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Geochemical Flux Analysis of Glacial River Runoff for Sólheimajökull, Iceland

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GEOCHEMICAL FLUX ANALYSIS OF GLACIAL RIVER RUNOFF FOR SÓLHEIMAJÖKULL, ICELAND

A Capstone Experience/Thesis Project Presented in Partial Fulfillment

of the Requirements for the Degree Bachelor of Science

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at Western Kentucky University

By

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ABSTRACT

Geochemical fluxes in aqueous studies are an essential component of research to understand weathering and changes in a hydrologic system. These data can indicate any discrepancies, outliers, or gradual changes in a water environment to gain information on pollutants, carbon cycles, biological input, etc. Glacial melt is the majority of the surface water present throughout the country. The melting amount is increasing with the temperatures, which can be monitored by the changes in geochemical flux during increased discharge in glacial rivers. A high-resolution data set of Sólheimajökull Glacier in Iceland was used to determine how changing climatic conditions for the region affected glacial meltwater. This dataset was collected from October 3-5, 2019. Four sites were measured every two hours for six hours total. The four sites included the glacier tongue, a site half the distance to the proglacial lake, a site where the glacier feeds into the river, and a site about two km downstream. Temperature, pH, alkalinity, specific conductivity, turbidity, total dissolved solids, and total suspended solids were measured. Partial pressure of CO_2 (pCO_2) and dissolved inorganic carbon (DIC) were calculated. The fluxes in these parameters and historical data provide insight into how the glacier is responding to warming temperatures and affecting the landscape's geomorphology and indicates how they may respond to continued warming. The results showed a pattern of continuous dilution of the measurements as precipitation increased throughout the sampling period. A slight, overall increase in DIC and pCO_2 was also seen downstream from the glacier. Due to the precipitation, warmer waters could be releasing more CO_2

and be indicative and higher erosion rates. The small dataset and unusual conditions only allow for limited interpretation.

ACKNOWLEDGEMENTS

I would like to thank my advisor Dr. Jason Polk for all his help through this project. He organized the trip itinerary, transportation, and more to ensure that the project went smoothly while I was on my own. The collection process changed on a daily basis, and his constant communication despite different time zones allowed for data to still be collected. I would also like to thank him for allowing this project to exist. The planning and funding for research changed multiple times throughout its initiation, yet he continued to pursue it with me.

I would also like to thank my peers Mariah Slaughter and Abby Preston along with others. They spent hours editing and being a soundboard for this thesis over the last year, providing any support needed. Finally, I would like to thank Dr. Leslie North and students Cara Walters and Natalie Kincheloe for assistance and accompanying me in Iceland to conduct the fieldwork and data collection for this project.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

Climate change is one of the most discussed topics in modern society. As climate change begins to impact Earth's systems, it will continue to be discussed more often as society tries to find a way to slow down or even reverse the effects. The International Panel on Climate Change (IPCC) reports that an increase in temperature of 1.5 degrees Celsius will have significant ramifications and the next step is to work towards living within the remaining CO_2 budget and reducing greenhouse gas emissions (Hoegh-Guldberg et al. 2019). Innovation and research are required to determine the current extent of climate change effects and how to mitigate them.

Arctic regions are at high risk, due to Arctic amplification (National Snow and Ice Data Center, n.d.), which is a positive feedback loop that increases their rate of warming. An example would be the increase of ice melting in the summer due to higher temperatures exposing more land and sea to be warmed. This causes further ice melt, or a longer cooling time in the winter, preventing more ice production. Iceland, in particular, has seen a large amount of ice melt from the increased temperatures. Berkeley Earth (n.d.) shows that Iceland's mean daily high and mean daily low temperatures have increased by almost 1.5 degrees Celsius since the Industrial Revolution as of 2010 and have continued to rise. The country has already reached the projected "point of no return" stated by the IPCC. It will continue to warm along with the rest of the world. Glaciers in Iceland cover 10% of the country and have already lost 2,100 km^2, where about 700 km^2

of loss has occurred since 2000 (Iceland Met Office, n.d.). A primary cause of this is the reduced snow accumulation in winter from Arctic amplification feedback systems.

The objective of this thesis is to determine the amount of carbon present along Sólheimajökull's glacial runoff river due to melting caused by global warming. The relation of carbon flux to the glacial melting can be used as a proxy for the amount of CO_2 being released into the atmosphere as glaciers are retreating.

LITERATURE REVIEW

Iceland Climate

Iceland is a small island located between longitudes 13°29.6’W and 24°32.1W and latitudes 63°23.4’N and 66°32.3’N (Denk et al. 2011). This location has placed it at the crossing of polar and some tropical air masses. This has led to an unstable climate and weather systems. The annual mean temperatures range from -0.6°C and 10.8°C in the coldest and warmest months of the year, respectively (Denk et al. 2011). Precipitation amounts fluctuate from 40 to 500 mm/month, with higher precipitation in the winter than the summer, particularly in the southern region (Iceland Met Office n.d.).

Iceland’s temperatures have slowly been rising since the early 1900s. It had a warming period above average in the 1930s, and again in the past few decades (Hanna et al. 2004). These trends also show a considerable temperature rise during Autumn, with the warmer weather lasting longer than previous summers. Iceland has not typically followed the temperature trends of the overall Northern Hemisphere, due to the North Atlantic oscillation. The current warming period mentioned has caused increased temperatures similar to the rest of the world.

Iceland Geology

Iceland is a relatively young and volcanically active island. It is located on top of a mantle plume along the Mid-Atlantic Ridge and the GSTR (created from the mantle plume at the plate boundaries) (Denk et. 2011). This has led to active faulting and extensive tectonic features, such as volcanic fissures. The bedrock consists of young volcanic material from Miocene to Holocene in age. The rock is volcanic in origin, mainly basaltic and rhyolitic. These are both extrusive rocks but with significantly different compositions. Basalts are mafic and have significant amounts of magnesium and iron with lower silica content. Rhyolites are felsic with a lot of feldspar and silica. Their silica content is much higher and they are generally lighter from trapped gases reducing their mass.

Basalts are the majority of the rock present, though, and have the most substantial effect on the composition of glacial waters. These basalts range in type. The main ones are low potassium, high magnesium basalts, iron-titanium basalts, and olivine tholeiites (Oskarsson, 1994). Tholeiites are similar to basalts but have a higher concentration of iron. Due to the composition of basalt, there is little place for carbon to go in the main crystal structures, so they instead form secondary minerals, often form calcite for carbon storage. Basalt is extremely effective at this; Iceland has been using it for carbon sequestration to capture the excess CO_2 in the atmosphere (Daniel, 2019).

The process of basalt weathering itself is a portion of the carbonate weathering in Iceland. These calcium-bearing minerals contain a vast store of carbon in the geologic record. Studies have been done to trace this calcium to correlate to the associated carbon within the minerals and erosion rates (Jacobsen et al., 2015). They have shown that roughly 90% of calcium in Icelandic rivers is from the weathering of hydrothermal calcite, as opposed to the weathering of silicate minerals. The weathering of these minerals releases calcium, which will then stabilize again through the hydrothermal conditions. The increased geothermal activity from sitting on active calderas heats the water and affects the weathering and equilibrium. The mineral content in the water will then rise, increasing the amount of CO_2 present. With rising temperatures, a "more vigorous hydrologic cycle" will occur (Jacobsen et al. 141. 2015). A higher rate of silicate weathering will begin, and hydrologic conditions might not permit the crystallization of calcite, releasing more CO_2 in the rivers and eventually the oceans and atmosphere.

The hydrologic conditions mentioned are already complicated due to the volcanic and tectonic nature of Iceland. The mountains present from glacial movement create shorter response times during storm events and a higher discharge in general. Some of the most significant factors affecting the water volume are snowmelt and the volcanic regions present, causing the ability for river discharge to increase by almost ten times (Ros and Mouri, n.d.). River discharge in these regions has been affected by the warming temperatures, increasing the volume of meltwater as well as tectonic activity. Glacial rivers in Iceland have an average annual mean discharge of 100 m^3/s (Adalsteinsson et al., 2000). River discharge varies through the seasons, but summers with warmer temperatures have higher discharge rates.

Glaciers

With Iceland's unique geologic conditions with increased volcanic and tectonic activity, glaciers have shown some of the earliest effects of a warming climate and have continued to have increased effects as the temperatures increase. The largest effect is glacial melting and retreat. The glaciers in Iceland have been in retreat since the 1990s

(Bradwell et al. 2013). This indicates a lack of equilibrium in the glaciers, since they are not replenishing what they lose in ice volume.

