A novel protocol for identifying storm derived waves on
substrate reworking in lakes: implications for selection of
optimal sites for paleolimnological research

by

Veronica Mazzella

A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Master of Science

in

Earth Science

Carleton University
Ottawa, Ontario

© 2019, Veronica Mazzella

Abstract

Harvey Lake, located within the Atlantic region of Canada, endures many storms, including Hurricane Arthur in 2014, and likely archives lake sediment records including past storm signals. Lakes are often characterized by a single central site, rather than a suite of sites, due to cost and time constraints. This research sought to develop a novel geomatics protocol to optimize coring site selection using a multi-site ($n = 96$) characterization. Areas prone to resuspension were modeled using lake morphology and historical wind speed records (1953-2015). Modeled resuspension areas agreed with the spatial distribution of sedimentary proxies (i.e., grain size and Itrax-XRF). End member mixing analysis identified a very coarse grain end member that likely reflects the deposition of resuspended sediments. In addition to the central basin, our approach highlighted Herbert's Cove as a suitable coring target as it was in closer proximity to a source of allochthonous sedimentation (i.e., catchment hydrological signal).

Summary

Limnological and paleolimnological studies often characterize a lake based on data collected from a single site, generally the central and deepest part, rather than a suite of sites, because of often prohibitive costs and time required to carry out a broader scale study. This research was carried out to develop a novel new geomatics derived protocol for locating optimal coring sites in lakes to assess impact of storm activity on lake bottom sediments, and using sediment data obtained from 96 stations throughout Harvey Lake, New Brunswick, Canada (45°43'45"N, -67°00'25"W). This study assessed the impact of varying intensities of historically documented wind speeds (1953-2015) to determine what areas of the substrate are most prone to sediment remobilization, and direct deposit of sediments derived from catchment runoff, particularly during large storms.

Sedimentary proxies used in the study were end member mixing analysis of grain size data and Ti abundances derived from Itrax x-ray fluorescence data. These data, in conjunction with available lake bathymetric data, lake morphological data, and historical meteorological data were used to model, using standard GIS tools, the frequency of lake bottom sediment mixing and resuspension by wind waves throughout Harvey Lake. This was carried out to identify areas of deposition and resuspension based on assessment of end member mixing analysis of grain size data and Ti. This approach permitted visualization of the spatial distribution and trends of the variables with minimal post processing led to the identification of sediments at any water depth greater than 4.4 m to z-max at 11.8 m having a 0% mixing probability of being directly disturbed by storms. Therefore, the z-max (deepest part of the lake) and Herbert's Cove, located on the SW margin of the lake are the two best areas to core to detect records of past storm activity.

Acknowledgements

This research was funded by a NSERC Discovery grant and NRCan Clean Technology grant to RTP. We thank Jochen Schroer of NATECH Environmental Services for providing a shapefile for the baseline Bathymetry Map. We also acknowledge the contributions of Dr. Sheryl Bartlett, the Harvey Lake Association, and the New Brunswick Alliance of Lake Associations for facilitating the research on Harvey Lake. We thank Roy T. Patterson for contributing his time and a boat during sample collection and to Zacchareus Compton of the University of New Brunswick for providing assistance in the field during the collection of samples.

Table of Contents

Abstract.....	i
Summary.....	ii
Acknowledgements	iii
List of Tables	vi
List of Figures.....	vii
List of Appendices.....	viii
1.1 Introduction.....	1
1.2 Lake Physiography	4
1.3 Methods.....	6
1.3.1 Field.....	6
1.3.2 Laboratory	6
1.3.2.1 Grain-Size Analysis.....	6
1.3.2.2 Geochemistry (Itrax XRF-CS)	7
1.3.3 Data Analysis.....	8
1.3.3.1 Frequency of Wind-Induced Resuspension.....	8
1.3.3.2 Itrax XRF-CS	10
1.3.3.3 End Member Mixing Analysis	11
1.3.3.4 Geospatial Data Handling	12
1.4 Results	13
1.4.1 Lake Bottom Sediment Mixing Probability.....	13
1.4.2 Grain Size Mode.....	21
1.4.3 Titanium	24
1.4.4 End Member Mixing Analysis	24
1.4.5 Correlations	29

1.5 Discussion.....	31
1.5.1 Potential Impact of Resuspension on Sedimentation.....	31
1.5.2 Allochthonous Sediment Runoff	33
1.5.3 Application to Identifying Paleo-Storms	35
1.6 Conclusions.....	36
1.7 Future Directions	37
1.7.1 Enhancing sample selection.....	37
1.7.2 Application of methodology	38
References	39
Appendices.....	49

List of Tables

Table 1. Sediment water interface samples collected during the 2015 field season.....	14
Table 2. Hourly wind speed (km/h) between 1953-2015 from Fredericton A Station	19
Table 3. Descriptions of robust end members.	27
Table 4. Pearson correlation matrix of select Harvey Lake variables.	29

List of Figures

Figure 1. Location maps.	5
Figure 2. Wind speed required to mix the lake bottom.....	20
Figure 3. Relationship between water column depth (m) and mixing probability (%)	22
Figure 4. Spatial distribution of mixing probability (%)	23
Figure 5. Spatial distribution of grain size mode of lake sediment based on 96 sites	25
Figure 6. Spatial map showing lake sediment Ti concentrations.....	26
Figure 7. Grain-size frequency distributions for each robust end member.....	28
Figure 8. Distribution of the very coarse silt end-member	30

List of Appendices

Appendix A Grain size distributions of Harvey Lake surface sediments.....	49
Appendix B Correlogram showing scatterplots	50
Appendix C Correlogram of select environmental variables.....	51

1.1 Introduction

Atlantic hurricane activity is variable with ongoing speculation on climatic indexes that are affecting these storm patterns (Landsea et al., 2006; Kossin et al., 2007). Reconstructing past storm intensity and frequency places current trends into a historical context, enables comparison to known climate phenomena (e.g., Atlantic Multidecadal Oscillation and ENSO) and anticipates future patterns (Page et al., 1994). Atlantic storminess can likely be influenced by the El Niño Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (AMO) (Burn et al., 2015). El Niño Southern Oscillation is a driver in hurricane variability due to its influence of increasing the vertical wind shear from warmer sea surface temperatures of the Pacific Ocean, preventing tropical disturbances from developing into hurricanes from the Atlantic Ocean (Goldenberg, et al., 2001; Nyberg et al., 2001; Burn et al., 2015;). The AMO is a measure of natural variability, based upon the average irregularities of sea surface temperatures (SST), in the North Atlantic Ocean (Alexander et al., 2014). Warmer SSTs are associated with positive AMO phases, while cooler SSTs are associated with negative AMO phases (Alexander et al., 2014). Therefore, AMO drives climate anomalies around the world, during different phases, with the periodicity of hurricane and storminess in the Atlantic increasing during positive AMO phases (Goldenberg et al., 2001).

Harvey Station, New Brunswick, a small village approximately 35 km southwest of Fredericton, is situated on the southeast shores of Harvey Lake. Being located within the Atlantic region of Canada, Harvey Station has endured multiple Atlantic storms. The most recent was Hurricane Arthur, which passed as a post-tropical storm on July 5, 2014. Arthur generated large wind waves in Harvey Lake that mobilized a considerable volume

of sediment into the water column. The resuspended sediment turned the entire water column in the lake brown for several days following the passage of the storm (personal communication, S. Bartlett, Harvey Lake Association). Anecdotal evidence such as this provides the rationale for investigating whether an inland lake, such as Harvey Lake, might preserve paleo storm signals. Storms like post-tropical storm Arthur, increase precipitation, resulting in greater sediment erosion of the surrounding catchment delivering coarser sediments to the lake (Håkanson et al., 1983; Peng et al., 2005). Lake sediment archives that preserve coarse allochthonous sediments can be used to estimate the intensity and frequency of past storm events placing current trends in a historical context and allows comparison to known climate phenomena (e.g., AMO and ENSO; Page et al., 1994).

These sedimentary archives (e.g. Brandon et al., 2014; Swindles et al., 2018) can be used to reconstruct Atlantic storminess prior to human monitoring by recording evidence associated with changes in lake processes (i.e., grain size, geochemistry), allowing us to analyze, interpret and predict the causes of these environmental shifts (Smol, 2002; Bichet et al., 2014). For example, lake sediments can range from providing information on historical changes in pollutant deposition (Shotbolt et al., 2005) to reconstructing hydroclimatological variability (Macumber et al., 2018). Sedimentary archives also preserve storm signals (Swindles et al., 2018) but this has rarely been studied in inland lakes (Page et al., 1994; Eden et al., 1998). Lake sedimentary archives are typically extracted as a single core from the deepest part of the lake (i.e., z-max). The z-max is most likely to preserve continuous and undisturbed sedimentary archives of overall lake changes due to sediment focusing (Flower et al., 2004), and deeper water

sedimentary environments are less likely to be influenced by wave-induced resuspension (Tomonori Naya et al., 2003). One drawback to coring the z-max is the distal location from the allochthonous source. As flowing water erodes the catchment and deposits in a lake, the velocity of flow decreases and the water's ability to move coarser sediment decreases (Morales-Marin et al., 2017). Therefore, eroded storm materials would have difficulty consistently making it to the z-max, resulting in a dampened storm signal (Morales-Marin et al., 2017). In addition, for steep sided basins, turbidity currents or slope instabilities could cause age reversals and disturbances that do not truly hold the best paleoclimate record (Smol, 2002; Cohen, 2003). Thus, identifying several suitable coring sites for reconstructing paleo storm events, other than the z-max, would be of great value.

