Paleoenvironmental and Paleolimnological Reconstruction of the Big Quill Lake, SK

A B.Sc Honours Thesis in Geology

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Abstract

Paleoenvironmental reconstruction of a saline, closed basin Big Quill lake provides insight into the lake's past hydrological conditions in terms of water level and salinity. The research performed on a 140 AD year old core outlines long-term variability of dry and wet cycles under natural and anthropogenic conditions. The reconstruction was performed through analyses of ^{14}C and ^{127}Cs dates, lithology, geochemistry of stable isotopes, and diatom counts that highlighted three periods. From 140 to 1550 AD, saline and lowstand lake level conditions were prevalent, specifically with an overlap with the Medieval Warming Period (1000 to 1200 AD). During 1550 to 1960 AD the lake experienced subsaline conditions under rising lake levels. The high water levels were influenced by the wet climatic conditions posed by the Little Ice Age (1300 to 1850 AD) and interannual oceanic-atmospheric phenomenas of ENSO and PDO (1955 AD), which influence the hydrological balance by elevating precipitation above evaporation. From 1960 to today, the lake has experienced a transition from a low lake levels with saline conditions to highstand water levels with subsaline conditions. The water level reached an observed highstand from 515.9 masl in 1960 to 520.8 masl in 2017, specifically in the last four years, where the climatic conditions have favoured evaporation over precipitation. The reconstruction of the past hydrological conditions under natural forcing gives insight into the lake's modern conditions under regional climate response to natural climatic phenomenas and anthropogenic influences.

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1. Introduction

The Quill Lakes complex consists of Big Quill Lake, Little Quill Lake, and the conjoining Mud Lake. The complex is an internal drainage basin located 52° north latitude and 104° west longitude, Saskatchewan, Canada. Located 160 km northeast of the provincial capital, Regina, the endorheic basin is one of the largest drainage basins in the province covering approximately 78,000 ha (139,000 ac) alongside possessing one of the highest inland salinities of 70,000 mg/L in the country (Whitting 1977; KGS Group, 2016). Water levels of Big Quill and Little Quill have risen in the past decade from 514.2 masl in 2005 to 520.8 masl in 2017, resulting in flooding of approximately 30,700 ha (75,861ac) of surrounding private and crown farmland (Environment Canada, 2018; KGS Group, 2016). At the water levels of 519.6 masl, Mud Lake is created and the Quills become one water body, overtopping grid 640 (Golder Associates, 2015; Kamp, *et al,* 2008). Increasing water levels of the lakes poses a serious threat to the adjacent land, provincial highways 6, 16, and 35, and the CP railway (Golder Associates, 2015). Water levels of the Quill Lakes are expected to continue rising in the next 10 years, creating a natural spill way to Saline Lake, Peter Lake, and Last Mountain Lake, which possess a great danger to the water quality and aquatic habitat of the freshwater lakes (KGS Group, 2016). Several studies have been conducted on the lakes and surroundings including geological, paleolimnological and limnological mainly. However, there is little known about historical water levels and limnological variations of the lake. The present study is a paleolimnological and paleoenvironmental reconstruction based on cores collected from the depocenter of the Big Quill Lake. The main aim of the study is to identify historical events of droughts and floods that may explain the catastrophic rise of the lake levels since 2006.

1.1 Geological Setting

The Quill Lakes complex is a large, but shallow lacustrine basin formed during a Late Wisconsinian glaciation in the Pleistocene Epoch of the Quaternary Period (Whitting, 1977; Hammer and Haynes, 1978). As the glacier retreated northward, the isostatic pressure from the overlying snow mass created surface depressions later filled by proglacial meltwater to create several lacustrine lakes in the drainage basin (Last and Ginn, 2005) including Quill (Big and Little Quill), Fishing, Basin, Middle, Lenore, Haughton, and Deadmoose lakes (Hammer and Haynes, 1978). The Quill Lake basin has a low relief of 3 to 25m/km and is divided into three geographic sections of Touchwood Hills, Northern Sector Hills, and Lake Plain (Figure 1) (Whitting, 1977). The Touchwood Hills southeast of the Lake Plain lie 130 m (730 masl) above the lakes and are characterized by 100 to 300 m sloughs that form what is known as

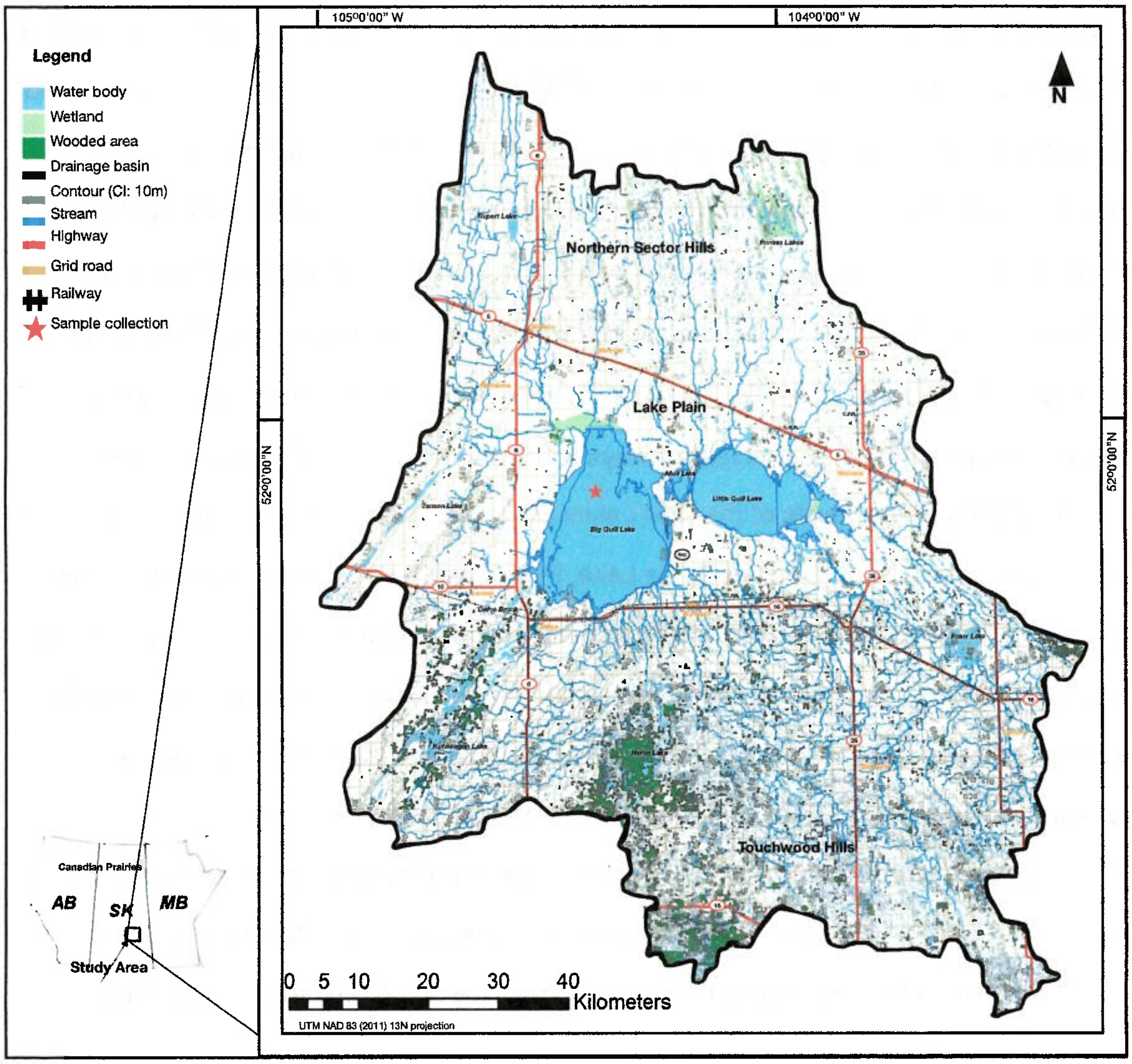


Figure 1. Geographic distribution of the Quill Lake's gross drainage basin (black). Map prepared in ArcGIS and edited in Photoshop. Data retrieved from (NRCAN, 2018).

hummocky terrain, with poor soils. Incised streams, and Wynyard and Magnusson creeks are responsible for runoff drainage into the lakes from the south. The Touchwood Hills are accountable for controlling the warm uniform temperature progression to the south, ultimately decreasing precipitation and frost periods of Lake Plains (Whitting, 1977). The alkaline grasslands of the Northern Hills have a much lower relief than the Touchwood Hills, which lie 50 m (550 masl) above the lakes. The developing creeks of the Northern Hills, Romance, Ironspring, Quill, and Wimmer, are responsible for runoff into the Big Quill Lake and are controlled by man-induced drainage (Whitting, 1977).

The transmission of surface water to subsurface aquifers and surface runoff to the Lake Plain from topographic depressions is governed by the soil types of the complex. The Quill Lakes complex has dark brown Chernozemic soils rich in calcium and magnesium to the south,

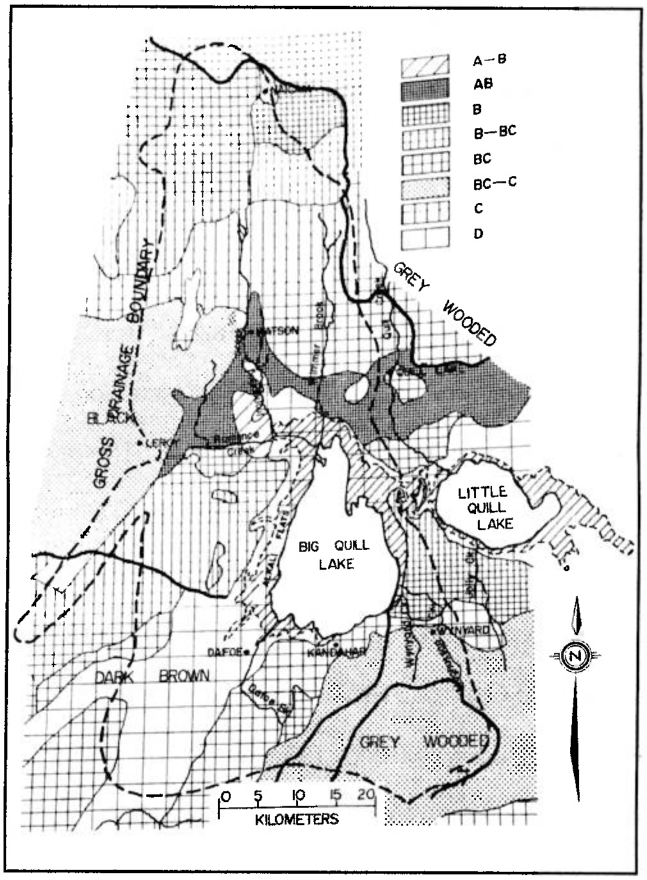


Figure 2. Soil types of the Quill Lakes Complex.
A: High infiltration rates with low runoff potential. Deep, well drained sands or gravels. Water passes easily through soil. High water transmission rates
B: Moderate infiltration rates. Moderately deep, fine to coarse soil texture. Moderate water transmission rates.
C: Low infiltration rates. Moderately fine to very fine soils. Low, slow water transmission.
D: Very low infiltration rates with high runoff potential. Soils rich in clay with high swelling potential or clay layer near surface. Very low to no water transmission. (Whitting, 1977).

thin black Chernozemic soils to the north, and abundant areas of poorly drained Saline Regosolic soils adjacent the lakes (Figure 2) (Whitting, 1977; Hammer and Haynes, 1978).

The surrounding area of the Quill lakes is dominated by glacially drifted debris, which constitutes the input of allogenic sediments to the lakes and ionic composition of the water table (Last, 2002; Last and Ginn, 2005). Glacial drift is overlain by surficially stratified deposits of silts and sands created by eolian, fluvial, and alluvial post-glacial geomorphological processes (Simpson, 2000; Pomeroy, *et al,* 2005). The glacial drift of the drainage basin varies in thickness from 200 m in the lower Touchwood Hills to a few metres in the Lake Plain area (Simpson, 2000). Glacial drift consists of sediment from Tertiary Empress Group, and Quaternary Sutherland and Saskatoon Groups with mainly sands and gravels. These rock groups, specifically the Sutherland Group, act as exceptional aquifers for the town of Wynyard and the surrounding area. Below the glacial drift, lies the Tertiary Wynyard Formation characterized by calcareous to non calcareous silts to gravels and Cretaceous Bearpaw, Judith River, and Lea Park Formations of non calcareous silts and sands (Whitting, 1977; Simpson, 2000).

1.2 Climate

The Quill Lakes complex is situated in a semi-arid climate of the Palliser Triangle in the Saskatchewan Prairies (Hammer and Haynes, 1978). From 1981 to 2010 the recorded climate normal for January temperature is -15.9 ^{o}C and the July temperature is 17.9 ^{o}C. The annual average precipitation is 313.8 mm in the summer and 112.2 mm in the winter, for a total of 413.3 mm per year (Environment of Canada, 2018). Mean annual evaporation based on a ten year study in 1955 to 1966 are of 700 mm annually, which in the majority of times exceeds the precipitation (Figure 3) (Fisheries and Environment Canada, 1978). The average difference between precipitation and evaporation (P-T) in the complex from 1913 to 2017 is -299.2 mm, with a maximum difference of -514.5 mm in 1929 and minimum of -7.7 mm in 2010.

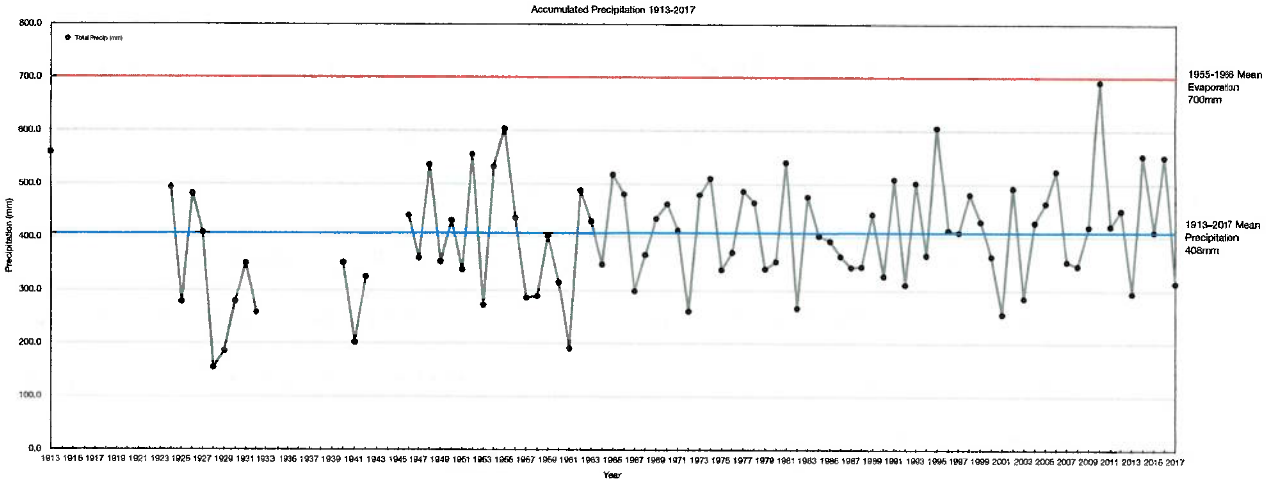


Figure 3. Total annual precipitation (mm) from Quill Lake SK (52°04’ N, 104°14’ W) and Wynyard, SK (51°46’ N, 104°12 W). Annual precipitation for each year was calculated manually from the sum of monthly precipitation. Reference lines for mean evaporation 1955-1966 (red) and mean precipitation 1913-2017 (blue) are plotted (Environment Canada, 2018).

Climate variability associated with precipitation and evaporation differences is one of the main forcings behind lake level fluctuations of the Big Quill lake prior to modern day lake conditions (Whitting, 1977; KGS Group, 2016). The response between teleconnections and the regional climate in the complex varies between years and is highly responsible for climatic variability in the Quill Lakes region. The main atmospheric-oceanic phenomena that affects the climate and ultimately the weather in Southern Saskatchewan are: El Niño/La Niña Southern Oscillations (ENSO), Pacific Decadal oscillation (PDO), and the Pacific North American (PNA) (Bunkers, *et al*, 1996; Bonsal and Shabbar, 2011). When analyzing the anomalies of ENSO and PDO teleconnections, patterns of temperature and precipitation in the region may be outlined on a low-resolution scale. ENSO is a two part El Niño (positive) and La Niña (negative) climatic oscillation that measures the sea surface temperature (SST) of the Southern Pacific Ocean. The ENSO is an irregular cycle that occurs every 3 to 7 years, which governs the climate of Western Canada during El Niño above average temperatures and below average precipitation, while during El Niño below average temperatures with an above average accumulation in snowpack and rainfall prevail (Bonsal and Shabbar, 2011). The PDO is a measure of SST from the Northern Pacific Ocean, which cycles every 20 to 30 years. The PDO is characterized by above average winter temperatures during positive anomalies and vice versa during negative anomalies. A relationship between ENSO and PDO exists; La Niña coupled with negative PDO, bring cooler temperatures and greater precipitation accumulation, while El Niño and positive PDO pose drier conditions and low streamflow in Western Canada (Figure 4) (Bunkers *et al*, 1996; Bonsal and Shabbar, 2011). The relationship between global climatic phenomena and regional climate of the Big Quill lake is evident during overlapping phases of positive ENSO and PDO, as seen in 1982, 1986, 1992, and 2015 (Figure 4). While the correlation between negative phases are seen in 1955, 1975, and 2010 (Bunkers *et al*, 1996; Gurrapu, *et al*, 2009).

Since the Quill Lakes Complex is a large endorheic basin, the main and only form of outflow from the lakes that exists is credited to evaporation (KGS Group, 2016). The greatest change in water levels is correlated to years with minimal runoff, a decline in precipitation, and an increase in evaporation (Kamp, *et al*, 2008). Often, the evaporation rates exceed precipitation rates in the basin, therefore the Standardize Precipitation Evapotranspiration Index (SPEI) can act as an aid in the analysis of climatic water balance of the lake. The SPEI is mathematically calculated by finding a difference between precipitation and potential evapotranspiration on weekly or monthly scales (Vincente-Serrano, *et al*, 2010). In a twelve month SPEI index (Figure 4) when evaporation/evapotranspiration is higher than precipitation, the index is negative and if precipitation rates exceed evaporation, the index is positive as seen in the year of 2010. The response of regional climate of the Quill Lakes complex to the phenomenas of PDO and ENSO are outlined when comparing negative and positive phases to the SPEI index (Figure 4). Distinct dry periods are often a result of positive ENSO and PDO that show a negative response in the SPEI index, thus higher evapotranspiration rates and an overall decline in the water budget of the Quill Lake complex. The cycles of warm and dry climate can be observed in the hydrological balance of the Big Quill Lake.

