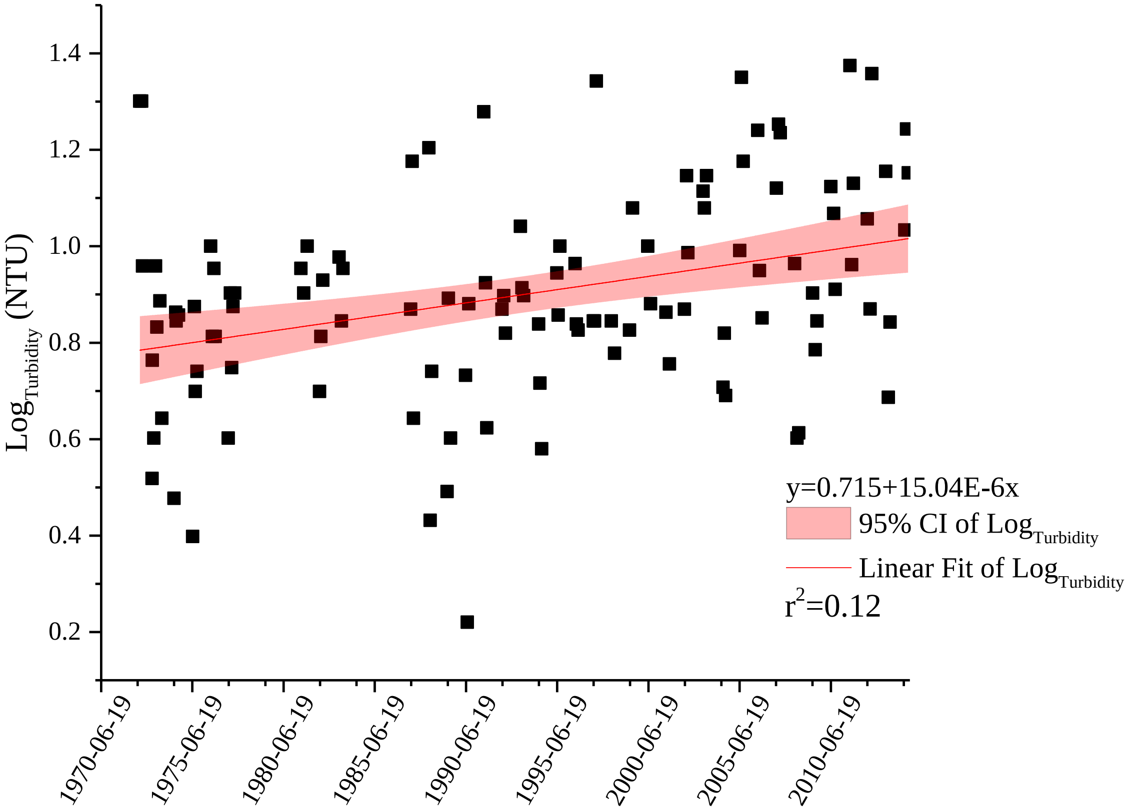

Figure 2.4 Linear regression of turbidity over time in the Nelson River at Norway House (1972-2014).

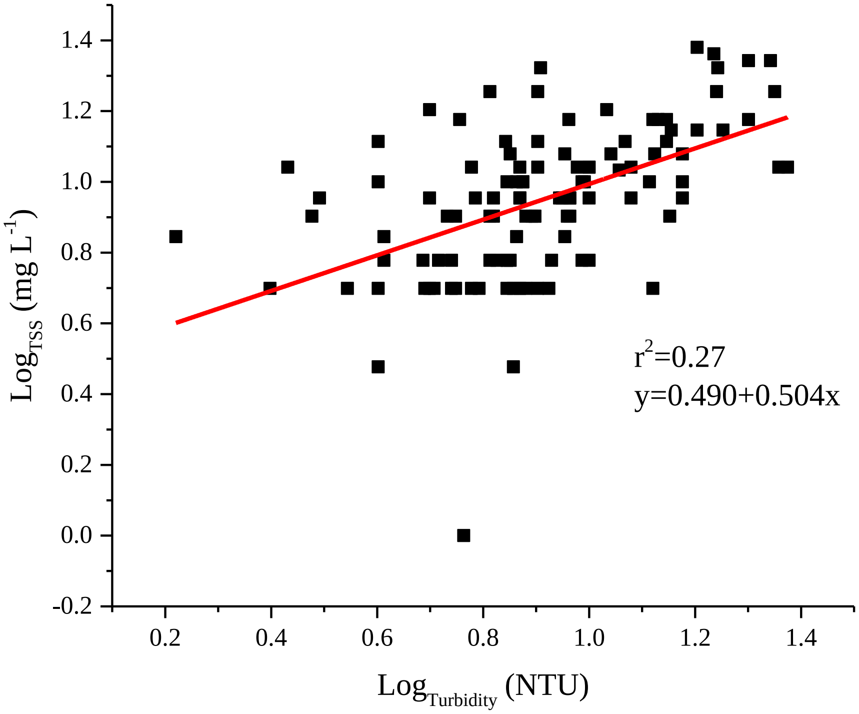

Figure 2.5 Linear relationship between turbidity and TSS in the Nelson River at Norway House (1972-2014).

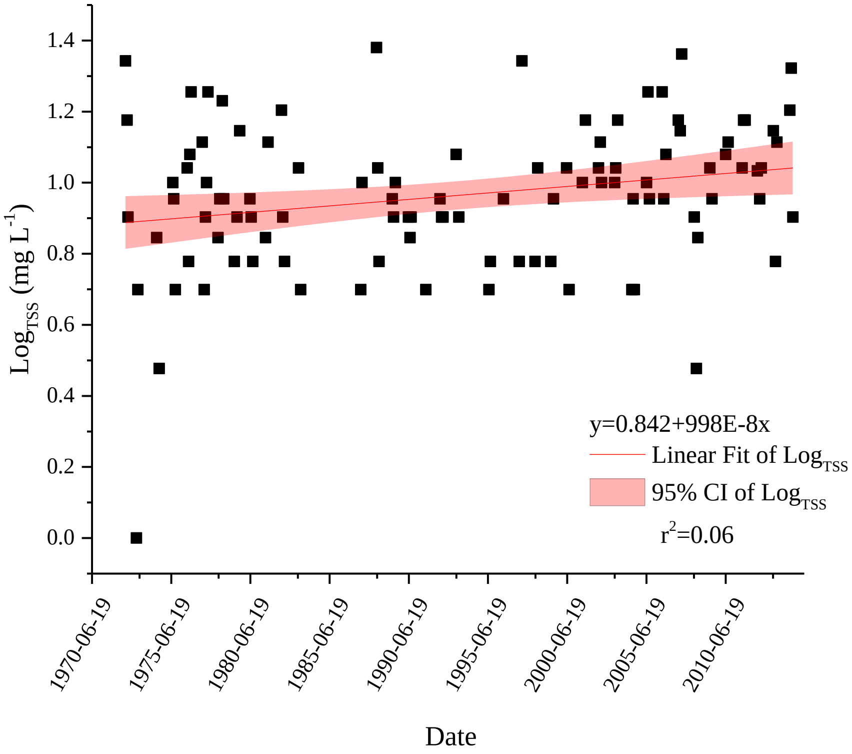

Figure 2.6 Linear regression of TSS over time in the Nelson River at Norway House (1972-2014).

Table 2.2 Parameter estimates of the linear regression models of turbidity over time and TSS over time in NHCN (1972-2014)

LogTurbidity	DF	Value	Standard Error	t-Value	Prob>|t|
Intercept	1	0.715	0.052	13.83	<0.001
Slope	1	1.50E-05	3.92E-06	3.839	2.00E-04
LogTSS					
Intercept	1	0.842	0.054	15.51	<0.001
Slope	1	9.98E-06	4.11E-06	2.429	0.017

2.4.1.3 Temporal Variation

Turbidity readings were correlated with multiple environmental parameters (Table 2.3) in order to explain the temporal variability in turbidity as indicated by the relatively small r^2 value of 0.12 (Figure 2.4). Results show that TSS (r=0.56), one-day antecedent mean wind (r=0.19), and same-day water flow (r=0.27) were significantly ($p<0.05$) positively correlated to turbidity (Table 2.3). The positive correlation of TSS and turbidity was anticipated given that both parameters are indicators of water clarity. Table 2.3 also summarizes the correlation of turbidity with the daily precipitation from one-to-10 antecedent days to the turbidity measurement. The results indicate that the largest significant correlation occurs at two days. A summary of the correlations of turbidity with total accumulated precipitation for up to 15 antecedent days to the turbidity measurement are also presented, where the ten-day accumulated precipitation had the most significant influence on turbidity with a positive Spearman correlation coefficient of 0.21 ($p<0.05$).

Table 2.3 Correlation of environmental parameters with turbidity in NHCN

Environmental parameters (log-transformed)	Correlation Coeff.	Significance level
1-day antecedent mean wind (km h^{-1})	0.19*	0.044
2-day antecedent mean wind (km h^{-1})	0.10*	ns
3-day antecedent mean wind (km h^{-1})	0.05*	ns
Same day max wind (km h^{-1})	0.08*	ns
Same day mean wind (km h^{-1})	0.09*	ns
Same day water flow (m^{3} s^{-1})	0.27	0.0005
TSS (mg L^{-1})	0.56	<0.0001
1-day antecedent precipitation (mm)	0.07*	ns
Same day precipitation (mm)	-0.20	ns
Same day + antecedent day mean precipitation (mm)	-0.01	ns
Antecedent precipitation (mm)		
1-day	0.07	ns
2-day	0.20	0.012
3-day	0.11	ns
4-day	0.17	0.033
5-day	0.02	ns
6-day	0.03	ns
7-day	-0.09	ns
8-day	0.02	ns
9-day	0.10	ns
10-day	0.02	ns
Accumulated Precipitation (mm)		
2-day	0.06	ns
3-day	0.14	ns
4-day	0.12	ns
5-day	0.12	ns
6-day	0.1	ns
7-day	0.11	ns
8-day	0.08	ns
9-day	0.11	ns
10-day	0.21	0.031
11-day	0.19	0.041
12-day	0.2	0.041
13-day	0.2	0.032
14-day	0.17	ns
15-day	0.13	ns

ns= not statistically significant
*= Pearson correlation coefficient used

2.4.1.4 Stepwise Multiple Linear Regression

The four environmental parameters shown to be significantly correlated with turbidity were entered into a stepwise multiple linear regression model to determine the total variation in turbidity explained by the addition of each parameter. From the model, it was determined that the correlation with time, indicating a temporal influence, had the largest effect with a partial $r^2=0.19$ followed by 1-day prior mean wind ($r^2=0.07$) and 10-day accumulated precipitation ($r^2=0.05$) (Table 2.4). A significance level of $p<0.25$ was used for parameter entry into the model and a significance level of $p<0.15$ was used for parameters to remain in the model. The results indicate that these three parameters combined can reliably explain approximately 31 % of the observed variation in turbidity.

Table 2.4 Stepwise selection of parameters influencing turbidity in NHCN from the multiple linear regression model

Step	Variable Entered	# of Variables In Model	Partial r^2	Model r^2	C(p)	F-Value	Pr>F
1	Time	1	0.19	0.19	16.398	22.88	<0.001
2	1-day antecedent mean wind	2	0.07	0.25	8.917	8.95	0.004
3	10-day accumulated precipitation	3	0.05	0.31	3.408	7.55	0.007

2.4.2 Dissolved Oxygen Analysis

DO levels collected on the East Channel of the Nelson River at NHCN from 1975-2014 are presented in Figure 2.7. From the linear regression of log-transformed measurements, it is evident that DO has been decreasing significantly over time ($p<0.05$, $r^2=0.15$) with a mean value of 8.65 mg L^{-1} over the 39-year period (Figure 2.7). This result indicates that source water quality in NHCN is becoming increasingly at risk, since DO is an indicator for good water quality and ecosystem health and is essential for the metabolism of all aerobic aquatic organisms

(CCME, 1999). The DO guideline for the protection of early stages of aquatic life in freshwater is 6.0-9.5 mg L^{-1}, indicating that the mean DO level in NHCN is currently within guideline limits. The parameter estimates are summarized in Table 2.5.

Table 2.5 Parameter estimates of the linear regression model of DO over time in NHCN (1975-2014)

Variable	DF	Value	Standard Error	t-Value	Prob>|t|
Intercept	1	1.009	0.018	57.48	<0.0001
Slope	1	-5.57E-06	1.29E-06	-4.301	<0.0001

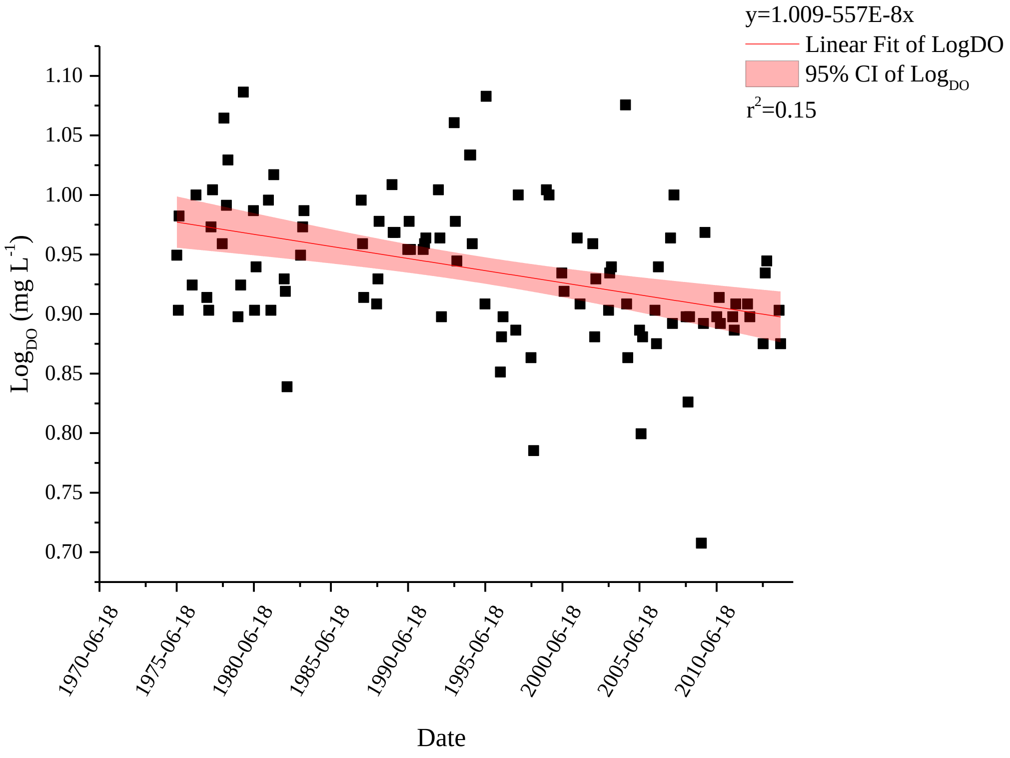

Figure 2.7 Linear regression of DO over time in the Nelson River at Norway House (1975-2014).

2.4.3 Water Flow and Level Analysis

Water flow was analyzed directly downstream of NHCN at station 05UB008 (Nelson River East Channel below Sea River Falls) for pre- and post-channel construction periods (1967-1975 and 1976-2014, respectively) using a simple linear regression model. The datasets show that water flow has been increasing over time for both time periods ($p<0.05$) (Figure 2.8 and 2.9). Mean water flow was compared for both time periods using a non-paired student's t-test and the Satterthwaite method for unequal variance to determine the t-Value. The mean water flow pre-channel construction is 445 m^3 s^{-1} and post-channel construction is 342 m^3 s^{-1}, a statistically significant decrease of 30 % (Table 2.6). Water flow analysis also shows that although the mean water flow has decreased significantly, there is a temporal increase in each time period (Figure 2.8 and 2.9). These results indicate that the construction of the Jenpeg dam may have caused a decrease in water flow, despite greater water volumes entering the system over time. Water level data were also compared for pre-channel (September 1913 –January 1976) and post-channel (January 1976-November 2015) periods. The data set shows a pre-channel mean daily water level of 217.076 m above sea level and a post channel mean daily water level of 217.265 m above sea level, a statistically significant increase ($p<0.05$) (Table 2.6). The results indicate that Lake Winnipeg Regulation has significantly increased water level which coincides with MB Hydro reports (217.44 MASL- 217.51 MASL) however; MB Hydro attributes this increase to other environmental factors, such as climate variability (MB Hydro, 2014b).

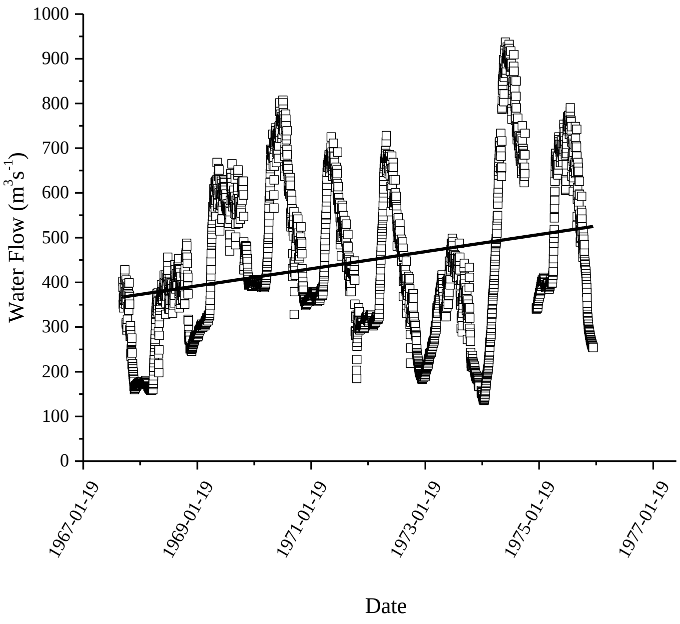

Figure 2.8 Linear regression of water flow in the Nelson River below Sea River Falls before channel construction (1967-1975).