A multi-site lake characterization approach could determine areas prone to resuspension and allochthonous sedimentation by using geomatics to map the spatial variability of catchment hydrological proxies (e.g., grain size and Ti). Grain size analysis has been demonstrated to be a very useful indicator of lake depositional processes and can be carried out quickly and relatively inexpensively (Gammon et al., 2017; Macumber et al., 2018). End member mixing analysis (EMMA) of grain size results can further be used to model the depositional signature (i.e., end members) of specific catchment and lake hydrological processes (Weltje & Prins, 2003, 2007; Dietze et al., 2012; Macumber et al., 2018). The development of XRF-CS core scanning technology has revolutionized geological research as it can be used to analyze sediment geochemistry much faster and with lower cost than traditional geochemical techniques (Gregory et al., 2017; Bloemsmas et al., 2018). Spatial variability of elements such as Ti can identify areas of frequent

resuspension that are characterized by coarser grains enriched with Ti *versus* areas of deposition associated with finer grains enriched with Al (Taboada et al., 2006; Boës et al., 2011). The results could highlight areas outside of the z-max that could also be suitable for the collection of sediment cores. Areas of resuspension *versus* deposition could also be identified using geomatics to generate spatial models for the probability, based on historical meteorological records, of wind wave induced sediment mixing based solely on the lake morphology (i.e., water column depth and lake fetch). In many cases this could be done at little to no cost as bathymetric information for many lakes is freely available (or easily collected), as is lake morphological data (i.e., measuring fetch) and historical meteorological data. This approach could be done in advance to plan optimal coring sites.

The aim of this study is to apply a multi-site lake characterization using sedimentary proxies of catchment hydrological variability (i.e., grain-size and Ti) in conjunction with a novel protocol for estimating the frequency of wind wave induced resuspension to map areas of deposition *versus* resuspension and allochthonous sedimentation. The results will identify suitable coring areas, in addition to the z-max, that can be applied to future coring programs.

1.2 Lake Physiography

Harvey Lake (45°43'45"N, -67°00'25"W) is located adjacent to the village of Harvey Station, York County, New Brunswick, Canada (Figure 1). The lake has a surface area of 7.15 km² and a maximum depth of 11.8 m. Inlet streams are small, with the most significant one entering the lake at the head of Herbert's Cove, at the southwest corner of

the lake and midway along the eastern margin of the lake (Figure 1). Highway 636 runs north-south

Figure 1. Location maps. (A) With respect to Canada, (B) with respect to the Province of New Brunswick and (C) a generated map of Harvey Lake in ArcGIS.

along the eastern margin of the lake with a large number of homes and cottages positioned directly on the shore and agricultural land behind. There are also extensive wetlands along the northeastern and north shore, and in the area between Harvey and Mud lakes. Cherry Mountain (45°43'38"N 67°00'59"W; 240 m elevation) is comprised of Harvey Formation rocks, comprised of assemblages of felsic volcanic rocks with elevated concentrations of fluorite and uranium (Industrial Minerals Summary Data, 2014). New Brunswick Southern Railway operates a rail line, constructed in 1869, which runs along the southwestern shore of Harvey Lake between the foot of Cherry Mountain and lakeshore.

1.3 Methods

1.3.1 Field

Sediment-water interface samples were collected over two days in September 2015 from Harvey Lake using an Ekman grab sampler. The geographic location for each sample station was determined using a Garmin GPSmap 76CSx GPS unit. Analyzed samples for this research were obtained from the top 0.5 cm of sediments from each grab, which represents a potential average of the last five to ten years of sedimentation.

1.3.2 Laboratory

1.3.2.1 Grain-Size Analysis

Prior to grain-size analysis, subsamples were processed using a protocol modified from Murray (2002) and van Hengstum et al. (2007) where 30% H₂O₂ was added to subsamples in an 80°C water bath to oxidize organic matter. Standard HCl pretreatment

was deemed unnecessary as tests using 10 % HCL indicated that sediment carbonate content was insignificant. Treated subsamples were analyzed using a Beckman Coulter LS 13 320 laser diffraction grain size analyzer equipped with a universal liquid module. Suspended subsamples were pipetted into the analyzer until an obscuration of 10 ± 3 % was achieved. Material circulated within the module for sixty seconds prior to the first of three replicate runs. The three runs were later averaged, producing grain size distributions ranging from 0.4 to 1500 μm for the sample dataset. Gradistat v8 (Blott and Pye, 2001) was used to generate summary statistics (i.e., mode) for the grain size distribution data. Grain size modes were grouped into three size categories: mud ($<63 \mu\text{m}$), very fine sand ($63\text{--}125 \mu\text{m}$) and fine-coarse sand ($>125 \mu\text{m}$).

1.3.2.2 Geochemistry (Itrax XRF-CS)

All 96 sediment samples were analyzed using an Itrax high-resolution XRF-CS to provide a spatially comprehensive geochemical dataset. Although Itrax-XRF-CS is designed for analysis of sediment cores, a recently developed sequential sample reservoir vessel enabled analysis of discrete sediment samples (Gregory et al., 2017). For XRF-CS analysis, a 15-cc aliquot was removed from each sample and centrifuged at 4000 rpm for 4 minutes, and the supernatant decanted. Samples were then covered and allowed to dry at room temperature until the sediment reached a paste consistency. Sediments were placed in the sequential sample reservoir and analyzed using a Mo-anode X-ray tube, at 0.2 mm resolution, 15 second exposure time, 19 mA current and 30 kV voltage at the McMaster University Core Scanning Centre. The results of XRF-CS analysis for each

sample were evaluated using the Cox Analytics RediCore software to refine the fit of predicted and observed elemental concentrations as determined by the Itrax software.

1.3.3 Data Analysis

1.3.3.1 Frequency of Wind-Induced Resuspension

A wind speed able to generate wave base equal to the water column depth is assumed to result in sediment resuspension, and is termed the mixing speed for a specific depth or station. The wave base (WB), the maximum depth at which wave-induced resuspension of sediment occurs, was equal to:

$$WB = 0.25 * L \quad (Eq.1)$$

where L is the wavelength of a deep-water wave (Sly, 1978). The deep-water wavelength was calculated based on the period, T, of a wave using the formula:

$$L = 1.56 * T^2 \quad (Eq.2)$$

Equation (1) and equation (2) were combined (equation 3) to calculate the wave base using wave period:

$$WB = 0.39 * T^2 \quad (Eq.3)$$

The period of a wave was determined using wind speed and fetch distance using the equation derived by Smith and Sinclair (1972):

$$\frac{gT}{w} = 0.46 \left(\frac{gF}{w^2}\right)^{0.28} \quad (\text{Eq.4})$$

where g is the acceleration due to gravity (m/s), w is the wind speed (m/s) and F is the fetch (m). To calculate fetch, it was assumed that a perfectly oriented storm strike would occur at an ideal angle high enough to produce the largest waves possible. The longest open-water distance on Harvey Lake is 5100 m trending roughly NNE. To estimate the mixing speed, depth and fetch were substituted into the equation. The results were translated into the Beaufort Wind Scale, a standardized ordinal scale ranging from 0-13 for categorizing wind speeds.

The historical probability of winds strong enough to induce resuspension is termed the mixing probability of each sample site. To calculate the mixing probability, hourly wind speed data covering the interval from 1953-2015 was obtained from the Fredericton A (45.87 °N, -66.53°W) climatological station, excluding winter months (December-April) when ice cover prevents winds from influencing the lake water column (Climate.weather.gc.ca, 2019). This station is approximately 40 km ENE from Harvey Lake. Individual CSV files, each representing a month of hourly logged meteorological data, were merged into a single dataset using the Pandas, Glob and Os modules of the Python computer programming language (version 3.7.4; Macumber, 2019). Python and the Pandas and Numpy modules were used to bin the hourly data by wind speed (km/h) according to the Beaufort Scale to generate the frequency, cumulative sum and

percentage of occurrence (Macumber, 2019). Python and the Pandas and Seaborn modules were used to generate the correlograms and Pearson correlation matrix (Macumber, 2019).

1.3.3.2 Itrax XRF-CS

Itrax XRF-CS results are considered semi-quantitative due to inherent issues of analyzing unprepared sediment using X-ray fluorescence; down-core shifts in sediment bulk density, sediment surface roughness, variations in organic and water content, etc., which can interfere with XRF-CS signal in an unpredictable and non-linear fashion (Kido et al., 2016). Techniques have been developed to compensate for these problems, and, as described below, to calibrate the semi-quantitative Itrax XRF-CS results to quantitative inductively coupled plasma-mass spectrometer (ICP-MS) results (Weltje et al. (2015).

