The hydroecological response of Greenlandic streams to a changing climate

by

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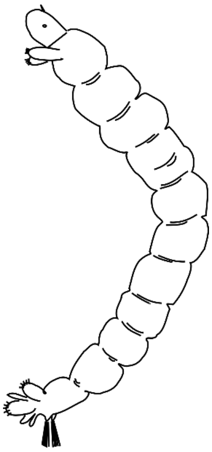
Abstract

Arctic streams are vulnerable to climate change due to the strong linkage between cryosphere, hydrology, physicochemical habitat and ecology. Our knowledge on how stream hydroecological dynamics will respond to climate change is largely based on the impact of the reduction in glacial extent in a warmer Arctic, however our knowledge of the response of Arctic streams with low glacial input are poorly understood. To address this knowledge gap, three field campaigns to Zackenberg (northeast Greenland) were carried out (2013 – 2015) to investigate snowmelt stream hydroecological patterns and processes. Streams were chosen that were sourced from both small and large snowpacks, representing low and high snowfall conditions. Streams with large snowpacks were found to have low channel stability and high suspended sediment concentration compared to streams with small snowpacks. Channel stability, rather than water temperature, was the most important factor influencing macroinvertebrate community dynamics, where streams with low channel stability had reduced macroinvertebrate density and taxa richness. The results of this research recommend new classifications to Arctic and alpine stream habitat types, and suggest that, as snowfall is predicted to increase in the Arctic, snowmelt-fed streams may experience decreased channel stability, and as such, a decline in macroinvertebrate density and diversity.



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CHAPTER 1: INTRODUCTION

1.1. Climate change and stream systems in the Arctic

Mean air temperature in the Arctic has increased by 2.9°C since the start of the 20th century (Overland et al. 2015), greater than three times the global average of 0.8°C (Comiso & Hall 2014). This warming is predicted to continue, with increases of up to 9°C forecast by the end of the 21st century (Anisimov et al. 2007). Precipitation (Kattsov et al. 2005; Kattsov et al. 2007; Mahlstein et al. 2012) and extreme climatic events (Brown et al. 2008) are also expected to increase. These climatic changes are markedly influencing Arctic ecosystems by altering sea ice extent, glacial mass, snowpack volume, and permafrost extent (Anisimov et al. 2007; Vaughan et al. 2013), These changes inherently alter how water will be stored in Arctic regions for later release.

The natural and unmodified state of Arctic ecosystems, combined with the extensive climate change occurring in the region, provides a model ecosystem to predict environmental change. Stream ecosystems in Arctic regions are especially vulnerable to climate change due to their high sensitivity to climatic and cryospheric conditions (eg. Brown et al. 2007; Jacobsen et al. 2012). Hannah et al. (2007) identified a strong cascading impact between climate – hydrology – ecology in Arctic and alpine regions that could be used to predict environmental changes and develop conservation strategies. This linkage has been investigated principally in glacier-fed streams through a conceptual model (Milner et al. 2001), where decreased glacial contributions alter stream physicochemical habitat which influences stream biotic communities. This research has covered a large geographical area including; the European Pyrenees (Hannah et al. 2007; Finn et al. 2013; Khamis et al. 2016), the Arctic (Svalbard and Swedish Lapland (Blaen et al. 2014; Mellor et al. 2016)), the New Zealand Alps (Cadbury et al. 2011) and the Andes of South America (Jacobsen et al. 2014; Cauvy-Fraunié et al. 2016) – for a summary see Milner (2015). However, this conceptual model focuses on glacier dominated systems not those by snowmelt, which is an important water source for streams in the Arctic. Streams primarily fed by snowmelt are defined as having large variation in water temperature (Ward 1994), typically possessing greater channel stability than glacial streams (Milner & Petts 1994) and for turbidity and ionic enrichment to be highest during peak snowmelt, but to be low throughout summer (Ward 1994; Malard et al. 1999; Brown et al. 2003). Snowfall has been predicted to increase in the Arctic by up to 50% by the end of the 21st century (Kattsov et al. 2007; Collins et al. 2013) with local variations causing certain areas to be higher e.g. up to 60% in northeast Greenland (Stendel et al. 2008). Decreased extent of winter sea ice with climate change leads to intensified local surface evaporation, amplifying the hydrological cycle in the Arctic (Bintanja & Selten 2014) and leading to significant increases in freshwater discharge at certain times of the year (Dankers & Middelkoop 2008). With a decrease in glacial extent, snowfall is predicted to become a more dominant meltwater source for many streams in some Arctic regions. Understanding the impact of this change towards increased snowmelt inputs to streams is vital if we are to fully understand the impact of a changing climate on Arctic ecosystems.

1.2 Research gaps

Following an extensive review of the literature as outlined in the corresponding chapters, the following research gaps were identified:

1. Snowpacks modify the local environment through nivation processes (Christiansen 1998a) and can lead to flooding in streams during peak spring melt (Christiansen et al. 1998b). However, the impact of these processes on channel stability and water chemistry is not well documented (chapter 2; chapter 3).

2. Stream water temperature regimes are likely to change with a changing Arctic climate, influencing a wide range of physicochemical and biological processes. Whilst controls on summer water temperature in glacierised catchments are well studied (e.g. Blaen et al. 2013; Mellor et al. 2016), the controls on snowmelt streams have been less so. In addition, winter temperature dynamics in Arctic streams have not been studied to the same extent as during the summer months (chapter 4).
3. Nutrient cycling dynamics in streams are likely to alter in a changing climate through increased nutrient concentrations caused by permafrost melt and increased biofilm biomass to uptake nutrients due to warmer waters. However, the possibility of increased sediment and channel mobility due to reduced stability from increased snowpacks could limit biofilm colonisation. Whilst there has been some effort to characterise nutrient uptake dynamics in Arctic streams (Blaen et al. 2013; Schade et al. 2016), the impacts of reduced channel stability have not been considered (chapter 5).
4. Longitudinal patterns in macroinvertebrate community composition in glacially influenced streams and deterministic patterns have been well documented due to the overriding influence of low water temperature and channel stability (Milner et al. 2001). In contrast, longitudinal patterns of macroinvertebrates in snowmelt dominated streams have not been so widely studied and patterns in macroinvertebrate community assemblages are considered to be more stochastic (Ward 1994). We need to understand if longitudinal patterns are evident in snowmelt systems (Chapter 6).
5. Climate change has the potential to alter stream physicochemical habitat

(as identified in research gaps 1 – 3) and the effect of these changes on macroinvertebrate community composition between different streams needs to be addressed (chapter 7).

The aim of this research is to address these research gaps through the objectives outlined in section 1.3 below.

1.3 Aim and objectives

The overarching aim of this research is to **elucidate the key variables controlling hydroecological patterns and processes of northeast Greenland stream systems and their likely response in a changing climate**. Through this research, recommendations will be suggested for Arctic stream research and monitoring programmes, and the findings will be placed in a pan-Arctic context to add to past research in snow and ice dominated systems from other Arctic and alpine locations.

To achieve this aim and address the identified research gaps, research was conducted through an interdisciplinary approach, considering interactions between geomorphic processes, stream habitat and macroinvertebrate communities. The objectives were as follows:

1) To understand the geomorphic processes responsible for variation in channel stability and hydrochemistry (chapters 2 and 3).
2) To characterise stream thermal dynamics and to determine the principal drivers influencing water temperature throughout the year (chapter 4).
3) To elucidate the limiting nutrients and understand nutrient cycling dynamics (chapter 5).

4) To determine macroinvertebrate community structure and understand the influence of geomorphic and hydrologic processes on community assemblages both longitudinally and between streams (chapters 6 and 7).

1.4 Research design

The approach taken in this study was to focus on the cascade of processes that link climate, cryosphere, hydrology and ecology by modifying the key components proposed by Hannah et al. (2007) which suggests with climate change an increase in groundwater as glacial melt deceases (Figure 1.1). Climate acts as a control on the cryosphere through melting (decreasing extent of ice and snowpacks) and precipitation (increasing extent of ice and snowpacks through snowfall in winter, or decreasing through warm rainfall in summer), which in turn controls water sources in the Arctic. Different water sources create different physicochemical characteristics in stream habitats (Brown et al. 2003). Groundwater sourced streams typically have more stable channels, lower turbidity and warmer waters than glacier-fed streams. Snowmelt streams typically have higher stability than glacial streams, low turbidity except for during peak snowmelt when it may be high, and variable water temperature (Milner & Petts 1994; Ward 1994; Brown et al. 2003). As such, alterations to the proportions of water sources entering streams can impact freshwater biota (Prowse et al 2006; Milner et al. 2009) influencing food-web structure, community assemblages and species richness and abundance (Berkman & Rabeni 1987; Bilotta & Brazier 2008, Chin et al. 2016).

This modified model was tested in snowmelt streams near the Zackenberg research station. The site was used for an analogous study based on size of snowpacks, in which streams sourced from larger, perennial snowpacks were used to infer potential future conditions of higher snowfall, meaning larger spring floods and increased nivation processes, reducing channel stability and increasing sediment content, whilst streams sourced from small, seasonal snowpacks were used to infer less winter snowfall accumulation.

Detailed methodologies can be found in the corresponding empirical chapters, however, Figure 1.2 gives an overview of techniques used for the different components of the study. In the appendix, a list of instrumentations used (appendix A1) and images of selected methods and sites (appendix A2) are presented.

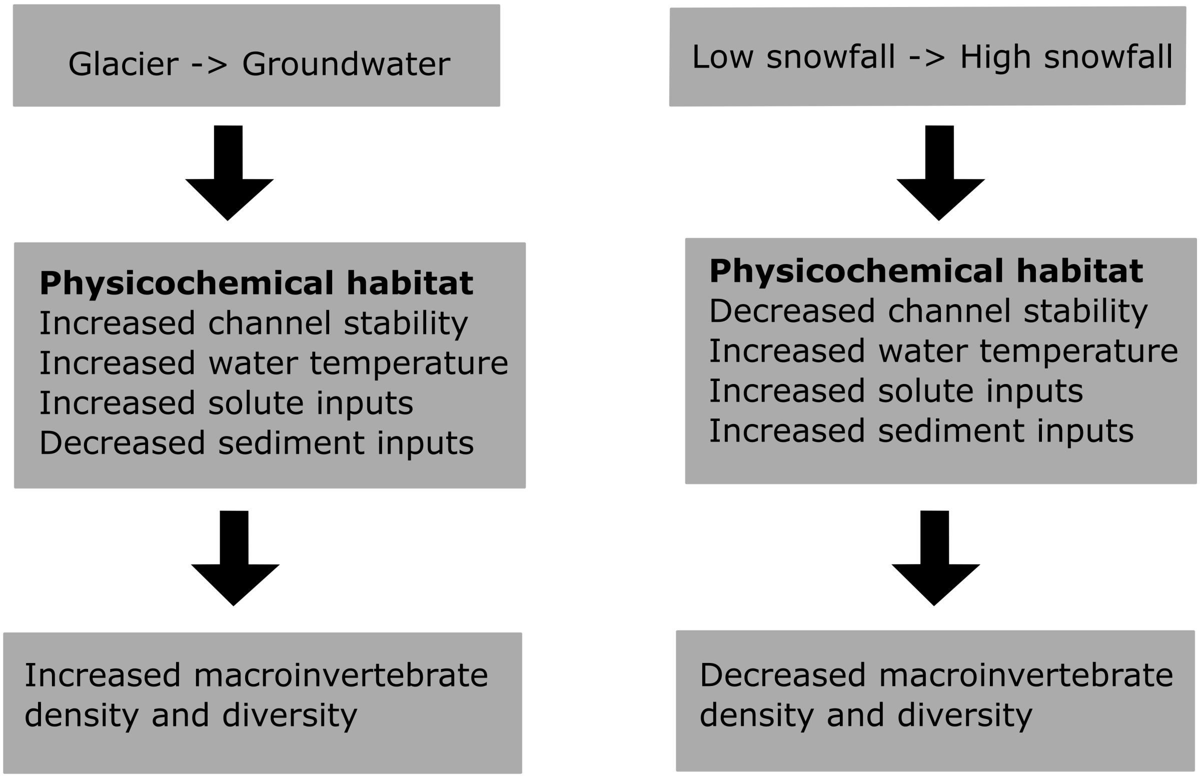
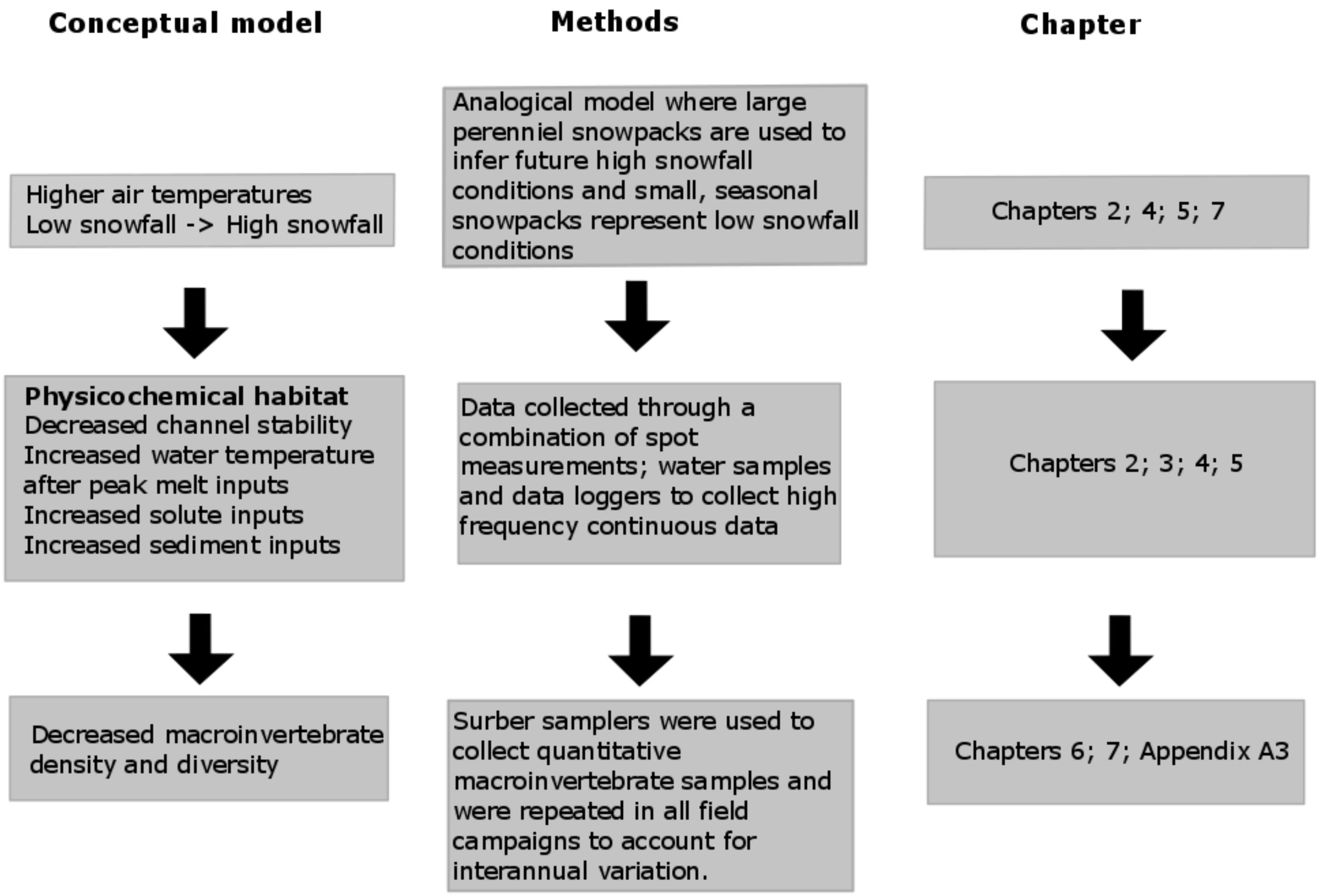


Figure 1.1. Left hand side is the flow diagram of cascading interactions between water source, physicochemical habitat and stream ecology modified from Hannah et al (2007) which suggests increased groundwater contribution as glacial melt decreases. A modified flow diagram proposed for snowmelt dominated streams in areas of increased precipitation, which was investigated by the research outlined in the thesis.



Higher air temperatures
Low snowfall -> High snowfall

Physicochemical habitat
Decreased channel stability
Increased water temperature after peak melt inputs
Increased solute inputs
Increased sediment inputs

Decreased macroinvertebrate density and diversity

Analogical model where large perenniel snowpacks are used to infer future high snowfall conditions and small, seasonal snowpacks represent low snowfall conditions

Data collected through a combination of spot measurements; water samples and data loggers to collect high frequency continuous data

Surber samplers were used to collect quantitative macroinvertebrate samples and were repeated in all field campaigns to account for interannual variation.

