Analyses of hydrochemical properties of four watersources in the vicinity of the Pasterze glacier, Austria
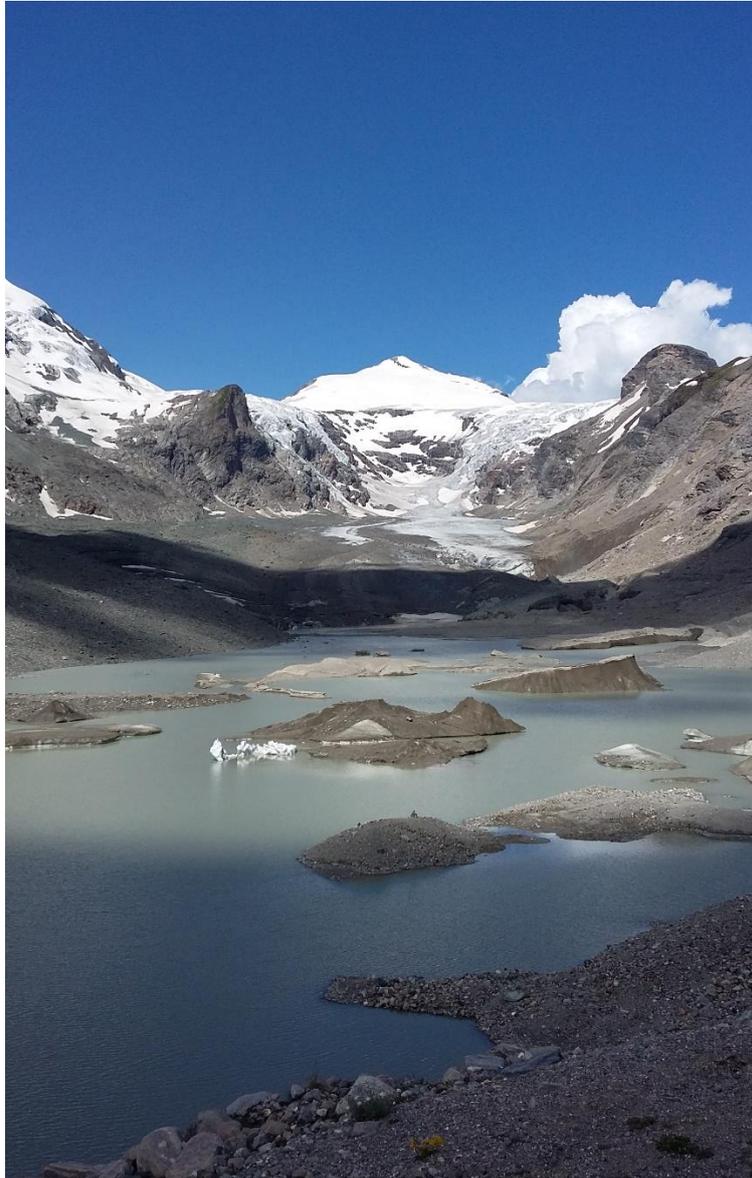
Rupp Marina Annabel

201078088

School of Geography

BSc Geography and Mathematics

2019

ACKNOWLEDGEMENTS

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Changing climate is affecting the glaciers on our planet; glaciers respond to the changes, through either expanding or declining in size. Since glaciers are reacting sensitively towards changes, they are utilized as an indicator for climate change. 75% of the freshwater available on our planet is stored in glacial ice and therefore forms an important source for humans. Mountain glaciers correspond to approximately 4% of the lands ice surface area. This study will focus on the Pasterze glacier, which is located in the Hohe Tauern mountain group in Austria. The Pasterze is an alpine valley-glacier and is a part of the Hohe Tauern National Park east of the highest mountain of Austria, the Großglockner (3798m above sea level (a.s.l.)). The Pasterze is regarded as a temperate glacier system, which currently recedes like most alpine glaciers. When glaciers are retreating, they are likely to form lakes in front of the glacier or on top of them. The chemical structure of the lake's surface water mirror the quality of the water, which is important as the water quality or changes in this affect the aquatic ecosystem. It is crucial to investigate changes in hydrochemistry as changes in the chemical composition might affect the ecosystem as well as the water quality of the lakes. This study investigated if the lake water in the vicinity of the Pasterze glacier shows diurnal changes and if there is a difference in chemical composition between the sampling sites. The results of the study hardly showed diurnal changes of the hydrochemical properties, possibly caused by sampling design of the project. The changes between the locations have been more pronounced than the diurnal changes. pH lies within the range of 7-10 which has been suggested for glacial meltwater. Conductivity values have shown to increase downstream (L1-L2-L4) and are lowest at L1 in comparison to all other sampling sites, which can be explained through the input of fresh glacial meltwater. For L1-L2-L4 the concentrations were as follows: Ca<Mg<K<Si<Na<Mn<Al<Fe<Cu and for L3 they were in the following order: Ca<Mg<Si<K<Na<Fe<Mn<Al<Cu. Through the conducted study it could have been confirmed that most hydrochemical properties are changing between the different sampling sites and that there are hardly diurnal changes present.

Word count: 7732

1   INTRODUCTION

1.1   Glaciers

Within the past 2.6 million years, glaciers and continental ice-sheets in the mid-latitudes have been spreading and receding (Holden, 2012). Between 60ka and 18ka there has been the last major glaciation and it finished with the Last Glacial Maximum at around 24ka to 18ka (Rowan, 2018). Nowadays about 10% of the Earth's landmasses are covered by glaciers (Holden, 2012; Tweed and Carrivick, 2015). Moreover, it is to note that glaciers act as a water storage and that their melting will lead to an increase of sea-level (Holden, 2012). 75% of the freshwater available on our planet are stored in glacial ice (Jansson et al., 2003). During times of maximum glaciation the sea-level dropped by around 130m (Holden, 2012). Current glaciation holds water corresponding to roughly 75m of global-sea level rise. Most of this is stored within the Antarctic and Greenland ice sheets (Holden, 2002). These ice sheets do not only play a role in global sea-level rise, they further influence the oceanic as well as atmospheric circulation and the ice sheets also affect surface air temperatures (Sherriff-Tadano et al., 2018).

There are two key factors governing the development of glacier ice, these are low temperatures and snow (Holden, 2012). Glaciers can only occur in high altitudes within equatorial regions; this altitudinal gradient decreases towards the poles where glaciers can also be found at sea-level (Benn and Evans, 2010).

Ice on planet Earth can be categorized into sea ice and glacial ice. Sea ice is formed at temperatures around -1.9°C and during that process nearly all the salt is removed. It is an important factor for regional climate, since its presence cuts off the heat transfer from the ocean to the atmosphere (Ruddiman, 2014).

Glacial ice can principally be found on land in the form of mountain glaciers or continental ice sheets. Mountain glaciers are constrained to mountain valleys at higher elevations, since these are only able to exist where mean annual temperatures remain below freezing (Ruddiman, 2014).

The size of a glacier is affected by mass balance, which refers to the gain and loss of the ice within a glacier system (Benn and Evans, 2010). A glacier receives inputs from snowfall, windblown snow and avalanches and it will lose mass through melting, calving and evaporation (Benn and Evans, 2010). These processes are termed accumulation and ablation respectively. The area of the glacier where accumulation and ablation are the same is referred to as the equilibrium line. The accumulation will exceed ablation for growing glacier systems and vice versa for shrinking ones (Benn and Evans, 2010; Rowan, 2018).

Changing climate is affecting the glaciers on our planet; these in response to the changes will either expand or decline in size. As glaciers are reacting sensitively towards changes, they are utilized as an indicator for climate change (Benn and Evans, 2010; Geilhausen et al., 2012).

Ice sheets belong to the biggest mass of ice on our planet; major ice sheets are found in Greenland and the Antarctic (Holden, 2012). These ice masses are generally slow flowing, but they also contain faster flowing ice streams and outlet glaciers. The difference between those two is that outlet glaciers are surrounded by rock, whereas ice streams are found within the walls of the ice sheets (Holden, 2012). Some of the ice streams of Antarctica fuel ice shelves. These are floating ice masses that either melt directly into the ocean below or cause the formation of icebergs through the process of calving (Holden, 2012). Other glacier forms are confined to the underlying topography, such as ice fields, valley glaciers or Cirque glaciers (Benn and Evans, 2010).

Glaciers are a vital water source for humans, as these act as a water storage (Holden, 2012). Meltwater serves as a water source for agricultural usage and during hotter summers glacial meltwater increases in the river systems and therefore provides more water. Another important use of glacier meltwater is the production of electricity through meltwater runoff via the use of hydroelectric power plants (Holden, 2012; Moore et al., 2009).

The next section will focus on mountain glaciers followed by an outline of the fieldsite used in this study.

1.2   Mountain glaciers

Mountain glaciers are found at high altitudes even in lower latitudes, this is because the air temperature declines as altitude increases. Therefore, snow and ice can persist in those areas up to centuries (Rowan, 2018). Often glaciers are covered by rock debris, which is insulating the glacier itself and therefore reducing the ablation on the surface. These glaciers are likely to persist over longer time periods than clean-ice glaciers (Rowan, 2018). According to Hotaling et al. (2017) mountain glaciers within low and mid latitudes are likely to be warm-based.

Approximately 680km^2 of the Earth is covered by mountain glaciers, this corresponds to 4% of the lands ice surface area (Ruddiman, 2014). Although this seems to be a relative small proportion of the total ice volume, their impact on the environment is relatively big on a short timescale due to their short response time. Therefore, omitting them in research could falsify the results, as mountain glaciers are quite abundant, so their contribution towards the total ice volume of the world is significant (Carrivick et al., 2015). Moreover, their impact on sea-level rise is greater than that of the Antarctic or Greenland ice sheet if considered over a short time period (Carrivick et al., 2015). Mountain glaciers usually have a response time of 10-40 years (Ruddiman, 2014), hence they are considered as vital indicators for changes in climate (Carrivick et al., 2015). Some ice cores have been taken from mountain glaciers, of which some reveal climate history from many thousands years ago, and other only date back a few hundreds of years (Ruddiman, 2014). According to Rowan (2018) it takes 20-500 years for a mountain glacier to be rebalanced again after a change in climate occurred.

Further, it is vital to mention that mountain glaciers do not react the same way everywhere. Solar radiation and precipitation influence the glaciers at lower latitudes as well as local climate. In middle and high latitudes local climate change is the main factor for glacier responses, these include changes in temperature of the summer season and differences in the amount of winter snowfall (Ruddiman, 2014).

1.2.1 *Pasterze glacier (Austria)*

This study will focus on the Pasterze glacier, which is located in the Hohe Tauern mountain group in Austria. The Pasterze is an alpine valley-glacier and is a part of the Hohe Tauern National Park east of the highest mountain of Austria, the Großglockner (3798 m above sea level (a.s.l.)) (Herbst and Neubauer, 2000; Avian et al., 2018). In 1993 it covered an area of 20km^2 and is the biggest glacier found in Austria (Herbst and Neubauer, 2000), in 2009 it's area decreased to 17.3km^2 (Avian et al., 2018).

The Pasterze can be split into three sections according to its morphology: the accumulation area, the Hufeisenbruch and the glacier tongue (Herbst and Neubauer, 2000). The accumulation area is specified with gentle slopes of around 22° covering nearly 15 km^2. The Hufeisenbruch is an ice fall dominated by crevasses and steep slopes of up to 50°, where the highest velocities occur just beyond it. Lastly, the glacier tongue stretches over around 4250 m where it terminates on an area with slopes of around 5°. At the terminus the velocity is nearly equal to zero (Herbst and Neubauer, 2000). An important feature of the Pasterze is that it is covered by supraglacial debris (Geilhausen et al., 2012), which covered approximately an area of 1.8 km^2 in 2002 (Kellerer-Pirklbauer et al., 2008).

The Pasterze is regarded as a temperate glacier system, which currently recedes like most alpine glaciers. However, it should be noted that the glacier has been smaller than today during the Holocene, which can be implied from wood findings as well as glacially reworked peat (Avian et al., 2018). Its ablation rate is up to 6.4m/yr. and since the end of the Little Ice Age in the 1850's, where the Pasterze reached its maximum size, it lost 130m of ice thickness (Herbst and Neubauer, 2000). During the Little Ice Age (LIA) the glacier tongue of the Pasterze reached down to 1890m above sea level (Nicolussi and Patzelt, 2000). The top of the glacier has supraglacial meltwater channels, and its englacial and subglacial channels are influenced by inflowing water (Kellerer-Pirklbauer and Kulmer, 2018).

The Pasterze has a long record of glaciological monitoring for the Alps, which began around 1878. (Avian et al., 2018). Moreover, the tongue of the Pasterze glacier, which flows from the Johannisberg, has been measured on an annual base starting around 1880 (Hall et al., 2003).

The north-eastern ranges are dominated by calcareous mica-schist and the north-western part is a combination of gneiss and mica-schist (Geilhausen et al., 2012). Prasinite, which is a type of greenschist, dominates the bedrock (Avian et al., 2018).

The area around the Pasterze is defined as having continental climate, with precipitation of around 909mm and mean annual air temperatures of 1.6°C, these values have been measured near the Margaritze reservoir (47°4'16.73''N, 12°45'54,45''E) which is 2070 m a.s.l. (Geilhausen et al., 2012). The "Margaritzenstausee" is a reservoir that has been built in the early 1950s and is a vital part of Austria's hydropower network (Geilhausen et al., 2012). It has to be noted, however, that damming might alter factors such as turbidity, nutrient content or water temperature (Anselmetti et al., 2007). The area in front of the Pasterze consists of channel patterns that are extremely prone to changes, these might occur on a weekly and seasonal cycle (Geilhausen et al., 2012). Further downstream of the glacier a sandur has formed, which is forming a shallow lake in summer caused by high flow conditions (Geilhausen et al., 2012).

1.3 Literature Review

Since the beginning of the 20th century, glacier and ice sheets have been receding (Tweed and Carrivick, 2015). Researching them is important as glaciers are influencing streamflow as well as the quality of the water at different time scales (i.e. diurnal, seasonal) (Moore et al., 2009). Within the European Alps, lakes at higher altitudes act as sensitive barometers for changes in climate as well as in the environment (Thies et al., 2007). Moreover, it is important to note that mean annual air temperatures have been rising by more than 1°C in the Alps since 1980 (Thies et al., 2007; Strang and Aherne, 2015), this causes alterations within the hydrological cycle as well as the duration of snow and ice cover (Rogora et al., 2003; Sommaruga-Wögrath et al., 1997). The increasing temperatures also lead to a rise in weathering for granite and gneiss (Thies et al., 2007; Sommaruga-Wögrath et al., 1997). Climate warming appears to be more noticeable in alpine regions (Rogora et al., 2003), however care needs to be taken as the influence of climate change on for example the lake system is not entirely understood yet (Koinig et al., 2002).

1.3.1 *Water in the glacier system*

Water is an agent that shapes our planet together with other processes. Its importance within glacier systems lies within the fact that water can cause the glacier to flow or melt faster (Benn and Evans, 2010).In glacier systems water can be found in the form of surface melt throughout the summer season, geothermal heating or at the bed of the glacier or directly through rainfall. Water can therefore be found supraglacial (on the surface), englacial (within the glacier) or subglacial (below the glacier) (Holden, 2012).

Mountain glaciers are an important source of water locally and regionally. Further, their retreat could not only cause a lack of access to water but also poses the risk of becoming a potential geohazard (Bach et al., 2018). Mountain glaciers also act as an important habitat for certain microbial communities and the glaciers response to climate change is altering the habitat for these communities (Hotaling et al., 2017).

1.3.2 *Glacier lakes*

When glaciers are retreating, they are likely to form lakes in front of the glacier or on top of them (Rowan, 2018). Due to the melting of glaciers proglacial lakes are increasing in number (Tweed and Carrivick, 2015; Josberger et al., 2006). Glacier lakes can be found at or near the margin of a glacier or ice sheet, they might be attached to the glacier system or not (Carrivick and Tweed, 2013). Often those glacier lakes are found in overdeepenings that have been eroded into the bedrock over time and these are often surrounded by moraines, which act like a natural dam (Rowan, 2018). Glacier lakes can have dams of several forms, like moraine, landslide, bedrock or ice dams (Tweed and Carrivick, 2015). This of course poses a risk on the areas downstream of the catchment, as the moraine dams might destabilize over time or being damaged during earthquakes and therefore might result in a glacier outburst flood (Rowan, 2018).

Glacier lakes do not only pose a risk in the form of glacier lake outburst floods, they may also lead to increased melting of the glacier through heat transfer (Tweed and Carrivick, 2015). However, the formation of glacier lakes also give the possibility for hydropower production (Frey et al., 2010). Moreover, glacial meltwater is a vital supplement to streamflow, particularly during dry periods, as some streams depend on the meltwaters contribution (Schmieder et al., 2018). Lakes in the glacier system serve as sediment traps; these lake sediments can help to interpret changes of local hydrology as well as changes in climate

(Tweed and Carrivick, 2015). The chemical structure of the lake's surface water mirror the quality of the water, which is important as the water quality or changes in this affect the aquatic ecosystem (Gurung et al., 2018).

1.3.3 *Snow- and hydrochemistry*

As noted in the study of Kumar et al. (2009) the chemical composition of glacial meltwater seems to show a higher chemical activity than in the tropics. The hydrological processes of a glacier and its physical state are influenced by the climatic region they occur in, this includes the position of the equilibrium line altitude (ELA), accumulation rates and ice temperature as well as the morphology (Wu, 2018). All of these factors could alter the glacial meltwater path as well as the duration of the flow through the system, which further affects the duration of the water at the water-rock interface and therefore altering the influences of the chemical reaction, leading to changes in dissolved ions within the glacial meltwater runoff (Wu, 2018, Brown, 2002). Moreover, anthropogenic and biotic community influences impact the chemical composition (Tiberti et al., 2010). As snow falls through the atmosphere it picks up pollutants and carries them all the way to the glacier (Fountain, 1996). The chemical composition of the snow on any glacier could therefore have a unique fingerprint, depending on where the natural or anthropogenic source of the pollutant is, the chemical properties of the region from the source and the patterns of atmospheric transport on the local or long-range scale (Fountain, 1996).

Meltwaters obtain solutes as they flow through the glacier system (Brown et al., 1994a; Moore et al., 2009), these solutes are obtained from weathering rocks, moraines, dust from within the snowpack as well as from the atmospheric deposition (Singh et al., 2015a; Kumar et al. 2009)). Ionic strength in alpine glacial meltwaters have different strengths, for example supraglacial water tends to be more dilute and water from recession flow is more concentrated (Brown et al. 1994a). Moreover, the glacier meltwater solute concentration mirrors the hydrogeochemical reaction below the glacier (Singh et al., 2015a). Increasing temperatures have shown to lead to a rise in electrical conductivity (CDC), SO_4, Ca and Mg through higher weathering rates (Thies et al., 2007; Ilyashuk et al., 2014). Low solute concentrations are usually common for glacier meltwater since it is originating from snow-ice (Dong et al., 2017). The decrease of permafrost and glaciers lead to discharge which can be profoundly enriched in

solute concentration due to longer contact times with recently exposed mineral surfaces as well as fine-grained rocks (Ilyashuk et al., 2014).

The catchment's hydrochemical composition is affected by human and biological influences, atmospheric deposition and the interaction of water and rock (e.g. Wu, 2018; Tiberti, et al., 2010; Wögrath and Psenner, 1995). Other factors contributing to seasonal hydrochemical changes include mixing, melting of snow as well as redox reactions in deep waters (Wögrath and Psenner, 1995). Humid regions tend to have water with low chemical contents and a higher sea salt concentration; dry regions on the other hand have higher chemical contents and bigger proportions of halite (Wu, 2018). Water-rock interactions are the main influence on major ions within the water in regions between humid and dry regions, which means that longer interactions lead to higher ion concentration (Wu, 2018). Chemical characteristics of surface waters in areas which are not easy to reach, are impacted by changing climate as well as the atmospheric deposition chemistry (Rogora et al., 2003). It has to be noted, however, that most of the studies are made during the ablation season, therefore potential changes of hydrochemistry from winter to summer season are not fully known (Hindshaw et al., 2011). The origin of minor and trace elements is thought to be akin in glacierized catchments that are similar in terms of geology (Mitchell et al., 2006). Overall one can say that the chemistry of dissolved ions in natural water gives vital information about the underlying geology, different weathering types as well as the precipitation (Singh et al., 2015b). Further, it has to be noted that the rate of chemical weathering is not the same throughout catchments of different rock lithology (Wu, 2018).

1.4   Rationale, Aims, Hypotheses

1.4.1   Rationale

The importance of research on glaciers is mainly coming from the current decrease of the glacier systems. Decreasing glacier systems may lead to glacier lake outburst floods, an increase in avalanches, potential decline in water sources and sea-level rise (Benn and Evans, 2010). According to Wu (2018) there is a lack of hydrochemical data from glacierized regions, and the available data is usually accounting for short observational time-scales. Measuring the chemical compounds of meltwater diurnally is vital since it enables us to study the impact of how dramatic glacier change influences the meltwater (Dong et al., 2017). Moreover,

assessment of glacier meltwater chemistry is important, as the current increase of glacier melting might affect water resources (Dong et al., 2017).

Due to increased temperatures, the glacier systems experience changes in the duration of snow cover and melt period, which is affecting the transport of weathered material, weathering processes as well as biological processes (Rogora et al., 2003), which in turn have an effect on the hydrochemistry of the glacier lakes. Temperature and precipitation changes will affect hydrochemistry and therefore it is vital to investigate which chemical components are more prone to those changes (Strang and Aherne, 2015). It is crucial to investigate changes in hydrochemistry as changes in the chemical composition might affect the ecosystem as well as the water quality of the lakes (Williams et al., 1996).

This study is for the Paterze glacier in Austria. The Pasterze has a very good record in terms of glacier measurements, however no studies could have been found on the chemical compositions for the lakes developed by glacier recession. Therefore, this study aims to give a first insight on the chemical characteristics of the watersources in the vicinity of the Pasterze glacier. This gives an idea of the chemical properties in this area, which can be further investigated on the origin of the solute concentrations as well as their evolution.

1.4.2 *Aims*

- ❖ To investigate how field measurements, metals and anions vary between each sample site to the next one
- ❖ To investigate diurnal changes at the same sample site

1.4.3 *Objectives*

- ❖ Take water samples from four glacier lakes in the vicinity of the Pasterze
- ❖ Measure turbidity, pH, electrical conductivity and dissolved oxygen at the four glacier lakes
- ❖ Measure anion and metal concentrations
- ❖ Perform statistical tests

2 METHODOLOGY

2.1 Fieldwork

The samples for the analyses have been taken along the "Gletscherweg"; figure 1 shows a map with the sampling sites (locations according to GPS grid references taken on the first sampling day using a Garmin Etrex 10 GPS). The locations may vary slightly depending on the height of the water and the therefore changing accessibility. Sampling started from the "Margaritzenstausee" (L4), followed by the "Naßfeld Speicher" (L3), the "Sandersee" (L2) and ending at the forefield (L1) of the Pasterze glacier, in Austria. The sampling sites have been chosen after a tour with a guide, focusing on safety and accessibility of the water source. The chosen sampling sites were the most appropriate for investigating the hypotheses as L1, L2 and L4 flow into each other and therefore the change in hydrochemistry from one location into the other can be researched. L3 has been chosen because its position is not connected to the Pasterze glacier, therefore it can be seen how the glacier lake will differ from the other three locations. However, L3 is still fed by the "Freiwandkees" and has an impact from glacial meltwater input; although this is going to be different from for the other locations as the glacier is approximately 2 km (measured in a straight line on google earth) away from the lake.

Sampling took place in the time from the 21st of June until the 3rd of July 2018, this time period has been chosen for sampling since locations cannot be accessed to due winter closure until May. Moreover, the majority of studies are undertaken during the summer ablation season (e.g. Collins, 1979, Yde et al., 2005 and Wu, 2018), which is due to accessibility, however, this allows for a better comparison of the data. The initial goal was to take measurements and samples twice a day (before midday and after midday); this has not always been possible due to changing weather and health of the group members.

50ml tubes (polypropylene) have been used for water collection in the field, the tubes have been rinsed several times with the water at the study site before being filled up, which is a similar approach as in Singh et al. (2015a).

Samples have been stored in a cooling box with an approximate temperature of 4°C in the field. They have been placed in an electric cooling box, including a thermometer to make sure temperatures are within the desired range of 1-4°C, in the accommodation. On one of the days the cooling box did not work properly, however, and some of the samples reached temperatures above 4°C, this might have led to incorrect results for the lab analysis. The water samples have been filtered into new bottles, within 24 hours, using 0.45μm filters (13mm nylon mesh with a 0.45 μm pore size) and a syringe, all of which have been rinsed in deionized water (type 2) prior to usage. In order to prevent dilution through the deionized water the first couple of drops that have been filtered have been discarded.

The measured variables could be considered standard for glacier hydrochemical research as it is used in several articles (e.g. Singh et al., 2015a, Yde et al., 2005; Wu, 2018).

The direct measurements in the field included pH, electrical conductivity (EC), dissolved oxygen (DO) and turbidity. All the equipment has been provided by the University of Leeds fieldstore, moreover, all of the tools have been calibrated beforehand by a member of the fieldstore. For turbidity, an Oakton T-100 has been used and for pH, EC and DO a Hach flexi HQ 30d has been used. Before usage the equipment has been rinsed several times with the water from the location in order to prevent contamination from previous sampling. This equipment has been chosen for practicality reasons, as the Hach flexi is able to measure three of the desired variables, moreover the use of chemicals in situ has been discarded in order to minimize the pressure on the environment.

Figure 1 places where samples have been taken. (Google Maps, 2019)

2.2   Analysis in the laboratory

Water samples have been brought to the laboratory on the 5th of July 2018 and been prepared for analyses the following day. Samples have been filled into 2.5 ml and 14 ml tubes, every ten samples one of the samples has been repeated in order to serve as a control. Moreover, the deionized water (type 2) has been analysed as well as a filtered sample (using the same filters type of filters as used for the other samples) of the deionized water. The samples have then been analysed by the laboratory staff using *Inductively coupled plasma optical emission spectrometry* (ICP-OES) for metal analyses and *Ion Chromatography* (IC) for anion analyses, as it has been used in the study of Hindshaw et al. (2011) for example. The instruments used were a Thermo Scientific iCAP 7600 and a Dionex ICS-3000 chromatograph respectively. The list below gives the anions and metals chosen for analyses.

ANIONS

- ❖ Chloride (Cl)
- ❖ Fluoride (Fl)
- ❖ Nitrate (NO$_3$)
- ❖ Bromide (Br)
- ❖ Sulfate (SO$_4$)

CATIONS

- ❖ Calcium (Ca)
- ❖ Manganese (Mn)
- ❖ Potassium (K)
- ❖ Iron (Fe)
- ❖ Sodium (Na)
- ❖ Aluminium (Al)
- ❖ Magnesium (Mg)
- ❖ Silicon (Si)
- ❖ Copper (Cu)

3 RESULTS

Summary statistics have been calculated for the available data. All three datasets (data collected in field, anions and cations) have been tested for normality using the Shapiro-Wilk test in RStudio. Depending on this result, either a t-test or a Mann-Whitney test have been performed to investigate on the following hypothesis:

- ❖ **Hypothesis 1:** there is a significant difference between the data collected before midday and after midday (diurnal variations)
- ❖ **Hypothesis 2:** there is a significant difference between the data obtained from different locations

In order to visualize the data bar charts have been used for H1 (see appendix A) and boxplots have been used to support the outcome of the statistical testing. Boxplots are found in main body for discussed variables, for the other variables see appendix B.

For values below detection limit, the values have been set to zero, as in a mathematical sense their contribution can be seen as negligible. Where exact p-values could not be computed due to ties a Mann-Whitney test has been performed, because ties could not be removed and as the p-value was not know there remained the possibility for the data to be not normally distributed.