The calibration of the semi-quantitative counts per second (cps) output of the Itrax XRF-CS data to an approximation of elemental concentrations followed a multivariate log-ratio calibration method, where a subset of the Itrax-XRF-CS results are compared to ICP-MS results (Weltje et al. (2015). This approach has been determined to be the most rigorous and successful method for calibration XRF-CS data developed to date (Gregory et al. 2019). As part of a study to refine this Itrax XRF-CS – ICP-MS calibration methodology, Gregory et al. (2019) carried out a calibration of the 96 Itrax analyzed Harvey Lake samples, using 28 unique samples and 10 additional triplicates (total 48 samples), which were analyzed using ICP-MS at Bureau Veritas Mineral Laboratories, Vancouver, British Columbia following the acid digestion techniques (DYAIR, PULCB and MA250 packages). Results obtained from samples digested using the four-acid

method are indicative of the total or whole rock elemental composition (Parsons et al., 2012), which is a result most directly comparable to Itrax XRF-CS output (Gregory et al., 2019).

The ItraXelerate software was used to calibrate the XRF-CS data (Weltje and Bloemsma, 2015; Gregory et al., 2019). As ItraXelerate was initially designed to compare XRF-CS data to energy dispersive or wavelength dispersive XRF data, the primary purpose of the software was to use a specific set of elements always observed in XRF data. This caused issues with our data as ItraXelerate requires input of Si concentrations, but Si cannot be measured by ICP-MS. We therefore manually substituted an arbitrary value of 0.001 ppm Si into our dataset to allow ICP-MS data to be loaded. This value was several orders of magnitude lower than any other element detected in ICP-MS, and has been previously determined to not alter Itrax-XRF-CS calibration results (Weltje et al., 2008).

Weltje et al., (2015) recommended that the total number of elements calibrated should be no more than one-third of the number of unique samples analyzed with ICP-MS. As we analyzed 28 unique samples, nine elements were selected for calibration, with Titanium being of particular interest in this study due to its known correlation to catchment runoff, making it directly comparable to the grain size data (Macumber et al. 2018).

1.3.3.3 End Member Mixing Analysis

End member mixing analysis (EMMA) is a methodology used to provide a genetic interpretation of multi-modal grain size distributions with minimal assumptions

(Weltje & Prins 2003; Weltje & Prins 2007; Dietze et al. 2012). End members are modeled by un-mixing multi-modal distributions, thought to reflect the sum of many depositional processes, and the end members can then be associated with specific depositional processes (Macumber et al., 2018). End member mixing analysis was carried out using the grain size analysis results from the 96 analyzed Harvey Lake stations to characterize depositional processes influencing sedimentation in the lake. EMMA was performed following the procedure of Dietze et al., (2012) and Dietze et al., (2014) using extensions implemented in the R package EMMAgeo (Dietze and Dietze, 2019). Only robust end members (EMs) were included, defined as those with non-overlapping, interpretable end member loadings, with the addition of those in which similar EM loadings occurred in most of the model runs (Dietze et al., 2014).

1.3.3.4 Geospatial Data Handling

Kriging was used to visualize the geospatial distribution of measured analytical results for Harvey Lake. Kriging is a spatial interpolation method that predicts probable values for an unsampled target location using a linear combination of observed values at nearby sample locations that are weighted based on a stochastic model of the spatial dependence that is quantified by a semivariogram (Shiode, 2011). With interpolation, a value is ascribed to a grid cell based upon the values from known points. Interpolation weights are based not only on the distance between the measured points and the prediction location, but also on the overall spatial arrangement of the measured points. Spatial and non-spatial statistical methods, such as kriging, have played an important role in geochemical pattern recognition in lakes (Panahi, 2004). Results displayed in a spatial

manner facilitate the identification of depositional areas and catchment influences, which is important for designing subsequent sampling plans for future field work.

Ordinary kriging, which is the most widely used form of spatial interpolation among the various kriging methodologies, was adopted to generate continuous maps of the results throughout the entirety of the Harvey Lake basin. The default setting of 12 nearby data points was used to interpolate the value of a given cell in the analysis using Ordinary Kriging. Shapefiles for Harvey Lake, local water bodies and rivers, and natural and anthropogenic land use were retrieved from the GeoGratis Database (Natural Resources Canada, n.d.).

1.4 Results

Ninety-six sediment-water interface samples were collected over two days in September 2015 from Harvey Lake using an Ekman grab sampler (Figure 1; Table 1).

1.4.1 Lake Bottom Sediment Mixing Probability

The percent of hours, during the last ~60 years, where wind speeds matched each subdivision in the Beaufort wind scale are listed in Table 2 (Climate.weather.gc.ca, 2019). For example, there were no recorded events where wind velocities exceeded a fresh gale (62- 74 km/h). The spatial distribution of wind speed needed to generate wave bases likely to mix the sediment (i.e., mixing speed) are displayed in Figure 2. At the z-max in Harvey Lake (depth = 11.8 m; Figure 1) the required mixing speed to resuspend sediments is greater than 118 km/h (i.e., hurricane), while the mixing

Table 1. Sediment water interface samples collected during the 2015 field season including results of end member, Grain size, titanium, Beaufort wind category/ speed and depth to mix results. Latitude and Longitude are in decimal degrees.

Samples	Lat	Long	EM1	EM2	EM3	EM4	Mode	Titanium (uncorrected ppm)	Titanium (corrected ppm)	Category	Beaufort Speed	Depth To Mix
1	45.7327	-67.01152	NA	NA	NA	NA	NA	1792	543.21	8	50-61km/h	4.4
2	45.73282	-67.01122	NA	NA	NA	NA	NA	1981	512.49	8	50-61km/h	4.4
3	45.73313	-67.01097	0.4018655	0.2867028	0.3114317	0	169.056	1754	440.32	6	29-38km/h	2.9
4	45.73328	-67.01077	0.2745447	0.1269955	0.5984599	0	169.056	816.5	150.00	4	12-19km/h	1.6
5	45.73338	-67.01145	NA	NA	NA	NA	NA	1544	935.94	6	29-38km/h	2.9
6	45.73297	-67.01015	0.0481999	0.2672614	0.6845387	0	169.056	2007	1116.80	3	6-11km/h	1
7	45.7332	-67.01177	0.2348844	0	0	0.5237939	471.6525	1846	699.81	8	50-61km/h	4.4
8	45.7329	-67.01207	0.4093102	0.5906898	0	0	38.0099	1973.5	512.76	9	62-74km/h	5.3
9	45.73402	-67.01207	0.4240898	0.5759102	0	0	34.6249	1971	565.94	8	50-61km/h	4.4
10	45.73395	-67.01298	0.4941618	0.5058382	0	0	19.78505	1575	314.00	10	75-88km/h	6.1
11	45.73408	-67.01402	0.1826614	0.8173386	0	0	38.0099	1802	469.52	9	62-74km/h	5.3
12	45.73452	-67.01577	0.2237443	0.7762557	0	0	34.6249	1720	420.34	10	75-88km/h	6.1
13	45.73455	-67.01813	0.1562322	0.7073685	0.1363993	0	41.72585	1766.5	461.09	13	>118km/h	8
14	45.73492	-67.01663	NA	NA	NA	NA	NA	1662.5	450.98	11	89-102km/h	7
15	45.73507	-67.01598	0.1583611	0.8416389	0	0	41.72585	1837	464.03	11	89-102km/h	7
16	45.73543	-67.01512	0.3660626	0.6339374	0	0	21.7193	1972	677.57	10	75-88km/h	6.1
17	45.73685	-67.01562	NA	NA	NA	NA	169.056	1715	371.45	5	20-28km/h	2.2
18	45.73607	-67.01678	0.3992019	0.5601073	0.0406908	0	19.78505	1720	817.78	8	50-61km/h	4.4
19	45.7355	-67.01807	0.1614196	0.8385804	0	0	41.72585	1800	487.09	13	>118km/h	8