Glacial equilibrium has been measured through mass-balance and dynamic models (Jóhannesson 1997). Mass-balance models find a glacier's mass through altitude, temperature, and precipitation. Dynamic models view glaciers as one-dimensional flow systems. The more relevant aspect of these models is their computation of glaciers' response time to changes in climate. At this current rate, Tomas Jóhannesson (1997), in his research on two Icelandic glaciers' response times, has concluded that it will take roughly 100 years to reach equilibrium if the temperature remains steady for multiple decades. He also states that this will cause glacier volume to reduce by 40%. As their volume is reduced, the discharge will increase by almost 25% (Aðalgeirsdóttir et. 2006).

Glaciers are a primary concern for sea-level rise due to this amount of melting that will possibly occur globally, leading to flooded cities and neighborhoods. Along with this, flooding of the immediate surroundings is possible. Some farms and residences are located near glaciers that would potentially have to relocate entirely from the amount of drainage.

As they retreat, many southern glaciers have formed proglacial lakes, or their lakes have increased in size. This relates to the increased discharge amounts from glacial melting. The size of lakes has not only grown, but flow velocities are increasing along with calving activity (Dell et al. 2019). This will lead to more glacial retreat as well as chemical weathering. More area of rock has been exposed to result in weathering, also with more vigorous weathering from increased velocity. The immediate vicinity of a glacier is the most chemically reactive and with more exposure, this vicinity will continue to grow (Nowak and Hodson 2014).

Carbon Cycling

The carbon cycle is where carbon is stored and released in its many forms. As a greenhouse gas, CO_2 had increased rates of release are a substantial cause of the warming climate. It flows between reservoirs in the atmosphere, ocean, and land; the atmosphere has been the most significant issue when trapping heat (Riebeek 2011). It is not uncommon for increased temperatures to occur as the Earth itself will cycle carbon naturally. Urey's reaction dictates that carbon degassing and return to carbon-silicate rocks is one of the most extensive effects on Carbon in the atmosphere (Berner et al. 1983). Mostly, carbon is released from the ground during volcanic activity and slowly is reincorporated into carbon-silicate rocks, and then burial will return the rock to magma to repeat the process. This is the main effect in Iceland, which is 100% volcanic in origin. Iceland has a higher than average number of volcanoes for its size, which will then degas more often than other regions. Urey's reaction also indicates that "very slight imbalances in an otherwise steady-state cycle can lead to rapid changes" (Berner et al. 1983). The increased amount of CO_2 in the atmosphere from anthropogenic sources has created an imbalance that has led to increased temperatures.

Glaciers are also a sink for carbon, both organic and inorganic. Organic carbon comes from the microorganisms and the surrounding flora that enters the ice. In a study conducted on the amount of organic carbon in glaciers, it was seen that glacier runoff globally sees 1.04 +/- 0.18 TgC per year (Hood et al. 2015). Glaciers in Iceland do contain a fair amount of organic carbon, but a significant portion is due to inorganic carbon. The sources of inorganic carbon vary. Southern and western Iceland glaciers contain CO_2 from mantle degassing in high and low-temperature waters. Glaciers that are further off-rift have lower values from fractionation of minerals (Stefánsson 2017). Using the Urey reaction example, inorganic carbon is also entering the glacier through leaching of the basalt rock (Sveinbjörnsdóttir et. al). Southern lowland springs see a higher amount of carbon from the basalt present being weathered. All of the sources of carbon are combined to produce the total amount within a glacier.

Glacial carbon cycling is unique in and of itself. The seasonal redox that occurs with the glaciers helps to drive the weathering of basalt, releasing more carbon (Burns 2016; Quiroga 2018). This type of chemical weathering is the largest source of carbon for the glacier. This occurs through leaching out of the basalt as well as the chemical break down of rock over time.

The chemical weathering can be increased through geothermal sources. Some Icelandic glaciers, such as Sólheimajökull, and ice sheets are located directly on top of, or very close to, geothermal heat sources. This will often continue to cause an increased weathering rate from the ice and a higher internal drainage rate from melting (Jacobsen et al, 2015). Glaciers such as Sólheimajökull in southern Iceland will release H_2S with its distinctive smell, indicating that geothermal activity has occurred recently.

Glaciers also have a distinctive solute chemistry. They can be differentiated from nonglacial rivers and have different mineral weathering reactions (Torres et al. 2017; Tuladhar 2017). The proportions of the various weathering conditions can be reflected in the solute amounts in the glacial waters. With this, carbon is primarily seen in glacial waters in comparison to nonglacial source, which would potentially create a negative feedback preventing colder conditions. In the larger geologic cycles, this is a beneficial response to help prevent ice ages and helping to create a warmer Earth. With the current issue of climate change, it is doing the opposite of what researchers are attempting to cool the earth. This has revolved back to the positive loop to increase warming. As the glaciers are melting and releasing more carbon through myriad sources, the temperature is continuing to increase. The monitoring of this amount of carbon will continue to indicate the effect on glaciers and the planet.

STUDY AREA

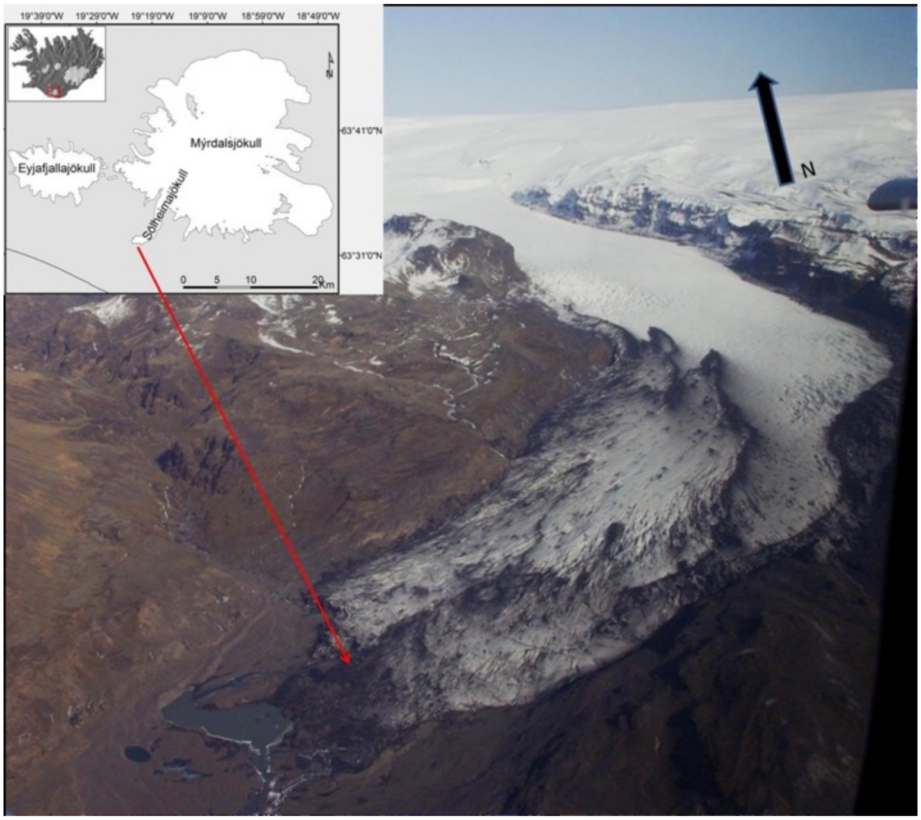


Figure 1. Map of Sólheimajökull in relation to the Mýrdalsjökull ice sheet. (Geocaching, n.d.).