3.1 Summary statistics

variable	L1			L2		
	min	max	mean	min	max	mean
turbidity (NTU)	48.40	154.0	91.99	41.50	183.0	67.40
pH	8.5	12.8	9.693	7.4	8.9	8.364
CDC (µS/cm)	46.7	61.7	52.11	55.6	93.7	68.59
LDO (mg/L)	9.13	10.2	9.786	7.73	9.72	9.096
Cl	0.064	0.151	0.0869	0.072	0.204	0.1163
NO_3	0.39	0.543	0.4845	0.322	0.667	0.4437
SO_4	4.989	7.025	5.763	4.335	8.927	7.166
F	0.007	0.015	0.008286	0.007	0.011	0.00825
Ca	13.15	15.49	14.09	13.69	23.64	18.77
Fe	0	0.011	0.004636	0.001	0.007	0.004818
Mg	0.769	1.061	0.8711	0.710	1.580	1.232
Mn	0.009	0.015	0.01173	0.009	0.028	0.01764
Na	0.129	0.176	0.1458	0.156	0.302	0.2101
Si	0.179	0.211	0.1995	0.169	0.416	0.3099
K	0.715	1.023	0.8185	0.733	1.433	1.123
Al	0.009	0.01	0.009636	0.007	0.011	0.008364
Cu	0	0.001	0.000727	0	0.001	0.000818
variable	L3			L4		
	min	max	mean	min	max	mean
turbidity (NTU)	2.7	31.8	8.011	22.5	406.00	77.71
pH	7.8	9.3	8.39	7.7	9.2	8.433
CDC (µS/cm)	73.0	107.6	97.77	66.3	96.1	83.22
LDO (mg/L)	8.910	10.110	9.491	9.010	10.230	9.705
Cl	0.0520	0.2040	0.0755	0.0730	0.1690	0.0970
NO_3	0.5100	0.6760	0.5986	0.2560	0.6680	0.5050
SO_4	4.689	10.169	8.760	6.852	13.395	9.330
F	0.007	0.009	0.008	0.008	0.016	0.01017
Ca	19.86	26.59	23.86	17.36	38.37	22.9
Fe	0	0.008	0.003167	0	0.013	0.005083
Mg	1.401	3.177	2.739	1.322	2.3	1.844
Mn	0	0.008	0.002583	0.004	0.009	0.006417
Na	0.098	0.205	0.1293	0.196	0.337	0.2449
Si	0.189	0.407	0.3379	0.278	0.572	0.4168
K	0.217	0.314	0.2564	0.447	0.66	0.555
Al	0	0.001	0.000667	0.003	0.007	0.0055
Cu	0	0.001	0.000583	0	0.001	0.000583

Table 1 showing maximum, minimum and mean values for all measured variables at the different locations

3.2   Field data

Sample	Site number	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Turbidity (NTU)	1	**R1:**p=0.06852 **R2:** p=0.002912	Mann-Whitney: W=19 p=0.9451	no
pH		**R1:** p=0.000774 **R2:** p=0.6305	Mann-Whitney: W=12.5 p=0.319	no
CDC (µS/cm)		**R1:** p=0.3145 **R2:** p=0.4147	t-test: t=2.6124 df=11.994 p=0.02271	yes
LDO (mg/L)		**R1:** p=0.2601 **R2:** p=0.9199	t-test: t=-0.58936 df=5.5535 p=0.5788	no
Turbidity (NTU)	2	**R1:** p≤0.001 **R2:** p=0.9339	Mann-Whitney: W=8 p=0.1059	no
pH		**R1:** p=0.5256 **R2:** p=0.001241	Mann-Whitney: W=5.5 p=0.0448	yes
CDC (µS/cm)		**R1:** p=0.5457 **R2:** p=5706	t-test: t=1.8046 df=10.931 p=0.09872	no
LDO (mg/L)		**R1:** p=0.2482 **R2:** p=8636	t-test: t=-0.82932 df=11.654 p=0.4236	no
Turbidity (NTU)	3	**R1:** p=0.0001885 **R2:** p=0.001476	Mann-Whitney: W=52 p=0.917	no
pH		**R1:** p=0.5134 **R2:** p=5003	t-test: t=0.13611 df=12.199 p=0.894	no
CDC (µS/cm)		**R1:** p=0.006353 **R2:** p=6006	Mann-Whitney: W=63.5 p=0.5223	no

Sample		Shapiro-Wilk	t-test / Mann-Whitney	Difference
LDO (mg/L)		**R1:** p=0.2186 **R2:** p=0.191	t-test: t=1.6406 df=18.348 p=0.1179	no
Turbidity (NTU)		**R1:** p=0.0001794 **R2:** p≤0.001	Mann-Whitney: W=35 p=0.193	no
pH	4	**R1:** p=0.7214 **R2:** p=0.9024	t-test: t=-1.2727 df=18.257 p=0.2191	no
CDC (µS/cm)		**R1:**p=0.3172 **R2:** p=4154	t-test: t=0.18045 df=13.053 p=0.8596	no
LDO (mg/L)		**R1:** p=0.0772 **R2:** p=0.3886	t-test: t=0.90008 df=13.923 p=0.3834	no

*Table 2 statistical data of field measurements. Difference has been tested between round 1 **(R1)** and round 2 **(R2)** for each sampling site*

Sample	Comparison between location	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Turbidity (NTU)		**L1:** p=0.04603 **L2:** p≤0.001	Mann-Whitney: W=152 p=0.01225	yes
pH		**L1:** p=0.007499 **L2:** p=0.04746	Mann-Whitney: W=188 p≤0.001	yes
CDC (µS/cm)	1-2	**L1:** p=0.04989 **L2:** p=0.09859	Mann-Whitney: W=7 p≤0.001	yes
LDO (mg/L)		**L1:** p=0.3869 **L2:** p=0.04303	Mann-Whitney: W=181 p=0.0001496	yes
Turbidity (NTU)		**L2:** p≤0.001 **L4:** p≤0.001	Mann-Whitney: W=207 p=0.04406	yes
pH	2-4	**L2:** p=0.04746 **L4:** p=0.6128	Mann-Whitney: W=144.5 p=0.9461	no
CDC (µS/cm)		**L2:** p=0.09859 **L4:**p=0.286	t-test: t=-4.2449 df=22.198 p=0.0003263	yes

LDO (mg/L)		**L2:** p=0.04303 **L4:** p=0.1192	Mann-Whitney: W=45 p=0.0006288	yes
Turbidity (NTU)		**L2:** p≤0.001 **L3:** p≤0.001	Mann-Whitney: W=294 p≤0.001	yes
pH		**L2:** p=0.04746 **L3:** p=0.3962	Mann-Whitney: W=160.5 p=0.6592	no
CDC (µS/cm)	2-3	**L2:** p=0.09859 **L3:** p=0.01079	Mann-Whitney: W=8 p≤0.001	yes
LDO (mg/L)		**L2:** p=0.04303 **L3:** p=0.1212	Mann-Whitney: W=85.5 p=0.03991	yes
Turbidity (NTU)		**L3:** p≤0.001 **L4:** p≤0.001	Mann-Whitney: W=9 p≤0.001	yes
pH		**L3:** p=0.3962 **L4:** p=0.6128	t-test: t=-0.36084 df=37.86 p=0.7202	no
CDC (µS/cm)	3-4	**L3:** p=0.01079 **L4:** p=0.286	Mann-Whitney: W=400 p≤0.001	yes
LDO (mg/L)		**L3:** p=0.1212 **L4:** p=0.11920	t-test: t=-1.7909 df=39.948 p=0.0809	no

Table 3 results for statistical analyses between the different sample sites
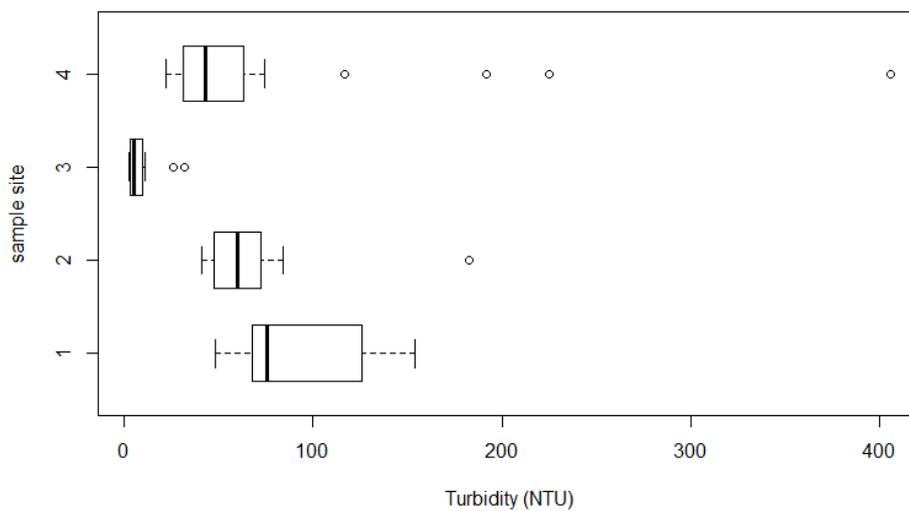
Figure 2 boxplot for turbidity of the different sampling sites
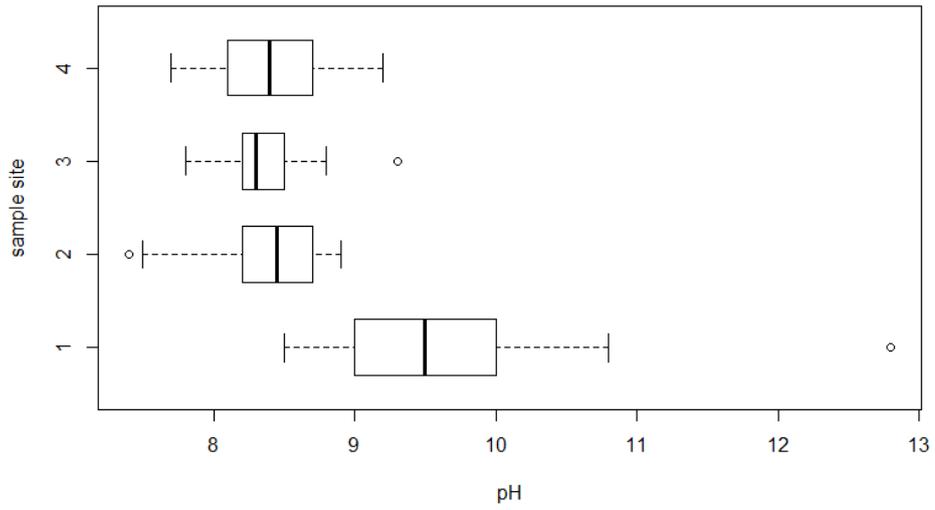
Figure 3 boxplot showing pH for the different sampling sites
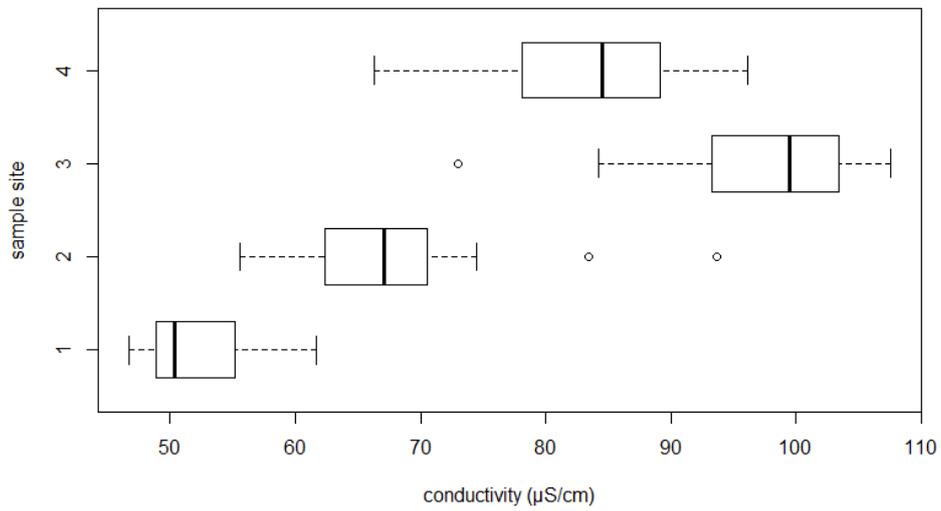
Figure 4 boxplot for conductivity measurements for the four sampling sites
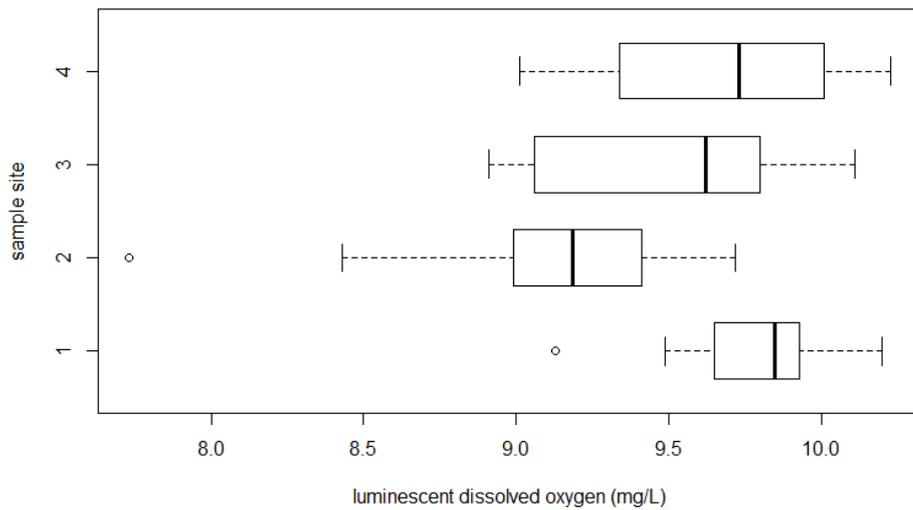
Figure 5 boxplot for LDO measurements for the four sampling sites

As seen in table 2 only conductivity (CDC) at location 1 (L1) and pH at location 2 (L2) changed between the measurements of the two rounds.

One can see that nearly all variables show a significant difference between the two tested locations (table 3). It is striking that pH only varies between location 1 and 2, which can be seen in figure 3. From figure 2, it can be seen that turbidity decreases further away from the glacier and statistically there is a difference between the locations. Figure 4 shows that conductivity increases downstream from the glacier comparing L1, L2 and L4, moreover there is a clear difference between the locations noticeable. No clear trend can be seen for LDO (figure 5), however it has to be noted that there is a significant difference between the locations (L1-L2, L2-L3 and L2-L4) except between L3 and L4.

3.3 Anions

Sample	Site number	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Cl	1	**R1:** p=0.04539 **R2:** p=0.3954	Mann-Whitney: W=18.5 p=0.4476	no
NO_3		**R1:** p=0.4356 **R2:** p=0.6734	t-test: t=0.23541 df=5.4761 p=0.8224	no
SO_4		**R1:** p=0.2912 **R2:** p=0.7951	t-test: t=1.5047 df=8.4377 p=0.1689	no
F		**R1:** p=0.018 **R2:** p cannot be computed as all values are the same	Mann-Whitney: W=9 p=0.2703	no
Cl	2	**R1:** p=0.3405 **R2:** p=0.05466	t-test: t=0.75091 df:8.968 p=0.472	no
NO_3		**R1:** p=0.2333 **R2:** p=0.3911	t-test: t=0.19468 df=6.6067 p=0.8515	no
SO_4		**R1:** p=0.4435 **R2:** p=0.4846	t-test: t=0.014073 df=4.1955 p=0.9894	no

Sample	Comparison between location	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
F		R1: p=0.1458 R2: p cannot be computed, all values are the same	Mann-Whitney: W=15 p=0.03033	yes
Cl	3	R1: p=0.0001008 R2: p=0.3192	Mann-Whitney: W=13 p=0.5152	no
NO₃		R1: p=0.3643 R2: p=0.997	t-test: t=0.11978 df=8.9072 p=0.9073	no
SO₄		R1: p=0.003973 R2: p=0.441	Mann-Whitney: W=21 p=0.6389	no
F		R1: p=0.1444 R2: p cannot be computed, only two non-zero values	Mann-Whitney: W=7 p=1	no
Cl	4	R1: p=0.0968 R2: p=0.7332	t-test: t=1.3134 df=7.2067 p=0.2293	no
NO₃		R1: p=0.3945 R2: p=0.8392	t-test: t=-1.3486 df=7.2983 p=0.2178	no
SO₄		R1: p=0.1988 R2: p=0.1257	t-test: t=0.026855 df=7.7082 p=0.9793	no
F		R1: p=0.008291 R2: p=0.05368	Mann-Whitney: W=15 p=0.7339	no

Table 4 results for statistical analyses of diurnal changes for anion data

Sample	Comparison between location	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Cl		L1: p=0.00241 L2: p=0.123	Mann-Whitney: W=28 p=0.03551	yes
NO₃	1-2	L1: p=0.09618 L2: p=0.1927	t-test: t=1.1392 df=15.083 p=0.2724	no
SO₄		L1: p=0.1135 L2: p=0.5048	t-test: t=-2.8892 df=14.62 p=0.01148	yes

F		**L1:** p≤0.001 **L2:** p=0.1143	Mann-Whitney: W=19,5 p=0.3127	no
Cl	2-4	**L2:** p=0.123 **L4:** p=0.006291	Mann-Whitney: W=83 p=0.3164	no
NO$_3$		**L2:** p=0.1927 **L4:** p=0.1261	t-test: t=-1.4373 df=20.522 p=0.1657	no
SO$_4$		**L2:** p=0.5048 **L4:**p=0.01926	Mann-Whitney: W=27 p=0.01561	yes
F		**L2:** p=0.1143 **L4:** p=0.003905	Mann-Whitney: W=19 p=0.02478	yes
Cl	2-3	**L2:** p=0.123 **L3:** p≤0.001	Mann-Whitney: W=115.5 p=0.002551	yes
NO$_3$		**L2:** p=0.1927 **L3:** p=0.7278	t-test: t=-4.5009 df=13.51 p=0.0005431	yes
SO$_4$		**L2:** p=0.5048 **L3:** p=0.006001	Mann-Whitney: W=20 p=0.00356	yes
F		**L2:** p=0.1143 **L3:** p=0.03729	Mann-Whitney: W=37.5 p=0.9196	no
Cl	3-4	**L3:** p≤0.001 **L4:** p=0.006291	Mann-Whitney: W=21.5 p=0.003854	yes
NO$_3$		**L3:** p=0.7278 **L4:** p=0.1261	t-test: t=2.9694 df=15.638 p=0.009213	yes
SO$_4$		**L3:** p=0.006001 **L4:** p=0.01926	Mann-Whitney: W=83 p=0.5512	no
F		**L3:** p=0.03729 **L4:** p=0.003905	Mann-Whitney: W=13.5 p=0.003517	yes

Table 5 results for statistical analyses of the difference between the different locations
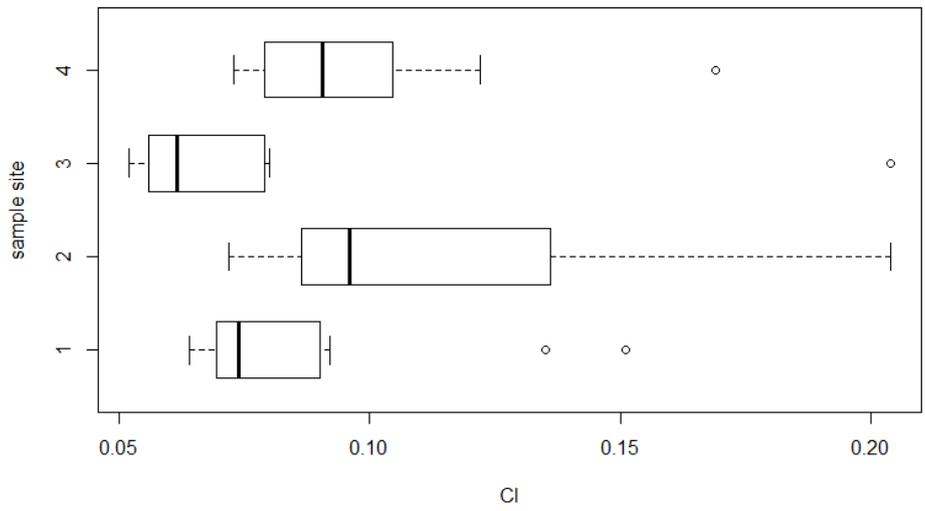
Figure 6 boxplot showing Cl for the different sample sites
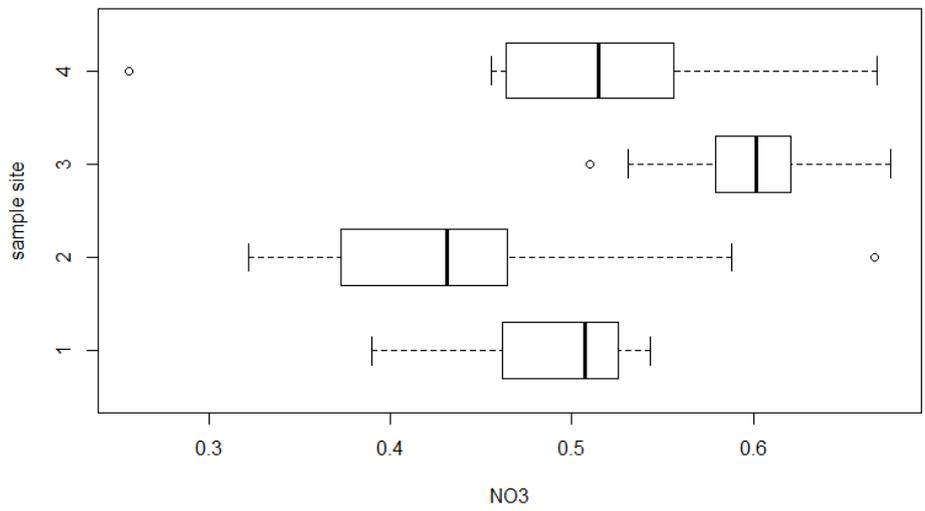
Figure 7 boxplot for NO3 between the different locations
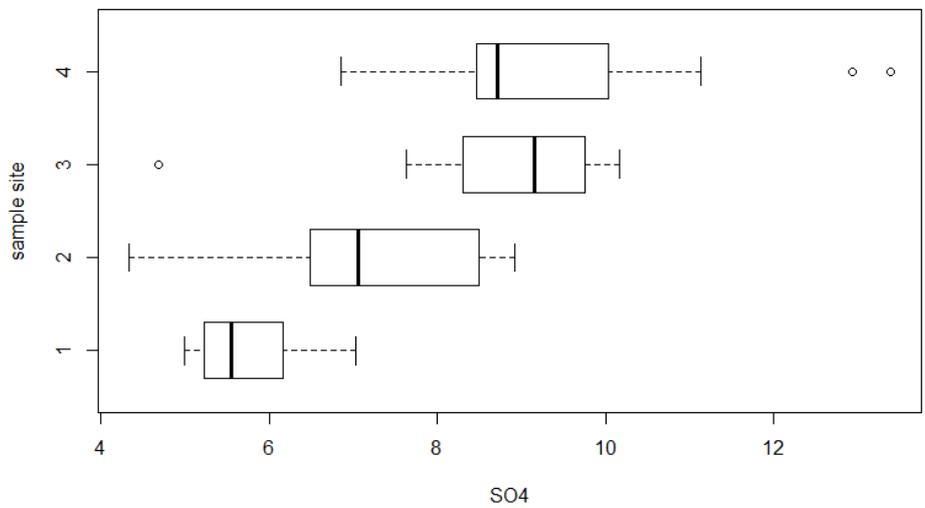
Figure 8 boxplot for SO4 measurements for the different sampling sites
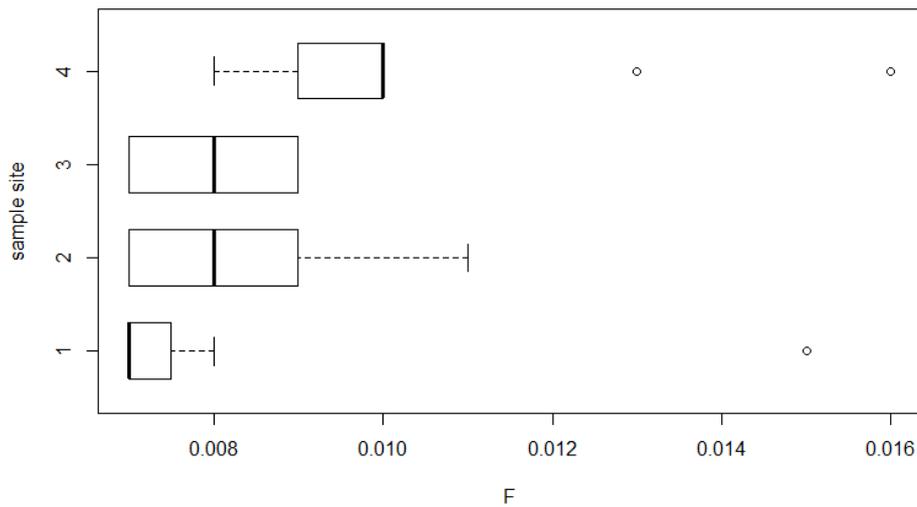
Figure 9 boxplot for F measurements for all locations

As seen in table 4 only F changes diurnally at L2, all other variables do not do so.

As can be seen in figure 6 Cl increases from L1 to L2, however it does not change further downstream, i.e. between L2 and L4, see also table 4. Also, note that Cl for L3 is lower than for all the other locations. The boxplot in figure 7 indicates that NO_3 values are highest at L3. According to the statistical analyses (table 5) there is no change in NO_3 downstream of the glacier, i.e. there is no change between L1-L2 and L2-L4. SO_4 changes between all sites except for L3 and L4. Figure 8 shows that there is an increase in SO_4 further away from the glacier, however there is no change between L3 and L4 present. Figure 9 would lead to the assumption that F increases further away from the glacier, however this is not supported by statistical analyses (table 5) as there is no significant difference between L1-L2. Interestingly L2 and L3 are nearly exactly the same.

Bromide has been excluded from the analyses since there has only been one value above detection limit.

3.4 Metals

Sample	Site number	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Ca	1	**R1:** p=0.8995 **R2:** p=0.6889	t-test: t=1.6421 df=8.3306 p=0.1377	no
Fe		**R1:** p=0.0078 **R2:** p=0.515	Mann-Whitney: W=13 p=0.924	no
Mg		**R1:** p=0.7621 **R2:** p=0.5166	t-test: t=1.3428 df=8.4966 p=0.2141	no
Mn		**R1:** p=0.8632 **R2:** p=0.683	t-test: t=1.2729 df=8.3947 p=0.2372	no
Na		**R1:** p=0.4008 **R2:** p=0.1716	t-test: t=0.98333 df=8.5198 p=0.3525	no
Si		**R1:** p=0.2162 **R2:** p=0.1566	t-test: t=1.3704 df=8.8976 p=0.2042	no
K		**R1:** p=0.6612 **R2:** p=0.2967	t-test: t=1.3269 df=8.6756 p=0.2184	no
Al		**R1:** p=0.001497 **R2:** p=0.001241	Mann-Whitney: W=11.5 p=0.6514	no
Cu		**R1:** p=0.001497 **R2:** p cannot be computed since all p-values are the same	Mann-Whitney: W=8 p=0.1796	no
Ca	2	**R1:** p=0.8065 **R2:** p=0.4563	t-test: t=0.19256 df=5.2773 p=0.8545	no
Fe		**R1:** p=0.8632 **R2:** p=0.1612	t-test: t=-1.7398 df=8.5709 p=0.1176	no

Mg		**R1:** p=0.2348 **R2:** p=0.2264	t-test: t=0.095775 df=4.7149 p=0.9276	no
Mn		**R1:** p=0.117 **R2:** p=0.041	Mann-Whitney: W=12 p=0.7753	no
Na		**R1:** p=0.763 **R2:** p=0.482	t-test: t=1.0285 df=8.9267 p=0.3308	no
Si		**R1:** p=0.7462 **R2:** p=0.7447	t-test: t=0.32308 df=4.6918 p=0.7605	no
K		**R1:** p=0.7139 **R2:** p=0.8073	t-test: t=-0.081876 df=4.5101 p=0.9383	no
Al		**R1:** p=0.06243 **R2:** p=0.1945	t-test: t=-0.21707 df=4.8475 p=0.837	no
Cu		**R1:** p=0.0002752 **R2:** p cannot be computed since values are the same	Mann-Whitney: W=10 p=0.3241	no
Ca		**R1:** p=0.3434 **R2:** p=0.5631	t-test: t=0.51565 df=9.6894 p=0.6177	no
Fe		**R1:** p=0.4691 **R2:** p=0.4925	t-test: t=-0.31135 df=9.4224 p=0.7623	no
Mg	3	**R1:** p=0.001793 **R2:** p=0.2181	Mann-Whitney: W=22 p=0.5303	no
Mn		**R1:** p=0.001242 **R2:** p=0.7471	Mann-Whitney: W=13.5 p=0.5593	no
Na		**R1:** p=0.1078 **R2:** p=0.6704	t-test: t=0.43199 df=9.32 p=0.6756	no
Si		**R1:** p=0.00481 **R2:** p=0.04939	Mann-Whitney: W=23.5 p=0.3701	no

25

K		**R1:** p=0.2955 **R2:** p=0.5547	t-test: t=0.87434 df=9.9897 p=0.4025	no
Al		**R1:** p=0.001497 **R2:** p=0.000131	Mann-Whitney: W=13.5 p=0.4879	no
Cu		**R1:** p≤0.001 **R2:** p=0.000131	Mann-Whitney: W=29 p=0.03709	yes
Ca	4	**R1:** p=0.02722 **R2:** p=0.3228	Mann-Whitney: W=24 p=0.3434	no
Fe		**R1:** p=0.04441 **R2:** p=0.01603	Mann-Whitney: W=15.5 p=0.8042	no
Mg		**R1:** p=0.1915 **R2:** p=0.2881	t-test: t=0.67108 df=7.1075 p=0.5234	no
Mn		**R1:** p=0.7724 **R2:** p=0.07067	t-test: t=-0.24673 df=7.0762 p=0.8121	no
Na		**R1:** p=0.4766 **R2:** p=0.2	t-test: t=1.1295 df=9.9279 p=0.2852	no
Si		**R1:** p=0.8621 **R2:** p=0.4762	t-test: t=0.74886 df=6.2152 p=0.4813	no
K		**R1:** p=0.4396 **R2:** p=0.1495	t-test: t=-0.53809 df=9.6792 p=0.6027	no
Al		**R1:** p=0.8733 **R2:** p=0.3254	t-test: t=-1.4316 df=9.4245 p=0.1846	no
Cu		**R1:** p=0.001497 **R2:** p=0.00647	Mann-Whitney: W=17 p=1	no