Samples	Lat	Long	EM1	EM2	EM3	EM4	Mode	Titanium (uncorrected ppm)	Titanium (corrected ppm)	Category	Beaufort Speed	Depth To Mix
20	45.73482	-67.01905	0	0.5956108	0.3067483	0	154.0005	1636	472.56	13	>118km/h	8
21	45.73458	-67.02025	0	0.7485606	0.2514394	0	45.80505	1651	427.76	13	>118km/h	8
22	45.7332	-67.01968	0.2574427	0.7425573	0	0	38.0099	1904	515.08	11	89-102km/h	7
23	45.73237	-67.0215	0.1208038	0.8791962	0	0	41.72585	1778	473.15	11	89-102km/h	7
24	45.73072	-67.02195	0.2111733	0.7888267	0	0	38.0099	2022.5	520.24	10	75-88km/h	6.1
25	45.7293	-67.02238	0.2844452	0.7155548	0	0	38.0099	2036	611.42	10	75-88km/h	6.1
26	45.72887	-67.0222	NA	NA	NA	NA	NA	2071	626.14	9	62-74km/h	5.3
27	45.72813	-67.02223	0.2630603	0.7369397	0	0	38.0099	2424	791.56	9	62-74km/h	5.3
28	45.7272	-67.02423	NA	NA	NA	NA	NA	2278	758.30	8	50-61km/h	4.4
29	45.72608	-67.02423	0.6412158	0.3587842	0	0	19.78505	2227.5	701.62	8	50-61km/h	4.4
30	45.7258	-67.02502	0.7335708	0.2664292	0	0	18.0231	2901	1296.35	7	39-49km/h	3.7
31	45.7269	-67.02485	0.2711774	0.7288226	0	0	38.0099	2735	1115.59	8	50-61km/h	4.4
32	45.72783	-67.02427	0.3052174	0.6947826	0	0	31.54135	2521	918.27	9	62-74km/h	5.3
33	45.7288	-67.02375	0.400906	0.599094	0	0	26.1736	2739.5	1053.12	9	62-74km/h	5.3
34	45.73097	-67.02348	0.4211326	0.4765108	0	0.1023565	19.78505	2523	1522.66	8	50-61km/h	4.4
35	45.73247	-67.02235	0.1739531	0.8260469	0	0	38.0099	2514	825.66	11	89-102km/h	7
36	45.73357	-67.02173	0.2975889	0.7024111	0	0	19.78505	1885	471.72	13	>118km/h	8
37	45.7349	-67.02105	NA	NA	NA	NA	NA	2095	626.78	11	89-102km/h	7
38	45.73657	-67.02013	NA	NA	NA	NA	NA	2727	839.04	11	89-102km/h	7
39	45.73903	-67.01853	0.4372171	0.5627829	0	0	38.0099	3040	1390.24	10	75-88km/h	6.1
40	45.7395	-67.01743	NA	NA	NA	NA	NA	3403	2167.03	7	39-49km/h	3.7
41	45.74197	-67.01723	NA	NA	NA	NA	NA	3200.5	2242.33	8	50-61km/h	4.4
42	45.74097	-67.01848	NA	NA	NA	NA	185.5835	2683.5	1628.23	9	62-74km/h	5.3

Samples	Lat	Long	EM1	EM2	EM3	EM4	Mode	Titanium (uncorrected ppm)	Titanium (corrected ppm)	Category	Beaufort Speed	Depth To Mix
43	45.74007	-67.01907	0	0	0.8438949	0.1561051	NA	2630	1466.70	11	89-102km/h	7
44	45.73912	-67.01963	0.234509	0.765491	0	0	34.6249	2776	943.62	11	89-102km/h	7
45	45.73817	-67.02052	0.1778105	0.8221895	0	0	34.6249	2746.5	815.99	11	89-102km/h	7
46	45.73688	-67.02185	0.1495373	0.8504627	0	0	38.0099	3098	1009.61	10	75-88km/h	6.1
47	45.73583	-67.02245	0.1857548	0.8142452	0	0	34.6249	2892.5	898.79	10	75-88km/h	6.1
48	45.73488	-67.02338	0.1543911	0.8456089	0	0	34.6249	2618	798.19	10	75-88km/h	6.1
49	45.734533	-67.0256	0.1661497	0.8338503	0	0	34.6249	2613	858.69	9	62-74km/h	5.3
50	45.733867	-67.0262	NA	NA	NA	NA	NA	1889	587.62	9	62-74km/h	5.3
51	45.733433	-67.0271	0.0821136	0.9178864	0	0	41.72585	1950	597.96	9	62-74km/h	5.3
52	45.732167	-67.02757	0.1006675	0.8993325	0	0	41.72585	1966	597.46	9	62-74km/h	5.3
53	45.73288	-67.02908	0.0751038	0.9248962	0	0	41.72585	1993	635.39	9	62-74km/h	5.3
54	45.737033	-67.0367	0.3868423	0.6131577	0	0	19.78505	2083	941.31	8	50-61km/h	4.4
55	45.7382	-67.0346	0.0726521	0.9273479	0	0	41.72585	2068.5	700.56	9	62-74km/h	5.3
56	45.74033	-67.03128	0.0899431	0.9100569	0	0	41.72585	2444	962.13	10	75-88km/h	6.1
57	45.74205	-67.02848	0.1521134	0.8478866	0	0	41.72585	2276.5	891.34	10	75-88km/h	6.1
58	45.74417	-67.02525	0.4534557	0.5465443	0	0	19.78505	2563	1877.49	8	50-61km/h	4.4
59	45.7452	-67.02388	0.1798662	0.7137748	0.106359	0	45.80505	2536	1281.63	10	75-88km/h	6.1
60	45.74677	-67.02182	0.571946	0.428054	0	0	18.0231	2627	1767.70	8	50-61km/h	4.4
61	45.74415	-67.03978	0.5482697	0.4517303	0	0	16.41805	2597	1241.48	6	29-38km/h	2.9
62	45.74678	-67.04145	0.3237761	0.1610015	0.1240348	0.3911876	471.6525	2831	1786.31	6	29-38km/h	2.9
63	45.74877	-67.04332	0.2994396	0.7005604	0	0	55.19885	2507.5	1097.73	8	50-61km/h	4.4
64	45.75005	-67.04595	0.5565675	0.4434325	0	0	55.19885	2738	1802.89	5	20-28km/h	2.2
65	45.75132	-67.04405	0.5070513	0.4929487	0	0	38.0099	2678	1206.59	6	29-38km/h	2.9

Samples	Lat	Long	EM1	EM2	EM3	EM4	Mode	Titanium (uncorrected ppm)	Titanium (corrected ppm)	Category	Beaufort Speed	Depth To Mix
66	45.75168	-67.04265	0.1418168	0.4998216	0.3583617	0	87.99785	2633.5	1587.93	7	39-49km/h	3.7
67	45.7507	-67.03972	0.0093242	0.3780299	0.6099067	0	127.7925	2377	1493.44	6	29-38km/h	2.9
68	45.7489	-67.0381	0.5427318	0.4572682	0	0	16.41805	2348	957.56	7	39-49km/h	3.7
69	45.74705	-67.03743	0.4070843	0.5929157	0	0	19.78505	2410	1140.67	7	39-49km/h	3.7
70	45.7429	-67.01693	0.4569682	0.5302701	0.0127617	0	18.0231	2386	1749.26	7	39-49km/h	3.7
71	45.74192	-67.01829	0.122536	0.2682924	0.6091716	0	185.5835	2277.5	1757.69	8	50-61km/h	4.4
72	45.74048	-67.02016	0.1211713	0.8788287	0	0	41.72585	2316.5	999.46	11	89-102km/h	7
73	45.73882	-67.02236	0.0381254	0.9618746	0	0	41.72585	2114	608.08	10	75-88km/h	6.1
74	45.73712	-67.02496	0.0510816	0.9489184	0	0	41.72585	2015.5	565.65	10	75-88km/h	6.1
75	45.73525	-67.02761	0.0483536	0.9516464	0	0	45.80505	2100.5	609.95	9	62-74km/h	5.3
76	45.73373	-67.0306	NA	NA	NA	NA	NA	1967.5	481.15	9	62-74km/h	5.3
77	45.73349	-67.03233	0.6918443	0.1993762	0.0501929	0.0585866	471.6525	2382	1419.58	8	50-61km/h	4.4
78	45.73557	-67.03478	0.3052287	0.6947713	0	0	34.6249	2255	673.60	8	50-61km/h	4.4
79	45.7364	-67.03359	0.1916119	0.8083881	0	0	34.6249	2141.5	543.96	9	62-74km/h	5.3
80	45.73844	-67.03098	0.1521048	0.8478952	0	0	38.0099	2064.5	583.84	10	75-88km/h	6.1
81	45.74106	-67.02833	0.1816296	0.8183704	0	0	38.0099	2244	530.44	10	75-88km/h	6.1
82	45.74466	-67.02373	0.5808379	0.4191621	0	0	18.0231	2569	1072.06	9	62-74km/h	5.3
83	45.74569	-67.0227	0.5319766	0.184456	0.1327073	0.1508602	429.649	2928	1965.85	8	50-61km/h	4.4
84	45.74632	-67.0211	0.4565669	0.5434332	0	0	18.0231	2553	1166.72	7	39-49km/h	3.7
85	45.75045	-67.02116	0.3183021	0	0	0.6816979	471.6525	1806	1055.85	4	12-19km/h	1.6
86	45.74994	-67.02263	0	0.086316	0.6147141	0	127.7925	2717	1429.83	8	50-61km/h	4.4
87	45.74845	-67.02494	0	0.3356658	0.4503978	0	80.1611	2882	1298.76	8	50-61km/h	4.4
88	45.74939	-67.02623	0.1708978	0.3304024	0.4986998	0	80.1611	2940.5	1358.79	6	29-38km/h	2.9