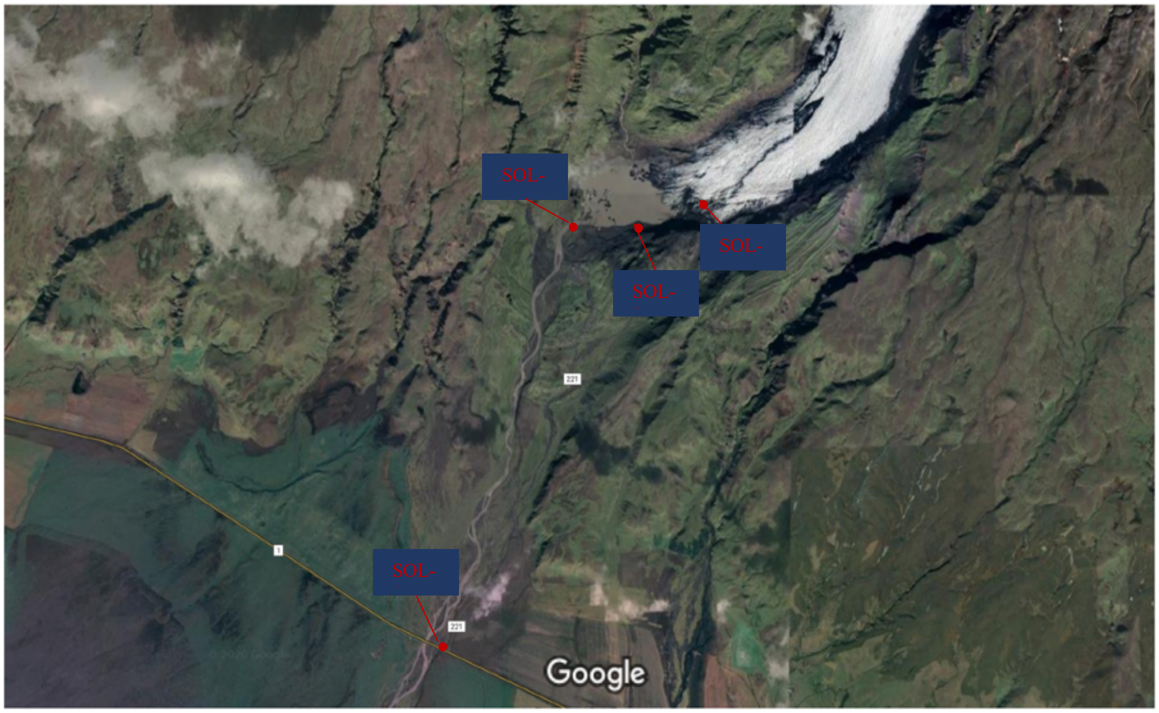
Sólheimajökull is an outlet glacier for the Mýrdalsjökull ice sheet (Figure 1). It is located in southern Iceland, where temperature and precipitation are increasing. This response is also due to the climate of southern Iceland, which is fairly mild with few seasonal variations from the oceanic currents surrounding the coasts with temperatures averaging between 0^{o} C and 11^{o}C (Einarsson 1984). This is combined with high precipitation amounts in southern Iceland, measuring at 1000 to 4000 mm/yr (Hannesdottir et al. 2013). These factors affect the growth and retreat of Sólheimajökull's ice mass.

Iceland is a geologically young island as most of its formation is due to recent volcanism from the Miocene to present (Tuladhar 2017). Formations formed from lava flows and explosive volcanic events are present, with the majority of exposed rock being basaltic lava flow. This is paired with volcanic intrusions and fault systems from the Mid-Atlantic Ridge that transects the island. Active spreading and plumes along the ridge create many dike and fault systems which expose the surface to increased geothermal energy and events (Einarsson 2008).

Sólheimajökull is situated closely to an active volcanic system. The Mýrdalsjökull ice sheet sits on top of the Katla caldera, a volcano that is still active. The glacier has been retreating at a mean rate of 40 m/year for over a decade (Staines et al. 2014). Some of the retreat has been attributed to the jökulhlaup (glacier flood outburst) caused by the surrounding volcanic system in the late 1990s. The glacier's proximity to Katla is considered a factor to its rapid retreat rate. The increased temperatures of the climate have also resulted in increased volcanic activity, meaning the glacier will be more affected by climate change (Mackintosh 2000). As the glacier sits on the Katla caldera, the effects of increased volcanic activity can cause increase melting. An indicator of the volcanic activity is the persistent sulfur smell released from the meltwater (Wynn et al. 2015). Volcanic-induced melting has led to a higher thinning rate than other glaciers in the country. It was 40 m thinner than average in 2000 and has continued to thin with the calculated rate (Schomacker et al. 2012).

The volcanic systems present and the high precipitation rates of Southern Iceland greatly affect the draining river present at Sólheimajökull, Jökulsá á Sólheimasandi (Schomacker et al. 2012). The glacial valley has a high gradient that increases velocity during rain and melting events, which leads to higher rates of weathering and erosion. The basalts present can form a CO_2 sink. Higher weathering rates will release the CO_2 present into the river where they can be monitored. Southern Iceland has recorded higher precipitation amounts and larger melting events in recent years that lead to increased CO_2 measurements from the river.

METHODOLOGY



Imagery ©2020 CNES / Airbus, Landsat / Copernicus, Maxar Technologies, U.S. Geological Survey, Map data ©2020 2000 ft

Figure 2. Map of Sólheimajökull glacial river and sampling locations. (Google, n.d., modified by author).

Sampling locations were decided to be at the glacier itself, the midway point of the glacial lagoon, and headwaters where the river and lagoon meet, then four km downriver at an access point by the road bridge. These sampling locations allowed for shorter sampling intervals that allowed for less time in between samples. A sample was collected from each site every two hours starting at 10:00 and finishing before 16:00. On October 3 and October 4, 2019, three rounds of data were collected. October 5 did cause an issue due to a storm. The river has a very high flow velocity and high winds of 60+ kmph. The wind gusts were at this speed every day, but on October 5, it was persistent.

After one round of sampling, it was determined to be unsafe to sample. The decision was made along with the local tours deciding to cancel.

At each sampling point, 100 mL of water was collected from the shoreline in a beaker. The temperature (Celsius), pH, conductivity (µS/cm), total dissolved solids (ppm), and salinity (ppm) were collected first with a handheld YSI ProDSS Multiparameter Sonde. This method is done by collecting 10 mL of the sample into the small cap for the machine. The Sonde's probes are then placed into the sample where they measured all five variables. The equipment was rinsed between each sample to ensure the quality of data.

A colorimeter was then used to measure the turbidity and suspended solids of the sample. A deionized (DI) water blank was measured before each reading for this sample. This standardized the data. The same DI water was used for all samples. The water samples could then be measured by the colorimeter. During sampling, there were continuous rain events that created very high reading for turbidity and suspended solids alike. Some were too high to be read by the colorimeter. For those samples, DI water was then used to dilute the water to record an actual measurement. This was done in increments of 5, 10 and 20 mL as needed and was marked with the data. In select cases, the dilution still did not produce a reading. The glass tubes would then have to be rinsed between each sample collected. In some cases, the slot to enter the tube would also have to be rinsed. The wind would move sediment, and some would enter the machine. This would be rinsed to remove as much sediment as possible.

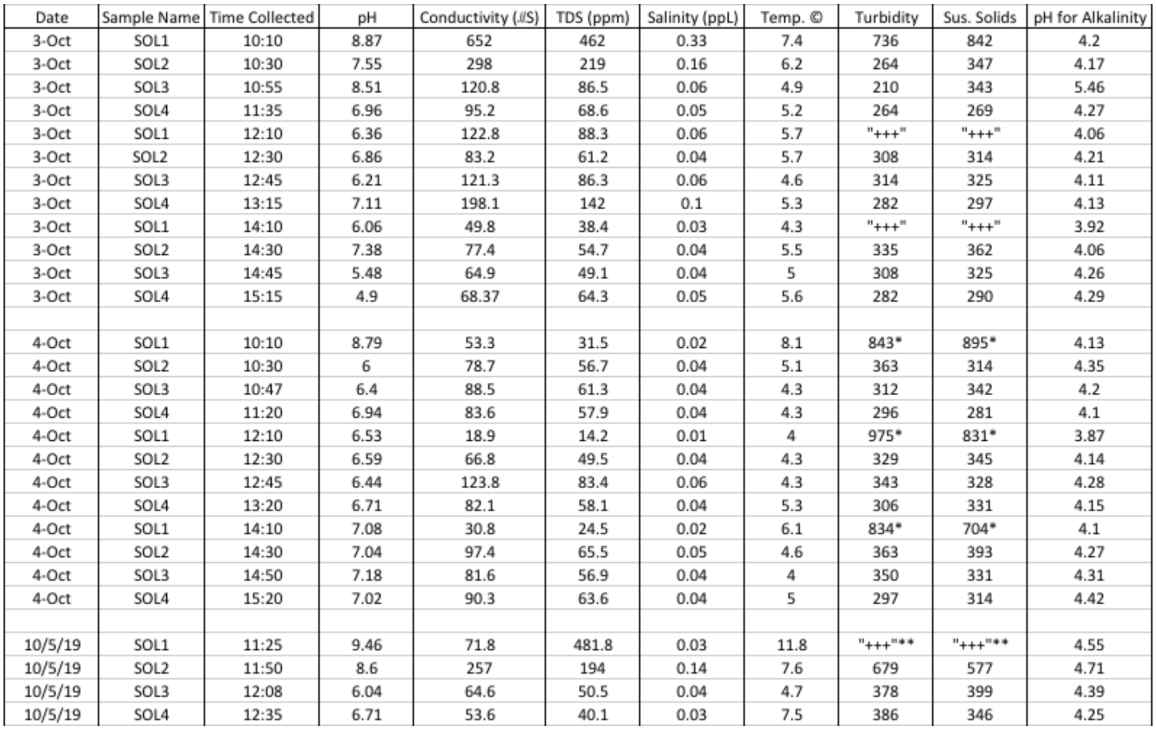
The final measurement collected was the alkalinity of the water. Using the 50 mL of sample left from the previous tests, 5 mL of alkalinity titration solution was added and was stirred until mixed. The Sonde was then used again to get another pH reading. These measurements were then converted to alkalinity post-collection using a conversion chart. The equipment was rinsed again before the next sample collection.