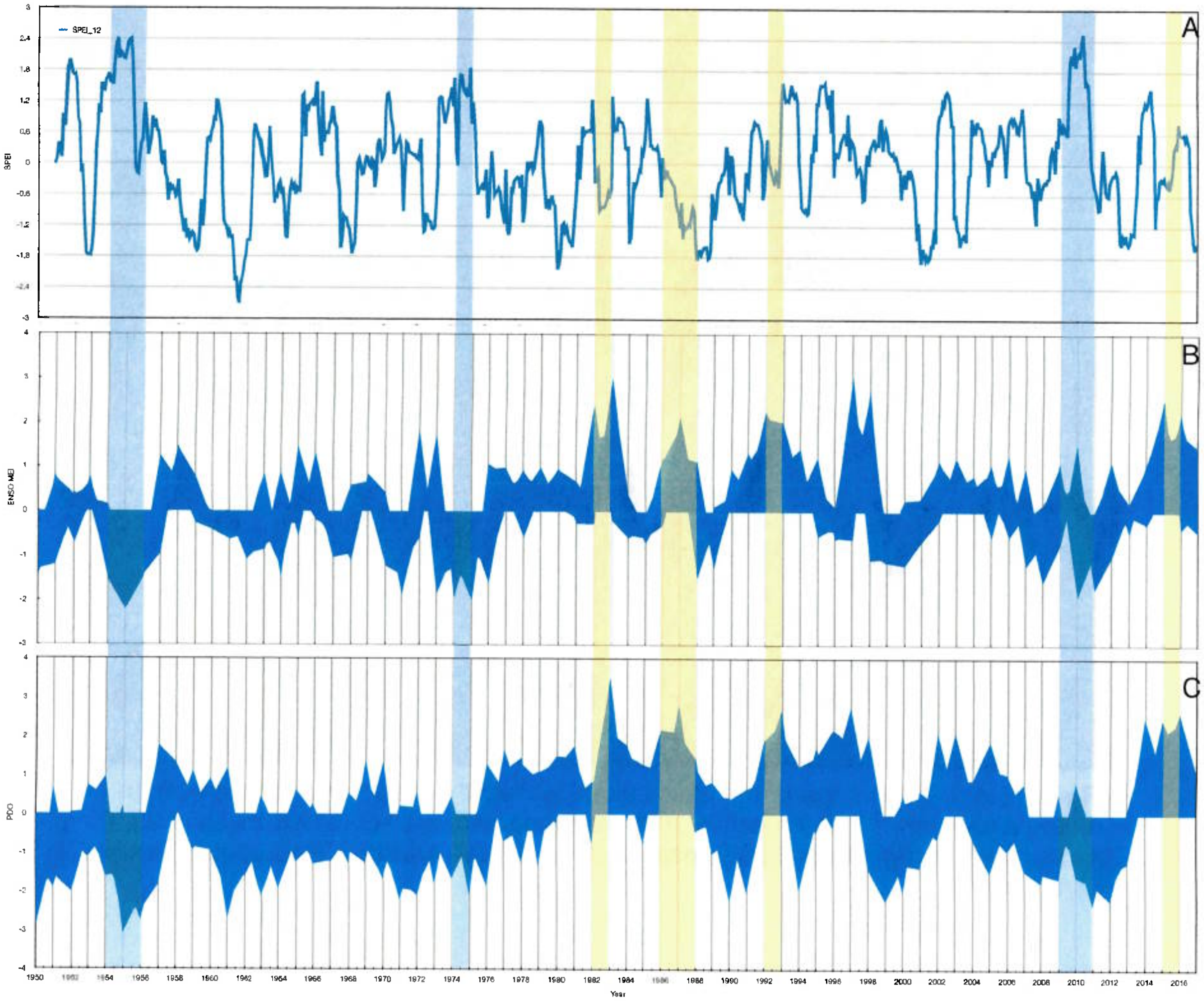


Figure 4. 1950 -2017 climatic trends in terms of dry (orange) and wet (blue) of the Quill lake basin based on the response of the SPEI (A) to the phenomenas of ENSO (B) and PDO (C) (NOAA, 2017; CSIC, 2018).

1.3 Hydrology

The Big Quill lake is the second largest body of water next to Lake Diefenbaker in Saskatchewan (Hammer and Haynes, 1978). The Quill Lakes complex is situated in a 8760 km^2 drainage basin, where only 3370 km^2 is considered to be effective drainage (KGS Group, 2016; Environment Canada, 2018). The surface area of Big Quill has been persistently expanding over the past decade, with surface area growing from 307 km^2 in 1985 to 432 km^2 in 2010, and 562 km^2 in 2015 (Figure 5) (Hammer and Haynes, 1978; Google Earth, 2018). Since the 1930s, and

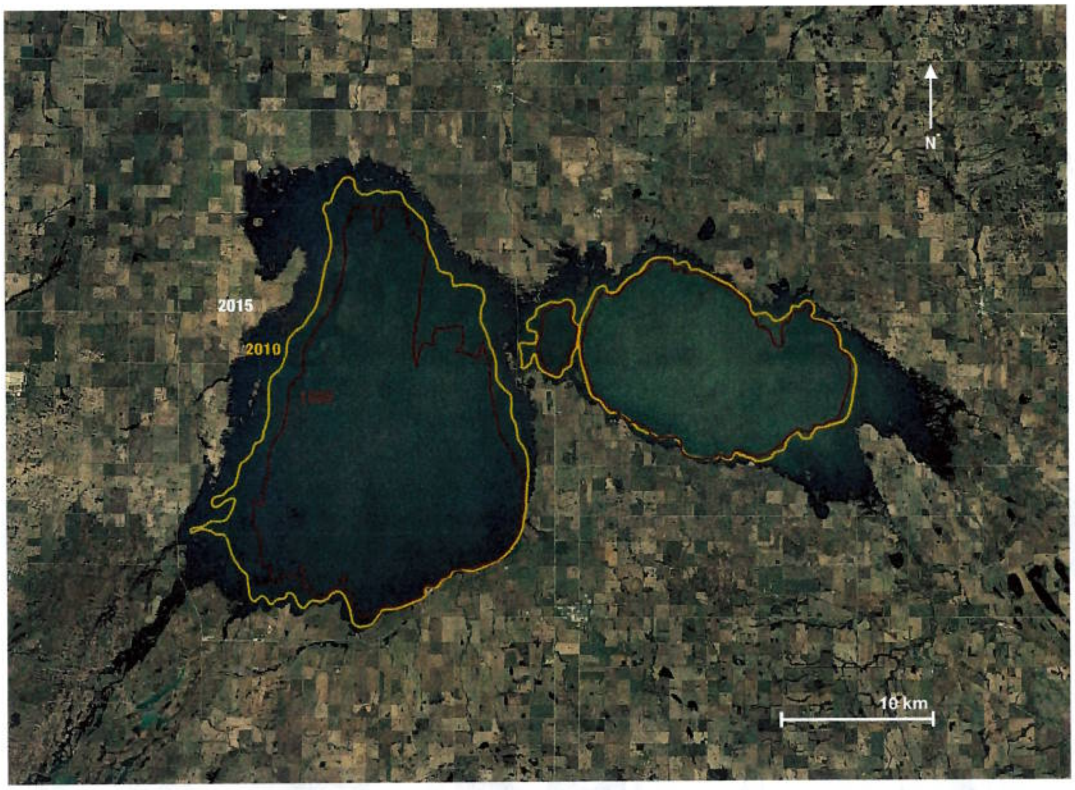


Figure 5. Satellite image of the Quill Lakes. Variability in surface water elevation during a lowstand (515.2 masl) in 1985, a transgressive tract (518.3 masl) in 2010, and to current highstand (520.5 masl) in 2015. Image crated in Photoshop (Google Earth, 2018).

up to 2005 the lake had been in a low water level phase with water elevations below 518 masl, and mean depth level of only 1.5 m (Whitting, 1977). The water levels of the Quill Lakes rose with the start of a wet cycle in 2006, rising to a record high of 520.8 masl in 2017. During this time the mean depth level rose to ~ 5 m with maximum depth of 8 m (Figure 6) (WSA, 2016).

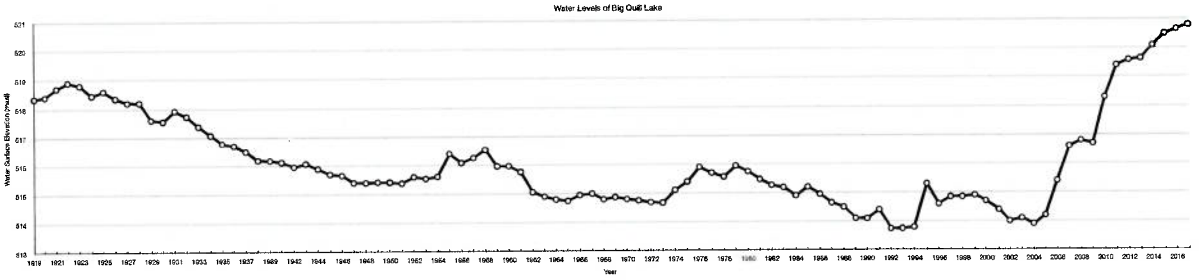


Figure 6. Water surface elevation of Big Quill Lake from 1919 to 2017. Data retrieved and combined from (Environment Canada, 2018; KGS Group, 2016).

The water balance of the lake changes the concentration of total dissolved solids (TDS), and salinity. The salinity of the lake is directly proportional to the TDS concentration. The concentration of TDS rise with a decline in surface area and the water column of the lake on inter-annual scale (Whitting, 1977; Last, 2002). However, the salinity of the lake does not decline instantaneously with the rising water column. The concentrations can also change on a monthly scale due to variability in weather. When comparing monthly concentrations between two years, variability in the salinity exists due to snowpack and ice accumulation, summer precipitation, and westward winds responsible for internal water mixes of the polymictic lake (Hammer 1978; Wetzel, 2001). In 1920 the TDS concentration was 16,000 mg/L before it increased to 42,000 mg/L by 1977 (Whitting, 1977). According to the KGS Group (KGS, 2017) the TDS concentrations may reach as high as 70,000 mg/L at water elevations below 515 masl and decline to around 10,000 mg/L at elevations of 520 masl. Currently, the TDS concentration of the Big Quill lake at is measured to be 8,800 mg/L at 1 m water level (519.8 masl), and 8,910 mg/L at 7 m depth (WSA, 2018).

The ions of the lake are governed by the ionic compositions of the surrounding soils. The water of the lake closely mimics the ionic concentration of groundwater in the aquifers of surficially stratified deposits (Hammer, 1978). The ionic composition (Table 1) is enriched in magnesium and sodium cations evenly, and possesses the highest anion concentration of sulphate. The cation sequence of the lake is Na ≥ Mg > Ca ≥ K and an anion sequence is $SO_4 > Cl > HCO_3 > CO_3$, making Ca and K minor ionic constituents (Hammer, 1978; Whitting, 1977). Since the lake is oligotrophic and has an aerobic hypolimnion year round, the oxidized microzone then stops the diffusion of soluble ions into the lake from sediments below the mud-water interface by increasing the redox potential, unless the sediment is disturbed by benthic organisms (Wetzel, 2001). During the winter under shallow water conditions, the formation of the ice depletes the oxygen of the lake and decreases the redox potential of the sediment, therefore promoting the diffusion of stable ions into the water column (Hammer and Haynes, 1978; Wetzel, 2001).

Sample Date	Water surface level (masl)	pH	Na	K	Mg	Ca	Cl	SO_4	HCO_3	CO_3
1922	518.9		2537	163	1169	502	1937	8368	236	
1978	515.7	8.7	8050	575	4482	382	3510	30200	793	133
2013	519.6	8.8	1727	175.7	1008	147.6	1032	5940	428.4	31.4

Table 1. Ionic composition of Big Quill Lake (ppm) during highstand water levels of 1922 and 2013, and lowstand water levels of 1878. The ionic concentration is observed to increase under lowstand water conditions, besides (Ca), which is observed to have declined over time (Hammer, 1986; Haig, 2018).

The only form of outflow for Big Quill Lake is through evaporation. When the net inflow exceeds outflow, rising water levels by overtop the shoreline and flood out the adjacent land. Net inflow of the lake can be summarized into: watershed runoff from Ironspring, Romance, Wimmer, Dafoe, Wynyard, Quill, and Magnusson creeks and total precipitation (Whitting, 1977; KGS Group, 2016). The 1966 to 2016 discharge from Ironspring, Magnusson, Quill, and Romance creeks were chosen based on record availability to summarize the trends of discharge to the lake (Figure 7). When observing recent discharge levels to the past, elevated extreme discharge can be highlighted by the third quartile (Q3) of 19.3 m^3. From 2006 to 2016, it is highlighted that the discharge surpassed the Q3 seven out of the eleven years, while in 1966 to 2005 the Q3 was only surpassed in six years out of the forty year period.

The influence of groundwater seepage to the lake is insignificant as the water level during ice coverage remains constant with water levels of the fall period, while the summer period shows elevated water levels from increased inflow from runoff or precipitation (Whitting,

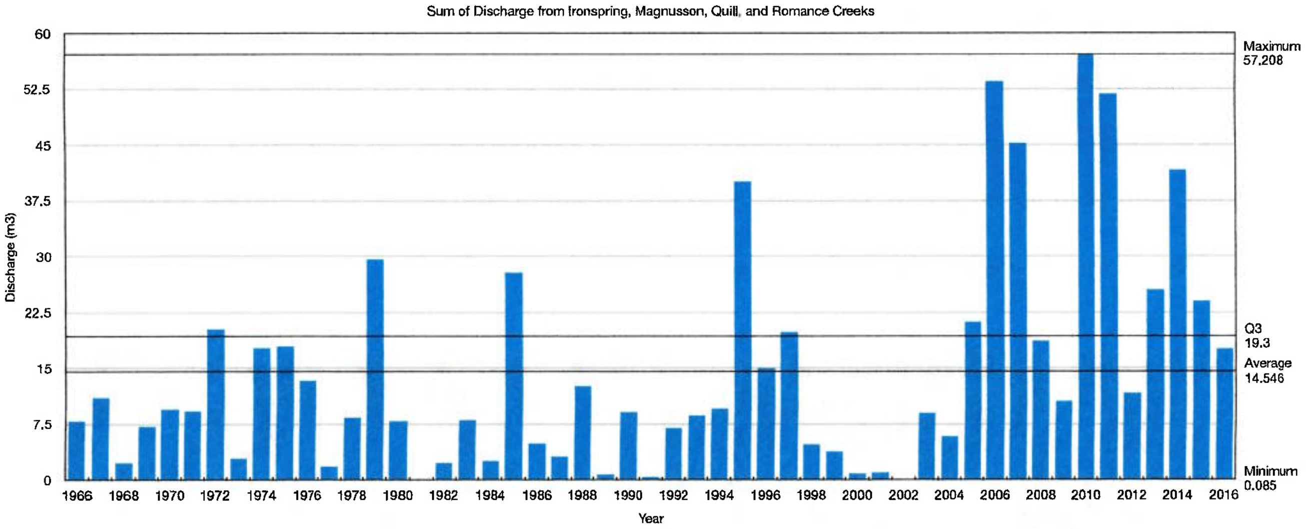


Figure 7. Sum discharge to the Big Quill lake from Ironspring (North), Romance (North), Quill (North), and Magnusson (South) creeks from 1966 to 2016. Stations listed are the only operating hydrometric stations in the Quill Lake basin. Annual sum of discharge for each station was calculated for a six month period May-October. Data retrieved from (Environment Canada, 2018).

1977; Kamp, *et al,* 2008). Groundwater influence on the lake's hydrological balance is limited as shown by comparing water levels from 2014 to 2016 between ice cover months (January, February, March, December) to summer period (June, July, August) and the fall period (September, October, November).

During years of increased snowpack accumulation and summer precipitation, the surrounding hummocky terrain acts as a source of water to the lake through groundwater seepage or surface runoff (Whitting, 1977; Pomeroy, *et al,* 2015). The transmission rates of water towards the basin is extremely slow as the topographic depressions have a low hydraulic conductivity due to glacial clays and do not posses a well-developed drainage network unless artificially drained (Hayashi, *et al,* 2016). Based on the soil characteristics of the complex, the transmission rates are presumed to vary with the highest infiltration rates directly north of the Quill Lakes, moderate to low in the Northern Sectors Hills and Touchwood hills, and very low southwest of Big Quill Lake (Whitting, 1977). The topographic depressions of the Touchwood Hills to the south are a perfect reflection of accumulated precipitation during dry and wet cycles in the basin (Figure 8). The hummocky terrain is visualized to have expanded under wet conditions and either decreased or completely disappeared during dry conditions (Figure 8). The expansion of these topographic depressions are a nuisance to the agricultural industry as it may limit land for grazing or cultivation and may promote land owners to establish artificial drainage towards the lake basin (Hayashi, *et al,* 2016; Leavitt, 2018).

Figure 11. Satellite images of hummocky terrain of the Touchwood Hills during a dry cycle in 1985(A) and 2001(B), and a wet cycle in 2010(C) and 2015(D). (Google Earth, 2018)

The total water from the watershed is not only controlled by precipitation, but agricultural water drainage. Growth of the agricultural sector in the Quill Lakes area has increased the total water drainage and nutrient concentration flushing to the lakes due to the removal of permanent vegetation and expansion of cultivated land (Whitting, 1977; Kamp, *et al,* 2008). Recent lake level changes in the Big Quill lake can not be completely attributed to climate, as there are a handful of anthropogenic variables affecting the lake's hydrological and biological balance (KGS Group, 2016).