Figure 1.2. Conceptual model with corresponding methodologies and cross-referencing chapters

1.5 Zackenberg

Zackenberg (74º28’ N, 20º34’ W) is located approximately 25km from the coast and 60km from the Greenland ice sheet. Monthly mean air temperatures during July and August vary between 3°C and 7°C and during winter fall below -20°C. Annual precipitation is low (1996 – 2005 average of 261mm water equivalent), of which 17% is made up of rain or mixed precipitation that falls between May and November, with the remaining 83% falling as snow during the winter (Hansen et al. 2008).

The region currently has a high Arctic, dry climate, however, declining sea ice along the east Greenland coast due to rising air temperatures means that by the end of the century the climate at Zackenberg is expected to shift from continental to being wetter and more maritime, and more characteristic of the low Arctic (Stendel et al. 2008). Presently, interannual variation in winter weather conditions in the region has been found to be intrinsically related to the extent of sea ice in the Greenland Sea and variability in the North Atlantic Oscillation (Hansen et al. 2008). Above average sea ice export and more than three negative North Atlantic Oscillation months have led to cold, dry winters, characteristically averaging less than 100mm of precipitation, whilst low sea ice export and three or more months of positive North Atlantic Oscillation generally cause warm wet winters (Hansen et al. 2008). This shift towards a more maritime, low Arctic climate with increased air temperatures, is predicted to, by 2100, cause up to a 60% increase in precipitation, including increased snowfall during the winter, and rainfall during the summer, and an increase in the number of thaw days (days above 0°C) from the current average of 80, to 248 per year (Stendel et al. 2008).

Research in this study focused on five streams (Figure 1.3) but additional sites are included in specific chapters. The majority of the regions glaciers are located to the west of the

Zackenberg catchment, with minimal glacial cover in the study area (Figure 1.4). However, the main river receives large glacial contributions as it is sourced from the A.P. Olsen Ice Cap and other small glaciers. All streams included in this study were sourced principally from snowmelt. Although Aucellaelv and Palnatokeelv also received contributions from small glaciers, these streams were still classed as snowmelt dominated streams as their glacial contribution was minimal (defined as < 30% total water contribution in Brown et al. (2003)). The five main streams can be seen in figures 1.5 to 1.9.

The regions geology is divided into two types (Figure 1.10). All five principal streams are overlying sedimentary rocks, however one stream (Unnamed2) included in a few of the chapters (chapters 2; 4; Dichotomous key to Chironomidae) is overlying Caledonian gneiss. More streams overlying gneiss bedrock were not included in the study due to the steep gradients, creating difficulties comparing sites.

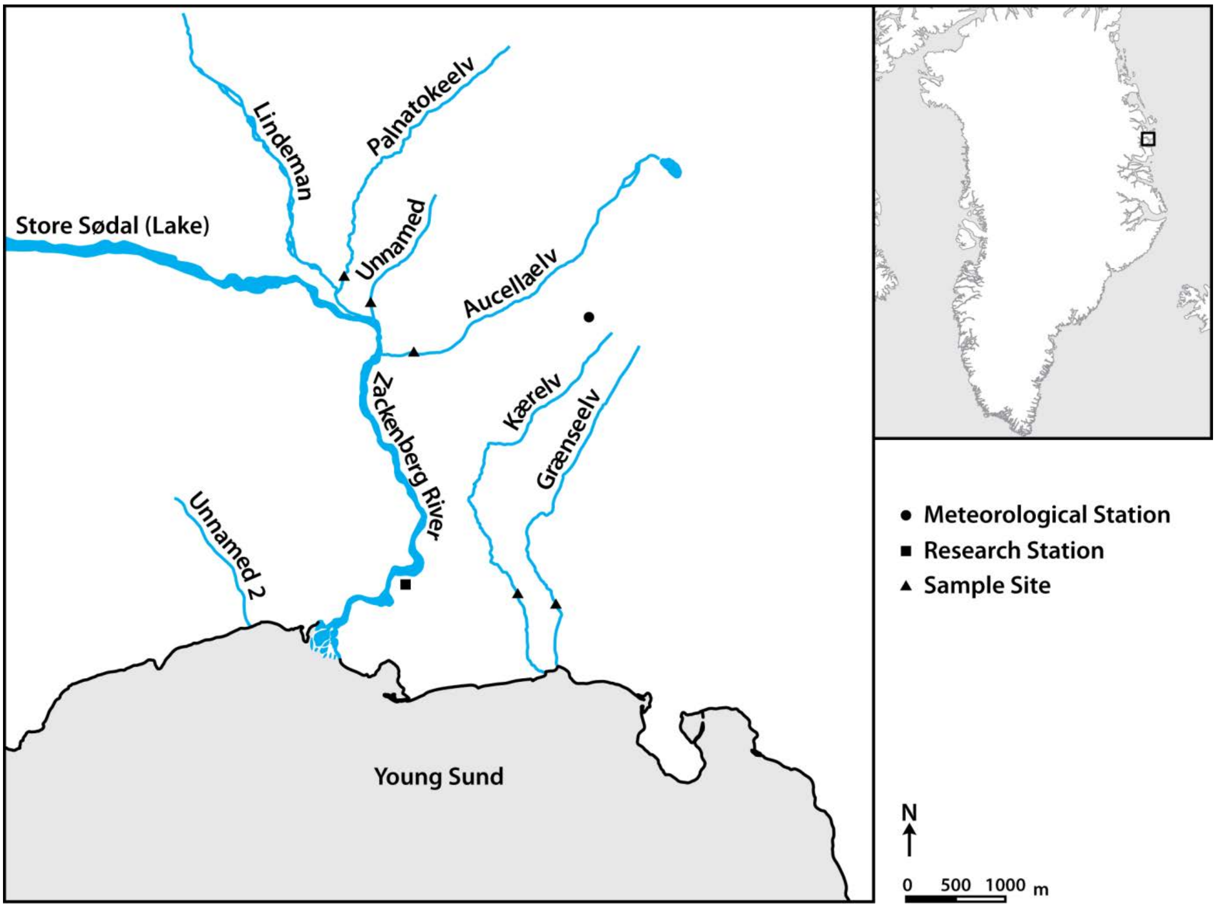


Figure 1.3. Map of the principal five streams used throughout the study. Additional streams researched are presented in maps in the corresponding chapters. In the top right the location of the study area in Greenland can be seen.

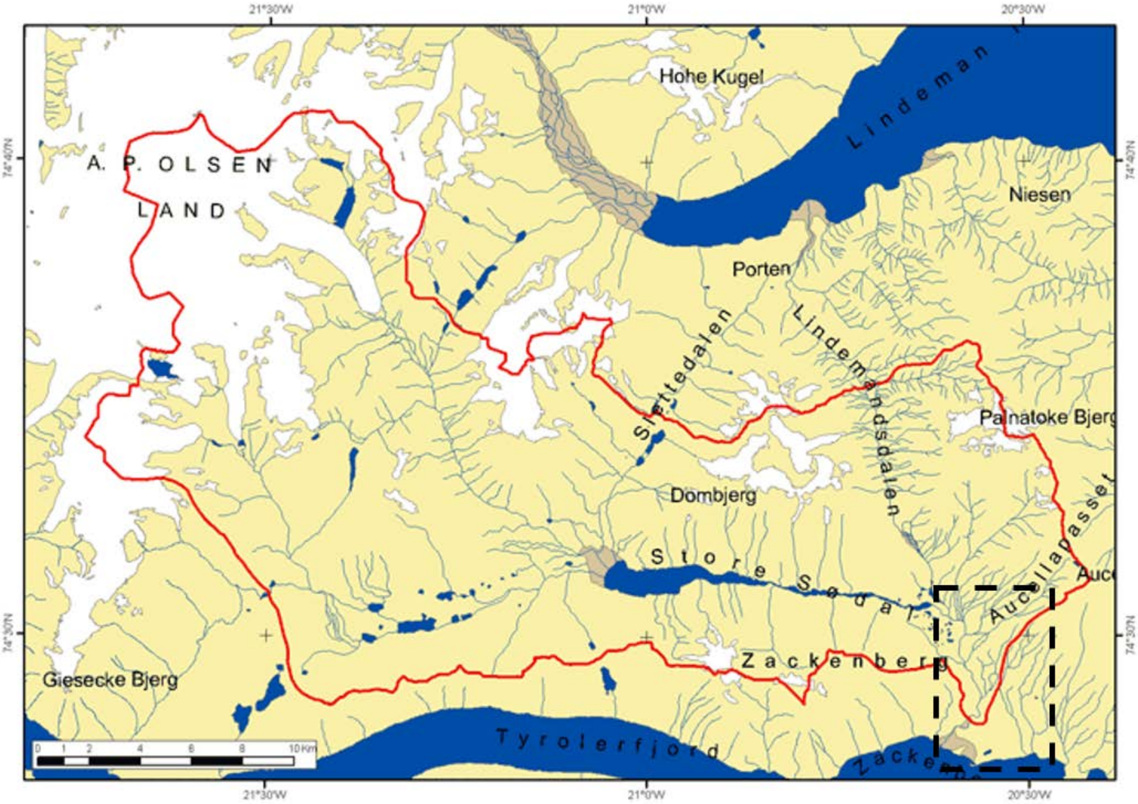


Figure 1.4. Zackenberg drainage basin is shown by the red outline (modified from the Greenland Ecosystem Monitoring Programme (GEM)) and includes the A.P. Olsen Ice cap and small mountain top glaciers mostly to the west of the main study area. The main study area for the work detailed in this thesis is highlighted in the black dashed box in the bottom right corner.