Table 6 results for statistical analyses of diurnal metal changes

Sample	Comparison between location	Shapiro-Wilk (p<0.05 = not normally distributed)	t-test / Mann-Whitney	Difference: yes / no
Ca		L1: p=0.5308 L2: p=0.9994	t-test: t=-5.2101 df=11.369 p=0.0002604	yes
Fe		L1: p=0.1273 L2: p=0.1853	t-test: t=-0.13901 df=15.258 p=0.8913	no
Mg		L1: p=0.2756 L2: p=0.5948	t-test: t=-4.1225 df=12.166 p=0.001375	yes
Mn		L1: p=0.8498 L2: p=0.4405	t-test: t=-2.9063 df=11.514 p=0.01368	yes
Na	1-2	L1: p=0.2289 L2: p=0.4871	t-test: t=-4.5373 df=11.613 p=0.0007393	yes
Si		L1: p=0.2337 L2: p=0.8703	t-test: t=-4.8364 df=10.812 p=0.0005482	yes
K		L1: p=0.1633 L2: p=0.8486	t-test: t=-4.1103 df=13.771 p=0.001096	yes
Al		L1: p≤0.001 L2: p=0.02035	Mann-Whitney: W=95 p=0.01946	yes
Cu		L1: p≤0.001 L2: p≤0.001	Mann-Whitney: W=55 p=0.6514	no
Ca		L2: p=0.9994 L4: p=0.005443	Mann-Whitney: W=31 p=0.03174	yes
Fe	2-4	L2: p=0.1853 L4: p=0.364	t-test: t=-0.21078 df=17.14 p=0.8355	no
Mg		L2: p=0.5948 L4: p=0.09195	t-test: t=-4.5851 df=20.358 p=0.0001723	yes

Mn		L2: p=0.4405 L4: p=0.07221	t-test: t=5.4967 df=11.688 p=0.0001506	yes
Na		L2: p=0.4871 L4: p=0.1728	t-test: t=-1.8865 df=20.613 p=0.07339	no
Si		L2: p=0.8703 L4: p=0.7698	t-test: t=-3.1413 df=20.841 p=0.004962	yes
K		L2: p=0.8486 L4: p=0.4776	t-test: t=8.0302 df=11.789 p≤0.001	yes
Al		L2: p=0.02035 L4: p=0.1564	Mann-Whitney: W=129 p≤0.001	yes
Cu		L2: p≤0.001 L4: p=0.0002342	Mann-Whitney: W=81.5 p=0.2472	no
Ca	2-3	L2: p=0.9994 L3: p=0.2187	t-test: t=-4.9046 df=17.541 p=0.0001227	yes
Fe		L2: p=0.1853 L3: p=0.5811	t-test: t=1.8122 df=20.965 p=0.08431	no
Mg		L2: p=0.5948 L3: p=0.00407	Mann-Whitney: W=4 p≤0.001	yes
Mn		L2: p=0.4405 L3: p=0.02409	Mann-Whitney: W=132 p≤0.001	yes
Na		L2: p=0.4871 L3: p=0.0444	Mann-Whitney: W=127 p=0.0001958	yes
Si		L2: p=0.8703 L3: p=0.002402	Mann-Whitney: W=48 p=0.2812	no
K		L2: p=0.8486 L3: p=0.7455	t-test: t=12.702 df=10.277 p≤0.001	yes
Al		L2: p=0.02035 L3: p=0.0001254	Mann-Whitney: W=132 p≤0.001	yes

Cu		**L2:** p≤0.001 **L3:** p=0.0002342	Mann-Whitney: W=81.5 p=0.2472	no
Ca		**L3:** p=0.2187 **L4:** p=0.005443	Mann-Whitney: W=101 p=0.1005	no
Fe		**L3:** p=0.5811 **L4:** p=0.364	t-test: t=-1.4894 df=18.24 p=0.1535	no
Mg		**L3:** p=0.00407 **L4:** p=0.09195	Mann-Whitney: W=130 p=0.0003713	yes
Mn		**L3:** p=0.02409 **L4:** p=0.07221	Mann-Whitney: W=14 p=0.0008285	yes
Na	3-4	**L3:** p=0.0444 **L4:** p=0.1728	Mann-Whitney: W=1.5 p≤0.001	yes
Si		**L3:** p=0.002402 **L4:** p=0.7698	Mann-Whitney: W=40.5 p=0.0733	no
K		**L3:** p=0.7455 **L4:** p=0.4776	t-test: t=-13.689 df=14.319 p≤0.001	yes
Al		**L3:** p=0.0001254 **L4:** p=0.1564	Mann-Whitney: W=0 p≤0.001	yes
Cu		**L3:** p=0.0002342 **L4:** p=0.0002342	Mann-Whitney: W=72 p=1	no

Table 7 results for statistical analyses for testing difference between two locations
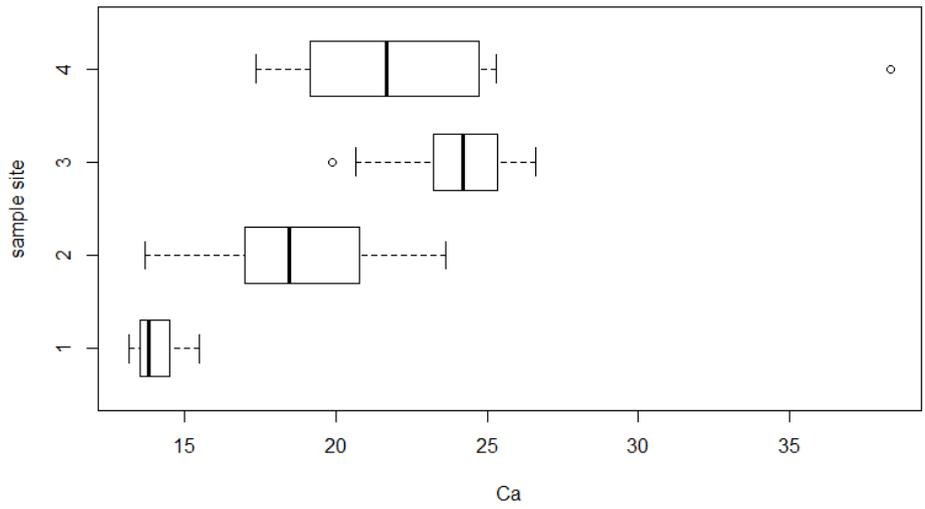
Figure 10 boxplot showing Ca for the sampling sites
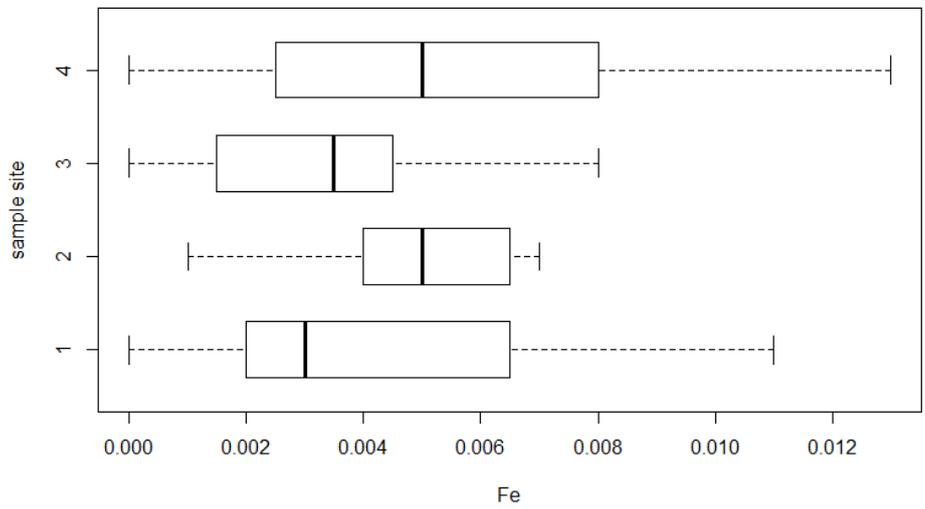
Figure 11 Fe measurements for the different locations
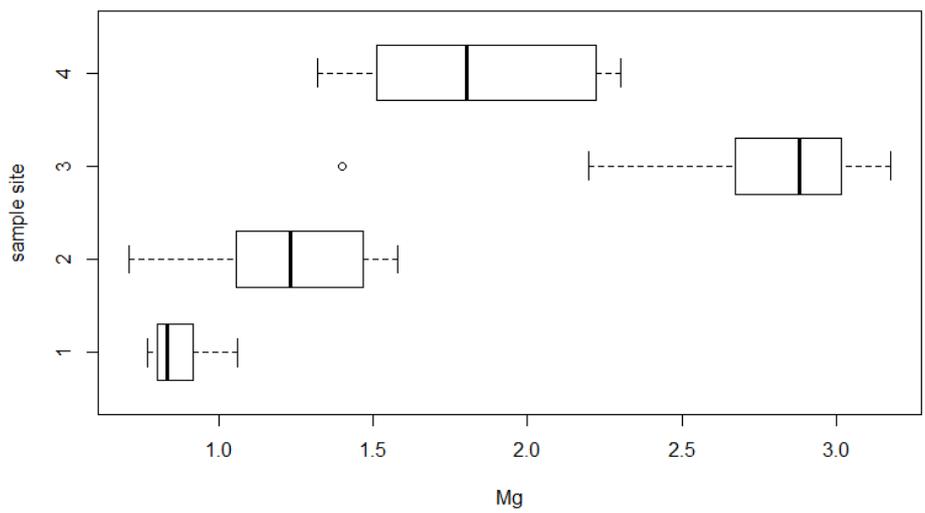
Figure 12 boxplot for Mg values for all sample sites
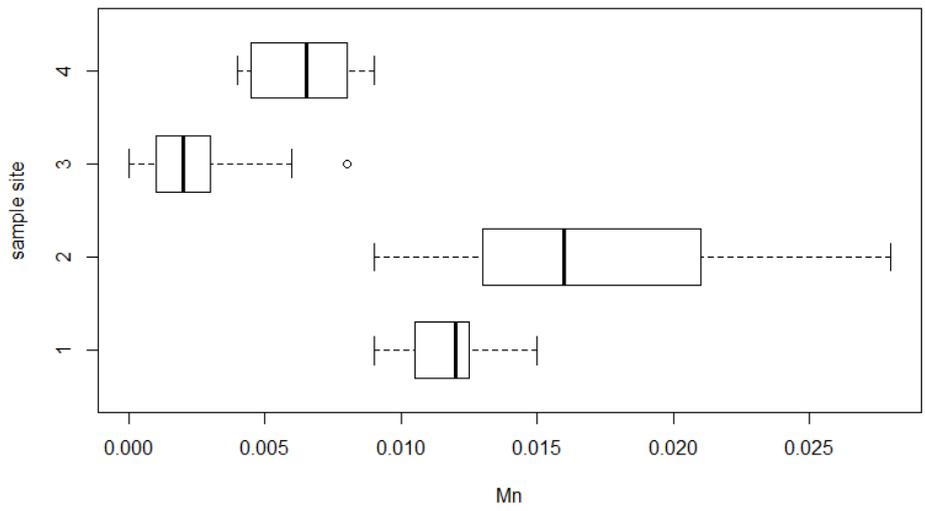
Figure 13 Mn values for all sampling sites
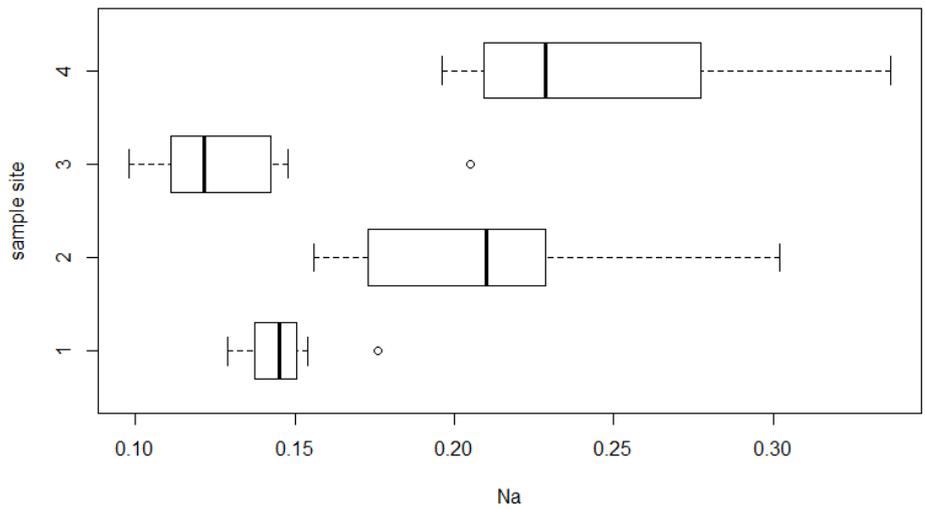
Figure 14 boxplot for Na measurements per sample sites
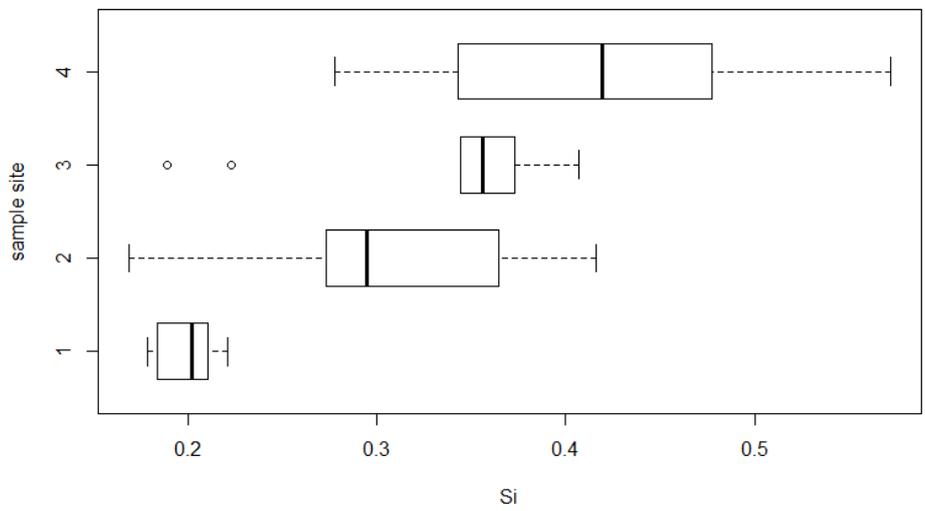
Figure 15 boxplot for Si values for the different sampling sites
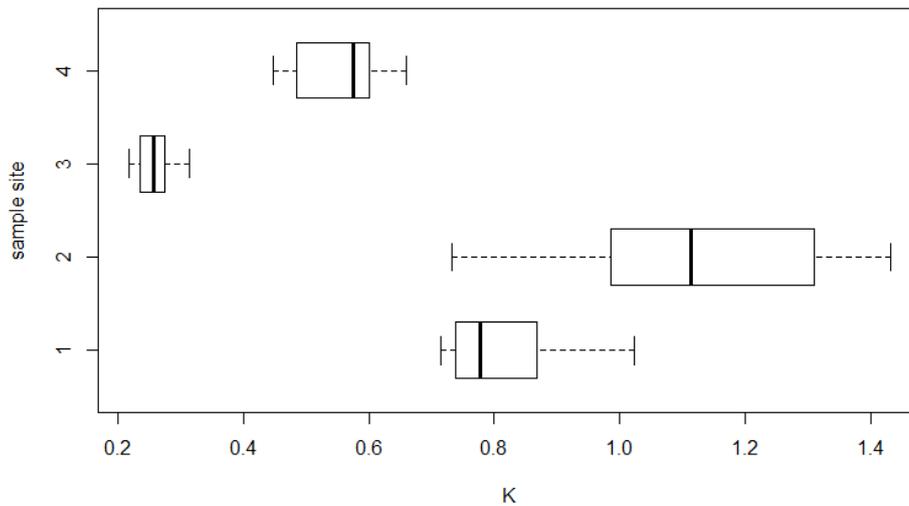
Figure 16 K measurements for the different sampling sites
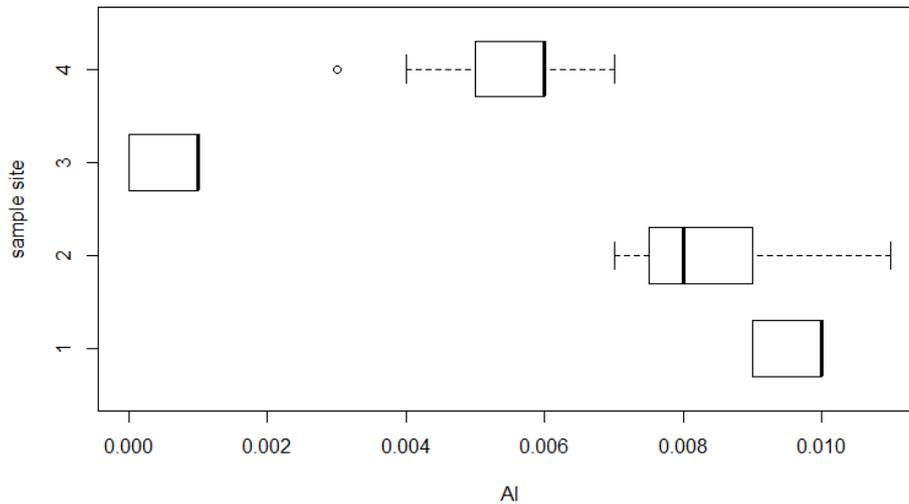
Figure 17 boxplot showing Al for the different sampling sites

From table 6 it can be seen that only Cu changes diurnally for L3, all other variables do not change diurnally.

Table 7 shows the results for the statistical analyses between two different locations. Note that Fe and Cu do not change at all, whereas Mg, Mn, K and Al show a change between all tested locations. From figure 11, no clear trend can be seen in Fe levels, which is supported by statistical analyses. Figure 12 shows that Mg is increasing downstream of the glacier, moreover it is notable that L3 shows the highest Mg concentrations. Mn increases from L1 to L2, however it decreases then from L2 to L4 and L3 shows the lowest values (figure 13). As can be

seen in figure 16 K values increase from L1 to L2 and then they decrease to L4, again L3 has the lowest concentrations, which has the same pattern as Mn. Al concentrations decrease downstream (figure 17) and L3 shows again the lowest concentrations. Si values increase away from the glacier forefield, however there is no statistical difference compared to L3 (figure 15). Na is showing differences between all locations besides between L2 and L4, however, there is an increase downstream and L3 has the lowest values (figure 14). Figure 10 shows that that Ca increases downstream from the glacier; moreover, there is no significant difference between L3-L4.

Ca and Mg have been the most abundant at all four locations and Cu showed the lowest concentrations at all sampling sites. Anions have shown to be in the same order, according to their strength, at all four sites; these were as follows: $SO_4<NO_3<Cl<F$. Metal concentrations have shown the same pattern in terms of strength for L1, L2 and L4, however there was a slight difference in the concentration content to L3. For L1-L2-L4 the concentrations were as follows: $Ca<Mg<K<Si<Na<Mn<Al<Fe<Cu$ and for L3 they were in the following order: $Ca<Mg<Si<K<Na<Fe<Mn<Al<Cu$.

4 DISCUSSION

It will be assumed that the majority of water from L1 is originating from the glacier. However, care has to be taken considering the other locations, as water is feeding them from other parts of the mountain system, which are partly unknown and one might not see all the different input sources immediately. Furthermore, meltwater input from snow is not continuous for the entire summer period and therefore only contributes to the system for a specific amount of time. All of the above mentioned might have an effect on the water chemistry, as the water might not be thoroughly mixed and therefore displays the hydrochemistry of the water from a specific source rather than the entire system. Moreover, it has to be noted that the collected samples have been taken at shallow water conditions.

4.1 Hypothesis 1 – diurnal changes of hydrochemistry

As seen in table 1, 3 and 5 hardly any variables show diurnal changes for the four given locations; in total only four changes have been observed: CDC at L1, pH and F at L2 and Cu at L3, no diurnal changes occurred at L4. This would suggest that there are no diurnal changes at this study site and that hypothesis 1 should be rejected, however this seems inappropriate when comparing the finding of this work to others.

According to Wu (2018) glacier meltwater runoff shows diurnal and seasonal alterations, which can lead to changes in period of water-rock interaction, diffusion of atmospheric CO_2 into the water as well as particle size distribution. Hindshaw et al. (2011) found that maximum concentrations occurred during the night whereas minimum values occurred around mid-afternoon. This prompts a reconsideration of the sampling approach for diurnal changes in the conducted study, as the chosen time frame seems too small to show variations in the system.

LDO is usually used to observe the ecological health of streams and it has been shown that LDO follows diurnal changes (Nimick et al., 2011). Suspended solids lead to a decrease of diurnal cycles of LDO concentrations, which has been seen in larger river systems (Nimick et al., 2011), however this might also be affecting glacial meltwaters which often carry a lot of suspended material. Moreover, it has to be noted that these diurnal variations usually only have little effects on the geochemistry of the streamwater (Nimick et al., 2011).

Although there are diurnal variations in glacier systems present, as mentioned above, Krainer and Mostler (2002) mention that chemical composition and temperature within glacial meltwater derived from active rock glaciers tends to be quite steady and therefore does not show diurnal changes. As the Pasterze is partly debris-covered it might to a certain degree act like a rock glacier and therefore does not show diurnal changes. However this would only explain the absence of diurnal changes for L1, to a certain extent, therefore there have to be other reasons for the absence of diurnal changes.

4.2 Hypothesis 2 – hydrochemical changes between the sample sites

4.2.1 Turbidity

L3 is not connected directly to a glacier anymore and the water travels a longer way to the lake, this might mean that most of the available sediment has already been transported out of the system, leading to clearer water than at the other locations.

Turbidity increases with increased discharge and these suspended particles in turn tend to increase the amount of concentration for dissolves ions (Wu, 2018). Although turbidity is commonly measured for research, it is hardly discussed in the published literature and therefore a proper discussion is not possible to date.

4.2.2 pH

Meltwaters coming directly from the glacier are considered of low buffering capacity. As these flow downstream into areas where huge amounts of reactive material are available protons will be picked up faster than CO_2 is able to replace them through diffusion. This process will cause pH levels to rise (Sharp et al. 1995). This might explain the striking difference in pH from L1 compared to the other three locations. Further downstream pH values will then drop due to mixing of the waters and diffusion processes. Strang and Aherne (2015) noted that pH values decline with rising elevation within high-elevation lakes. This does not seem true for this study; however, there have been some outliers within the data of this work, which might have affected statistical testing. Resampling of pH should be taken into consideration to see if this statement is true or not. Glacial meltwaters are usually turbid and have pH values in the range of 7-10 (Mitchell et al., 2006), which fits the data of this study, besides the outlier at L1, which therefore must have been caused by a sampling error. This would explain why the pH values at L2, L3 and L4 site are mostly between seven and nine and not like in other studies around six (Strang and Aherne, 2015 state that 20% of the studied lakes show a pH below six). This shows that comparison between pH values for different regions are relatively difficult as there are several factors that need to be accounted for, such as anthropogenic effect, climate, biological activity and lithology. Engstrom et al. (2000) found that surface-water pH values for relatively young lakes (<200 years) has been consistently high (i.e. >8) and decreases for older lakes. This would again suggest that the found pH values are within the range for the study sties as the water sources are below 200 years. Tiberti et al. (2010) note in their study that pH values usually appear to be lower during times of snowmelt and these will rise during ice-free cycles. This could be investigated in further research to evaluate if these water systems act like suggested by Tiberti et al. (2010). The high pH values for L1 can also be explained due to the

fact that the glacier bed, that might not be in contact with the atmosphere, can lead to high pH values in runoff (Anderson et al., 2000). This would need a further investigation of the glacier.

4.2.3 *CDC*

During times of increased discharge, electrical conductivity (CDC) will drop (Collins, 1979); this might be a reason why CDC is lower at L1, as these samples were the last to be measured. Therefore, discharge might have been increasing before L1 was reached and altered its CDC. In order to validate if the given location follows the pattern mentioned above, discharge could be calculated or where possible measured in the field.

Zeng et al. (2012) states that CDC minimum is a sign of fresh glacial meltwater entering the system. This could explain why L1 has the lowest concentrations of CDC, as this location is the closest to the glacier and the measurements were taken during the ablation season. Another reason for the low values of CDC can be due to the altitude of the location, as higher altitudes result in lower CDC values (von Fumetti et al., 2016). This, however, does not seem to be the case for the given locations, since L3 is the location with highest altitude (~2270m a.s.l.), but this one shows the highest CDC. This leads to the conclusion, that there have to be other factors which are more important in driving CDC changes, which in this case is quite likely to be the input of fresh glacial meltwater. High CDC values can be an indicator of groundwater contribution to the system, whereas low CDC is most likely to derive from glacier melt and rain (Schmieder et al., 2018). This might explain why L3 has the highest CDC concentrations, as this glacier is not getting as much glacier meltwater through the system anymore and groundwater might be acting as an input source, which however would be needed to be confirmed. The study of Wang et al. (2017) found that the order of CDC was groundwater (206.12 µS/cm), river water (106.74 µS/cm) and last glacial meltwater (53.75 µS/cm), which seems to overlap with our data as CDC at L1 was in the range between 50-60 µS/cm whereas further down the CDC increased, which might be cause by multiple input sources.

For the future, it should be considered to further investigate the contribution of different water sources in order to get a better idea of how different water inputs (i.e. precipitation and groundwater) effect the CDC as well as the chemical composition. It could also be investigated whether the fieldsite follows the pattern, which is often seen in glacierized catchments, of lower CDC values during summer and higher CDC values during the winter period (Schmieder

et al., 2018). Additionally discharge should be measured, as CDC tends to show an inverse relation to discharge and it also shows diurnal and seasonal changes (Hindshaw et al., 2011).

4.2.4 *LDO*

The initial meltwater oxygen saturation is influenced by the amount of O_2 in snow and ice as well as the length it is in contact with atmospheric O_2, this in turn also affects the diffusion rate of the atmospheric O_2 into the water (Brown et al., 1994b). LDO will be closer to saturation during minimum discharge events as well as during recession flow and when contact to atmospheric O_2 and residence time are longer (Brown et al., 1994b). This again would stress to measure discharge in order to understand why changes of LDO are present or not.

4.2.5 *Anions and Metals*

In the study of Wu (2018) the concentration of the abundant ions (Cl, NO_3, SO_4, F, Ca, Mg, Na and K) increased downstream as the water-rock interaction time extended. Wu (2018) has taken samples from supraglacial water, a proglacial river and at a gauging station. In this study, this would corresponds to the concentration alteration between L1, L2 and L4, as these are the locations flowing into one another. This finding seems to be consistent for Cl, SO_4, F, Ca, Mg and Na by examining figures 6, 8, 9, 10, 12 and 14, however statistically only SO_4, Ca, Mg, and K show an increase downstream. This is quite likely to be caused by the fact that L2 and L4 have several locations of water input from different sources. Since L4 is linked to L3 and sampling has taken place closer to the source of L3 inflow than other inflow locations it is quite likely that L3 alters the measurements at L4 significantly, this would for example explain the relatively low values of K at L4.

Raiswell (1984) states that Ca concentrations are the most abundant in approximately 88% of the melt waters and that SO_4 and HCO_3 are the dominant anions (Raiswell, 1984; Tranter et al., 1993); this is also the case in this study for Ca and SO_4 concentrations. Moreover, changes in hydrochemical properties could be explained through an analyses of the lithology. And as mentioned in the literature review the effect of damming could be researched further in order to see if this affects the water properties at L4.

4.3   Limitations

As mentioned in the methodology section issues with storage of the samples occurred during the duration of fieldwork. This might have been causing alterations in the chemical contents of the samples and potentially falsifying some of the results. In order to avoid that there should always be another option available for sample storage; if possible, a fridge would be the best option to keep the samples at the temperature of 1-4°C. Moreover, it should be considered to do lab analyses in the country of sample origin to avoid long journeys during which the ideal storage settings cannot be guaranteed.

This study has found only few variables that change on a diurnal basis. This might have been caused by the design of the fieldwork, as sampling took place at an approximate 2-hour interval, which is a relatively small time frame to allow for changes. Moreover, the small sample size as well as the short sampling period may have led to statistically insignificant results. In order to improve this the sampling approach should be reconsidered, for example it might be useful to set up continuous sampling methods at all locations. This would give better data to observe diurnal changes and the comparability between the locations could increase, because as mentioned in section 4.2.3. CDC values might have been affected by the time of sampling. Moreover, by increasing the sampling period one could investigate seasonal patterns of CDC, as CDC tends to result in higher values during the ablation season and in lower values within the freezing season (Zeng et al., 2012).

In order to gain a better understanding of the entire system discharge should be measured to see its impact on the hydrological system. Furthermore, taking several snow, ice and rainwater samples and potentially groundwater samples should be considered, so assumptions of the influence on the hydrochemistry from different input sources can be made.

The different input sources and locations for one lake make it harder to repeat the study, as the ion concentration will depend partly on the water input and so sampling at a different place as well as under different weather and time conditions might alter the results.

5 CONCLUSION

The aim of this study was to investigate if there is a difference between the different sampling sites and whether there is a diurnal difference present or not at each of the sampling sites. These have been investigated through analyses of water samples from water sources in the vicinity of the Pasterze glacier in Austria.