1.5 Biology

The Quill Lakes are located in the prairie ecozone of aspen parkland and consist of prairie grasslands, shallow water marshes, and grassy wetlands of trembling aspen (*Populus tremuloides)* and balsam poplar (*Populus balsamifera*) (Callaghan, *et al,* 2015). The lakes are a Ramsar Convention wetland, Saskatchewan Heritage Marsh, and a Western Hemisphere Shorebird Reserve as they provide over 6,500 ha (16,000 ac) of critical habitat for migrating waterfowl (Callaghan, *et al,* 2015; IBA, 2017). Nearly 80,000 individuals of 400 species of waterfowl have been recorded annually in the area, among them are: Piping Plovers, Whooping Cranes, Northern Pin Tails, Canada Geese, Snow Geese, and Sandhill Cranes (IBA, 2017). The lakes provide a necessary shorebird staging area for up to 197,000 birds (Callaghan, *et al,* 2015; IBA, 2017). Despite providing a prospering home for the waterfowl and shorebirds, the Quill Lake fauna is very small and has decreased substantially since the 1930s. In the 1920s the Quill Lakes were abundant with stickleback (*Pygosteus pungitius*), the sucker (*Catostomus commersoni*) and pike (*Esox zucius*), which supported the commercial fishing industry until the lake levels gradually dropped from 518 masl to 515 masl and the salinity levels rose (Whitting, 1977). In current water level conditions there have been reports of pike (*Esox Zucius*) swimming in flooded out pasture land (CBC, 2018). During times of lower salinity, the Little Quill Lake, becomes habitat for fresh water molluscs of *Lymnaea plssturis* and *Physa gyrina.* (Moziey, 1939). Along with the molluscan fauna the Quill Lakes are abundant with copepods, Crustacean brine shrimp (*Diaptomus and Artemia)*, and fresh water algae (Whitting, 1977; Bowman and Sachs, 2008).

1.4 Land use

The Quill Lakes are exposed to to heavy agriculture and industry. The surrounding Quill Lakes area lands originally belonged to Aboriginal people and then became home to European settlers in the early twentieth century (Quill Lake Historical Society, 1984). The construction of the Canadian Northern Railway began in 1904, and the surrounding lands have been a hotspot for agricultural development ever since (Quill Lake Historical Society, 1984). Currently, the lands are exploited for wheat, barley, oats, canola, and field peas (Callaghan, *et al,* 2015). Alongside the agriculture sector, the lakes support an industrial mining sector. Since 1984 Big Quill has been home to a potassium sulphate production plant, currently operated by Compass Minerals (Bowman and Sachs, 2008). Potassium sulphate (K_2SO_4) and sodium sulfate (Na_2SO_4) are exploited by ion exchange and solution processes, which have a production capacity of 910,000 tons annually (Compass Minerals, 2018).

2. Methods of Study

A 66cm core from the depocenter of Big Quill lake was extracted on March 26th, 2018. The deepest area of the lake (8 m at 51.887226 N/104.386763' W) was accessed by a snowmobile from Lampard road. Two cores, 5 m apart were extracted using a modified Livingston-piston corer. The site location was chosen based on depth with no groundwater seepage since groundwater interaction can have a serious effects on the hydrological balance of the lake unrelated to climate (Whitting, 1977; Laird, *et al,* 2003). The cores were then transported to the University of Regina in plexiglass tubes where the first core (Q1) was extracted in full into plastic tubing and the other (Q2) was extracted in 1 cm increments into plastic bags. The cores were stored in the laboratory refrigerator at 4 ^{O}C.

2.1 ^{14}C and ^{123}Cs Dating

The Q2 core was sampled for ^{14}C at 63 cm, 30 cm, and 21 cm. A ^{127}Cs peak (1960) was examined to be at 15 cm from a ^{210}Pb radioisotope analysis.

2.2 Lithological Analysis

Dry samples were analyzed in 1 cm increments from the Q2 core under a stereoscope. The sediment was classified based on: colour, grain size (clay: <62um, very fine lower: 62-88um, very fine upper: 88-125um, fine lower: 125-177um), bedding, structures, and composition. Composition of the sediment was classified as biogenic, allogenic, and endogenic. Smear slides were also analyzed in 5 cm increments under a petrographic microscope for fabric, grain size, sorting, roundness, and principal component.

2.3 Geochemical Analysis

The Q2 core was analyzed for isotopic carbon and nitrogen analysis. The top 0-1 cm and 1-2 cm were combined to give sufficient sediment mass for the analysis. The sediments were dried, crushed, and packed into tin capsules for the first isotopic analysis performed in September 2018. The second analysis was performed in October 2018 on the acidified samples. The sediment samples were acidified by 0.2M HCL and once again prepared for isotopic analysis. The results of the acidified samples were combined with the original bulk samples to generate C/N, $\delta^{13}C$, $\delta^{15}N$, and TOC% graphs.

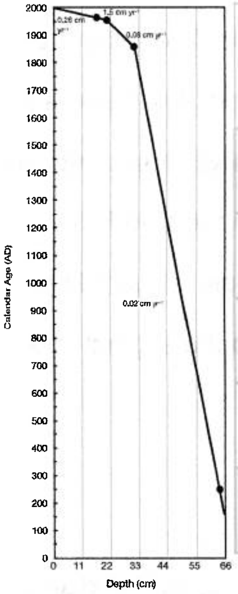
2.4 Diatoms

A total of 15 slides were prepared and analyzed for the relative abundance of diatoms. In 5 cm increments 0.2 mg of dry sediment was submerged in 30 mL of 0.3 M Hydrogen Peroxide for ~30 hours. The samples were then distilled in ionized water at 80-100 mL. 0.1 mL of distilled sample was dried on a slide and later glued with a cover slip using Naphrax, with a refraction index of 1.7. The prepared slides were analyzed by identifying the 28 species of diatoms in a 400 species count under a Olympus (x31) LM biological microscope. The relative abundance of species was calculated and plotted on a Tilia and CONISS cluster diagrams for further analysis.

3. Results

3.1 ^{14}C and ^{127}Cs dating

At 63.5 cm depth the organic matter was dated to be 1790 ± 20 yr BP, and the bulk sediment at 30 and 21 cm was dated to be 140 to 20 yr BP and -6 ± 2 yr BP respectively. Dates derived from ^{14}C analysis were calibrated on a linear fractional scale of OxCal and converted to calendar age (AD). The age model was developed by using the calibrated ages of three ^{14}C dates and a ^{127}Cs peak at 15 cm. Accumulation rates were calculated between dates (Table. 2).



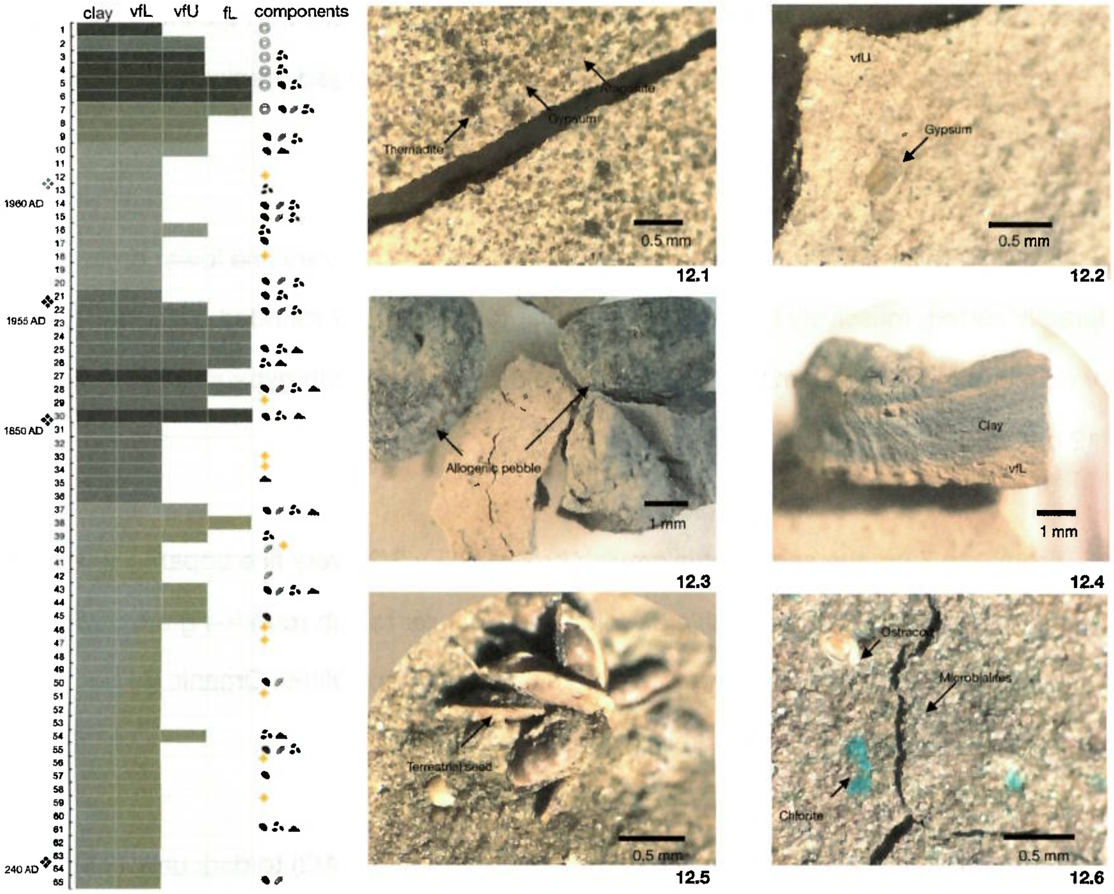
Depth (cm)	Calendar Age (AD)	yr/cm	cm/yr
0	2017		
15	1960	0.263158	3.8
21	1956	1.5	0.666667
30	1850	0.084906	11.77778
63.5	240	0.02080745	48.0597

Table 2. Calibrated age model of Q2 sediment and accumulation rates between sampled dates.

3.2 Lithology

Distribution of the lithological components highlight Big Quill Lake past activity in terms of biological activity, lake mixing, temperature conditions, and transportation of detrital sediments (Last and Scweyen, 1983). The lithological analysis indicate the following intervals of lithological change (Figure 12):

From 66 to 37 cm the sediment is light brownish grey (2.5 Y 6/2) to grey (2.5 Y 6/1), with diffuse bedding, composed of clay to very fine lower in size, poorly sorted. The principal detrital constituents are quartz and feldspathic clay; evaporitic minerals include gypsum ($CaSO_4\ 2H_2O$), aragonite ($CaCO_3$), and thenardite (Na_2SO_4). Ostracod, cocoons, terrestrial seeds, and well-rounded (>1mm) pebbles are common and increases with an increase in grain size to very-fine upper at 43, 39 to 37 cm. The concentration of chemical precipitates is prominent with a decrease in grain size to clay and very fine lower silt, specifically at 59, 56, and 46 to 45 cm depths. However, detrital sediment is still a major component of the sediment.



Legend

Munsell colour index

■ 2.5 Y 4/1 - dark grey
■ 2.5 Y 4/2 - dark greyish brown
■ 2.5 Y 5/1 - grey
■ 2.5 Y 5/2 - greyish brown
■ 2.5 Y 6/1 - grey
■ 2.5 Y 6/2 - light brownish grey

Symbology

◎ Microbialites
⁂ Terrestrial seeds
● Ostracod
✎ Cocoon
▲ Detrital sediments
✦ Mineral precipitation(>20%)
❖ ^{14}C date
❖ ^{127}Cs date

Figure 12. Lithology of Q2 depocenter core combined with photographs of the identified components: precipitates (12.1), gypsum in vfU grain size (12.2), pebbles (12.3), clay to vfL grain size (12.4), terrestrial seeds in vfU (12.5), and combination of chlorite, ostracod, and microbialites (12.6).

From 36 to 31 cm the sediment transitions to grey (2.5 Y 5/1) in colour, clay to very-fine lower, moderately sorted, massive, angular to sub angular, with quartz and clay as major constituents and gypsum along with aragonite as a minor constituents.

From 30 to 22 cm the sediment is grey (2.5 Y 5/1) to dark greyish brown (2.5 Y 4/2) colour, very fine upper to fine lower in size, moderately sorted with massive bedding, sub angular to sub rounded particles, with detrital debris as a principal component, including: quartz, feldspar, muscovite, biotite, olivine, and pyroxene. The presence of terrestrial seeds, cocoons, ostracod, and well-rounded (> 1mm) pebbles is prominent with the increase in grain size. Evaporitic minerals are minor with gypsum as the only recorded precipitate at 29 cm in a vfU grain size.

From 20 to 11 cm the sediment becomes grey (2.5 Y 5/1), very fine lower grain size, moderately sorted, massively bedded, with angular to sub angular rounded particles. The major constituent of the sediment is quartz and feldspathic clay with gypsum precipitate at 18 and 12 cm, and organic debris at 14 to 16 cm.

From 9 to 7 cm the sediment is greyish brown (2.5 y 5/2), very fine upper to fine lower grain size, moderately sorted, massive bedding, sub angular to sub rounded grains, with principal constituent as quartz, along with precipitates of microbialites. Organic debris, gypsum, and chlorite are present as minor constituents.

From 6 to 3 cm the sediment is dark greyish brown (2.5 Y 4/2) to dark grey (2.5 Y 4/1) in colour, very fine upper to fine lower grain size, moderately sorted and massively bedded, with sub rounded grains of quartz, muscovite, biotite, and feldspar. Precipitation of microbialites is prominent. Terrestrial seeds and chlorite are present.

From 2 to 0 cm, the sediment transitions from very fine upper to very fine lower grain size, with moderate sorting and massive bedding, the main constituents of the sediment are detrital particles, microbialites, and chlorite. Minor crystallization of gypsum is present and no ostracod or terrestrial debris was observed.

3.2 Geochemistry

Stratigraphic changes observed in $C_{organic}$/ N_{total}, $d^{13}C$, $d^{15}N$, and TOC% help reconstruct changes in the processes of the lake as well as changes in the watershed (Kendall and Caldwell, 1998; Meyers, 1994).

The $C_{organic}$/ N_{total} ratio is an aid in paleoenvironmental reconstruction as it helps characterize the composition and source of organic material preserved in sediment. Since organic matter differs between vascular and non-vascular plants in terms of the proportions of protein and cellulose, they produce different C/N ratios (Meyers, 2003; Lamb, *et al,* 2006). Ratios between 4 and 10 are indicative of non-vascular plants, algae and phytoplankton, whereas ratios greater than 12 are indicative of vascular terrestrial grasses and shrubs, or aquatic macrophytes (Meyers, 2003).

Based on C/N ratios, the lake experienced minimal changes in organic sources. The average ratio was 9.50 with a maximum of 11.27 at 61 cm (Figure 13.1). The ratio remained consistent for the entirety of the core, suggesting that since 240 AD the lake has been dominated by autochthonous algal organic matter. The bulk C/N ratio is helpful in terms of outlining influx of terrestrial material to the lake, which is prominent at 32 cm 27.89. The bulk C/N ratio also confirms dominance of algal matter from 14 cm to 1 cm with an average ratio of 7.54.

Values of $\delta^{13}C$ are indicative of the lake's biomass and productivity rates, and vegetation in the watershed (Meyers, 2003). When the acidified stable isotope concentration is coupled by acidified C/N ratios, it is possible to identify the contribution of C3 or C4 plants to the organic matter accumulated (Meyers, 1994). Plants that use the C3 pathway, such as algae, have values between -25 to -30‰, and acidified C/N ratios of 5-10 while terrestrial C3 plants produce similar values, but with larger C/N ratios greater than 12 due to their nitrogen depletion in comparison to algal plants (Meyers, 1994; Lamb, *et al,* 2006).

Acidified concentrations do not vary much along the core with an average $\delta^{13}C$ value of -24.36‰ before a gradual decline to -26.79‰ at 9 to 0 cm depths (Figure 13.2). The $\delta^{13}C$ values confirm that the organic matter accumulated in the lake has been predominantly concentrated with algal material, while allochthonous plant material has been a minor constituent in the preserved lake sediment. The bulk $\delta^{13}C$ isotope concentrations outline that the lake began to increase in algal productivity with significance at 9 cm -21.21‰ to 1 cm -24.52‰.

The total organic carbon TOC% is indicative of organic matter stored in lake sediment (Meyer, 2003). From 66 to 30 cm the TOC% was low with an average of 2.81% (Figure 13.3). At depths of 29 to 10 cm the organic matter in the lake increased to an average of 6.81%. At 9 to 1 cm the accumulation of organic matter become significant in the lake sediment with an average value of 13.0%. The highest TOC% was observed at 3 and 4 cm with 14.97% and 14.87% respectively. The rise in TOC% depict higher productivity rates in the lake's water column from 9 cm.

The measure of stable nitrogen isotope concentration, $\delta^{15}N$, is useful for identifying sources of eutrophication to the lake, as well as reconstructing past productivity rates within the lake (Meyers, 2003; Leavitt, *et al,* 2006). In the prairies the phosphorus concentrations are abundant, therefore nitrogen is a primary limiting agent of the lake's productivity (Leavitt, *et al,* 2006, Leavitt, 2018). Multiple sources of nitrogen influx to the lake exists: atmosphere, flushing of the surrounding soil, denitrification, agricultural fertilization, and human waste (Meyers, 1994; Lamb, *et al,* 2006). Isotopic values differ between all pathways. The $\delta^{15}N$ concentration of air is low (-1 to 2 ‰), the concentrations from denitrification can range (10 to 25‰), human waste is generally elevated to (10 to 25 ‰), while fertilized soils at 0 to 4‰ and natural soils at 2 to 8‰ (Meyers, 2004; Kendall and Caldwell, 1998). Changes in the $\delta^{15}N$ concentrations over time can not only be attributed to the influx of nitrogen, but productivity within the lake as well. Cyanobacteria that fixates N_2 to ammonium (NH4), can reduce the concentration of $\delta^{15}N$ (-3 to 1‰) under eutrophic conditions (Meyers, 2004; Kendall and Caldwell, 1998).