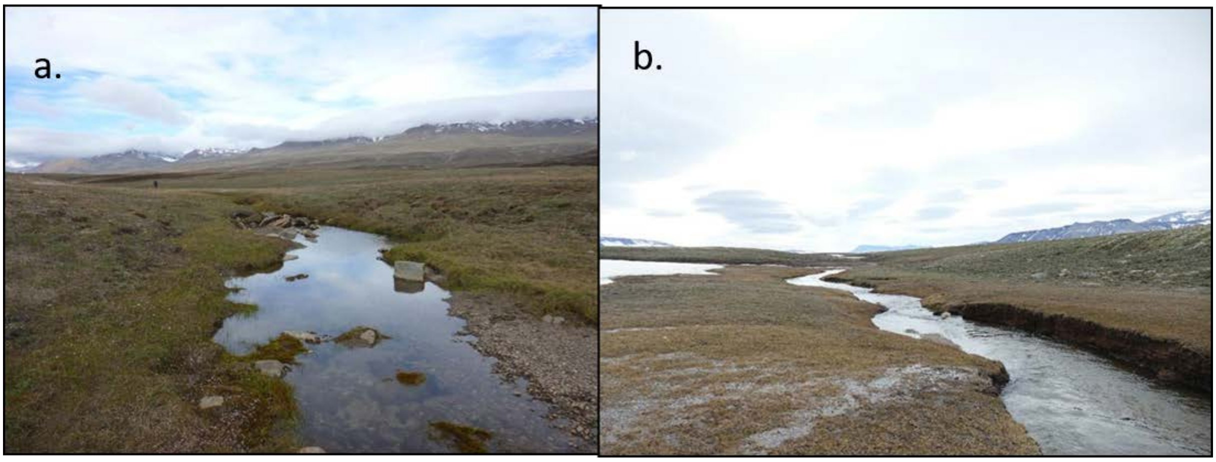


Figure 1.5. Kaerelv in a) 2013 and b) 2015

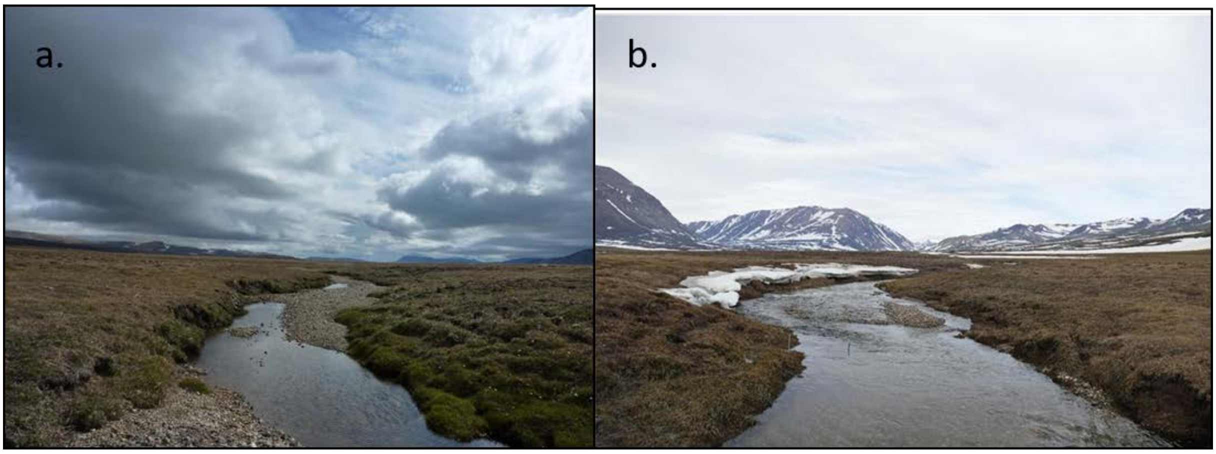


Figure 1.6. Graenseelv in a) 2013 and b) 2015

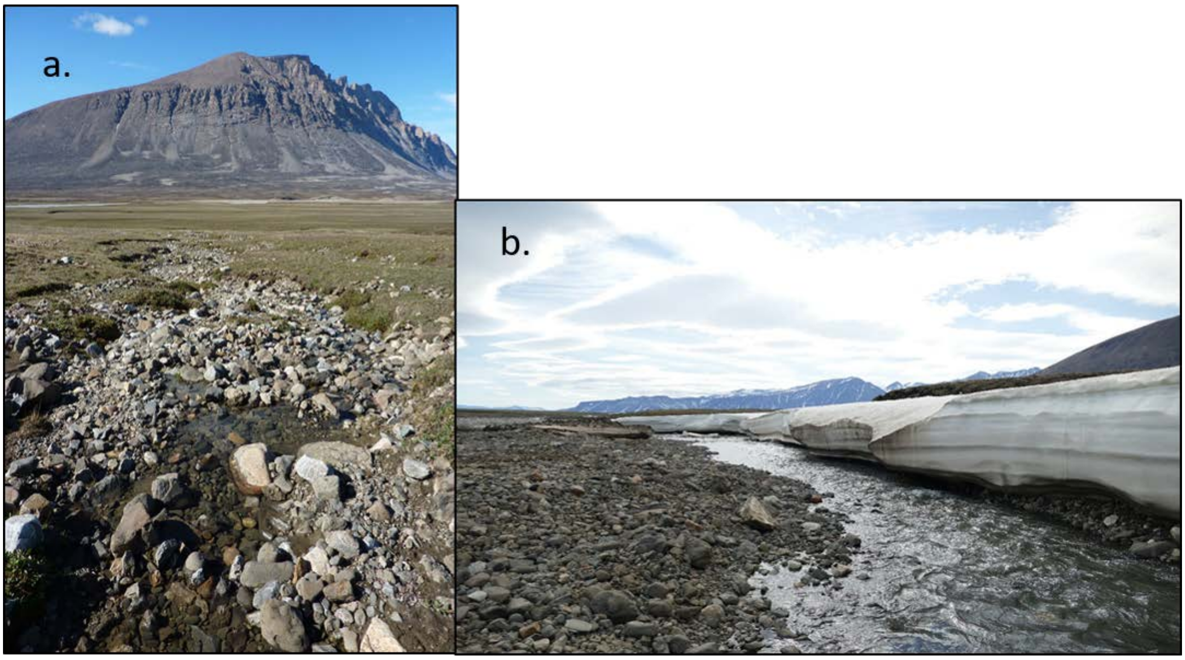


Figure 1.7. Unnamed in a) 2013 and b) 2015

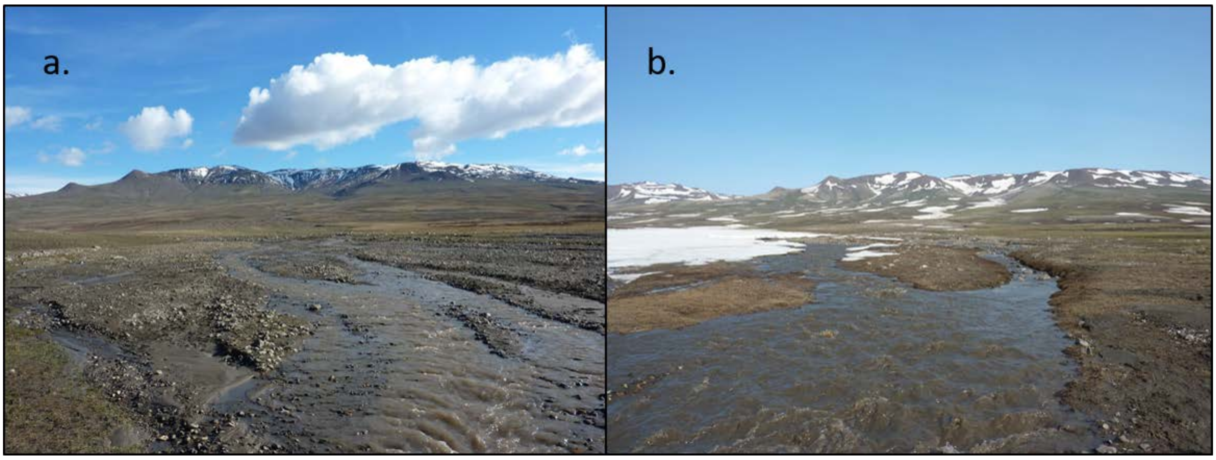


Figure 1.8. Aucellaelv in a) 2013 and b) 2015

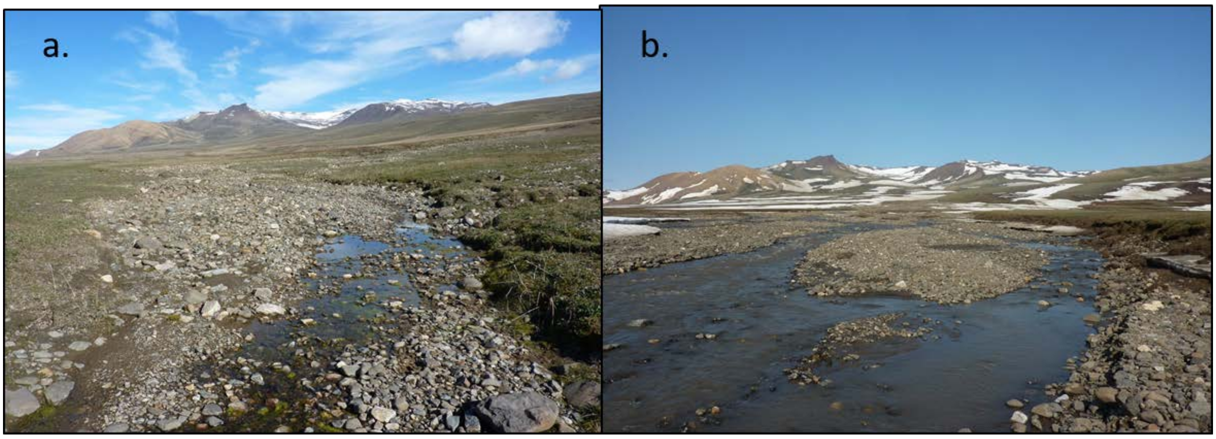


Figure 1.9. Palnatokeelv in a) 2013 and b) 2015

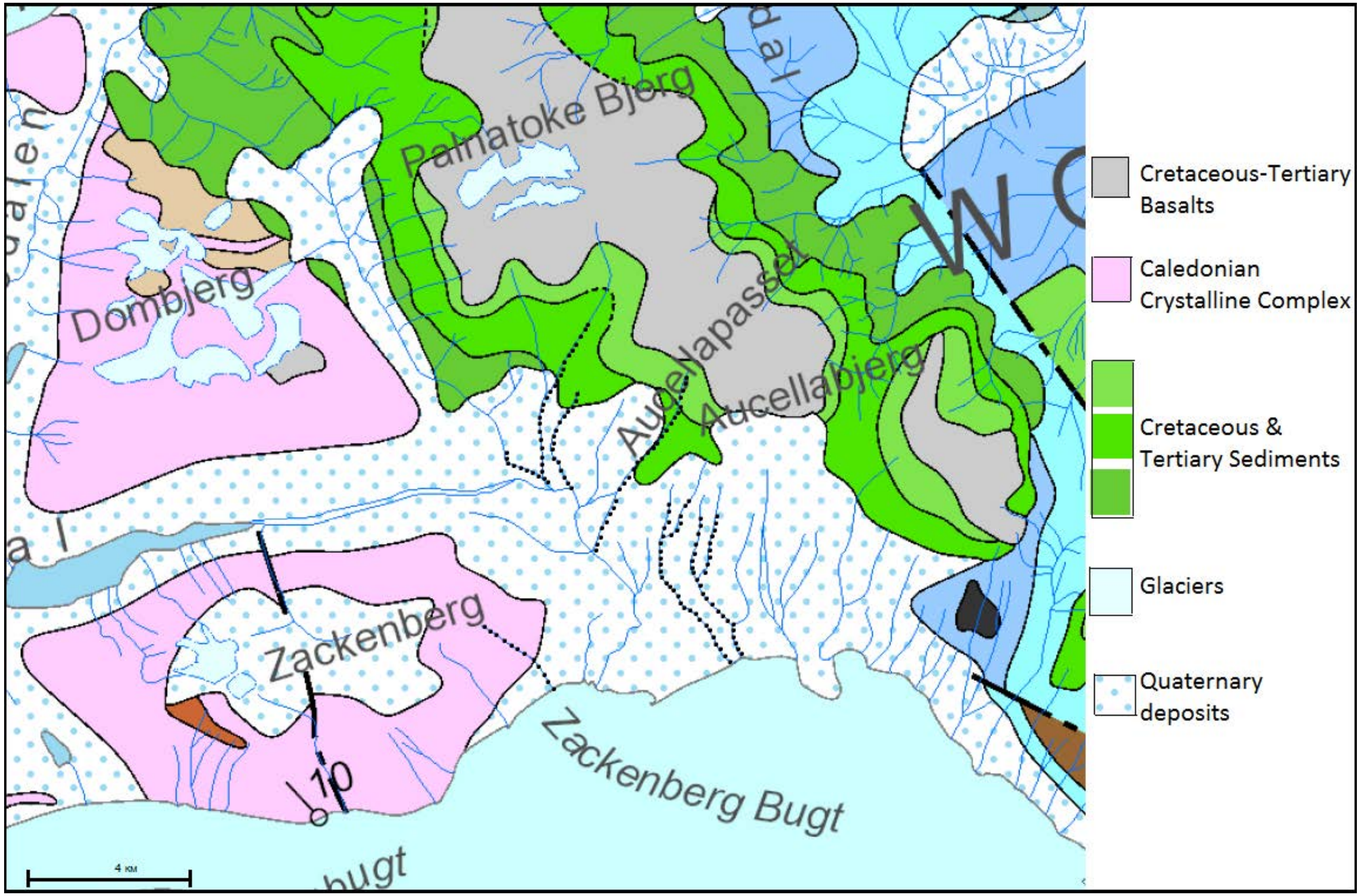


Figure 1.10. Geological map (modified from Koch & Haller 1965; Hasholt & Hagedorn 2000 and Geological Survey of Denmark and Greenland (GEUS)). The main five streams are all overlying sedimentary rocks. Some studies included a stream overlying crystalline rocks.

1.6 Previous research at Zackenberg

River research in northeast Greenland has largely focused on hydrological dynamics, principally sediment and solute transport dynamics (Ladegaard-Pedersen et al. 2016; Hasholt et al. 2008; Hasholt & Hagedorn 2000; Rasch et al. 2000), in the main river system. Only one study to date has investigated hydrological dynamics within the small tributary streams in the region (Hasholt & Hagedorn 2000) and included two of the streams which are important study sites in this thesis. Hasholt & Hagedorn (2000) found that streams drainin the sedimentary area had high sediment and solute loads compared to streams draining the crystalline area. Previous ecological studies of freshwater ecosystems at Zackenberg have been restricted to the ponds and lakes in the region (eg. Christofferson et al. 2008). River ecological studies in Greenland have been restricted to the southwest coast (Friberg et al. 2001; González-Bergonzoni et al. 2014) were diversity as been relatively l, including Annelida, Chironomidae, Ephemeroptera, Tricoptera and Pisidium. The northeast coast is considerably more isolated than the southwest, which is thought to limit invertebrate dispersal and coupled with harsher climatic conditions reduces stream macroinvertebrate abundance and diversity (Böcher et al. 2015). Documenting the stream taxa inhabiting this region will provide a vital baseline record to monitor change in stream ecosystems over the coming decades.

1.7 Thesis structure

This thesis is written as a series of submitted and draft papers and as such some information on study site and field methodologies is repeated.

- **Chapter 2** highlights the influence of snowpacks and local geomorphology on channel stability and water chemistry.
- **Chapter 3** is a short commentary of a thermo-erosional tunnel which developed over one of the streams in summer 2015 highlighting the high disturbance regime and unpredictable nature of some high Arctic streams.
- The spatial and temporal variation in a 24-month, high resolution dataset on stream thermal dynamics is synthesised in **Chapter 4**.
- Nutrient cycling dynamics are explored in **Chapter 5** where short term uptake experiments and nutrient diffusing substrata were used during the 2014 field campaign.
- **Chapter 6** summarises a longitudinal examination of stream benthic community assemblages that took place in July 2015. Patterns in macroinvertebrate community assemblages in snowmelt streams are compared to those found in glacier-fed streams.
- Temporal and spatial variation in macroinvertebrate community structure is presented in **Chapter 7** using data collected over the three field campaigns, in relation to hydrological variables presented in chapters 2 – 5.
- **Chapter 8** provides a synthesis on the outcomes of the thesis and its implications in terms of a changing climate, as well as providing directions for future research.

A dichotomous key of the Chironomidae of the region is provided in the Appendix (A4), which has been produced for future researchers working with macroinvertebrates in the region to assist in their identification. Peer reviewed articles that have been accepted for publication are included in the appendix (A5).

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CHAPTER 2: CONTROLS ON STREAM HYDROCHEMISTRY DYNAMICS IN A HIGH ARCTIC SNOW-COVERED WATERSHED

Abstract

Arctic streams are highly sensitive to climate change due to warmer air temperature and increased precipitation associated with an encroaching low Arctic climatic zone into currently high-Arctic coastal areas. Increases in nivation processes and permafrost degradation will lead to potential changes in stream physicochemical habitat, although these impacts are poorly understood. To address this gap physicochemical habitat characteristics in streams around Zackenberg in Northeast Greenland National Park, were investigated during the summers of 2013 to 2016. Streams with different sized snowpacks represented both low and high snowfall conditions leading to different nivation processes. Streams with larger snowpacks displayed lower channel stability, with higher channel mobility, suspended sediment and solute concentration. Suspended sediment concentration was identified as a key driver of stream solute concentrations, and varying snowpack levels caused high interannual variability in solute concentrations. It was found that winter snowpack size to be an important driver of stream physicochemical habitat in an Arctic region with low glacial cover. We predict climate change will strongly impact stream hydrochemistry in this region through increased nivation processes alongside active layer thickening and solifluction, thereby increasing stream suspended sediment and solute concentrations. These findings indicate that hydrochemistry was principally a function of erosion, with variation being determined by spatial and temporal patterns in erosional processes, and as such, this traditional method could not be used to fingerprint water sources in this region.

2.1 Introduction

Channel geomorphology influences stream nutrient spiralling, in-stream processing efficiency, suspended sediment concentration, and water temperature thereby significantly impacting on stream biota and their functioning (Brussock et al. 1985; Hawkins et al. 1997). In the Arctic, stream physicochemical processes are defined by a combination of their bed material, local geomorphology and principal water sources, whether glacial melt, snowmelt or groundwater. Local geomorphology is moulded through a suite of cryogenic processes, nivation processes associated with, and intensified by, the presence and disappearance of perennial and seasonal snowpacks (Christiansen 1998b), and permafrost thaw which can modify streams by altering stream water source, sediment load, and geochemistry (Callaghan et al 2011; Kokelj et al. 2013; Thienpont et al. 2013; Chin et al. 2016). During spring snowmelt, sheet floods – where water moves in sheets instead of streams – can occur due to the frozen active layer preventing infiltration, causing large sediment deposition. Within a small area, permafrost landscapes can have diverse geomorphology, hydrology and permafrost conditions (Haeberli, 2013). Both nivation processes and localised permafrost thaws can release large amounts of sediment and solutes to streams (Christiansen 1998; Kokelji et al. 2013; Malone et al. 2013; Messenzehl et al. 2014; Kokelji et al. 2015; Chin et al. 2016) and alter landscapes (Kokelj & Jorgenson 2013). Given the low solute load of meltwater, the majority of solutes in stream water come from weathering processes (Holland 1978), including through the erosion of suspended sediment in turbulent streamflow (Chin et al. 2016). In the Arctic, as in other cold climate regions, sub-zero temperature causes frost cracking and wedging, increasing both physical and chemical weathering (Peters 1984; Bluth & Kump 1994).

Whilst global climate models predict air temperature in Greenland by 2100 to increase by up to 5 – 7 °C (IPCC 2013), decreased continentality caused by declining sea ice may cause air temperature in the coastal northeast region to increase even higher with a potential 60% rise in precipitation as both snow and rain (Stendel et al. 2008). During this time, the number of thaw days in Northeast Greenland is expected to increase from 80 to 248 per year (Stendel et al. 2008) and upper permafrost layers could be at risk of degradation (Daanen et al. 2011; Hollesen et al. 2011; Westermann et al. 2015**)**. Deeper snowpacks can warm permafrost to a depth of 18 m (Rassmusen et al. 2017) due to greater insulation. Increased stream sediment and nutrient fluxes are expected through increased nivation processes and solifluction, identified as important periglacial processes impacting the regions geomorphology (Christiansen et al. 1998a), and through permafrost degradation, thaw slumps and rain-induced erosion events. Increased snow depth and active layer depth will increase nutrient and carbon runoff contributions to streams. Stream physicochemical processes influences stream nutrient spiralling, in-stream processing efficiency, suspended sediment concentration, and water temperature thereby significantly impacting on stream biota and their functioning (Berkman & Rabeni 1987; Prowse et al. 2006; Bilotta & Brazier 2008, Milner et al. 2009; Chin et al. 2016),

The aim of this project was to understand the variability in channel stability in northeast Greenlandic streams in relation to their snowpack size and its influence on physicochemical processes and stream hydrochemistry, and to put this into the context of a changing climate. This was done by investigating the relationship between changing hydrology, the interaction with hydrogeology and the influence on hydrochemistry dynamics. Seven streams were selected in close proximity to Zackenberg research station in northeast Greenland sourced from small, seasonal to large, perennial snowpacks, to represent low and high snowfall conditions respectively. Streams were characterised in terms of their geomorphological and physiochemical characteristics. The hypotheses tested were: (1) Streams sourced from large snowpacks will have reduced channel stability due to the increased influence of nivation processes and spring floods on the stream bed and banks; and (2) lower channel stability will lead to higher solute concentrations due to high erosion and suspended sediment concentrations. The findings were placed in the context of a changing climate to understand snowmelt stream hydrochemistry dynamics in Arctic streams might shift in the future.

2.2 Methods

2.2.1 Study site

The Zackenberg research station (74º28’ N, 20º34’ W) is located within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 2.1). Mean annual air temperature is -9.1˚C with July the warmest month with a mean of 5.8˚C and February the coldest month with a mean of -22.4 °C. Annual mean precipitation is 261mm of which approximately 10% falls as rain (Hansen et al. 2008).

The valley floor was deglaciated 8000 ybp with only a few small high altitude glaciers remaining in the area. Lying in the 1300 km long East Greenland Caledonian belt (Higgins et al. 2000), geologically the area is divided into two parts, with crystalline (gneiss and granite) to the west and cretaceous and tertiary sandstones, conglomerates, black shale and basalts to the east. The valley floor and low altitude slopes have a layer of loose soils that are well developed in some places, but are generally vulnerable to erosion (Hasholt & Hagedorn 2000; Mernild et al. 2007a).

The area is a zone of continuous permafrost, with depth modelled to be 200-300m in the main valley and 300-500 m in the mountains (Christiansen et al. 2008) with an active layer between

0.4 and 0.8 m (Hollesen et al. 2011; Westermann et al. 2015). Altitude varies between 0 and 1450 m a.s.l with the glacial plateaux occurring above 1000 m with wide horizontal valleys caused by glacial erosion below (Mernild et al. 2007a). Periglacial features can be found in the area including ice wedges in the east and rock glaciers in the west, separated by the different geologies (Christiansen et al. 2008). Active layer sliding has been observed on Aucellabjerg.