The THINCARB (Thermodynamic modeling of Inorganic Carbon) data sheet was used to calculate the dissolved inorganic carbon (DIC) present in the water. The program allowed for the raw data to be entered for various calculations. For this project, the PCO_2 (partial pressure of carbon dioxide compared to atmospheric background) was calculated, along with the DIC concentration. PCO_2 gives a value for the amount of CO_2, or dissolved carbon, present in the samples and can be used along with the DIC for overall trends of the carbon flux in the glacial river during the sampling period. The relationship between alkalinity and pH is largely how levels of carbon in water can be determined. Alkalinity is a measurement based on carbonate and bicarbonate ions present, directly related to the amount of carbon dioxide and sources of carbon in the water. The interaction of CO_2 and rock results in the release of hydrogen ions (Boyd, 2000). Thus, the pH and alkalinity are proportional to carbon dioxide content, allowing for calculations between them to determine dissolved inorganic carbon (DIC) and CO_2.

The method of sampling also could be the source of potential issues with this dataset. There were no access roads to the sampling sights, so all data were collected in the open during continuous storms. This allowed more rain to enter the sample while the equipment was used, as well as exposing to equipment to the weather conditions. Along with exposed conditions, there was likely human error involved. The equipment was rinsed with river water between each sample, but there is the possibility that the alkalinity titration solution was not fully removed and affected pH readings. The results were analyzed with these possibilities in mind.

RESULTS AND DISCUSSION

Table 1. Raw Data Collected from Sampling Sites. Symbol (*) means the sample was diluted with 10 mL DI Water. Symbol (**) means diluted with 25 mL. Symbol (+++) is the symbol was diluted but sample had too high a content to be read.



Date	Sample Name	Time Collected	pH	Conductivity (µS)	TDS (ppm)	Salinity (ppL)	Temp. ©	Turbidity	Sus. Solids	pH for Alkalinity
3-Oct	SOL1	10:10	8.87	652	462	0.33	7.4	736	842	4.2
3-Oct	SOL2	10:30	7.55	298	219	0.16	6.2	264	347	4.17
3-Oct	SOL3	10:55	8.51	120.8	86.5	0.06	4.9	210	343	5.46
3-Oct	SOL4	11:35	6.96	95.2	68.6	0.05	5.2	264	269	4.27
3-Oct	SOL1	12:10	6.36	122.8	88.3	0.06	5.7	"+++"	"+++"	4.06
3-Oct	SOL2	12:30	6.86	83.2	61.2	0.04	5.7	308	314	4.21
3-Oct	SOL3	12:45	6.21	121.3	86.3	0.06	4.6	314	325	4.11
3-Oct	SOL4	13:15	7.11	198.1	142	0.1	5.3	282	297	4.13
3-Oct	SOL1	14:10	6.06	49.8	38.4	0.03	4.3	"+++"	"+++"	3.92
3-Oct	SOL2	14:30	7.38	77.4	54.7	0.04	5.5	335	362	4.06
3-Oct	SOL3	14:45	5.48	64.9	49.1	0.04	5	308	325	4.26
3-Oct	SOL4	15:15	4.9	68.37	64.3	0.05	5.6	282	290	4.29
4-Oct	SOL1	10:10	8.79	53.3	31.5	0.02	8.1	843*	895*	4.13
4-Oct	SOL2	10:30	6	78.7	56.7	0.04	5.1	363	314	4.35
4-Oct	SOL3	10:47	6.4	88.5	61.3	0.04	4.3	312	342	4.2
4-Oct	SOL4	11:20	6.94	83.6	57.9	0.04	4.3	296	281	4.1
4-Oct	SOL1	12:10	6.53	18.9	14.2	0.01	4	975*	831*	3.87
4-Oct	SOL2	12:30	6.59	66.8	49.5	0.04	4.3	329	345	4.14
4-Oct	SOL3	12:45	6.44	123.8	83.4	0.06	4.3	343	328	4.28
4-Oct	SOL4	13:20	6.71	82.1	58.1	0.04	5.3	306	331	4.15
4-Oct	SOL1	14:10	7.08	30.8	24.5	0.02	6.1	834*	704*	4.1
4-Oct	SOL2	14:30	7.04	97.4	65.5	0.05	4.6	363	393	4.27
4-Oct	SOL3	14:50	7.18	81.6	56.9	0.04	4	350	331	4.31
4-Oct	SOL4	15:20	7.02	90.3	63.6	0.04	5	297	314	4.42
10/5/19	SOL1	11:25	9.46	71.8	481.8	0.03	11.8	"+++"**	"+++"**	4.55
10/5/19	SOL2	11:50	8.6	257	194	0.14	7.6	679	577	4.71
10/5/19	SOL3	12:08	6.04	64.6	50.5	0.04	4.7	378	399	4.39
10/5/19	SOL4	12:35	6.71	53.6	40.1	0.03	7.5	386	346	4.25

The data were collected in October 2019 over the course of three days to measure the changes in carbon levels along the river. The data collected in this study represent standard measurements for water quality and geochemical composition. The main variables analyzed were pH, alkalinity, temperature, specific conductivity, total dissolved solids, and turbidity. These were collected on-site at the various times seen in Table 1. The data were interpreted and used to calculate other measurements for the water samples. The partial pressure of CO_2 in the atmosphere (pCO_2) is the measurement that was used to determine carbon levels, while the others provide information for the general geochemistry of the glacial outlet river.