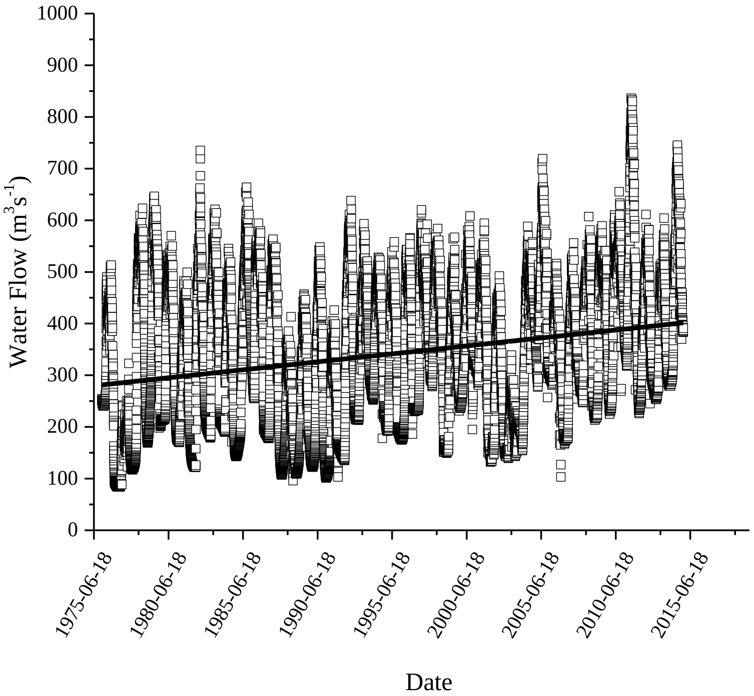

Figure 2.9 Linear regression of water flow in the Nelson River below Sea River Falls after channel construction (1976-2014).

Table 2.6 Summary results of the student's t-test for water flow and water level in the Nelson River below Sea River Falls pre-channel (1967-1975) and post-channel (1976-2014) construction

Mean water flow ($m^3 s^{-1}$)		95% CI		St.Dev
Pre-Channel	444.525	438.141	450.909	176.245
Post-Channel	341.463	339.084	343.841	144.346
Method	Variance	DF	t-Value	Pr>|t|
Satterthwaite	Unequal	3785.7	-29.67	<0.001
Mean water level (MASL)				St.Dev
Pre-Channel	217.076	217.068	217.083	0.473
Post-Channel	217.227	217.222	217.232	0.303
Method	Variance	DF	t-Value	Pr>|t|
Satterthwaite	Unequal	26907	33.02	<0.001

2.5 Discussion

2.5.1 Turbidity Dynamics and the Effects of the 2-Mile Channel

The increase in TSS and turbidity from 1972-2014 in the Nelson River at Norway House (Figure 2.4 and 2.6), along with the observed changes in water flow (Figure 2.8 and 2.9), and decreasing trend in DO (Figure 2.7) are largely explained by the hydrology upstream in the LWB. No significant peaks in TSS or turbidity were observed in the years immediately following the construction of the 2-Mile Channel in the fall of 1975, indicating that channel construction likely did not have a direct significant effect on long-term sediment concentrations in NHCN source water, however, caution should be used in interpreting this dataset as measurements were not taken at frequent or regular intervals, which could have resulted in omitting peaks in the data. The predicted turbidity levels from 1978-1980 as indicated by the regression equation with TSS also show that no significant peaks occurred (Figure 2.5). The gradual increase in both turbidity and TSS over the 42-year period indicate that a shift is occuring at a larger scale and is influenced by changes in hydrology, including precipitation and water flow in the LWB and its tributaries.

2.5.2 Precipitation Influences on Turbidity

The temporal variation in both turbidity and TSS in the Nelson River at Norway House (Figure 2.4 and 2.6) can be explained in-part by precipitation in the LWB. Increases in precipitation trigger increased in-stream water flow, which mobilizes sediments through shoreline and channel bank erosion. Precipitation also mobilizes surface-eroded sediments via overland flow during rainfall and snowmelt events. Global precipitation trends in the 20th century have shown increasing overall precipitation from 1925-1999 between the 40th and 70th degree latitude (Zhang et al., 2007). A significant increase has also been shown to be occuring in the Canadian Prairies of 0.62 mm year^{-1} in the same time period of 1921-1995 (Akinremi et al., 1999).

The three major tributaries to Lake Winnipeg include the Saskatchewan River, the Red River, and the Winnipeg River. In the last two decades, the Winnipeg River and the Red River contributed approximately 40 % and 14 % to total Lake Winnipeg inflow, while the Saskatchewan River contributed approximately 22 % (McCullough, 2015). The Red River is the most turbid of the major tributaries with a sechhi depth of 0.35 m at the outlet compared to 1.5-2.0 m and 0.8 m for the Saskatchewan and Winnipeg Rivers, respectively (Brunksill et al., 1980). Precipitation trends for both the Winnipeg and Red River Basins show significant increases over the past 100 years (1914-2014) (Novotny and Stefan, 2007; St.George, 2007; McCullough, 2015) while no trend in precipitation is evident in the Saskatchewan River (Dibike et al., 2012). It has also been studied that in the Red River Basin, the precipitation-runoff ratio has increased by three-fold in the past 70 years, which is attributed to the increased precipitaiton triggering the depression storage threshold in this surface depressions dominated landscape (Ehsanzadeh et al., 2012). Land use changes and wetland drainage are also speculated to be a contributing factor (Gleason et al., 2007).

The observed precipitation increases in the LWB are likely caused by large scale oceanic and atmospheric climate patterns associated with sea surface temperatures, pressures, and surface windstress, namely, the Pacific Decadal Oscillation, a 20-30 year pattern of Pacific climate variability (McCullough, 2015). This pattern, along with hemispheric-scale anthropogenic forcing of the Earth's heat budget are likely the strongest factors influencing precipitation in the LWB over the last century (Zhang et al., 2007; McCullough, 2015).

2.5.3 Water Flow Influences on Turbidity

Increasing water flow, a consequence of increased precipitation, along with decreases in water retention on the landscape caused by land use changes are major processes that may also contribute to the observed increase in turbidity in the East Channel at Norway House. Sediment transport is highly influenced by streamflow, where higher flows are capable of carrying higher loads of sediment. High flows also exert more shear stress on shorelines and channel banks, causing erosion of subsurface soils and scouring. Water flow has increased in both the Red River and the Winnipeg River over the last century, causing a net increase in inflow to Lake Winnipeg, due to the above-mentioned precipitation increases, and frequent flooding in the Red River Basin, which is the main source of sediment to the South Basin of Lake Winnipeg (McCullough et al., 2001; 2012; 2015). Conversely, the Saskatchewan River has experienced decreases in water flow due to land use changes in the watershed, reservoir construction, and increased water consumption, and has not contributed to the net increase in water inflow observed in Lake Winnipeg (McCullough, 2015). It is also speculated that the Saskatchewan River would have a dilution effect on the sediment concentration in the North Basin of Lake Winnipeg due to the inflow of less turbid water (Schindler et al., 2012), however; this phenomenon is not well studied and would also be diminished by decreasing inflow from this tributary. The Red River Basin in particular, has experienced the most dramatic increase in water flow in recent years, with flooding occuring in seven of the 10 years from 1995-2005 and a mean water flow 55 % higher than any previous 10-year period in the past century (McCullough et al., 2012). The increasing turbidity levels at NHCN (Figure 2.4 and 2.6) along with the increasing water flow downstream of the community (Figure 2.8 and 2.9), indicate that increased channel erosion in major tributaries is likely the contributing factor.

The temporal variation in water flow in the Nelson River below Sea River Falls indicates that a 30 % decrease in mean water flow occurred between the pre- and post-channel construction periods (Table 2.6). The decrease in mean water flow reflects the decrease of total inflow to Lake Winnipeg from tributary channels during the same period as described by McCullough (2015), indicating that the decrease is reflective of the watershed hydrology upstream of NHCN and may not be a direct consequence of hydropower development. It is commonly reported that hydropower development has reduced the magnitude and frequency of flooding (MB Hydro, 2014b), indicating that the decrease in mean water flow may be resulting in part from regulation of Lake Winnipeg and the control of water outflow at the Jenpeg generating station. The limited number of years of water flow data in the pre-hydropower development period cause some uncertainty to the direct cause of the decrease. The observed significant increase in water level from 217.1 MASL to 217.2 MASL is a contentious point of interest, suggesting that hydropower development has caused a significant increase in the water level of Lake Winnipeg. This result is expected and is reported by Manitoba Hydro, however; these reports indicate that other environmental factors, such as natural climate variability and water consumption are also influencing the increase (MB Hydro, 2014b).

2.5.4 Land Use Changes

The alteration of the landscape such as wetland drainage to expand agricultural land and increased urbanization, has also been implicated to influence water flow and turbidity (Lévesque and Page, 2011). Wetlands reduce runoff velocity and increasing water residence times on the landscape, allowing sediments to deposit and decreasing large water influxes after rain or snowmelt events (LWSB, 2006). Modelling studies have also shown that wetland drainage increases streamflow frequencies and magnitudes (Gleason et al., 2007; Yang et al., 2008). Since 1900, it is estimated that 40-70 % of wetlands in the US portion of the Red River Basin have been drained and converted to cropland (Dahl, 1990). It has also been shown that in the same time period, runoff has increased three-fold due to increases in precipitation (Ehsanzadeh et al., 2011), however, a lack of clear evidence exists to imply wetland drainage is the cause. These studies suggest that land use changes in the main tributaries to the LWB may be contributing to increased runoff and flooding, influencing the 42-year increasing trend in turbidity observed near NHCN.

2.5.5 Temperature Influences in the LWB

Regional climatic warming may also influence the hydrodynamics of the LWB. Increases in maximum winter temperatures have been observed in the LWB, along with increases in minimum temperatures in winter, spring and summer, leading to temperature increases of 0.32 ^{0}C to 0.85 ^{0}C per decade (Xuebin, 2000; Dibike et al., 2012). This temperature increase could affect the hydrological cycle in the watershed by increasing evaporation and evapotranspiration, however, it has been studied that the increases in temperature occur largely in April, with no significant increase in the peak-evaporation summer months, and have no significant effect on annual evaporation (Skinner and Gullet, 1993; Burn and Hesch, 2006). The increases in temperature in the Canadian prairies therefore have likely little to no significant effect on the hydrological cycle and resulting sediment dynamics downstream at NHCN. In this study, the gradual increase in water flow observed in both pre- and post-channel periods (Figure 2.8 and 2.9) indicates that evaporation caused by regional climactic warming had no observable influence on water flow.

2.5.6 Environmental Influences on the Variation in Turbidity

Variation in non-point source generated turbidity can be explained by environmental and hydrological variables influencing surface and bank erosion, including wind, precipitation, and flow velocity from tributary rivers. The results of the correlations in Table 2.3 show that the 1-day antecedent mean wind and same day water flow had a significant correlation with turbidity (r=0.19 and r=0.27, respectively). In the LWB, persistent high winds have been shown to increase shoreline erosion and nearshore (<12 m) re-suspension of sediments (McCullough et al., 2001). Similar correlations have also been observed using satellite imagery on Lake Winnipeg, where mean 6-hour and 2-day antecedent mean winds were shown to be significantly correlated to suspended sediment concentrations with an r>0.57 (McCullough et al., 2001). The results in this study show that 2-day mean wind was not significantly correlated (Table 2.3). The discrepency in these results is likely due to the difference in measurement techniques, time periods studied, and frequency of turbidity measurements. It is also well studied that streamflow is often strongly correlated with turbidity and suspended sediment concentrations, with the majority of sediment being transported during peak flow events (Leopold et al., 1964; Allan, 1995; Doyle et al., 2005; Ellison et al., 2010; Huey and Meyer, 2010). The significant positive correlation between water flow and turbidity (Table 2.3) coincides with previous studies, however, the relatively small coefficient observed is indicative of the infrequent and irregular collection of turbidity data over the 42-year period.

Precipitation can also influence turbidity, with rainfall events generating greater turbidity through mobilization of surface erodible soils and increased water flow generating channel bank erosion. The time required for precipitation to influence flow downstream is known as the hydrological response-time and is influenced by rainfall duration and intensity as well as river characteristics including catchment area, riparian zone, slope, soil permeability, and landcover (Post and Jakeman, 1995; Goransson et al., 2013). In this study, the greatest correlation between 2-day antecedent precipitation and turbidity was observed at 2-days, indicating that flow generated turbidity as a result of precipitation (Table 2.3). The 2-day response is consistent with previous studies, which have shown that response time varies between a few minutes for small catchments and up to 12 days for large drainage areas (Guy, 1964; Hamilton and Luffman, 2009). A 2-day response time was also observed in a hydropower regulated river in Sweden (Goransson et al., 2013). The correlation between turbidity and accumulated precipitation describes the threshold of water retention on the landscape before significant surface runoff is generated. The results (Table 2.3) indicate that 10-days of accumulated precipitation have the most significant correlation with turbidity. These results are consistent with research by Goransson et al. (2013) who observed an increase in the correlation of turbidity and accumulated precipitation for up to 11-days. The relatively short (2-day) correlation, along with the 10-day water retention threshold are reflective of the geology and landcover in the study area. The peat-covered soils and forested areas characteristic of the Norway House Ecodistrict do not readily generate surface sediment during precipitation events, as these are not characteristically erodible soils. This soil characteristic results in the relatively large water retention threshold of 10 days. Conversely, the 2-day correlation observed is reflective of channel bank erosion processes. This indicates precipitaion events trigger increases of water flow, causing increases in turbidity from the erosion of the cleyey glaciolacustrine sediments exposed on channel banks in the study area. The relatively small correlation coefficients ($r<0.25$) in these results indicate that precipitation and turbidity are not strongly correlated at this location. This is also likely due to the geology and landcover of the area, which is not readily eroded by precipitation or wind and is not largely urbanized, causing greater water retention on the landscape. The extensive shoreline vegetation along the East Channel near the monitoring stations, also have the ability to reduce water flow and increase sediment deposition. The irregular and infrequent turbidity readings, along with the size of the catchment and the large volume of water flowing through the East Channel may also play an important role in attenuating the strength of the correlation.

From the stepwise linear regression model (Table 2.4) 10-day accumulated precipitation and 1-day antecedent mean wind had the largest additive effect on influencing the variability in turbidity, and along with temporal influences, explains a total of 30.47 % of the variability in turbidity measurements. Lana-Renault et al. (2007) has shown that environmental variables such as water flow and precipitation can explain up to 71 % of the observed variability in suspended sediment concentrations. The relatively low r^2 value of 0.31 observed at NHCN (Table 2.4) may be reflective of the infrequency of the turbidity measurements and the large time-scale of the dataset. This relatively low r^2 value may also reflect the large watershed and the multitude of hydrological and climactic processes upstream that can be influencing turbidity in NHCN.

2.5.7 Dissolved Oxygen

The observed decrease in DO in the Nelson River at Norway House (Figure 2.7) is likely due to the decomposition of phytoplankton biomass in the summer of recent years, which increases biological oxygen demand. It is well studied that large phytoplankton blooms have been occuring on the North Basin of Lake Winnipeg since the 1990s, due to increased phosphorus inputs from anthropogenic sources along with increased flooding in the largely agricultural Red River Basin. Cyanobacteria accounts for the majority of the species composition in these phytoplankton blooms (Kling et al., 2011; Schindler et al., 2012). These species are often filamentous and cannot be readily consumed by phytoplankton grazers. Supporting this explanation is a study by Wassenaar (2012), which showed for the summer season that the mean respiration to photosynthesis ratio increased from 2006 to 2008. An increase in this ratio suggests that dissolved oxygen was being consumed faster than it was being produced during these years.

Due to the increased solubility of oxygen in colder water, it is also possible that an increase in water temperature over the years could cause a decrease in dissolved oxygen concentration, however, Wassenaar (2012) demonstrated that there is no correlation between summer dissolved oxygen concentration and temperature in the North Basin of Lake Winnipeg due to large amounts of primary productivity and spatial variability. Based on the reported temperature increases of 1.5 ^{o}C for southern Manitoba in the past century (McCullough, 2015) it is therefore unlikely that an increase in temperature of this magnitude over the 42-year study period would have a significant effect on dissolved oxygen solubility in the North Basin of Lake Winnipeg. A significant decrease in dissolved oxygen due to phytoplankton decomposition is concerning for NHCN because this phenomenon can lead to bottom water hypoxia, fish kills, habitat loss, and can produce dead-zones in the lake (Carpenter et al., 1998; Smith et al., 1999). The increase in turbidity over time (Figure 2.4) due to the above-mentioned changes in watershed hydrology could also reduce dissolved oxygen levels by reducing light penetration and inhibiting photosynthesis. Dissolved oxygen levels may also be affected by Lake Winnipeg regulation due to decomposition of organic matter from flooding, or increased nutrient residence times in the lake during low flow periods (MB Hydro, 2014c).

2.6 Conclusion

The results indicate that the construction of the 2-Mile Channel did not have a significant long-term effect on the turbidity in the source water near NHCN, including the absence of peaks in the measurements directly following 1975, after the channel was built. The gradual increase in turbidity over time is largely due to the upstream hydrology of Lake Winnipeg and its tributaries, including increases in precipitation and water flow in the Red and Winnipeg River Basins, and a decrease in water flow from the less turbid Saskatchewan River. Caution should however be taken from these results given that the information from pre-hydropower development is limited, and historical turbidity data were not collected at regular or frequent intervals. Large amounts of variation in turbidity at this location is attributed to several environmental influences, including the 1-day antecedent wind, and the 10-day antecedent accumulated precipitation, which additively explains approximately 30 % of the variation in turbidity. The increase in water flow at this location is attributed to increases in precipitation from major tributary rivers. The 30 % decrease in mean water flow from the pre- and post-hydropower time periods (1967-1975 and 1975-2014), respectively, is reflective of the total inflows to Lake Winnipeg, which have experienced identical variations, and is not a cause of hydropower development during the mid-1970s.