Vegetation is divided by the geological areas; the western crystalline area is dominated by *Vaccinium uliginosum* (Bog bilberry) heath and is found with fens, whilst the easten sedimentary side is characterised by *Cassiope tetragona* (Arctic white heather) heath with *Salix arctica* (Arctic willow) (Bay 1998). Grasslands, fens and snowbeds are common in the east, and the mountains are often unvegetated apart from the lower altitude slopes dominated by mountain avens (*Dryas*) (Bay 1998).

The runoff regime for the wider Zackenberg area is described as glacionival (Hasholt & Hagedorn 2000). The principal streams included in this study were Kærelv, Grænseelv, Aucellaelv, Unnamed1 and Palnatokeelv (Figure 2.1) which were all located in the sedimentary catchment and were sourced predominantly from snowmelt, however Aucellaelv and Palnatokeelv had small high-altitude glaciers within their catchment. Kærelv and Grænseelv were sourced from small, seasonal snowpacks and Aucellaelv and Palnatokeelv were sourced from large perrenial snowpacks. Unnamed1 was sourced primarily by a seasonal snowpack, but also received contributions from a larger snowpack located nearby. Lindemanelv, and Unnamed2 were also included to represent contrasting physicochemical conditions. Lindemanelv received glacial meltwater, and Unnamed2 was located in the crystalline catchment (Figure 2.1). The floodplains of streams Aucellaelv and Palnatokeelv consisted largely of stones, pebbles and silt and lacked vegetation. Kærelv and Grænseelv floodplains are largely vegetated. The floodplain for Unnamed1 is vegetated at sites A and B, but consists of stones and pebbles at site C. Table 2.1 shows site characteristics.

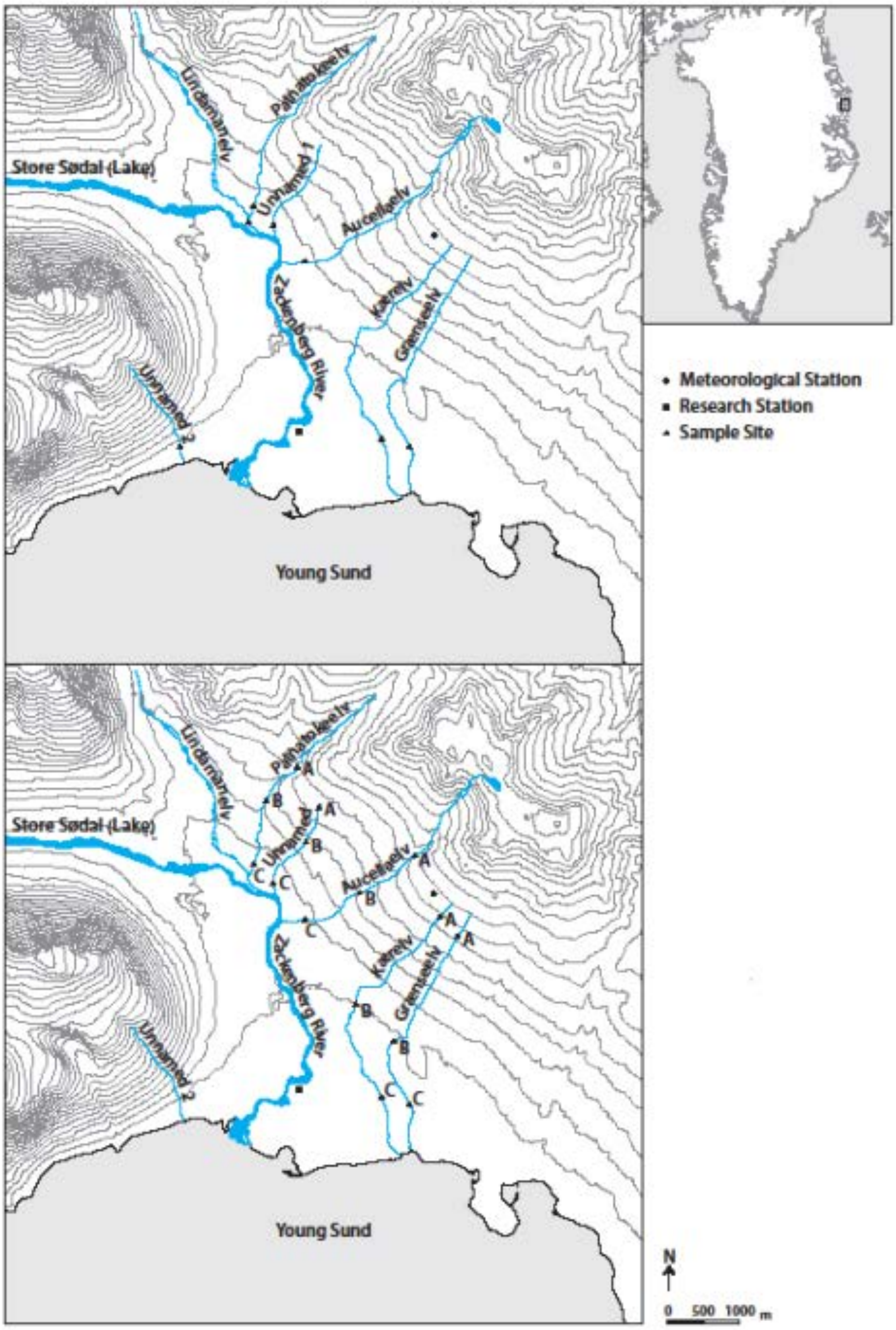

Figure 2.1. Top) Sampling sites in 2013 - 2015; Bottom) longitudinal sampling in 2015.

Table 2.1. Site characteristics and physicochemical measurements during the July 2015 field campaign *Spot measurements

	Altitude (m)	Aspect (facing)	Conductivity (µS cm^{-1})*	pH*	DO (%)*	Water temperature ˚C*	Mean depth (cm)	Mean width (m)	Mean Velocity (m/s)	Mean Sediment particle size (mm)
Kærelv										
A	179	SW	26	7.02	82.4	2.7	13	2.5	0.7	113.83
B	102	SW	36	6.89	92	6.3	24	3.4	0.57	71.05
C	47	S	36	6.99	76.5	9.4	33	3.5	0.62	51.2
Grænseelv										
A	125	SW	32	7.4	79.1	2.3	20	2.5	0.51	190.65
B	46	SW	34	7.18	81.2	3.4	20	2.2	0.51	115.41
C	19	S	32	7.08	78	4.4	30	3	0.57	33.9
Unnamed1										
A	193	SW	38	7.61	79.4	2.8	10	2.2	0.48	87.45
B	136	SW	32	7.2	79.9	2.2	7	2.1	0.62	76.04
C	113	SW	42	7.03	88	2.3	15	9.6	0.79	90.3
Unnamed2	52	S	31	NA	NA	3.5	10	1.5	NA	55
Aucellaelv										
A	185	SW	86	7.35	74.1	2.6	35	2.9	0.82	197.21
B	101	SW	94	7.16	73.8	4	35	10.9	0.59	156.53
C	68	SW	88	7.01	75.1	5.3	20	6.1	0.81	96.5
Palnatokeelv										
A	137	SW	23	7.62	78.7	3.1	12	5.2	0.54	246.14
B	124	SW	22	7.27	74.5	4.2	12	7.3	0.31	151.57
C	56	SW	26	7.15	77.8	5.8	15	15.4	0.5	101.35
Lindemanelv	50	S	52	NA	NA	3.46	NA	10	NA	NA

2.2.2 Sampling framework

Air temperature (˚C), precipitation (mm) and snow depth (cm) data were obtained from a weather station maintained by the Greenland Ecosystem Monitoring Programme (Hansen et al. 2008), within 5km of all sites. Air temperature and snow depth were recorded every 30 minutes whilst precipitation was recorded hourly.

Sampling took place over three early summer field seasons, from 26 June to 17 July 2013, 1 July to 22 July 2014 and 6 July to 22 July 2015. Data from stream Unnamed2 was collected only in 2013, and from Lindemanelv only in 2014. Futher samples were collected between 26 – 28 August 2016 to explore late summer soil water contributions to streams.

In 2013 and 2014, samples were collected in the lower reaches of each stream, whereas in 2015 three sites were selected at each stream to show longitudinal patterns (Figure 2.1).

Channel stability was calculated using the whole Pfankuch Index in 2015 (Pfankuch, 1975). Stream discharge was calculated using the velocity-area method using a flow meter (µP-TAD from Höntzsch instruments, Germany) and was measured on sampling days in 2015 and on sample day or on numerous days in 2014, highlighting stage variation throughout the season and stream sensitivity to rain events. Suspended sediment was measured in 2014 and collected from site C in the lower reaches. Samples were collected in 1L containers before being passed through a preweighed Whatman Glass Fibre Filter paper. Filter papers with sediment were dried at 60˚C for 48 hours and then re-weighed to calculate sediment weight.

Electrical conductivity was measured continuously at three sites for 11 days in July 2014 using gauging stations which were installed at the streams. Data were recorded on Campbell Scientific CR1000 data loggers and EC sensors which scanned every 10 s and recorded data every 15 minutes.

Water samples were collected in all years to analyse for major ions, and in 2014 and 2015 snow samples were collected from different locations around the valley, in close proximity to the sampling sites to elucidate chemical characteristics and determine the influence of snow melt on stream chemistry. In 2013, due to low snow fall during the winter 2012/13, only two snow samples could be collected, namely; (1) from the summit of Aucellabjerg where streams Aucellaelv, Kærelv and Grænseelv have their headwaters, this is refered to as 'dirty snow'due to the high sediment content, and (2) near Young Sund. Soil water samples were collected in 2015 and 2016. Samples were collected 3 to 5 m from the stream bed. Shallow active layer depth in July 2015 meant only one soil water sample was collected at approx 20 cm depth. In August 2016, deeper active layer depth allowed for soil water sample collection at 80 – 90 cm depth, All samples were collected by hand and passed through a Whatman GF/F paper in the field. Logistical constraints and short field seasons limited the frequency of sampling from each site. Samples were frozen within 6 hours of collection until analysis.

Snowpack size was determined by calculating snowpack area from satellite imagery available on Google Earth (Digital Globe). Due to a lack of available imagery from the summer months of during the field campaign, imagery was used from August 2012.

2.2.3 Sample analysis

Water samples were analysed for major nutrient ions NH_4^+, NO_3^-, and PO_4^{3-} using the hypochlorite, cadmium reduction, and ascorbic acid methods, respectively using Lachat QuikChem flow injection analyzer (Lachat Instruments, APC Bioscientific Limited, England; APHA 2012). Dissolved Mg^{2+}, Ca^{2+}, Na^+, K+ and Si were determined by Inductively Coupled Plasma optical emission spectrometry (ICP, Optima 2000 DV). Silicate weathering and carbonate dissolution were examined using the ratios molar K^+ : dissolved Si and Ca^{2+} : Mg^{2+}

ratios to understand the influence of weathering dynamics on stream systems. Low ratios of K^+: Si represent stoichiometric silicate dissolution, such as is typical of older moraines (eg Cooper et al. 2002) and low Ca^{2+} : Mg^{2+} ratios signify high dolomite weathering, as is typical in non-glacierized basins (Blaen et al. 2013 and references therein). Crustal proportions could not be calculated due to the lack of Cl^- data however this was presumed to not be a problem for these ratios due to the small proportion of these solutes that originates in the sea (Mg^{2+}: 0.06, Ca^{2+}:0.02, K^+: 0.02) as opposed to the snowpack (Holland 1978).

2.2.4 Data analysis

Normality of data was tested using Levene's test and residual plots. Non-normally distributed data were natural log transformed before analysis. One-way ANOVAs were undertaken for air temperature, precipitation and snow depth variables to characterise differences in weather conditions between the field seasons, and Pfankuch Index and suspended sediment between streams to determine significant differences in channel stability. To analyse variation in stream hydrochemistry between years, sites and stream, both one way and two-way ANOVAs were used and significant results then underwent Tukey post-hoc tests. Differences between streams were not analysed in 2013 due to the lack of repeated samples. Pearson product-moment correlation coefficient was employed to ascertain the relationship between Pfankuch stability index with stream hydrochemistry, suspended sediment concentration and conductivity, and to test for the relationship between stream conductivity and precipitation.

2.3 Results

2.3.1 Hydroclimatological variables during the three field campaigns

Snow depth varied markedly between years (Table 2.2). Winter 2012/13 was a record dry year with maximum snow depth of 7.7 cm whereas the following two winters received relatively high snowfall (114.3 cm and 90.2 cm respectively) (November-May all years). Air temperature in 2013 and 2014 was significantly cooler compared to 2015 with a mean temperature of 5.9 ˚C and 6.0 ˚C in 2013 and 2014 respectively compared to 7.1 ˚C in 2015 (Table 2.2). Air temperature between 2013 and 2014 was not significantly different. Total rainfall was significantly different between years, with 8.8 mm in 2013, 37.6 mm in 2014 and 0.4 mm in 2015.

Table 2.2. Descriptive statistics for air temperature and precipitation during each field season and snow depth for the winter months November-May previous to each field season.

Variable	Statistic	Year		
		2013	2014	2015
Temperature (°C)	Mean ± SD (min-max)	5.9 ± 2.71 (-0.5, 14.9)	6.0 ± 3.26 (-0.7, 16.7)	7.1 ± 3.51 (-0.3, 16.7)
	ANOVA	2013 – 2014: F($_{1,2110}$)=0.14, P=0.71 2013 - 2015: F($_{1,1870}$)=69.67, P<0.0001 2014 – 2015: F($_{1, 1870}$)=53.73, P<0.0001		
Precipitation (mm)	Mean ± SD (min-max)	0.02 ± 0.07 (0.0, 0.9)	0.07 ± 0.3 (0.0, 3.5)	<0.01 ± 0.14 (0.0, 0.4)
	ANOVA	2013 - 2014: F($_{1,1054}$)=16.65, P=<0.0001 2013 -2015: F(1,1054)=24.2, P=<0.0001 2014 - 2015: F(1,1054)=28.6, P=<0.0001		
Snow depth (cm)	Mean ± SD (min-max)	3.45 ± 2.66 (0-7.7)	88.4 ± 12.52 (61.3 - 111.3)	48.56 ± 13.32 (30.2 - 90.2)
	ANOVA	2013 - 2014: F($_{1,8627}$)=82040, P=<0.001;		

		2013 - 2015 F(1,7731)=20437.66, P=<0.001 2014 - 2015 $F_{(1,12754)}$=30283.75, P=<0.001;

2.3.2 Snowpack size and stream channel stability

The area of principal snowpacks varied. Kaerelv, Graenseelv and Unnamed1 were sourced from snowpacks with an area of 0.01km^2 or under, Aucellaelv was sourced from a snowpack of 0.06km^2 and Palnatokeelv from a snowpack of 0.08km^2.

Discharge at streams Kærelv, Grænseelv and Unnamed1 increased downstream in 2015 (Table 2.3) but not at Aucellaelv where discharge was difficult to determine at the most downstream site due to the highly braided nature of the stream. Discharge for Palnatokeelv was not measured at its upstream and intermediate site due to high water velocities and depth. Given that the upstream site at Palnatokeelv was not located near the source like other streams, it is expected to have a similar discharge at all sampled sites. Discharges measured at all sites in 2014 were generally lower than 2015 although as some sites were sampled on more than one occasion, the variation in discharge caused by rain events is highlighted, especially in Unnamed1 where discharge varied from 181 l s^{-1} on a dry day to 622 l s^{-1} following a rainstorm event.

Channel stability was classified as either fair or poor channel stability at all sites except Kærelv sites B and C which were designated as good (Table 2.3). Channel stability increased downstream in Kærelv and Grænseelv. Unnamed1 displayed the highest channel stability at site B, and the lowest channel stability was measured at Palnatokeelv site B. Kærelv and Grænseelv were significantly more stable than Unnamed1, Aucellaelv and Palnatokeelv at sites A and C ($F_{(1,3)}$= 18.52 *P*=< 0.05, $F_{(1,3)}$= 417.63 *P*=<0.0001 respectively). Kærelv, Grænseelv and Unnamed1 were significantly more stable than Aucellaelv and Palnatokeelv at site B ($F_{(1,3)}$= 24.15 P= <0.05)

Suspended sediment concentrations were highly variable between streams (Table 2.3) with significantly higher levels in Aucellaelv, Lindemanelv and Palnatokeelv compared to Kærelv, Grænseelv and Unnamed1 ($F_{(1,2)}$ = 77364.54 P<0.0001, $F_{(1,2)}$ =8192.247 P= 0.0001, $F_{(1,2)}$ = 525.6693 P <0.01 respectively). Channel stability and suspended sediment concentration were not significantly correlated. Aucellaelv was found to be highly dynamic, displaying irregular channel migration and having a loose silt floodplain. In 2015, evidence of a new permafrost degradation site occurred between sites B and C of Aucellaelv where the stream travelled for approximately 70 m in a thermo-erosional tunnel causing slumping (Docherty et al. 2017), and the channel shifted by 1 m after a heavy rain event (personal observation). Palnatokeelv was also characterised as highly dynamic, and changed course frequently. Streams were divided into three groups based on channel stability and suspended sediment. Through these, the categories of stable, unstable and intermediate channel stability are used to define the streams, which also correspond with snowpack size, where Kærelv and Grænseelv (seasonal snowpacks) are stable, Aucellaelv and Palnatokeelv (perennial snowpacks) are unstable and Unnamed1 (both seasonal and perennial) had intermediate stability due to it falling into both categories.