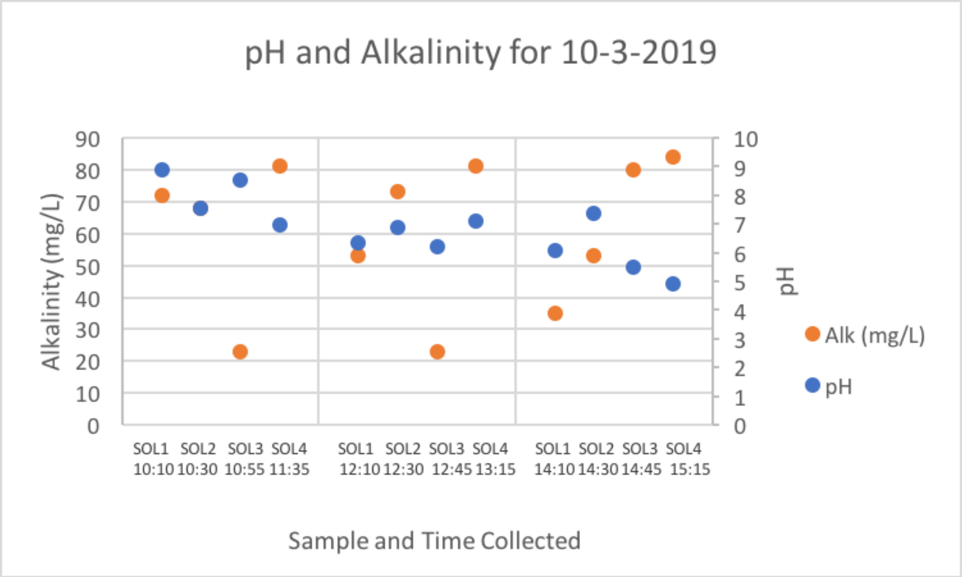


Figure 3. pH and Alkalinity measurements for 10-3-2019. Source: author

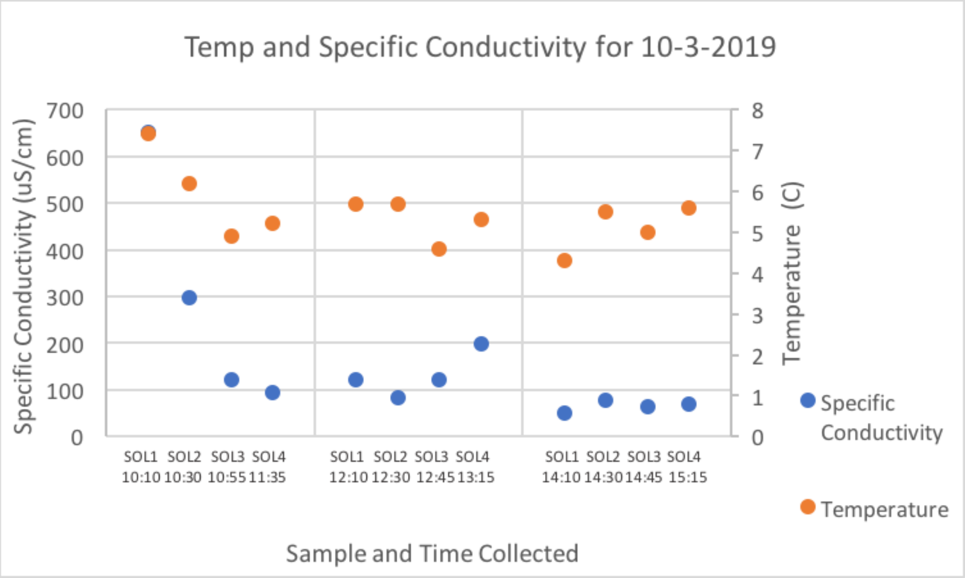


Figure 4. Temperature and Specific Conductivity measurements for 10-3-2019. Source: author

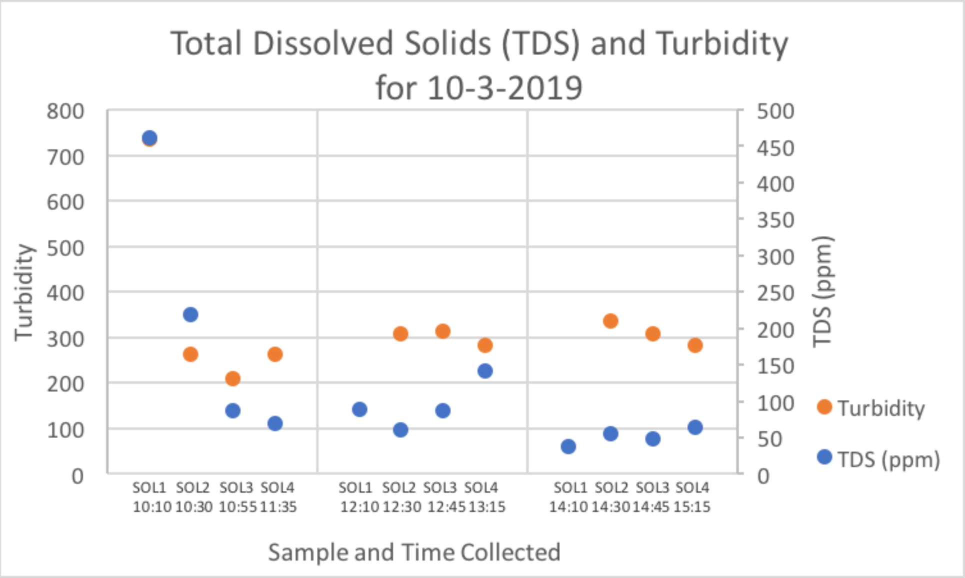


Figure 5. Total Dissolved Solids and Turbidity (NTUs) measurements for 10-3-2019. Source: author

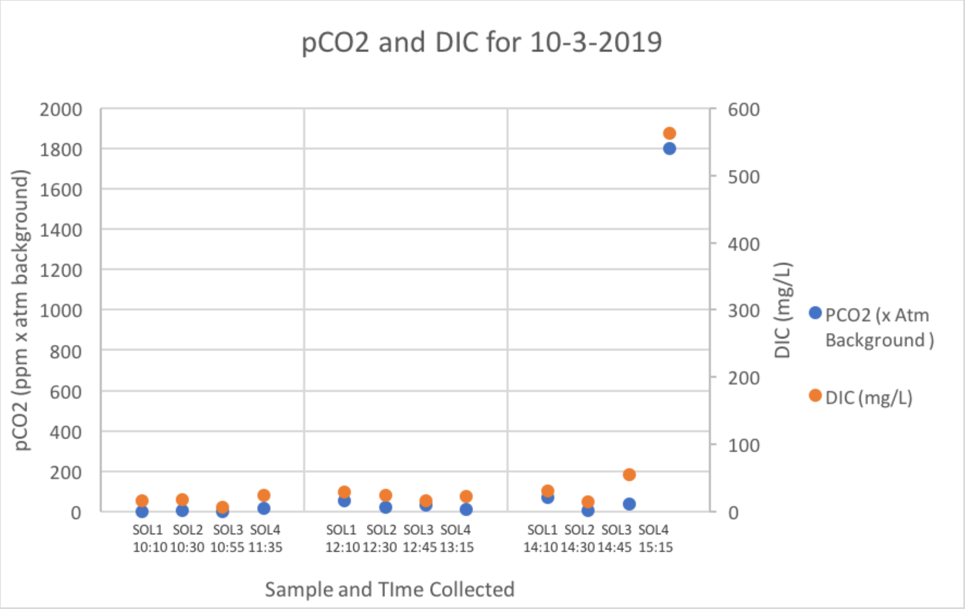


Figure 6. Carbon measurements of pCO_2 and Dissolved Inorganic Carbon (DIC) for 10-3-2019. Source: author

Figures 3 through 6 show data for 10-3-2019. Weather conditions for this day had temperatures around 13°C and consistent rainfall starting slightly before the first sample was collected, which continued throughout the collection period. This is the cause for the high variability in data, specifically seen in Figure 3. While the alkalinity showed no pattern, but there is a consistent decrease in pH throughout the day. This is likely from additional melt pulses as the warmer precipitation interacted with the glacier. The meltwater could be releasing more CO_2 along with other trapped gases. Some readings were much lower than others, almost as outliers. The rate of precipitation, sampling locations, water volumes, etc. could have led to these results. Another possibility is a lack of data; only three rounds of sampling were plausible with the time and resources available. Trends with alkalinity could potentially be seen in larger datasets if fieldwork had permitted.

Dilution of the river and, thus, the water samples is an explanation for multiple patterns seen in the results. In Figure 4, conductivity had a steep decrease at the beginning of the day and eventually plateauing during the third round of sampling. Figure 5 shows a similar occurrence for TDS and turbidity. Conductivity and TDS are both affected by the number of dissolved ions and solids in the water. Large amounts of rain would dilute the water and lower the concentration of dissolved species. Turbidity is often related to both as the speed and flow of the water affects how much sediment can be suspended versus how much will settle out. High turbidity often indicates more suspended sediment and results from higher velocity water.

PCO_2 and DIC were fairly steady and roughly equal throughout most of the day. In SOL4 15:35, the values are high, with pCO_2 being extremely higher than any other value. This would be caused by the increase in alkalinity. Temperature, pH, and alkalinity are all factors for calculating the amount of carbon in water (Boyd, 2000). So, an increase in alkalinity is proportional to an increase in CO_2. Though, the alkalinity is not much higher than morning samples. The rainfall could account for this increase. Higher TDS levels and turbidity would allow for more calcium to enter the water, causing an increase in alkalinity and therefore, carbon.