With the gradual increase in turbidity, and large amounts of reported and observed shoreline and channel bank erosion occuring on the north shoreline of Lake Winnipeg and the 2-Mile Channel, it is possible that suspended sediments in the Nelson River at Norway House are being generated from this area and are exacerbating the effects of suspended sediments generated from upstream tributaries to Lake Winnipeg. In order to determine if sediments are being generated by the erosion occuring directly upstream from the community at the 2-Mile Channel, sediment fingerprinting is required and is the next step in this study.

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3. IDENTIFYING SEDIMENT SOURCES IN NORWAY HOUSE CREE NATION DRINKING WATER USING SEDIMENT FINGERPRINTING

Abstract

Sediment fingerprinting is an increasingly popular technique used to trace the origins of suspended sediments back to the source materials from which they originate using specific physical, chemical, or biological sediment properties that are distinguishable among sources. In Norway House Cree Nation (NHCN), a First Nation located in north-central Manitoba, Canada, suspended sediments in drinking water are an environmental concern for the community based on the contentious history of hydropower development in their territory, including the construction of the 2-Mile Channel in the mid 1970s. The objective of this study was to determine if the 2-Mile Channel generated significant sediments in NHCN drinking water during the study period, compared to other sediment sources.

Passive, time-integrated suspended sediment samples were deployed and collected at six locations near NHCN in the summer of 2014 and supplemental point samples were also collected in the spring of 2015. Source soil samples were collected in the summer of 2014. Samples were analyzed for Cs-137 and spectral reflectance, where 15 colour coefficients were generated. Four distinguishable source areas were identified using a canonical discriminant function analysis: 1) 2-Mile Channel suspended and deposited sediments labelled "2-Mile Suspended", 2) the predominantly organic soils labelled "Organics", 3) the predominantly clay soils labelled "Clays", and 4) the upstream sediment from the natural outlet of Lake Winnipeg labelled "Warren's". The tracers with the best discriminatory power were selected using several statistical tests including the Shapiro-Wilk tes,, biplot analysis, the Kruskal-Wallis H-test, quadratic and stepwise discriminant function analysis. The results of the statistical tests indicated that the colour coefficients Z, G, and B representing the primary virtual component of the colour spectra,

green, and blue, provided the optimal combination of tracers to distinguish the four source areas. These tracers were included in the MixSIAR unmixing model to determine the proportion of sediments generated from each source in two sediment mixtures, the Jack River drinking water intake, and the 2-Mile Channel. The results of the unmixing model indicate that sediments collected at the Jack River drinking water intake largely reflected the source material “Warren’s” (79.3 % (SD 31.2 %)), 9.3% (SD 18.8%) of the sediment reflected the source material “Clays” 8.0% (SD 18.2%) reflected the source “2-Mile Suspended” and the remaining 3.3% (SD 6.4%) of the sediments reflected the source “Organics”. The results indicate that during the study period, sediments originating from the bank erosion of the 2-Mile Channel did not significantly contribute to sediments in the drinking water intake, despite substantial visual evidence of sediment generation from this source. The results indicate that sediments generated in the area are strongly influenced through the West Channel of the Nelson River, by-passing NHCN. This is likely caused by high water levels during the study period which causes Manitoba Hydro to operate the downstream Jenpeg generating station at maximum outflow capacity, influencing water and sediment through the West Channel and towards Jenpeg.

3.1 Introduction

The Norway House Cree Nation (NHCN) is a First Nation located in central Manitoba, Canada. In 1970, Manitoba Hydro was granted an interim license under the Water Power Act for hydropower development along the Nelson River and for the regulation of Lake Winnipeg water levels. Under this license, a series of developments were undertaken through the 1970s including the construction of the 2-Mile Channel, a channel which alleviates the natural constriction of Lake Winnipeg and was one of the three channels built on the upper Nelson River to increase the outflow capacity of the lake. The Northern Flood Agreement was signed in 1977 between Manitoba Hydro and four First Nations, including NHCN, however; based on recent hearings for the final Water Power Act license, Lake Winnipeg regulation remains a contentious issue for First Nations who are still experiencing the impacts (MB CEC, 2015). Consultation between Manitoba Hydro, the province of Manitoba, and First Nations has brought several of these impacts to the forefront, including mercury contamination from flooding, erosion, loss of traditional land, impacts of sediments on water quality, fisheries and fish habitat, increases in debris causing navigational hazards, and loss of the traditional way of life (MB Hydro, 2014a). For NHCN, sediment contamination is concerning due to the erosion of the north shore of Lake Winnipeg over the past four decades and of the 2-Mile Channel, with reported erosion rates of approximately 1.35 m year^{-1} occurring at the channel inlet (MB Hydro, 2014b). Reports from the Jack River drinking water treatment plant also indicate a spike in turbidity in mid-May 2014, indicating that sediment contamination may be affecting the security and reliability of the community’s drinking water source (Appendix A). Increases of suspended sediment in source water is problematic because removal through coagulation and filtration increases the costs of drinking water treatment (Dearmont et al., 1998). Suspended sediments can also act as contaminant vectors, where contaminants such as pesticides, metals, and nutrients are exchanged from the surface of sediment particles into the drinking water source (van den Berg et al., 2001; Hamilton and Crossley, 2004; Yang et al., 2008; ECCC, 2016). Furthermore, increases of sediments containing organic matter can impair drinking water disinfection processes and contribute to the production of disinfection by-products which are classified as carcinogenic and are harmful to human health (Barretta et al., 2000; Nieuwenhuijsen et al., 2000; Chowdhury et al., 2011; Zhao et al., 2014). Identifying the origin of dominant sediment sources in drinking water can be a useful tool for water managers to implement effective and targeted on-the-ground mitigation strategies to increase the safety and reliability of the drinking water source for their community.

Sediment fingerprinting is a technique which can be used to determine the origin of suspended sediments in drinking water. This technique identifies and quantifies a set of properties which provide optimal discrimination between sediment sources and can be used as a fingerprint to track the sediment back to its source material (Collins and Walling, 2004). By measuring the sediment fingerprint of both upstream source soils and downstream suspended sediment mixtures, and employing a statistical unmixing model, the relative contribution of each source in the suspended sediment mixture can be determined (Collins and Walling, 2004). The sediment fingerprinting method is based on the assumptions that suspended sediments will contain properties that are measurable, reflect the source soils from which they originate, and behave conservatively in sediment transport processes or vary in predictable ways along the transport path and over time (Haddadchi et al., 2013; Koiter et al., 2013a) Choosing tracers that will meet the assumptions while providing a high level of statistical discrimination is key to employing this technique. One or multiple sediment properties can be analyzed and used as a tracer to characterize sediment sources in a watershed including physical, biochemical, and geochemical properties (Haddadchi et al., 2013; Koiter et al., 2013a). Some properties which have been used successfully in previous sediment fingerprinting studies include spectral reflectance (i.e., colour) (Grimshaw and Lewin, 1980; Martinez-Carreras et al., 2010; Barthod et al., 2015), radionuclides (Foster and Walling, 1994; Mukundan et al., 2010; Koiter et al., 2013b), isotopic properties (Douglas et al., 1995), magnetic properties (Walling et al., 2005), and biochemical properties (i.e., enzyme activity) (Nosrati et al., 2011).

The selection of sediment properties to use in the fingerprint is based on statistical discriminatory function analyses to achieve optimum source discrimination. In early sediment fingerprinting research, single sediment properties and property ratios were used to discriminate between sources (Oldfield and Clark, 1990; Walling and Woodward, 1992). It was later determined that employing a single sediment property provides inadequate source discrimination when the spatial variability and transport processes of sediments becomes complex (Collins et al, 1998). Consequently, using multiple independent properties that respond differently to environmental controls to form a robust, composite fingerprint has shown to largely improve sediment source discrimination (Collins et al., 1998; Walling et al., 1999; Mukundan et al., 2012).

Spectral reflectance (i.e., sediment colour) is advantageous to use as a sediment fingerprint because it is easily measurable, identifiable, non-destructive, and can be highly accurate to describe and predict soil properties (Pirie et al., 2005; Davis et al., 2009; Pinheiro et al., 2017). Soil colour has traditionally been used to identify soil properties using the Munsell system of colour notation; however; to describe colour as a continuous variable, colour analysis using diffuse reflectance spectrometry is used which allows the reflectance of light from a sample surface to be measured on a continuous gradient. The spectral reflectance of soil will vary depending on the soil organic matter content, redox reactions, moisture content, and through chemical and biological weathering processes, including decomposition (Baumgardner et al., 1969; Krein et al., 2003). Spectral reflectance is also indicative of many geochemical soil properties including clay (absorption in the short-wave infrared spectrum), free-iron oxides (absorption in the visible near infrared spectrum), and carbonates (absorption in the far short-wave infrared spectrum) (Viscara-Rossel and Behrens, 2010; Soriano-Disla et al., 2014). Spectral reflectance has been used successfully as a tracer in sediment fingerprinting studies in the South Tobacco Creek Watershed (STCW), a tributary to the Lake Winnipeg Basin (LWB) in Manitoba, and has proven to be a relatively quick and cost-effective method (Barthod et al., 2015).

An additional sediment property which has been used successfully as a tracer is the radionuclide Caesium-137 (Cs-137) (Wallbrink et al., 1998; Gruszowski et al., 2003; Koiter et al., 2013b). Radionuclide Cs-137 is advantageous in discriminating surface versus subsurface erosional areas due to its highly distinguishable and diminishing concentration with soil depth (Beck, 1966; Ritchie et al., 1970). This characteristic allows radionuclides to be used by researchers to distinguish between erosional areas with depleted Cs-137 and depositional areas with an accumulation of Cs-137 (Walling, 2005; Koiter et al., 2013b). Cs-137 is also favorable as a tracer because it was anthropogenically derived due to high-yield thermonuclear testing throughout the 1950s and 1960s (Perkins and Thomas, 1980) and therefore; behaves conservatively from source to sink in the watershed, while its concentration remains independent of soil type, geology, chemical and biological processes (Walling, 2005; Caitcheon et al., 2012; Olley et al., 2012). Cs-137 diminishes with a known half-life of 30.2 years, resulting in predictable declines in concentration from source to sink (Belmont et al., 2014). Cs-137 has been used successfully as a tracer in conjunction with geochemical properties in the STCW, and has provided valuable insight on the shift of suspended sediment sources from the headwaters to the watershed outlet (Koiter et al., 2013b).

The objective in this study was to employ a sediment fingerprinting technique using spectral reflectance and Cs-137 as tracers to determine the significant sources contributing to suspended sediments at the Jack River drinking water intake in NHCN. A secondary objective of this study was to determine if the 2-Mile Channel specifically could be discriminated from other source areas to determine the relative impact its erosion has on NHCN drinking water.

3.2 Materials and Methods

3.2.1 Suspended Sediment Collection

3.2.1.1 Phillips samplers

Suspended sediment samples were collected using 12 passive time-integrated samplers that were deployed in duplicates at six locations from June 2014 to October 2014 (Figure 3.1). The samplers were built based on the design by Phillips et al. (2000) and consist of a main PVC cylinder that is 1 m in length by 98 mm in diameter. The internal cross section is 7543 mm^2. The main cylinder is sealed by threaded end-caps with threaded O-rings. Drilled into the end caps are inlet and outlet tubes made of semi rigid nylon pneumatic tubing (4 mm diameter by 150 mm length) with internal cross section of 12.6 mm^2. These tubes pass through holes in the centers of the end caps, which are sealed with silicone sealant and extend 20 mm into the main cylinder. A polyethylene funnel is placed over top of the inlet tube to streamline the design and reduce friction. Metal clamps are attached to the front and back of the sampler to secure two metal rings. Aircraft cable was threaded through the metal rings and through a cinder block anchor. The

Phillips samplers were secured at each location by attaching the cable to a tree on the channel bank. Samplers were anchored at approximately 1.2 m water depth from the surface, with the inlet in the direction of the channel flow. The Phillips samplers were emptied in August 2014 and again at the end of October 2014. Samplers were inspected every four weeks. Four samplers were lost and damaged from the 2-Mile Channel in July 2014 and were consequently replaced in August 2014.

The Phillips sampler is designed based on Bernoulli's Principle of hydrodynamics and the law of the conservation of energy. Bernoulli's Principle states that as the speed of a moving fluid (liquid or gas) increases, the pressure within the fluid simultaneously decreases. The law of the conservation of energy states that, in a steady flow, the sum of all forms of energy in a fluid along a streamline is the same at all points on the streamline. In the application of Bernoulli's Principle, as water moves from a constriction into a larger volume, there is a decrease in speed and therefore an increase in potential energy. Based on Bernoulli's principle, water travelling through the Phillips sampler, from a small diameter in the inlet tube into the greater diameter of the main cylinder, will slow down by a factor of >600 relative to ambient flow (Phillips et al., 2000). The reduction in velocity will induce sedimentation within the main cylinder because the cross-sectional area is approximately 1000x that of the inlet tube (Phillips et al., 2000).

Figure 3.1 Map of sample locations for the 12 Phillips samplers deployed in duplicate in the Summer of 2014 near NHCN.

3.2.1.2 Continuous Flow Centrifuge

Insufficient amounts of suspended sediments (<10 g) were retrieved from the Jack River and the Opatinow Channel throughout the summer of 2014 using the Phillips time-integrated samplers, therefore, in the spring of 2015, supplemental samples were collected using the continuous flow centrifuge (US Centrifuge M512). The continuous flow centrifuge is a sampling method that provides a point sample of suspended sediment. Water is pumped continuously into the centrifuge using a high power generator for 6-8 hours and suspended sediments are collected in the centrifuge bowl for analysis. For centrifuge sampling, two locations were selected as proxy locations for the Opatinow Channel: the Feeder Channel and the Jack River Bridge, while the Fisherman's Co-op was used as a proxy location for the Jack River (Figure 3.2). Proxy locations were selected based on easily available road access for centrifuge transportation and proximity to the original sampling sites.

Figure 3.2 Map of the Spring 2015 sampling locations using the continuous-flow centrifuge in NHCN.

3.2.2 Source samples

Source samples (n= 62) were collected directly upstream of each of the six sampling locations (Figure 3.1) to determine the origin and relative contribution to suspended sediments in the Jack River drinking water intake. Sampling locations were primarily identified based on discussion with community members as areas with a potential for erosion that could be contributing to suspended sediments in the drinking water intake. A description of the engagement and relationship building activities are described in Appendix B. Other site selection criteria included visible evidence of erosion, connectivity to the outlet, and access by boat. All source samples were collected upstream of the drinking water intake. Surface soil samples were collected from the riparian zone and into the more heavily forested areas, where accessibility permitted. Landcover throughout the study area is largely forested, with no agricultural development. Samples were taken using a soil corer in the top 0-7 cm of the soil profile, representing the entire A-horizon with each sample consisting of a composite of four subsamples. Erodible road gravels along Hwy 373 and the peat-filled depressions in the bedrock outcrops along the Jack River were collected using a handheld garden shovel to scrape the top 0-7 cm. Channel bank samples were collected in areas upstream of the suspended sediment samplers where a visible and erodible channel bank was accessible by boat, mainly at the 2-Mile Channel (Table 3.1). Channel bank samples were collected in 10 cm increments from the top of the channel bank downwards to represent the channel bank profile. Due to the sheer height of the banks (10 m) and uniformity of the soil at the 2-Mile Channel sampling locations, larger 1 m increments were used after the 30 cm profile depth was reached. Due to the cohesiveness and hardness of the clay textured particles along these banks, samples were collected using a stainless steel handheld garden shovel. For the collection of subsurface deposited sediments, a Ponar grab sampler was used. This sampler consists of two hinged jaws that lower into the sediment by gravitational force, triggering a spring-loaded pin that closes the jaws upon impact. The deposited sediments were collected to capture sediments which were settled out, and could potentially be re-suspended during inclement weather. (Table 3.1).

Table 3.1 Number of source samples and types collected at each sampling location

Sampling Site	Surface	Channel Bank	Suspended sediment	Deposited sediment	Peat	Hwy 373
2-Mile Inlet	6	8	2	1	na	na
2-Mile Outlet	4	8	2	1	5	na
Jack River	6	n/a	n/a	1	n/a	2
Warren's Landing	1	n/a	3	1	n/a	n/a
Opatinow *	n/a	n/a	6	n/a	n/a	n/a
Mouth of Nelson	1	n/a	2	1	n/a	n/a

*Proxy locations were also used including the Jack River Bridge and the Feeder Channel
n/a= Source not available at this sampling location

3.2.3 Analysis: Diffuse Reflectance Spectrometry

Source sediment samples (n=61) and suspended sediment samples (n=22) were analyzed for spectral reflectance and Cs-137. Source samples were air dried for a minimum of 14 days at 21°C to remove moisture before for processing. Suspended sediment samples were collected into a plastic pail and left sealed and undisturbed for a minimum of seven days as per Stokes' law to allow the fine-grained particles to adequately settle to the bottom. Water was then carefully siphoned off the top and the remaining mixture was air dried at 21 °C for a minimum of seven days to remove moisture. Samples to be analyzed for spectral reflectance were scraped out and pulverized using a mortar and pestle and manually sieved to <0.063 mm. Analysis of visible, near-infrared reflectance spectrometry was done using a spectroradiometer (ASD FieldSpecPro, Analytical Spectral Device Inc.). To prepare the samples, a 52 mm petri dish was filled with a sample to reduce glare from the walls of the petri dish onto the sample surface. A ruler was then used to ensure the sample was level to eliminate unevenness causing shading onto the sample surface. A 9.2 cm white reference standard (Spectralon) containing a certified reflectivity was used to calibrate the spectrometer before each sample was analyzed. Petri dishes were then placed onto a 100 mm plate with a black paper ring on the turntable of the spectrometer. The fiber optic cable was placed in a wood support to maintain the fiber optic cable at a 45^0 angle and at a constant (2 cm) distance from the surface of the samples throughout the experiment, resulting in an effective target area of 1.0 cm^2 (Barthod et al., 2015). The light source used to illuminate the samples was a halogen-based lamp (12 VDC, 20 Watt) mounted above the sample at approximately 10 cm (Barthod et al., 2015). Samples were turned constantly and light was collected off the sample through the fiber optic cable and projected onto a holographic diffraction grating where 1 nm wavelengths from 350-2500 nm were separated and measured by detectors. Relative reflectance spectra were returned by the FieldSpecPro and measured using RS3 software. Absolute reflectance spectra were calculated by multiplying the relative reflectance of the sample spectra with the reflectivity of the Spectralon standard. Each sample was analyzed 10 times and an average was computed.