Table 2.3. Pfankuch Index channel stability scores (Pfankuch 1975), discharge and suspended sediment concentration for each stream and longitudinal site (A – C). For channel stability, ‘excellent’ represents highly stable channels and ‘poor’ represents highly unstable channels. Significant differences for channel stability are shown where *= $P<0.05$, ***= $P<0.0001$ significant difference with Unnamed1, Aucellaelv, Palnatokeelv, **= $P<0.05$ significant different with Aucellaelv and Palnatokeelv. Significant differences in suspended sediment are shown where ***= $P<0.0001$ and **=$P<0.01$ significant difference with Aucellaelv, Palnatokeelv and Lindemanelv.

Stream	Longitudinal site	Channel stability				Discharge (l s^{-1})		Suspended sediment (mg L^{-1})
		Excellent (<38)	Good (39-76)	Fair (77-114)	Poor (115+)	2014	2015	2014
Kærelv	A			93^{*}		-	190	-
	B		70^{**}			-	235	-
	C		74^{***}			151	316	5.14(σ: 0.004; n: 7)***
Grænseelv	A			104^{*}		-	177	-
	B			83^{**}		-	186	-
	C			78^{***}		189	199	7.3(σ: 0, n: 1)***
Unnamed1	A				116	-	69	-
	B			85^{**}		-	68	-
	C			113		181/204/622	376	0.5 (σ: 0; n: 1)**

Aucellaelv	A		119	-	631	-
	B	111		-	976	-
	C		116	388/580	646	1120.25 (σ: 0.59, n: 4)
Palnatokeelv	A		116	-	-	-
	B		124	-	-	-
	C	114		247	788	96.3 (σ: 0; n: 1)
Lindemanelv	C	87		-	-	367.45 (σ: 0.32; n: 4)

2.3.3 Spatial variation in stream hydrochemistry dynamics

Conductivity varied markedly between streams but not within streams (Table 2.4). Conductivity was highest in streams with low channel stability (Palnatokeelv: 339 µS cm^{-1} and Unnamed1: 340 µS cm^{-1}) in 2013 and lowest in Unnamed 2 draining the crystalline catchment (31 µS cm^{-1}). Variation in conductivity between streams was characterised by the marked difference in the low stability stream Aucellaelv compared to all other streams (e.g. in 2015: Aucellaelv: 86-94 µS cm^{-1}, all other streams: between 22 and 42 µS cm^{-1}). Marked diurnal cycles in conductivity peaking in the afternoon were evident in Aucellaelv, coinciding with maximum snow melt. Peaks in conductivity and water level coincided with rain storm events, as evidenced by 8 July (Figure 2.2). No diurnal variability was observed in Lindemanelv despite glacial melt additions, possibly due to the larger stream size. Conductivity was significantly correlated with precipitation in Kærelv (r=0.199 *P*=<0.01) and Aucellaelv (r=0.268, *P*= <0.0001) but not in Lindemanelv and with suspended sediment at all sites (r=0.999, *P*=<0.001). Conductivity was significantly correlated with channel stability in 2013 only (r=0.9801, *P*=<0.01).

Marked differences were found between streams in hydrochemistry dynamics (Table 2.5). There was no significant correlation found between channel stability and hydrochemistry, Na^+, K^+, Si, NO_3^- and NH_4^+ were all significantly positively correlated with suspended sediment concentration (Table 2.6).

Low solute concentrations were characteristic of the stream draining the crystalline catchment, Unnamed2 compared to other sites. The low stability stream, Aucellaelv, was characterised by high solute concentrations compared to other sites, where, in 2013, all solutes, except Si, were significantly higher (*P*=<0.01) (Table 2.5) and in 2015, for Mg^{2+},

Ca^{2+} and Na^+ (P=<0.001). As Aucellaelv was markedly different from other streams in hydrochemistry, a one-way ANOVA removing Aucellaelv was conducted and solutes showed no significant differences between the remaining streams.

The low and intermediate stability streams, Palnatokelv and Unnamed1 (P=0.001; P=0.01 respectively) had significantly lower Na^+ concentrations than the high stability stream Kærelv in 2015, and K^+ concentrations were significantly lower in Palnatokeelv than Kærelv and Unnamed1 (both P=<0.01). Si concentration was significantly higher in the unstable stream Aucellaelv than in Kærelv, Grænseelv and Palnatokeelv (all P=<0.01). Longitudinal differences in hydrochemistry (Table 2.7) were generally not significant. In 2014, NO_3^- concentrations were significantly higher in Aucellaelv and Palnatokeelv than Kærelv, Grænseelv and Unnamed1 (all P=<0.0001) and in 2015 in Aucellaelv compared to all other streams, and Palnatokeelv compared to Grænseelv and Unnamed1 (all P=<0.05). Analyses were repeated without Aucellaelv, which led to no new significant differences being found between streams.

Low K^+: Si and Ca^{2+} : Mg^{2+} ratios indicated stoichiometric silicate dissolution and high dolomite weathering in the region. In 2015, Ca^{2+} : Mg^{2+} was significantly higher in Unnamed1 compared to all other streams (ANOVA=$F_{(5,23)}$=7.25, P=<0.001, Tukey=P=between 0.02 and 0.001 for all streams), however Ca^{2+} : Mg^{2+} was low at all sites and showed little variation longitudinally (Figure 2.3). For K^+: Si ratios, whilst there was no significant difference found between streams, an increase in K^+: Si was found downstream from the source in the three most stable streams (Kærelv, Grænseelv and Unnamed1) (Figure 2.3), paralleling an increase in downstream discharge.

Table 2.4. Spot measurements of electrical conductivity in years 2013, 2014 and 2015.

Stream	Site	Electrical conductivity (µS cm^{-1}) by year and site		
		2013	2014	2015
Kærelv	A	-	-	26
	B	-	-	36
	C	192.2	55.1	36
Grænseelv	A	-	-	32
	B	-	-	34
	C	208	54	32
Unnamed1	A	-	-	38
	B	-	-	32
	C	340	-	42
Aucellaelv	A	-	-	86
	B	-	-	94
	C	313	127	88
Palnatokeelv	A	-	-	23
	B	-	-	22
	C	339	58.2	26
Unnamed 2		31	-	-
Lindemanelv		-	45	-

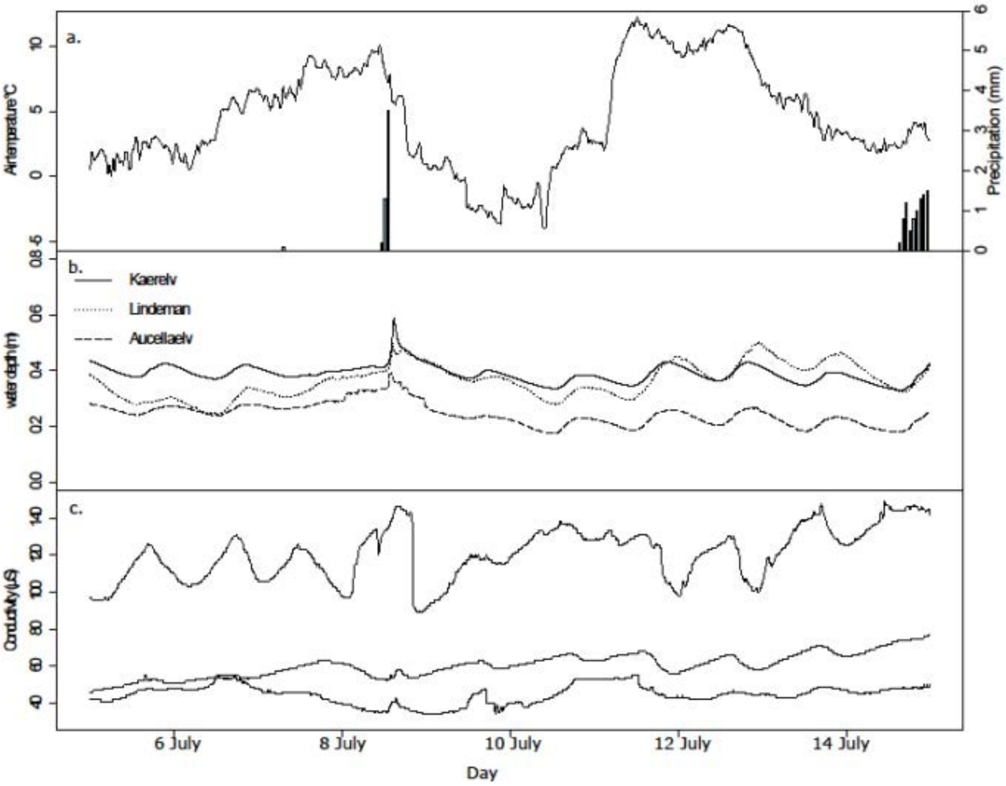

Figure 2.2. a) Air temperature and precipitation, b) water depth and c) conductivity timeseries for Kærelv, Aucellaelv and Lindemanelv between 5 – 14 July 2014.

Table 2.5. Descriptive statistics for major ions for stream water, soil water and snow in the 2013, 2014, 2015 and 2016 melt seasons. N= number of samples, M = Mean, σ = Standard deviation.

Site		Mg^{2+}		Na^{+}		K^{+}		Ca^{2+}		Si		NH_4^{+}		NO_3^{-}		PO_4^{3-}	
		(µEq L^{-1})								mg L^{-1}		(µEq L^{-1})					
	n	M	σ	M	σ	M	σ	M	σ	M	σ	M	σ	M	σ	M	σ
Kærelv 2013	1	122.6	NA	143.4	NA	24.15	NA	641.3	NA	2.2	NA	NA	NA	NA	NA	NA	NA
Kærelv 2014	6	64.6	16.9	143.9	171.5	14.7	7.2	195.0	50.1	1.1	NA	1.1	0.8	0.0	0.1	0.3	0.4
Kærelv 2015	3	50.1	4.5	64.4	8.2	13.0	3.5	144.2	20.3	1.3	0.11	0.8	0.2	0.1	0.1	0.1	0.01
Kærelv 2016	3	287.91	3.32	559.06	30.34	39.65	6.29	913.77	19.03	2.03	0.22	NA	NA	NA	NA	NA	NA
Grænseelv 2013	1	266.7	NA	321.6	NA	48.2	NA	728.7	NA	2.0	NA	NA	NA	NA	NA	NA	NA
Grænseelv 2014	4	54.3	13.4	41.4	11.9	9.6	2.7	143.3	37.7	1.1	NA	0.4	0.1	0.01	0.01	0.1	0.01

Grænseelv 2015	3	38.4	20.9	36.8	14.9	10.3	4.5	102.9	41.6	1.3	0.2	3.1	3.1	0.04	0.02	0.1	0.02
Grænseelv 2016	3	224.03	3.24	179.36	30.63	30.90	4.74	732.32	13.18	3.10	0.33	NA	NA	NA	NA	NA	NA
Unnamed1 2013	1	291.7	NA	130.0	NA	29.7	NA	1504.8	NA	1.75	NA	NA	NA	NA	NA	NA	NA
Unnamed1 2014	3	138.1	44.4	42.0	16.2	13.2	3.8	586.5	292.7	1.2	NA	0.4	0.1	0.0	0.01	0.1	0.01
Unnamed1 2015	3	38.0	6.0	39.1	5.2	10.7	1.5	157.1	16.6	1.0	0.1	0.7	0.1	0.1	0.6	0.1	0.00
Unnamed2 2013	1	12.5	NA	<6.5	NA	6.7	NA	16.5	NA	<0.4	NA	3.5	1.3	1.3	0.2	0.1	0.11
Aucellaelv 2013	1	345.8	NA	592.6	NA	42.8	NA	933.3	NA	2.0	NA	2.4	0.4	1.80	0.2	0.1	0.04

Aucellaelv 2014	3	211.0	62.8	305.8	62.9	26.1	3.4	460.2	118.6	2.2	NA	1.9	0.4	0.8	0.2	0.1	0.05
Aucellaelv 2015	3	88.6	18.4	148.8	23.6	5.3	0.6	227.8	30.0	0.8	0.1	1.1	0.1	0.4	0.2	0.1	0.02
Aucellaelv 2016	3	770.61	66.49	606.42	47.70	45.34	2.20	3152.77	65.82	1.72	0.02	NA	NA	NA	NA	NA	NA
Palnatokeelv 2013	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Palnatokeelv 2014	2	71.46	2.29	66.96	4.35	10.38	0.38	164.25	15.5	1.23	NA	0.69	0.23	0.19	0.12	0.13	0.03
Palnatokeelv 2015	3	38.60	10.05	19.52	16.51	4.16	3.51	102.46	13.4	0.95	0.11	1.06	0.27	0.69	0.26	0.10	0.03
Snow 2013	1	7.50	NA	83.91	NA	1.54	NA	19.00	NA	<0.4	NA	NA	NA	NA	NA	NA	NA

Dirty snow 2013	1	16.25	NA	83.91	NA	14.87	NA	70.00	NA	<0.4	NA	NA	NA	NA	NA	NA	NA
Snow 2014	2	19.38	11.04	28.70	28.70	3.85	1.03	31.63	1.88	0.45	0.05	1.09	0.09	0.23	0.23	0.17	0.02
Snow 2015	24	2.75	2.02	36.94	31.45	6.32	4.02	15.10	13.12	<0.4	0.00	NA	NA	NA	NA	NA	NA
Grænseelv soil water 2015	1	103.16	NA	212.96	NA	9.43	NA	147.14	NA	1.27	NA	NA	NA	NA	NA	NA	NA
Kærelv soil water 2016	3	1651.22	505.97	2845.35	118.50	119.53	8.49	2971.97	666.88	4.55	1.01	NA	NA	NA	NA	NA	NA
Grænseelv soil water 2016	3	334.51	18.64	233.61	16.79	36.13	6.17	693.48	22.42	2.62	0.37	NA	NA	NA	NA	NA	NA

Aucellaelv soil water 2016	3	690.58	13.28	341.61	45.39	40.80	5.00	3109.71	89.93	2.81	0.20	NA	NA	NA	NA	NA	NA

Table 2.6. Pearson Correlation results for channel stability and suspended sediment with stream hydrochemistry. Bold text indicates a significant relationship.

	Channel stability			Suspended sediment		
	r	r^2	p	r	r^2	p
Mg	0.686	0.471	0.201	0.856	0.732	0.064
Na	0.246	0.061	0.690	**0.922**	**0.850**	**0.026**
K	0.380	0.145	0.528	**0.935**	**0.874**	**0.020**
Ca	0.627	0.393	0.257	0.388	0.150	0.519
Si	0.563	0.316	0.324	**0.993**	**0.987**	**0.001**
NO3	0.556	0.309	0.330	**0.989**	**0.978**	**0.001**
NH4	0.233	0.054	0.706	**0.899**	**0.808**	**0.038**
PO4	-0.387	0.150	0.520	-0.039	0.002	0.950
Suspended sediment	0.870	0.757	0.055			

Table 2.7. Descriptive statistics for major ions from streams longitudinal for 2015 melt season. M=mean, σ = standard deviation.