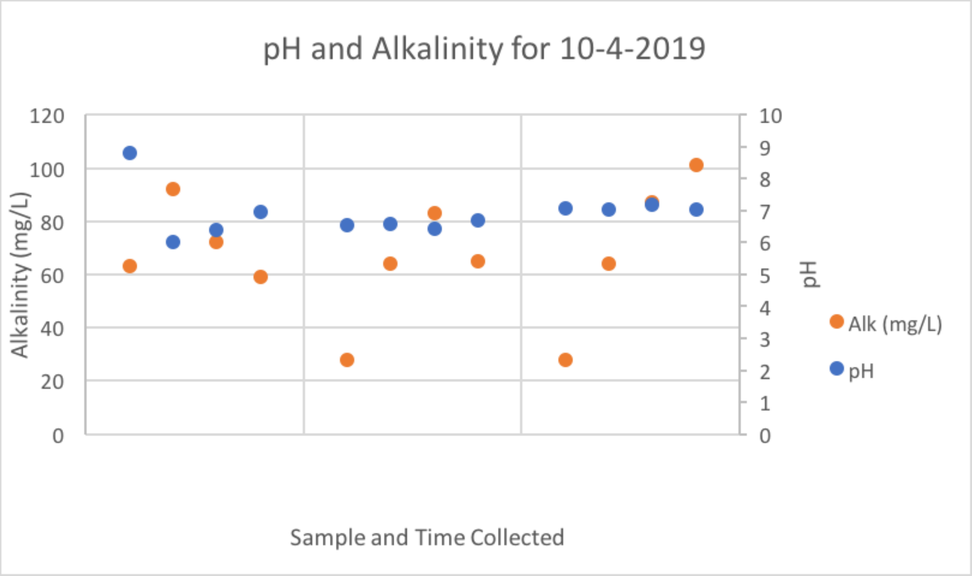


Figure 7. pH and Alkalinity Measurements for 10-4-2019. Source: author

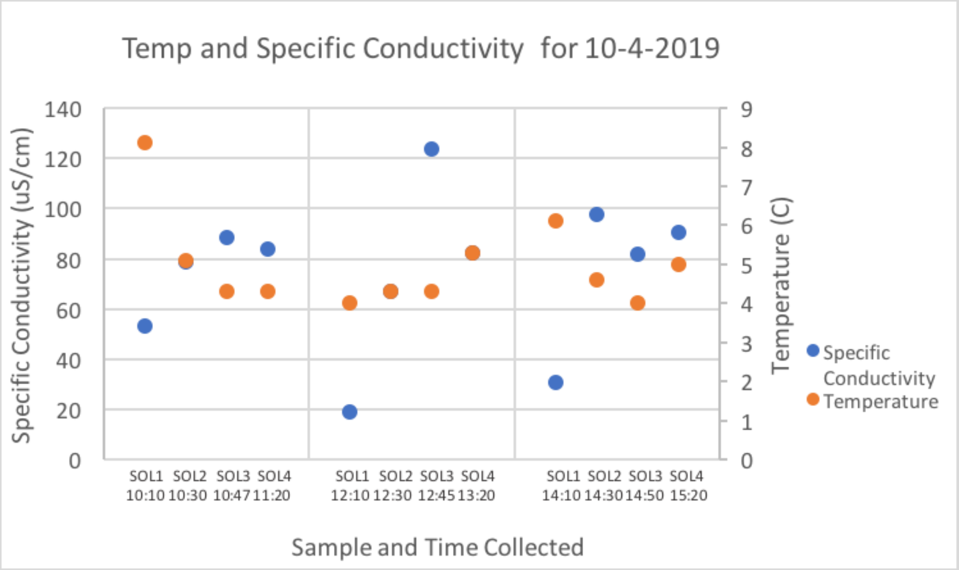


Figure 8. Temperature and specific conductivity measurements for 10-4-2019. Source: author

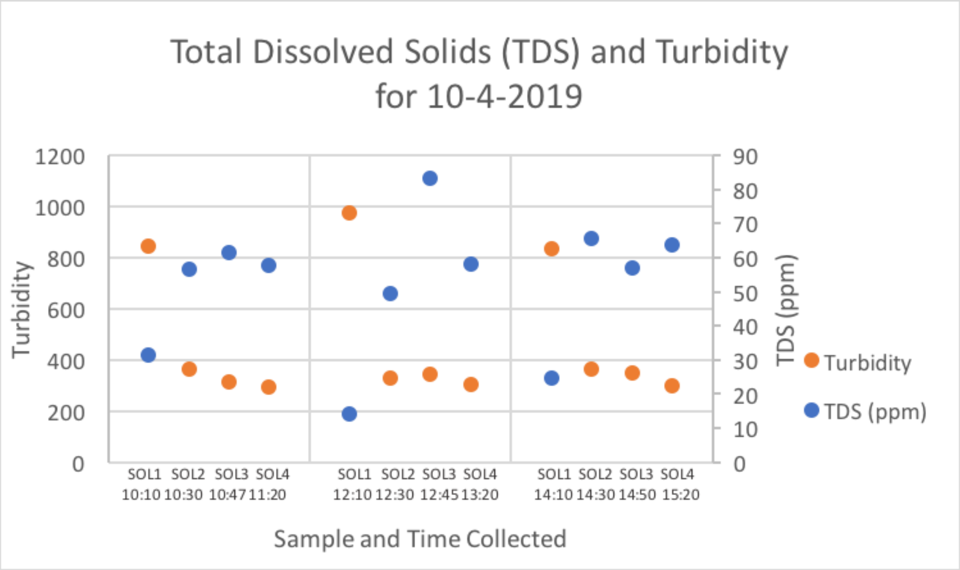


Figure 9. Total dissolved solids and turbidity (NTUs) measurements for 10-4-2019. Source: author

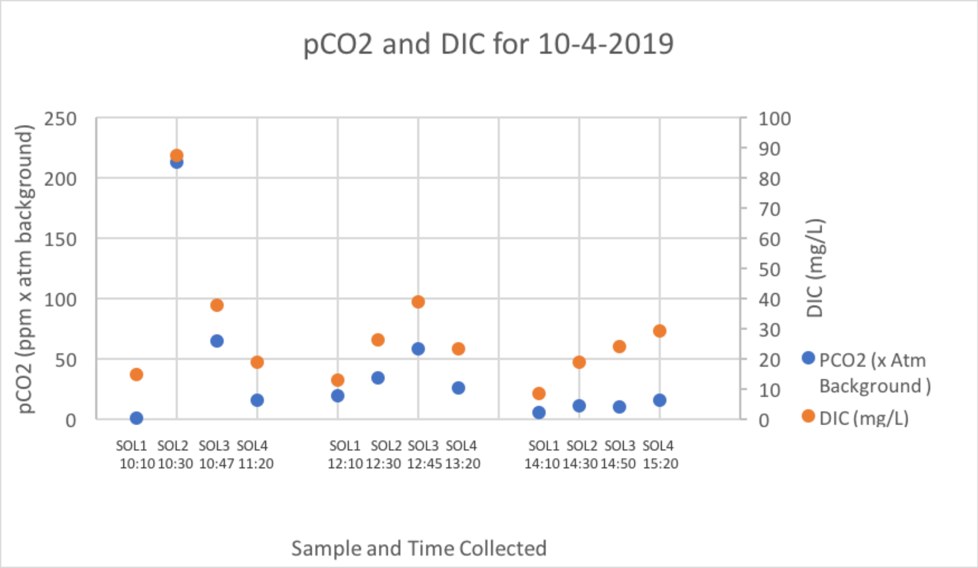


Figure 10. Carbon measurements of pCO_2 and Dissolved Inorganic Carbon (DIC) for 10-4-2019. Source: author

Collection date 10-4-2019 was the driest sampling day of this period. It was overcast with mild temperatures around 13°C. There was still some light precipitation. Like 10-3-2019, the alkalinity measurements are not consistent and do not show any trends (Figure 7). The levels were in the same range as the previous day as well. Conductivity varied more though, as seen in Figure 8. With less precipitation, there was less dilution affecting the geochemistry of the river. The additional water that was added could account for the larger variation, but overall, there is not a pattern to the conductivity.

Figure 9 shows a consistent trend with turbidity. SOL1 had much higher measurements than the other sites. This location was directly on the glacier and was a runoff stream that led into the proglacial lake. Its small width and depth likely led to more turbulent flow, whereas sites SOL2 – SOL4 were more open with laminar flow. TDS levels were very low for all three rounds of sampling, with the lowest being at SOL1 as well. TDS and turbidity can occasionally follow the same trends as higher turbidity can create murkier waters. TDS is more related to specific conductivity and the dissolved content in the water. In this case, it seems that the possibility of suspended solids being higher than dissolved is likely.