3.2.4.1 Calculation of Colour Coefficients

Fifteen colour coefficients were calculated from the absolute reflectance spectra using the Commission Internationale de l'Eclairage method (CIE, 1932) (Table 3.2). This method describes each colour as a three-dimensional variable with X, Y, and Z, representing brightness, the virtual Y, and the virtual Z component of the primary spectra (Barthod et al., 2015). The coefficients x, y, and L represent the colour difference from blue to red, from blue to green and brightness, while the coefficients a, b, u, and v represent the chromacity coordinates as opponent red-green and blue-yellow scales (Barthod et al.,2015; Viscarra Rossel et al., 2006; Table 3.2). The XYZ variables were converted into RGB coefficients using MATLAB (version 8.5) (Westland et al., 2012; Barthod et al., 2015). Useable RGB colour coefficients are calculated from reflectance spectra by averaging reflectance values of spectral ranges corresponding to the red, green, and blue Landsat bands (630-690 nm, 520-600 nm, 450-520 nm) and multiplying by 255 to get 8-bit colour encoding (Viscarra Rossel et al., 2006; Westland et al., 2012). The remaining 12 colour coefficients were calculated using the following formulas 1-15 (CIE, 1932; Viscarra Rossel et al., 2006).

$$X = K \sum_{\lambda} R(\lambda) \cdot S(\lambda) \cdot \bar{x}(\lambda) \qquad [1]$$

$$Y = K \sum_{\lambda} R(\lambda) \cdot S(\lambda) \cdot \bar{y}(\lambda) \qquad [2]$$

$$Z = K \sum_{\lambda} R(\lambda) \cdot S(\lambda) \cdot \bar{z}(\lambda) \qquad [3]$$

Where λ is the wavelength, S is the spectral distribution of the light source, R is the spectral reflectance of the sample, and $\overline{x}$, $\overline{y}$, $\overline{z}$, are the colour matching functions of the Standard Observer. K is a constant resulting in Y=100 for a perfect white surface.

$$K = \frac{100}{\sum_{\lambda} S(\lambda)\overline{y}(\lambda)} \qquad [4]$$

The chromacity coordinates x and y are given by the following Eq. [5-15].

$$x = \frac{X}{X+Y+Z} \qquad [5]$$

$$y = \frac{Y}{X+Y+Z} \qquad [6]$$

$$L = 116f\left(\frac{Y}{Yn}\right) - 16 \qquad [7]$$
$$a = 500(f\left(\frac{X}{Xn}\right) - f\left(\frac{Y}{Yn}\right)) \qquad [8]$$
$$b = 200(f\left(\frac{Y}{Yn}\right) - f\left(\frac{Z}{Zn}\right)) \qquad [9]$$

with $f(I)= I^{1/3}$ if $I>(6/29)^3$ else $f(I)= (841/108)I+4/29$

$$u = 13L \cdot (u - u_n{}') \qquad [10]$$

$$v = 13L \cdot (v - v_n{}') \qquad [11]$$

$$u' = 4X/(X + 15Y + 3Z) \qquad [12]$$

$$v' = 9Y/(X + 15Y + 3Z) \qquad [13]$$

c, and h were calculated using linear combinations of a and b.

$$c = \sqrt{}(a^2 + b^2) \qquad [14]$$

$$h = tan^{-1}(\frac{b}{a})(\frac{180}{\pi}) \qquad [15]$$

Table 3.2 Fifteen spectral reflectance colour coefficients generated using diffuse reflectance spectrometry and MATLAB adapted from Martinez-Carreras (2010b) Source: Boudreault (2016).

Colour Space Model	Parameter	Parameter abbreviation
RGB	Red	R
	Green	G
	Blue	B
CIExYY	chromacity coordinate x	x
	chromacity coordinate y	y
	Brightness	Y
CIEXYZ	Virtual Component X	X
	Virtual Component Z	Z
Decorrelated RGB	Light intensity (brightness)	L
CIELAB	C.c. opponent red-green scales	a
	C.c. opponenent blue-yellow scales	b
CIELUV	C.c.a opponent red-green sclaes	u
	C.c opponent blue-yellow scales	v
CIELCH	CIE hue	c
	CIE chroma	h

3.2.4 Analysis: Cs-137

In preparation for Cs-137 analysis, all samples were manually sieved down to <2 mm and were packed down with a plunger into plastic jars with the sample weight, height, and geometry recorded. Cs-137 was measured using a gamma-ray spectrometer located in the Landscape Dynamics Laboratory at the University of Manitoba. The spectrometer measures gamma photons that are produced as a result of nuclear fission, where nuclei of radioactive caesium (Cs-137) decay to nuclei of lower energy (Ba-137), emitting 662 keV. The energy resulting from nuclear fission of Cesium-137 within the sample is measured with a high purity germanium radionuclide detector and sent to a multi-channel analyzer, where the activity is measured in Bq kg^{-1}. The spectrometer was calibrated by running Cs-137 and Na-22 standards under the detectors for several hours to identify clear energy peaks, with minor peaks identified using past International Atomic Energy Agency proficiency test samples. These peaks were saved into a calibration file.

Samples were analyzed for a total of 86400 seconds. The Cs-137 activity was obtained from the 662 keV peak (85 %) of Ba-137 and was decay corrected back to the sampling day. Cs-137 activity was analyzed using the following equation:

$\text{Cs activity} = \Sigma \text{Cs} / 0.85 \text{ x Eff-137 x } 1/e\text{-}\lambda t$

Where:

Cs activity = activity of Cs-137 at time of sampling (dps)

ΣCs = counts per second (cps) of 662 keV photo peak

Eff -137 = counting efficiency for Cs-137 at 662 keV for the sample geometry used

λ = decay constant for Cs-137 (years)

t = elapsed time (years) between sampling and counting

3.2.5 Statistical Analysis

Selecting multiple sediment properties that respond differently to environmental factors is considered best practice to form a robust sediment fingerprint (Collins et al., 1998; Walling et al., 1999). This multivariate approach relies on the statistical testing of individual tracers and the subsequent selection of an optimum tracer combination to best allocate suspended sediment to source material (Davis et al., 2009). Several statistical methods have been used in sediment fingerprinting to classify sources and determine the optimal combination of tracers to minimize error and redundancy in the unmixing model including biplot analysis, Kruskal-Wallis H-Test, and discriminant function analysis (Collins et al., 1998, 2010; Walling et al., 2001; Davis et al., 2009). In this study, several statistical methods were used following the process flowchart depicted in Figure 3.3 (Boudreault, 2016). A statistical unmixing model (MixSIAR v.3.3.1) was then employed to determine the relative proportion of each source in the sediment mixture collected at the drinking water intake.

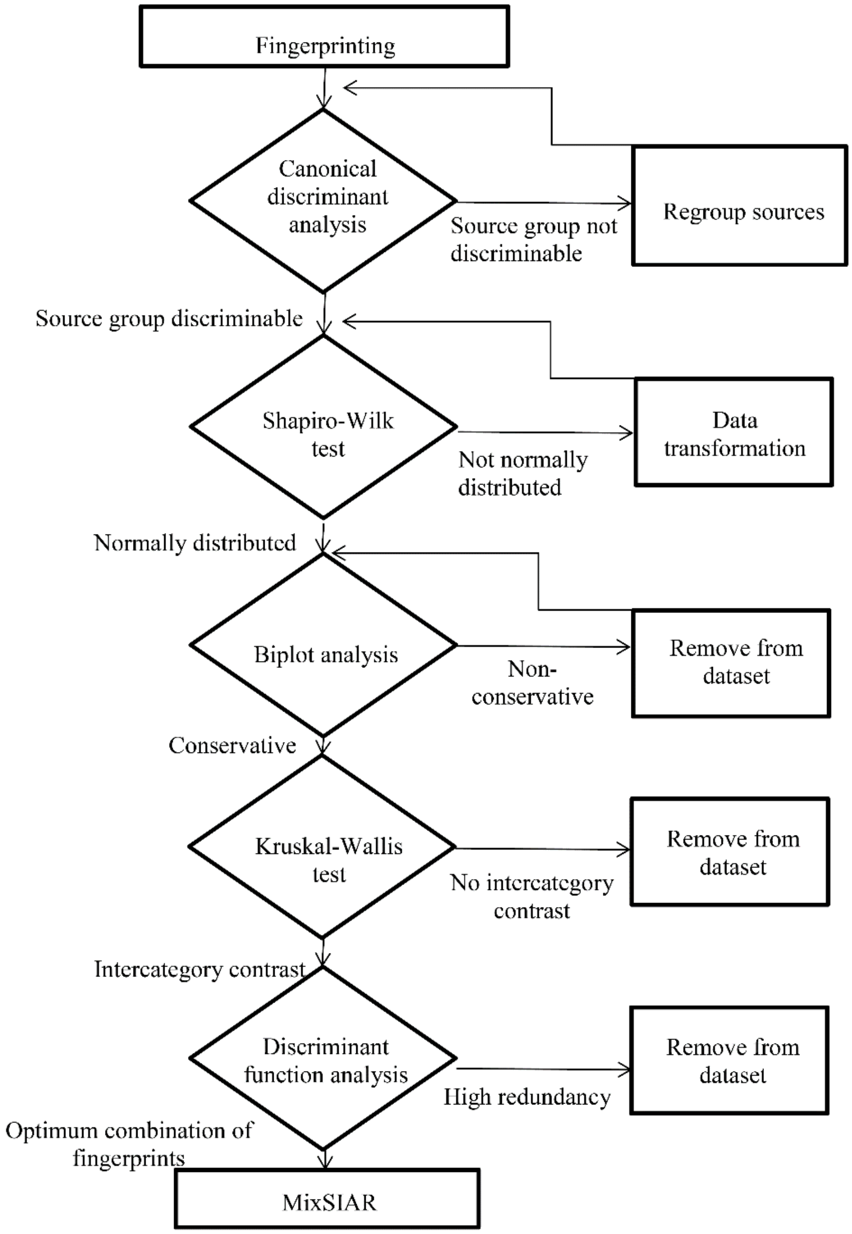

Figure 3.3 Flowchart of the statistical classification of source areas and selection of tracers utilized in sediment fingerprinting. Source: Boudreault, 2016.

The first step in the selection of sediment properties is to determine logical source groups based on statistical differences between sources. A canonical discriminant function analysis (proc CANDISC) in SAS (SAS Institute Inc., 2013) was used to determine source groups which could be discriminated from one another using spectral reflectance and Cs-137 data. The resulting canonical scores were then plotted to determine which sources have discriminatory power. Overlapping sources were grouped together and re-classified to minimize the number of source areas to reduce error in the unmixing model and increase the discriminatory power of the sources (Phillips et al., 2014). One source area "Opatinow" was eliminated due to its inability to be discriminated from other sources and because it is not a source of significant interest to NHCN. Three data points from the source area "Clays" were also eliminated as outliers, since they lied well outside of the respective source grouping.

The second step verified that all sediment properties meet the assumption of normality, an assumption commonly used for the MixSIAR model (Barthod et al., 2015; Boudreault, 2016). To do this, a Shapiro-Wilk Test was performed in SAS for all tracers at a 95 % significant level ($p > 0.05$) (SAS Institute Inc., 2013).

The third step to ensure that all sediment sources have been accounted for is to run a biplot analysis for each pair of sediment properties. Biplots were generated using the graphical user interface MixSIAR in R open source statistical software (R Package, 2016). The two axes in the biplot represent two sediment properties. Source areas are represented by a single point (mean) intersected by a vertical and horizontal error bar representing +/- 1 SD for each property. Sediment mixture samples are represented by single data points. In this study, sediment properties passed the biplot analysis if all mixture samples fell within the standard error bars (+/- 1 SD) of the source means.

The fourth step to determine if sources are statistically different from one another and can therefore be discriminated using sediment property data is the Kruskal-Wallis H-test. In this study, the R open source statistical software (R Package, 2016) was used to perform the Kruskal-Wallis H-test where the null hypothesis assumes that no differences exist between the source groups ($p<0.05$). Sediment properties that failed to reject the null hypothesis were unable to discriminate between sources and were consequently eliminated from the selection. Files are displayed in Appendix C.

The final step is the discriminant function analysis (DFA). This test is used to determine the likelihood that a sample was correctly classified into the correct source group using the sediment properties selected and the stepwise DFA determines the optimum sediment fingerprint to achieve maximum source discrimination based on the minimization of the Wilks' lambda ($p<0.05$). In this study, the DFA was performed on all sediment properties that passed the previous statistical tests outlined in Figure 3.3 using R open source statistical software (R Package, 2016).

Sediment properties that passed these statistical tests outlined in Figure 3.3 were included as properties in the multivariate unmixing model MixSIAR. The final three colour coefficients (Z, B, G) were input into the MixSIAR unmixing model as the sediment fingerprint for the first modelling exercise and the previous 8 sediment properties (X, Z, Y, L, h, R, G, B) were also run in a second modelling exercise to compare the results of the sediment mixture proportions with both tracer combinations. The unmixing model was run using the "long" Markov-Chain Monte-Carlo to ensure that the model reached convergence. The Jack River mixture was analyzed along with the 2-Mile Channel mixture to verify the results.

3.3 Description of Statistical Tests

3.3.1 Canonical Discriminant Function Analysis

Aerial photos, visual inspections, land user interviews, and land mapping are all techniques used to classify sediment sources (Krause et al., 2003; Minella et al., 2004). In sediment fingerprinting studies, there is a need to minimize the number of sources included in the unmixing model based on evidence that an increased number of sources increases the uncertainty of the source contribution, particularly if there are more than six sources (Walden et al., 1997; Nosrati et al., 2014; Phillips et al., 2014; Barthod et al., 2015). Grouping similar sources together and re-classifying them is required to use unmixing models such as MixSIAR effectively. The canonical discriminant function analysis is a multivariate test that computes linear functions of sediment properties resulting in maximal separation between source groups. Each source sample is assigned two canonical scores based on the discriminant functions. The first canonical score is the maximum multiple correlation from the linear combination of sediment properties of the sample. The second score is the linear combination uncorrelated with the first canonical variable that has the maximum multiple correlation with the source group. Plotting the canonical scores on a scatterplot produces a visual representation of the dimensionality of each source. Sources with a high degree of overlap on the scatterplot are not able to be discriminated in the unmixing model and should be combined with similar sources if possible and re-classified. Alternatively, analyzing for additional tracers that display greater discriminatory power would also satisfy the source classification.

3.3.2 Shapiro-Wilk Test

One of the key assumptions of the MixSIAR unmixing model is that sediment property data are normally distributed. Datasets that violate this assumption can result in misrepresentation of the data, leading to inaccuracies in the results of the source contributions (Barthod et al., 2015). The Shapiro-Wilk Test is a commonly used test to verify the assumption of normality for small sample sizes, with the null hypothesis indicating that the population is normally distributed.

3.3.3 Biplot Analysis

Biplots are two-dimensional scatterplots used in sediment fingerprinting to provide a visual representation of the source areas and sediment mixture data. Biplots are used as a preliminary technique to ensure that for each sediment property, mixture data lies within the error bars of the source area, indicating that all major source groups have been accounted for, and is sometimes called the “range test”. Omitting major sources in the MixSIAR model may lead to inaccurate and nonsensical results because the model is designed to fit a residual error term and therefore, will always generate a solution (Stock and Semmens, 2013; Nosrati et al., 2014). Consequently, analyzing for additional sediment properties or collecting additional source samples may be necessary if the selected tracers cannot account for all sources. The biplot analysis is also used as a means for eliminating sediment properties that do not behave conservatively, which is one of the main assumptions underlying the sediment fingerprinting technique. Physical properties such as colour, particle size and density, along with several geochemical properties including organic matter content, iron oxides and aluminum oxides have shown non-conservative behaviour by exhibiting fluctuations due to weathering processes during sediment storage and transport (Motha et al., 2002; Motha et al., 2003; Davis et al., 2009).

In the biplot analysis, non-conservative behaviour is also displayed by mixture data lying outside of the error bars of the sources. MixSIAR allows the user to produce a biplot for every possible pairing of sediment properties to evaluate each property and eliminate those that do not classify the mixture data within the source data range.

3.3.4 Kruskal-Wallis H-Test

The Kruskal-Wallis H-test is used in sediment fingerprinting studies to determine if sources are statistically different from one another and can therefore be discriminated based on the sediment property data. This rank-based non-parametric test evaluates differences between two or more groups of an independent variable (sediment source) from a continuous dependent variable (sediment property). It was first introduced in sediment fingerprinting research as part of a two-stage statistical selection procedure to identify the optimal composite sediment fingerprint based on an initial group of sediment properties (Collins et al., 1996; Collins et al., 1997). The Kruskal-Wallis H-test continues to be used in studies today as part of the suite of statistical tests used to select the optimal sediment properties that offer the greatest source discrimination (Collins and Walling, 2002; Carter et al., 2003; Stone et al., 2014).