This study suggests that there are no or hardly any changes before (R1) and after midday (R2) at the sampled areas, however taking into account other studies (e.g. Wu, 2018; Hindshaw et al., 2011) this result was unexpected. The cause for these results probably lies within the set time period for sampling. It should be considered to re-examine this hypothesis setting the sampling in the morning and at around peak discharge time; moreover it should be considered to use equipment for automated measurement throughout the day so it could be seen if there is some sort of evolution present.

This study has shown that there is a difference between the tested variables of most of the sampling sites. pH lies within the range of 7-10 which has been suggested for glacial meltwater by Mitchell et al. (2006). Conductivity values have shown to increase downstream (L1-L2-L4) and are lowest at L1 in comparison to all other sampling sites, which can be explained through the input of fresh glacial meltwater. SO_4, Ca, Mg, and K concentrations have shown to increase further downstream (L1-L2-L4). For all the changes observed care has to be taken as there have been several input sources which might lead to alterations of measured concentrations.

This study has provided a first insight on the hydrochemical properties for the lakes in the vicinity of the Pasterze glacier. Through the conducted study it could have been confirmed that most hydrochemical properties are changing between the different sampling sites, however hardly any diurnal changes were present.

Changes have been observed for the given study, the next step would be to investigate the origin of these changes: for example, are these changes temperature driven, how much does lithology affect the measured variables, how much do anthropogenic factors contribute to changes in the variables?

This could be taken further by investigating how much the different input sources contribute to hydrochemical aspects at each site.

5.1.1 *Future research*

For future research, one could consider investigating on the potential use of meltwaters and assessing the future of hydroelectric power schemes. Moreover, the data can be compared to EU and WHO drinking water standards to investigate if the glacier lakes could be a potential source for drinking water in the future.

It should be considered to extend the sampling period in order to obtain a continuous record to enable investigations for long-term trends as well as seasonal patterns. Moreover, discharge should be measured along the chemical components, for reasons mentioned above. It is also essential to determine the water source as well as its flowpath in order to understand how the solutes are obtained (Hindshaw et al., 2011).

6   REFERENCES

Anderson, S.P., Drever, J.I., Frosst, C.D. and Holden, P. 2000. Chemical weathering in the foreland of a retreating glacier. *Geochimica et Cosmochimica Acta.* **64** (7), pp. 1173-1189

Anselmetti, F.S., Bühler, R., Finger, D., Girardclos, S., Lancini, A., Rellstab, C. and Sturm, M. 2007. Effects of Alpine hydropower dams on particle transport and lacustrine sedimentation. *Aquatic Sciences*. **69**, pp. 179-198

Avian, M., Kellerer-Pirklbauer, A. and Lieb, G.K. 2018. Geomorphic consequences of rapid deglaciation at Pasterze Glacier, Hohe Tauern Range, Austria, between 2010 and 2013 based on repeated terrestrial laser scanning data. *Geomorphology*. **310**, pp. 1-14

Bach, E., Radić, V. and Schoof, C. 2018. How sensitive are mountain glaciers to climate change? Insights from a block model. *Journal of Glaciology*. **64** (244), pp. 247-258

Brown, G.H. 2002. Glacier meltwater hydrochemistry. *Applied Geochemistry*. **17**, pp. 855-883

Brown, G.H., Sharp, M.J., Tranter, M., Gurnell, A.M. and Nienow, P.W. 1994a. Impact of post-mixing chemical reactions on the major ion chemistry of bulk meltwater draining the Haut Glacier d'Arolla, Valais, Switzerland. *Hydrological Processes*. **8**, pp. 465-480

Brown, G.H., Tranter, M., Sharp, M.J., Davies, T.D. and Tsiouris, S. 1994b. Dissolved oxygen variations in alpine glacial meltwaters. *Earth Surface Processes and Landforms*. **19**, pp. 247-253

Benn, D.I. and Evans, D.J.A. 2010. *Glaciers & Glaciation*. 2nd ed. London: Hodder Education

Carrivick, J.L., Berry, K., Geilhausen, M., James, W.H.M, Williams, C., Brown, L.E., Rippin, D.M. and Carver, S.J. 2015. Decadal-scale changes of the Ödenwinkelkees, Central Austria, suggest increasing control of topography and evolution towards steady state. *Geografiska Annaler: Series A, Physical Geography*. **97**, pp.543-562

Carrivick, J.L. and Tweed, F.S. 2013. Proglacial lakes: character, behavior and geological importance. *Quaternary Science Reviews*. **78**, pp. 34-52

Collins, D.N. 1979. Hydrochemistry of Meltwaters Draining from an Alpine Glacier. *Arctic and Alpine Research*. **11** (3), pp. 307-324

Dong, Z., Kang, S., Qin, D., Qin, X., Yan, F., Du, W. and Wei T. 2017. Temporal and diurnal analysis of trace elements in the Cryospheric water at remote Laohugou basin in northeast Tibetan Plateau. *Chemosphere*. **171**, pp. 386-398

Engstrom, D.R., Fritz, S.C., Almendinger, J.E. and Juggins S. 2000. Chemical and biological trends during lake evolution in recently deglaciated terrain. *Nature*. **408**, pp. 161-166

Fountain, A.G. 1996. Effect of snow and firn hydrology on the physical and chemical characteristics of glacial runoff. *Hydrological Processes*. **10**, pp. 509-521

Frey, H., Haeberli, W., Linsbauer, A., Huggel, C. and Paul, F. 2010. A multi-level strategy for anticipating future glacier lake formation and associated hazard potentials. *Natural Hazards and Earth System Sciences*. **10**, pp. 339-352

Geilhausen, M., Otto, J. and Schrott, L. 2012. Spatial distribution of sediment storage types in two glacier landsystems (Pasterze & Obersulzbachkees, Hohe Tauern, Austria). *Journal of Maps*. **8** (3), pp. 242-259

Gurung, S., Gurung, A., Sharma, C.M., Jüttner, I., Tripathee, L., Bajracharya, R.M., Raut, N., Pradhananga, P., Sitaula, B.K., Zhang, Y., Kang, S. and Guo J. 2018. Hydrochemistry of Lake Rara: A high mountain lake in western Nepal. *Lakes & Resevoirs: Science, Policy and Management for Sustainable Use*. **23** (2), pp. 87-97

Hall, D.K., Bayr, K.J., Schöner, W., Bindschadler, R.A. and Chien, J.Y.L. 2003. Consideration of the errors inherent in mapping historical glacier positions in Austria from the ground and space (1893-2001). *Remote Sensing of Environment*. **86** (4), pp. 566-577

Herbst, P. and Neubauer, F. 2000. The Pasterze glacier, Austria: an analogue of extensional allochthon. *Geological Society, London, Special Publications*. **176**, pp. 159-168

Hindshaw, R.S., Tipper, E.T., Reynolds, B.C., Lemarchand, E., Wiederhold, J.G., Magnusson, J., Bernasconi, S.M., Kretzschmar, R. And Bourdon, B. 2011. Hydrological control of stream water chemistry in a glacial catchment (Damma Glacier, Switzerland). *Chemical Geology*. **285**, pp. 215-230

Holden, J., ed. 2012. *An Introduction to Physical Geography and the Environment*. 3rd ed. Harlow: Pearson

Hotaling, S., Hood, E. and Hamilton, T.L. 2017. Microbial ecology of mountain glacier ecosystems: biodiversity, ecological connections and implications of a warming climate. *Environmental Microbiology*. **19** (8), pp. 2935-2948

Ilyashuk, B.P., Ilyashuk, E.A., Psenner, R., Tessadri, R. and Koinig, K.A. 2014. Rock Glacier Outflows May Adversely Affect Lakes: Lessons from the Past and Present of Two Neighboring Water Bodies in a Crystalline-Rock Watershed. *Environmental Science & Technology.* **48** (11), pp. 6192-6200

Jansson, P., Hock, R. and Schneider, T. 2003. The concept of glacier storage: a review. *Journal of Hydrology*. **282**, pp. 116-129

Josberger, E.G., Shuchman, R.A., Meadows, G.A., Savage, S. and Payne, J. 2006. Hydrography and Circulation of Ice-Marginal Lakes at Bering Glacier, Alaska, U.S.A. *Arctic, Antarctic and Alpine Research*. **38** (4), pp. 547-560

Kellerer-Pirklbauer, A., Lieb, G.K., Avian, M. and Gspurning, J. 2008. The Response of Partially Debris-Covered Valley Glaciers to Climate Change: The Example of the Pasterze Glacier (Austria) in the Period 1964 to 2006. *Geografiska Annaler*. **90**, pp. 269-285

Kellerer-Pirklbauer, A. and Kulmer, B. 2018. The evolution of brittle and ductile structures at the surface of a partly debris-covered, rapidly thinning and slowly moving glacier in 1998-2012 (Pasterze Glacier, Austria). *Earth Surface Processes and Landforms*. [no pagination]

Koinig, K.A., Kamenik, C., Schmidt, R., Agusti-Panareda, A., Appleby, P., Lami, A., Prazakova, M., Rose, N., Schnell, Ø. A., Tessadri, R., Thompson, R. and Psenner, R. 2002. Environmental changes in an alpine lake (Gossenköllesee, Austria) over the last two centuries – the influence of air temperature on biological parameters. *Journal of Paleolimnology*. **28**, pp. 147-160

Krainer, K. and Mostler, W. 2002. Hydrology of Active Rock Glaciers: Examples from the Austrian Alps. *Arctic, Antarctic and Alpine Research*. **34** (2), pp. 142-149

Kumar, K., Miral, M.S., Joshi, S., Pant, N., Joshi, V. and Joshi, L.M. 2009. Solute dynamics of meltwater of Gangotri glacier, Garhwal Himalaya, India. *Environmental Geology*. **58** (6), pp. 1151-1159

Mitchell, A.C., Brown, G.H. and Fuge, R. 2006. Minor and trace elements as indicators of solute provenance and flow routing in a subglacial hydrological system. *Hydrological Processes*. **20**, pp. 877-897

Moore, R.D., Fleming, S.W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K. and Jakob, M. 2009. Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes*. **23**, pp. 42-61

Nicolussi, K. and Patzelt, G. 2000. Discovery of early-Holocene wood and peat on the forefield of the Pasterze Glacier, Eastern Alps, Austria. *The Holocene*. **10** (2), pp. 191-199

Nimick, D.A., Gammons, C.H. and Parker, S.R. 2011. Diel biogeochemical processes and their effect on the aqueous chemistry of streams: A review. *Chemical Geology*. **283**, pp.3-17

Raiswell, R. 1984. Chemical Models of Solute Acquisition in Glacial Melt Waters. *Journal of Glaciology*. **30** (104), pp. 49-57

Rogora, M., Mosello, R. and Arisci, S. 2003. The effect of climate warming on the hydrochemistry of alpine lakes. *Water, Air, and Soil Pollution*. **148**, pp. 347-361

Rowan, A.V. 2018. Mountain glaciers under a changing climate. *Geology Today*. **34** (4), pp. 134-139

Ruddiman, W.F. 2014. *Earth's Climate: Past and Future*. 3rd ed. New York: W.H. Freeman and Company

Sherriff-Tadano, S., Abe-Ouchi, A., Yoshimori, M., Oka, A. and Chan, W. 2018. Influence of glacial ice sheets on the Atlantic meridional overturning circulation through surface wind change. *Climate Dynamics.* **50** (7-8), pp. 2881-2903

Schmieder, J., Garvelmann, J., Marke, T. and Strasser, U. 2018. Spatio-temporal tracer variability in the glacier melt end-member – How does it affect hydrograph separation results? *Hydrological Processes*. **32**, pp. 1828-1843

Sharp, M., Tranter, M., Brown, G.H. and Skidmore, M. 1995. Rates of chemical denudation and CO_2 drawdown in a glacier-covered alpine catchment. *Geology*. **23** (1), pp. 61-64

Singh, V.B., Ramanathan, A.L. and Sharma, P. 2015a. Major ion chemistry and assessment of weathering processes of the Patsio glacier meltwater, Western Himalaya, India. *Environmental Earth Sciences.* **73**, pp. 387-397

Singh, V.B., Ramanathan, A.L., Sharma, P. and Pottakkal, J.G. 2015b. Dissolved ion chemistry and suspended sediment characteristics of meltwater draining from Chhota Shigri Glacier, western Himalaya, India. *Arabian Journal of Geosciences*. **8** (1), pp. 281-293

Sommaruga-Wögrath, S., Koinig, K.A., Schmidt, R., Sommaruga, R., Tessadri, R. and Psenner, R. 1997. Temperature effects on the acidity of remote alpine lakes. *Nature*. **387**, pp. 64-67

Strang, D. and Aherne, J. 2015. Potential Influence of Climate Change on the Acid-Sensitivity of High-Elevation Lakes in the Georgia Basin, British Columbia. *Advances in Meteorology*. **2015**, article no: 536892

Thies, H., Nickus, U., Mair, V., Tessadri, R., Tait, D., Thaler, B. and Psenner, R. 2007. Unexpected Response of High Alpine Lake Waters to Climate Warming. *Environmental Science and Technology*. **41** (21), pp. 7424-7429

Tiberti, R., Tartari, G.A. and Marchetto, A. 2010. Geomorphology and hydrochemistry of 12 Alpine lakes in the Gran Paradiso National Park, Italy. *Journal of Limnology*. **69** (2), pp. 242-256

Tranter, M., Brown, G., Raiswell, R., Sharp, M. and Gurnell, A. 1993. A conceptual model of solute acquisition by Alpine glacial meltwaters. *Journal of Glaciology*. **39** (133), pp. 573-581

Tweed, F.S. and Carrivick, J.L. 2015. Deglaciation and proglacial lakes. *Geology Today*. **31** (3), pp. 96-102

Von Fumetti, S., Bieri-Wigger, F. and Nagel P. 2017. Temperature variability and its influence on macroinvertebrate assemblages of alpine springs. *Ecohydrology*. **10**, article no: e1878 [no pagination]

Wang, X., Li, Z. and Jiang, C. 2017. Run-off analyses using isotopes and hydrochemistry in Yushugou River basin, eastern Tianshan Mountains. *Journal of Earth System Science.* **126**, [no pagination]

Williams, M.W., Losleben, M., Caine, N. and Greenland, D. 1996. Changes in climate and hydrochemical responses in a high-elevation catchment in the Rocky Mountains, USA. *Limnology and Oceanography*. **41** (5), pp.939-946

Wögrath, S. and Psenner, R. 1995. Seasonal, annual and long-term variability in the water chemistry of a remote high mountain lake: acid rain versus natural changes. *Water, Air, and Soil Pollution*. **85** (2), pp. 359-364

Wu, X. 2018. Diurnal and seasonal variation of glacier meltwater hydrochemistry in Qiyi glacierized catchment in Qilian Mountains, Northwest China: implication for chemical weathering. *Journal of Mountain Science*. **15** (5), pp. 1035-1045

Yde, J.C., Knudsen, N.T. and Nielsen, O.B. 2005. Glacier hydrochemistry, solute provenance, and chemical denudation at a surge-type glacier in Kuannersuit Kuussuat, Disko Island, West Greenland. *Journal of Hydrology*. **300**, pp. 172-187

Zeng, C., Gremaud, V., Zeng, H., Liu, Z. and Goldscheider, N. 2012. Temperature-driven meltwater production and hydrochemical variations at a glaciated alpine karst aquifer: implication for the atmospheric CO_2 sink under global warming. *Environmental Earth Sciences.* **65** (8), pp. 2285-2297