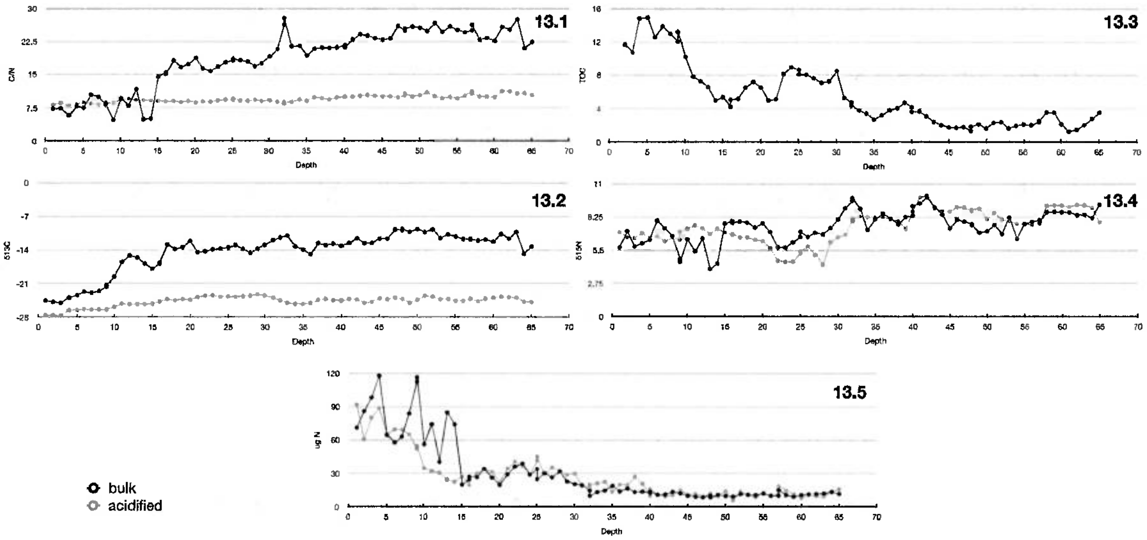


Figure 13. Geochemical plots of bulk and acidified samples for C/N (13.1), $\delta^{13}C$ (13.2), TOC% (13.3), $\delta^{15}N$ (13.4), and umg N (13.5). The TOC% was corrected and calculated by finding the linear relationship between bulk C% vs acidified C% (y=1.2969x - 5.0828) and applying the equation to bulk C%.

When analyzing the bulk $\delta^{15}N$ from the core, the concentrations of the stable isotope were high for the entirety core, which are similar to the proximal lakes of the Qu'Appelle drainage basin (Leavitt, *et al,* 2006). Values vary from an average of 8.17‰ from 66 to 30 cm, with rises at 42 cm to 9.90‰ and at 31 cm to 9.84‰ (Figure 13.4). From 30 to 15 cm the $\delta^{15}N$

was an average of 7.16‰. The concentration of $\delta^{15}N$ at 14 cm has a significant decline to a minimum of 3.96‰. From 13 cm to 1 cm the values were significantly lower with an average of 6.07‰. The mass of bulk ^{15}N (umg) confirms a rise in eutrophication and concentration of nitrogen from 14 cm. From 31 to 15 cm an average of 27.46 umg predominately rose to 80.4 umg from 14 to 1 cm. The mass of nitrogen was very small below 31 cm with an average value of 11.9 umg (Figure 13.5).

3.3 Diatoms

The relative abundance of bacillariophyceae, diatoms, will be used as proxy for reconstruction of the salinity and relative water level of the Big Quill. Diatoms are sensitive phytoplankton that preserve hydrological changes of the endorheic basin and therefore are extremely useful for paleoenvironmental reconstruction (Fritz, *et al,* 1991). Dominant species of diatoms reflect the lake's stability and drastic changes over time, as particular diatoms require specific pH, conductivity, salinity, nutrients, and availability of aquatic plants. Three zones were identified within the 66 cm interval based on the changes in relative abundance of dominant species and apparent transitions amongst species between zones indicated by a cluster analysis and visual inspection of the Tilia diagram.

The dominant taxa of the Big Quill Lake consisted of planktonic *Cyclotella* and *Chaetoceros*, tychoplanktonic *Nitzschia* and *Pseudostaurosina,* and several benthic species of *Surirella*, *Navicula*, and *Tryblionella* (Figure 14).

In the lowermost zone, Zone A, from 66 to 35 cm, 120 to 1550 AD, (Figure 14) the *Cyclotella quillensis* is the dominant species, averaging 55.5%. *Cyclotella meneghiniana* and *Chaetoceros elmorei cysts* are the second and third most dominant species averaging 23.89% and 8.38% respectively. *Nitzschia compressa* made a significant appearance at 60 cm with a relative abundance of 29.72%, it then had a decline to an average of 1.13% at 35 cm depth.

Nitzschia palea is also present in the zone, averaging 3.29%, which only is apparent at 65, and 40 to 45 cm depths. Other notable taxa recorded are; *Tryblionella hungarica* and *Surirella striatula*, which averaged 0.56% and 0.61% respectively.

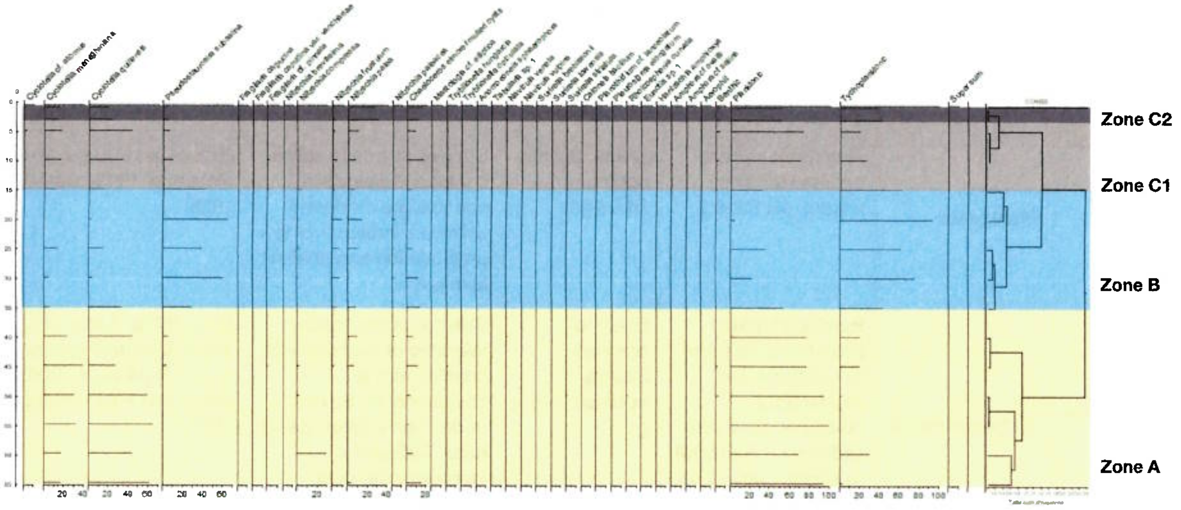


Figure 14. Tlia and CONISS cluster plot of observed diatom taxa. Zones are colour coded: Zone A (yellow), Zone B (blue), Zone C1 (violet), Zone C2 (dark violet).

In the middle Zone B, from 35 to 15 cm, 1550 to 1960 AD, *Pseudostaurosira subsalina* is the dominant species, averaging 51.79%; *Cyclotella quillensis* declined to an average of 13.89% (Figure 14). *Cyclotella meneghiniana* and *Chaetoceros elmorei cyst* remain in the zone with a decline to an average of 7.60% and 7.69% respectively. The abundance of *Nitzschia palea* and *Nitzschia compressa* increases relative to Zone A with an average of 7.89% and 1.95% respectively. Notable taxa of *Nitzchia paleacea* 2.26% and Nitzschia cf. pinnata (1.31%) make an appearance in Zone B.

The uppermost Zone C, from 15 to 0 cm, 1960 to present, is divided into two sub zones of Zone C1 and C2. This zone shows significant changes between identified taxa in Zone A and B (Figure 14). In Zone C1 from 15 to 3 cm the *Cyclotella quillensis is dominant* with an average of 30.71%, while *Cyclotella meneghiniana* has a rise in the average from Zone B to

Name	Group	Habitat	Salinity	Ecology	References
Cyclotella atomus	Planktonic/ Epipelic	Attaches to substrate, remains in the water/sediment interface, neutral pH	Intermediate salinities	Species prefers warm, nutrient enriched waters.	(Lowe, 2015) (Krammer and Lange-Bertalot, 2000) (Moro and Furstenberger, 1997)
Cyclotella meneghiniana	Planktonic	Wide range of habitat, attaches to substrate and plants or algae, mostly planktonic, prefers standing, but can tolerate moving water, neutral pH	Saline to slightly saline waters. Salinity optimum: 3.38 g/L	Strives in shallow, nutrient rich waters. Can tolerate oligotrophic conditions .	(Lowe and Kheiri, 2015) (Moro and Furstenberger, 1997) (Fritz, *et al,*1993)
Cyclotella quillensis	Planktonic	Planktonic habitat, prefers standing waters, pH 8.2-9.2	Saline. Salinity optimum: 20.56 g/L	Species strives in saline conditions (halophile), can tolerate moderate salinities. Indicator of low precipitation and shallow lake level.	(Edlund and Burge, 2016) (Fritz,*et al,*1993) (Bailey, 1928)
Pseudostaurosira subsalina	Tychoplanktonic	Benthic littoral to planktonic, attaches to substrate and plants/algae, colonizes deep lake sediment, pH neutral to slightly basic 7.46	Fresh to brackish. Salinity optimum 2-4 g/L	Cosmopolitan species, tolerable of freshwater to coastal marine environments. Strives under high eutrophication rates. Indicator of increase in nutrient pollution and slightly basic to neutral pH.	(Fritz, 2018) (Leira, *et al,* 2015) (Cejudo-Figueiras, *et al,* 2011) (Morales, 2005) (Moro and Furstenberger, 1997)
Nitzschia compressa	Tychoplanktonic	Attaches to substrate and algae or plants, as well as floats in standing waters, indifferent for pH	Saline waters. Salinity optimum: 11.07 g/L	Marine to brackish water species, strives in high salinities. Indicator of saline waters and rise of aquatic macrophytes.	(Krammer and Lange-Bertalot, 2000) (Fritz, *et al,* 1993) (Moro and Furstenberger, 1997)
Nitzschia frustulum	Tychoplanktonic	Commonly found as benthic species, can can exist as tychoplanktonic, basic pH	Fresh to intermediately saline waters Salinity optimum: 2.17 g/L	Species is cosmopolitan and tolerant of freshwater to intermediate salinities. Found in inland and coastal waters.	(Krammer and Lange-Bertalot, 2000) (Moro and Furstenberger, 1997) (Fritz, *et al,*1993)
Nitzschia palea	Tychoplanktonic	Benthic littoral to planktonic species, neutral to slightly basic pH	Freshwater, <5 g/L. Salinity optimum: 2.89 g/L	Species prefers eutrophic to hypereutrophic waters. Strives in lakes with high nutrient inflow. Indicator of increased eutrophication and decline in salinity.	(Kociolek, 2011)(Moro and Furstenberger, 1997) (Fritz, *et al,*1993) (Krammer and Lange-Bertalot, 1988)
Chaetoceros elmorei cyst	Planktonic	Planktonic colonial species	Saline. Salinity optimum: 12.03 g/L	Strives in saline and shallow lake level conditions. Good indicator of elevated salinity levels.	(Edmund and Burge, 2016) (Fritz, 2013)(Fritz, *et al,*1993)
Tryblionella hungarica	Tychoplanktonic	Littoral highly motile benthic species, basic pH	Saline. Salinity optimum: 9.55 g/L	Cosmopolitan, found in saline lakes to coastal brackish waters. Indicator of high salinity.	(Kociolek, 2011) (Fritz, *et al,* 1993) (Krammer and Lange-Bertalot, 2000)

Table 3. Ecology of dominant diatom taxa of the Big Quill Lake. Selected species in the table are good indicators of hydrological regimes of the lake in terms of pH, salinity, and productivity. Listed references were used for the identification of species combined with ecology.

16.81%. *Chaetoceros elmore cyst* is present with a 12.75% average. In Zone C2 from 3 to 1 cm *Nitzschia palea* increases to an average of 29.27%. *Pseudostaurosira subsalina* experiences a decline in the zone with an average abundance of 6.41%. Notable taxa of Zone C are: *Cyclotella atomus* (2.17%), *Nitzchia paleacea* (1.80%), and *Tryblionella hungarica* (1.19%).

4. Discussion

The paleoenvironmental and paleolimnological reconstruction of the lake may be summarized into three periods based on: the stratigraphic distribution amongst major components of the lithology, geochemistry, and diatoms. Salinity was inferred based on the relative abundance of saline tolerant diatoms and diatom ecology in general (Table. 3), and reconstructions of water level are based on salinity as discussed in the Introduction, the Quill lakes are a closed basin therefore changes in salinity reflect changes in the precipitation/ evaporation rates. Salinity and evaporitic conditions are interpreted from the diatom and lithological data. Thus, an increase in abundance of saline diatoms relative to subsaline diatoms is interpreted as a salinity increase, and a water level decrease; conversely, a decrease in saline diatoms and an increase in subsaline diatoms is interpreted as a decrease in salinity and increase in water level. Increase in evaporitic minerals of gypsum, aragonite, and thernadite relative to the detrital proportion is interpreted to have occurred under arid climatic conditions. When the analysis is coupled by geochemical data the change between periods is illuminated through productivity and eutrophication of the lake. The combination of outlined proxies then highlights the hydrological conditions based on the lake's water level and salinity conditions under natural or anthropogenic forcing (Figure 15).

4.1 Period 1 140 to 1550 AD (66-35 cm)

This zone differs amongst others due to the abundance of clay, prominent crystallization of gypsum, aragonite, and thenardite, abundance of saline diatoms, elevated δN concentrations, low C/N ratios and $\delta^{13}C$ concentrations, and depleted TOC%.

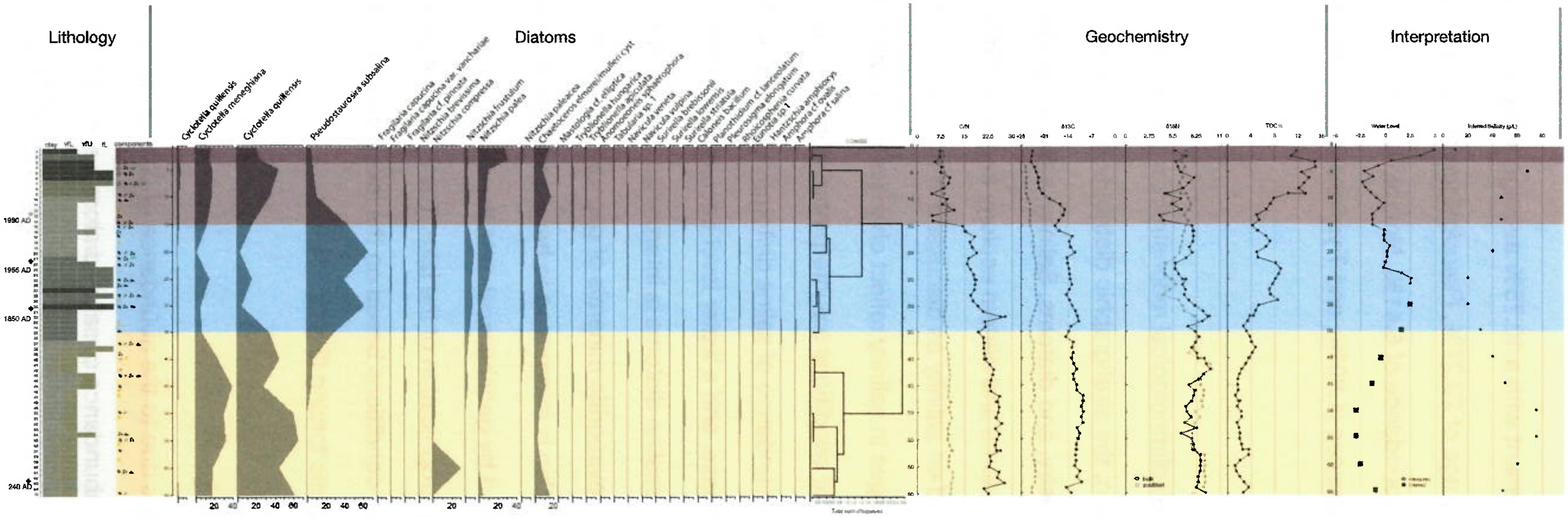


Figure 15. Distribution of three periods, Period 1(140 to 1550 AD) in yellow, Period 2 (1550 to 1960 AD) in blue, and Period 3 (1960 to 2017 AD) in violet across three proxies of study (lithology, diatoms, geochemistry) combined with inferred water levels and salinity (interpretation). Normalized recorded water levels are plotted with inferred water levels beyond 26 cm. The water levels were inferred by the ecology of dominant diatoms.

During this time the lake was was low under a regime of evaporation exceeding precipitation, and thus suggest arid climates as indicated by the abundance of gypsum and aragonite. The climate led to a decline in annual influx to the lake from precipitation, runoff, or groundwater seepage, which in return lowered the water column and increased the solute concentrations. Mineralization of endogenic minerals in the clay matrix most likely reflects a rise in solute concentrations of: carbonate, sulphate, sodium, magnesium, calcium, and potassium ions (Last, 2002). However, sedimentation of allogenic sediments still occurs (Figure 12), most likely due to the size and distant wind fetch of the lake basin, which continuously transported coarse detrital sediments to the depocenter of the lake (Last, 2002). High salinity is indicated by the abundance of planktonic saline diatoms of *Cyclotella quillensis and Chaetoceros elmorei cyst,* as well as brackish tychoplanktonic *Nitzschia compressa.* A decrease in salinity under elevated inflow to the lake provided optimal environment for the species. The appearance of *Nitzschia compressa* is indicative of an increase of aquatic macrophytes and lower salinity, as the species is epiphytic and prefers attachment to aquatic plants in the basin (Table. 3). At 45 cm depth, 1100 AD, lake conditions correlate to the ending of the dry Medieval Warming Period 'MWP' (1000 to 1300 AD) and a transition from a dry to a wet period (Laird, *et al,* 1998; Fritz, *et al*, 2000). The transition to the wet period may be attributed to elevated precipitation responsible for transporting Nitrogen to the lake from the surrounding natural soils (Kendall and Caldwell, 1998). The $\delta^{13}C$ and C/N show little variability across the zone. The average δC concentrations of -24.4‰ and C/N ratio of 10.0 are indicative of aquatic plant dominance and some terrestrial plant presence in the lake. The TOC% of the lake during the period is low (2.81%), therefore the deposition of organic matter in the lake sediment of very low in comparison to other zones.