Samples	Lat	Long	EM1	EM2	EM3	EM4	Mode	Titanium (uncorrected ppm)	Titanium (corrected ppm)	Category	Beaufort Speed	Depth To Mix
89	45.75083	-67.02263	0.3167872	0.3578018	0.325411	0	185.5835	2434.5	1167.20	6	29-38km/h	2.9
90	45.75269	-67.02873	0	0	0.1850766	0.3047381	169.056	2346	741.84	6	29-38km/h	2.9
91	45.75464	-67.02758	0.4040021	0.2594433	0.2218086	0.114746	223.6435	2000	1264.31	6	29-38km/h	2.9
92	45.75472	-67.02442	0.1112792	0	0.5106726	0.3780482	203.7265	2590.5	1727.95	5	20-28km/h	2.2
93	45.75555	-67.0263	0.8060152	0.0181255	0.1758594	0	169.056	2407	1534.34	6	29-38km/h	2.9
94	45.75285	-67.02278	1	0	0	0	517.7625	2880	1472.43	5	20-28km/h	2.2
95	45.75168	-67.02225	0.8045518	0.1221564	0.0732918	0	169.056	2243	973.92	6	29-38km/h	2.9
96	45.744733	-67.032667	0.0972851	0.1837283	0.1184614	0.6005252	471.6525	2455.5	1337.94	10	75-88km/h	6.1
97	45.7449	-67.034667	0	0.1390996	0.6660918	0.1541018	185.5835	2175	558.87	8	50-61km/h	4.4
98	45.74505	-67.0314	NA	NA	NA	NA	NA	2430	731.81	10	75-88km/h	6.1
99	45.746	-67.029883	0.4469041	0.5530959	0	0	34.6249	2329	956.60	9	62-74km/h	5.3
100	45.746817	-67.028	0.6694317	0.3305683	0	0	18.0231	2527	1261.22	6	29-38km/h	2.9

Table 2. Hourly wind speed (km/h) (Climate.weather.gc.ca, 2019) between 1953-2015 from Fredericton A Station (45.87N, -66.53W) excluding winter months (December-March). Scale and Description represent the Beaufort wind speed scale (Canada, 2019). Frequency is the number of hours that matched that wind speed. Percent of Record (i.e., percentage frequency), is based on Cumulative Sum, and is the percent of hours that matched those wind speeds. For example, wind speeds greater than 39 km/h happened less than 1% of that time and calm (0 -1 km/h) wind speeds were experienced 100% of the time.

Scale	Description	Min. Speed (km/h)	Max. Speed (km/h)	Frequency (n)	Cumulative Sum (n)	Percent of Record (%)
0	Calm	0	1	134905	368728	100
1	LightAir	1	5	95567	233823	63.413
2	LightBreeze	6	11	53022	138256	37.495
3	GentleBreeze	12	19	40197	85234	23.116
4	ModerateBreeze	20	28	32630	45037	12.214
5	FreshBreeze	29	38	10115	12407	3.365
6	StrongBreeze	39	49	2159	2292	0.622
7	NearGale	50	61	120	133	0.036
8	FreshGale	62	74	13	13	0.004
9	StrongGale	75	88	0	0	0
10	WholeGale	89	102	0	0	0
11	ViolentStorm	103	117	0	0	0
12	Hurricane	118	1000	0	0	0

Figure 2. Spatial map of Harvey Lake based on the Fredericton A meteorological dataset (45.87 °N, -66.53°W) displaying the wind speed required, in terms of the Beaufort Wind Scale, to generate wave base likely to mix the lake bottom (i.e., mixing speed).

speed to resuspend sediments in the deepest part of Herbert's Cove (depth = 2.9 m) is only 20-28 km/h (i.e., moderate breeze).

Table 2 shows the percentage frequency at which different levels of the Beaufort wind scale occurred at nearby Fredericton A station since wind data record keeping began there in 1953. For example, calm winds are most frequent, having a 100% percentage frequency, while fresh breezes (29-38 km/h) only have a percentage frequency of 3.4% of wind speeds recorded. The relationship between water column depth and the percentage frequency of wind - derived mixing speed for that depth (mixing probability) are presented in Figure 3. For example, sediments in the lake at any water depth greater than 4.4 m to z-max at 11.8 m have a 0% mixing probability of being directly disturbed by winds that have impacted the lake since wind record keeping for the area began, and similarly the deepest part of Herbert's Cove (2.9 m) has a mixing probability of 3.4%. Figure 4 is a spatial distribution map of mixing probability for the entire Harvey Lake basin. These observations do not preclude sediment being resuspended in the water column being redeposited at greater water depths.

1.4.2 Grain Size Mode

Grain size analysis results for the Harvey Lake bottom sediments was based on samples obtained from 96 sample stations (Appendix A). Figure 5 displays the spatial distribution of the three major grain size modes: mud (<63 μm), very fine sand (63-125 μm), and fine to coarse sand (> 125 μm). Mud (<63 μm) was the most common grain size in the deepest section of the lake (max depth = 11.8 m) and Herbert's Cove (max depth = ~ 2.9m; Figure 5). There is a trend toward progressively coarser

Figure 3. Biplot showing relationship between water column depth (m) and mixing probability (%). Depositional areas were defined as those with a mixing probability less than 5%.

Figure 4. Map of Harvey Lake displaying the spatial distribution of mixing probability (%). For example, the brown margins are constantly mixed while conditions needed to mix the blue central area have never been observed at the Fredericton Station (45.87°N, -66.53°W).

substrate toward the northern part of the lake and in the cove adjacent to the village of Harvey Station (Figure 5).

1.4.3 Titanium

The central area in the vicinity of the z-max was characterized by the lowest concentrations of Ti, which when calibrated to the Itrax XRF-CS results ranged from 480 - 848 ppm (Table 1; Figure 6). The highest concentration of Ti is observed from the mouth of the east stream ranging between 1345-1733 ppm (Figure 6). Titanium concentrations in Herbert's Cove were lower than at the mouth of the east stream ranging between 848-1119 ppm, however these concentrations were still elevated compared to the z-max (Figure 6).

1.4.4 End Member Mixing Analysis

An EMMA model that explained $78.7\% \pm 13.0\%$ of the variance in the Harvey Lake surface sediment grain size dataset (see Appendix for model selection) was chosen which consisted of four robust end members (Table 3; Figure 7). Robust is a quantifiable value that measures the variability in modelling an end members grain size distribution; the greater the variability the less robust the end member. A robust end member with a mode of 40 μm (very coarse silt) explained 42.6% of the variation in the dataset (Table 3; Figure 7), which was particularly abundant in the SW area of the lake (73.5-93.6%), including the z-max and the outer area of Herbert's Cove. The abundance of the very coarse silt end member, which was also the only end member to follow a unimodal grain size distribution, decreased to 0.3-31% in the north east part of Harvey Lake. The fine sand end member (mode = 177 μm) was the least robust of the four end

Figure 5. Spatial map of Harvey Lake showing grain size mode of lake sediment based on 96 sites.

Figure 6. Spatial map of Harvey Lake showing lake sediment Ti concentrations, measured using Itrax x-ray fluorescence, based on 96 sites.

Table 3. Descriptions of robust end members.

Description	Mode (μm)	Variance Explained (%)
Fine silt	6.16	24.29
Very coarse silt	39.78	42.64
Fine sand	176.94	21.64
Medium sand	449.67	8.73

Figure 7. Grain-size frequency distributions for each site (upper panel) and each robust end member (rEM). Y-axis is frequency. X-axis is the grain-size (μm) on a log scale. V – very; F – fine; M – medium; C – coarse.

members (Figure 7). The fine silt end member (mode = 6 μm) had secondary modes similar to the modes for the fine sand (mode = 177 μm) and medium sand (mode = 450 μm) end members (Figure 7). The medium sand end member (mode = 450 μm) was quite robust but only explained ~9% of the variation in the dataset (Table 3; Figure 7).

1.4.5 Correlations

A correlogram (Appendix B) was used to explore the distribution of the measured variables and their relationships to one another. The fine silt (mode = 6 μm) and the very coarse silt (mode = 40 μm) end members, Ti, wind mixing speed and water depth all had unimodal near normal distributions. Water column depth is used to calculate wind mixing speed explaining the strong positive relationship between these two variables. A second correlogram was generated (Appendix C) using only near-normal distributed variables and excluding depth. Pearson correlation showed that the very coarse silt end member was positively correlated with mixing speed ($r^2 = 0.7$) and negatively related to Ti ($r^2 = -0.5$; Table 4).

Table 4. Pearson correlation matrix of select Harvey Lake variables (see Figure S1). Of note, the very coarse silt end member is positively correlated with mixing speed, i.e., the wind speed that would generate wave base likely to mix bottom sediments.

	Fine Silt End-Member	Very Coarse Silt End-Member	Ti (ppm)	Mixing Speed (Beaufort)
Fine Silt	*			
V Coarse Silt	-0.422	*		
Ti	0.361	-0.500	*	
Mixing Speed	-0.398	0.700	-0.501	*

Figure 8. Spatial map of Harvey Lake displaying the distribution of the very coarse silt end-member (mode = 40 μ m, thought to reflect sediment deposition after resuspension).

1.5 Discussion

1.5.1 Potential Impact of Resuspension on Sedimentation

Sediments undergo resuspension when lake bottom shear exceeds a critical shear stress by wind, which causes orbital movements within the water column (Gilbert, 1999). This results in sediments being lifted and displaced precluding the preservation of complete environmental archives (Evans, 1994; Gilbert, 1999). Thus, areas of lake bottoms with minimal wind-induced sediment mixing should be targeted to recover the most undisturbed paleoenvironmental archives.