3.3.5 Discriminant Function Analysis

The quadratic DFA is used to determine if there are tracers that are redundant, or describing the same sediment property. DFA is a multivariate predictive model used in sediment fingerprinting to predict membership to a categorical variable (source group) based on the values of continuous variables (sediment properties). From the DFA, it is possible to identify the number of source samples correctly classified into their respective groups. Following the quadratic DFA, a stepwise DFA is used to determine the optimum combination of sediment properties to be used in the final sediment fingerprint. In the stepwise DFA, sediment properties are evaluated step-by-step to determine which property provides the greatest discrimination between sources while minimizing the number of sources to avoid problems associated with over-parameterization in unmixing models (Collins and Walling, 2002; Nosrati et al., 2014). The property with the largest discriminatory power is added to the model and the stepwise selection repeats until no further addition of properties provides a significant increase in discrimination. The DFA selects sediment properties based on the minimization of the Wilks' lambda (Collins and Walling, 2002). The Wilks' lambda value is minimized and approaches zero as sediment properties are added into the model and the variability within the source groups is reduced relative to the variability between sources (Smith and Blake, 2014). The sediment properties that contribute significantly to the discriminatory power of the model ($p<0.05$) constitute the final sediment fingerprint.

3.3.6 MixSIAR

MixSIAR is a model which uses a graphical user interface to quantify contributions of the source material to a mixture of interest. MixSIAR was developed as a collaborative coding project between the makers of MixSIR and SIAR for ecological research to determine population structure, diet composition, and animal movement; however, it has many other uses including pollutant sourcing, carbon sourcing in soils, and suspended sediment sourcing in waterbodies (Stock and Semmens, 2013).

MixSIAR uses a hierarchical Beyesian model framework to determine source contributions based on probability distributions (Moore and Semmens, 2008; Stock and Semmens, 2013). The fundamental components of a Beyesian analysis can be outlined in 4 steps: 1) Formulation of the probability model, 2) Determining the prior distribution that quantifies the uncertainty in the model, 3) Construction of the likelihood function based on data observations and development of the posterior distribution based on the product of the likelihood function and the prior distribution, and 4) Calculation of quantities of interest based on the posterior distribution (Glickman and Van Dyck, 2010). A large advantage to using the Beysian model framework for sediment fingerprinting over linear models using frequentist statistics is the ability to translate all known and residual errors into the model results (Moore and Semmens, 2008; Ward et al., 2010; Cooper et al., 2014; Nosrati et al., 2014). Other advantages include the ability to partition multiple sources, include categorical and continuous covariates such as time and site, and prior information (Semmens et al., 2009; Parnell et al., 2013; Nosrati et al., 2014; Cooper et al., 2014).

To construct the likelihood function, given prior information, the MixSIAR model uses Markov-Chain Monte-Carlo (MCMC) as its model fitting framework to estimate sediment source contributions. In MixSIAR, the MCMC uses the Gibbs sampling simulation algorithm to obtain posterior estimates approximated from a multivariate probability distribution (Cooper et al., 2014). In Gibbs sampling, posterior estimates are generated from multiple simulations of random sampling of the input variables and model parameters (Nosrati et al., 2014). The MCMC simulation then translates uncertainties from model inputs to model outputs by calculating the probability distributions for the proportional contribution of each source to the mixture in the above-mentioned stages (Nosrati et al., 2014; Smith and Blake, 2014). The Markov chain is generated as the number of simulations increases and the equilibrium probability distribution converges to the posterior distribution. In MixSIAR, convergence is illustrated through trace plots and model diagnostic tests. A burn-in procedure also contributes to model convergence by eliminating the beginning values of the Markov-Chain. Once the model has converged, sediment source proportions are generated as a mean and standard deviation of the simulations.

3.4 Results

3.4.1 Source Discrimination

From the canonical discriminant function analysis, four unique source areas were identified and are largely distinguishable including 1) Clays, representing the predominantly clay soils of the Jack River and the 2-Mile Channel, 2) Warren's, representing the suspended sediment collected in areas upstream of the drinking water intake including Warren's Landing, the mouth of the Nelson River, and the Jack River, 3) Organics, representing the predominantly peat surface soils, and 4) 2-Mile Suspended, representing the suspended sediments collected at the inlet and outlet of the 2-Mile Channel (Table 3.3; Figure 3.4). After source re-classification, 85.6 % of the variability in the sources is explained by the first discriminant function, while 9.5 % is explained by the second, totalling 95.1 %, demonstrating that the four re-classified sources are largely distinguishable (Figure 3.4). From this analysis, it was determined that the soils from the 2-Mile Channel banks could not be discriminated as a separate, unique source using Cs-137 and colour, however; given the predominant bedrock geology along the Jack River minimizing surface erodible soils, it was determined that the "Clays" would largely represent the 2-Mile Channel banks (Table 3.3). The suspended sediments collected from the 2-Mile Channel were unique and distinguishable and therefore, it was determined that Cs-137 and colour adequately distinguish the sources of interest for NHCN and would continue to be used as sediment properties in the study.

Table 3.3 Source sample descriptions and re-classification based on canonical discriminant function analysis

Source	Source Description	Re-Classification	# of samples
2-Mile Channel Bank	Clay subsurface soils	Clays	32
2-Mile Surface	thin topsoil overlying clay/sandy soil	Clays	
Jack River Surface	thin topsoil overlying clay soils	Clays	
Hwy373	surface clays with road sand	Clays	
Mouth Nelson Suspended	Organic particles	Warren's	8
Warren's Landing suspended	Sands/organic particles	Warren's	
Jack River deposited upstream of the intake	Fine-grained substrate	Warren's	
2-Mile Peat	Peat along 2-Mile Channel	Organics	6
Mouth Nelson surface	Mosses and peat deposits in rock depressions	Organics	
2-Mile Suspended and deposited	Organic particles mixed with fine-grained sediments	2-Mile Suspended	6
Opatinow	Particles of organic matter	n/a	7

n/a= Unable to discriminate source area

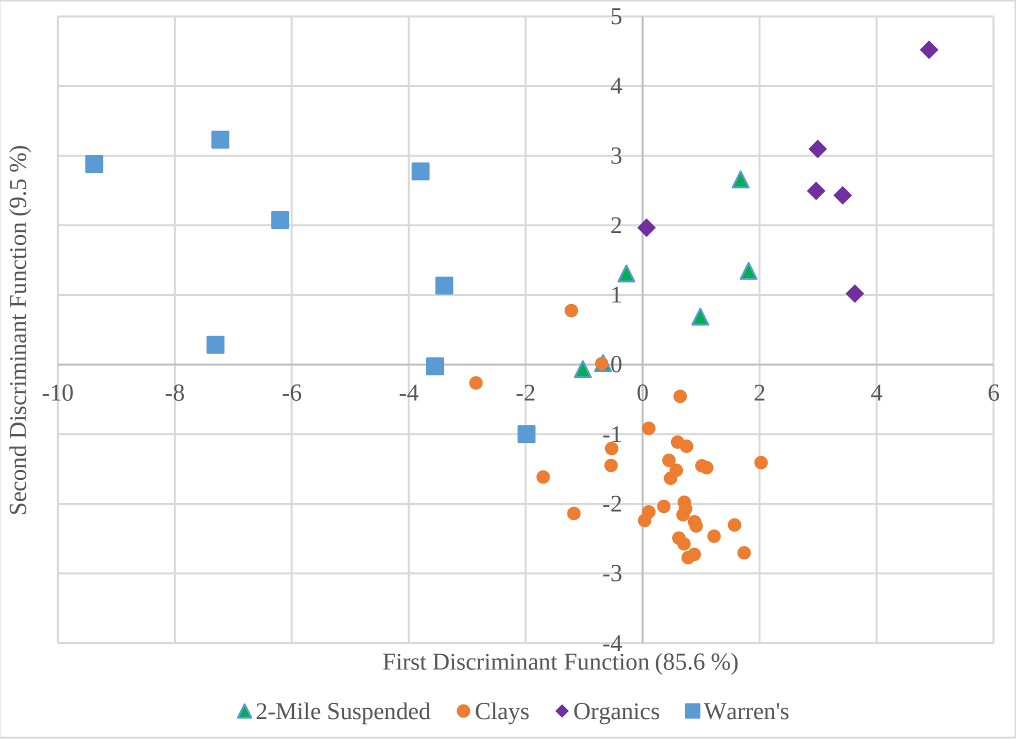

Figure 3.4 Scatterplot of canonical scores of the source samples generated from radionuclide Cs-137 and spectral reflectance in the discriminant function analysis and classified into four main source groups including 1) Clays, 2) Organics, 3) Warren's and 4) 2-Mile Suspended

3.4.2 Shapiro-Wilk

The MixSIAR unmixing model assumes that all sediment fingerprinting properties are normally distributed; therefore, the 15 colour coefficients and Cs-137 were tested for normality using the Shapiro-Wilks test. From this analysis, Cs-137 was eliminated from the selection due to non-normality for each source ($p>0.05$). All the colour coefficients demonstrated normality in a minimum of one source area and were kept in the selection for further analysis.

3.4.3 Biplot Analysis

Biplot analysis was used to determine which sediment properties could classify the mixture samples within the source data range. From the biplot analysis, it was determined that eight colour coefficients showed the greatest discriminatory power: X, Z, Y, L, h, R, G, B (Figure 3.5). The chromacity coordinates (x and y), the opponent red-green and blue-yellow scales (a,b,u,v) and hue (c) were eliminated at this stage due to the inability to classify the mixtures within the target range. In the biplot analysis, sources that are highly distinguishable are plotted further apart and similar sources are plotted closely together. The results show that the four source areas appear to be discriminable at this stage, given relatively low standard error bars; however, it was observed that the sources "Clays" and "Warren's" contained similar source mean values, and could be potentially difficult to discriminate in the MixSIAR unmixing model (Figure 3.5). The eight selected properties also show that the source "Organics" is highly distinguishable from the other three sources. Files used for biplot analysis in MixSIAR are displayed in Appendix D.

The main mixture of interest in this study is the Jack River drinking water intake; however, other mixtures were included in the biplot analysis including the 2-Mile Channel, Warren's Landing, and the mouth of the Nelson River to verify that all sediment mixtures were represented in the source samples collected (Figure 3.5). In this study, the 2-Mile Channel mixture was used specifically to verify the model results since the mixtures collected in the channel were subject to extreme channel bank erosion and would theoretically reflect the source "Clays" in the model output.

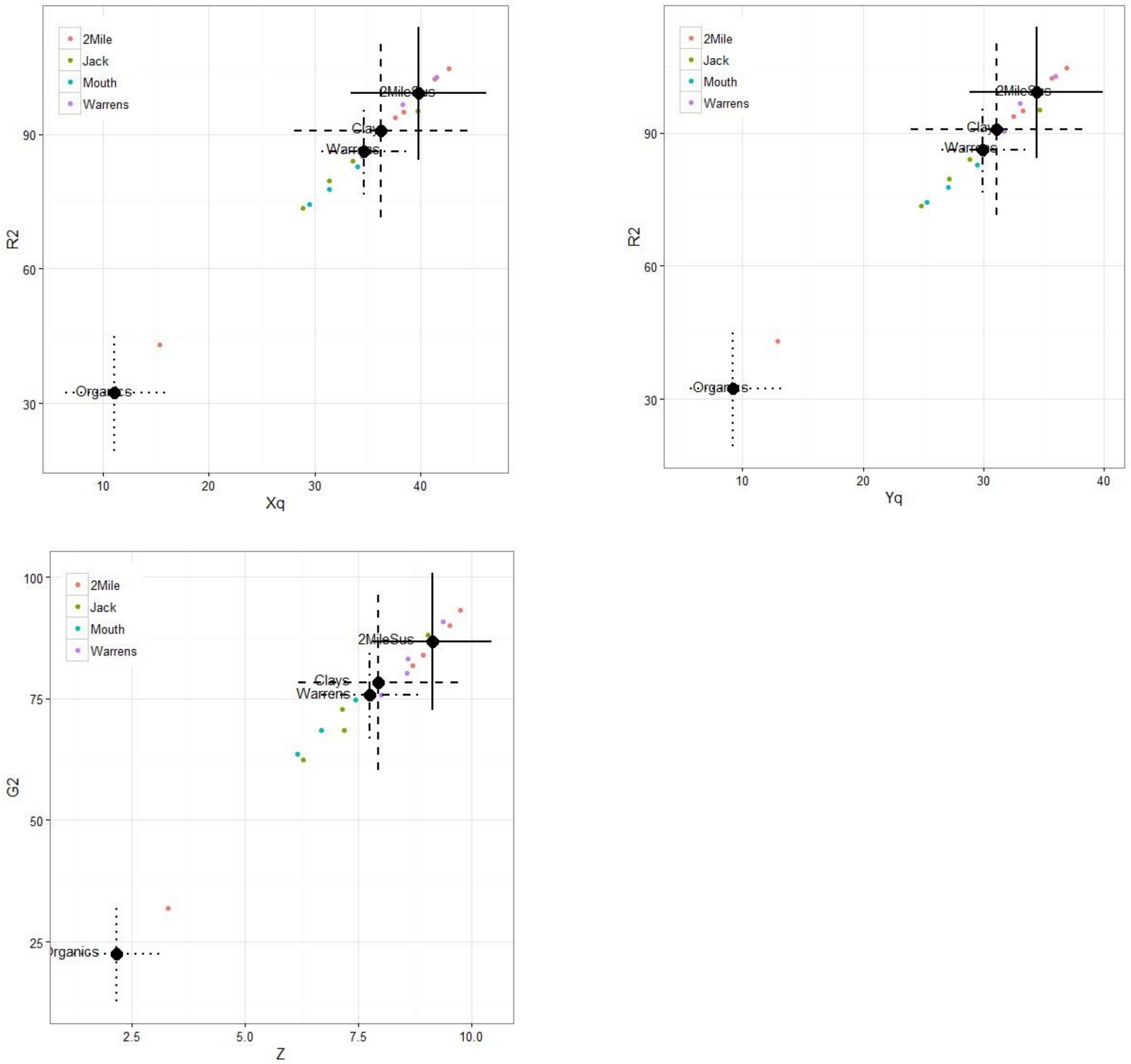

Figure 3.5 Three biplots generated from MixSIAR using all remaining sediment properties to verify that the four suspended sediment mixtures lie within the standard error bars of the sources

3.4.4 Kruskal-Wallis H-test

The results of the Kruskal-Wallis H-test determined that for each of the remaining eight sediment properties that were analyzed, there were statistically significant differences ($p<0.05$) among the four source groups (Table 3.4). These results indicate that all eight sediment properties will remain in the selection for further statistical testing.

3.4.5 Quadratic Discriminant Function Analysis

Spreadsheets of the DFA files used in MixSIAR are displayed in Appendix C. The results of this test showed the percentage of sources correctly classified using each of the remaining eight colour coefficients with 69.2-71.3% of samples correctly classified (Table 3.4**).** The stepwise DFA showed that Z, G, and B are significant variables ($p<0.05$) and combined, provided the optimal number of source samples correctly classified with 33.3%, 81.3%, 50%, and 75% for the sources 2-Mile Suspended, Clays, Organics, and Warren's, respectively. Given these statistical tests, it was determined that the MixSIAR model would be run with the remaining three properties (Z, B, G) and again with the prior eight properties (X, Z, Y, L, h, R, G, B) to compare the results and assess the effectiveness of using the minimized optimal tracer combination.

Table 3.4 Results of the Kruskal-Wallis H-test and the quadratic DFA in R to determine the inter-category contrasts among source groups and the % of sources correctly classified using the remaining eight colour coefficients: X, Z, Y, l, h, R, G, B

	Kruskal-Wallis H-test		DFA % Correctly classified				
Property	F-statistic	p-value	2-Mile Suspended	Clays	Organics	Warren's	Total (%)
X	**16.45356**	<0.05	0	96.9	83.3	0	69.2
Z	**17.519**	<0.05	0	96.9	100	0	71.2
Y	**16.01887**	<0.05	0	96.9	83.3	0	69.2
l	**16.01887**	<0.05	0	96.9	83.3	0	69.2
h	**23.09919**	<0.05	50	96.9	66.7	0	73.1
R	**16.72474**	<0.05	0	96.9	83.3	0	69.2
G	**16.01887**	<0.05	0	96.9	83.3	0	69.2
B	**17.10609**	<0.05	0	96.9	100	0	71.2

The Kruskal-Wallis H-test showed that all remaining eight sediment properties displayed statistically significant inter-category contrast among the source groups ($p<0.05$). The quadratic DFA showed that none of the remaining eight sediment properties individually could correctly distinguish and classify the “2-Mile Suspended” sediment mixture and the “Warren’s” sediment mixture into the correct source group (Table 3.4). The results are consistent with the biplot analysis (Figure 3.5), displaying the three sources overlapping, and indicating that when a single sediment property is analyzed, only one of the three sources can be correctly classified. The total percentage of mixtures correctly classified varied from the properties between 69.2 % and 73.1 %, indicating that the majority of samples were correctly classified, with the sources “Clays” and “Organics” showing the largest percentage correctly classified (Table 3.4).

The results of the stepwise DFA indicate that the three sediment properties Z, B, and G were statistically significant based on the minimization of Wilks-lambda. From this analysis, it was observed that the addition of each additional sediment property changed the % of source samples correctly classified into their respective source groups. The combination of Z+B+G was chosen as the final sediment fingerprint based on the largest total % of samples correctly classified (71.2 %) while minimizing the number of sources with 0 % (Table 3.5). A minimum number of three tracers is also required to classify four sediment sources in the modelling software MixSIAR.