		Mg^{2+} µEq L^{-1}		Na^{+} µEq L^{-1}		K^{+} µEq L^{-1}		Ca^{2+} µEq L^{-1}		Si mg L^{-1}	
Site	n	M	σ	M	σ	M	σ	M	σ	M	σ
Kærelv A	3	37.59	3.93	56.98	1.34	6.75	0.22	99.95	8.49	1.47	0.12
Kærelv B	3	34.04	10.04	35.87	10.23	9.06	2.04	119.97	22.75	1.17	0.07
Kærelv C	3	50.09	4.48	64.37	8.15	12.99	3.51	144.20	20.26	1.28	0.11
Grænseelv A	2	42.60	9.58	56.07	16.56	5.10	1.44	115.14	17.12	1.57	0.09
Grænseelv B	3	32.20	12.26	29.57	8.43	7.18	1.95	97.65	25.29	1.35	0.01
Grænseelv C	3	38.39	20.87	36.83	14.90	10.30	4.45	102.90	41.59	1.42	0.00
Unnamed1 A	3	33.06	4.22	36.03	3.01	7.67	0.66	149.98	8.77	1.01	0.05
Unnamed1 B	3	14.94	9.65	19.93	6.06	6.94	2.11	87.86	32.01	0.72	0.17
Unnamed1 C	3	38.01	5.96	39.09	5.17	10.73	1.47	157.10	16.58	0.95	0.06
Aucellaelv A	3	102.71	12.09	187.37	25.26	7.34	0.82	238.80	7.82	1.02	0.04

Aucellaelv B	3	110.56	2.60	226.24	27.61	6.84	0.14	256.43	3.45	0.94	0.01
Aucellaelv C	3	88.57	18.43	148.78	23.58	5.31	0.64	227.75	30.01	0.80	0.08
PalnatokeelvA	3	39.47	3.09	68.19	3.41	5.29	0.71	86.78	3.70	1.14	0.03
PalnatokeelvB	2	44.01	1.15	69.25	2.98	4.65	0.09	94.67	2.75	1.19	0.00
PalnatokeelvC	3	38.60	10.05	64.19	16.30	4.84	1.14	102.46	13.41	0.95	0.11

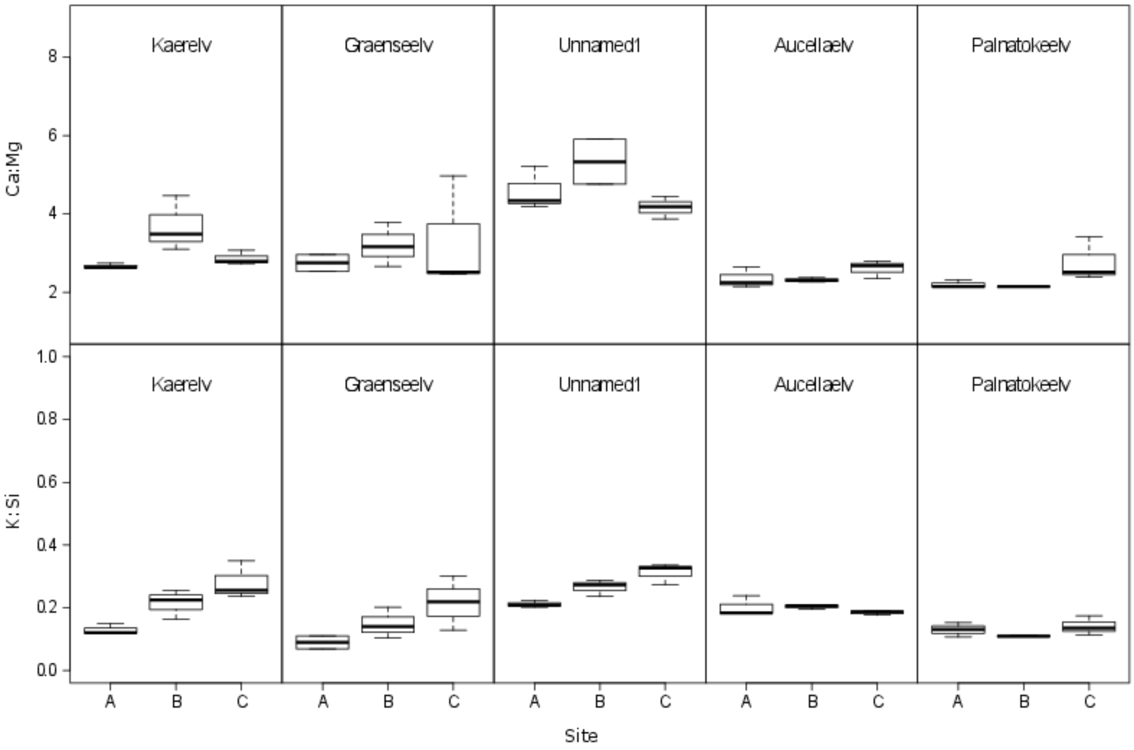

Figure 2.3. Longitudinal variation in stream Ca^{2+} :Mg^{2+} (top pane) and K^{+}:Si (bottom pane) ratios.

2.3.4 Interannual variation in stream hydrochemistry dynamics

Large differences in hydrochemistry were found between years. Conductivity was highly variable, with the highest conductivity recorded in 2013 (Unnamed1 340 µS cm^{-1}) and lowest in 2015 (Palnatokeelv 26 µS cm^{-1}) (Table 2.4).

There were significant differences in stream hydrochemistry between the 2013, 2014 and 2015 for all solutes apart from Si (Table 2.8; Table 2.9). Ca^{2+} enrichment was highest in 2013 when concentrations were highest in Unnamed1 (1504 µEq L^{-1}) and Aucellaelv (933 µEq L^{-1}). Solute concentrations were highest in surface water in August 2016, where the highest Mg^{2+}

concentration (770.6 µEq L^{-1}) and Ca^{2+} concentration (3152.8 µEq L^{-1}) were recorded in Aucellaelv.

Significant differences were found in nutrient concentrations between years (Table 2.8). There were significant differences in NH_4^+ between years but no significant differences between streams in 2015. In 2014, Aucellaelv had higher NH_4 concentrations than all other streams (Table 2.5). Significantly higher NH_4^+ concentrations were also reported for Kærelv than Grænseelv and Unnamed1 in 2014 (P=<0.01). For NO_3^-, Tukey post hoc tests revealed significant variation between 2013-2014 and 2014-2015 (Table 2.9). Ca^{2+} :Mg^{2+} was significantly higher in 2015 than 2013 and 2014 (ANOVA= $F_{(2,23)}$=29.76, P=<0.001, Tukey= P=<0.05, P=<0.001 respectively), whilst K^+:Si was significantly higher in 2013 than 2015 (ANOVA= $F_{(2,23)}$=5.257, P=0.01, Tukey for 2013-2015 P=<0.05) (Figure 2.4).

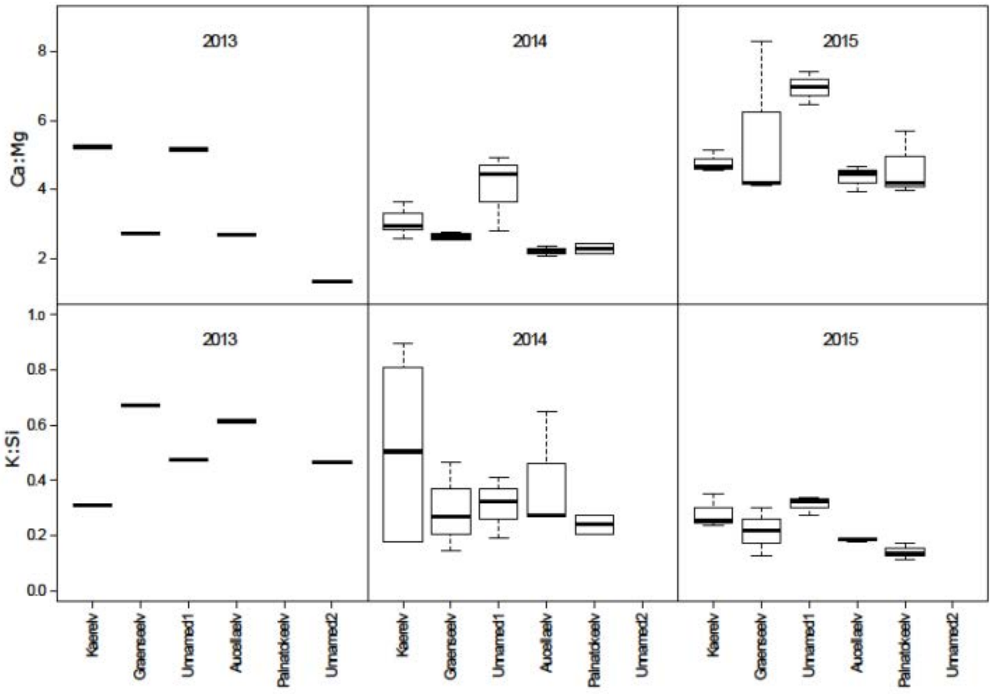

Figure 2.4. Interannual variation in Ca^{2+} :Mg^{2+} (top pane) and K^+:Si (bottom pane) ratios for streams between 2013 and 2015.

Table 2.8. ANOVA between streams in 2014 and 2015, longitudinal sites in 2015, and between years.

	Streams 2014	Streams 2015	Longitudinal 2015	Year
Mg	F($_{4,13}$)=11.32, *P*=0.0004	F($_{4,27}$)=14.924, *P*=<0.001	F($_{2,27}$)=2.371, *P*=0.11	F($_{2,23}$)= 25.801, *P*=<0.0001
Na	F($_{4,12}$)=30.43, *P*=<0.001	F($_{4,27}$)=55.826, *P*=<0.0001	F($_{2,27}$)=4.523, *P*=0.02	F($_{2,22}$)= 24.253, *P*=<0.0001
Ca	F($_{4,13}$)=5.47, *P*=0.01	F($_{4,27}$)=21.987, *P*=<0.0001	F($_{2,27}$)=1.752, *P*=0.19	F($_{2,23}$)=45.260, *P*=<0.0001
K	F($_{4,12}$)=13.07, *P*=<0.001	F($_{4,27}$)=14.924, *P*=<0.001	F($_{2,27}$)=2.371, *P*=0.12	F($_{2,22}$)=32.434, *P*=<0.0001
Si	F($_{4,13}$)=1.493, *P*=0.261	F($_{4,27}$)33.537, *P*=<0.0001	F($_{2,27}$)=13.902, *P*=<0.0001	F($_{2,23}$)=2.768, *P*=0.0837
PO_4^{3-1}	F($_{4,31}$)=4.835, *P*=0.004	F($_{4,30}$)=3.224, *P*=0.025	NA	F($_{2,53}$)=1.141, *P*=0.3272
NH_4^+	F($_{4,31}$)= 17.25, *P*=<0.0001	F($_{4,30}$)=0.803, *P*=0.53	NA	F($_{2,53}$)=7.839, *P*=<0.001
NO_3^-	F($_{4,31}$)= 17.81, *P*=<0.0001	F($_{4,30}$)=18.294, *P*=<0.0001	NA	F($_{2.47}$)=16.52, *P*=<0.0001

Table 2.9. Tukey post-hoc results of variation in stream hydrochemistry between years

	2013-2014	2013-2015	2014-2015
Mg	<0.001	<0.0001	<0.01
Na	<0.0001	<0.0001	NS
Ca	<0.0001	<0.0001	<0.01
K	<0.0001	<0.0001	<0.01
Si	NS	NS	NS
PO_4^{3-1}	NS	NS	NS
NH_4^+	NS	NS	<0.001
NO_3^-	0.01	NS	<0.001

2.3.5 Water source characteristics

Solute concentration was low in snow relative to surface waters, except for PO_4^{3} where the second highest concentration was in snow (0.17 µEq L^{-1} from 2014, with the highest in Kærelv in 2013: 0.29 µEq L^{-1}). Si was negligible in snow, below the detection limit (< 0.4 mg/L) (Table 2.5). Soil water collected in 2016 had very high solute concentrations including highest Si concentrations measured (between 2.61 and 4.55 mg/L) (Table 2.5).

2.4 Discussion

2.4.1 Stream channel stability and suspended sediment characterisation

Stream channel stability in this region is dependent upon a number of geomorphological and hydrological variables. The largest snowpacks accumulate on south facing lee slopes, where northerly winds blow winter snow and sediment into moraine ridges and fluvial terraces (Christiansen 1998b) which then melt to feed streams during the summer months. Larger snowpacks can cause greater geomorphological disturbance through nivation processes, which are emphasised on loose unconsolidated sedimentary soils due to increased water infiltration and greater surface area in contact with melted snow, increasing stream suspended sediment load and reducing channel stability (Christiansen 1998b; Hasholt & Hagedorn 2000).

Sheet floods occur during spring snowmelt around the streams at Zackenberg, typically until June due to the frozen active layer preventing infiltration. These flood waters carry high sediment loads leading to sediment deposition (Christiansen et al. 1998a; Cable et al. 2017). Aucellaelv and Palnatokeelv have higher spring discharges than streams sourced from smaller snowpacks, and carry a larger sediment load. This can lead to increased downstream disturbance, leading to bare ground where vegetation is unable to colonise and through this method, create a supply of loose sediments that can enter the water column throughout the summer season. Highest suspended sediment concentrations at upstream sites in Aucellaelv have been found previously (Hasholt & Hagedorn 2000) highlighting sediment deposition on alluvial cones. Alongside spring floods as a source of sediment, the dirty snow found on Aucella mountain in 2013 indicates aeolian sediment transport into snowpacks during winter (Cable et al. 2017), and, although infrequent, rainstorm events have also been found to highly influence sediment flux by driving increased erosion in sparsely vegetated areas in the sedimentary region (Rasch et al. 2000).

Significantly lower channel stability in streams sourced from perennial snowpacks than smaller, seasonal snowpacks, allowed acceptance of hypothesis 1. However, as channel stability was not significantly associated with solute concentration hypothesis 2 could not be accepted. Variability in suspended sediment concentration between streams was directly related to different geomorphological processes occurring within that area. The smaller snowpacks - and so smaller spring floods of Kærelv and Grænseelv did not cause large-scale nivation processes, sediment deposition, active layer slides or permafrost degradation compared to larger snowpacks, therefore leading to lower suspended sediment concentrations and extensive proximal vegetation cover and thereby more stable stream channels. In contrast, snowpacks in Aucellaelv and Palnatokeelv were larger and so the drainages were vulnerable to larger nivation processes and sedimentation along the banks caused by intense spring floods, resulting in a lack of bank-side vegetation, whilst nival erosion and high velocity flow contribute to the production of active layer slides and slumping and permafrost degradation (Docherty et al. 2017), resulting in low stability streams with high suspended sediment concentration. This is also highlighted by the increased snowpack size in Kærelv and

Grænseelv in 2014 and 2015 compared to 2013 and the associated increase in bankside erosion witnessed in these streams (personal observation).

Within the wider Zackenberg river catchment, the predominantly glacier sourced streams overlying crystalline bedrock carry very little sediment to the Zackenberg river. The streams in the sedimentary catchment, which account for only 10 - 20% of total catchment area and include Aucellaelv, Palnatokeelv, Unnamed1 and Lindemanelv, account for 90% of the sediment transported to the main Zackenberg river (Jakobsen 1992). Whilst glacial streams are known to be highly turbid, especially in the early melt season (Gurnell 1987; Milner & Petts 1994), it is the snowmelt streams of the Zackenberg drainage basin that transport the most sediment due to their underlying sedimentary material. This situation highlights the importance of characterising geology into studies of Arctic streams and the important influence of nivation processes and permafrost degradation for sediment transport.

2.4.2 Spatial variation in channel stability and stream hydrochemistry dynamics

The geological division in the Zackenberg valley between the sedimentary eastern hills and the crystalline western hills caused the differing solute concentrations in Unnamed2 compared to the other study streams. The eastern slopes, which sourced all other study streams, are modified by a combination of cryogenic, nival, fluvial, aeolian, and mass movement processes, which lead to loose, fine-grained sediment entering stream channels in this region. Unnamed2 on the western slopes which are dominated by gravitational processes, as thus such sediment transported by streams in this region is coarser and less likely to reach as far downhill (Cable et al. 2017). Nivation processes and permafrost degradation have limited influence in this catchment (Christiansen & Humlum 1993). This lack of loose, fine sediment and erosional processes leads to reduced solute load in Unnamed2 compared to the other streams.

Of the streams within the sedimentary region, Aucellaelv and Palnatokeelv, with larger snowpacks, also overlie large areas of solifluction and have notable nivation hollows along their stream banks, which could be responsible for the large sediment load within the stream channels. Kærelv, Grænseelv and Unnamed1 are largely overlying alluvial fans, peat bogs and lateral moraines, similar in Aucellaelv and Palnatokeelv in their lower reaches (Cable et al. 2017). The higher suspended sediment concentration in Aucellaelv compared to other streams is likely the cause of the significant difference in solute load for most cations through instream weathering processes of suspended sediment through turbulent stream flow (Chin et al. 2016). Similar to Aucellaelv, the higher suspended sediment concentrations recorded in Palnatokeelv and Lindemanelv was likely due to weathering of rock-derived sediment from nivation processes and permafrost degradation. Although high suspended sediment concentration is a characteristic feature of streams receiving glacial inputs, given the timing of this field campaign in early July during the peak snowmelt period, and the small size of glaciers located in this catchment, glacial inputs were thought to be minimal during the sampling period.