In Harvey Lake, depositional areas were identified with potentially undisturbed sedimentary archives as those with a mixing probability of $< 5\%$ (Figures 3,4), fine grain size modes (Figure 5) and relatively low concentrations of Ti (Figure 6). In contrast, areas of Harvey Lake with mixing probabilities greater than 5% are characterized by coarse grain size modes (i.e., fine sand) and sediments enriched in Ti (e.g. the area near the eastern inlet stream; Figure 1). In such areas, fine grains enriched in Al (Egemose et al., 2012) have been winnowed away through frequent resuspension events leaving behind coarse grains enriched with high concentrations of Ti (Cohen, 2003; Croudace et al., 2015). The degree to which such resuspension events occur in a given lake is dependent on the frequency of higher Beaufort wind speed scale events, water depth, which is in part offset by the rate of sedimentation. If sedimentation rates are relatively high buried sediments will be protected from wind driven disturbance. The primary area in Harvey Lake characterized by relatively undisturbed substrates is the z-max and surrounding area, which has a mixing probability of 0% (Figure 4), is composed of a fine grain size mode (Figure 5), and has the lowest concentration of Ti observed in the lake

(480-848 ppm; Figure 6). Protected coves provide additional areas that are sheltered from winds, where relatively undisturbed sedimentation can occur, which in Harvey Lake include a cove near the village, and Herbert's Cove (Figure 1). The substrate of the cove near the village has unfortunately been negatively impacted by wood chips and other debris originating from decades of runoff from the now closed lumber mill operations. However, Herbert's Cove also has a very low mixing probability of 3.4% (Figure 4), fine grained sediments ($<63\ \mu\text{m}$; Figure 5) and concentrations of Ti ranging from 848-1119 ppm (Figure 6). These Ti values although higher than at the z-max, are lower than measured in most areas of the lake.

Areas protected from resuspension events are not immune from fallout from sediments that were resuspended in the water column elsewhere in the lake and which will sink to the substrate again once turbulence in the water column becomes reduced. The EMMA modeled a very coarse silt (mode = $40\ \mu\text{m}$) robust end member that had a strong positive correlation with mixing speed ($r^2 = 0.7$), a negative relationship to Ti ($r^2 = -0.5$; Table 4) and which is only common in areas of Harvey Lake with low mixing probabilities (Figure 8). The very coarse silt end member is the product of sediment resuspension, especially during storm events and subsequent deposition in quieter parts of Harvey Lake. End member mixing analysis has been previously used to model specific depositional processes including on the Norfolk Coast, where Swindles et al. (2018) used EMMA to identify the sedimentary record of a particularly strong 1953 North Sea storm surge in a UK salt marsh. Being able to characterize specific depositional processes in the sedimentary record, via EMMA, would provide an important tool for identifying and perhaps estimating the magnitude of paleo-storm signals in longer sedimentary records.

1.5.2 Allochthonous Sediment Runoff

Allochthonous sediments are an important catchment runoff proxy that can often be directly related to storm events, given that grain size reflects different transportation or depositional processes (Middleton, 1976; Sun et al., 2002; Xiao et al., 2012), which are influenced by changes in the hydrology associated with regional climate (Håkanson et al., 1983). High precipitation rates associated with storms increases the rate of soil erosion within the catchment, enhances the sediment transport capacity of streams, which results in coarser materials becoming available for stream transport into a lake (Håkanson et al., 1983; Peng et al., 2005). It is important to note though that in colder climates, such as exists at Harvey Lake allochthonous runoff can also be associated with Spring freshet (Zhang et al., 2001).

The primary sources of sediment in the Harvey Lake catchment from which allochthonous material is eroded into Harvey Lake include the steep topographic high of Cherry Mountain (Figure 1) on the south shore of the of the z-max, and two streams; one midway along the east shore, which drains through cleared agricultural land, and the other flowing through forest into Herbert's Cove. The z-max has long been identified as an ideal target for coring studies (Håkanson et al., 1983). In Harvey Lake the central location of the z-max is both a benefit, sediment from all over Harvey Lake is focused there (Figure 1; Smol, 2002; Smol, 2004), and a detriment, the z-max could present logistical difficulties due to water depth and the distal location of the z-max from its allochthonous sediment source, Cherry Mountain. As flowing water erodes the surrounding catchment and deposits sediments in a lake, the velocity of flow decreases and the water's ability to move coarser sediment, associated with storm events, decreases

making it difficult for eroded storm materials to consistently make it to the z-max, resulting in a dampened storm signal (Morales-Marin et al., 2017).

The area near the outflow of the stream on the eastern shore is characterized by sandy sediments enriched in Ti and high mixing probabilities resulting in frequent resuspension events preferentially winnowing away fine grains enriched in Al, leaving coarse, Ti rich sediment (Cohen, 2003; Egemose et al., 2012; Croudace et al., 2015). Thus, the area near this stream is unsuitable for sediment coring due to an incomplete sedimentary record.

As discussed above, our basin-wide characterization of Harvey Lake has resulted in the identification of Herbert's Cove (Figure 1) as an additional potential coring site to identify paleo-storm records. Herbert's Cove, as compared to the z-max, is also logistically easier to access and is characterized by a muddy substrate ($<63\mu\text{m}$). Herbert's Cove has a small stream eroding allochthonous materials into it from the south. The cove morphology, both water depth and the sheltering nature of the surrounding topography, reduce the frequency of resuspension events (i.e., mixing probability) likely resulting in a near complete sedimentary record being preserved here. The area near the outflow of the stream flowing into the cove has elevated concentrations of Ti as compared to the north section of Herbert's Cove (480-848 ppm vs 848-1119 ppm). This gradient provides evidence of the influence of allochthonous stream derived sedimentation into Herbert's Cove. The Herbert's Cove depositional environment is also much closer to its allochthonous sediment source (stream), increasing the probability of sediments carried during episodic storms being deposited there (Morales-Marin et al., 2017). Ease of access and proximity to its allochthonous sediment source, coupled with the cove only being

prone to wind- derived resuspension events during strong storm events makes Herbert's Cove an ideal target for core research targeted to the identification of a paleo-storm events.

1.5.3 Application to Identifying Paleo-Storms

Lake depositional systems are comprised of sedimentary archives that preserve signals of past storms as spikes in coarser grains. These particles are derived from: 1) the greater precipitation generally associated with storm events, which increases runoff from the catchment into inlet streams running at an increased velocity resulting in coarser grains being carried into a lake (Cohen, 2003; Gallagher et al., 2016;); and 2) sediments resuspended from the substrate by wind associated with a storm event, which eventually resettle to the lake bottom once the storm abates, with coarser grains settling out first. These sedimentary records are valuable as they could potentially enable researchers to observe past trends in storm intensity and frequency, and place present-day storm events into a historical context (Donnelly et al., 2007; Toomey et al., 2013). The capacity to identify storm events predating instrumental records is particularly valuable as this information can be used to better understand the past trends and cycles of cyclic climate drivers known to influence major storm intensity and frequency in the North Atlantic region (e.g. AMO, ENSO) during cooler and warmer climatic intervals (Boës et al., 2008; Olafsdottir et al., 2013); important data for researchers modeling future storm patterns.

Our study identifies Harvey Lake's z-max and Herbert's Cove to be the best areas to collect sediment cores for a paleo storm study. In general, the z-max tends to be preferred over shallower sites, as the latter is susceptible to mixing processes, while a flat

central basin would likely achieve the most complete sediment profile (Smol, 2002).

Lake depositional processes carry sediments from all over the lake to the z-max (Bengtsson et al., 1990), where sediments collect without being disturbed by wind waves (Figure 2). However, steep slopes related to the local topographic high within the catchment (i.e., Cherry Mountain) may result in slope instabilities and the mixing of the sedimentary record. In addition, the distal location of the z-max could dampen paleo storm signals. Gentler slopes in Herbert's Cove that reduce the probability of slope instabilities and its proximity to allochthonous inputs likely result in the preservation of strong and clear signals of past storm events. Ideally cores would be collected from both sites to corroborate historical reconstructions to provide a more robust paleo storm history.