Overall, within this period the lake experienced lake level lowstand, evaporitic conditions, and saline conditions for the majority of ~1400 yrs. This timeline contained the most chemical precipitates out of the entire core, therefore the hydrological conditions favoured endogenic sediment precipitation.

4.2 Period 2 1550 to 1960 AD (35-15 cm)

This period is characterized by clay to fine lower grain size, minimal crystallization of endogenic material, dominance of subsaline diatoms, significant fluctuations of $\delta^{15}N$ concentrations, and rise of $\delta^{13}C$ concentrations and TOC% relative to period 1.

At this time the lake changes from saline to subsaline lake conditions, thus suggesting a humid, semi-arid climate. The gradual increase to fine lower grain size from 37 to 30 cm and the reduction in evaporitic minerals, suggest decrease in salinity, and increase in water levels relative to period 1. The contents within a fine lower matrix from 33 to 22 cm depths are dominated by terrestrial organic debris and allogenic sediments as indicated by the lithology (Figure 12) and bulk C/N ratio of 27.89 at 32 cm depth (Figure 13.1). It is possible that the expanding shoreline of the lake eroded the surrounding lacustrine materials and transported coarser allogenic material towards the deep lake centre. The dominant *Pseudostaurosira subsalina* species is a colonial species that prefers shallow waters to colonize deep basin locations within the lake (Table. 2; Leira, *et al,* 2015). The *Pseudostaurosira* is observed to become the dominant species of this period at 30 cm from its first appearance at 45 cm depth of period 1 during shallow water conditions. At rising water levels at 30 cm, ~1850 AD, the *Pseudostaurosira* established its dominance alongside *Nitzschia palea*, and *Fragilaria cf. pinnata*, which all strive under high eutrophic and subsaline conditions (Table 2). However, the saline species of *Cyclotella quillensis and Chaetoceros elmore cyst* remain in the lake during this period, possibly indicating periods of dry conditions.

The $\delta^{15}N$ concentrations within the zone are observed to have declined after time from a peak value at 31 cm depth of 9.84‰. The drastic peak of $\delta^{15}N$ concentration may be related to the end of the Little Ice Age 'LIA' (1300-1850 AD), which brought subsaline conditions and runoff to the lake under excessive melting (Laird, *et al,* 1998; Fritz, *et al*, 2000). Another transgressive rise of the water level is observed at 20 to 22 cm, ~1956 AD, where the accumulation of allogenic material coincides with small increase in bulk C/N and $\delta^{13}C$ concentrations. Between 1954 to 1958, the lake experienced a gradual water level rise above 516 masl, which is likely the result of wet climatic conditions promoted by negative ENSO and PDO teleconnections. From 1954 to 1956, the lake received above average precipitation of 524.1 mm that resulted in precipitation accumulation exceeding evaporation rates (Figure 7) (Environment Canada, 2018). The rise of the water column and increased nutrient supply at 31 cm and 20 cm depths governed the productivity of the lake shown by a TOC% increase to 6.81% (Figure 13.3). The acidified C/N ratios and $\delta^{13}C$ concentrations remained relatively stable for the entirety of the period, supporting dominance of algal matter with minor terrestrial organic debris within the lake.

During this period, the Big Quill lake entered a state that reflects wetter climatic conditions that promoted the decline in salinity, escalated nutrient flushing to the lake, and an increase in biological productivity. This timeline coincides with the wet 'LIA' period and modern lake conditions of the twentieth century. Within this period it is evident that the climatic variability is the main forcing on the hydrological balance of the lake with minor anthropogenic forcing after 1850 due to beginning of agriculture in the prairies (Leavitt, 2018).

4.3 Period 3 1960 to 2017 (14-0 cm)

This period reflects modern lake conditions. This period is characterized by clay to fine lower sediment matrix, transition in endogenic precipitation of ($CaCO_3$) to microbialites, elevated eutrophication and productivity rates, and change from saline to subsaline lake conditions under forcing decoupled from climate. The productivity rates of the lake exceed the two prior zones with decline of $\delta^{15}N$ concentration, rise in algal productivity supported by the decline in C/N and $\delta^{13}C$, and a significant increase in TOC%.

This period can be divided into two sub-periods of variable hydrological conditions. During period 3.1, 15 cm to 7 cm, the lake experienced shallow water levels and saline conditions, while in period 3.2, 7 cm to 0 cm, the lake experienced an increase in the water level and subsaline conditions. In period 3.1 the lithology is governed by clay to very fine lower grain size, with little endogenic precipitation and allogenic material. In period 3.2 the grain size of the sediment increased to fine lower with newly deposited material of ($CaCO_3$) microbialites. The transition of aragonite precipitation to a spheroidal crystal is indicative of high microbial activity; microbial nucleation of microbialites or an increase in photosynthesis can raise the pH by expelling (OH^-) and changing the geochemistry of a microenvironment along the bottom lake sediment from bicarbonate (HCO_3) to carbonate (CO_3) without affecting the entire water column (Brady, *et al,* 2010). The dominant presence of *Cyclotella quillensis* from 1960 to 2005 AD is indicative of saline lake conditions, before the transition to eutrophic and subsaline conditions from 2006 to present depth supported by the dominance of *Nitzschia palea* (Table 3). Within the entire period 3 the geochemistry of the lake completely changes relative to the two prior periods. The $\delta^{15}N$ concentrations declined to an average of 6.07‰ with a minimum value of 3.96‰ (Figure 13.4), which possibly indicates a change in composition of the surrounding soil from natural to excessively fertilized (Kendall and Caldwell, 1998). The flushing of the surrounding fertilized soils from the drainage basin promoted eutrophic conditions within the lake that resulted in an increase in algal productivity and total accumulation of organic matter in the lake sediment. This is supported by a decline in the bulk C/N ratio from a 66 to 15 cm average of 21.77 to a 14 to 1 cm average of 7.54 (Figure 13.1) and a decline of the $\delta^{13}C$ concentrations (Figure 13.2). The TOC% is observed to have drastically risen at 9 cm to an average of 13% from a period 2 average of 6.81% (Figure 13.3). The rise in total accumulated organic matter is significant and supports a rise in algal productivity within the lake due rise in eutrophic conditions from anthropogenic influences.

	Dry lowstand (<515 masl)	Wet (515 - 518 masl)	Wet highstand (>518 masl)
Period	1986 to 1990	2006 to 2010	2011 to 2015
Annual Precipitation	442.9	467.3	425.7
Average Annual Temperature	2.9	1.9	2.1
Average Winter Temperature (D, J, F)	-13.1	-15.0	-13.6
Average Summer Temperature (J, J, A)	17.3	16.3	17
Max Discharge	12.7	57.2	51.8
Mean Discharge	6.1	37.0	30.9
Min Discharge	0.7	10.5	11.6
Total Discharge	30.4	185.2	154.5

Table 4. Comparison of inflow to the Big Quill during a five year lowstand period (1986 to 1990), and two wet periods (2006 to 2010, 2011 to 2015).

Since sub-periods 3.1 and 3.2 reflect modern lake conditions, limnological and meteorological data is available. When comparing the two sub-periods in terms of discharge to the lake and water level, the forcing decoupled from climate may be outlined. To compare the variation in lake level between dry and wet periods, a five year dry period (1986 to 1990), and two five year wet periods (2006 to 2010, 2011 to 2015) were selected (Table 4). During 1986 to 1990 the lake experienced water levels below 515 masl and occurred during positive ENSO and PDO. The oceanic-atmospheric teleconnections induced above average winter temperatures and nearly average precipitation. The mean discharge during the five year dry period was very low; even lower than the 14.5 m^3 average of the entire 1966 to 2016 record period. During the wet period of 2006 to 2010 the negative ENSO and PDO induced below average winter and summer temperatures and above average precipitation. The inflow to the lake raised the water column by 2.9 m with a total discharge of 185.2 m^3. The wet period of

2011 to 2015 occurred under the change from negative to positive PDO and ENSO teleconnections. The climate variability correlates to the positive forcing of the teleconnections; however instead of the lake experiencing a level decrease after 2011 due to elevated evaporation rates, the lake levels continued to increase, during this time the water levels surpassed 518 masl. The discharge of the 2011 to 2015 period remained elevated as it was in 2006 to 2010 (Table 4). Since 2014, the climate conditions have supported an increase in evaporation and total outflow from the endorheic lake basin, but the elevated discharge to the lake has remained and therefore has continued to to raise the inflow of the lake (KGS Group, 2016).

Overall, Period 3 is distinguished by aragonite precipitation as microbialites due microbial activity, transition between saline to subsaline lake conditions, increased productivity and eutrophication rates of the lake, and climatic variability that does not correlate to recent lake changes. When the two sub-periods of period 3 are compared in terms of climate and discharge during dry and wet periods, the forcing responsible for water surface levels may be outlined. The main forcing behind lake elevation above 521 masl may not be attributed to climate since the climatic conditions have favoured warmer temperatures and less precipitation distinctly since 2014 to 2016 when accounting for a two year lag period of ENSO. Therefore other forcings than climatic are likely responsible for current hydrological conditions.

5. Conclusion

When combining the lithology and the geochemistry proxies to the relative abundance of diatom species, three separate periods are described. Period 1, 140 to 1550 AD, is marked by the presence of endogenic precipitates of aragonite, gypsum, and thernadite, saline diatom species of *Cyclotella quillensis and Chaetoceros elmore cyst* suggest lowstand lake levels, and saline lake conditions. During this period the lake experienced periods of severe droughts, which coincide with the 'MWP' and its transition to a wet climate of the 'LIA'. Period 2, 1550 to

1960 AD, is highlighted by the presence of allogenic material of terrestrial plant debris and rounded pebbles. Saline to subsaline diatoms of *Pseudostaurosira subsalina* and *Nitzschia palea* suggest a decrease in salinity relative to period 1. The rise of the water column began during the transition from the 'MWP' to the 'LIA', which posed wetter conditions due to decline in evaporation and an increase in evaporation in the drainage basin. Period 3, 1960 to present, depicts modern day hydrological conditions between a dry sub-period 3.1 (1960 to 2005) and a wet sub-period 3.2 (2006 to 2010). This period is marked by the transition from subsaline conditions during period 2 to saline conditions sub-period 3.1 and back to subsaline conditions of sub-period 3.2. The fluctuation in the lake level within Period 3 is outlined by allogenic debris presence in a very fine upper to fine lower grain size matrix, hypersaline *Cyclotella quillensis* to subsaline *Nitzschia palea,* and by climatic cycles. The anthropogenic impacts on the lake are observed within period 3 from an increase in aquatic productivity, and increase of discharge to the lake under climatic conditions favourable of evaporation over precipitation after 2014.

The presented paleoenvironmental research of the Big Quill Lake examines the conditions of the lake on a coarse scale of 5 cm and provides insight into the variability of the lake's hydrological balance under climatic influence to the combination of climatic and anthropogenic physical influences. This research illuminates the hydrological conditions under a natural responses to climate up to 1550 AD, to a minor anthropogenic contribution up to 1960 AD, and to a climate driven system with extreme anthropogenic influence from 1960 to today. Conclusively, the effective drainage basin of the Big Quill Lake is expanding and beholds an extensive amount of complexities. The complexities within the drainage basin exist in: the heterogeneity of soils and the associated hummocky terrain, regional climatic response to oceanic-atmospheric oscillations, runoff and ground water seepage variability, involvement of plants, and human modified drainage networks (Whitting, 1977; Wetzel, 2001; Leavitt, 2018). Additional high resolution research of the Big Quill core and other lakes within the basin, coupled with Whiting's extensive hydrological study from 1977, will act as an aid for more precise reconstruction of past and current hydrological conditions in the Quill Lake basin.

6. Future Work

In the future research of the Quill Lake basin additional cores will be extracted from Kutawagan Lake, Mud Lake, and Little Quill at the depocentre and littoral areas of the lakes. Additional cores will help understand paleo conditions of the entire basin eg. Little Quill Lake spilling into Big Quill Lake and Big Quill spilling into Katawagan Lake. The cores will be sampled at 1 cm increments for lithological and mineralogical analysis, stable isotopes (C/N, $\delta^{13}C$, $\delta^{15}N$, and TOC%), XRF, and XRD. The cores will also be sampled in 2 cm increments for diatom counts and diatom derived transfer-function of salinity. Hydrological regimes of the basin will also be analyzed on a finer scale in terms of regional climatic response, total water budget of the basin (runoff, groundwater, percipitation/evaporation), and human altered drainage networks.

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Appendix A: Climate Data

Table A.1: The historical climate of the Quill Lake Plain was combined from three stations surrounding the Big Quill Lake. The stations include: Quill Lake, SK (1913-1938), Wynyard (1939-2005), and Wynyard AUT (2006-2017) Data retrieved from http://climate.weather.gc.ca/ climate_data.

	Mean Max Temp (°C)	Mean Min Temp (°C)	Mean Temp (°C)	Total Rain (mm)	Total Snow (cm)	Total Precip (mm)
1913	3.5	-8.2	-2.4	510.1	49.3	559.4
1914						
1915						
1916						
1917						
1918						
1919						
1920						
1921						
1922						
1923						
1924	13.7	1.2	4.5	421.2	72.3	493.4
1925	6.4	-6.5	-0.1	150.8	127.1	277.8
1926	6.1	-5.5	0.3	382.4	99.6	481.9
1927	7.2	-5.6	0.8	339.0	69.1	408.1
1928	4.9	-6.5	-0.8	116.6	38.2	154.7
1929	8.7	-3.8	2.5	165.6	19.8	185.5
1930	5.2	-7.1	-0.9	158.7	119.6	278.3
1931	6.7	-4.6	1.1	289.3	61.3	350.5
1932	9.0	-2.8	3.1	208.4	49.8	258.1
1933						
1934						

1935						
1936						
1937						
1938						
1939						
1940	8.6	-4.5	2.0	297.9	60.5	352.1
1941	6.7	-5.6	0.6	163.1	61.7	202.1
1942	7.6	-3.9	1.9	275.9	49.5	325.5
1943						
1944						
1945						
1946	6.3	-5.3	0.5	281.8	159.0	440.7
1947	7.4	-5.3	1.1	240.4	120.7	361.1
1948	6.5	-5.8	0.4	387.2	149.8	536.8
1949	6.9	-5.6	0.6	218.5	135.6	354.0
1950	6.9	-5.2	0.9	336.4	94.9	431.2
1951	4.1	-7.5	-1.7	211.5	127.6	339.1
1952	3.9	-7.4	-1.8	443.5	112.2	555.7
1953	7.6	-5.0	1.3	225.9	46.0	271.9
1954	7.3	-4.0	1.7	398.2	134.4	532.5
1955	5.7	-4.0	0.8	516.2	88.0	604.1
1956	5.2	-5.5	-0.2	296.5	139.4	435.8
1957	6.5	-4.8	0.8	197.7	87.9	285.6
1958	7.4	-4.0	1.7	179.1	109.9	289.0
1959	6.5	-4.3	1.1	310.0	92.6	402.7
1960	6.7	-4.9	0.9	230.4	84.6	315.0
1961	8.2	-4.8	1.7	67.5	123.5	191.0
1962	7.2	-5.1	1.1	330.6	157.5	488.3
1963	8.3	-4.3	2.0	325.7	103.9	429.7

1964	6.6	-5.9	0.4	230.9	124.2	348.7
1965	5.6	-5.4	0.1	352.2	179.3	517.8
1966	5.7	-5.5	0.1	363.6	131.9	481.0
1967	6.6	-4.8	0.9	150.0	170.0	299.1
1968	7.4	-3.6	1.9	292.2	101.9	366.8
1969	6.6	-4.5	1.1	319.9	159.3	434.9
1970	6.1	-4.5	0.8	296.4	222.2	462.3
1971	6.8	-4.4	1.2	285.3	148.6	412.9
1972	5.2	-5.6	-0.2	131.6	150.9	260.4
1973	7.2	-3.5	1.9	361.0	142.4	479.5
1974	6.5	-4.0	1.3	396.3	135.6	511.1
1975	6.4	-4.0	1.2	236.8	127.0	338.8
1976	8.3	-3.5	2.4	261.8	145.4	371.5
1977	7.6	-3.1	2.2	379.5	115.5	486.7
1978	6.1	-4.2	1.0	399.0	67.9	464.9
1979	5.7	-5.0	0.3	180.4	168.3	340.6
1980	8.1	-3.1	2.5	261.7	99.9	354.4
1981	9.6	-1.3	4.2	478.7	67.2	540.8
1982	5.9	-5.2	0.4	190.7	77.2	266.5
1983	7.0	-3.5	1.8	375.8	122.3	475.9
1984	7.9	-3.1	2.4	257.1	149.3	402.5
1985	6.1	-5.0	0.5	296.1	105.2	392.9
1986	8.4	-2.7	2.9	271.6	109.2	364.1
1987	10.3	-0.9	4.7	277.0	81.2	343.8
1988	8.8	-3.0	2.9	238.9	120.0	344.9
1989	7.2	-4.4	1.4	320.1	127.8	442.9
1990	8.5	-3.0	2.8	217.9	114.0	327.1
1991	7.9	-3.3	2.3	350.5	174.8	509.2
1992	7.3	-3.2	2.0	223.5	113.8	311.1

1993	6.9	-3.3	1.9	410.8	105.0	502.4
1994	7.3	-3.3	2.0	294.3	84.0	366.1
1995	6.1	-3.8	1.2	419.6	212.4	605.9
1996	5.0	-5.4	-0.2	294.4	125.2	413.0
1997	7.9	-2.9	2.5	312.6	118.3	408.9
1998	8.6	-1.9	3.4	390.6	115.2	480.6
1999	8.6	-2.0	3.3	336.6	108.0	429.3
2000	7.8	-4.0	1.9	295.9	88.0	364.0
2001	9.2	-2.5	3.4	200.5	61.4	254.7
2002	6.8	-4.1	1.4	393.1	102.0	492.7
2003	7.7	-3.6	2.1	214.0	85.1	284.6
2004	6.5	-4.6	0.9	324.8	104.4	427.6
2005	7.5	-2.6	2.5	377.2	89.2	463.6
2006	8.5	-1.6	3.5	427.9	96.6	524.5
2007	7.1	-3.3	1.9	291.5	48.6	354.2
2008	6.6	-4.9	0.8	0.0	0.0	346.3
2009	6.1	-4.8	0.7	0.0	0.0	419.4
2010	7.4	-2.5	2.4	0.0	0.0	692.3
2011	7.9	-2.6	2.6	0.0	0.0	420.8
2012	7.7	-3.0	2.4	0.0	0.0	450.3
2013	6.5	-4.5	1.0	0.0	0.0	294.2
2014	6.0	-4.1	0.9	0.0	0.0	553.2
2015	8.7	-1.9	3.4	0.0	0.0	409.9
2016	8.9	-1.1	3.9	0.0	0.0	551.2
2017	8.3	-2.3	3.0	0.0	0.0	314.5