Carbon levels are varied throughout the sampling period. The overall pattern was a slow decrease in carbon as time passed. PCO_2 levels had one large spike at SOL2 10:30. The change correlates with a drop in pH. This could likely be from another pulse of meltwater. The temperature is also dropping as this point, which could indicate colder glacial water. As mentioned, a dataset this small does not allow for larger patterns to be seen, leaving little explanation for some events.

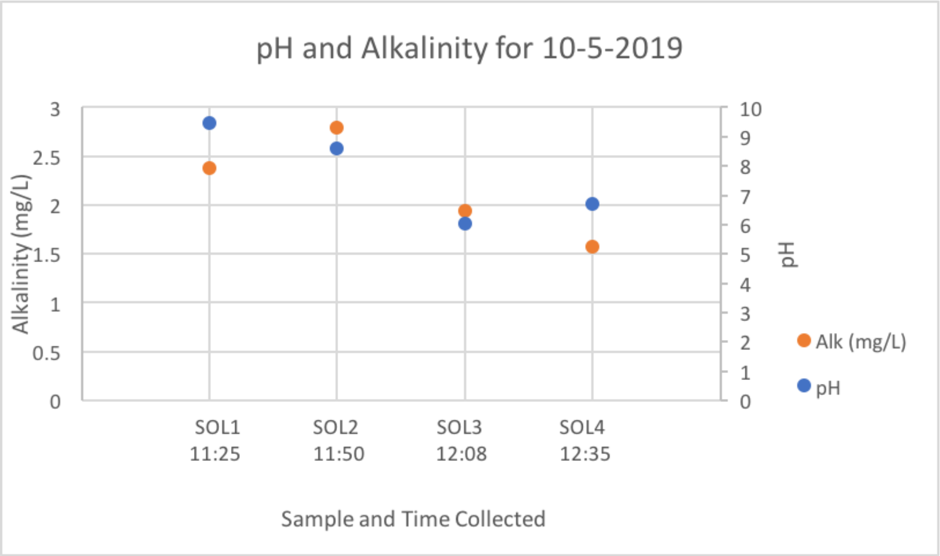


Figure 11. pH and Alkalinity levels for 10-5-2019, Source: author

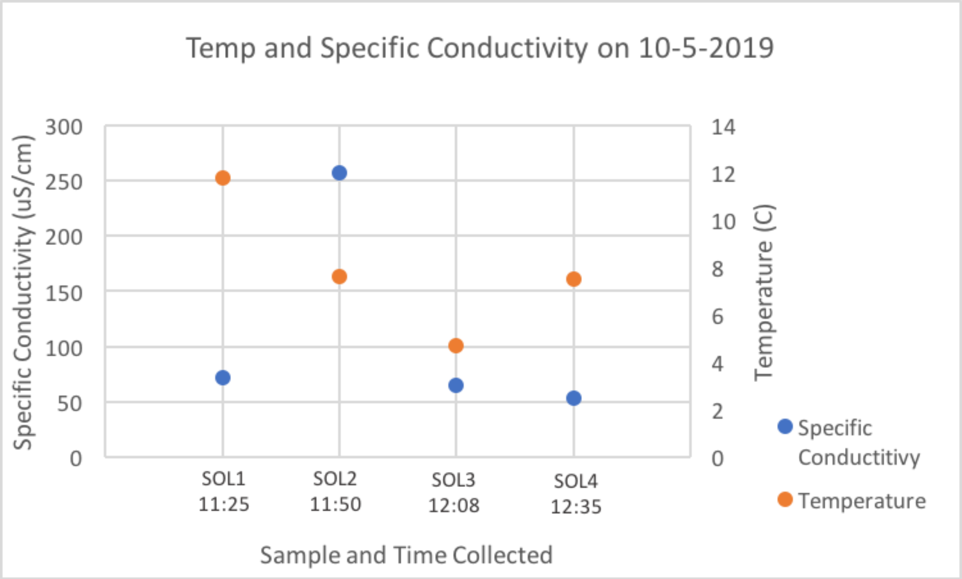


Figure 12. Temperature and specific conductivity levels for 10-5-2019. Source: author

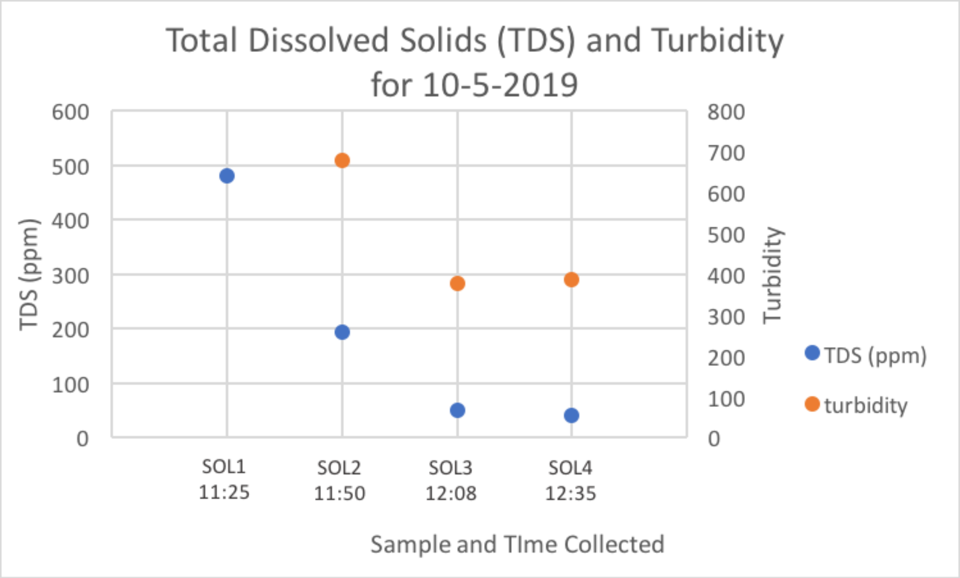


Figure 13. Total dissolved solids and turbidity measurement for 10-5-2019. Source: author

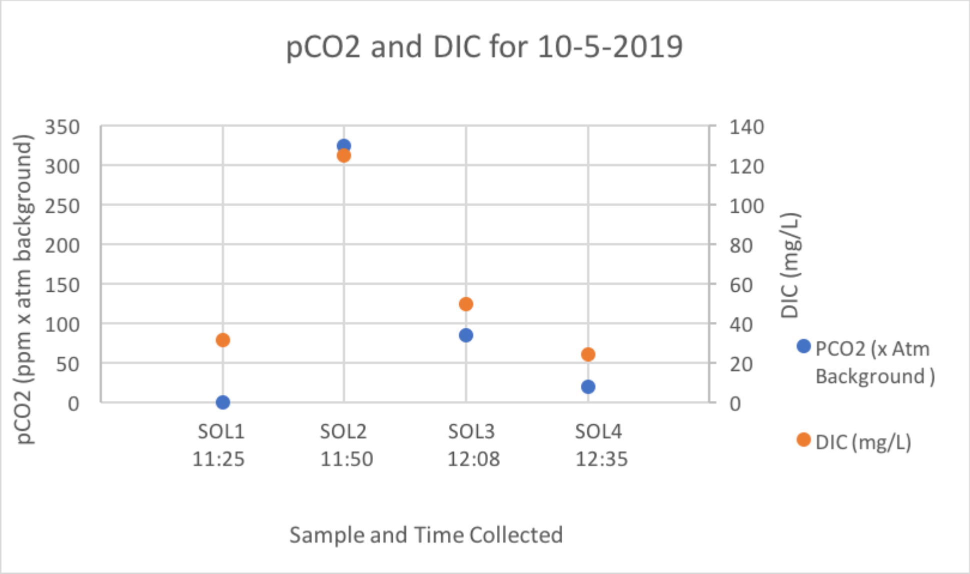


Figure 14. Carbon measurements of pCO_2 and Dissolved Inorganic Carbon (DIC) for 10-5-2019. Source: author

Multiple rounds of sampling were not possible for 10-5-2019. There was very heavy precipitation, as well as stronger wind gusts in the glacial valley along the sampling locations. One round of sampling was done in the middle of the day at an attempt to wait for milder conditions. It was deemed unsafe to continue sampling after. This does provide an interesting insight to geochemistry during a large storm event.

Alkalinity was higher on this day than previous days as seen in Figure 11, with 10-3 being the second highest on average. Alkalinity increases with precipitation. This indicates higher levels of carbonate present, counteracting the effects of dilution seen in the majority of the data.