The higher levels of Ca^{2+} and Mg^{2+} in Aucellaelv are probably derived from black shales in this region (Hasholt & Hagedorn 2000). Differences between the study streams in terms of weathering processes were not found but did corroborate findings from Hasholt & Hagedorn (2000) that silicate weathering is the dominant weathering process in the region as shown in the low K^{+}:Si ratios and the low carbonate dissolution in the Ca^{2+} :Mg^{2+} ratios. This is typical of non-glacierized Arctic catchments, where carbonates and evaporates typical of glacierized catchments (Bluth & Kump 1994) have been used up, and due to the increased contact with rock, longer residence times and interaction with the active layer (Anderson et al. 2000; Fortner et al 2005; Blaen et al. 2013).

2.4.3 Interannual variation in stream hydrochemistry dynamics

Interannual variation in solute concentration was principally due to climatic forcing. Large variation in precipitation falling as winter snowfall was evident throughout this study, and the effect of this was shown by the large temporal variation in conductivity as well as the variation in solute concentration. The low snowfall in winter 2012-2013 resulted in low snow meltwater inputs to streams the following summer, causing high solute concentration and conductivity compared to the following two years. The low water level in 2013 resulted in highly concentrated solute loads, as also found in late summer 2016. The low solute concentrations found in 2014 and 2015 occurred when meltwater inputs were highest, causing a dilution effect. This dilution effect was also noted in the temporal variation in K^+:Si ratios between 2013 and 2015 when ratios were lowest during high discharge.

2.4.4 Water sources and their impact on stream hydrochemistry

Water source is a known driver of hydrochemistry, and previous studies have shown variation in solute concentration throughout the summer period due to changes in water sources (e.g. Rasch et al. 2000). Conductivity was found to be highest during the first few days after spring ice break due to the high dissolved load washing out of the first summer snowmelt event (Mernild et al. 2007b). During the main field campaigns in July each year, the dominant water source for all sites was snow melt. Given the shallow active layer depth and snowmelt pools that had formed nearby, soil water input was probably low during this time period, with the soil water sample collected most likely recently leached snowmelt. Palnatokeelv, Lindemanelv and Aucellaelv also receive glacial meltwater contributions which is known to lead to reduced channel stability, increased sediment load, and more extreme physicochemical habitat for biota (Milner & Petts 1994). The relative minimal glacial inputs into these systems during the field campaign mean that they can be classified as nival systems following the classification of Brown et al. (2003). Given the low solute concentration of snow and the shallow active layer, stream hydrochemistry during July is likely a function of nivation processes causing localised erosion, and varying suspended sediment concentrations. However, towards the end of summer, as snowpacks decline and active layer thickness increases, streams receive larger soil water inputs, with the largest contributions during August (Rasch et al. 2000; Blaen et al. 2013). The high solute concentrations measured in Kærelv, Grænseelv and Aucellaelv in August 2016 reflect this. During this time, the interaction between stream water and soil water, and access to previously frozen solutes from the thicker active layer were key drivers of later summer stream hydrochemistry dynamics. The large spatial and temporal variation in Si concentration shows that in these systems, hydrochemistry cannot be used for fingerprinting water source as is traditionally used (e.g. Tranter et al. 1996), but rather, it's variation is a product of the spatial and temporal variation of erosion. As such, alternative methods would have to be implemented within this region to determine basin-scale water sources.

2.4.5 Regional implications of climate change and conclusions

Northeast Greenland has been predicted to be warmer, wetter and windier by the end of the century (Stendel et al. 2008), directly influencing stream systems in the region. Active layer thickness on Aucellabjerg and the valley bottom is predicted to increase by 8-12 cm, causing active layer detachments and slides to become frequent processes (Christiansen et al. 2008), leading to an increase in sediment, solutes and soil water entering streams. Winter precipitation is expected to increase by 40-60 % (Stendel et al. 2008). This could lead to larger spring floods increasing sedimentation along stream banks, higher water levels and increased sediment and solute load in streams due to increased nivation processes and permafrost slumping. The predicted increase in summer precipitation is highly likely to increase weathering processes and so increase stream solute loads (Hasholt et al 2008; Rasch et al 2000). These climatic changes are expected to cause stream systems to have reduced channel stability and increased suspended sediment concentration, with consequences for stream hydrological and ecological dynamics. The impacts of these climatic changes are predicted to cause low stability stream systems to become increasingly widespread. This study shows least stable streams and those with highest suspended sediment concentration to have the highest nutrient content. All streams in this study are known to be nutrient limited with respect to primary production (Docherty et al. *in press*). Increased N and P nutrient inputs into nutrient-poor Arctic streams can increase primary productivity, providing the base of the food-web for increased macroinvertebrate diversity and abundance. However, increased nutrient input through nivation processes and permafrost degradation is accompanied by increased suspended sediment inputs, and evidence shows a negative correlation between suspended sediment content and macroinvertebrate abundance (Chin et al. 2016), counteracting the positive impacts of additional nutrient inputs. High suspended sediment concentration causes reduced light penetration through the water column and this combined with high channel mobility can reduce primary producer growth (Ryan 1991), reducing food availability for macroinvertebrates. Previous studies have found an increase in suspended sediment to be correlated with decreases in macroinvertebrate density, abundance and richness (Nuttall & Bielby 1973; Wagener & LaPerriere 1985; Quinn et al. 1992; Shaw & Richardson 2001) and an increase in invertebrate drift (Rosenberg & Wiens 1978; Doeg & Milledge 1991; Bilotta & Brazier 2008). Suspended sediment can cause gills and guts to become clogged (Alabaster & Lloyd 1982; Billota & Brazier 2008), can smother macroinvertebrate eggs (Jones et al. 2012) and can impede respiration and feeding in Chironomidae, being especially damaging to those that produce silk tubes (Gray & Ward 1982; Chin et al. 2016). Species-types tolerant of harsh environments such as *Diamesa* spp. are expected to be more common in these environments. Further research is needed within the Arctic region to fully understand these process changes to their impact on benthic communities.

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CHAPTER 3: LARGE THERMO-EROSIONAL TUNNEL FOR A RIVER IN NORTHEAST GREENLAND

Abstract

Thermo-erosional river bank undercutting is caused by the combined action of thermal and mechanical erosion of the permafrost by Arctic rivers whilst the overlying sediment temporarily withstands collapse. Here, we document a large thermo-erosional tunnel that formed in the banks of a meltwater-fed stream in northeast Greenland in summer 2015. The tunnel was observed over eight days (14 – 22 July), during which period the tunnel remained open but bank-side slumping increased. Stream solute load increased immediately downstream and remained high 800m from the tunnel. Whilst this field observation was opportunistic and information somewhat limited, our study provides a rare insight into an extreme event impacting permafrost, local geomorphology and stream habitat. With accelerated climate change in Arctic regions, increased permafrost degradation and warmer stream water temperature are predicted thereby enhancing potential for thermo-erosional niche development and associated stream bank slumping. This change could have significant implications for stream physicochemical habitat and, in turn, stream benthic communities, through changes in aquatic habitat conditions.

3.1 Introduction

Thermo-erosional niches are river bank undercutting resulting from the combined action of thermal and mechanical erosion (Walker et al. 1987): running water infiltrates cavities in the frozen active layer, forming underground tunnels, from where fast water current and warmer water temperatures, relative to the frozen ground, simultaneously thaw and erode the permafrost (Walker & Arnborg, 1966; Perreault et al. 2016). Whilst water temperature has been identified as the principal factor influencing thermo-erosional niche development, ice, sand and silt content in the permafrost are also important considerations (Dupeyrat et al. 2011). Thermal erosion is most prevalent in the High Arctic landscape due to (1) higher river flows during summer peak snowmelt and (2) the presence of permafrost which strengthens the river banks but permits larger amounts of bank undercutting, and large slump blocks when the banks finally collapse (Scott 1978). Whilst the most common type of thermo-erosional niche occurs along stream banks or coastal areas where the above-lying sediment eventually collapses, they can also be created without the sediment above the niche collapsing, forming tunnels. However, due to their tendency to occur in these remote environments, large tunnel forming thermo-erosional niches have rarely been reported. Most reports of large-scale thermo-erosional niches have been from Alaska and Canada and have been formed through ice wedge thaw (eg. Fortier et al. 2007; Godin & Fortier 2012; Veillette et al. 2015; Kanevskiy et al. 2016). Limited information is available from other areas of the Arctic. To increase our knowledge on this phenomenon and create a pan-Arctic record, here we report and describe a large thermo-erosional tunnel over a stream in northeast Greenland.

3.2 Methods and Data

3.2.1 Site description

The snowmelt-fed stream Aucellaelv is in close proximity to the Zackenberg research station at 74º28’ N, 20º34’ W in the Northeast Greenland National Park (Figure 3.1). The mean annual air temperature is -9.1°C and the warmest month is July with a mean temperature of 5.8°C. The mean precipitation is 261mm and falls mainly as snow (Hansen et al. 2008). The site was located on lower mountain slopes within a wide horizontal valley formed by glacial erosion approximately 10,000 years before present (Mernild et al 2007; Bennike et al 2008). Zackenberg is an area of continuous permafrost, with depth modelled to be 200 – 300m deep and varying active layer thickness between 0.3 and 0.65m (Christiansen et al. 2008). The region is composed of Cretaceous and Tertiary sandstones with loose sediment of weak compaction that is susceptible to erosion (Hasholt & Hagedorn 2000) and is held together largely due to its frozen nature. Ice wedge polygons occur within the area and signs of thermal erosion have been observed before in the area along the banks of the larger Zackenberg River after an extreme flood event (Christiansen et al. 2008), however this did not result in tunnel formation.

The Aucellaelv channel has been characterised as having low channel stability and as being highly mobile with stream channel observed to shift course by 1m after an extreme storm event (Docherty et al. unpublished data). Suspended sediment concentration was high (>1100 mg/L). The Aucellaelv floodplain consisted largely of boulders, cobbles and silt; and there was limited vegetation in close proximity to the stream. The streams in this region are frozen to the stream bed typically between late September and early June, when thawing coincides with peak summer snowmelt (Docherty et al. unpublished data).

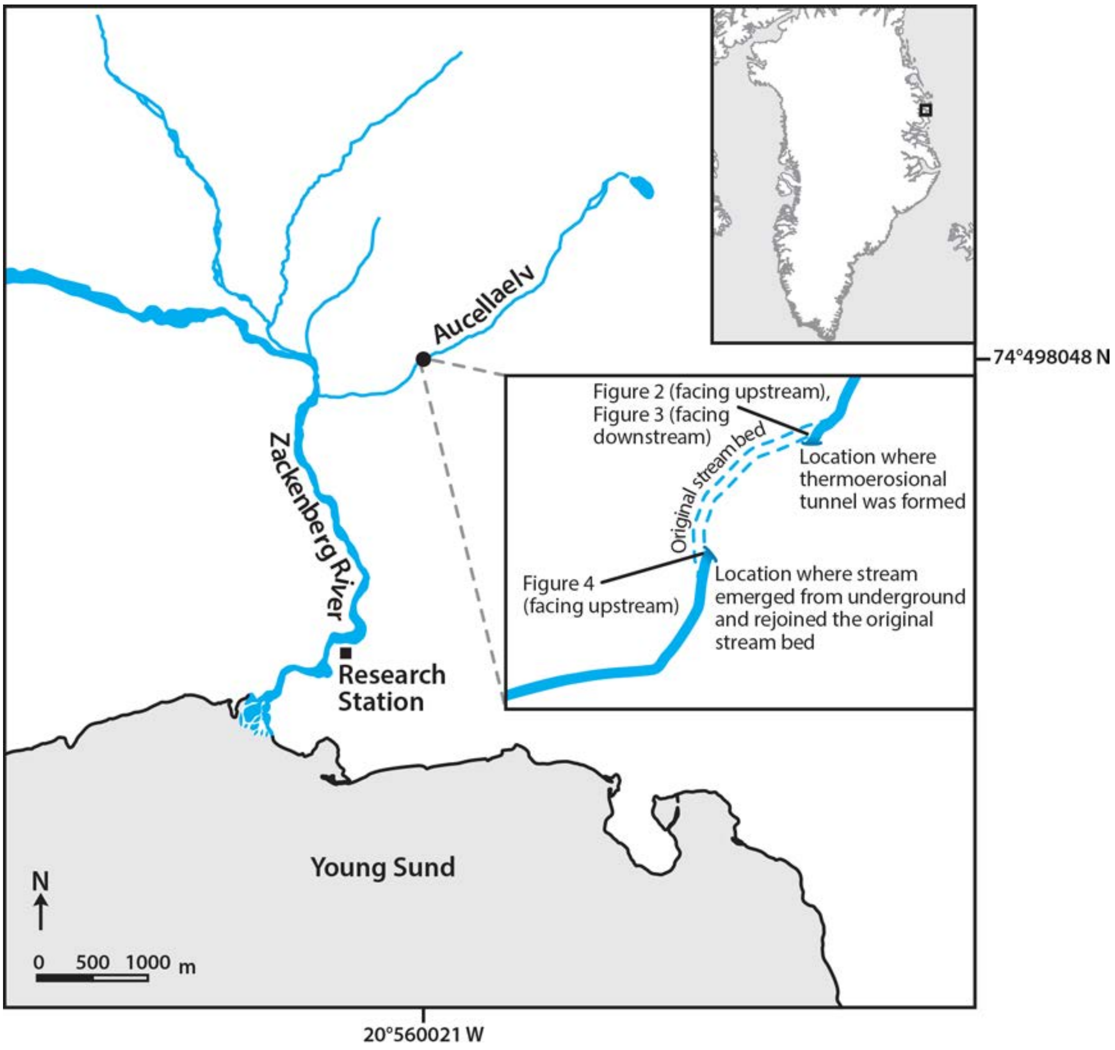

Figure 3.1 Study area showing location of the thermoerosional tunnel and points from which Figures 2 to 4 were taken.

3.3 Observation and description of thermo-erosional niche

First observed on 14th July 2015, the entire stream had ‘disappeared’ underground through a self-formed tunnel at approximately 1.5m below the surface, leaving the above soil intact, and travelled for approximately 70m before re-emerging downstream into the original stream channel. It is unknown how long the tunnel had been in existence before this date. A large amount of slumping was present at the entry point due to a loss of soil stability and compaction (Figure 3.2; Figure 3.3), with slump blocks undergoing fluvial erosion as they were unable to be transported downstream due to the tunnel roof blocking passage. Less slump blocks were present at the point of exit (Figure 3.4) due to them being transported away in the flow. Water temperature was 4°C and water velocity was relatively high (discharge 976L/s, average velocity within reach 0.59m/s). Water samples were collected at the entry and exit of the tunnel, filtered in the field using Whatmann GF/F filter papers and analysed for major ions. Higher concentrations of all major ions were found downstream, with Mg concentration increasing from $1.66\mathrm{mg/L}^{-1}$ to $2.72\mathrm{mg/L}^{-1}$ and Na increasing from $2.84\mathrm{mg/L}^{-1}$ to $4.05\mathrm{mg/L}^{-1}$ (Table 3.1) due to the erosion of permafrost acting as a major source of ions (Rasch et al 2000). Approximately 800m downstream of the tunnel, dissolved solute concentration remained high and in some cases, was slightly higher than directly below the thermos-erosional tunnel exit (Table 3.1).

The tunnel was still present on 22 July, eight days after first observation; however, bank-side slumping had increased around the niche throughout that time. Due to the logistical difficulties of fieldwork in northeast Greenland, it was not possible to conduct a long-term study on the evolution of this process and consequently, it is unknown how much longer the tunnel remained. Whilst Aucellaelv had been classified as having a low stability channel, no prior observation of such an event had been reported for Aucellaelv or elsewhere in the Zackenberg region.

Whilst other documented thermo-erosional tunnels have formed in a vertical direction due to meltwater runoff melting ice wedges, leading to waterfall and sinkhole formation previous to tunnel development (eg. Fortier et al. 2007; Godin & Fortier 2012), the horizontal formation of this tunnel in the river bank infers that the thermo-erosional tunnel reported in this paper was not caused by ice wedge thaw. We propose that the relatively warm stream temperature of 4˚C of Aucellaelv combined with high velocity of the meltwater thawed the frozen sediment in the river channel and created the observed tunnel.