Table 3.5 Results of the stepwise DFA in R to determine the optimum combination of sediment properties for maximum source discrimination

					% Correctly classified			
Property	F-statistic	P-Value	Fingerprint combination	Total %	2-Mile Suspended	Clays	Organics	Warren’s
Z	25.743633	<0.05	Z	71.2	0	96.8	100	0
B	4.910218	<0.05	Z+B	69.2	50	84.4	83.3	13
G	18.446425	<0.05	Z+B+G	71.2	33.3	81.3	50	75

3.4.6 MixSIAR modelling

Using the three final sediment properties Z, G, and B, the MixSIAR modelling results indicate that 79.3 % (SD 31.2 %) of sediments collected from the Jack River drinking water intake were reflective of the source “Warren’s”, 9.3 % (SD 18.8 %) were reflective of the source “Clays”, 8.0 % (SD 18.2 %) were reflective of the source “2-Mile Suspended” and the remaining 3.3 % (SD 6.4 %) were reflective of the source “Organics” (Figure 3.6). The 2-Mile Channel mixture indicated that 81.5 % (SD 31.5 %) of the sediments reflected the source “Clays”, 10.8 % (SD 27.1 %) reflected the source “2-Mile Suspended”, 6.5 % (SD 20.5 %) reflected the source “Warren’s” and 1.1 % (SD 3.0 %) reflected the source “Organics” (Figure 3.6). This result verifies that the model is classifying the mixture correctly since we would expect the large majority of the 2-Mile Channel mixture to reflect the source “Clays” (Figure 3.6). MixSIAR data files are displayed in Appendix D. Using the sediment colour properties (X, Z, Y, L, h, R, G, B) in the MixSIAR model to compare the results showed similar conclusions (Figure 3.6 and 3.7). The model produced similar results for both mixtures, however; the standard deviation for each estimate was noticeably reduced for each of the four sources using the eight-tracer combination (Figure 3.7). MixSIAR data files are displayed in Appendix E.

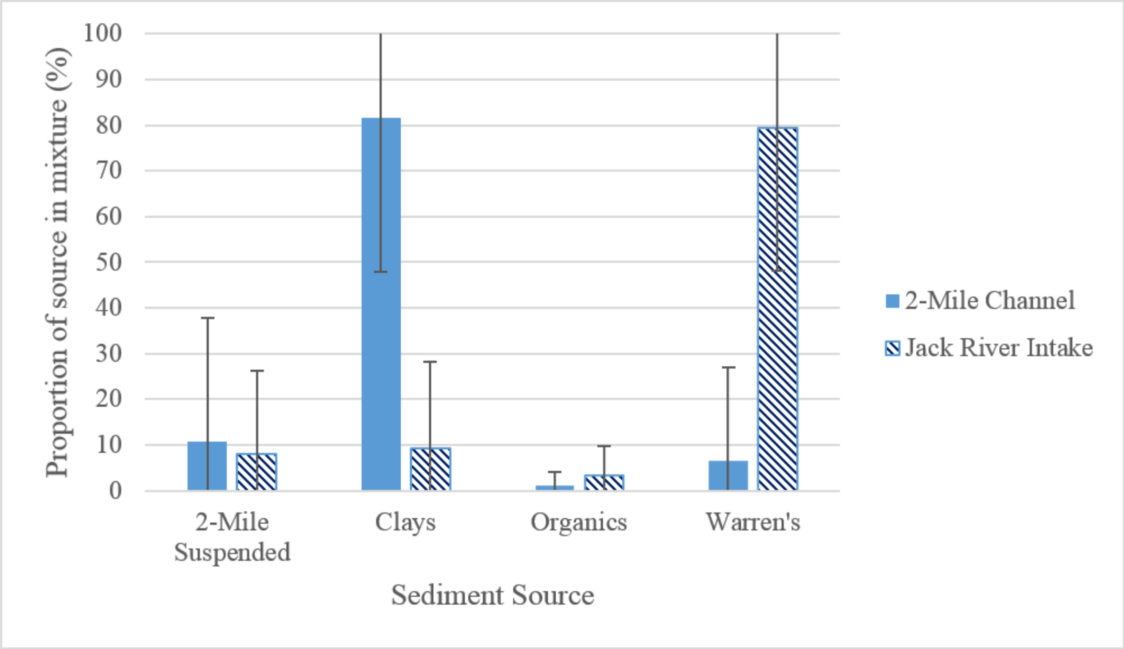

Figure 3.6 Bar graph of sediment source apportionment for the Jack River drinking water intake and 2-Mile Channel suspended sediment mixtures using the optimum sediment property combination Z, G, B as the sediment fingerprint.

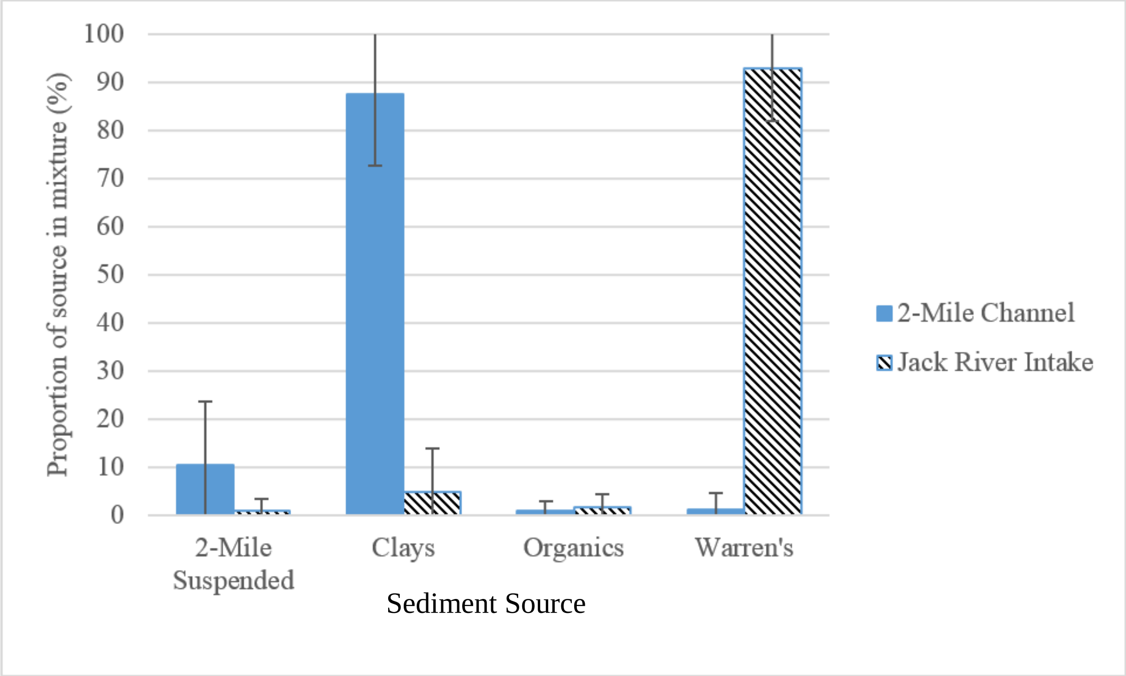

Figure 3.7 Bar graph of sediment source apportionment for the Jack River drinking water intake and 2-Mile Channel suspended sediment mixtures using the eight tracers X, Z, Y, l, h, R, G, B as the sediment fingerprint.

3.5 Discussion

3.5.1 Sediment Contributions to NHCN Source Water

The results of the sediment source apportionment in MixSIAR show that the large majority of sediments collected in the Jack River near the drinking water intake were reflective of the source “Warren’s”, representing the sediments originating upstream at Warren’s Landing, the mouth of the Nelson River, and deposited in the Jack River. For NHCN, the results indicate that during the study period, the sediments generated from 2-Mile Channel erosion did not significantly contribute to suspended sediment at the drinking water intake. Previous sediment fingerprinting studies in agricultural watersheds have indicated that channel banks can be a dominant suspended sediment source (Gellis and Noe, 2013; Koiter et al., 2013b; Voli et al., 2013). The visual evidence of substantial erosion from the 2-Mile Channel (Figure 1.4) also supports the hypothesis that channel bank erosion would be a significant contributor, however, the results are largely indicative of the soil and landscape characteristics of the NHCN study area and the operation of the Jenpeg hydropower generating station, influencing sediment transport.

3.5.2 Water Levels and Jenpeg

The inflows to Lake Winnipeg from major tributaries, including the Winnipeg River, and the Red River, have been increasing over the past 100 years, as described in the previous chapter (Table 2.6; McCullough, 2015). This is caused largely by increased precipitation along with land use changes in the Lake Winnipeg Basin. With greater water volumes and increasing water levels in Lake Winnipeg, Manitoba Hydro is required to operate the Jenpeg hydropower generating station at or near maximum outflow capacity, in order to maintain Lake Winnipeg within the operating limit of 216.7-217.9 MASL described in their *Water Power Act* license. The operation of Jenpeg at maximum outflow produces greater water and sediment transport through the West Channel of the Nelson River, allowing sediments generated upstream of NHCN to by-pass the community and flow westward (MB Hydro, 2014c). Approximately 15 % of total Lake Winnipeg outflow passes through the East Channel (CAMPP, 2014). Based on the real-time hydrometric data retrieved by the Water Survey of Canada (Station #05UB001), water levels surpassed the operating limit of 217.9 MASL in the months of July 2014-August 2014, coinciding with study period. This indicates that the Jenpeg dam was operating at or near maximum outflow capacity, further influencing sediment and water transport through the West Channel of the Nelson River, and by-passing NHCN.

3.5.3 Landscape Characteristics

Several landscape characteristics may also be contributing to the relatively low proportion of 2-Mile Channel bank sediments (labelled as “Clays”) in the Jack River (Figure 3.6 and 3.7). Primarily, the drinking water intake is located downstream of several smaller tributary rivers such as the Opatinow Channel, the Gunisao River, and a small feeder channel (Figure 3.2). These tributary rivers are originating from inland lakes in the boreal shield ecozone, in the Hayes River Upland ecoregion, which is characterized by bedrock outcrops, deposits of ridged to hummocky till covered by thin clayey lacustrine deposits and overlain by shallow to deep peat materials (Smith et al., 1998). The boreal shield region in Canada is known to provide many ecosystem services including carbon sequestration and water filtration (Schindler and Lee, 2010), indicating that the tributary rivers flowing into the Jack River are likely discharging water that is low in sediments, contributing to water clarity. The Google Earth© satellite imagery also indicates that the tributary discharges are contributing to a dilution effect, as indicated by the shift in the light reflectance from the mouth of the Jack River to the drinking water intake (Figure 3.2). Another important feature of the Jack River is the extensive shoreline vegetation

(Mb Hydro, 2014b) (Figure 2.2). Aquatic macrophytes including cattails (*Typha* spp.) have been shown to provide many water purification services in wetlands including water filtration by decreasing water velocity, allowing fine sediments to settle out, and absorbing contaminants and nutrients (Reddy, 1983; Koskiaho, 2003; Gottschall et al., 2007; Maddison et al., 2009). The extensive shoreline vegetation along the Jack River (Figure 2.2) indicates that water filtration and sediment deposition are likely contributing to water clarity. Visual evidence of sediment deposition upstream of the Nelson River was also witnessed at the outlet of 2-Mile Channel, where a delta has formed (Figure 3.9). Additionally, the relatively low sediment volume in the Jack River, as indicated by the small quantities (<10 g) of sediment collected by the time-integrated samplers deployed in this area indicate that sediment deposition and sediment dilution were potentially contributing factors. Despite the historical evidence of increasing sediment concentrations in NHCN (Figure 2.4 and 2.6) and the local data showing a spike in turbidity (Appendix A), the results indicate that several environmental and hydrological factors may have contributed to the relatively low proportion of 2-Mile Channel generated sediment at the drinking water intake.

Figure 3.8 Map of the main tributary rivers to the Jack River including the Gunisao River, Opatinow Channel, and the Feeder Channel.

Figure 3.9 Photograph evidence of sediment deposition and the formation of a delta at the outlet of the 2-Mile Channel near NHCN, May 2014.

3.5.4 Sources of Error in MixSIAR

MixSIAR incorporates several features to reduce error and uncertainty compared to previous unmixing models including the addition of discrimination uncertainty, concentration dependence, categorical covariates, multiplicative error structures, and source-tracer covariance (Stock and Semmens, 2013). Despite these improvements, error and uncertainty in modelling exercises is inevitable and must be considered in the interpretation of the results. In this study, several statistical analyses were employed to minimize error in MixSIAR including the canonical DFA, biplot analysis, Kruskal-Wallis H-Test, and the quadratic and stepwise DFA. This combination of statistical tests ensures that the number of tracers is kept low to avoid redundancy in the fingerprint composition as described by Phillips et al. (2014), and statistically validates the ability of tracers to discriminate between sources, while ensuring that no sources are excluded. The normality tests on the selected properties also ensures that the data meet the model assumptions. To better interpret the results which show relatively small proportions of 2-Mile Channel derived sediments at the Jack River drinking water intake, it is important to understand sources of error in the MixSIAR model which could be confounding the result. Stock and Semmens (2013) have identified four areas where MixSIAR could produce misleading results: 1) The Markov-chain Monte-Carlo not reaching convergence; 2) there is a missing sediment source; 3) model options were incorrectly selected; and 4) discrimination or correction factors were incorrectly selected. In this study, several methods were used to ensure these sources of error were reduced. Model convergence was tested using the model diagnostics, indicating that both the diagnostic tests (Gelman-Rubin and Geweke) passed for model convergence. Missing sources were verified through the biplot analysis, indicating that all mixture samples were contained in the standard error bars of the sources (Figure 3.5). Missing sources are particularly problematic for the MixSIAR model, since the results will always generate the sum of source contributions of 100 %, regardless of model inputs (Phillips et al., 2014). Model options were selected based on the processes outlined in Stock and Semmens (2013) and correction factors in this study were set to 0, indicating that tracers were not expected to magnify or dissipate in considerable amounts from source to sink, in agreement with similar studies (Martinez-Carreras et al., 2010; Barthod et al., 2015). This factor however remains a source of error given that colour tracers were used in the final fingerprint, and may exhibit non-conservative behavior (Phillips and Marion, 2001; Martinez-Carreras et al., 2010).

Sediment fingerprinting is based on the primary assumption that sediment properties will reflect their source material and can be used as tracers to track sediment back to its source (Koiter et al., 2013a). Sediment properties should exhibit linearly additive behaviour during mixing and conservative behaviour during erosion and transport (Foster and Walling, 1994; Lees, 1997; Koiter et al., 2013a). Colour coefficients have been shown to exhibit linearly additive behaviour during mixing (Barthod et al., 2015), however, the conservativeness of colour coefficients requires further study since these properties are sensitive to physio-chemical changes during sediment transport such as particle size sorting and enrichment, iron oxidation, and organic matter decomposition (Summers et al., 2011; Koiter et al., 2013a; Brosinsky et al., 2014). The colour coefficients l, a, b, u, and v have been shown to exhibit relatively low variation when immersed in river water (Legout et al., 2013), however, these properties were not used in the current study. The utilization of potentially non-conservative physical properties remains a contentious issue in sediment fingerprinting and further research is required to fully understand the possible transformations occurring from source to sink. Furthermore, particle size and organic matter content have been shown to influence the concentration of certain sediment properties (Yu and Oldfield, 1989; Horowitz, 1991; He and Owens, 1995). Correction factors have been employed to account for these transformations from source to sink (Walling and Woodward, 1995; Collins et al., 1997; Motha et al., 2003), however, it has been shown that incorporating correction factors that are not fully understood can result in over-correction and misleading results (Collins et al., 1997). Consequently, more recent studies in sediment fingerprinting have recommended that few or no correction factors be used due to the complex relationship between particle size, organic matter, and sediment property concentration (Martinez-Carreras et al., 2010; Smith and Blake, 2014). In this study, sieving samples to <63 µm prior to colour analysis ensures comparability of the samples from source to sink while no other correction factors were employed.

3.5.5 Rejection of Cs-137

It has been recommended that the selection of sediment properties used in fingerprinting should include properties from different groups, such as a combination of physical, chemical, or mineralogical properties (Mukundan et al., 2012). The rejection of Cs-137 from the final sediment fingerprint in this study violated this recommendation and may have compromised the reliability of the study results with spurious source-sediment linkages (Collins and Walling, 2002). Cs-137 was however, eliminated from the sediment fingerprint because it failed to exhibit normal distribution for any of the sources. This was likely caused by the substantial soil movement occurring throughout the 2-Mile Channel, causing surface soils to slump and become dislodged, and depositing onto subsurface soil layers (Figure 3.10). The historical construction in the area also brought into question if surface soils containing Cs-137 had been previously buried, as some subsurface samples contained high values of Cs-137. The 2-Mile Channel also displayed substantial variability from the inlet to the outlet, with sandy surface soils characteristic of soil deposition in the middle of the channel, potentially confounding the distinction between surface and subsurface soil layers in this area (Figure 3.11). Lastly, Cs-137 also displayed erroneous results in the biplot analysis, where it proved to be unable to classify mixtures within the mean and standard deviation of the sources, with many mixtures containing a Cs-137 concentration of 0 Bq kg^{-1}. This was also problematic as sources with many zero data points, along with a few large data points are characterized by a large degree of standard deviation, making these sources difficult to distinguish from one another. These contributing factors supported the elimination of Cs-137 from the analysis, despite its successful use in previous studies (Wallbrink et al., 1998; Gruszowski et al., 2003; Koiter et al., 2013b).