Table A.2: ENSO (MEI) anomalies. Data retrieved from: https://www.esrl.noaa.gov/psd/enso/mei/table.html

YEAR	DECJAN	JANFEB	FEBMAR	MARAPR	APRMAY	MAYJUN	JUNJUL	JULAUG	AUGSEP	SEPOCT	OCTNOV	NOVDEC
1950	-1.062	-1.163	-1.312	-1.098	-1.445	-1.376	-1.267	-1.03	-0.597	-0.433	-1.165	-1.261
1951	-1.07	-1.183	-1.204	-0.544	-0.374	0.319	0.676	0.842	0.773	0.736	0.703	0.478
1952	0.419	0.117	0.047	0.198	-0.307	-0.722	-0.307	-0.358	0.347	0.275	-0.349	-0.124
1953	0.03	0.377	0.257	0.668	0.773	0.226	0.379	0.228	0.527	0.093	0.075	0.324
1954	-0.051	-0.048	0.147	-0.634	-1.478	-1.528	-1.356	-1.446	-1.138	-1.348	-1.14	-1.113
1955	-0.762	-0.697	-1.147	-1.662	-1.663	-2.209	-1.977	-2.043	-1.803	-1.753	-1.841	-1.877
1956	-1.437	-1.303	-1.399	-1.248	-1.316	-1.49	-1.245	-1.106	-1.327	-1.486	-1.038	-1.022
1957	-0.941	-0.372	0.101	0.372	0.826	0.753	0.924	1.157	1.158	1.083	1.148	1.248
1958	1.472	1.439	1.32	0.987	0.685	0.841	0.7	0.442	0.209	0.213	0.486	0.671
1959	0.548	0.796	0.495	0.192	-0.026	-0.036	-0.112	0.13	0.126	-0.06	-0.17	-0.261
1960	-0.299	-0.274	-0.094	-0.005	-0.321	-0.254	-0.318	-0.233	-0.439	-0.355	-0.331	-0.417
1961	-0.163	-0.257	-0.088	0.004	-0.304	-0.153	-0.21	-0.283	-0.271	-0.539	-0.436	-0.634
1962	-1.087	-0.988	-0.712	-1.068	-0.894	-0.839	-0.682	-0.523	-0.528	-0.67	-0.623	-0.505
1963	-0.739	-0.863	-0.69	-0.768	-0.48	-0.112	0.403	0.611	0.778	0.814	0.844	0.744
1964	0.874	0.468	-0.269	-0.562	-1.249	-1.113	-1.386	-1.476	-1.284	-1.225	-1.239	-0.936
1965	-0.557	-0.353	-0.278	0.063	0.474	0.895	1.366	1.452	1.43	1.219	1.362	1.252
1966	1.306	1.17	0.681	0.506	-0.178	-0.169	-0.116	0.171	-0.06	-0.044	0.004	-0.199
1967	-0.473	-0.919	-1.066	-1.037	-0.453	-0.217	-0.489	-0.376	-0.601	-0.683	-0.426	-0.378
1968	-0.619	-0.749	-0.641	-0.959	-1.106	-0.777	-0.503	-0.087	0.244	0.435	0.586	0.347
1969	0.664	0.833	0.453	0.616	0.681	0.823	0.49	0.232	0.2	0.511	0.666	0.398
1970	0.372	0.415	0.22	0	-0.097	-0.608	-1.053	-0.995	-1.226	-1.088	-1.084	-1.223
1971	-1.223	-1.528	-1.817	-1.87	-1.444	-1.392	-1.206	-1.201	-1.439	-1.421	-1.329	-0.993
1972	-0.596	-0.424	-0.269	-0.171	0.428	0.995	1.824	1.828	1.574	1.643	1.726	1.766
1973	1.726	1.5	0.86	0.473	-0.096	-0.728	-1.057	-1.323	-1.712	-1.667	-1.503	-1.848
1974	-1.939	-1.793	-1.767	-1.643	-1.061	-0.663	-0.751	-0.649	-0.599	-1.052	-1.251	-0.905
1975	-0.538	-0.6	-0.879	-0.959	-0.841	-1.115	-1.498	-1.704	-1.853	-1.987	-1.773	-1.757
1976	-1.61	-1.392	-1.234	-1.18	-0.486	0.306	0.634	0.676	1.064	0.946	0.493	0.55
1977	0.521	0.273	0.139	0.545	0.318	0.443	0.888	0.706	0.824	0.986	0.975	0.86

1978	0.773	0.899	0.936	0.191	-0.381	-0.575	-0.421	-0.182	-0.364	-0.02	0.186	0.388
1979	0.6	0.362	-0.01	0.292	0.382	0.453	0.397	0.637	0.801	0.678	0.746	0.989
1980	0.672	0.585	0.689	0.927	0.966	0.931	0.768	0.349	0.302	0.201	0.251	0.089
1981	-0.262	-0.151	0.456	0.671	0.189	0.004	-0.027	-0.072	0.209	0.112	-0.038	-0.141
1982	-0.27	-0.137	0.103	0.013	0.445	0.947	1.613	1.806	1.835	2.024	2.428	2.411
1983	2.683	2.91	3.012	2.808	2.538	2.255	1.792	1.184	0.507	0.038	-0.132	-0.188
1984	-0.33	-0.529	0.139	0.373	0.189	-0.023	-0.054	-0.138	-0.085	0.001	-0.352	-0.603
1985	-0.561	-0.595	-0.709	-0.472	-0.715	-0.14	-0.126	-0.35	-0.508	-0.139	-0.059	-0.293
1986	-0.301	-0.195	0.028	-0.099	0.355	0.301	0.402	0.787	1.116	0.979	0.873	1.19
1987	1.25	1.205	1.722	1.859	2.134	1.975	1.878	2.003	1.905	1.647	1.271	1.282
1988	1.119	0.706	0.491	0.387	0.196	-0.556	-1.107	-1.284	-1.501	-1.326	-1.468	-1.328
1989	-1.12	-1.262	-1.054	-0.763	-0.402	-0.216	-0.429	-0.479	-0.287	-0.341	-0.073	0.115
1990	0.237	0.563	0.956	0.469	0.658	0.527	0.151	0.145	0.398	0.285	0.389	0.348
1991	0.313	0.314	0.402	0.454	0.748	1.074	1.044	1.031	0.778	1.009	1.189	1.32
1992	1.743	1.87	1.991	2.258	2.112	1.75	1.048	0.58	0.518	0.641	0.582	0.648
1993	0.687	0.974	0.99	1.417	2.019	1.635	1.206	1.05	1.011	1.069	0.834	0.589
1994	0.353	0.182	0.157	0.473	0.585	0.819	0.907	0.783	0.931	1.407	1.299	1.237
1995	1.22	0.946	0.853	0.469	0.576	0.53	0.234	-0.13	-0.416	-0.477	-0.478	-0.554
1996	-0.612	-0.58	-0.238	-0.386	-0.044	0.111	-0.173	-0.358	-0.426	-0.349	-0.146	-0.336
1997	-0.49	-0.621	-0.252	0.543	1.14	2.287	2.827	3.037	3.057	2.401	2.542	2.335
1998	2.466	2.761	2.755	2.661	2.237	1.356	0.392	-0.319	-0.6	-0.798	-1.086	-0.922
1999	-1.053	-1.14	-0.971	-0.903	-0.601	-0.31	-0.477	-0.725	-0.937	-0.973	-1.05	-1.161
2000	-1.139	-1.21	-1.113	-0.409	0.257	0.02	-0.157	-0.129	-0.21	-0.387	-0.714	-0.566
2001	-0.505	-0.661	-0.56	-0.055	0.288	0.071	0.299	0.35	-0.147	-0.275	-0.153	0.019
2002	0.009	-0.171	-0.121	0.414	0.891	0.945	0.716	1.025	0.921	1	1.09	1.145
2003	1.218	0.935	0.833	0.421	0.214	0.131	0.178	0.329	0.492	0.516	0.57	0.351
2004	0.327	0.359	-0.035	0.374	0.56	0.327	0.574	0.639	0.591	0.508	0.805	0.667
2005	0.32	0.81	1.067	0.637	0.893	0.612	0.519	0.362	0.329	-0.167	-0.392	-0.57
2006	-0.438	-0.424	-0.527	-0.575	0.043	0.546	0.718	0.77	0.84	0.955	1.286	0.951
2007	0.985	0.528	0.12	0.02	0.354	-0.136	-0.247	-0.427	-1.175	-1.217	-1.165	-1.193
2008	-1.02	-1.388	-1.579	-0.879	-0.349	0.164	0.089	-0.252	-0.545	-0.692	-0.597	-0.663

2009	-0.726	-0.707	-0.723	-0.105	0.328	0.779	1.06	1.073	0.745	0.909	1.121	1.045
2010	1.067	1.52	1.469	0.99	0.668	-0.211	-1.099	-1.662	-1.86	-1.899	-1.49	-1.577
2011	-1.739	-1.563	-1.575	-1.399	-0.202	0.016	-0.191	-0.502	-0.751	-0.933	-0.949	-0.957
2012	-0.993	-0.695	-0.398	0.112	0.769	0.866	1.128	0.628	0.351	0.081	0.125	0.094
2013	0.096	-0.08	-0.037	0.095	0.203	-0.078	-0.311	-0.466	-0.125	0.13	-0.053	-0.248
2014	-0.275	-0.266	0.027	0.312	1.01	1.057	0.921	0.961	0.593	0.438	0.763	0.558
2015	0.42	0.459	0.631	0.943	1.592	2.101	1.987	2.365	2.532	2.241	2.297	2.112
2016	2.227	2.169	1.984	2.124	1.77	1.069	0.354	0.186	-0.091	-0.379	-0.212	-0.121
2017	-0.055	-0.056	-0.08	0.77	1.455	1.049	0.461	0.027	-0.449			

Table A.3: PDO anomalies. Data retrieved from: https://www.ncdc.noaa.gov/teleconnections/pdo/data.csv

YEAR	JAN	DEC	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1950	-2.13	-2.91	-1.13	-1.2	-2.23	-1.77	-2.93	-0.7	-2.14	-1.36	-2.46	-0.76
1951	-1.54	-1.06	-1.9	-0.36	-0.25	-1.09	0.7	-1.37	-0.08	-0.32	-0.28	-1.68
1952	-2.01	-0.46	-0.63	-1.05	-1	-1.43	-1.25	-0.6	-0.89	-0.35	-0.76	0.04
1953	-0.57	-0.07	-1.12	0.05	0.43	0.29	0.74	0.05	-0.63	-1.09	-0.03	0.07
1954	-1.32	-1.61	-0.52	-1.33	0.01	0.97	0.43	0.08	-0.94	0.52	0.72	-0.5
1955	0.2	-1.52	-1.26	-1.97	-1.21	-2.44	-2.35	-2.25	-1.95	-2.8	-3.08	-2.75
1956	-2.48	-2.74	-2.56	-2.17	-1.41	-1.7	-1.03	-1.16	-0.71	-2.3	-2.11	-1.28
1957	-1.82	-0.68	0.03	-0.58	0.57	1.76	0.72	0.51	1.59	1.5	-0.32	-0.55
1958	0.25	0.62	0.25	1.06	1.28	1.33	0.89	1.06	0.29	0.01	-0.18	0.86
1959	0.69	-0.43	-0.95	-0.02	0.23	0.44	-0.5	-0.62	-0.85	0.52	1.11	0.06
1960	0.3	0.52	-0.21	0.09	0.91	0.64	-0.27	-0.38	-0.94	0.09	-0.23	0.17
1961	1.18	0.43	0.09	0.34	-0.06	-0.61	-1.22	-1.13	-2.01	-2.28	-1.85	-2.69
1962	-1.29	-1.15	-1.42	-0.8	-1.22	-1.62	-1.46	-0.48	-1.58	-1.55	-0.37	-0.96
1963	-0.33	-0.16	-0.54	-0.41	-0.65	-0.88	-1	-1.03	0.45	-0.52	-2.08	-1.08
1964	0.01	-0.21	-0.87	-1.03	-1.91	-0.32	-0.51	-1.03	-0.68	-0.37	-0.8	-1.52
1965	-1.24	-1.16	0.04	0.62	-0.66	-0.8	-0.47	0.2	0.59	-0.36	-0.59	0.06
1966	-0.82	-0.03	-1.29	0.06	-0.53	0.16	0.26	-0.35	-0.33	-1.17	-1.15	-0.32

1967	-0.2	-0.18	-1.2	-0.89	-1.24	-1.16	-0.89	-1.24	-0.72	-0.64	-0.05	-0.4
1968	-0.95	-0.4	-0.31	-1.03	-0.53	-0.35	0.53	0.19	0.06	-0.34	-0.44	-1.27
1969	-1.26	-0.95	-0.5	-0.44	-0.2	0.89	0.1	-0.81	-0.66	1.12	0.15	1.38
1970	0.61	0.43	1.33	0.43	-0.49	0.06	-0.68	-1.63	-1.67	-1.39	-0.8	-0.97
1971	-1.9	-1.74	-1.68	-1.59	-1.55	-1.55	-2.2	-0.15	0.21	-0.22	-1.25	-1.87
1972	-1.99	-1.83	-2.09	-1.65	-1.57	-1.87	-0.83	0.25	0.17	0.11	0.57	-0.33
1973	-0.46	-0.61	-0.5	-0.69	-0.76	-0.97	-0.57	-1.14	-0.51	-0.87	-1.81	-0.76
1974	-1.22	-1.65	-0.9	-0.52	-0.28	-0.31	-0.08	0.27	0.44	-0.1	0.43	-0.12
1975	-0.84	-0.71	-0.51	-1.3	-1.02	-1.16	-0.4	-1.07	-1.23	-1.29	-2.08	-1.61
1976	-1.14	-1.85	-0.96	-0.89	-0.68	-0.67	0.61	1.28	0.82	1.11	1.25	1.22
1977	1.65	1.11	0.72	0.3	0.31	0.42	0.19	0.64	-0.55	-0.61	-0.72	-0.69
1978	0.34	1.45	1.34	1.29	0.9	0.15	-1.24	-0.56	-0.44	0.1	-0.07	-0.43
1979	-0.58	-1.33	0.3	0.89	1.09	0.17	0.84	0.52	1	1.06	0.48	-0.42
1980	-0.11	1.32	1.09	1.49	1.2	-0.22	0.23	0.51	0.1	1.35	0.37	-0.1
1981	0.59	1.46	0.99	1.45	1.75	1.69	0.84	0.18	0.42	0.18	0.8	0.67
1982	0.34	0.2	0.19	-0.19	-0.58	-0.78	0.58	0.39	0.84	0.37	-0.25	0.26
1983	0.56	1.14	2.11	1.87	1.8	2.36	3.51	1.85	0.91	0.96	1.02	1.69
1984	1.5	1.21	1.77	1.52	1.3	0.18	-0.18	-0.03	0.67	0.58	0.71	0.82
1985	1.27	0.94	0.57	0.19	0	0.18	1.07	0.81	0.44	0.29	-0.75	0.38
1986	1.12	1.61	2.18	1.55	1.16	0.89	1.38	0.22	0.22	1	1.77	1.77
1987	1.88	1.75	2.1	2.16	1.85	0.73	2.01	2.83	2.44	1.36	1.47	1.27
1988	0.93	1.24	1.42	0.94	1.2	0.74	0.64	0.19	-0.37	-0.1	-0.02	-0.43
1989	-0.95	-1.02	-0.83	-0.32	0.47	0.36	0.83	0.09	0.05	-0.12	-0.5	-0.21
1990	-0.3	-0.65	-0.62	0.27	0.44	0.44	0.27	0.11	0.38	-0.69	-1.69	-2.23
1991	-2.02	-1.19	-0.74	-1.01	-0.51	-1.47	-0.1	0.36	0.65	0.49	0.42	0.09
1992	0.05	0.31	0.67	0.75	1.54	1.26	1.9	1.44	0.83	0.93	0.93	0.53
1993	0.05	0.19	0.76	1.21	2.13	2.34	2.35	2.69	1.56	1.41	1.24	1.07
1994	1.21	0.59	0.8	1.05	1.23	0.46	0.06	-0.79	-1.36	-1.32	-1.96	-1.79
1995	-0.49	0.46	0.75	0.83	1.46	1.27	1.71	0.21	1.16	0.47	-0.28	0.16
1996	0.59	0.75	1.01	1.46	2.18	1.1	0.77	-0.14	0.24	-0.33	0.09	-0.03
1997	0.23	0.28	0.65	1.05	1.83	2.76	2.35	2.79	2.19	1.61	1.12	0.67