7 APPENDICES

7.1 Appendix A

7.1.1 Bar charts location 1
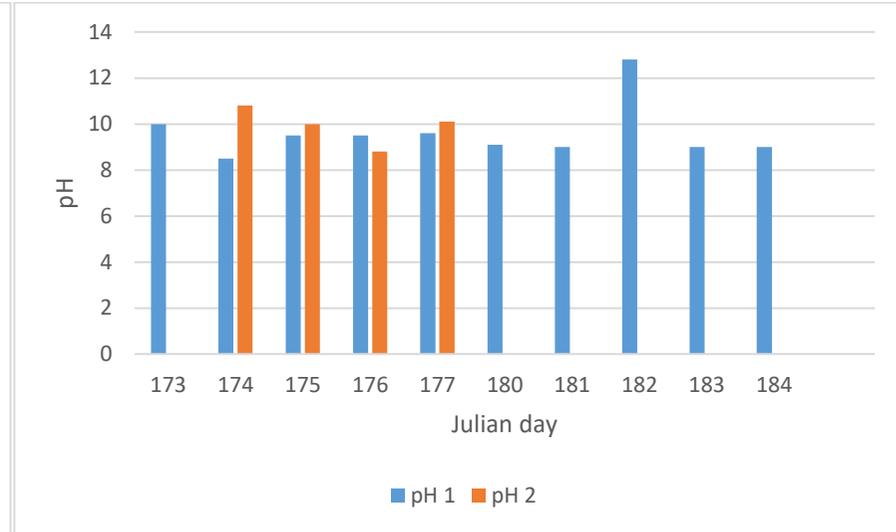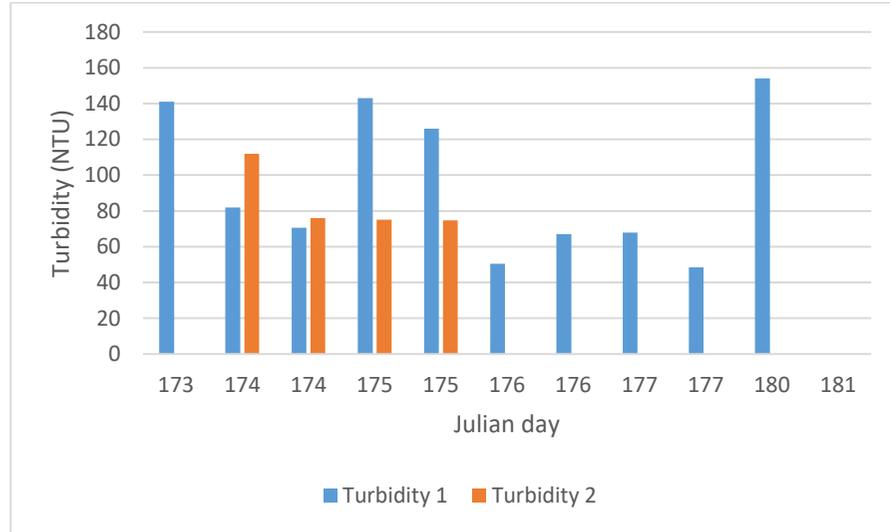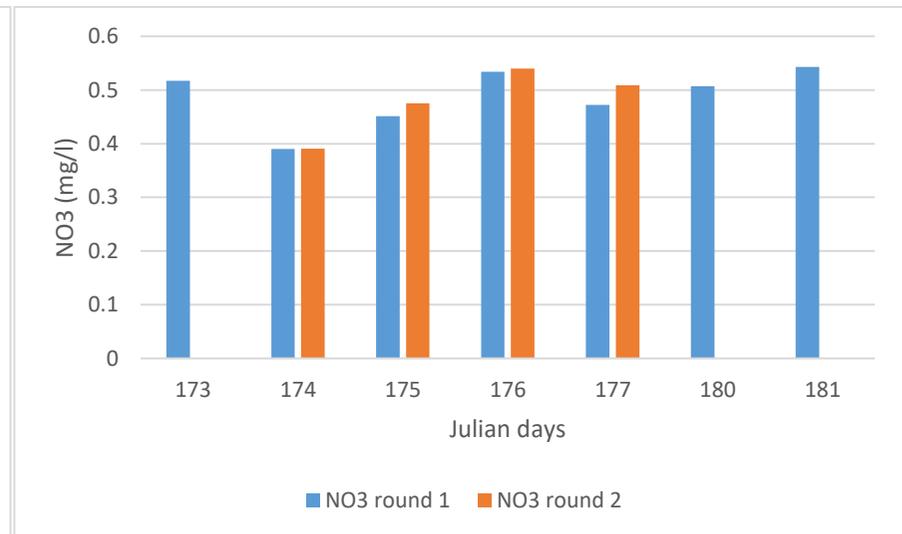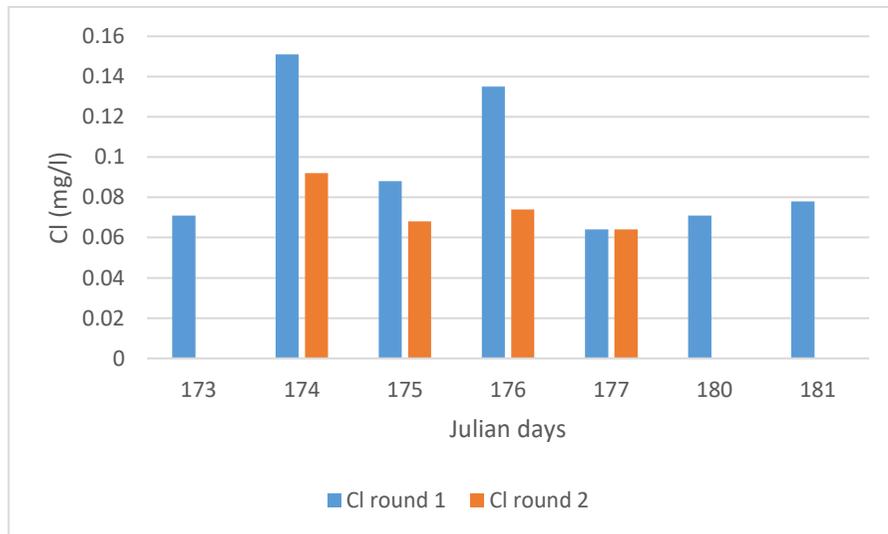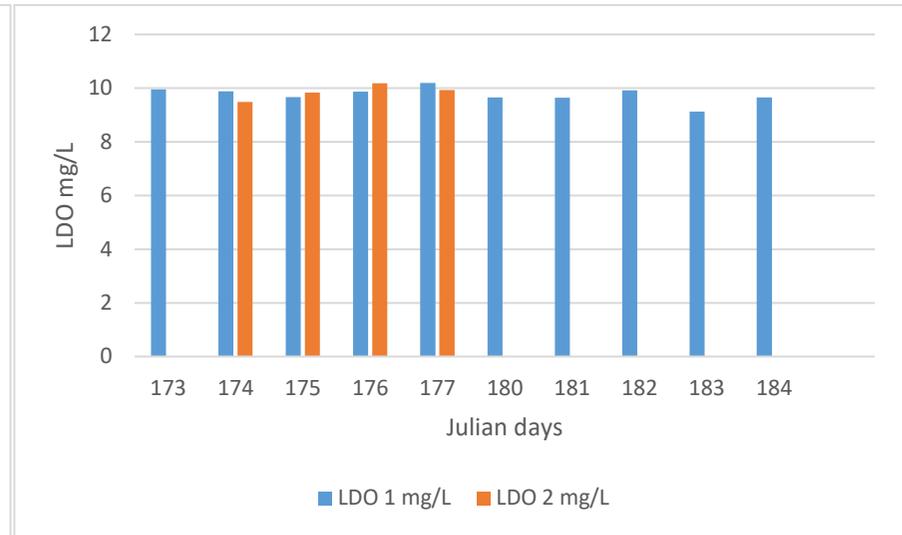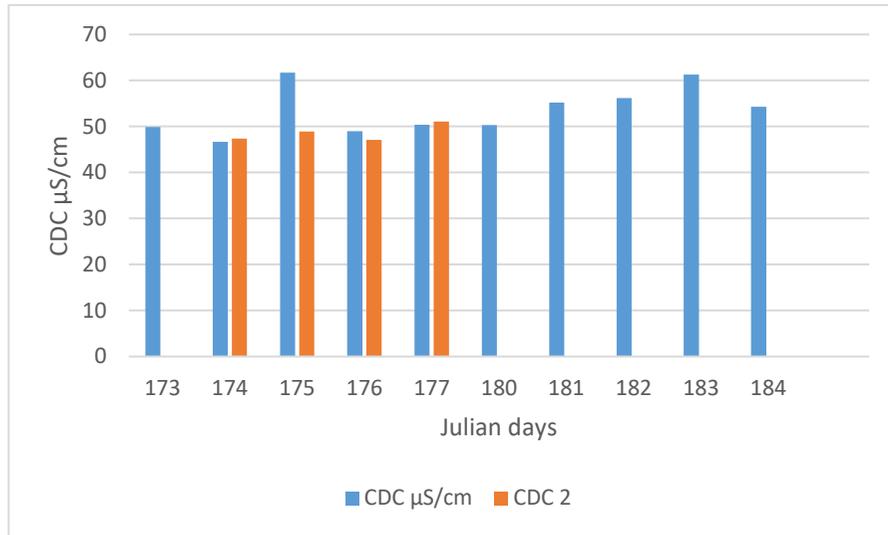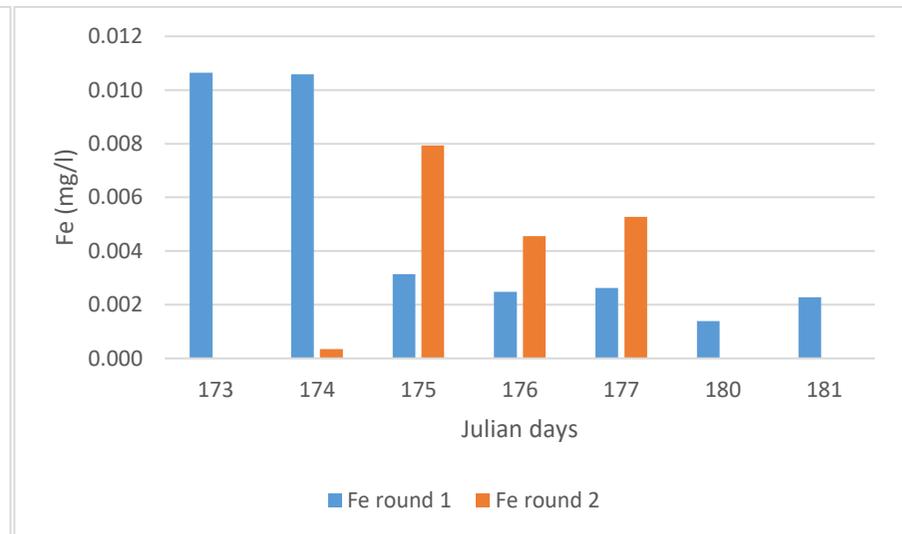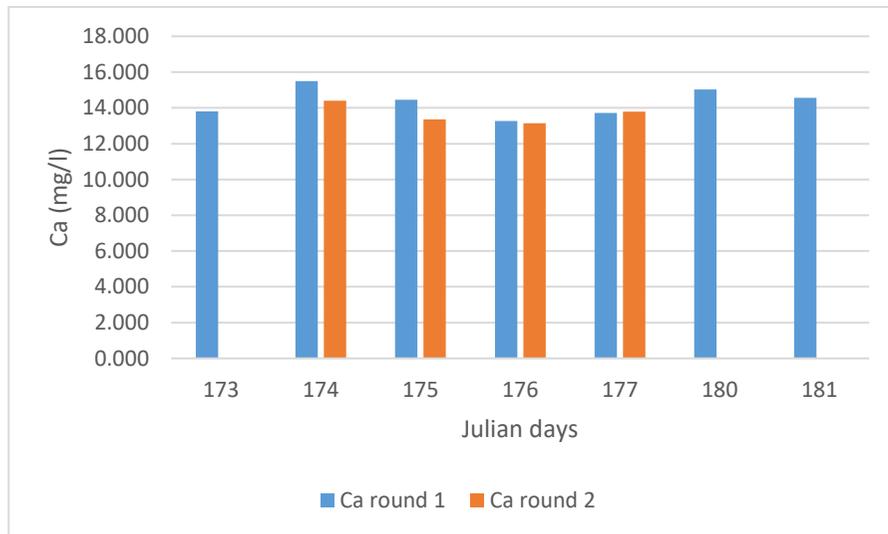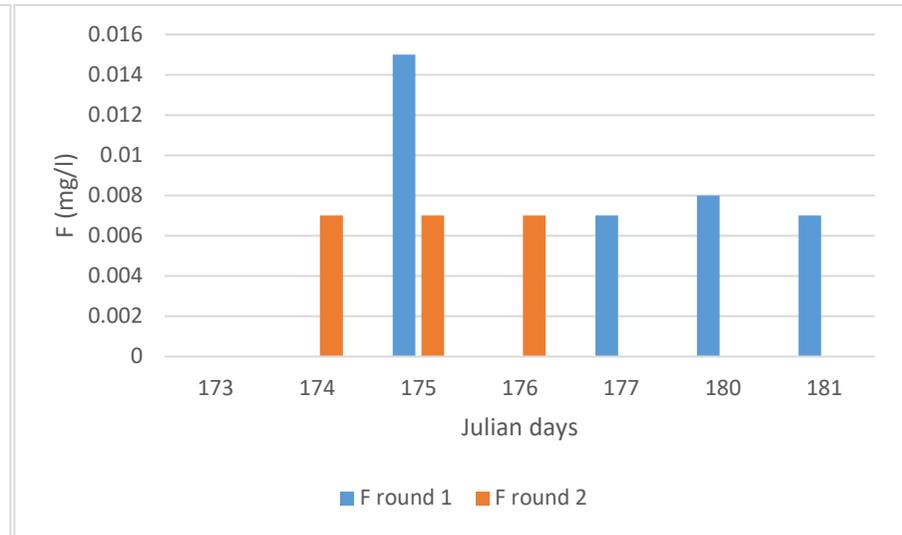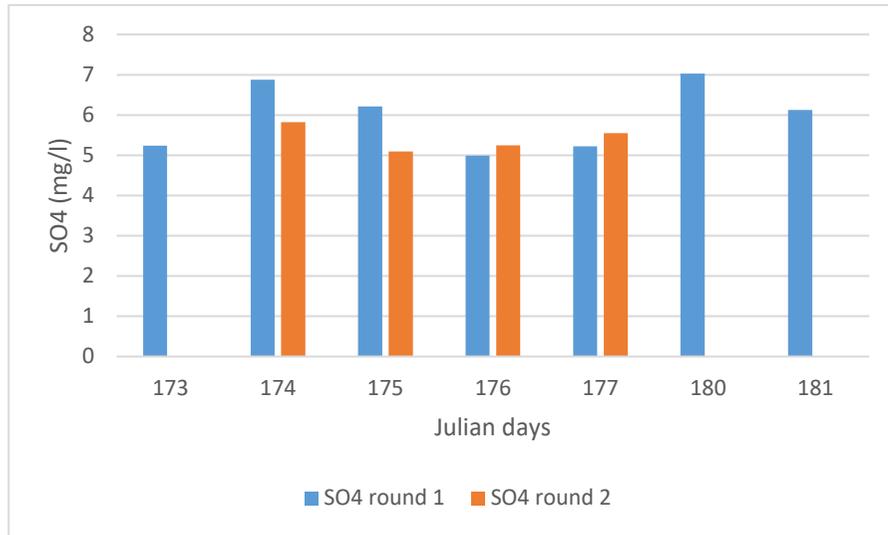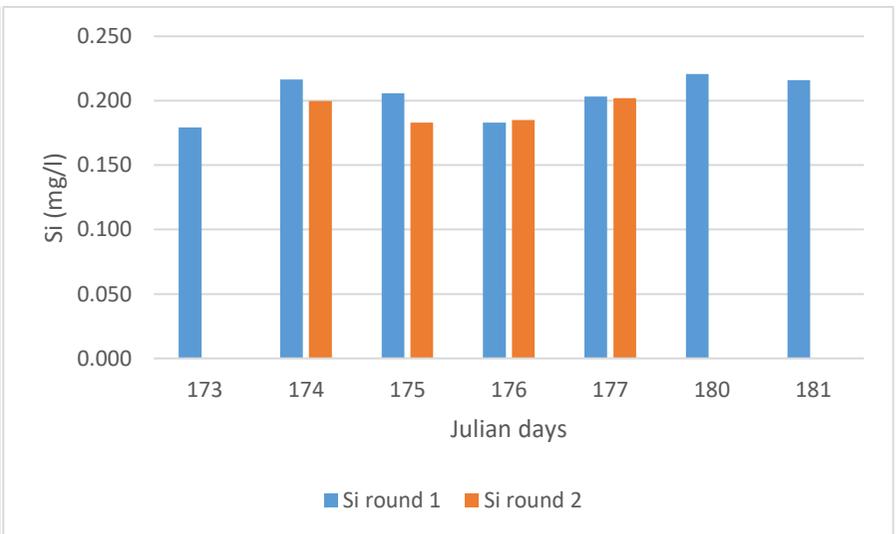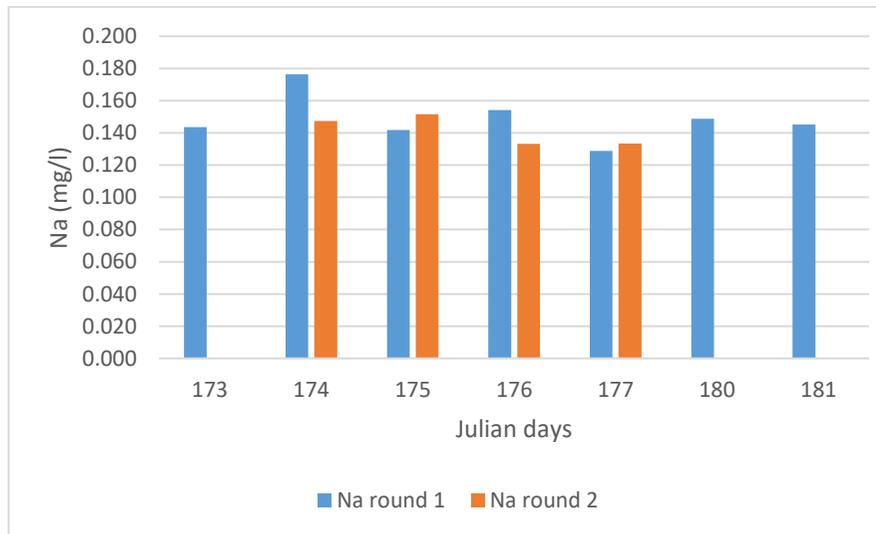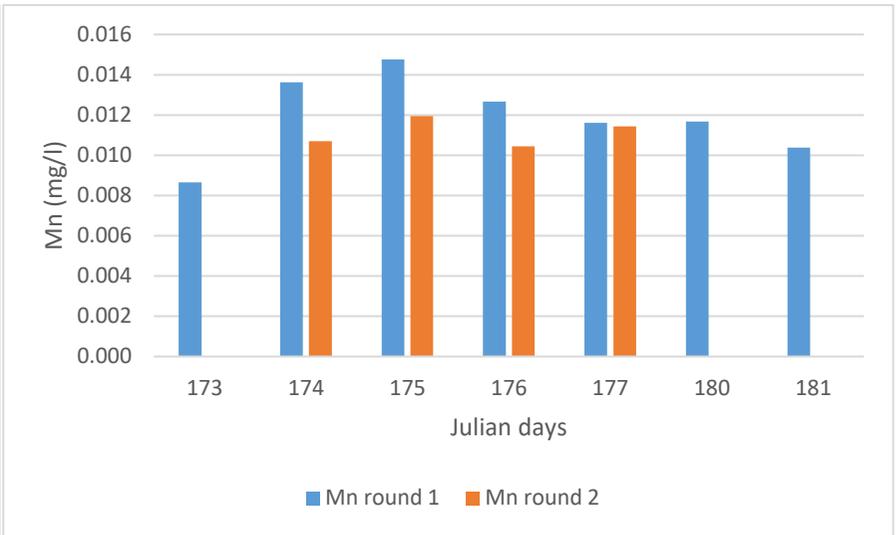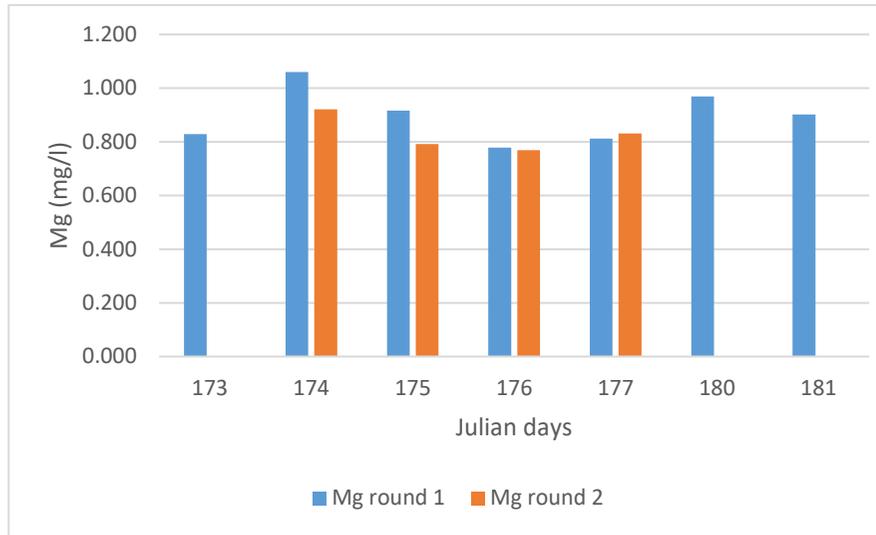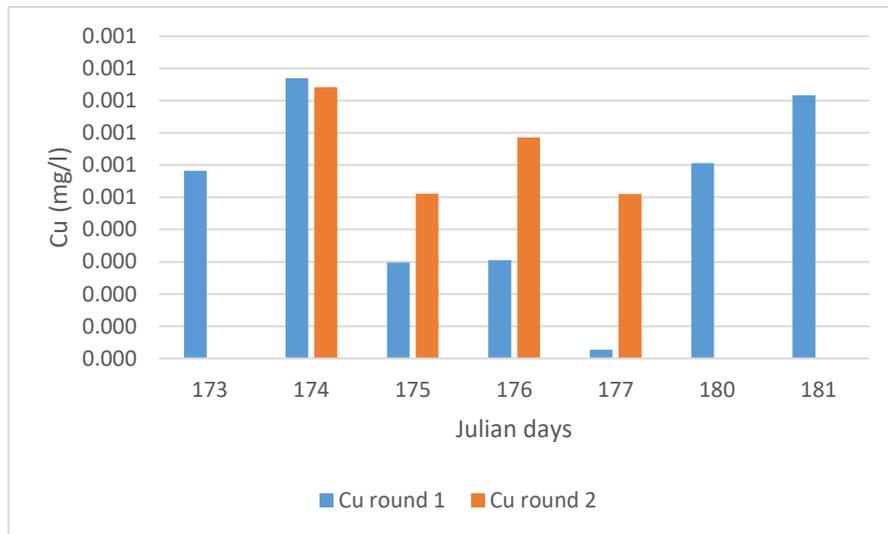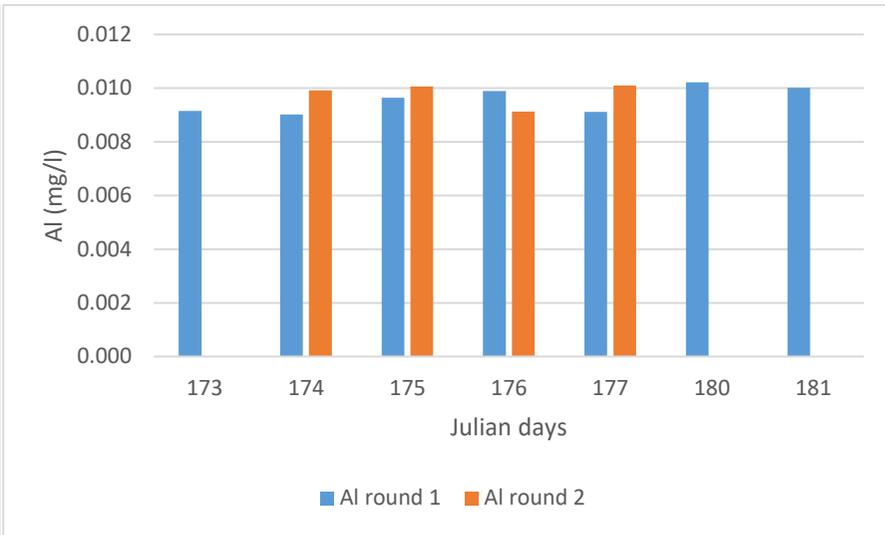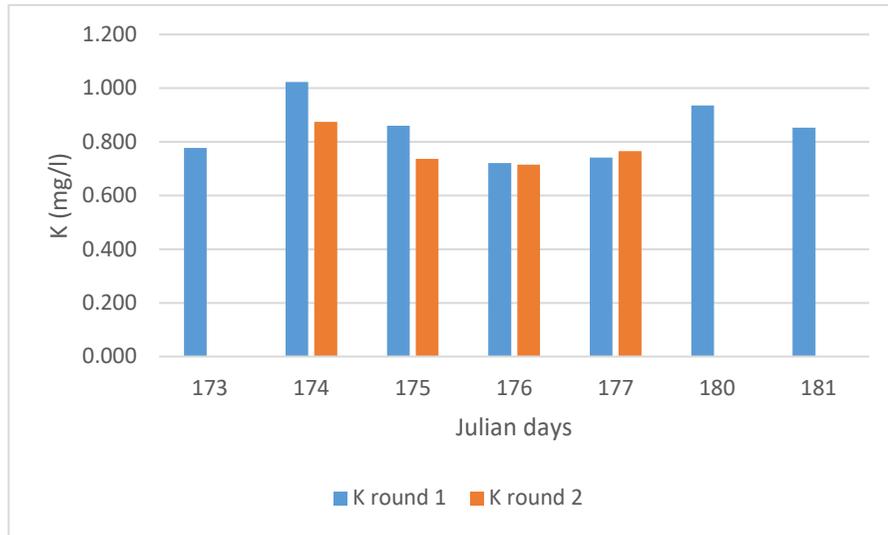
7.1.2 Bar charts location 2
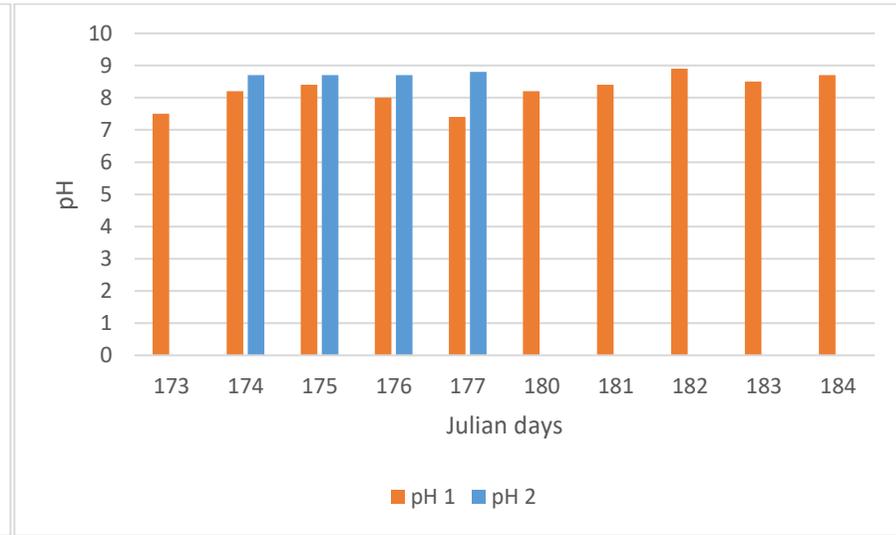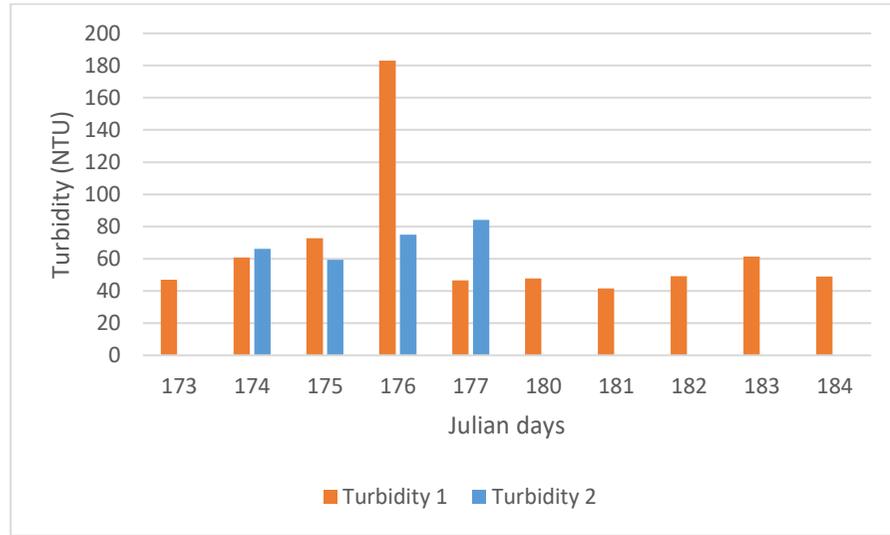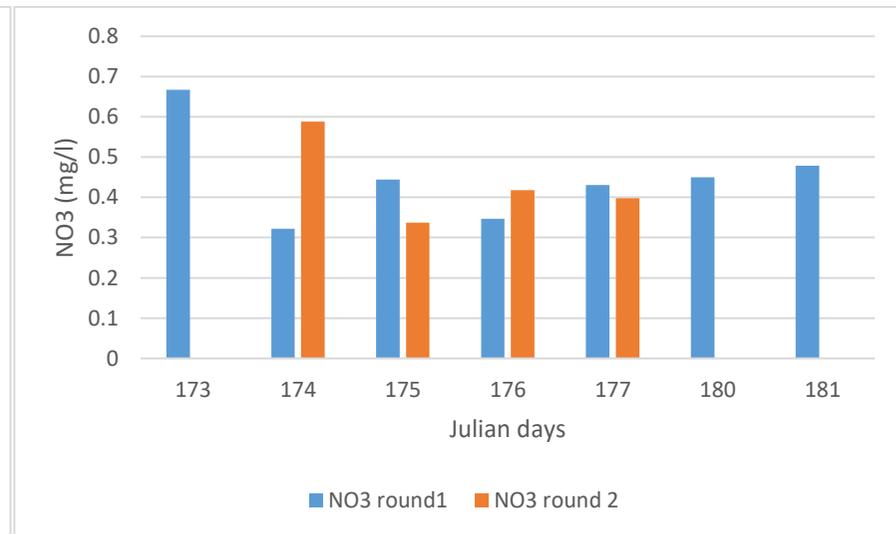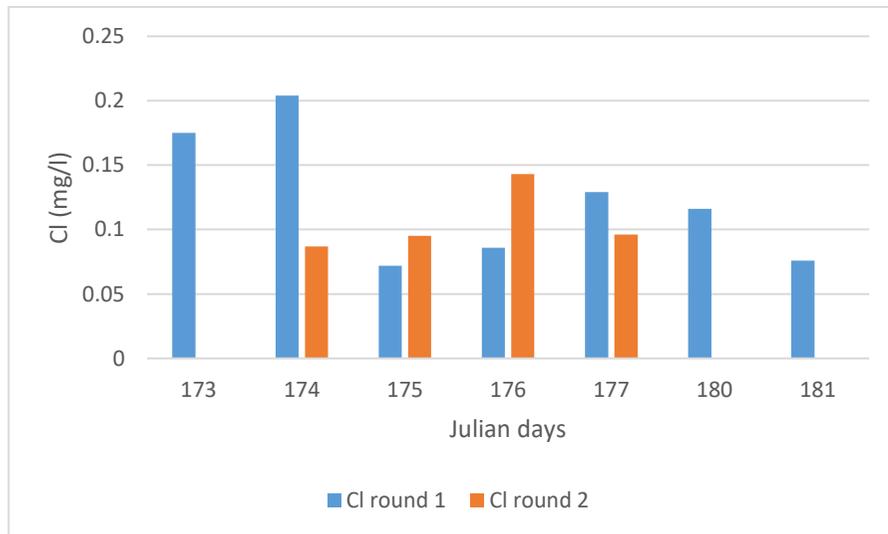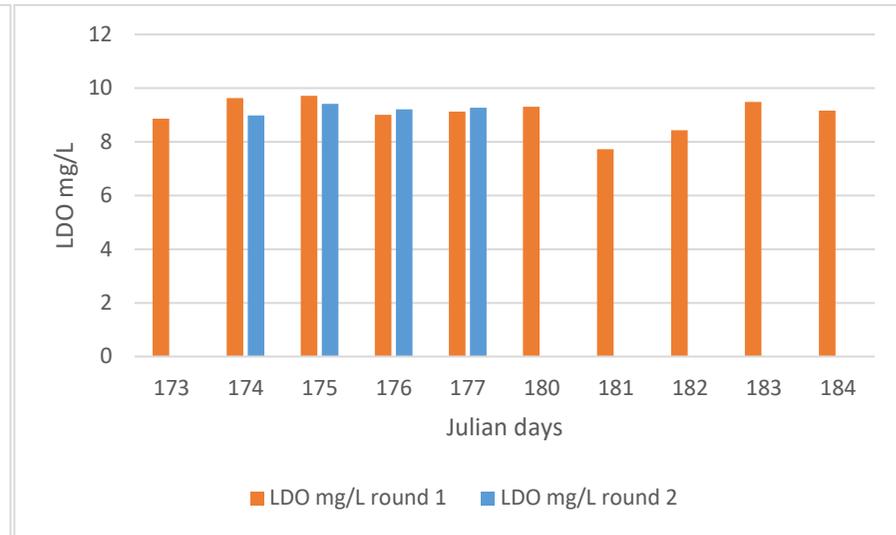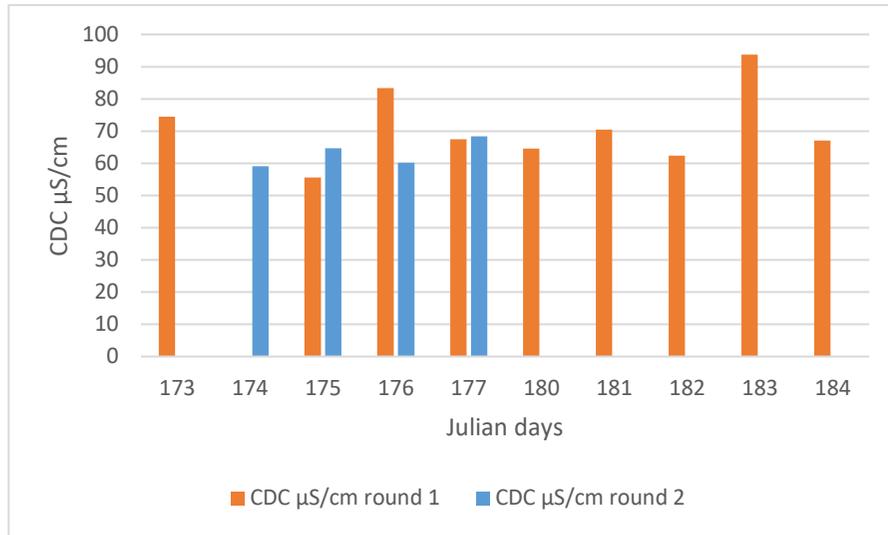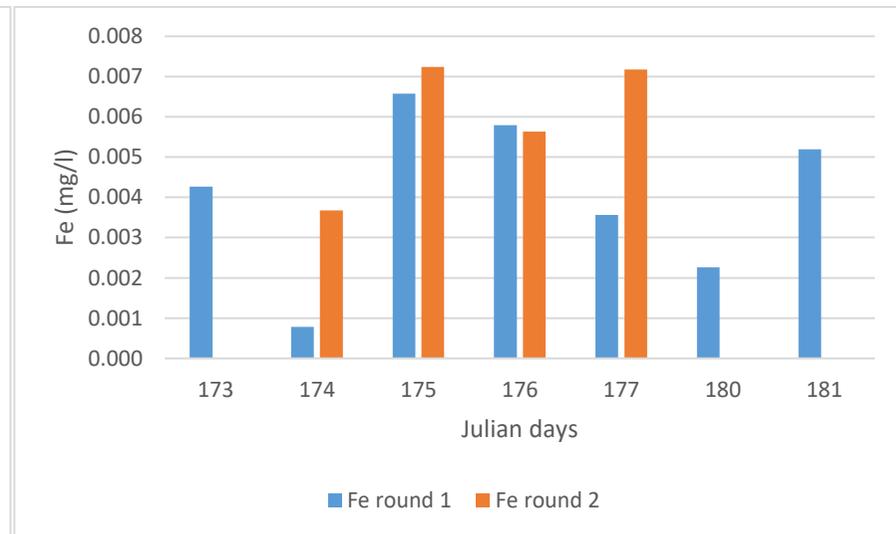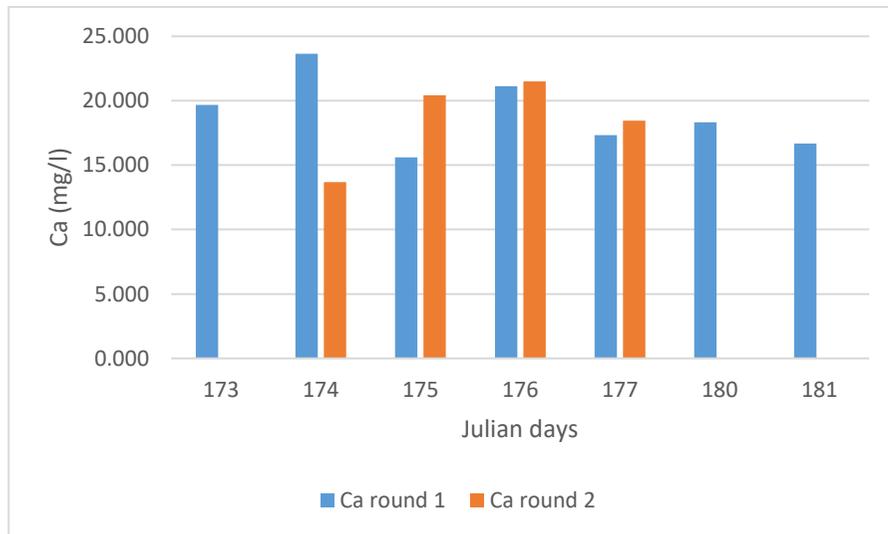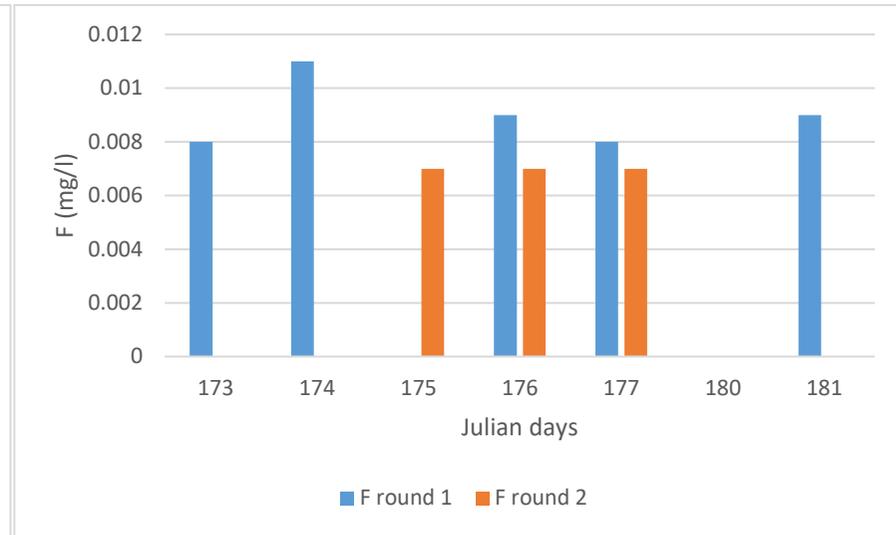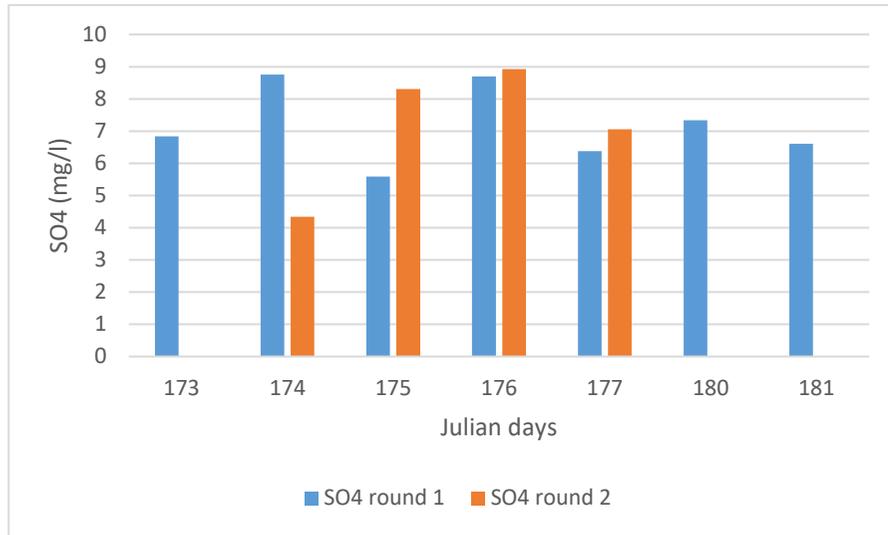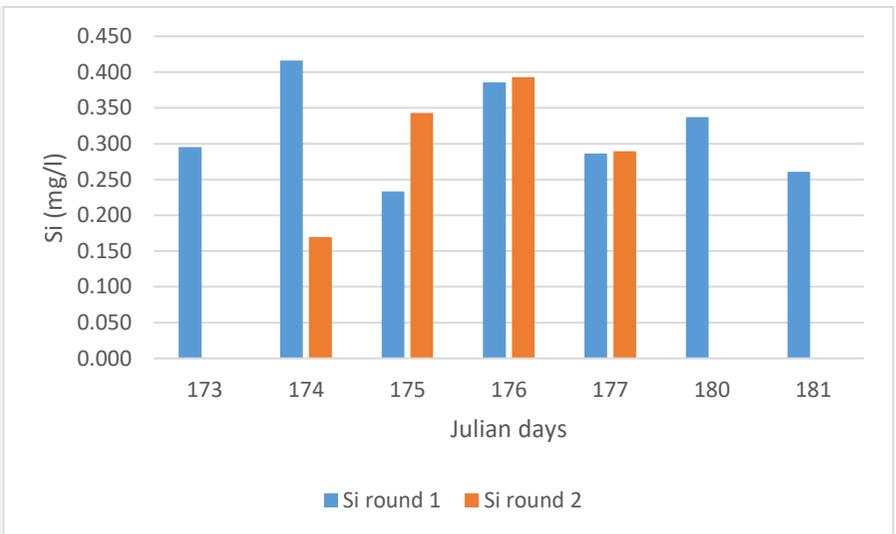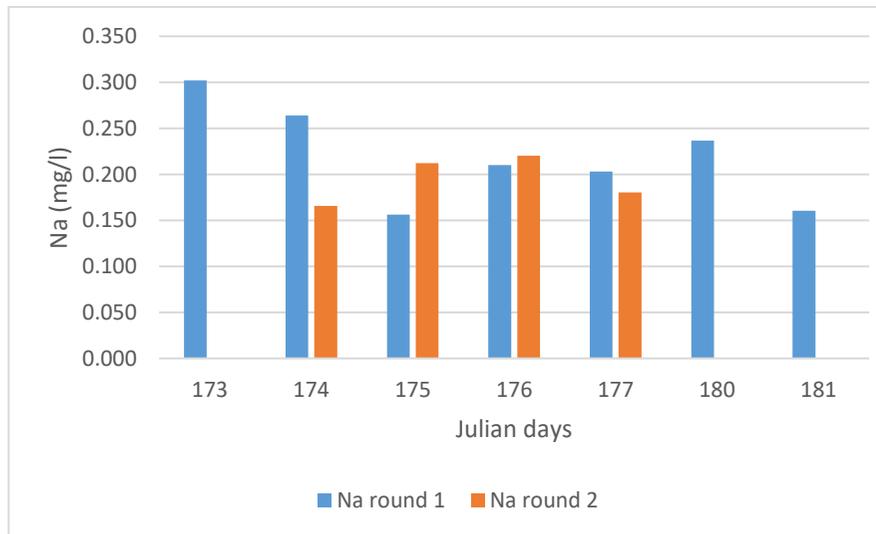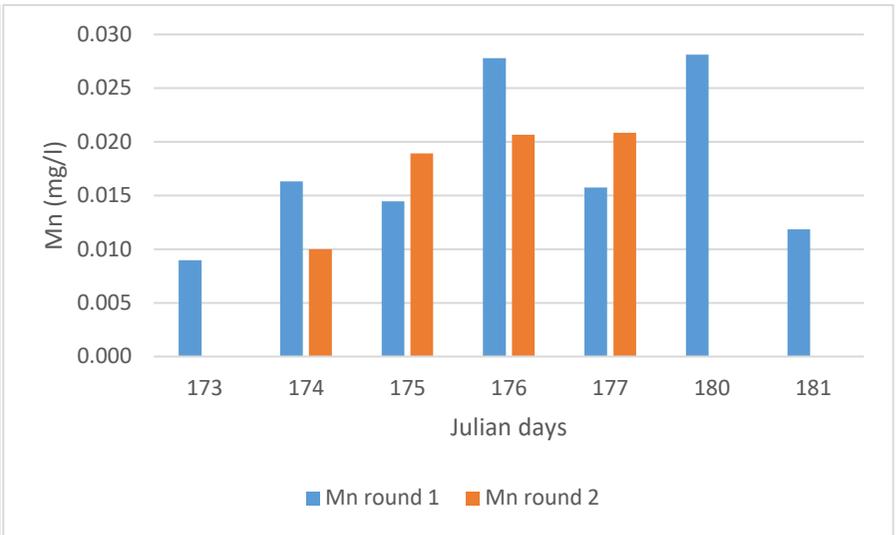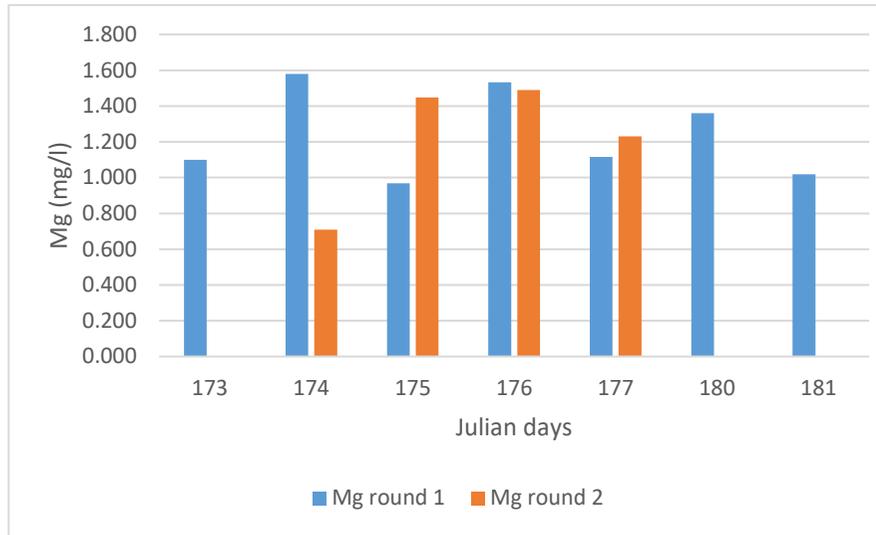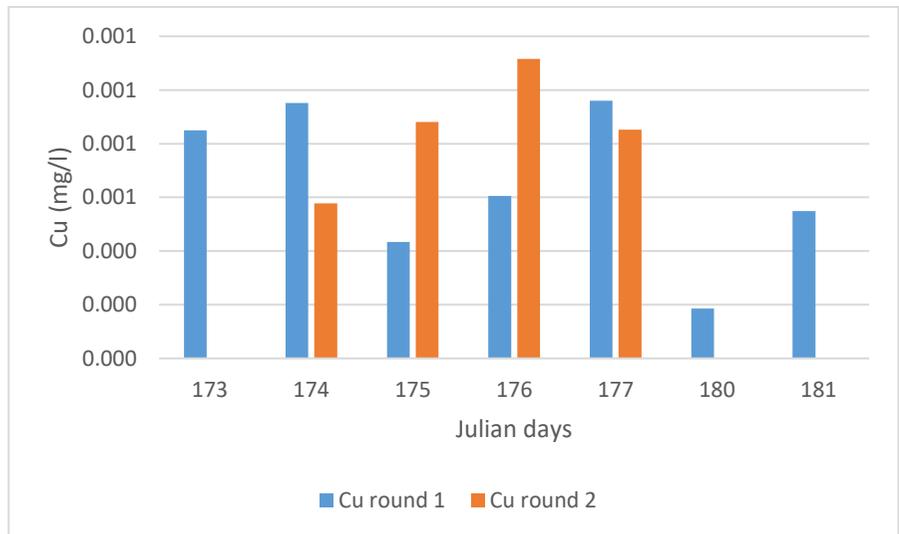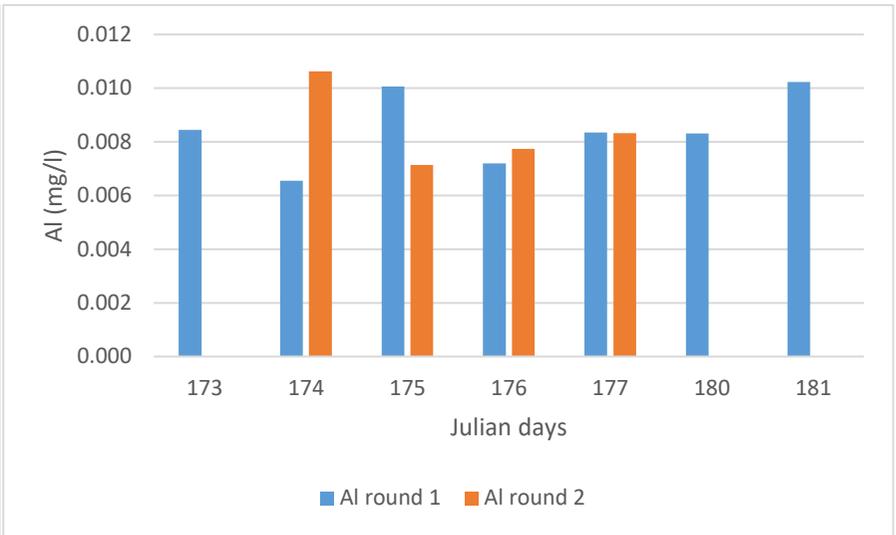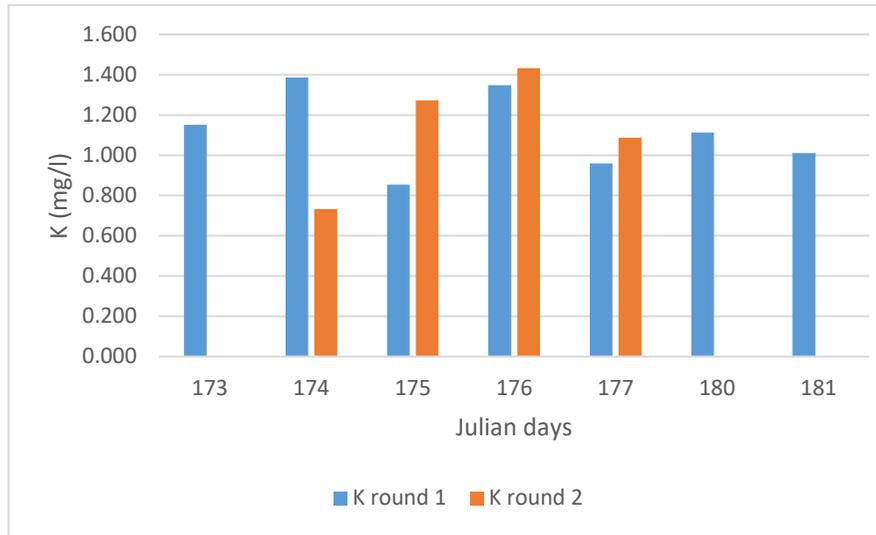