3.5.6 Model Verification and Validation

Model verification and validation are important processes to ensure that a model is generating functioning as it is intended, and accurately simulating the real-world processes. The MixSIAR modelling results were verified in three ways: 1) by running the model with the example data outlined in Stock and Semmens (2013) to verify the appropriate packages had been successfully installed; 2) by running the model with the 2-Mile Channel mixture to ensure that a large proportion was reflective of the 2-Mile Channel subsurface material, where erosion was visually very significant throughout the entire study period; and 3) by running the model with three sediment properties and again with eight sediment properties to verify the consistency of the results, since adding information into the model should theoretically not alter the results. One source of uncertainty in the MixSIAR model continues to lie with the fact that the model will always generate a sum of source contributions of 100 %, regardless of the model inputs. There is currently no straightforward way to validate the MixSIAR model for sediment fingerprinting research and as such, no model validation was performed in this study. Model validation would be possible by calculating a sediment budget over the watershed to identify where sediment loses are occurring. Unfortunately, this exercise would be incredibly resource consuming, especially in large, complex watersheds such as the LWB. Another possibility for model validation would be to introduce a tracer into the environment, such as a rare-earth metal, which could be added to a specific source area and traced at the NHCN drinking water intake. Time and resource constraints prevented model validation for this study.

Figure 3.2 Photograph of the 2-Mile Channel outlet, displaying slumping and signs of subsurface soil contamination from falling organic material, August 2014.

Figure 3.11 Photograph of sediment deposition contributing to surface soils along the shoreline of the 2-Mile Channel, August, 2014.

3.6 Conclusion

To summarize, the results of this study indicate that the 2-Mile Channel was not a significant contributor to suspended sediment at the Jack River drinking water intake during the study period, with a contribution of 9.3 % (SD 18.8 %). A large proportion of the remaining suspended sediment (79.3 % SD 31.2 %) was reflective of the source “Warren’s”, indicating that upstream sources such as the sediments originating from Warren’s Landing, the mouth of the Nelson River and deposited sediments in the Jack River were the most significant sediment source. These results indicate that several hydrological and environmental processes were contributing to water clarity at the NHCN drinking water intake including high water levels and the operation of the Jenpeg dam, promoting sediment transport through the West Channel; low turbidity discharges from tributary rivers causing a dilution effect; and aquatic shoreline vegetation promoting sediment deposition. This study offers a snapshot of the sediment sources in a very limited time period (Summer 2014-Spring 2015) and should be interpreted with caution, given that variations in water level have a significant influence on the operation of the Jenpeg generating station. Further investigation is required to understand how sediment transport from the 2-Mile Channel is affected under lower water level conditions, and the results shown should be viewed as the most favourable environmental condition for concerns of sediment transport to NHCN drinking water. In conclusion, to ensure clean and sustainable source water for drinking, and for the economic, cultural, and social well-being of the community, NHCN may wish to develop source water protection plans in the future to protect their waters from the risks of natural and industrial sources of sediment contamination. Alternatively, additional investigations may be useful for the community on sediment impacts to Playgreen Lake.

3.7 References

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4. REFLECTIONS ON SEDIMENT FINGERPRINTING IN NORWAY HOUSE CREE NATION

The results of this study indicate that the large majority of suspended sediment at the Jack River drinking water intake in Norway House Cree Nation (NHCN) during the summer of 2014 and the spring of 2015 was sediment generated from upstream sources such as Warren's Landing, the mouth of the Nelson River, and the deposited sediments from the Jack River itself, upstream of the drinking water intake. The eroding banks of the 2-Mile Channel contributed significantly less sediment, despite substantial visible erosion and increasing temporal turbidity in the East Channel of the Nelson River. The results disproved the original hypothesis that the 2-Mile Channel would be a significant contributor to suspended sediment during the study period. Several factors contributing to the results were identified including potential effects of small tributary channels, aquatic vegetation, and the operation of the Jenpeg generating station during high flow. This research enhances the understanding of sediment sources in NHCN and contributes to the literature by expanding on the current application of sediment fingerprinting in Canada, which has been largely based in relatively small agricultural streams and watersheds (Koiter et al., 2013b; Barthod et al., 2015; Boudreault, 2016). This research demonstrates that sediment fingerprinting techniques can be utilized in comparatively large, deep, and high velocity channels to examine the effects of an impacted area at an outlet of high interest, such as the drinking water intake. This study is currently the only study from a western science perspective that identifies sediment transport dynamics in the Nelson River system, targeting the controversial 2-Mile Channel. The modifications made to the samplers, using aircraft cable, and cinder block anchors, also expands on previous research, where samplers were primarily anchored to the channel bank and channel floor (Phillips et al., 2000; McDonald et al., 2010). Finally, this sediment fingerprinting study is the first of its kind to incorporate First Nations leadership, guidance, expertise, community knowledge, and concerns throughout the life of the project. The collaboration with NHCN provided valuable insight on the impacts the community is facing resulting from natural and anthropogenic changes in the Lake Winnipeg Basin (LWB). This research also demonstrates the potential for partnerships between First Nations in Canada and academia; to develop projects that advance scientific knowledge, while also providing opportunities for First Nations to contribute their local expertise to develop projects that will also be impactful to their social, economic, cultural, or spiritual wellbeing.

The review of historical data in Chapter 2 quantified the severity and extent of the suspended sediment increases in NHCN to determine if sediments were potentially contributing to deteriorating source water quality for the drinking water intake, a risk identified in the national assessment (AANDC, 2011). This chapter provided context for the research by determining the temporal variations in water quality at NHCN over a 42-year period including turbidity, total suspended solids, and dissolved oxygen. These water quality parameters, collected by the Government of Manitoba, have never previously been utilized in relation to sediment research in NHCN. The results, showing a temporal increase in turbidity and decrease in dissolved oxygen validifies the national assessment, stating that NHCN source water may be at risk due to deteriorating water quality over time (AANDC, 2011). The turbidity analysis in this chapter demonstrates that suspended sediments are becoming increasingly concerning to NHCN source water, as the mean turbidity level has increased by approximately 25% in the 42-year period (Figure 2.4). This is consistent with local knowledge, and demonstrates the increasing need to determine major sediment sources through sediment fingerprinting. The analysis of environmental and hydrological parameters to determine their influence on turbidity also contributes to the research by assessing if changes to turbidity are largely driven by a changing climate, or natural climactic variability. The analysis demonstrated that the increase in turbidity in NHCN was not solely driven by climactic factors. This analysis also provided background data on an area which has not been extensively studied relative to more populated agricultural watersheds. Furthermore, the analysis of climactic parameters in this chapter contributed to the study by providing information to the community to understand natural factors which may influence local turbidity and is particularly valuable for the managers and operators of the Jack River drinking water treatment plant to understand how large or prolonged storm events may require more concentrated water monitoring efforts, to ensure the safety of the outgoing drinking water.

4.1 Challenges in the Sampling Design

The results of the sediment apportionment in MixSIAR represent a snapshot of the sediments travelling through the Jack River during the spring and summer months, however, the results are not intended to be reflective of the relative proportions of the total sediment load transported during this time due to challenges associated with the study area and sampling design. The time integrated suspended sediment sampler designed by Phillips et al., (2000) and used in this study presented several key advantages including 1) it can be deployed unattended, 2) it collects a composite sample over time, integrating natural variations in the sediment, 3) it can collect a relatively large sample (>10g), allowing for a variety of analyses, and 4) it is relatively inexpensive with no power requirements. This sampler was also tested under field conditions to collect a statistically representative sample (Phillips et al., 2000); however, many of those field conditions could not be met in this study. Primarily, the sampler has only been proven to be suitable for relatively small streams, anchored in place with dexion uprights, where the main cylinder is placed in the centermost part of the channel at 60 % depth (Phillips et al., 2000).

This design was not possible in the study due to the large size of the channels, with mid-channel depths of up to 12.5 m in the 2-Mile Channel alone (CAMPP, 2014), limiting the sampler placement to near-shore areas. Navigability by boat, damages to the samplers, and accessibility to the sampling locations were also limiting factors in this study due to the safety hazards associated with the debris and flow velocity in the area, specifically the 2-Mile Channel (Figure 2.1). It was therefore determined that capturing a time-integrated sample at two locations for each sampling site would provide adequate insight into the sources of sediment in the Jack River drinking water. Further studies are needed to fully understand how the Phillips samplers perform in high flow and near shore conditions to assess the sampler efficiency.

Point source samples that were collected in April and May 2015 to increase the quantity of the Jack River suspended sediment sample were also not representative of the total sediment load transported. These samples were collected using the continuous flow centrifuge (US Centrifuge M512). The centrifuge captures the variations in sediment over the time in which the centrifuge is running and is not fully time-integrated. In this study, the collection time was approximately 8 hours at each sampling location (Figure 3.2). The sampling efficiency of the continuous flow centrifuge has been shown to vary between 42-91 % for different models (Ongly and Blatchford, 1982; Horowitz et al., 1989; Millington, 2014). A study evaluating the use of the US Centrifuge M512 has shown that the relatively poor retention efficiency of this model (42 % of agricultural and river sediments) may be due to the high pump flow rate and relatively low RPM velocity compared to other models (Millington, 2014). Sediment retention efficiency does not necessarily determine the instrument’s ability to collect a representative sample; however, several studies have demonstrated that the selection of fine particles and mineral rich sediment was determined to be one of the disadvantages of using continuous flow centrifugation (Ongley and Blatchford, 1982; Millington, 2014).

Many challenges with suspended sediment collection were faced in this study, given the size, velocity, and difficult navigation of the channels. Despite these factors, the results give some insight to NHCN on the sediment sources in their traditional territory that may impact drinking water treatment processes and provide some information on priority areas for source water protection planning and future monitoring efforts.

4.2 Implications for NHCN

Although erosion of the 2-Mile Channel did not largely contribute to sediment concentrations at the NHCN drinking water intake during the study period, these results should be interpreted with caution as the 2-Mile Channel continues to be an environmental, social, and cultural concern for the community (NHCN, 2016). Several additional impacts resulting from the construction of the 2-Mile Channel have been identified by NHCN including 1) severe shoreline erosion; 2) timber debris causing navigational hazards; 3) sedimentation of Playgreen Lake impacting fish and animal habitats; 4) deteriorating water quality from hydrocarbon and mercury contamination; 4) impacts to traditional livelihoods such as trapping and fishing; and 5) exposure of construction debris causing environmental safety concerns (NHCN, 2016). Sedimentation of Playgreen Lake is visible as a large delta of sediment has formed at the 2-Mile Channel outlet, harming the commercial fishing industry, as nets are now being damaged with mud, silt, and sticks and sturgeon have disappeared from the area (NHCN, 2016; Saunders and Apetagon, 2015). Sediment contamination from shoreline erosion and flooding can also contribute to the formation and biomagnification of methyl-mercury and is a concern for human health, as mercury exposure can impair the nervous system (Environment Canada, 2003; Health Canada, 2009). The erosion of the 2-Mile Channel itself, reported at over 1.35 m year^{-1} at the channel inlet and outlet (MB Hydro, 2014), is also contributing to a significant loss of land in the NHCN resource management area, impacting the opportunities for traditional, cultural, and economic activities (NHCN, 2016). For future activities or research, NHCN may wish to develop projects which investigate and remediate these concerns using the traditional knowledge and skills held in the community, or in partnership with government, academia, industry, or non-profit organizations.

The environmental impacts of the 2-Mile Channel identified by NHCN, along with the decreasing levels of dissolved oxygen and increasing levels of turbidity identified in Chapter 2, suggest that NHCN may benefit significantly from the development of source water protection plans. The Source water protection plans were identified as a contributing factor to the high overall risk score from the national assessment of First Nations water and wastewater systems (AANDC, 2011). Source water protection planning involves assembling a working committee, completing a source water assessment, identifying risk management actions, and developing an implementation strategy (Patrick, 2013). Source water protection plans are valuable to ensure that public health is protected, that the environment is managed sustainably, and to reduce water treatment challenges and operating costs (Machial, 2016). Other benefits of source water protection planning in First Nations include promoting community dialogue, gaining leverage for project implementation, sending correct messages to membership, youth, and industry, and reminding the community of the importance of safe drinking water (Patrick, 2013).

4.3 Recommendations for Future Research

One of the primary limitations of this sediment fingerprinting research is the relatively short time-period for which suspended sediment sampling was conducted, with time-integrated sample over the summer of 2014 combined with point samples in the spring of 2015. This sampling regime does not provide conclusive results of the sediment sources at the Jack River drinking water intake, since long term variability in the suspended sediment is not captured. To gain conclusive evidence of the sediment sources, further sediment sampling is required over multiple years. Conducting sediment fingerprinting in multiple years would also inform how changes in water levels and the consequent operation of the Jenpeg generating station influences sediment source contributions. Another limitation of this research was the relatively small number of source samples collected in several source areas including the mouth of the Nelson River, the Jack River, and the Opatinow Channel due to the limited number of areas where erodible soils were visible. The relatively small number of samples in these source areas lead to difficulty in discriminating between sources, resulting in combining source areas and eliminating the Opatinow Channel source, due to the inability of tracers to discriminate it from other sources. A larger number of samples would capture more of the variability in the soils, allowing sources to be grouped, increasing the discriminatory power of each source, and decreasing the standard deviation associated with each source. The inclusion of larger sample numbers would in turn provide more confidence in the results by reducing the standard deviation in the model output. Currently, no studies exist to determine the optimal number of source samples for maximum accuracy in the MixSIAR model, taking into consideration the resources required to perform extensive field sampling. It is recommended that studies to determine the optimal number of source samples in sediment fingerprinting studies be conducted in the future to provide researchers with a guideline for best practice. An additional method to reduce error associated with sources is to include a variety of sediment properties in the final sediment fingerprint. In this study, colour and Cs-137 were analyzed statistically for the ability to discriminate between sources. Previous research has shown that a multitude of sediment properties exist which can be used successfully as a sediment fingerprint, including geochemical, magnetic, radiochemical, and physical properties (Oldfield and Clark, 1990; Walling and Woodward, 1995; Collins et al., 1997; Carter et al., 2003; Walling et al., 2005). Several studies also recommend the use of multiple sediment properties in a composite fingerprint to increase the ability of the fingerprint to discriminate between sources (Peart and Walling, 1988; Walling et al., 1993). It is therefore recommended that future research in sediment fingerprinting near NHCN include the analysis of additional sediment properties. A final recommendation for future sediment fingerprinting in NHCN includes the addition of suspended sediment collection in the West Channel of the Nelson River to verify that soils eroding from the banks of the 2-Mile Channel are in fact being diverted towards the Jenpeg generating station. The addition of a suspended sampling point in the West Channel would also verify that the model is producing results consistent with the visual evidence shown in the satellite imagery of the area (Figure 3.1).

In conclusion, this research demonstrated that the erosion of the 2-Mile Channel did not significantly contribute to the suspended sediments in the Jack River drinking water intake during this specific study period, despite the increasing levels of turbidity observed in NHCN source water and the significant visible erosion of the 2-Mile Channel banks. Future research, including a larger numbers of source samples, analyzing for a greater suite of sediment properties, and allocating a greater time-period for suspended sediment sampling is recommended to provide confidence in the results. Additionally, this research demonstrated the ability of academia to successfully partner with a First Nation through collaboration, active engagement, and incorporation of local expertise and guidance to collect data in remote locations and produce a project that incorporates local concerns with scientific interests.

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APPENDICES

Appendix A: Incoming source water turbidity data

Turbidity of the incoming source water is measured by the water treatment operators in NHCN annually during their spring “Water Watch” program. From the data (Table A-1), it was identified that a spike in turbidity occurred in mid-May of 2014 and decreased by early June 2014. This data indicates that a potential influx in sediment may be occurring in NHCN. This data was useful to inform the time-period for sampling in the spring of 2015 with the continuous flow centrifuge. We were unable to obtain multi-year’s data to obtain average measurements.

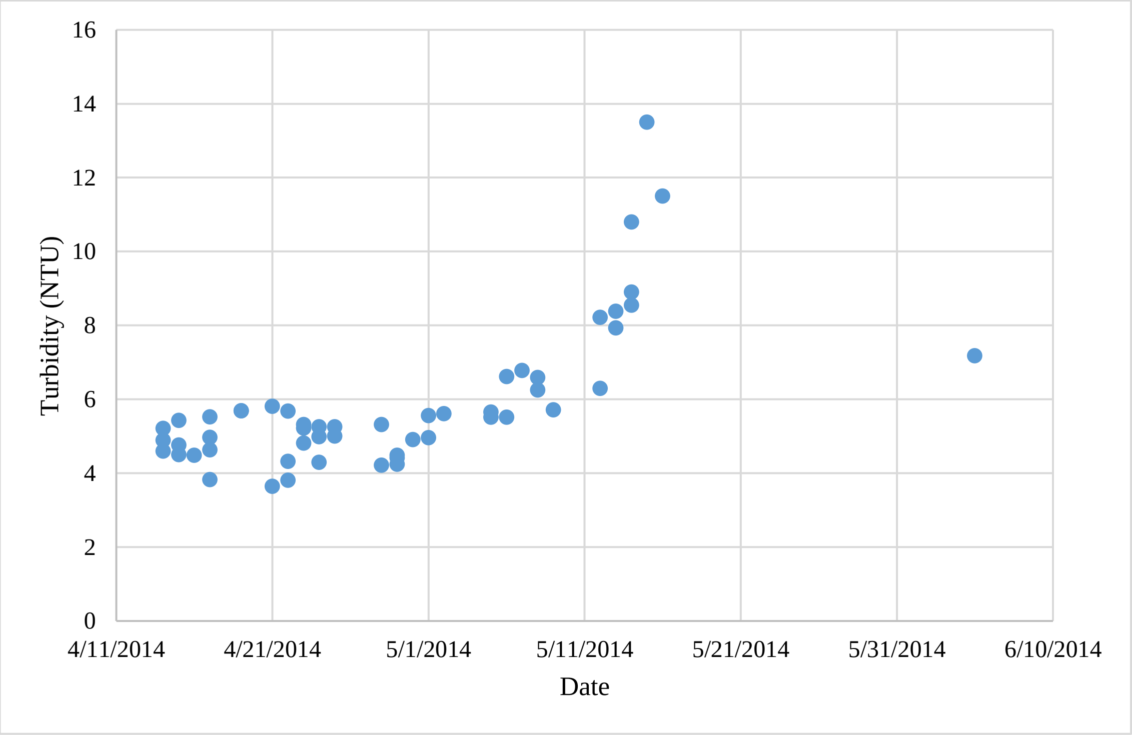

Figure A-1 Source water turbidity data from the NHCN drinking water treatment plant during the Spring of 2014

Appendix B: Relationship Building

Engagement with NHCN regarding this project began in October 2013. The engagement process began by connecting over e-mail and telephone with personnel from the Environmental Monitoring Agency (EMA) at NHCN and arranging an in-person meeting. At the meeting, the program was introduced, including its goals, and how First Nations communities could benefit from the data sharing and training opportunities. The engagement began by identifying key issues for water quality within the community. The representatives from NHCN identified that the community has several water quality concerns, namely, the water quality was contributing to poor health in the community, the 2-Mile Channel was contributing to poor water quality and degraded fish habitat, and mercury and hydrocarbons may be contaminating the soils and waters.