The results for conductivity, TDS, and turbidity are as expected for large amounts of precipitation. Figure 12 has the lowest conductivity readings of the three sampling days as rainfall dilutes the particulates. Turbidity was significantly higher, along with TDS (Figure 13). Both decrease with distance from the glacier as the river widens. Turbidity measurements did cause an issue during sampling. Limited amount of DI water was able to be brought due to flight regulations and packing material. By the last day of sampling, the unforeseen storm event required more than the expected number of samples needing to be diluted to get a measurement. There were multiple samples that were unable to receive a reading, indicated by a blank space of the graphs. These blanks indicate a high turbidity and TDS. Similar to previous sampling events, the carbon results do not allow for much interpretation. Though, SOL2 11:50 has a spike like SOL2 10:30 on 10-4-2019. This could also be due to meltwater pulses. It is likely that since this location is closer to the glacier, it would be able to signify more events as they are coming from the glacier. Conductivity also has a small spike at this time. A pulse of meltwater with increased gases and dissolved content could affect the pCO_2 levels.

Over the three-day data collection period, precipitation was by far the largest factor accounting for the variability and issues in the results. The main trends seen were the increasing carbon levels along the river along with increasing alkalinity with rainfall. Both of these are indicative of erosional variances. Erosion is difficult to measure with this small of a dataset. While difficult to measure, there are implications that the increased erosion from melting would lead to higher levels of carbon released. Glaciers hold some trapped air and CO_2 within the ice, but this would not account for the rapid warming of climate overall. Higher velocities will be seen as larger volumes of water are melting and travelling down the glacier and its valley, entirely composed of exposed basalts. Storm events lead to higher turbidity levels that are more aggressive for chemical and physical erosion. The basalts present at Sólheimajökull will dissolve any bicarbonate or carbonate present first (Hannesdóttir et al. 2015). Carbonate is a more soluble component in comparison to the mafic basalts. This carbonate is what causes higher alkalinity and potentially carbon levels in the water, in addition to the increased melting rate. Melting of the glacier during these storm events would likely increase. The precipitation would be warmer than the frozen ice, leading to increased melting from heat transfer.

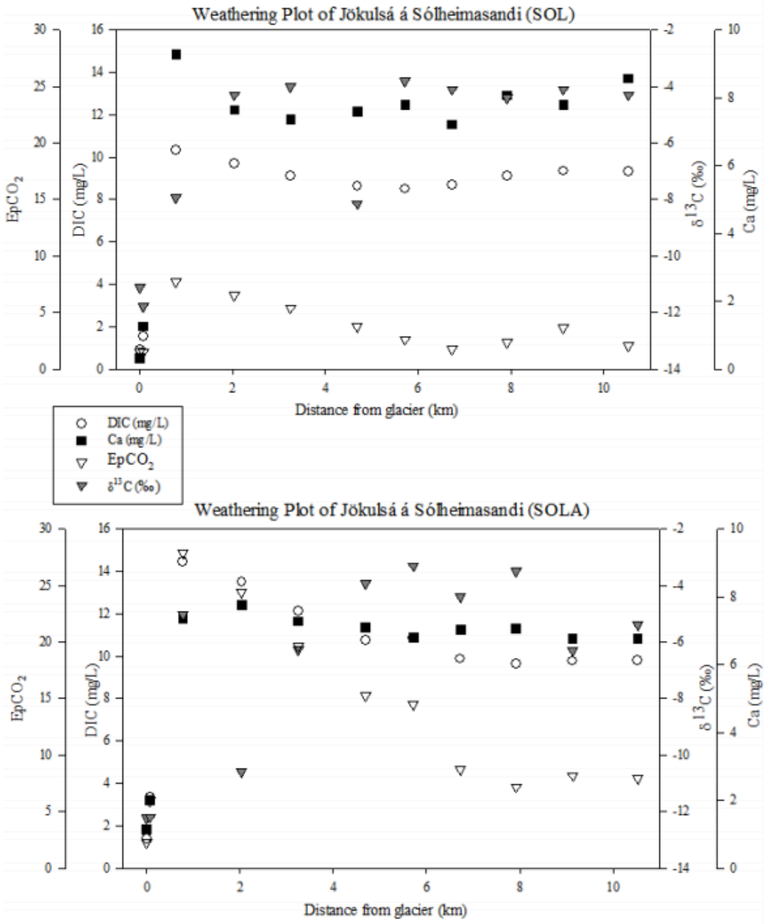


Figure 15. Various sources of carbon measurements along Sólheimajökull's river (Quiroga 2018)

Erosion is a slow process, and only shows small effects in this short of a time period. Allison Quiroga (2018) wrote a master's thesis over carbon flux at multiple Icelandic glaciers, including Sólheimajökull. With similar data sets along the same river, the carbon levels can be compared. The datasets were collected roughly one and a half years apart, which led to different trends. Figure 15 shows her graphed data. Her EpCO$_2$ data can be directly compared to those of this thesis. The 2018 data set shows similar results to the 2019 set. Both show a general decrease in carbon as the river is further from the glacier. This is a reasonable result as the most carbon released in this amount of time would be at the mouth of the glacier from melting. Melt is a quicker response when aligned with erosion. The glacier releases melt water daily where erosion will take years. The dilution from rain events did lead to a more rapid decrease in the 2019 data. The carbon would have been diluted quickly as the water rose.

Both datasets do suggest some predicted trends that will occur from warmer temperatures and increased melting. Increased erosion will continue to dissolve carbon from the basalts and be released into the atmosphere as the water temperature varies. Warmer water will hold lower levels as gases, allowing carbon to escape (Arnason 2013). The carbon will continue to enhance the warming allowing even more to escape through the same process. Eventually, the glacier will retreat to the point that it will not recover in the winter, possibly leaving a river behind. Without a further look into the glacial melt and retreat, it is not possible to predict if there will be remnant river or if there will only be storm drainage with temporary rivers.

The effects of these trends would not be limited to Iceland. Sólheimajökull can be used to determine trends for other glaciers as well. Increased erosion and released carbon are common throughout many glacial landscapes in the Arctic and beyond . The geology will determine the amount of carbon released and the rate. Similar studies can be replicated again at Sólheimajökull to compare results and fine-tune the data. They can also be replicated at other glaciers globally. The studies will quantify the amount of carbon being released from glaciers as a whole and help to make its impact known.

Comparison of datasets is necessary to find trends across seasons and explanations for inconsistent data. Quiroga’s (2018) dataset is larger and more comprehensive of the entire river. This thesis was limited in resources for multiple reasons. One is the scale of the project was made appropriate for a single investigator to collect data and process it on their own. The 2019 dataset was made small for this purpose. It is not large enough to make conclusions and to see larger events. Another is the event of COVID-19. A quarantine was implemented during this project that severely limited resources. Western Kentucky University's Department of Geography and Geology's labs were the source of the programs originally intended for use to process the data. Without access, basic graphs were used instead to observe general patterns.

These data are providing multiple insights to the glacier as a whole and the effects from climate change. Meltwater is a primary tool to determine the rate of glacial change and what will be released with the waters through weathering and dissolved gases being released. Gases trapped in the glacier will be released back into meltwater and eventually the atmosphere. Measuring meltwater geochemistry allows for tracking how much is being released. Carbon levels in the water is also indicative of how climate change is affecting the glaciers. Higher levels of carbon are being sourced to glaciers, and as these levels increase so is melting. These studies are necessary in order to measure melting rates, erosion, and the total amount of carbon being released. This project is a way to continue research on Sólheimajökull. It is one of the quickest changing glaciers in Iceland and is being monitored fairly regularly. In the future, a larger project focused solely on Sólheimajökull to determine carbon flux over an entire year would be required. This would allow for seasonal trends, glacial advance and retreat, biological factors, and mote to be monitored and accounted for in a carbon flux analysis.

CONCLUSION

Climate change is a pressing issue worldwide with glacial melt being a quickly occurring reaction to warmer temperatures. Glacial melt volumes, geochemistry, causes, and more are being continuously studied. With carbon dioxide being a major cause of the warming temperatures, it is necessary to quantify the carbon flux of glaciers as it is being released through melt. Glaciers like Sólheimajökull release carbon that can be measured in their runoff rivers and proglacial lakes. Calculating and creating models for this flux benefits climate model projections and helps create a more accurate image of future conditions. The preparation for its effects that result from these studies is what is helping global communities adjust and problem solve for the future.

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