7.1.3 Bar charts location 3
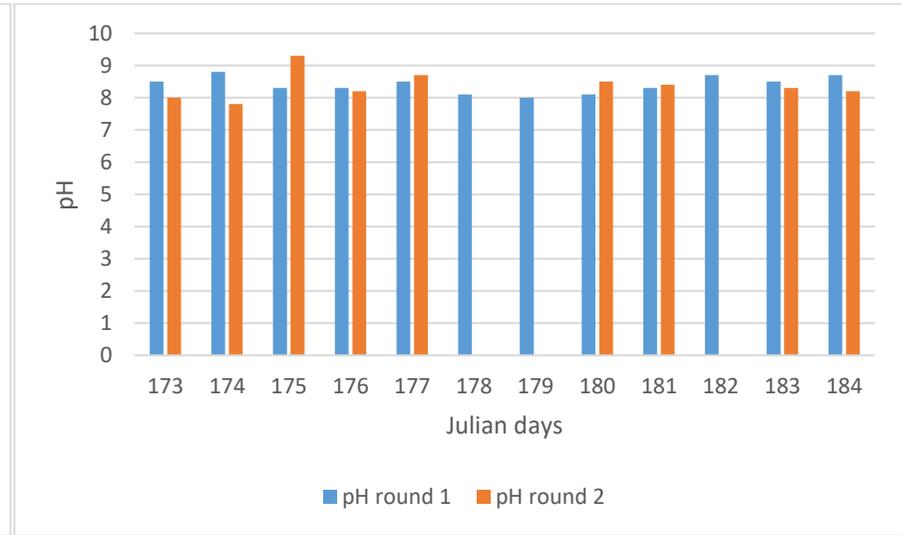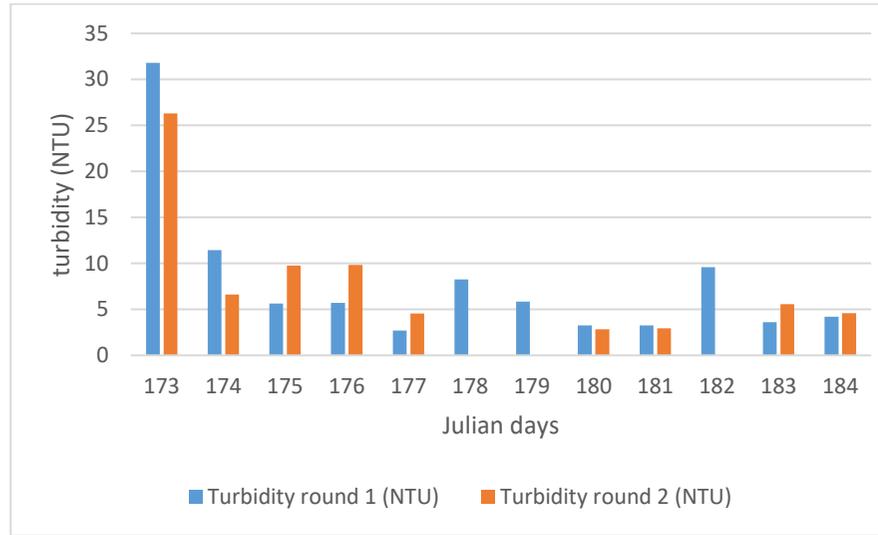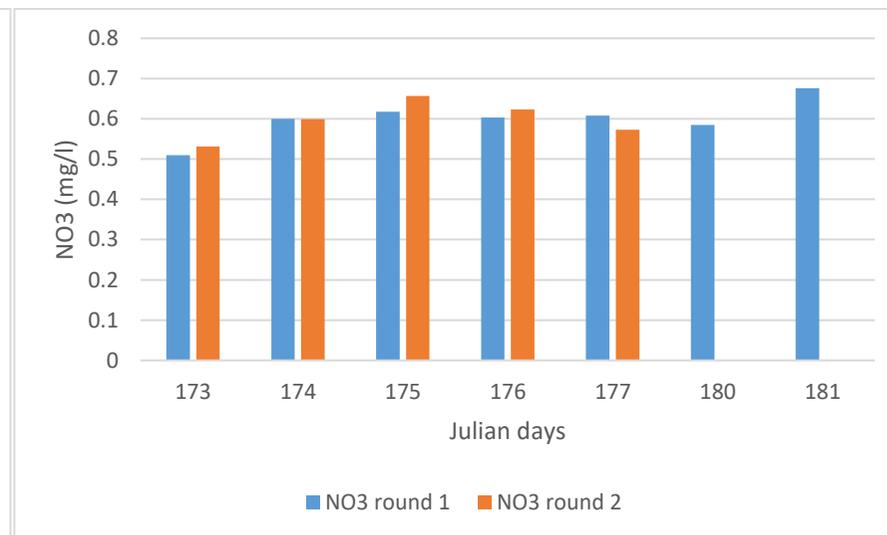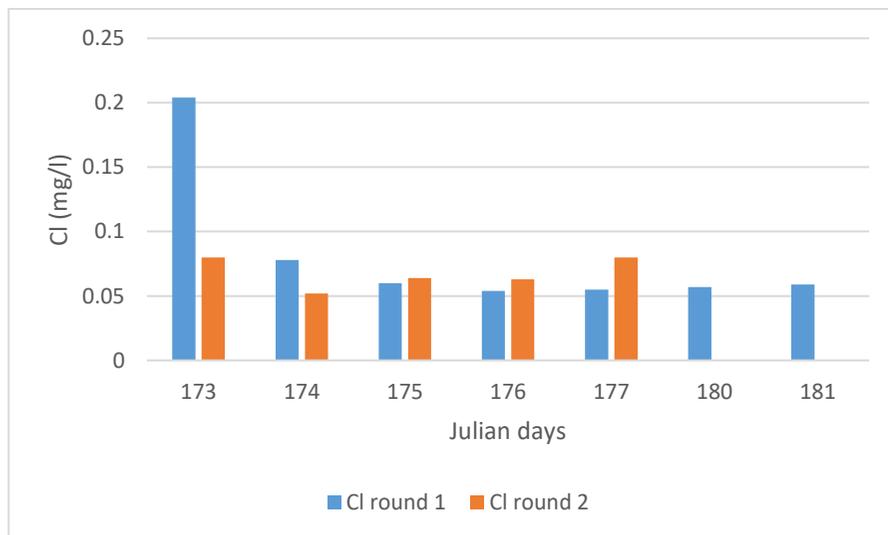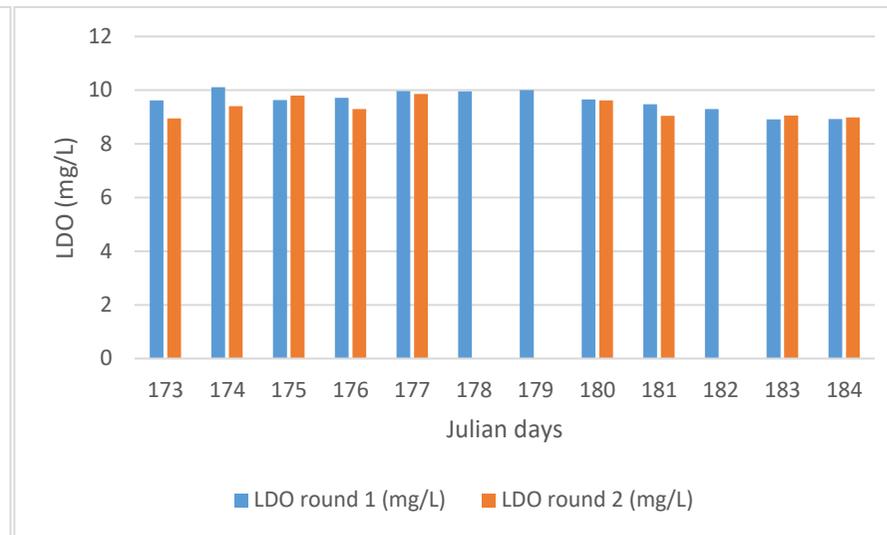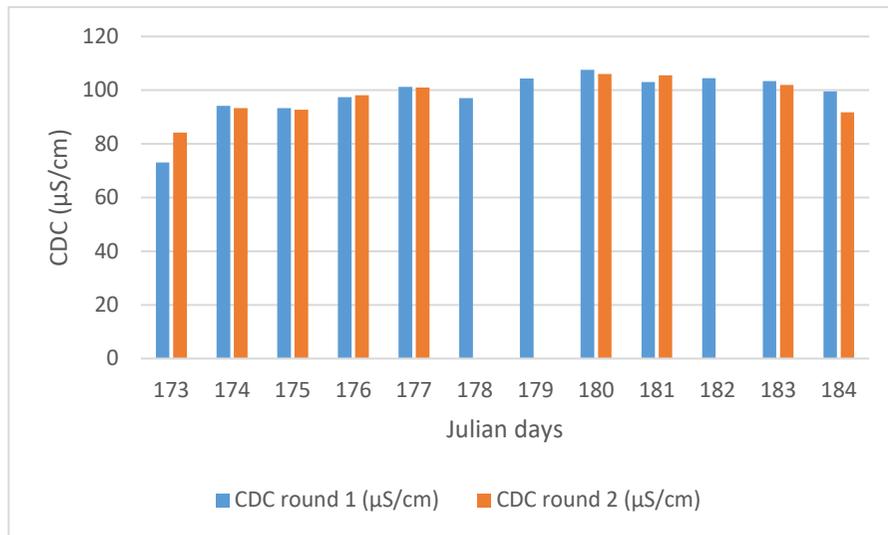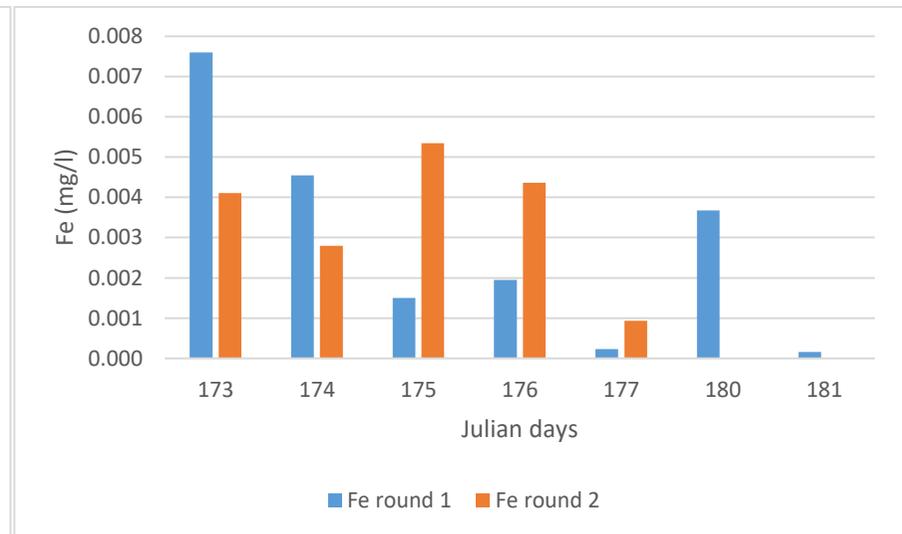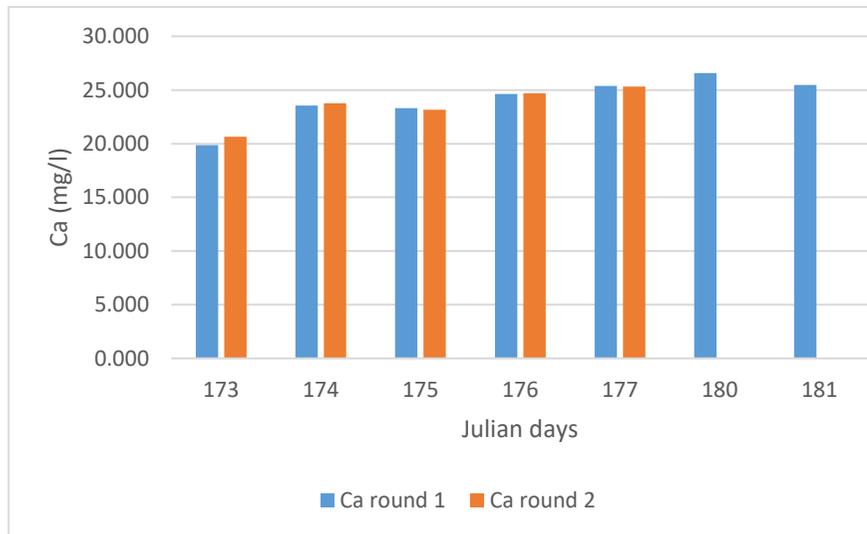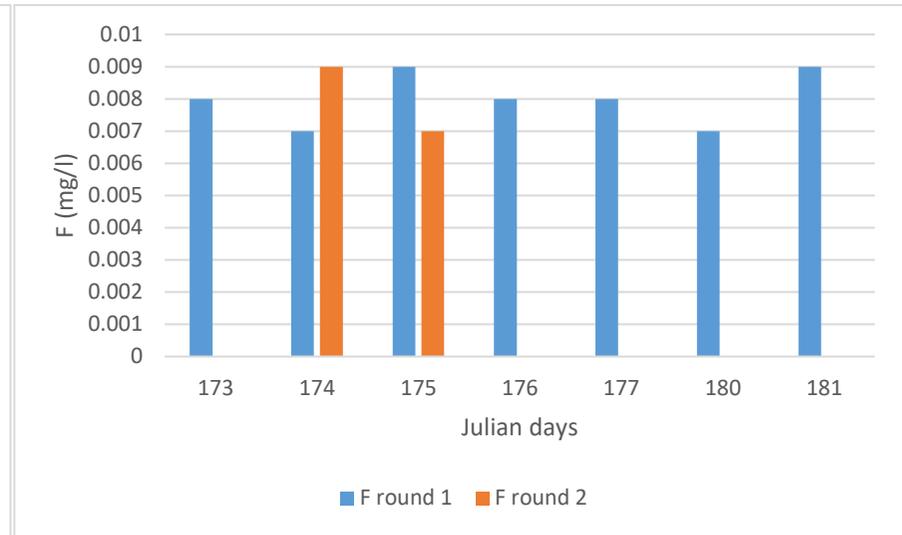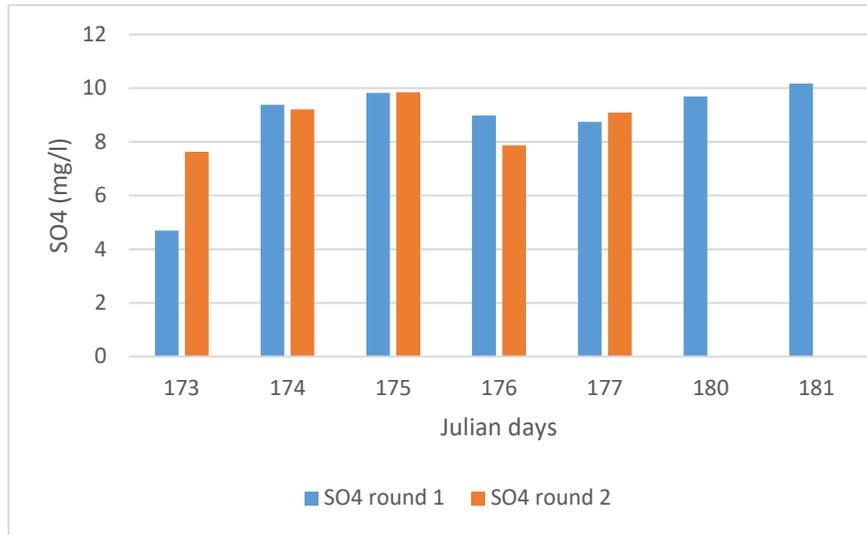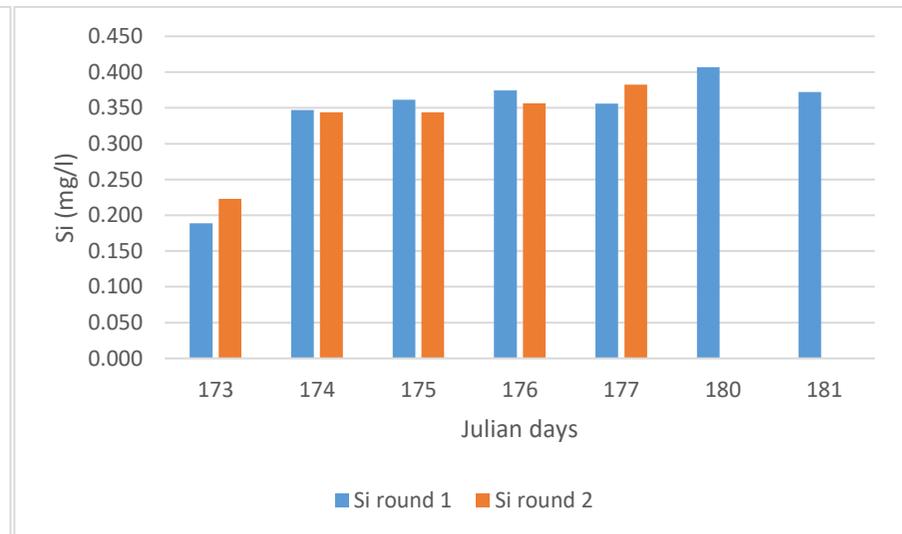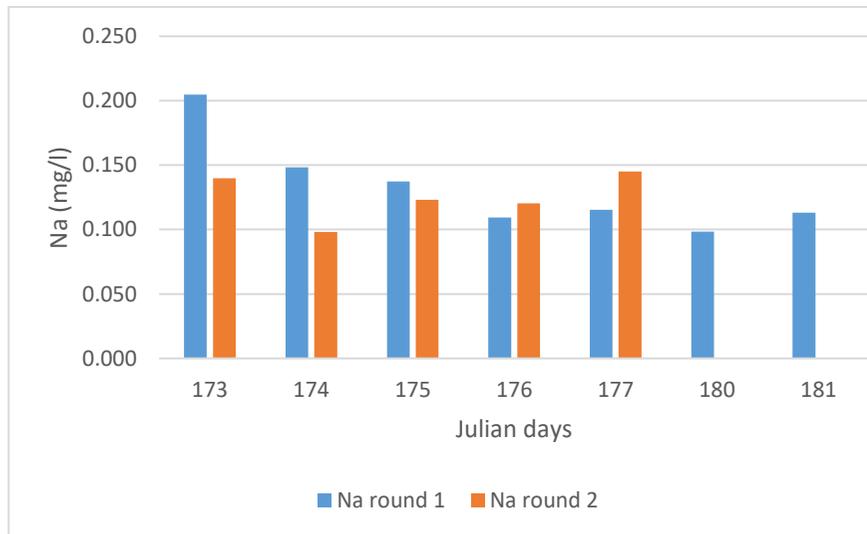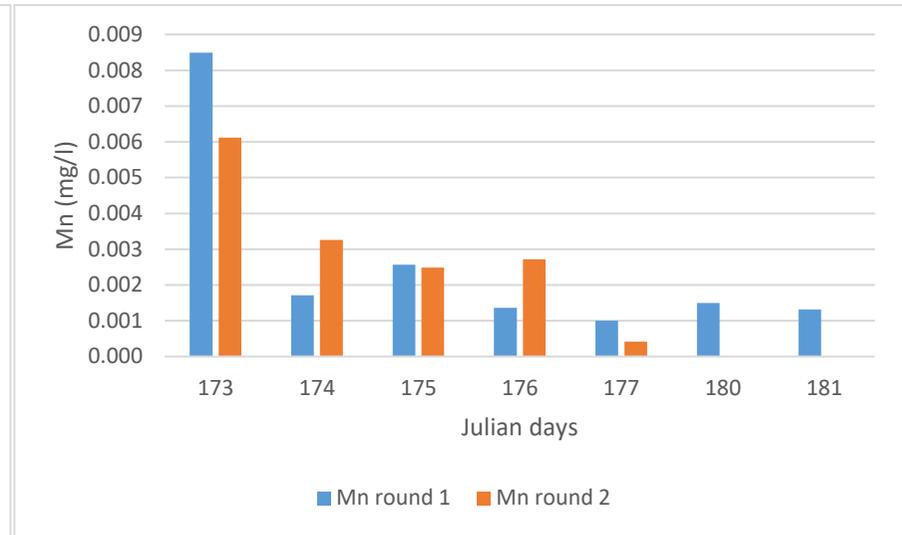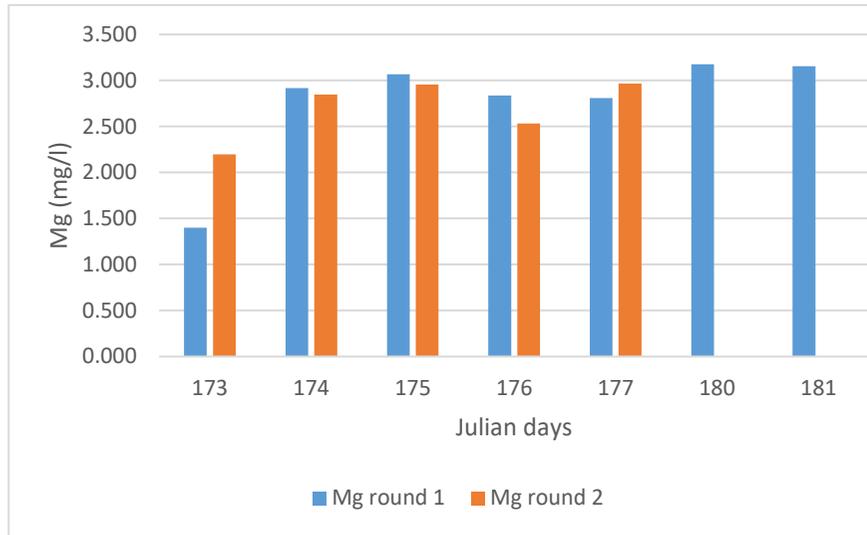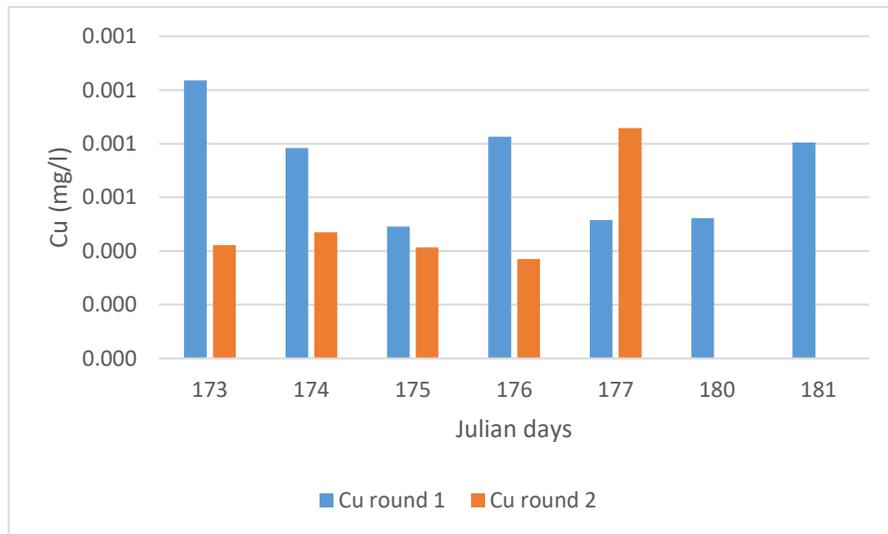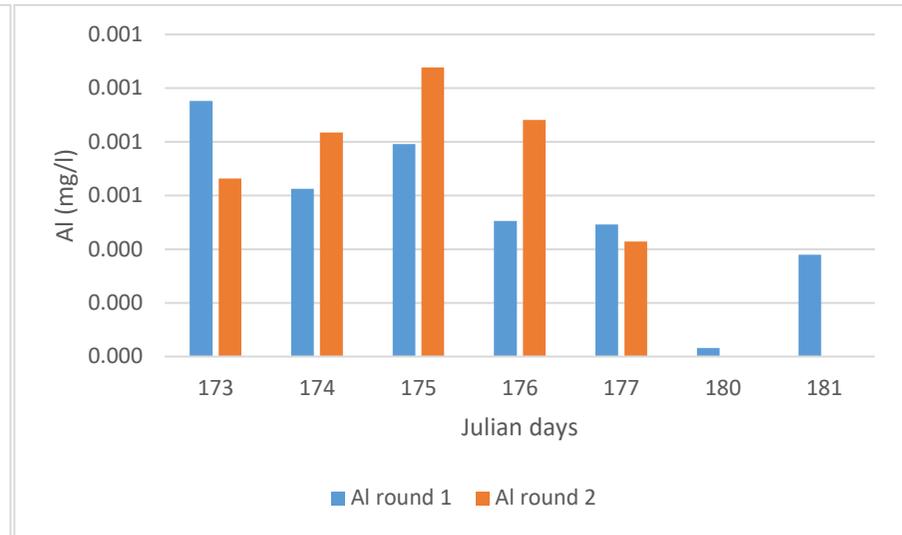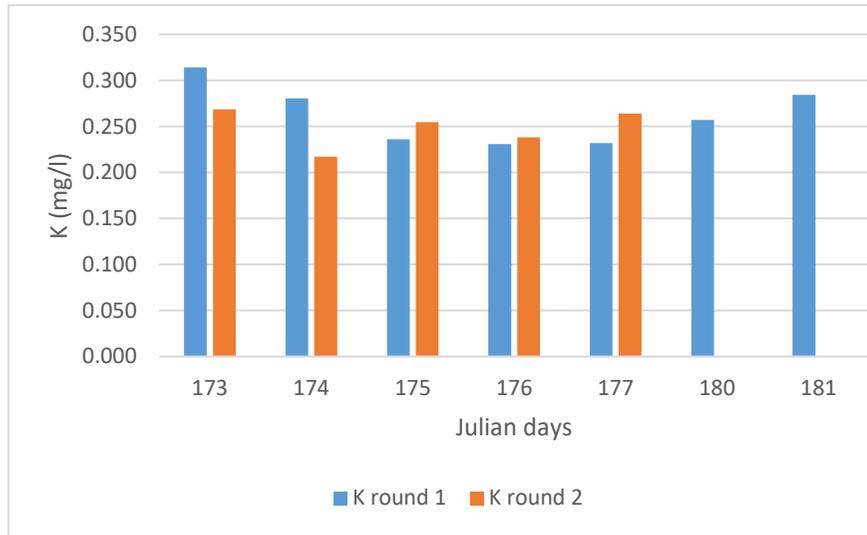
7.1.4 *Bar charts location 4*
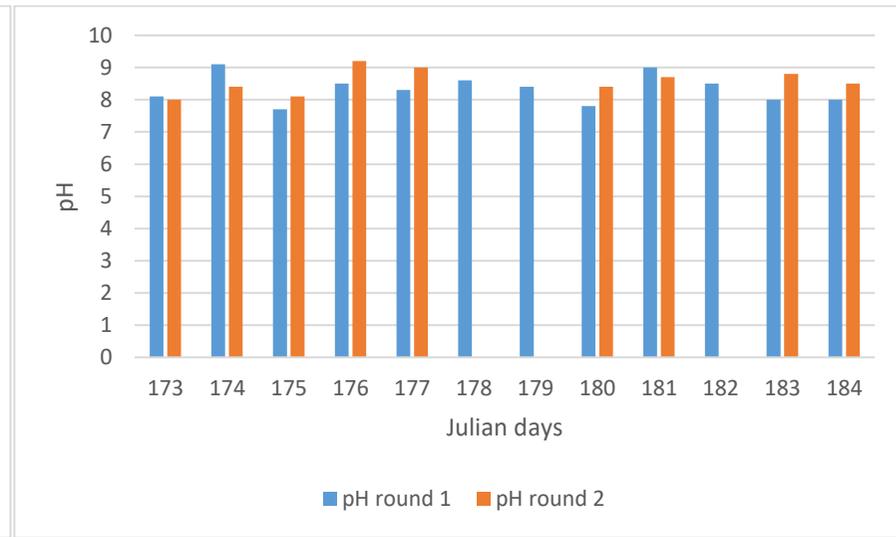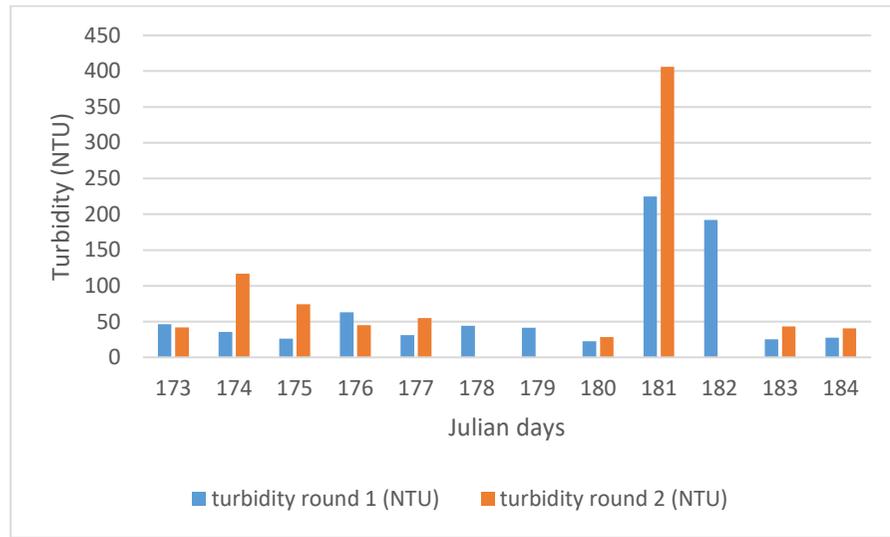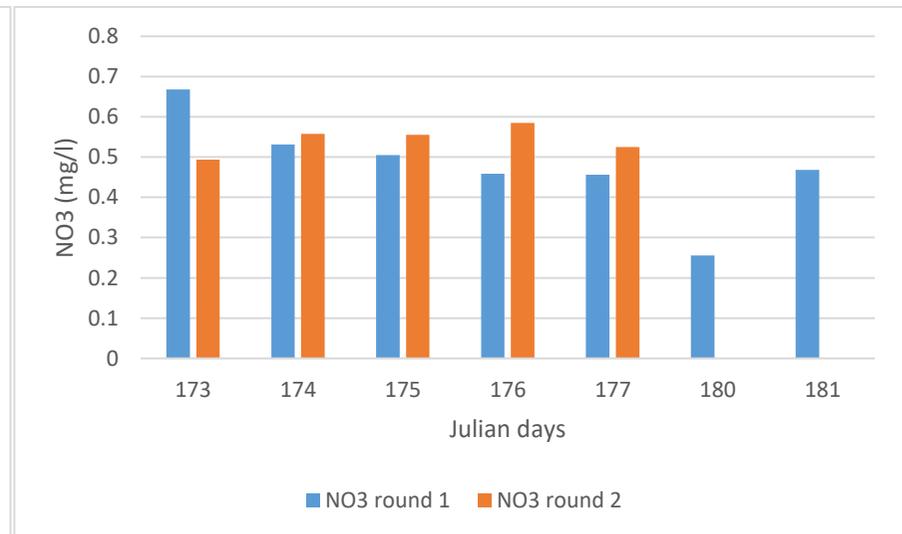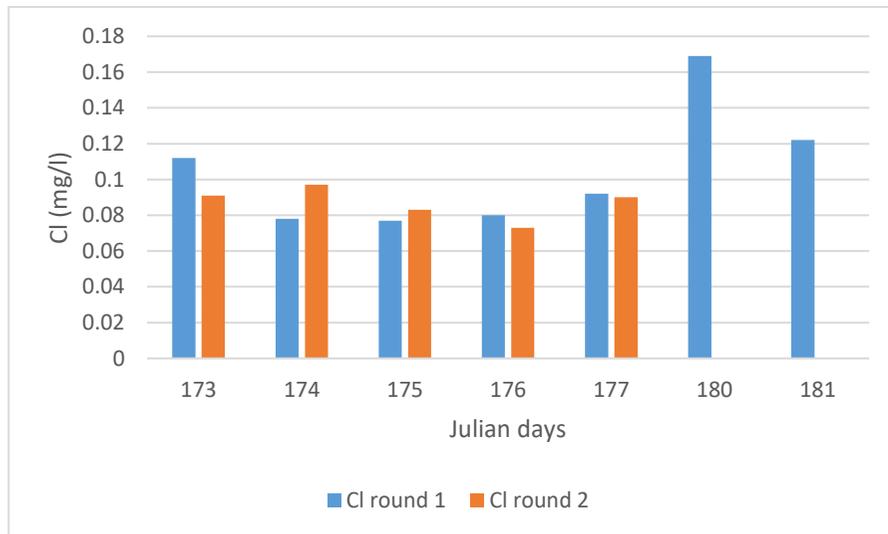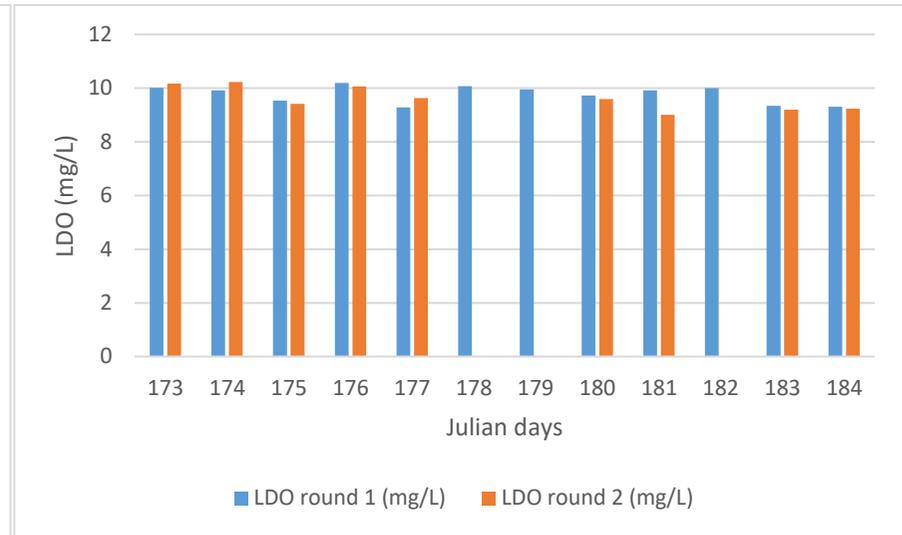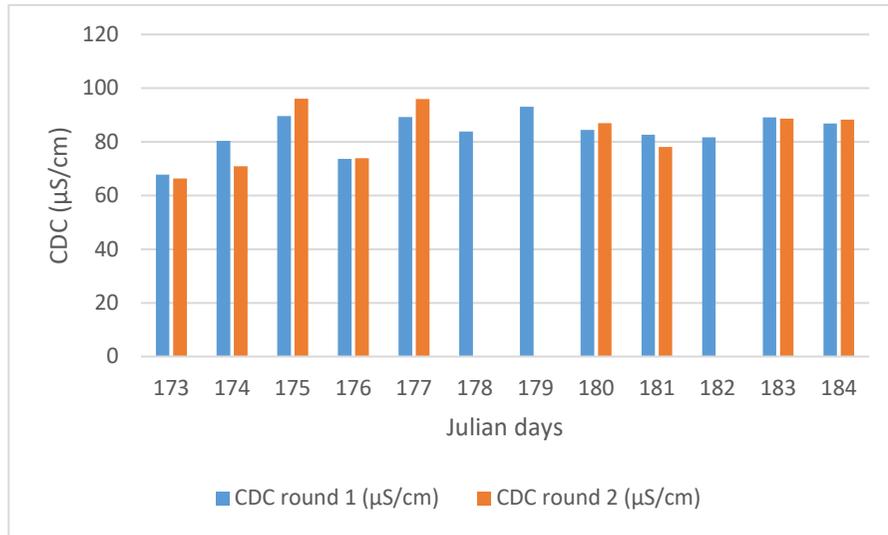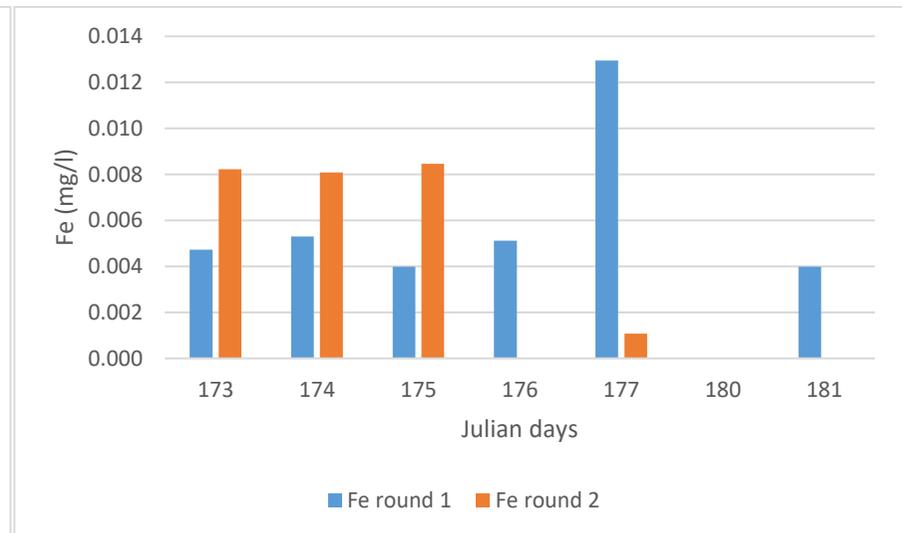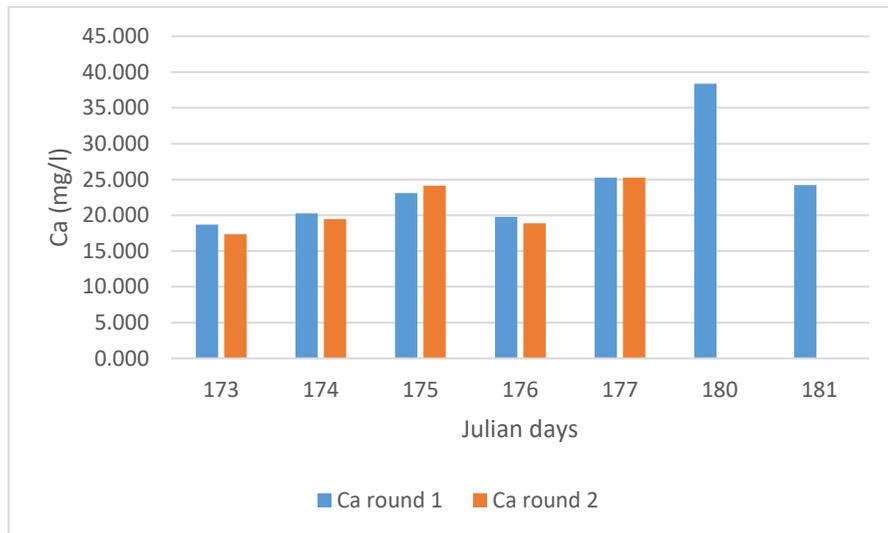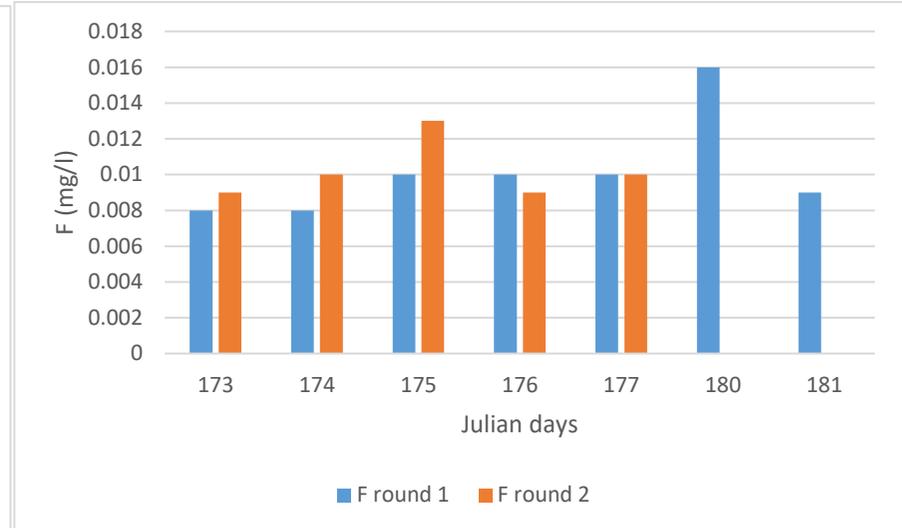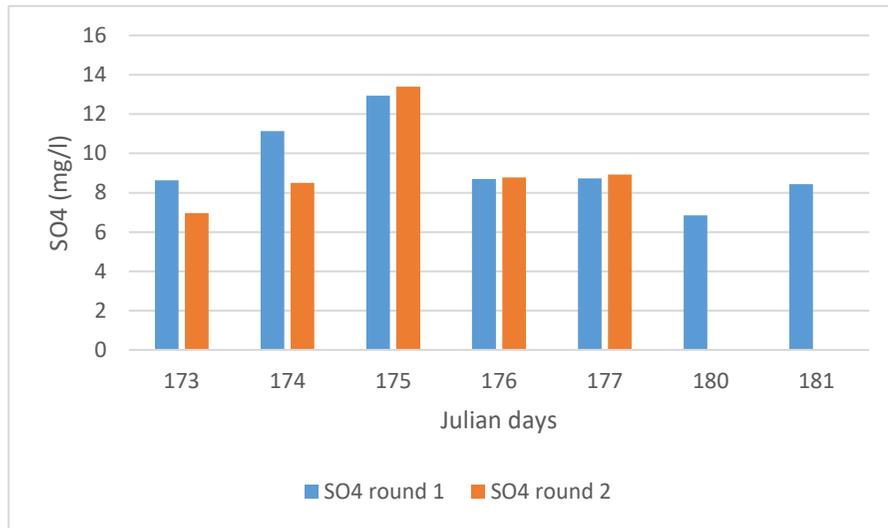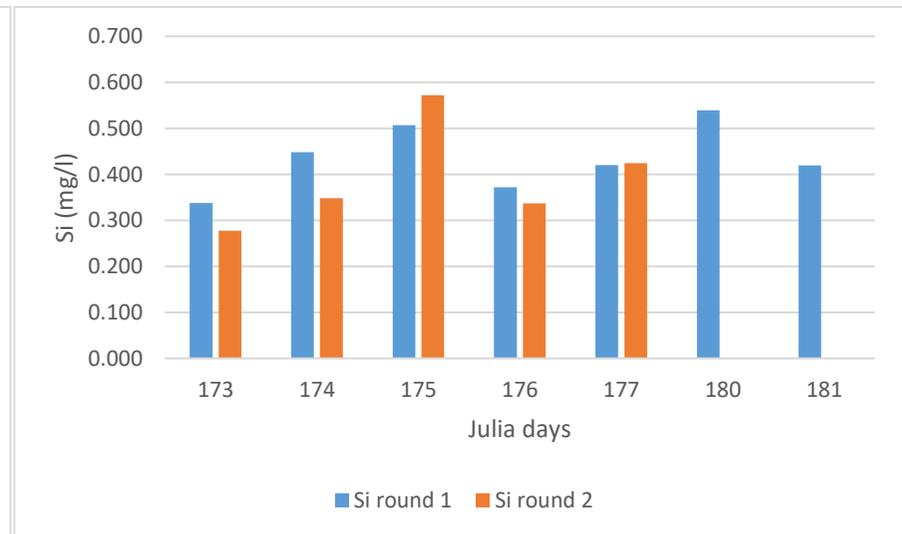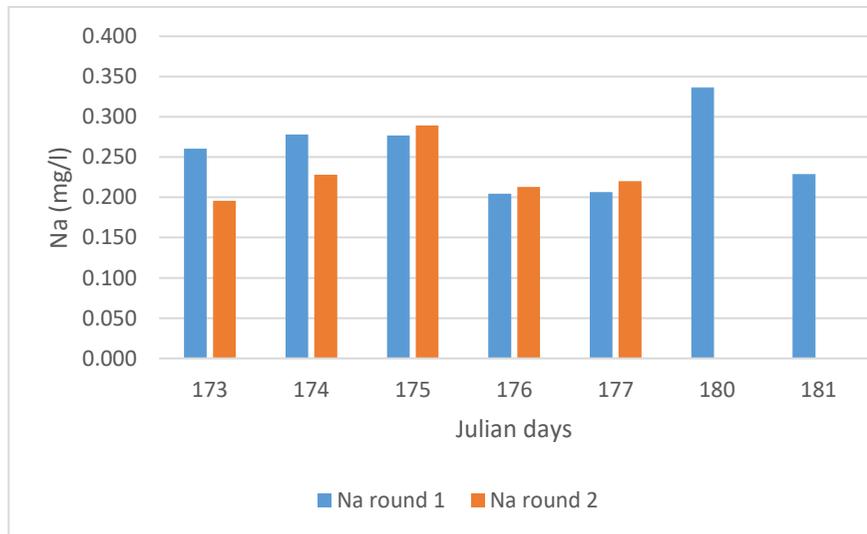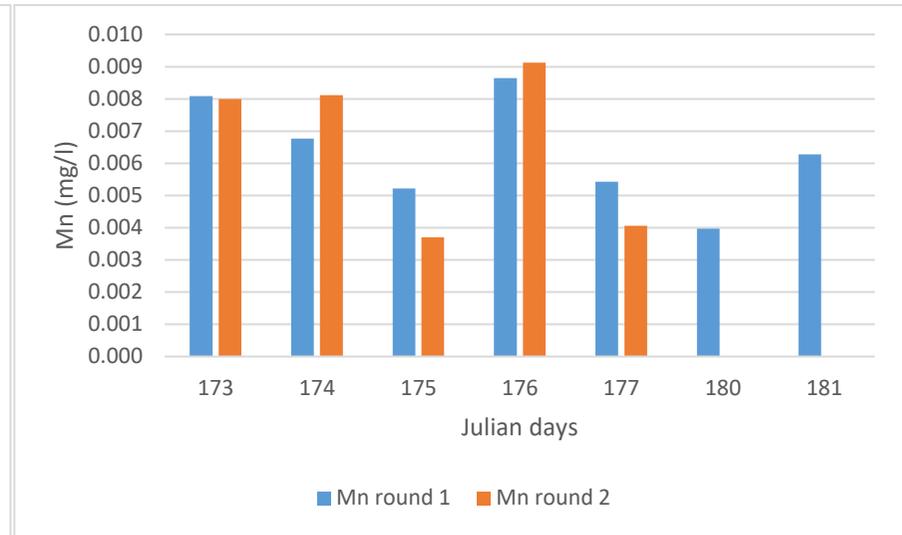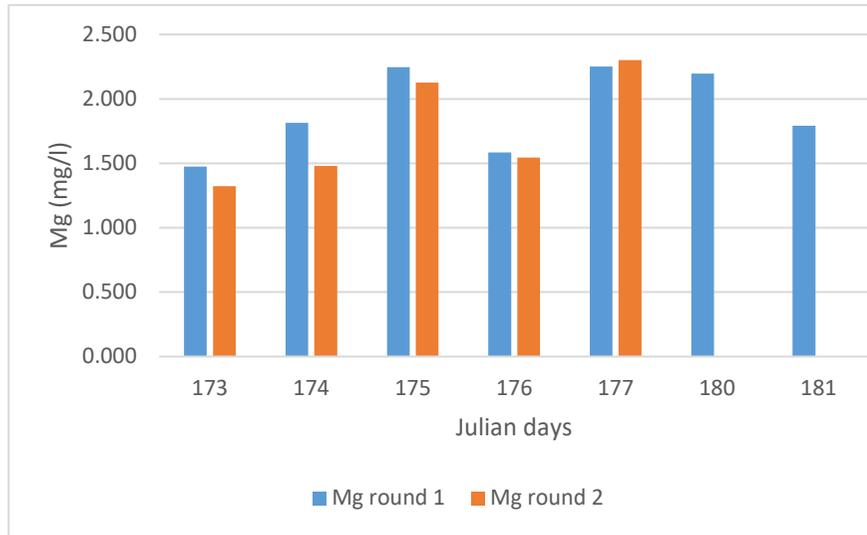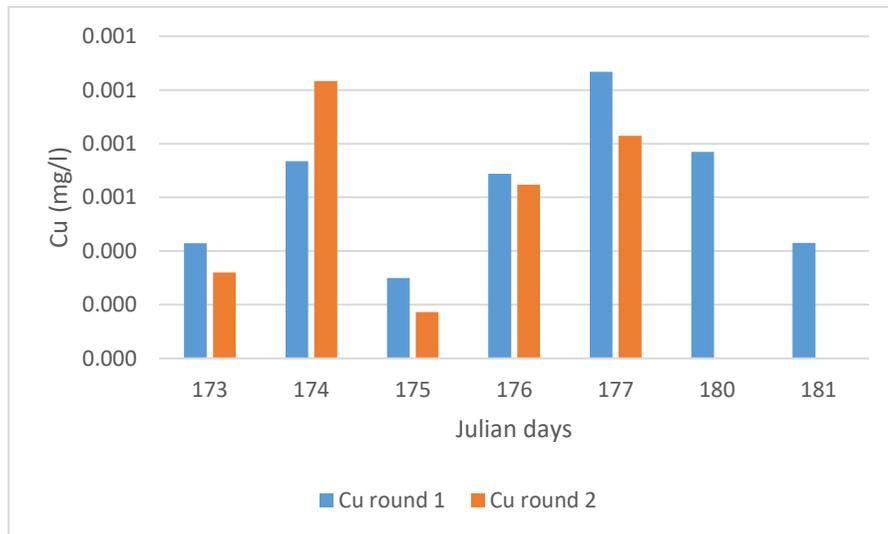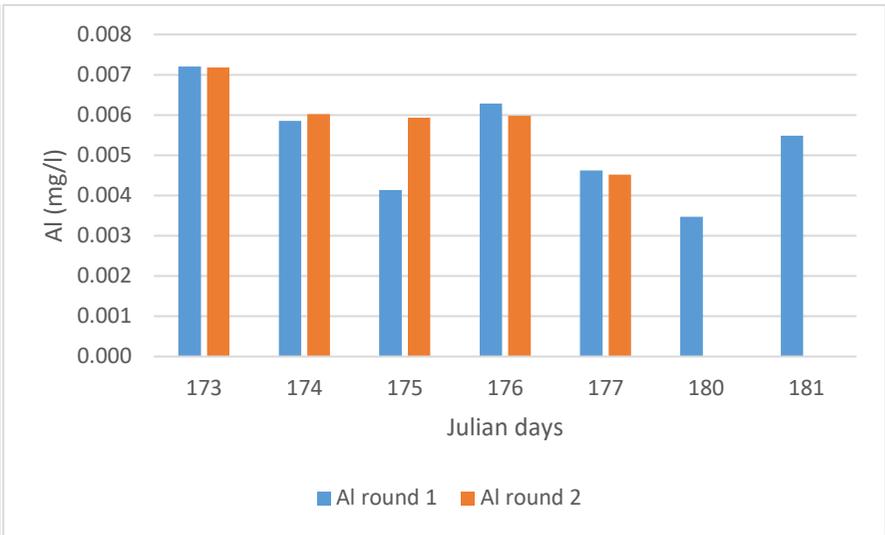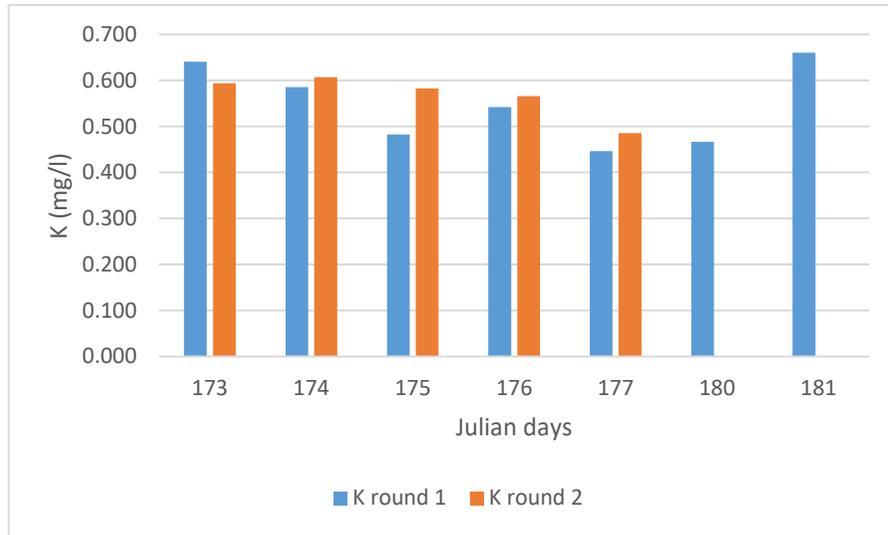
7.2 Appendix B