1998	0.83	1.56	2.01	1.27	0.7	0.4	-0.04	-0.22	-1.21	-1.39	-0.52	-0.44
1999	-0.32	-0.66	-0.33	-0.41	-0.68	-1.3	-0.66	-0.96	-1.53	-2.23	-2.05	-1.63
2000	-2	-0.83	0.29	0.35	-0.05	-0.44	-0.66	-1.19	-1.24	-1.3	-0.53	0.52
2001	0.6	0.29	0.45	-0.31	-0.3	-0.47	-1.31	-0.77	-1.37	-1.37	-1.26	-0.93
2002	0.27	-0.64	-0.43	-0.32	-0.63	-0.35	-0.31	0.6	0.43	0.42	1.51	2.1
2003	2.09	1.75	1.51	1.18	0.89	0.68	0.96	0.88	0.01	0.83	0.52	0.33
2004	0.43	0.48	0.61	0.57	0.88	0.04	0.44	0.85	0.75	-0.11	-0.63	-0.17
2005	0.44	0.81	1.36	1.03	1.86	1.17	0.66	0.25	-0.46	-1.32	-1.5	0.2
2006	1.03	0.66	0.05	0.4	0.48	1.04	0.35	-0.65	-0.94	-0.05	-0.22	0.14
2007	0.01	0.04	-0.36	0.16	-0.1	0.09	0.78	0.5	-0.36	-1.45	-1.08	-0.58
2008	-1	-0.77	-0.71	-1.52	-1.37	-1.34	-1.67	-1.7	-1.55	-1.76	-1.25	-0.87
2009	-1.4	-1.55	-1.59	-1.65	-0.88	-0.31	-0.53	0.09	0.52	0.27	-0.4	0.08
2010	0.83	0.82	0.44	0.78	0.62	-0.22	-1.05	-1.27	-1.61	-1.06	-0.82	-1.21
2011	-0.92	-0.83	-0.69	-0.42	-0.37	-0.69	-1.86	-1.74	-1.79	-1.34	-2.33	-1.79
2012	-1.38	-0.85	-1.05	-0.27	-1.26	-0.87	-1.52	-1.93	-2.21	-0.79	-0.59	-0.48
2013	-0.13	-0.43	-0.63	-0.16	0.08	-0.78	-1.25	-1.04	-0.48	-0.87	-0.11	-0.41
2014	0.3	0.38	0.97	1.13	1.8	0.82	0.7	0.67	1.08	1.49	1.72	2.51
2015	2.45	2.3	2	1.44	1.2	1.54	1.84	1.56	1.94	1.47	0.86	1.01
2016	1.53	1.75	2.4	2.62	2.35	2.03	1.25	0.52	0.45	0.56	1.88	1.17
2017	0.77	0.7	0.74	1.12	0.05	0.14	0.53	0.28	0.20			

Table A.4: SPEI index for 51º75’ N, 104º25’ W. Data retrieved from: http://spei.csic.es/database.html

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1950												-0.009
1951	0.0262	0.109	0.3968	0.2602	0.1134	0.9528	0.7205	1.1429	1.8155	2.0052	1.8702	1.7359
1952	1.7072	1.7264	1.5498	0.8774	0.7776	-0.1812	-0.0322	-0.4337	-1.2029	-1.7331	-1.7642	-1.7710
1953	-1.7800	-1.6335	-1.2802	-0.5581	0.3580	0.6893	1.1402	0.9680	1.5597	1.4273	1.4157	1.6210
1954	1.6619	1.749	1.5617	1.6939	1.5194	1.9777	2.2997	2.4285	2.0214	2.1540	2.1188	2.0338
1955	2.0217	2.1497	2.3277	2.3958	2.4164	2.1111	1.4484	-0.0274	-0.1711	-0.1954	0.1310	0.3861
1956	0.4409	0.8841	1.1637	0.6513	0.1682	0.3063	0.4813	0.9166	0.6910	0.8582	0.6501	0.6366

1957	0.4194	0.0492	-0.029	0.2428	-0.192	-0.301	-0.717	-0.381	-0.497	-0.455	-0.522	-0.6431
1958	-0.5981	-0.309	-0.667	-0.9397	-1.094	-1.330	-1.074	-1.448	-1.2621	-1.462	-1.401	-1.331
1959	-1.371	-1.620	-1.683	-1.6361	-1.300	-0.705	-1.211	-0.891	-0.143	0.4774	0.5055	0.4505
1960	0.6335	0.7065	0.8804	0.8592	1.2435	1.1744	0.9892	0.7476	-0.444	-1.095	-1.1791	-1.222
1961	-1.381	-1.309	-1.426	-1.4107	-1.764	-2.262	-2.184	-2.576	-2.7011	-2.330	-2.2107	-2.0887
1962	-1.880	-1.777	-1.4907	-1.476	-1.478	-1.157	-0.390	0.5965	0.7733	0.6470	0.5155	0.4408
1963	0.1986	0.0489	-0.254	-0.248	0.0589	0.7184	0.2505	-0.108	-0.323	-0.763	-0.606	-0.633
1964	-0.405	-0.350	-0.536	-0.506	-0.801	-1.3871	-1.447	-0.831	-0.496	-0.371	-0.4641	-0.4071
1965	-0.5997	-0.456	-0.477	-0.551	0.1795	1.3156	1.3501	0.5249	1.1411	1.0072	1.1431	1.1734
1966	1.2154	1.1086	1.2757	1.5843	0.7565	0.3476	0.1417	1.3946	0.4095	0.6190	0.6004	0.5944
1967	0.7794	0.8303	1.1077	0.8172	0.7154	-0.2491	-0.523	-1.627	-1.3827	-1.006	-1.053	-1.051
1968	-1.197	-1.2487	-1.5181	-1.7331	-1.622	-1.530	-0.892	0.0246	0.1001	-0.014	-0.202	-0.189
1969	-0.0171	0.1285	0.1142	-0.039	-0.0741	0.0821	0.0427	-0.453	-0.220	0.3784	0.4763	0.3080
1970	0.0867	0.1458	0.2451	1.0174	1.3403	1.3621	1.2021	0.8737	0.7193	0.1863	0.2815	0.3723
1971	0.4288	0.4995	0.3627	-0.117	-0.9147	-0.207	0.4098	0.3755	0.2212	0.2135	0.1947	0.1647
1972	0.1734	0.1158	0.0883	0.2559	0.4845	-0.652	-1.305	-1.275	-0.948	-1.052	-1.1157	-1.116
1973	-1.241	-1.2517	-1.215	-0.8251	-0.256	1.2617	1.2981	1.2842	1.0168	0.7844	0.9379	1.0149
1974	1.2304	1.3103	1.4761	1.1166	1.6643	0.2118	-0.0311	1.3464	1.7168	1.7092	1.4993	1.3934
1975	1.3478	1.4831	1.3006	1.8586	0.7793	1.1860	0.6692	-0.271	-0.579	-0.485	-0.4497	-0.407
1976	-0.508	-0.317	-0.110	-1.038	-0.972	-0.294	0.2482	-0.077	-0.601	-0.546	-0.528	-0.466
1977	-0.5527	-0.839	-0.978	-1.141	-0.103	-1.271	-1.3607	-1.170	-0.490	-0.514	-0.319	-0.278
1978	-0.248	-0.274	-0.458	-0.203	-1.122	-0.914	-0.477	0.0530	-0.087	-0.040	0.0546	-0.134
1979	-0.066	0.1935	0.3614	0.7185	0.8484	0.7350	-0.092	-0.504	-0.852	-0.668	-0.871	-0.690
1980	-0.602	-0.759	-0.805	-1.512	-2.026	-1.911	-1.701	-1.167	-1.133	-1.292	-1.221	-1.391
1981	-1.497	-1.5301	-1.598	-1.1961	-0.876	-0.457	0.3650	-0.2902	0.0792	0.7396	0.5799	0.6371
1982	0.6409	0.6550	0.6675	0.6485	1.2515	0.4340	-0.361	-0.111	-0.074	-0.891	-0.848	-0.8237
1983	-0.830	-0.772	-0.6897	-0.5307	-0.591	-0.462	1.3195	0.6315	0.7083	0.6864	0.9342	0.8361
1984	0.8288	0.8089	0.6887	0.3098	0.2873	0.3497	-1.529	-1.4117	-1.000	-0.334	-0.420	-0.350
1985	-0.2477	-0.103	-0.129	0.2675	0.2146	0.4023	0.7682	1.2829	0.9510	0.3662	0.3664	0.3072
1986	0.3045	0.2866	0.3392	0.2099	-0.169	-0.625	0.1354	-0.2911	-0.1191	-0.129	-0.253	-0.273
1987	-0.329	-0.3781	-0.424	-0.7101	-0.859	-0.9171	-1.227	-0.726	-1.4317	-1.184	-1.239	-1.2141

1988	-1.1477	-1.1761	-0.9565	-0.8285	-0.9058	-1.5218	-1.8437	-1.6738	-1.6620	-1.7416	-1.6700	-1.6026
1989	-1.6009	-1.5912	-1.8178	-1.7924	-1.6525	-0.5580	-0.7326	-1.0542	-0.8664	-0.4835	-0.343	-0.3109
1990	-0.1852	-0.1830	-0.0685	0.3487	0.1265	-0.5739	0.1859	0.10724	-0.2934	-0.5879	-0.6432	-0.7226
1991	-0.8291	-0.7219	-0.9525	-1.0646	-0.6775	-0.1389	-0.3814	-0.4289	0.1487	0.6645	0.6860	0.8267
1992	0.7839	0.7856	0.6889	0.5418	0.4107	-0.6686	-0.4577	0.0843	0.49464	0.03794	-0.0576	-0.1817
1993	-0.2789	-0.3885	-0.1273	-0.1752	-0.4384	0.2790	1.2104	1.5870	1.3556	1.2328	1.2606	1.2332
1994	1.3660	1.55254	1.3903	1.3178	1.3669	1.2262	0.03844	-0.3073	-0.8210	-0.8647	-0.9016	-0.8592
1995	-0.9481	-0.9160	-0.4637	0.1557	0.1198	0.61014	0.2670	1.2107	1.1384	1.44974	1.5420	1.5403
1996	1.5309	1.5746	1.2681	1.09794	1.3711	0.636	1.4695	-0.2267	0.2591	0.1648	0.1536	0.25018
1997	0.4377	0.5093	0.5981	0.57554	0.3798	0.9880	0.0944	0.4692	0.4171	0.3465	0.0991	-0.1669
1998	-0.1121	-0.0631	-0.1724	-0.6783	-0.6544	-0.0712	0.2118	-0.0101	0.2681	0.3571	0.4138	0.50428
1999	0.3383	0.4049	0.3909	0.8251	0.90624	0.27344	0.5827	0.6802	0.5711	0.2756	0.2329	0.2002
2000	0.2350	0.1245	0.1516	0.0343	-0.0948	-0.0983	-0.6568	-0.2762	-0.1732	-0.4476	-0.2281	-0.0810
2001	-0.2549	-0.1604	-0.2575	-0.4586	-0.6719	-1.4477	-1.0993	-1.6109	-1.8971	-1.6135	-1.7211	-1.8390
2002	-1.7630	-1.8350	-1.7823	-1.5569	-1.5676	-1.2210	-1.4957	0.5278	0.8303	0.9692	0.9959	1.21218
2003	1.1651	1.3676	1.4146	1.3677	1.2269	0.7751	0.7668	-0.9937	-0.9807	-1.2328	-1.2848	-1.5679
2004	-1.4087	-1.4053	-1.3132	-1.4841	-0.7935	-0.1964	-0.1784	0.9115	0.5953	0.7434	0.6798	0.8486
2005	0.7551	0.7460	0.71014	0.4856	0.4107	0.1596	0.0535	-0.3902	0.1222	-0.0047	0.2837	0.1741
2006	0.3213	0.3637	0.4595	0.8122	0.6482	0.5631	0.2579	-0.2202	0.21424	0.7823	0.8759	0.9175
2007	0.8176	0.9015	0.8347	0.6554	0.6238	0.8037	0.8960	1.1194	0.69334	0.0061	-0.2960	-0.3275
2008	-0.3221	-0.3759	-0.6070	-0.4662	-0.9076	-1.1417	-0.2158	-0.4194	-0.6509	-0.4618	-0.3716	-0.3257
2009	-0.3417	-0.2644	-0.2540	0.18784	0.30704	0.23404	-0.1389	0.4964	0.3571	0.9478	0.73424	0.6292
2010	0.7742	0.7118	0.62954	0.5652	1.4153	2.0071	2.1339	1.9562	2.3041	1.90274	2.1011	2.1540
2011	2.0762	2.3692	2.5456	2.1817	1.5317	1.6027	1.5579	0.7995	-0.0571	-0.1624	-0.4054	-0.5026
2012	-0.6571	-0.8612	-0.8480	-0.3010	0.3026	-0.0472	-0.4927	-0.5874	-0.6058	-0.33	-0.2689	-0.1904
2013	-0.1975	-0.1251	-0.2041	-0.5552	-1.4773	-1.5559	-1.3751	-1.4428	-1.3420	-1.4936	-1.5500	-1.5012
2014	-1.3060	-1.3312	-1.3425	-0.8566	-0.4958	0.6274	0.0521	0.8180	1.0495	1.0936	1.2081	1.1487
2015	1.2191	1.3897	1.4764	0.9286	0.6105	-1.1941	-0.6415	-0.5981	-0.2979	-0.2604	-0.2986	-0.2437
2016	-0.3366	-0.3867	-0.3217	-0.4670	-0.3121	-0.1196	0.2907	0.3731	0.3136	0.8127	0.6224	0.5882
2017	0.5741	0.6037	0.4867	0.5714	0.4618	0.3745	-0.8767	-1.1132	-1.4875	-1.6402	-1.5430	-1.5493

Appendix B: Hydrological Data

Figure B.1.1: Bathymetry map of the Big Quill Lake from current surface water levels of 521 masl. The map was modified from Whitting's Topography Map of Big Quill Lake that was presented in feet. Contours in feet were converted to metres and subtracted from 521 masl to derive modern bathymetry of the lake (Whitting, 1977).

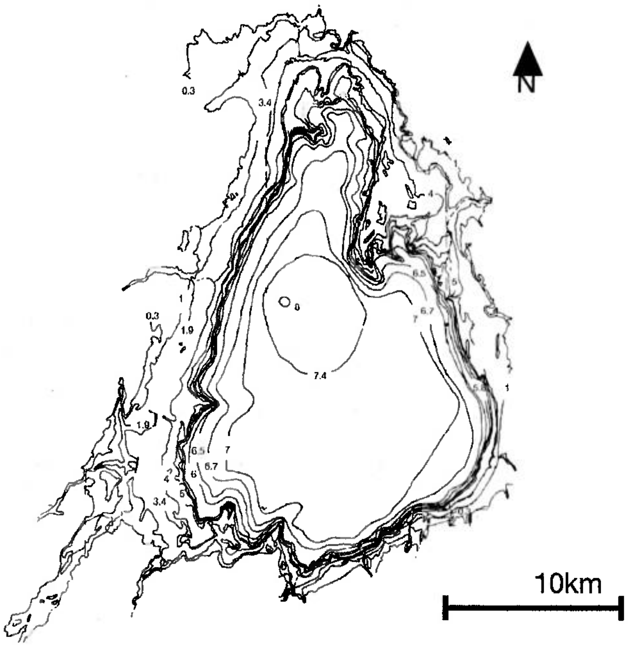


Figure B.1.2: Bathymetry map of the Big Quill Lake in 1975 at water surface elevation of 515.4 masl (Hammer and Haynes, 1978).

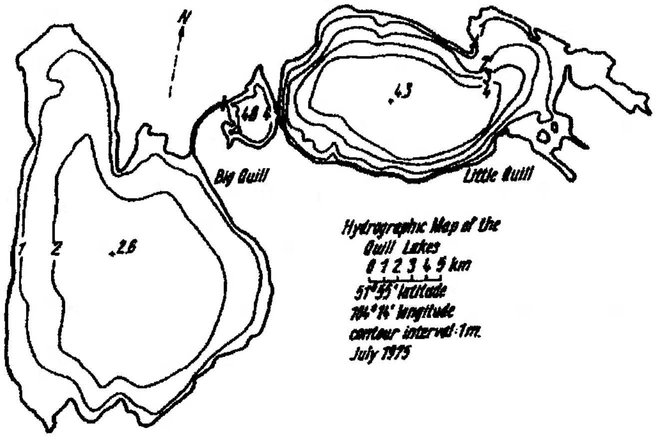


Table B.2: Surface water level of Big Quill Lake 1919-2017. The data was calculated on the combination of available hydrometric records on Environment Canada at station 05MA010 and KGS Group provided graphs. For years wth more than one record, the mean lake elevation was calculated for the corresponding year. Elevation derived manually from KGS Group graph are denoted in (bold) (KGS Group, 2016; Environment Canada, 2018).

YEAR	Level (m)	YEAR	Level (m)	YEAR	Level (m)	YEAR	Level (m)	YEAR	Level (m)
1919	**518.35**	1939	516.176	1960	515.968	1979	515.942	2000	**514.7**
1920	**518.4**	1940	516.118	1961	515.761	1980	515.7458	2001	**514.4**
1921	**518.7**	1942	515.956	1962	515.054	1981	515.4718	2002	**514**
1922	**518.9**	1943	516.066	1963	**514.9**	1982	515.2663	2003	**514.1**
1923	**518.8**	1944	515.886	1964	**514.8**	1983	515.19	2004	**513.9**
1924	**518.45**	1945	515.697	1965	**514.75**	1984	**514.9**	2005	**514.2**
1925	**518.6**	1946	515.658	1966	**514.95**	1985	**515.2**	2006	**515.4**
1926	**518.35**	1947	515.402	1967	**515**	1986	**514.95**	2007	**516.6**
1927	**518.2**	1948	515.399	1968	514.801	1987	**514.65**	2008	**516.8**
1928	**518.2**	1949	515.423	1969	514.872	1988	**514.5**	2009	**516.7**
1929	**517.6**	1950	515.417	1969	514.696	1989	514.1074	2010	**518.3**
1930	**517.55**	1951	515.383	1970	**514.8**	1990	**514.1**	2011	**519.4**
1931	517.92	1952	515.603	1971	514.756	1992	513.744	2012	519.58
1932	517.727	1953	515.539	1972	514.688	1993	513.75	2013	519.6346
1933	517.377	1954	515.609	1973	514.6732	1994	**513.8**	2014	520.1005
1934	517.07	1955	**516.4**	1974	515.1113	1995	**515.3**	2015	520.503
1935	516.776	1956	516.084	1975	515.3966	1996	**514.6**	2016	520.6536
1936	**516.7**	1957	516.255	1976	**515.9**	1997	514.85		
1937	516.493	1958	516.535	1977	**515.7**	1998	514.85		
1938	516.188	1959	515.962	1978	515.5636	1999	**514.7**		

Table B.3: Discharge of Ironspring (05MA012), Romance (05MA016), Magnusson (05MA021), and Quill (05MA020) creeks from 1966 to 2016. Total annual discharge was calculated by finding an annual sum for the corresponding year between the four creeks (Environment Canada, 2018).