1.6 Conclusions

This multi-proxy study assessed the impact of varying intensities of historically documented wind speeds (1953-2015) to determine what areas of the substrate of Harvey Lake, New Brunswick are most prone to sediment remobilization, and direct deposit of sediments derived from catchment runoff, particularly during large storms. The research was carried out using a novel cost-effective approach, which is based on mapping sediment mixing probabilities, using freely available bathymetric and historical weather data, in combination with hydrological proxy data (grain size analysis, Itrax-XRF). It was determined that the area in the vicinity of the 11 m deep- z-max, well below the calculated 4.4 m maximum storm wave base in the lake, would be a suitable coring area as it is an area of undisturbed deposition where storm derived sediments suspended in the

water column fallout from the water column in combination with sediment runoff from the catchment. The runoff signal is somewhat muted in the z-max area of the lake though due to the distal location of the deepest part of the lake from the primary sediment catchment source derived from the slopes of Cherry Mountain. A second more ideal coring target area was identified in Herbert's Cove on the SW margin of the lake. Although the cove is relatively shallow with a maximum depth of only 2.9 m, the surrounding topographic highs protect it from all but the most severe winds. In addition to being characterized by a non-erosional depositional system, the results of this study indicate that sediments are deposited in Herbert's Cove that are derived from the catchment of a small inlet stream that empties at the head of the cove, and sediments suspended in the water column throughout the lake during major storm events also fall out on the substrate in the cove when wave activity returns to normal. The results of this research on Harvey Lake demonstrate that prior to collecting cores for the assessment of paleo-storm event intensity and frequency that a careful study of a potential target lake be carried out. In the case of Harvey Lake, it was first assumed that the z-max would be the optimal coring target area, while in reality based on the results of this research, Herbert Cove is a better choice for the collection of cores that archive paleo-storm signals.

1.7 Future Directions

1.7.1 Enhancing sample selection

This step can be achieved by collecting more sediment water interface samples from the northern sections of Harvey Lake. These areas were not sampled as generously compared to other parts of the lake. Such enhancement will facilitate the following:

- A more accurate spatial representation of grain size, titanium concentrations and EMMA across the northern parts of the lake using ArcGIS interpolation methods such as Kriging.
- This spatial mapping of grain size, titanium concentrations and EMMA may aid in identifying ideal coring locations other than the z-max and Herbert's Cove.

1.7.2 Application of methodology

This step can be achieved by applying the methodology used in this case study to other lakes across New Brunswick in identifying ideal coring locations within in land lakes.

Such application will facilitate the following:

- A wider significance to this current study.
- Validity in the application of this new protocol and methodology.

References

- Alexander, M. A., Kilbourne, K. H., & Nye, J. A. (2014). Climate variability during warm and cold phases of the Atlantic Multidecadal Oscillation (AMO) 1871–2008. *Journal of Marine Systems*, 133, 14-26.
- Bengtsson, L., Hellström, T., & Rakoczi, L. (1990). Redistribution of sediments in three Swedish lakes. *Hydrobiologia*, 192(2-3), 167-181.
- Bichet, V., Gauthier, E., Massa, C., & Perren, B. B. (2014). Lake Sediments as an Archive of Land use and Environmental Change in the Eastern Settlement, Southwestern Greenland. *Journal of the North Atlantic*, 6, 47-63.
- Blott, S. J., & Pye, K. (2001). GRADISTAT: a grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth surface processes and Landforms*, 26(11), 1237-1248.
- Boës, X., Rydberg, J., Martinez-Cortizas, A., Bindler, R., & Renberg, I. (2011). Evaluation of conservative lithogenic elements (Ti, Zr, Al, and Rb) to study anthropogenic element enrichments in lake sediments. *Journal of Paleolimnology*, 46(1), 75-87.
- Boës, X., & Fagel, N. (2008). Relationships between southern Chilean varved lake sediments, precipitation and ENSO for the last 600 years. *Journal of Paleolimnology*, 39(2), 237-252.
- Brandon, C. M., Woodruff, J. D., Donnelly, J. P., & Sullivan, R. M. (2014). How unique was Hurricane Sandy? Sedimentary reconstructions of extreme flooding from New York Harbor. *Scientific Reports*, 4, 7366.
- Burn, M. J., & Palmer, S. E. (2015). Atlantic hurricane activity during the last

- millennium. *Scientific Reports*, 5, 12838.
- Canada, E. (2019). Beaufort wind scale table - Canada.ca. Retrieved from
<https://www.canada.ca/en/environment-climate-change/services/general-marine-weather-information/understanding-forecasts/beaufort-wind-scale-table.html>
- Chen, J. A., & Wan, G. (1999). Sediment particle size distribution and its environmental significance in Lake Erhai, Yunnan Province. *Chinese Journal of Geochemistry*, 18(4), 314-320.
- Climate.weather.gc.ca. (2019). *Station Results - Historical Data - Climate - Environment and Climate Change Canada*. [online] Available at:
http://climate.weather.gc.ca/historical_data/search_historic_data_stations_e.html?searchType=stnName&timeframe=1&txtStationName=fredericton&searchMethod=contains&optLimit=yearRange&StartYear=1840&EndYear=2019&Year=2019&Month=8&Day=17&selRowPerPage=25 [Accessed 18 Aug. 2019].
- Cohen, A. (2003). *Paleolimnology: The History and evolution of lake systems*. Oxford: New York.
- Croudace, I. W., & Rothwell, R. G. (Eds.). (2015). *Micro-XRF Studies of Sediment Cores: Applications of a non-destructive tool for the environmental sciences* (Vol. 17). Springer.
- Croudace, I. W., Rindby, A., & Rothwell, R. G. (2006). ITRAX: description and evaluation of a new multi-function X-ray core scanner. *Geological Society, London, Special Publications*, 267(1), 51-63.

- Dong, B., Sutton, R. T., & Scaife, A. A. (2006). Multidecadal modulation of El Niño–Southern Oscillation (ENSO) variance by Atlantic Ocean sea surface temperatures. *Geophysical Research Letters*, 33(8).
- Donnelly, J. P., & Woodruff, J. D. (2007). Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon. *Nature*, 447(7143), 465.
- Dietze, E., Hartmann, K., Diekmann, B., IJmker, J., Lehmkuhl, F., Opitz, S., ... & Borchers, A. (2012). An end member algorithm for deciphering modern detrital processes from lake sediments of Lake Donggi Cona, NE Tibetan Plateau, China. *Sedimentary Geology*, 243, 169-180.
- Dietze, M., & Dietze, E. (2013, April). A flexible open-source toolbox for robust end member modelling analysis-The R-package EMMAgeo. In *EGU General Assembly Conference Abstracts* (Vol. 15).
- Dietze, M., & Dietze, E. (2019). Grain-size distribution unmixing using the R packageEMMAgeo. *E & G Quaternary Science Journal*, 68(1), 29-46.
- Eden, D. N., & Page, M. J. (1998). Palaeoclimatic implications of a storm erosion record from late Holocene lake sediments, North Island, New Zealand. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 139(1-2), 37-58.
- Egemose, S., Reitzel, K., Andersen, F. Ø., & Jensen, H. S. (2013). Resuspension-mediated aluminium and phosphorus distribution in lake sediments after aluminium treatment. *Hydrobiologia*, 701(1), 79-88
- Evans, D.R.(1994).Empirical evidence of the importance of sediment resuspension in lakes. *Hydrobiologia*, 284(1), 5-12.

- Flower, R. J., Stickley, C., Rose, N. L., Peglar, S., Fathi, A. A., & Appleby, P. G. (2006). Environmental changes at the desert margin: an assessment of recent paleolimnological records in Lake Qarun, Middle Egypt. *Journal of Paleolimnology*, 35(1), 1-24.
- Gallagher, E., Wadman, H., McNinch, J., Reniers, A., & Koktas, M. (2016). A conceptual model for spatial grain size variability on the surface of and within beaches. *Journal of Marine Science and Engineering*, 4(2), 38.
- Gilbert, R. (1999). Calculated wave base in relation to the observed patterns of sediment deposition in northeastern Lake Ontario. *Journal of Great Lakes Research*, 25(4), 883-891.
- Goldenberg, S. B., Landsea, C. W., Mestas-Núñez, A. M., & Gray, W. M. (2001). The recent increase in Atlantic hurricane activity: Causes and implications. *Science*, 293(5529), 474-479.
- Government of New Brunswick, C. (2019, July 22). Lake Depths. Retrieved November 06, 2018, from https://www2.gnb.ca/content/gnb/en/departments/erd/natural_resources/content/fish/content/lake_depths.html
- Govin, A., Holzwarth, U., Heslop, D., Ford Keeling, L., Zabel, M., Mulitza, S., ... & Chiessi, C. M. (2012). Distribution of major elements in Atlantic surface sediments (36 N–49 S): Imprint of terrigenous input and continental weathering. *Geochemistry, Geophysics, Geosystems*, 13(1).

- Gregory, B. R., Reinhardt, E. G., Macumber, A. L., Nasser, N. A., Patterson, R. T., Kovacs, S. E., & Galloway, J. M. (2017). Sequential sample reservoirs for Itrax-XRF analysis of discrete samples. *Journal of Paleolimnology*, 57(3), 287-293.
- Gregory, B. R., Patterson, R. T., Reinhardt, E. G., Galloway, J. M., & Roe, H. M. (2019). An evaluation of methodologies for calibrating Itrax X-ray fluorescence counts with ICP-MS concentration data for discrete sediment samples. *Chemical Geology*, 521, 12-27.
- Håkanson, L. (1977). The influence of wind, fetch, and water depth on the distribution of sediments in Lake Vänern, Sweden. *Canadian Journal of Earth Sciences*, 14(3), 397-412.
- Håkanson, L.A. (1983). Principles of Lake Sedimentology. In *Springer* (p. 316 pp.). Berlin.
- Kido, Y., Koshikawa, T., & Tada, R. (2006). Rapid and quantitative major element analysis method for wet fine-grained sediments using an XRF microscanner. *Marine Geology*, 229(3-4), 209-225.
- Kodom, K., Preko, k., & Boamah, D.(2012).X-ray Fluorescence (XRF) Analysis of Soil Heavy Metal Pollution from an Industrial Area in Kumasi, Ghana.*Soil and Sediment Contamination: An International Journal*. 1006-1021
- Kossin, J. P., & Vimont, D. J. (2007). A more general framework for understanding Atlantic hurricane variability and trends. *Bulletin of the American Meteorological Society*, 88(11), 1767-1782.
- Landsea, C. W., Harper, B. A., Hoarau, K., & Knaff, J. A. (2006). Can we detect trends in extreme tropical cyclones?. *Science*, 313(5786), 452-454.