7.2.1 Boxplot for Cu measurements between different locations
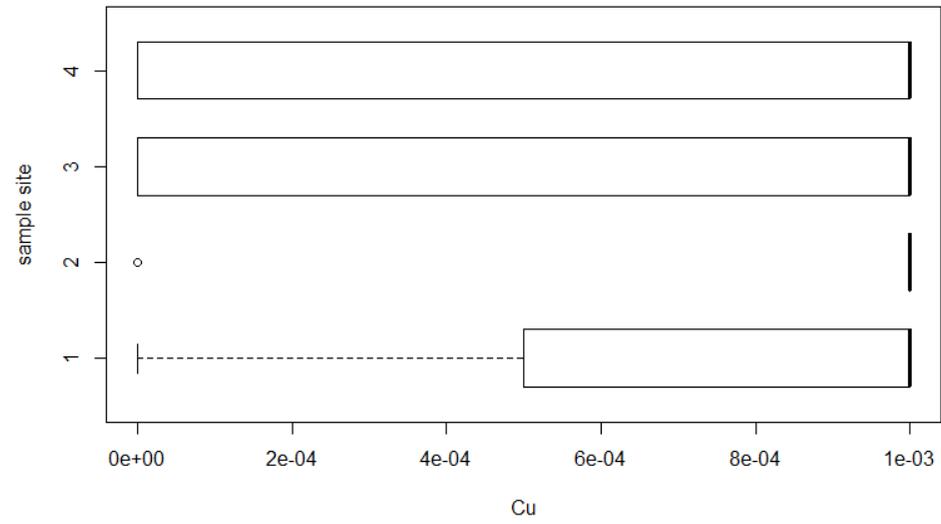
7.2.2 *Boxplots for diurnal comparison L1*