Year	Total Discharge (m3)	Year	Total Discharge (m3)
1966	7.921	1996	15.019
1967	10.961	1997	19.892
1968	2.218	1998	4.742
1969	7.202	1999	3.76
1970	9.502	2000	0.827
1971	9.238	2001	0.957
1972	20.272	2002	0.085
1973	2.845	2003	8.964
1974	17.697	2004	5.891
1975	18.022	2005	21.273
1976	13.252	2006	53.523
1977	1.743	2007	45.244
1978	8.359	2008	18.713
1979	29.589	2009	10.499
1980	7.856	2010	57.208
1981	0.089	2011	51.828
1982	2.222	2012	11.56
1983	8.027	2013	25.51
1984	2.498	2014	41.628
1985	27.809	2015	24.006
1986	4.845	2016	17.568
1987	3.144		
1988	12.617		
1989	0.666		
1990	9.094	0.085	min
1991	0.295	4.251	Q1
1992	6.913	9.238	Q2
1993	8.653	19.3025	Q3
1994	9.517	57.208	max
1995	40.108	14.546	mean

Table B.4: Big Quill Lake monthly surface water elevation from 2013 to 2016. Monthly water levels were used to depict groundwater influence on the hydrological balance of the lake (Kamp, *et al,* 2008; Environment Canada, 2018).

	2013	2014	2015	2016
JAN			520.19	520.43
FEB			520.24	520.43
MAR	519.46	519.46	520.28	520.46
APR	519.477	519.519	520.512	520.614
MAY	519.71	519.82	520.62	520.70
JUN	519.74	519.93	520.58	520.65
JUL	519.72	520.24	520.51	520.66
AUG	519.63	520.23	520.47	520.67
SEPT	519.533	520.183	520.434	520.584
OCT	519.475	520.2	520.403	520.661
NOV			520.447	520.704
DEC			520.46	520.70

Appendix C: Lithology

Table C.1. Lithological analysis.

Colour	Size	Roundness	Sorting	Fabric	Principal Name	Minerology	Fabric	Comments
2.5 Y 4/1	vfL							chl, small ooids, non ostracod or plants, small crystallization present of gypsum present
2.5 Y 5/1	vfU							chlorite, increase in ooids, crystallization of gypsum, ostracods, no seeds, no plant debris, no detritals visible
2.5 Y 4/1	vfU							chlorite, lots of ooids, little crystallization of gypsum and arg, seed presence, no ostracod seen
2.5 Y 4/2	vfU							chl, rise in seeds (most yet from top), ooids match the ones above, minor plant debris (root)
2.5 Y 4/2	vfU-fL	sub angular to sub rounded	mod	massive	Detrital	Quztz, muscovite, clay, biotite, chlorite, aragnoite	anhedral, needle, tabular, platy	chl huge, tons of calc, rise in root and seed debris and appear of ostracods, rise in energy and productivity?
2.5 Y 4/1	vfU-fL							same as above, seed, rise in ostracod tons of ooids, even long and tabular crystals near the seed
2.5 Y 5/2	vfU-fL							lots of ostracods, ooids, and seeds, high productivity and rise in sediment size, some ppt present
2.5 Y 5/2	vfU							ostracods, seeds, plant debris of seeds, detritals, little ppt. some gypsum
2.5 Y 5/2	vfU							same as above
2.5 Y 6/1	vfU	angular to sub angular	mod	massive	Detrital	Quartz, muscovite, biotite, clays, chlorite	anhedral, needle, tabular, platy	ostracods, detritals, v little ppt to none
2.5 Y 6/1	vfL							same as above, increase in clay
2.5 Y 6/1	vfL							no plant debris at all, a couple ostracods, prom ppt of gypsum esp. some arag >20
2.5 Y 6/1	vfL							roots and seeds present, mod ppt
2.5 Y 6/1	vfL							lots of plant debris (seeds) and ostracods, detrital material, gypsum present
2.5 Y 6/1	vfL	angular to sub angular	mod	massive	Detrital	Quartz, muscovite, clays, biotite, plagiocalse, calcite, chlorite	anhedral, needle, tabular, platy	same as above
2.5 Y 6/1	vfU							seeds only, no ostracods, likely a piece of charcoal
2.5 Y 6/1	vfL-clay							very little crystallization, ostarcods and seeds present, border line clay, lots of allogenics
2.5 Y 6/1	vfL-clay							detrital debris, seeds and ostracod, non calc, no chl, defs an increase in aragonite and gypsum since 15 >20
2.5 Y 6/1	vfL-clay							same as above
2.5 Y 6/1	vfL	angular to sub angular	mod	massive	Detrital	Quartz, orthoclase, muscovite, biotite, clay,chlorite,cpx, gypsum	anhedral, needle, tabular, platy, fibrous	a lot of acitivity with org, fragments of zoops, seeds, roots, ostracods, good cytsllization of gypsum as well, aragonite
2.5 Y 5/1	vfL							ostracod, detritals, v little ppt to non, woah massive chlorite, seeds
2.5 Y 5/1	vfU							ostracod, seeds, lots of coccoons, no to minimal ppt
2.5 Y 5/1	vfU-fL							ostracods, white org, plant debris and two types of seeds detrital debris
2.5 Y 5/1	vfU-fL							similar to 23, lots of organics, but decline in ppt (3), ostracods, brown seeds, white org
2.5 Y 5/1	vfU-fL	sub angular to sub rounded	mod	massive	Detrital	Quartz, clay, muscovite, plagioclase, chlorite, gypsum	anhedral, needle, tabular, platy, fibrous	tons of debris, org matter, seeds, ostracod, detritals, some ppt of gypsum aragonite present
2.5 Y 5/1	vfU-fL							less org than above, seeds only, large gypsum crystals, allogenics
2.5 Y 4/1	vfU							a lot of ostracods, org seeds debris, allogenics, ppt of gypsum present
2.5 Y 5/1	vfU-fL							lots of organics, coccoons, ostracod grave yard, ppt of gypsum, good ostracod photo
2.5 Y 5/1	vfU							root debris, lots of seeds, no ostracod visible, increase in ppt (5) aragonite/ gypsum >20
2.5 Y 4/1	vfU-fL	sub angular to sub rounded	mod	massive	Detrital	Quartz, clay, muscovite, plagioclase, chlorite, biotite, aragonite	anhedral, platy, tabular, needle	seeds, ostracod present, ppt decline from above
2.5 Y 5/1	vfL							lots of seeds and ostracods, mod ppt, clays
2.5 Y 5/1	vfL							ostracods, little plant debris, mod crystallization of gypsum
2.5 Y 5/1	vfL							min org, low energy, heavy ppt >20, no ostracod visible
2.5 Y 5/1	vfL							same as above, no organics, mostly all ppt >20, defs drop in water level
2.5 Y 5/1	vfL	angular to sub angular	mod	massive	Detrital	Quartz, clay clusters, plag, muscovite, gypsum, aragonite, chlorite, biotite	anhedral, needle, fragmented, tabular	same as above, allogenics
2.5 Y 5/1	vfL							ostracod present, no plan debris visible, must be at a minimal, massive gypsum ppt gains
2.5 Y 6/2 and 6/1	vfU							everything, ostracods, coccons, seeds, allogenics present, decline in ppt
2.5 Y 6/2 and 6/1	vfU-fL							little plant debris, ostracods present, decline in clay, allogenics
2.5 Y 6/2 and 6/1	vfL-vfU							v little ostracods, seed present, heavy ppt of gypsum and aragonite >20,
2.5 Y 6/2 and 6/1	vfL	angular to sub angular	mod	massive	Detrital	Quartz, plag, muscovite, biotite, clays, gypsu, arg	anhedral, needle, tabular,	ostracods, very little plant debris, heavy ppt >20, same as above good pic of gypsum ppt
2.5 Y 6/2 and 6/1	vfL							little ostracod, no visible plant debris, mod ppt of aragonite and gypsum,lots of clay
2.5 Y 6/2 and 6/1	vfL							little ostracod, coccoons, no visible plant debris, mod ppt of aragonite and gypsum, lots of clay
2.5 Y 6/2 and 6/1	vfU							organic debris, ostracods, detritals, dropstones, pebble size,ppt still present, rise in energy
2.5 Y 6/2 and 6/1	vfU							organics incase from above, seeds, ostracods, v little ppt, detrital, rise in energy, still lots of clay
2.5 Y 6/2 and 6/1	vfU	angular to sub angular	poor	massive	Detrital	Quartz, plag, clays, chlorite, horneblende, muscovite, pyroxene, biotite, weird min	anhedral, tabular, needle, frags	organic decline from above, ostracod present, ppt >20
2.5 Y 6/2 and 6/1	vfL							very little org debris, no ostracod visible, so much ppt almost >40, clay
2.5 Y 6/2 and 6/1	vfL							no org debris, no ostracod, ppt high >20, gypsum, themadite and anhy, lots of clay
2.5 Y 6/2 and 6/1	vfL							same as above
2.5 Y 6/2 and 6/1	vfL							same as above
2.5 Y 6/2 and 6/1	vfL	sub angular to sub rounded	mod	massive	Detrital	Quartz, plag, muscovite, biotite, clays, chlorite	anhedral, needle, tabular	same as above, ostracod and coccons present
2.5 Y 6/2 and 6/1	vfL							same as above, no org debris, ppt >20
2.5 Y 6/2 and 6/1	vfL							same as above
2.5 Y 6/2 and 6/1	vfL							no org debris, ppt is still mod, few ostracod present, lots of clay, laminations with clay
2.5 Y 6/2 and 6/1	vfU							org debris roots and seeds, no ostracod, detritals, gypsum ppt present, lots of clay, allogenics
2.5 Y 6/2 and 6/1	vfL-clay	sub angular to sub rounded	mod	massive	Detrital	Quartz, plag, muscovite, biotite, chlorite, clays, pyroxene,olivine?	anhedral, needle, tabular	org seeds, coccons,ostracod, ppt mod, laminations with clay, lots of clay
2.5 Y 6/2 and 6/1	vfL-clay							org debris, ostracod, rise in ppt >20, prom crystals of gypsum
2.5 Y 6/2 and 6/1	vfL-clay							same as above
2.5 Y 6/2 and 6/1	vfL-clay							v little org seeds, ostracod present, mod ppt, lots of clay
2.5 Y 6/2 and 6/1	vfL-clay							no org debris, few ostracods, jump in ppt to >20
2.5 Y 6/2 and 6/1	vfL-clay	angular to sub angular	poor	massive	Detrital	Plag, Clays, muscovite, quartz, biotite, chlorite, gypsum, aragnoite	anhedral, tabular, needle, fibrous	no org debris, ostracods, mod to lil ppt (2-3, lots of clay still, but defs rise in energy
2.5 Y 6/2 and 6/1	vfL-clay							seeds and ostracods, decline in ppt, lots of clay, allogenics
2.5 Y 6/2 and 6/1	vfL-clay							seeds, ostracod, v little debris, same as above, lot of clay
2.5 Y 6/2 and 6/1	vfL-clay							no org, no ostracod, little rise in ppt from above, lots of clay
2.5 Y 5/2 and 5/1	vfL-clay							same as above,little to mod ppt, lots of clay
2.5 Y 6/2 and 6/1	vfL-clay	angular to sub angular	poor	massive	Detrital	Quartz, Clays, muscovite, plag, biotite, chlorite, aragnoite, gypsum	anhedral, tabular needle, frags	ostracod and cacoons, v little ppt, lots and lots of clay, almost look like ooids are back

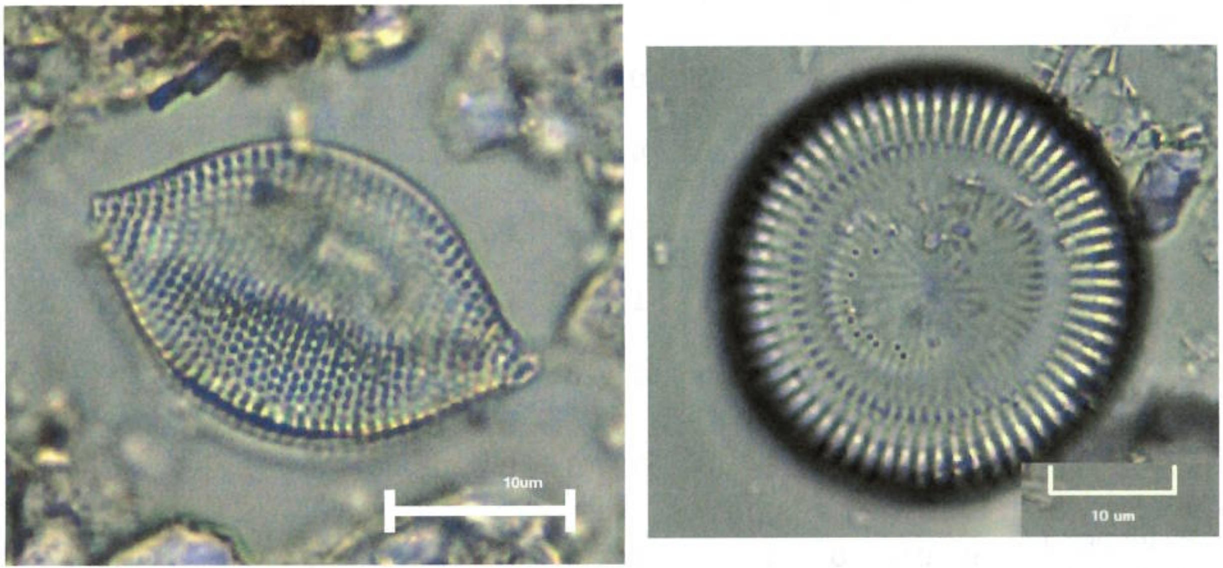
Appendix D: Diatoms

Table D.1. Counts of Diatoms taxa from 0 to 65cm.

Diatoms						De	pth								
Name	1	3	5	10	15	20	25	30	35	40	45	50	55	60	65
Cyclotella cf. atomus	6	7	15	8	6	0	4	4	3	5	5	0	0	0	3
Cyclotella meneghiniana	69	60	77	70	47	2	58	21	24	91	157	120	132	75	71
Cyclotella quillensis	86	96	183	140	61	8	60	16	131	170	110	236	266	182	254
Pseudostaurosira subsalina	15	23	27	40	173	256	156	242	112	20	17	0	0	0	0
Fragilaria capucina	0	0	0	1	1	3	0	0	0	0	0	0	0	0	0
Fragilaria capucina var. vanchariae	1	0	0	0	4	0	3	0	0	0	0	0	0	0	0
Fragilaria cf. pinnata	6	0	0	8	9	0	7	5	1	0	5	0	0	0	0
Nitzschia brevissima	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0
Nitzschia compressa	2	0	2	1	16	6	9	6	2	1	11	8	0.5	122	0
Nitzschia frustulum	12	14	9	16	12	37	26	32	18	6	9	0	0	1	0
Nitzschia palea	117	121	40	29	24	56	39	6	32	33	28	0	0	0	17
Nitzschia paleacea	11.5	9	4	5	7	11	7	12	8	10	1	0	0	0	0
Chaetoceros elmorei cyst	62	44	35	68	20	6	27	47	53	27	43	15	9	26	62
Mastologia cf. elliptica	0	0	2	0	0	0	0	0	0	0	0.5	1	0.5	0	0
Tryblionella hungarcia	2	2.5	7	8	7	2	2	2	0	3	8.5	1	0	1	0
Tryblionella opiculata	3	3.5	3	2	1	0	0	0	0	0	2	0	0	0	0

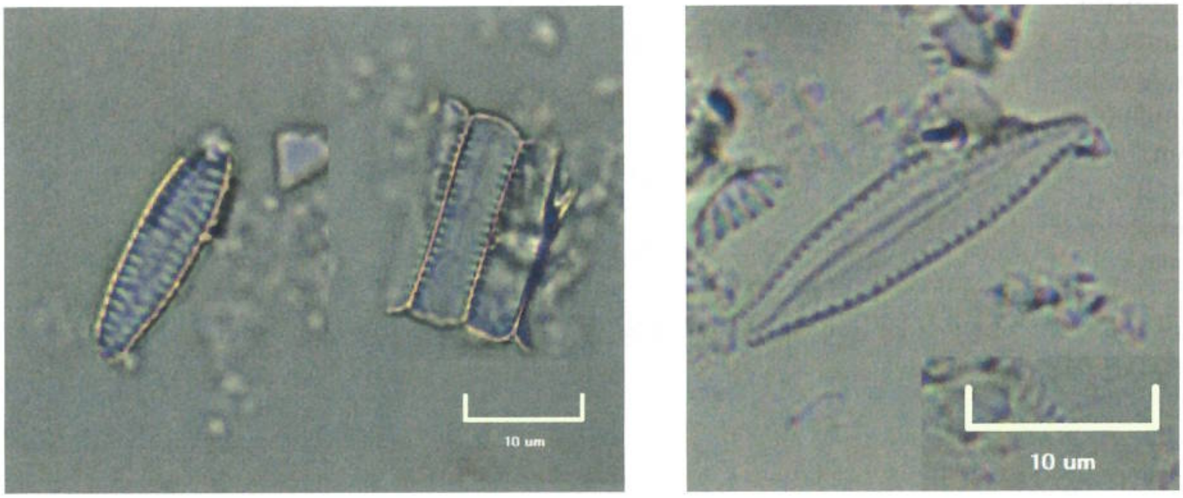
Anomoeoneis sphaerophora	0	0	1	0.5	0	0	0	0	0	0	0	0	0	0	1
Tabularia sp. 1	3	2	2	2.5	2	1.5	0	0	0	0	0	0	0	0	0
Navicula veneta	3	5	0	0.5	1	1	1	0	0	5	0	0	0	0	0
Navicula vulpina	0.5	0.5	1	1	0	0	0	0	0	4	0	0	0	0	0
Surirella brebissonii	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Surirella lowensis	1	0	1	2	1	0	0	0	0	0	2	0	0	0	0
Surirella striatula	2	3	5	1	5	1	1	0	2	2.5	3	5.5	1.5	2	0
Caloneis bacillum	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Planothidium cf. lanceolatum	5	8	5	3	0	0	0	0	0	0	0	0	0	0	2
Pleurosigma elongatum	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0.5
Rhoicosphenia curvata	0	0	0	0	0	5	0	5	0	1	3	6	0	0	0
Eunotia sp. 1	1	0	0	0	0	0	0	1	2	0	0	0	0	0.5	0
Hantzschia amphioxys	0.5	0	0	1	2	0	1	1	1	0	0	0	0	0	0.5
Amphora cf ovalis	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Amphora cf salina	3	1	0	0	1	0	0	0	3	0	0	1	0	0	0
sum	413	400	419	407	402	395	401	400	393	378	405	393	409	410	411

Figures D.2. Photos of dominant diatom species of the Big Quill Lake.



Nitzschia compressa

Cyclotella quillensis



Pseudostaurosira subsalina

Nitzschia palea