To address these concerns, two projects were developed through the EMA. Firstly, a project that would investigate current mercury and hydrocarbon levels in fish, soil, water, and sediments. Followed by mercury sampling in community members along with a dietary and health survey to investigate a potential link between the consumption of traditional food, environmental contamination, and current health. This project was realized with the successful application to Health Canada funding under the First Nations Environmental Contaminants Monitoring Program. The second project developed was a study investigating the upstream origins of suspended sediment in the Jack River, to identify if 2-Mile Channel generated sediments are contributing significantly to turbidity in the drinking water intake.

The relationship with NHCN was further built throughout the Fall of 2013, as both University of Manitoba researchers, and representatives from the community attended the Assembly of Manitoba Chiefs Food Security conference. From October 2013 to May 2014, a dialogue was established over e-mail between the University of Manitoba and NHCN representatives on the proceedings of the two projects. Several meetings were also held at the University of Manitoba, where project activities and timelines were discussed, and proposals were prepared collaboratively. Telephone meetings were also held during this time. In May 2014, a field visit and meeting was held in NHCN. During this visit, researchers were introduced to several people from the community, including the guide that would be assisting with field visits by boat. A tour of the community was arranged, potential sampling sites were identified and photographed, and information was shared. This part of the engagement process is important to establish a familiarity with the community and their customs, to network, and to acquire contacts prior to the fieldwork and sampling.

Further to the field visits, an important component of the relationship building was established in September 2014 with a visit to the community to present research and participate in the Lake Winnipeg Regulations consultation meeting. At this meeting, many First Nations representatives were present from communities surrounding Lake Winnipeg to share information and ideas for the renewal of the Water Power Act License granted to Manitoba Hydro. Travelling to the community for this event to present information and to participate in knowledge sharing played an important role in establishing a relationship of trust and understanding and also provided an opportunity to network with other communities as well as chief and council.

A key component to the engagement process for these projects was identified as the ability to communicate with many people in different environments. E-mail and telephone communication was essential, however; most of the communication was done in person, to curious community members, at meetings and conferences, and to the fishermen out on the water. This information sharing was important to build awareness towards environmental issues and the research being conducted, and to establish a network of connections in the community.

Appendix C: Spreadsheet of source sample data used in the Kruskal-Wallis H-Test and the quadratic discriminant function analysis

Table A-1 Source sample data for eight sediment colour properties (X, Z, Y, L, h, R, G, B) used to determine the optimum tracer combination in the Kruskal-Wallis H-Test and the quadratic discriminant function analysis

source	X	Z	Y	L	h	R	G	B
2MileSus	41.267	9.502	35.688	66.281	85.935	102.354	90.036	74.408
2MileSus	37.524	8.692	32.446	63.710	89.629	93.716	81.753	68.087
2MileSus	42.612	9.744	36.886	67.192	70.452	104.677	93.188	76.682
2MileSus	49.171	10.920	42.373	71.128	69.854	121.776	106.867	86.405
2MileSus	38.379	8.926	33.262	64.373	70.053	95.046	83.940	70.072
2MileSus	29.808	6.966	25.648	57.702	10.933	76.975	64.250	54.107
Clays	35.223	7.703	30.192	61.820	68.189	89.335	75.822	60.993
Clays	32.309	7.664	28.056	59.939	69.848	80.112	70.827	59.792
Clays	31.525	6.760	26.949	58.927	68.067	80.445	67.601	53.759
Clays	26.339	5.920	22.636	54.695	67.775	66.848	56.861	46.559
Clays	5.525	0.954	4.435	25.061	57.403	17.837	10.576	7.651
Clays	32.704	7.736	28.427	60.273	70.617	81.307	71.788	60.632
Clays	26.770	6.218	23.110	55.186	67.956	67.626	58.125	48.593
Clays	43.722	9.758	37.813	67.883	71.354	107.095	95.636	77.427
Clays	39.346	8.336	33.681	64.708	69.303	98.639	84.742	66.566
Clays	42.390	9.203	36.387	66.814	69.251	106.105	91.583	73.149
Clays	47.519	10.093	40.735	69.990	69.796	118.416	102.614	80.664
Clays	41.859	8.893	35.870	66.421	69.627	104.290	90.339	71.023
Clays	40.923	8.894	35.194	65.900	70.069	101.243	88.766	70.748
Clays	29.968	5.548	24.917	56.994	64.785	81.009	61.568	44.883
Clays	45.315	9.840	38.940	68.708	69.745	112.330	98.156	78.222
Clays	43.030	9.349	36.999	67.277	70.003	106.504	93.310	74.341
Clays	26.883	6.114	23.126	55.202	67.527	68.866	58.052	47.953
Clays	40.552	8.599	34.740	65.546	69.589	101.522	87.467	68.672
Clays	33.905	7.489	29.100	60.870	68.215	85.827	73.108	59.166
Clays	33.469	7.952	29.125	60.892	70.999	82.370	73.657	62.157
Clays	41.676	9.117	35.873	66.423	70.136	103.288	90.470	72.505
Clays	40.071	8.524	34.323	65.218	69.369	100.367	86.372	68.030
Clays	36.706	7.968	31.459	62.894	68.554	92.957	79.040	63.258
Clays	40.389	8.660	34.622	65.453	69.305	101.167	87.138	68.981
Clays	49.726	10.414	42.620	71.296	70.410	123.531	107.498	83.557
Clays	38.430	9.005	33.519	64.579	73.185	93.189	85.036	70.915
Clays	40.966	8.709	35.057	65.793	68.989	103.200	88.106	69.540
Clays	32.800	7.356	28.328	60.184	70.395	83.717	71.306	58.545
Clays	40.016	9.270	34.663	65.485	70.009	98.524	87.498	72.788
Clays	31.592	7.128	27.217	59.175	68.780	79.022	68.496	56.179
Clays	33.333	7.038	28.458	60.300	68.333	84.515	71.426	56.115
Clays	33.320	7.446	28.608	60.435	67.678	85.314	71.776	58.673
Organic	5.510	1.253	4.614	25.605	53.838	16.253	11.283	9.507
Organic	7.203	1.434	5.968	29.332	59.811	21.314	14.565	11.319
Organic	11.471	1.789	9.164	36.298	60.461	36.791	21.878	14.818
Organic	17.780	3.393	14.841	45.416	64.706	49.628	36.602	27.503
Organic	9.250	1.830	7.705	33.361	62.086	26.633	18.910	14.598
Organic	15.354	3.303	12.928	42.654	61.105	43.011	31.885	25.854
Warrens	31.390	7.172	27.168	59.129	70.409	79.516	68.439	56.783
Warrens	33.996	7.435	29.471	61.195	73.478	82.807	74.675	59.722
Warrens	31.384	6.675	27.080	59.049	72.603	77.688	68.427	54.094
Warrens	41.472	9.351	35.932	66.468	71.717	102.764	90.769	74.374
Warrens	29.488	6.158	25.288	57.355	70.760	74.404	63.665	49.783
Warrens	36.514	8.561	31.727	63.117	70.983	90.420	80.147	67.161
Warrens	34.499	8.004	29.988	61.644	71.849	85.154	75.812	63.158
Warrens	38.305	8.591	33.041	64.194	69.761	96.732	83.170	68.080

Appendix D: Spreadsheet design for biplot analysis in MixSIAR using 15 colour coefficients

Table A-2 Mixture data spreadsheet for biplot analysis in MixSIAR using 15 colour coefficients and four mixtures

region	x	y	X	Z	Y	L	a	b	u	v	c	h	R	G	B
2Mile	0.477	0.413	41.266	9.502	35.688	66.281	4.710	12.608	11.917	5.659	66.448	85.935	102.354	90.036	74.408
2Mile	0.476	0.413	38.379	8.926	33.262	64.373	4.349	11.984	11.032	5.396	12.749	70.053	95.046	83.940	70.072
2Mile	0.477	0.412	37.524	8.692	32.446	63.710	4.581	11.956	11.421	5.306	63.711	89.629	93.716	81.753	68.087
2Mile	0.477	0.413	42.612	9.744	36.886	67.192	4.647	13.087	11.956	5.937	13.888	70.452	104.677	93.188	76.682
2Mile	0.486	0.409	15.354	3.303	12.928	42.654	5.656	10.248	11.786	3.658	11.705	61.105	43.011	31.885	25.854
Jack	0.481	0.414	28.845	6.278	24.812	56.892	4.740	13.098	11.711	5.634	13.929	70.104	73.565	62.386	50.201
Jack	0.482	0.415	33.530	7.133	28.844	60.644	4.981	14.671	12.698	6.432	15.493	71.247	84.083	72.696	57.430
Jack	0.476	0.416	39.673	9.031	34.626	65.456	3.579	13.356	10.017	6.303	13.827	75.001	95.079	87.961	72.167
Jack	0.478	0.413	31.390	7.172	27.168	59.129	4.216	11.846	10.563	5.232	12.573	70.409	79.516	68.439	56.783
Mouth	0.479	0.416	33.996	7.435	29.471	61.195	4.148	13.985	11.051	6.339	14.587	73.478	82.807	74.675	59.722
Mouth	0.482	0.416	31.384	6.675	27.080	59.049	4.541	14.494	11.791	6.409	15.188	72.603	77.688	68.427	54.094
Mouth	0.484	0.415	29.488	6.158	25.288	57.355	5.101	14.616	12.744	6.264	15.481	70.760	74.404	63.665	49.783
Warrens	0.475	0.413	36.514	8.561	31.727	63.117	3.986	11.566	10.225	5.251	12.234	70.983	90.420	80.147	67.161
Warrens	0.476	0.414	34.499	8.004	29.988	61.644	3.867	11.795	10.018	5.360	12.413	71.848	85.154	75.812	63.158
Warrens	0.478	0.414	41.471	9.351	35.932	66.468	4.499	13.616	11.794	6.220	14.340	71.717	102.764	90.769	74.374
Warrens	0.479	0.413	38.305	8.591	33.041	64.194	4.896	13.278	12.348	5.890	14.152	69.761	96.732	83.170	68.080

Table A-3 Source data spreadsheet for biplot analysis in MixSIAR using 15 colour coefficients

sources	Meanx	SDx	Meany	SDy	MeanX	SDX	MeanZ	SDZ	MeanY	SDY	MeanL	SDL	Meana	SDa	Meanb	SDb	Meanu	SDu	Meanv	SDv	Meanc	SDc	Meanh	SDh	MeanR	SDR	MeanG	SDG	MeanB	SDB	n
Clays	0.482	0.006	0.413	0.001	36.197	8.209	7.927	1.779	31.099	7.096	61.886	7.997	5.299	0.965	13.748	2.052	13.046	2.199	5.936	1.017	14.747	2.178	68.914	2.556	90.829	19.485	78.274	18.036	62.876	14.230	32
Organics	0.494	0.010	0.409	0.002	11.095	4.748	2.167	0.940	9.203	3.986	35.444	7.624	6.133	1.641	11.045	3.610	12.117	3.804	3.597	1.314	12.649	3.904	60.334	3.613	32.272	13.004	22.521	9.889	17.267	7.579	6
2MileSus	0.478	0.001	0.413	0.001	39.793	6.402	9.125	1.314	34.384	5.534	65.064	4.456	4.748	0.368	12.497	1.432	11.913	1.096	5.567	0.755	38.560	26.877	66.143	28.422	99.091	14.770	86.672	14.114	71.627	10.711	6
Warrens	0.479	0.003	0.414	0.001	34.631	3.996	7.744	1.077	29.962	3.514	61.519	3.011	4.407	0.434	13.150	1.250	11.317	1.005	5.871	0.512	13.871	1.289	71.445	1.213	86.186	9.798	75.638	8.897	61.644	8.117	8

Table A-4 Discrimination data spreadsheet for biplot analysis in MixSIAR using 15 colour coefficients

sources	Meanx	SDx	Meany	SDy	MeanX	SDX	MeanZ	SDZ	MeanY	SDY	MeanL	SDL	Meana	SDa	Meanb	SDb	Meanu	SDu	Meanv	SDv	Meanc	SDc	Meanh	SDh	MeanR	SDR	MeanG	SDG	MeanB	SDB
Clays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2MileSus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Warrens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix E: MixSIAR spreadsheet design for sediment apportionment in the Jack River and the 2-Mile Channel using a three-tracer combination

Table A-5 Mixture data spreadsheet for sediment apportionment of the Jack River and 2-Mile Channel mixtures using three colour tracers (Z, G, B)

region	Z	G	B
2Mile	9.502	90.036	74.408
2Mile	8.926	83.940	70.072
2Mile	8.692	81.753	68.087
2Mile	9.744	93.188	76.682
2Mile	3.303	31.885	25.854
Jack	6.278	62.386	50.201
Jack	7.133	72.696	57.430
Jack	9.031	87.961	72.167
Jack	7.172	68.439	56.783

Table A-6 Source data spreadsheet for sediment apportionment of the Jack River and 2-Mile Channel mixtures using three colour tracers (Z, G, B)

sources	MeanZ	SDZ	MeanG	SDG	MeanB	SDB	n
Clays	7.927	1.779	78.274	18.035	62.876	14.229	32
Organics	2.167	0.940	22.520	9.889	17.266	7.579	6
2MileSus	9.125	1.314	86.672	14.114	71.627	10.711	6
Warrens	7.743	1.077	75.638	8.897	61.644	8.117	8

Table A-7 Discrimination data spreadsheet for sediment apportionment of the Jack River and 2-Mile Channel mixtures using three colour tracers (Z, G, B)

sources	MeanZ	SDZ	MeanG	SDG	MeanB	SDB
Clays	0	0	0	0	0	0
Organics	0	0	0	0	0	0
2MileSus	0	0	0	0	0	0
Warrens	0	0	0	0	0	0

Appendix F: MixSIAR spreadsheet design for sediment apportionment in the Jack River and the 2-Mile Channel using an eight-tracer combination

Table A-8 Mixture data spreadsheet for source apportionment of the Jack River and 2-Mile Channel mixtures using eight colour tracers (X, Z, Y, L, h, R, G, B)

region	X	Z	Y	L	h	R	G	B
2Mile	41.266	9.502	35.688	66.281	85.935	102.354	90.036	74.408
2Mile	38.379	8.926	33.262	64.373	70.053	95.046	83.940	70.072
2Mile	37.524	8.692	32.446	63.710	89.629	93.716	81.753	68.087
2Mile	42.612	9.744	36.886	67.192	70.452	104.677	93.188	76.682
2Mile	15.354	3.303	12.928	42.654	61.105	43.011	31.885	25.854
Jack	28.845	6.278	24.812	56.892	70.104	73.565	62.386	50.201
Jack	33.530	7.133	28.844	60.644	71.247	84.083	72.696	57.430
Jack	39.673	9.031	34.626	65.456	75.001	95.079	87.961	72.167
Jack	31.390	7.172	27.168	59.129	70.409	79.516	68.439	56.783

Table A-9 Source data spreadsheet for source apportionment of the Jack River and 2-Mile Channel mixtures using eight colour tracers (X, Z, Y, L, h, R, G, B)

sources	MeanXq	SDXq	MeanZ	SDZ	MeanYq	SDYq	MeanL	SDL	Meanh	SDh	MeanR2	SDR2	MeanG2	SDG2	MeanB2	SDB2	n
Clays	36.197	8.209	7.927	1.779	31.099	7.096	61.886	7.997	68.914	2.556	90.829	19.485	78.274	18.035	62.876	14.229	32
Organics	11.095	4.748	2.167	0.940	9.203	3.986	35.444	7.624	60.334	3.613	32.272	13.003	22.520	9.889	17.266	7.579	6
2MileSus	39.793	6.402	9.125	1.314	34.384	5.534	65.064	4.456	66.143	28.422	99.091	14.770	86.672	14.114	71.627	10.711	6
Warrens	34.631	3.996	7.743	1.077	29.962	3.514	61.519	3.011	71.445	1.213	86.186	9.798	75.638	8.897	61.644	8.117	8

Table A-10 Discrimination data spreadsheet for source apportionment of the Jack River and 2-Mile Channel mixtures using eight colour tracers (X, Z, Y, L, h, R, G, B)

sources	MeanX	SDX	MeanZ	SDZ	MeanY	SDY	MeanL	SDL	Meanh	SDh	MeanR	SDR	MeanG	SDG	MeanB	SDB
Clays	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Organics	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2MileSus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Warrens	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0