Cu
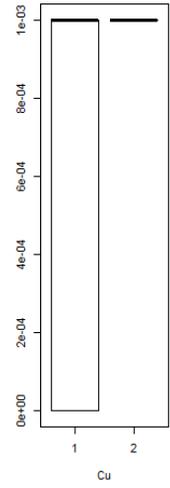
7.2.3 *Boxplots for diurnal comparison L2*
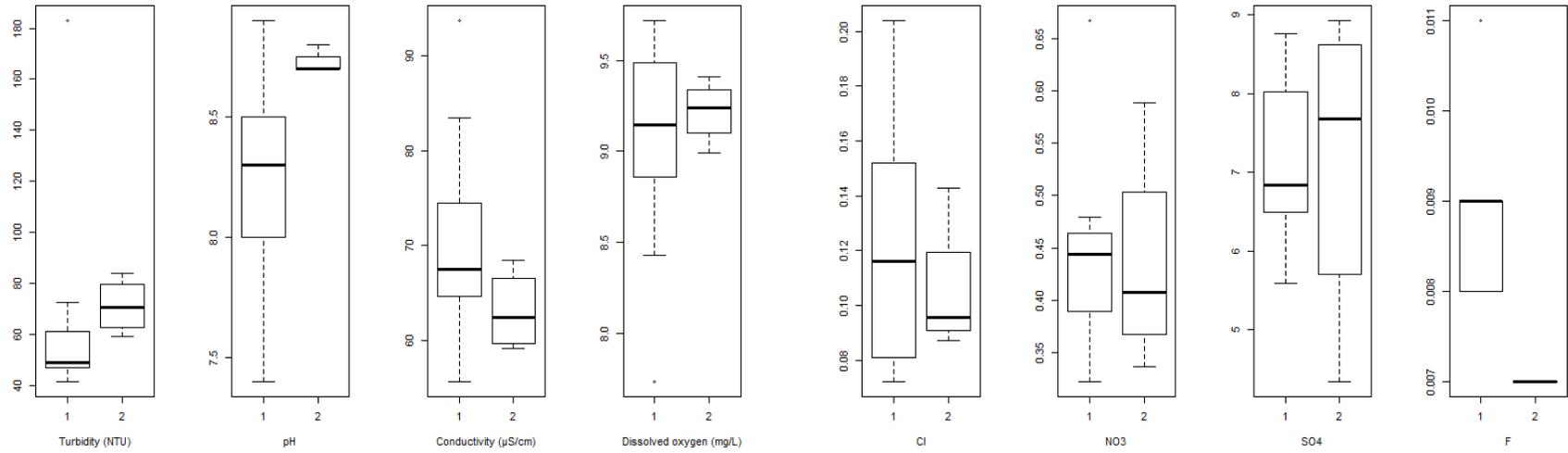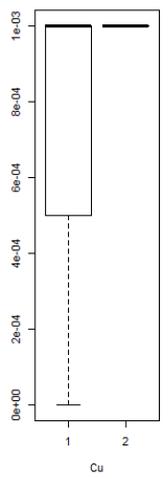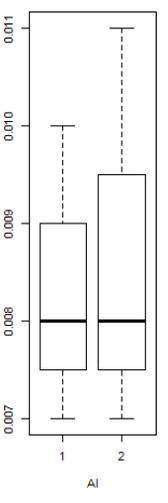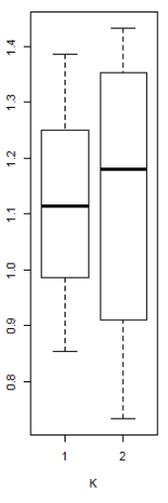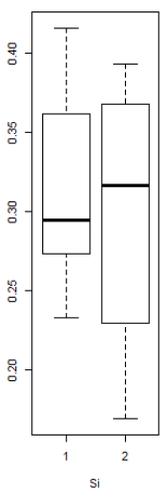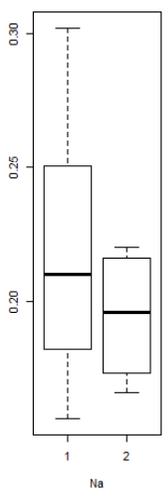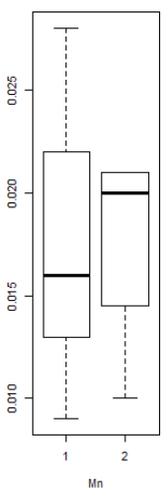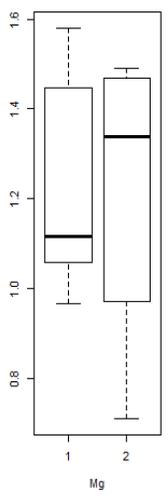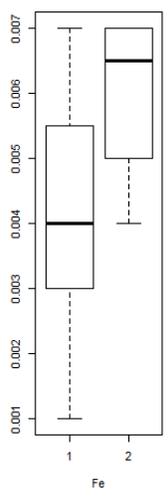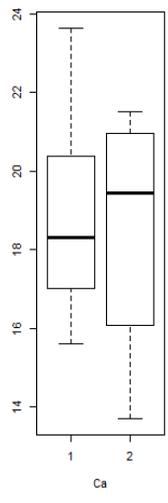
7.2.4   *Boxplots for diurnal comparison L3*

7.2.5   *Boxplots for diurnal comparison L4*

Turbidity (NTU)   pH   Conductivity (µS/cm)   Dissolved oxygen (mg/L)   Cl   NO3   SO4   F
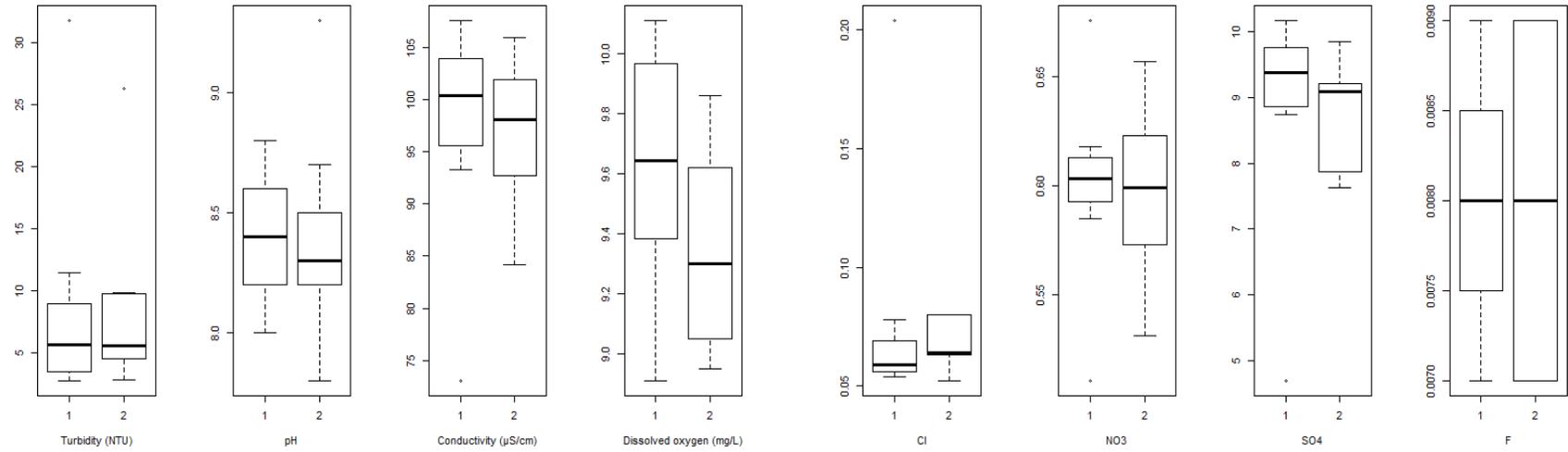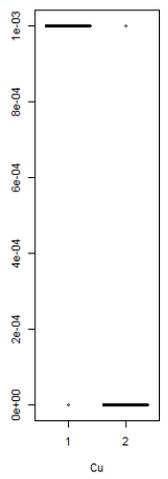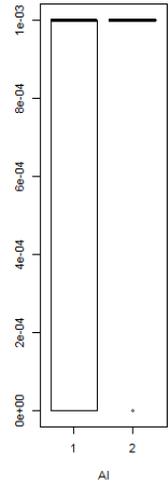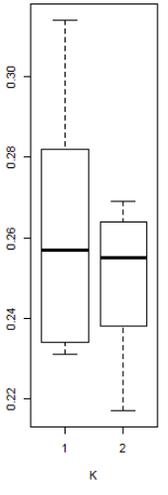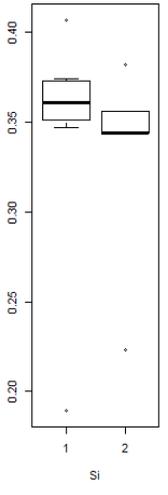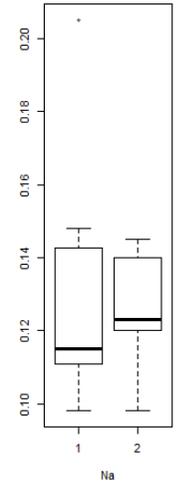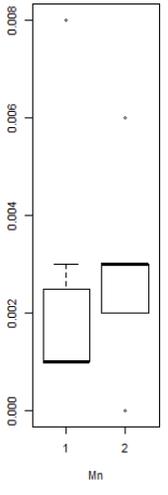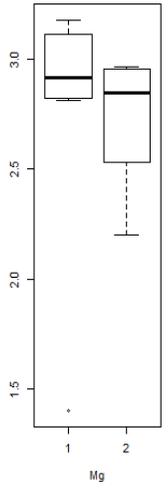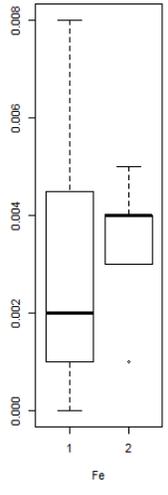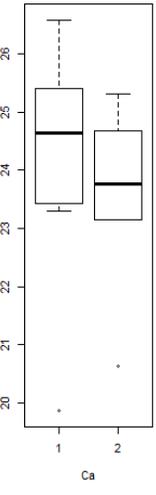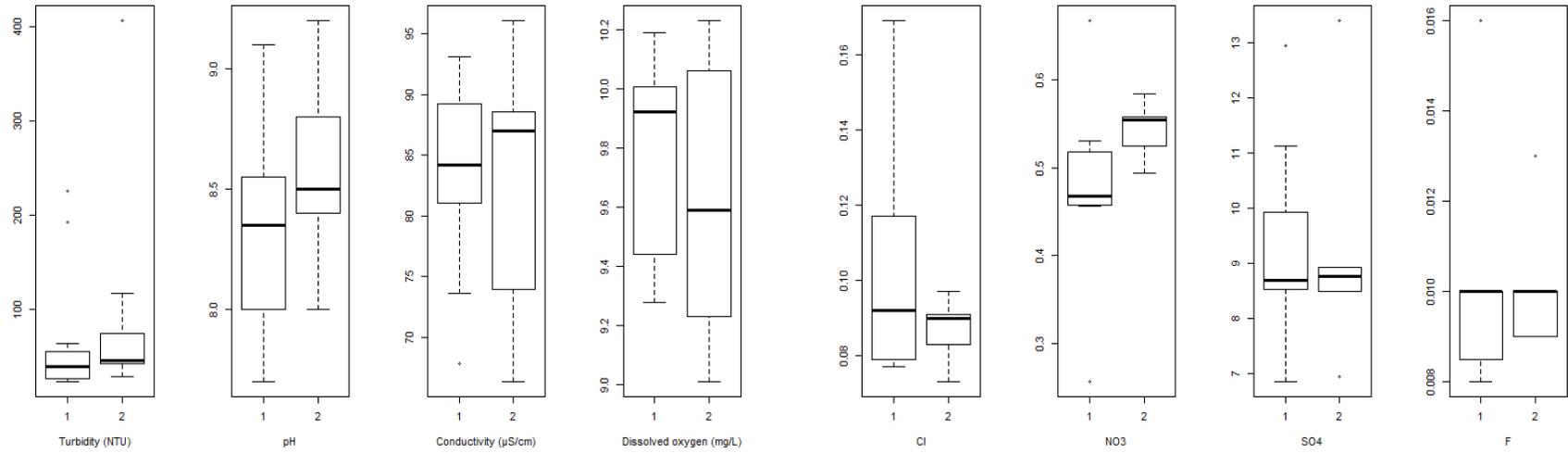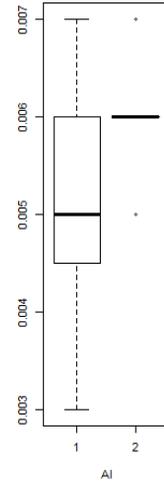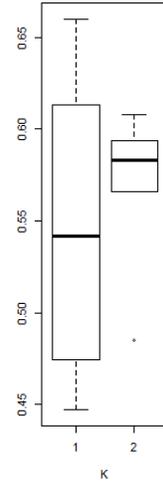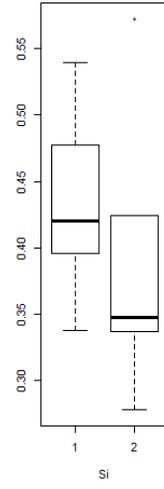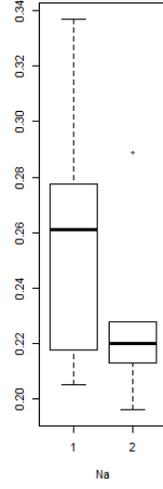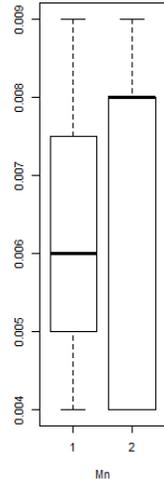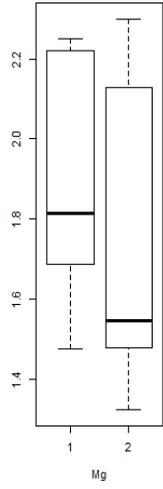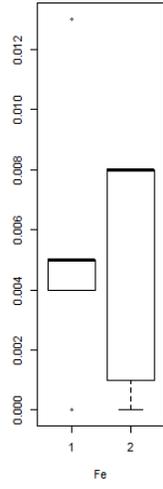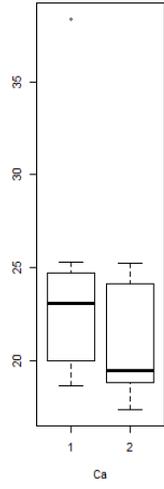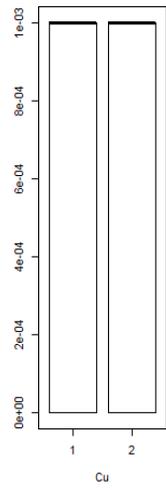
7.3 Appendix C – Declaration and DSG logs

GEOG3605: Physical Geography Dissertation Risk Assessment and Interim Reports Declaration

You do NOT need to submit the following documents again as they are archived on Minerva but you **MUST** confirm that you have submitted and (a) had approval if required for your fieldwork and (b) passed your interim reports prior to submitting your dissertation. You cannot use data that were collected without an approved risk assessment. You cannot pass the dissertation module without passing both interim reports. It is a requirement of GEOG3605 that you have an approved risk assessment (unless you have not undertaken fieldwork that required a risk assessment) AND that you pass both interim reports. Please see the handbook for further details. This form replaces the need to include these documents as appendices in the dissertation.

Please submit a copy of this form as an appendix with your dissertation.

(a1) I confirm that I have an approved risk assessment for my fieldwork (tick the box).   ✓

OR

(a2) I confirm that I did not undertake fieldwork requiring a risk assessment (tick the box).

AND

(b1) I confirm that I have passed my first interim report (tick the box).   ✓

AND

(b2) I confirm that I have passed my second interim report (tick the box).   ✓

Signature:

Print name:

RUPP Marina Annabel

Name of Student: Rupp Marina Annabel

Meeting Number: **1**   **Date: 1.10.2018**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- None

Solutions discussed (to be completed during/after the meeting)**:**
- Dissertation planning process and what to do until next meeting

---

Name of Student: Rupp Marina Annabel

Meeting Number: **2**   **Date: 15.10.2018**
Members present: Joseph Mallalieu, Marina Rupp
Meeting With Mentor (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Questions on labelling graphs (what is appropriate for my data collection to use? → Julian days, 24 hour format, calendar days…)
- Should unstable data be excluded?
- Tips on how to establish a good rationale
- Meaning of some variables measured (LDO hPa, LDO%...)

Solutions discussed (to be completed during/after the meeting)**:**
- Compare to literature to find most suitable labelling
- Plot data & check if unstable data represents mostly outliers or not; if yes exclude them, if not keep them and make a side note
- Read around the topic and try to find reasons why this study is important
- Unsure about these measuring outputs, try to find online and check if even needed for analyses

Name of Student: Rupp Marina Annabel

Meeting Number: **3**   **Date: 24.10.2018**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- None

Solutions discussed (to be completed during/after the meeting)**:**
- Discussing progress

Name of Student: Rupp Marina Annabel

Meeting Number: **4**   **Date: 12.11.2018**
Members present: Joseph Mallalieu, Marina Rupp
Meeting With Mentor (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Questions on interim report → has there been an improvement on the rationale and is the timetable set for the dissertation reasonable?

Solutions discussed (to be completed during/after the meeting)**:**
- Refine aims and objectives
- Start thinking of hypotheses for statistics
- Think of implications → why have you chosen this glacier
- Why did you use this equipment, sample number and lab technique

Name of Student: Rupp Marina Annabel

Meeting Number: **5** **Date: 19.11.2018**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Had no issues to discuss in this meeting

Solutions discussed (to be completed during/after the meeting)**:**
- Discussed progress of work

Name of Student: Rupp Marina Annabel

Meeting Number: **6** **Date: 26.11.2018**
Members present: Joseph Mallalieu, Marina Rupp
Meeting With Mentor (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- For statistical test should I change values below detection limit to NA or zero?

Solutions discussed (to be completed during/after the meeting)**:**
- See if results would be the same; arrange a meeting with Rachel Homer to discuss further

Name of Student: Rupp Marina Annabel

Meeting Number: **7**   **Date: 26.11.2018**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- None

Solutions discussed (to be completed during/after the meeting)**:**
- Discussed progress of individual work

Name of Student: Rupp Marina Annabel

Meeting Number: **8**   **Date: 28.1.2019**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting with mentor and individual meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Compare data to ice/rain sample and to drinking water standard? Do I have to mention that in my objectives?
- Data presentation → I have so many graphs, should I include everything in the dissertation?
- Do I have to show R-codes in the appendix?
- If I compare my data to drinking water standards, do I use the mean value per location?
- I cannot find a DEM for my location map, what are my options?
- Cannot compute correct p-values with ties → error message in RSudio, what to do?
- Should I put all 4 locations on one boxplot in order to save space?

Solutions discussed (to be completed during/after the meeting)**:**

- In the peer group meeting the content of the interim report has been discussed

- If comparing to ice/rain sample, do so by observation to see how things evolve
- EU/WHO drinking water standards → make an extra column to add your data and do use the mean values; mention it briefly and put it in the objectives and literature review
- Do not have to include R codes in appendix if these are basic ones
- Put important graphs in main body, rest can go in appendix
- Do put all 4 locations in one boxplot
- Show summary statistics only if mentioned/needed
- Bring plots and tables to the next meeting to see extend of it and decide further on how to condense it
- Use Google maps to generate own DEM

Name of Student: Rupp Marina Annabel

Meeting Number: 9 **Date: 4.2.2019**
Members present: Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Apologies for absence: Amie Jones
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Ask about location map
- How did interim reports go

Solutions discussed (to be completed during/after the meeting)**:**
- Mendeley is giving suggestions on what you might want to read, which can be helpful when searching sources
- What to put in the appendix → DSG forms, interim reports, risk assessment…
- Difference between aim and objectives
- What are people writing in their acknowledgments? → mentor, peer group, other lecturers talked to, if fieldwork has been done person who helped
- Structure of dissertation; where to put location map?
- How did each of us think of splitting the word count? How much statistics do others include? → conclusion will be kept relatively short
- How many references is everybody aiming for?

Questions for mentor (record after peer-group meeting only; bring to next meeting with mentor)**:**
- Do we have to put the risk assessment in the appendix? What do those without fieldwork put in there?
- What should be put in the acknowledgements?
- Is the abstract counting towards the word count?

Name of Student: Rupp Marina Annabel

Meeting Number: 10   **Date: 11.2.2019**
Members present: Joseph Mallalieu, Marina Rupp
Meeting With Mentor (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Feedback on interim report
- How long should the introduction be approximately?
- When referencing books, do I need the page number?
- What should I do with my location map?

Solutions discussed (to be completed during/after the meeting)**:**
- Use Google Maps for location map
- Page numbers need not to be included
- Set priorities since not all work planned might be accomplished in time (drop bits that cannot be done in time and focus on main topics)

Name of Student: Rupp Marina Annabel

Meeting Number: 11   **Date: 18.2.2019**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Do we have to include a word count after the abstract?
- My axis labels for Cu are not really good, how could I fix this?

Solutions discussed (to be completed during/after the meeting)**:**
- Page numbers → up to the abstract / introduction we have to use roman numbers
- Abstract is not a heading with a number, introduction is going to be first heading with number
- Check past dissertation and decide then if word count should be put below abstract or not
- When do people plan to print their dissertation?
- Could alter axis label by making a note that the numbers on the axis have to be multiplied by a certain number to provide actual numbers (has been used by others for really big numbers)

Name of Student: Rupp Marina Annabel

Meeting Number: **12**   **Date: 25.2.2019**
Members present: Joseph Mallalieu, Marina Rupp
Meeting With Mentor (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Is the amount of figures and their size ok?
- Should I put summary statistics in dissertation (most papers I read included one)
- Is the location map alright now?
- Do I need a figure caption in the abstract?
- What should I do about my axis label for Cu
- I set values below detection limit to zero is that ok?
- If I include the water quality, there is not a lot to discuss about, should I keep it as an aim?

Solutions discussed (to be completed during/after the meeting)**:**
- Try to get tables on one page
- When referring to specific figures in appendix include figure caption, make a note what 1 and 2 mean in the figures
- For the axis in the Cu figures the decimal places could be increased or units could be changed
- Mention that I set values to zero
- Even if water quality is not an aim on its own I can still talk about it just in one paragraph
- 50 references are considered as minimum
- Find links to other studies

Name of Student: Rupp Marina Annabel

Meeting Number: **13**   **Date: 27.2.2019**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- none

Solutions discussed (to be completed during/after the meeting)**:**
- Where do people put their abstract? → position it before acknowledgments
- No cover sheet needed, i.e. put word count under abstract
- Are people using colours for their headings? → personal preference
- Are others using references in their abstract? → no
- Compared DSG meeting logs to check if everybody has the same dates and double check what has been done
- Do not forget to change margins on DSG logs!

Name of Student: Rupp Marina Annabel

Meeting Number: **14**   **Date: 6.3.2019**
Members present: Amie Jones, Benjamin Grounsell, Daniel Grundy, Naomi Chavasse, Marina Rupp
Peer-Group Meeting (Delete as appropriate)

Issues to be raised (complete prior to each meeting)**:**
- Check dates for DSG meetings

Solutions discussed (to be completed during/after the meeting)**:**
- Amount of figures in dissertation have been discussed
- Choice of graphs, double check if chosen appropriate
- Sizing of graphs
- Word count of the dissertation, what does count and what does not
- Referencing Google Maps / Earth
- Formatting questions and pagination