- Macumber, A.L. (2019, August 07). Source code for wind frequency calculation, end member mixing analysis and correlogram. Retrieved from https://github.com/AMacumber/Mazzella_HarveyLakeMacumber, A. L., Patterson, R. T., Galloway, J. M., Falck, H., & Swindles, G. T. (2018). Reconstruction of Holocene hydroclimatic variability in subarctic treeline lakes using lake sediment grain-size end-members. *The Holocene*, 28(6), 845-857.
- Middleton, G. V. (1976). Hydraulic interpretation of sand size distributions. *The Journal of Geology*, 84(4), 405-426.
- Morales-Marin, L. A., French, J. R., Burningham, H., & Battarbee, R. W. (2018). Three-dimensional hydrodynamic and sediment transport modeling to test the sediment focusing hypothesis in upland lakes. *Limnology and Oceanography*, 63(S1), S156-S176.
- Murray, M.R. (2002) Is laser particle size determination possible for carbonate-rich lake sediments? *Journal of Paleolimnology* 27(2): 173-183.
- Natural Resources Canada.(n.d.).Retrieved from <https://www.nrcan.gc.ca/earth-sciences/geography/topographic-information/free-data-geogratis/11042>
- Nyberg, J., Malmgren, B. A., Winter, A., Jury, M. R., Kilbourne, K. H., & Quinn, T. M. (2007). Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years. *Nature*, 447(7145), 698.
- Olafsdottir, K. B., Geirsdóttir, Á., Miller, G. H., & Larsen, D. J. (2013). Evolution of NAO and AMO strength and cyclicity derived from a 3-ka varve-thickness record from Iceland. *Quaternary Science Reviews*, 69, 142-154.

- Page, M. J., Trustrum, N. A., & DeRose, R. C. (1994). A high resolution record of storm-induced erosion from lake sediments, New Zealand. *Journal of Paleolimnology*, 11(3), 333-348.
- Panahi, A., Cheng, Q., & Bonham-Carter, G. F. (2004). Modelling lake sediment geochemical distribution using principal component, indicator kriging and multifractal power-spectrum analysis: a case study from Gowganda, Ontario. *Geochemistry: Exploration, Environment, Analysis*, 4(1), 59-70.
- Parsons, M. B., LeBlanc, K. W. G., Hall, G. E. M., Sangster, A. L., Vaive, J. E., & Pelchat, P. (2012). Environmental geochemistry of tailings, sediments and surface waters collected from 14 historical gold mining districts in Nova Scotia. *Geological Survey of Canada, Open File*, 7150, 326.
- Peng, Y. J., Xia, J. L., Nakamura, T., Liu, B. L., Inouchi, Y. (2005). Holocene East Asian monsoonal precipitation pattern revealed by grain-size distribution of core sediments of Daihai Lake in Inner Mongolia of north-central China, *Earth and Planetary Science Letters*, 2005, 233: 467–479.
- Shiode, N. (2011). Street-level Spatial Interpolation Using Network-based IDW and Ordinary Kriging. *Transactions in GIS*, 457-477. Retrieved from <http://onlinelibrary.wiley.com.proxy.library.carleton.ca/doi/10.1111/j.1467-9671.2011.01278.x/full>
- Shotbolt, L. A., Thomas, A. D., & Hutchinson, S. M. (2005). The use of reservoir sediments as environmental archives of catchment inputs and atmospheric pollution. *Progress in Physical Geography*, 29(3), 337-361.

- Smith, I. R., & Sinclair, I. J. (1972). Deep water waves in lakes. *Freshwater Biology*, 2(4), 387-399.
- Smol, J.P. (2002). *Pollution of Lakes and Rivers*. Oxford University Press Inc.
- Smol, W.M.(Ed.). (2004). *Tracking Environmental Change Using Lake Sediments Volume I: Basin Analysis, Coring, and Chronological Techniques*. Dordrecht: Kluwer Academic Publishers.
- Sun, D., Bloemendal, J., Rea, D. K., Vandenberghe, J., Jiang, F., An, Z., & Su, R. (2002). Grain-size distribution function of polymodal sediments in hydraulic and aeolian environments, and numerical partitioning of the sedimentary components. *Sedimentary Geology*, 152(3-4), 263-277.
- Swindles, G. T., Galloway, J. M., Macumber, A. L., Croudace, I. W., Emery, A. R., Woulds, C., ... & Rushby, G. T. (2018). Sedimentary records of coastal storm surges: Evidence of the 1953 North Sea event. *Marine Geology*, 403, 262-270.
- Taboada, T., Cortizas, A. M., García, C., & García-Rodeja, E. (2006). Particle-size fractionation of titanium and zirconium during weathering and pedogenesis of granitic rocks in NW Spain. *Geoderma*, 131(1-2), 218-236.
- Tomonori, N.K.A. (2003). Characteristics of bottom surface sediments in relation to wind and wave action in Lake Kitaura, central Japan. *Geol. Soc. Japan*, 1-10.
- Toomey, M. R., Curry, W. B., Donnelly, J. P., & van Hengstum, P. J. (2013). Reconstructing 7000 years of North Atlantic hurricane variability using deep-sea sediment cores from the western Great Bahama Bank. *Paleoceanography*, 28(1), 31-41.
- Van Hengstum, P. J., Reinhardt, E. G., Boyce, J. I., & Clark, C. (2007). Changing

- sedimentation patterns due to historical land-use change in Frenchman's Bay, Pickering, Canada: evidence from high-resolution textural analysis. *Journal of Paleolimnology*, 37(4), 603-618.
- Vasseur, L., Catto, N., Burton, D., Chouinard, O., Davies, J., DeBaie, L., ... & Jacobs, J. (2007). Atlantic Canada. *From impacts to adaptation: Canada in a changing climate*, 119-170.
- Weltje, G. J., Bloemsa, M. R., Tjallingii, R., Heslop, D., Röhl, U., & Croudace, I. W. (2015). Prediction of geochemical composition from XRF core scanner data: a new multivariate approach including automatic selection of calibration samples and quantification of uncertainties. In *Micro-XRF Studies of Sediment Cores* (pp. 507-534). Springer, Dordrecht.
- Weltje, G. J., & Prins, M. A. (2003). Muddled or mixed? Inferring palaeoclimate from size distributions of deep-sea clastics. *Sedimentary Geology*, 162(1-2), 39-62.
- Weltje, G. J., & Prins, M. A. (2007). Genetically meaningful decomposition of grain-size distributions. *Sedimentary Geology*, 202(3), 409-424.
- Weltje, G. J., & Tjallingii, R. (2008). Calibration of XRF core scanners for quantitative geochemical logging of sediment cores: theory and application. *Earth and Planetary Science Letters*, 274(3-4), 423-438.
- Wetzel, R. (1983). *Limnology*. Estados Unidos: Saunders College.
- Wetzel, R. (2001). *Limnology: Lake and river ecosystems*. San Diego: Academic Press.
- Xiao, J., Chang, Z., Fan, J., Zhou, L., Zhai, D., Wen, R., & Qin, X. (2012). The link between grain-size components and depositional processes in a modern clastic lake. *Sedimentology*, 59(3), 1050-1062.

- Żarczyński, M., Szmańda, J., & Tylmann, W. (2019). Grain-Size Distribution and Structural Characteristics of Varved Sediments from Lake Żabińskie (Northeastern Poland). *Quaternary*, 2(1), 8.
- Zhang, X., Harvey, K. D., Hogg, W. D., & Yuzyk, T. R. (2001). Trends in Canadian streamflow. *Water Resources Research*, 37(4), 987-998.
- Zhao, H. (2017). Quantifying Variability of Metal Pollutants in Road-Deposited Sediments Using the Coefficient of Variation. *International Journal of Environmental Research and Public Health*.

Appendices

Appendix A: Grain size distributions of Harvey Lake surface sediment samples (n = 96)

showing median, maximum and minimum frequency at each observed grain size.

Appendix B: Correlogram showing scatterplots of analyses of Harvey Lake surface sediments and distributions on the diagonal.

Appendix C: Correlogram of select environmental variables that had close to normal

distributions. Scatterplots are read as row variable is the y-axis and column variable is the x-axis.

On the diagonal are the distributions of the environmental variable. Of note, the very coarse silt end member (mode = 40 μm) is positively correlated with mixing speed (i.e., Mixing_Beaufort).