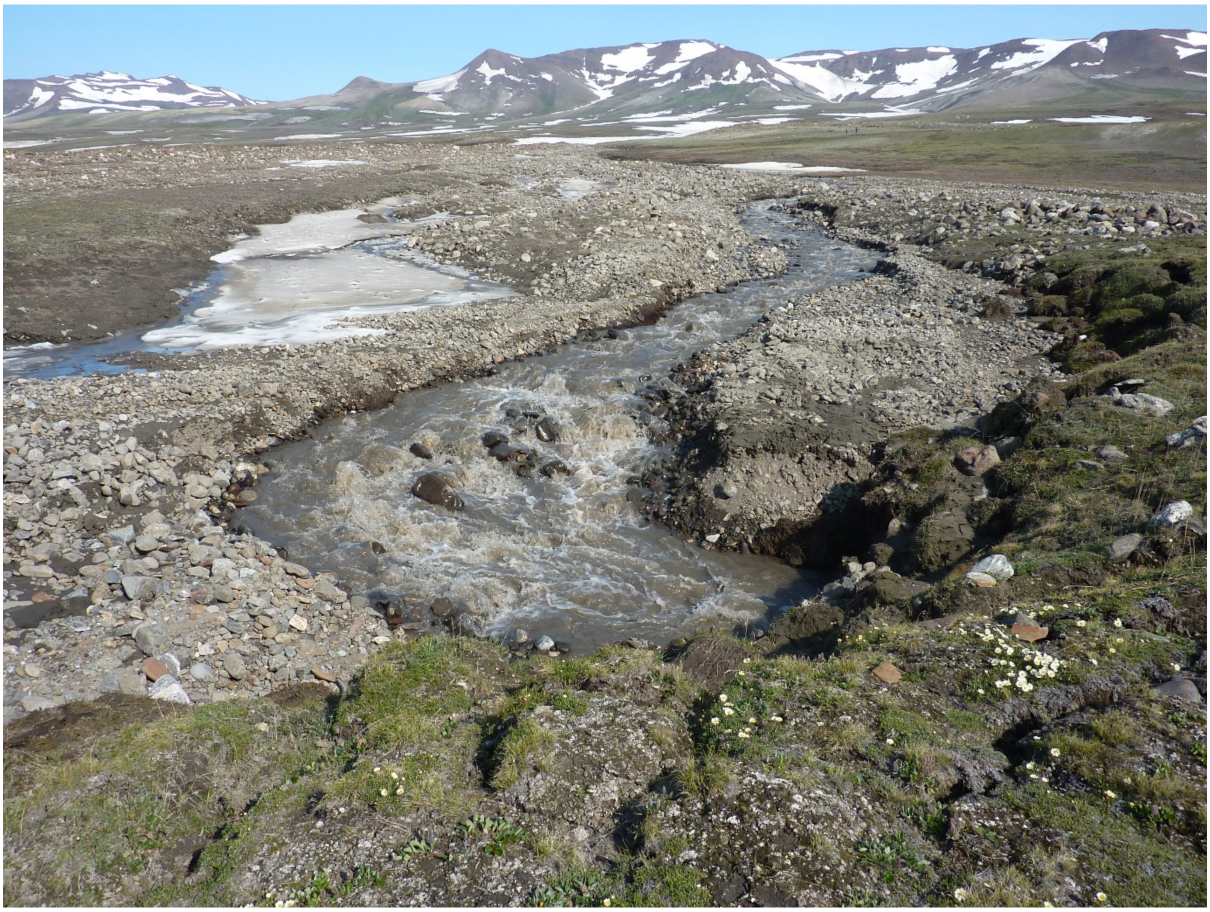

Figure 3.2 Aucellaelv looking upstream at the point of the thermo-erosional niche. At the bottom of the photograph, the stream can be observed to go underground.

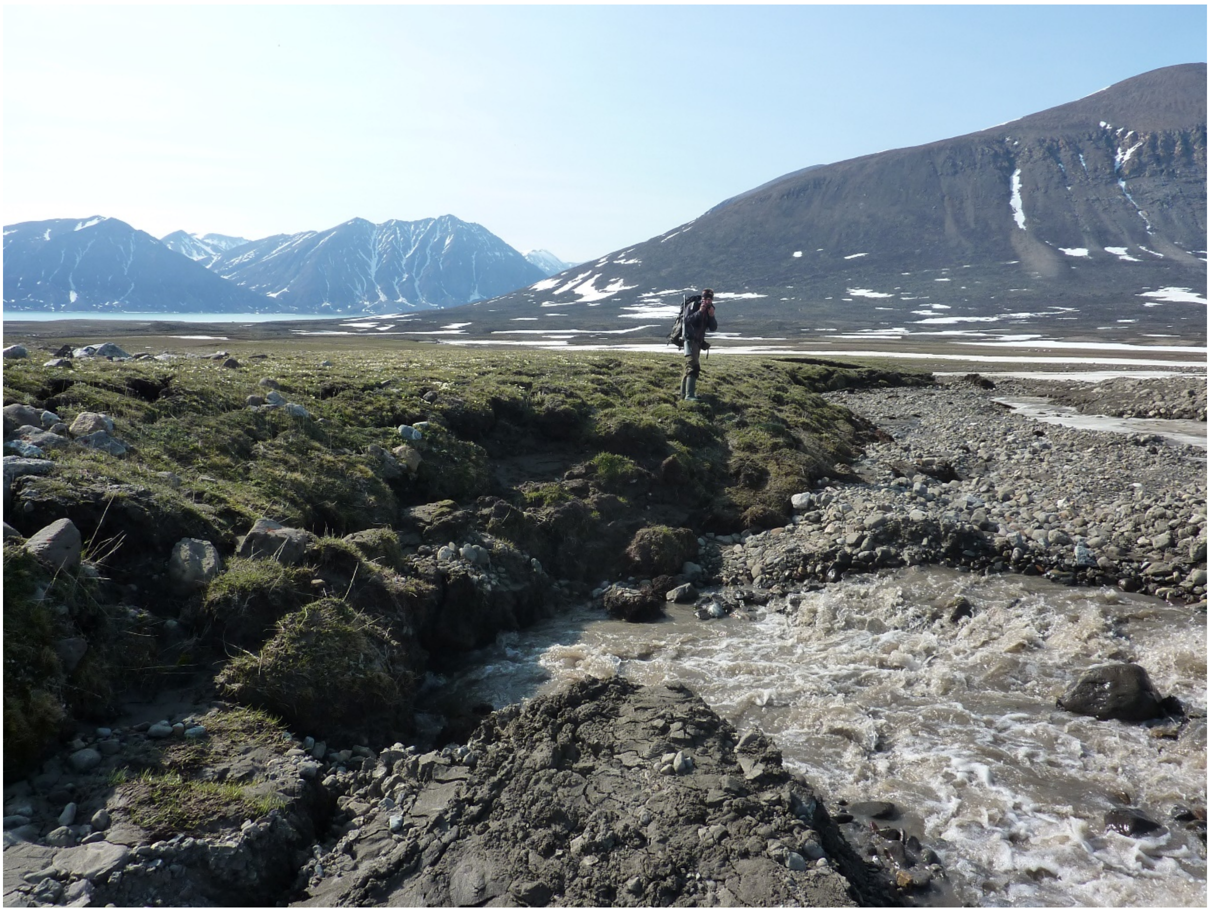

Figure 3.3 Looking downstream, the entry point of the thermo-erosional niche and associated slumping.

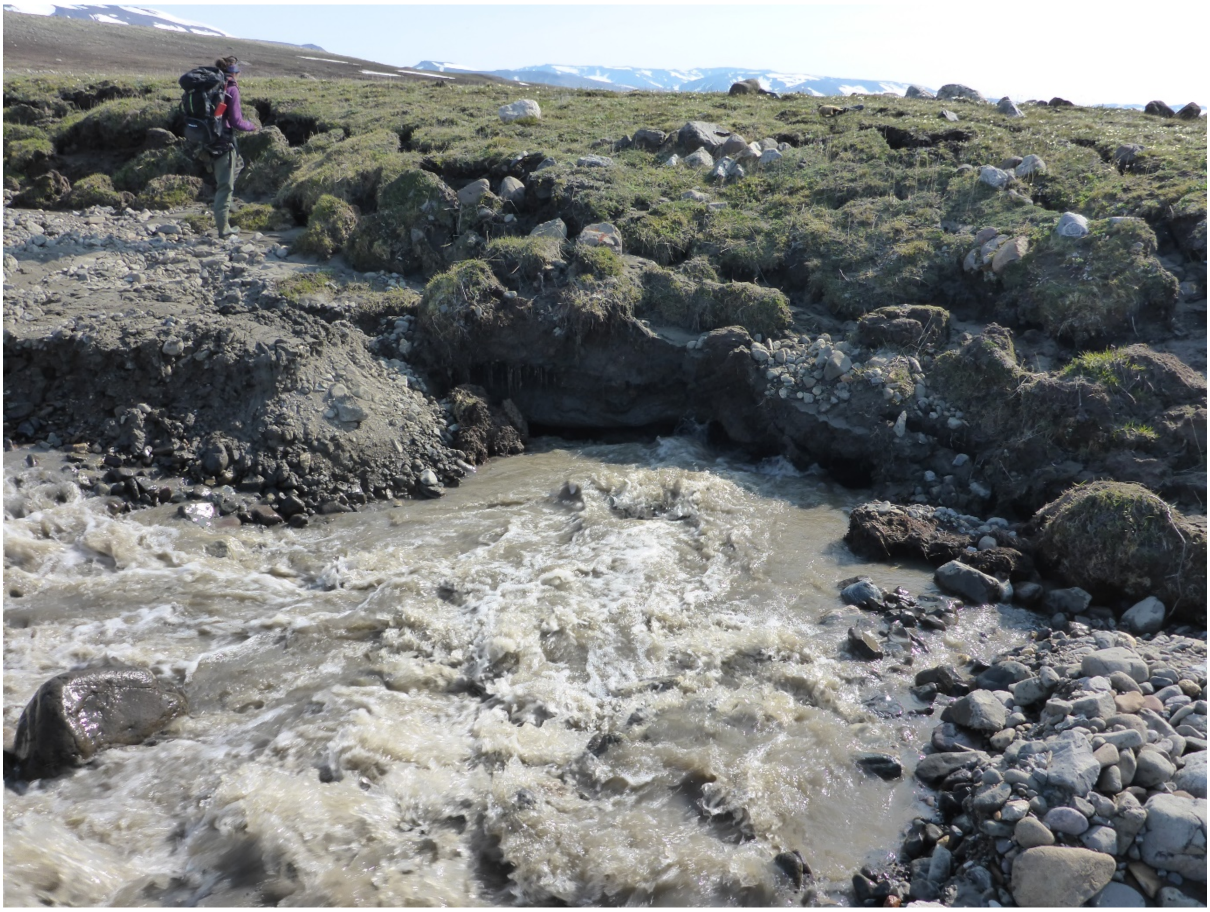

Figure 3.4. Looking upstream, the exit point of the thermo-erosional niche.

Table 3.1. Major cations in stream water upstream and downstream of the tunnel on 14 July 2015. All cations measured in mg L^{-1}.

Site	Mg	Na	K	Ca	S	Si
Upstream	1.66	2.84	0.10	7.62	5.44	0.66
0m downstream	2.72	4.05	0.16	10.54	8.67	0.84
800m downstream	2.67	4.56	0.2	9.91	9.05	0.94

3.4 Discussion and conclusions

3.4.1 Potential implications and processes in a changing climate

Whilst thermo-erosional tunnels are rarely observed, they may become more frequent in the future. By the end of the 21st century air temperature in northeast Greenland could increase by up to 18˚C on current winter temperatures, with more modest increases on summer temperatures (Stendel et al. 2008). Precipitation is predicted to increase by up to 60%, falling as snowfall during the winter but more commonly as rainfall throughout the summer (Stendel et al. 2008). The increase in nivation processes, permafrost degradation and larger spring floods will play a large role in reshaping local geomorphology, causing permafrost degradation to increase. Ice wedges will become increasingly exposed to thermal erosion as water temperatures warm and flow increases through increased meltwater inputs. Thus, permafrost thaw can have a large impact on the landscape (Kokelj & Jorgenson 2013) and on stream ecosystems through changes to physicochemical habitat (Christiansen et al. 2008; Callaghan et al. 2011; Kokelj et al. 2013; Thienpont et al. 2013; Chin et al. 2016). Increased sediment and ionic load and changes to channel stability are known to cause declines in macroinvertebrate abundance and community structure with consequent effects on the food web in these fragile stream systems (Chin et al. 2016).

In Zackenberg, the formation of a thermo-erosional tunnel led to increased ionic load in stream water and low stream bank stability, modifying the stream ecosystem over a large area. The high dissolved solute concentration at a distance from the tunnel, which in some cases was higher than directly below the tunnel exit, was due to a combination of the time taken for in-stream process to release solutes from suspended sediment, and additional contributions from downstream bankside sediment erosion and dissolution. As it is unknown how long the tunnel remained, the persistence of the impact on stream hydrochemistry and channel stability are unknown. Permafrost research has received a large amount of attention in some parts of the Arctic (eg. Alaska, Canada), but in Greenland it has received little attention. Zackenberg is the most intensively studied region in high-Arctic Greenland (Christiansen et al. 2008), but even so, no thermo-erosional tunnel had been reported previously in the area or had been witnessed by the scientists that had spent numerous summers in the area. Typical models and simulations for predicting permafrost thaw are generally unable to predict localised thaw events that have potential to transform landscapes through erosion and hydrological processes, as they are unable to account for the large spatial variability in ground thermal regime that is typical in Arctic regions (Westermann et al. 2014). For this reason, reporting of localised thaw events is vital to advance our understanding of their impact on local geomorphology. This paper provides insights into Greenlandic permafrost dynamics allowing us to understand the influence of extreme degradation events on the local landscape and adding to the increasing body of literature on thermo-erosional niche development. Increased documentation of underground tunnel development around the Arctic is necessary to understand how widespread the phenomenon is, and to understand the variety of conditions that lead to its formation.

3.5 References

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CHAPTER 4: ARCTIC RIVER TEMPERATURE DYNAMICS IN A CHANGING CLIMATE

Abstract

Climate change in the Arctic is expected to have a large impact on the region’s stream ecosystems, affecting hydrological and thermal regimes. Whilst temperature is important to a range of in-stream processes, previous research on Arctic stream thermal dynamics has been limited, and largely focused on glacierised catchments during the summer months of peak productivity. Limited attention has been given to snow meltwater streams or to understanding thermal dynamics during the winter months. This paper details the first high resolution study on stream thermal dynamics in northeast Greenland. Data was collected from five streams close to the Zackenberg research station over 24 months, between September 2013 and September 2015. Temperature loggers showed that during the winter months, streams were largely frozen solid and water temperature variability was low. Spring ice-off date occurred simultaneously in all streams, although the date of spring ice-off was 11 days earlier in 2014 compared to 2015 due to thicker snow insulation. During the summer months, water temperature was found to be highly variable and exhibited a strong relationship with atmospheric variables, particularly incoming shortwave radiation and air temperature. Mean summer water temperature in these snowmelt streams was found to be high compared to streams studied previously in Svalbard, yet was lower than streams in Swedish Lapland, as was expected given latitudinal patterns. In a future with higher air temperatures, Arctic streams could see reduced thermal variability in summer and increased thermal variability during the winter due to closer coupling with atmospheric conditions, as well as changes to the spring and autumn ice-on and ice-off dates, extending the running water season. This could lead to changes in thermal and hydrological regimes affecting stream productivity and diversity.

4.1 Introduction

In the last 100 years the rise in air temperature in the Arctic has been substantially more pronounced than the global average (2.9°C compared to 0.8°C; Comiso & Hall 2014; Overland et al. 2015). This trend of increased air temperature in the Arctic will continue alongside changes in precipitation and permafrost extent (Dyurgerov & Meier 2000; White et al. 2007; Foster et al. 2008) potentially having large consequences for freshwater ecosystems and affecting both hydrology and thermal regimes (van Vliet et al. 2013).

Water temperature influences chemical, physical and biological processes in all stream ecosystems (Caissie 2006; McNamara et al. 2008; Webb et al. 2008; Rawling et al. 2010; Cory et al. 2013). In terms of biochemical and physical processes, higher water temperatures are known to increase weathering (Anderson 2005), and nutrient uptake rates (Blaen et al. 2014). In terms of biological processes, warmer water temperature causes higher metabolic demands of both individuals and ecosystems as a whole (Brown et al. 2004). In Arctic and alpine regions, water temperature is the variable found to best explain macroinvertebrate community composition (Friberg et al. 2013) and taxa richness (Castella et al. 2001; Friberg et al. 2001), and increased water temperature can lead to a decrease in beta diversity (Finn et al. 2013).

Atmospheric conditions have been identified as having the largest control on water temperature dynamics particularly solar radiation due to the heat flux at the air-water surface boundary (Evans et al. 1998; Caissie 2006) with air temperature being the strongest explanatory variable. Nevertheless, there is evidence that snow depth and local geomorphology influences the relationship between air and water temperature in Arctic regions (Lisi et al. 2015). The predicted Arctic – wide increase in air temperature and precipitation and decrease in sea-ice extent that is predicted by the end of the century

(Anisimov et al. 2007; Vaughan et al. 2013) is likely to lead to large changes both in stream temperature dynamics and in the relationship between water temperature and atmospheric conditions. In the Zackenberg area of northeast Greenland, at approximately 60 km from the Greenland ice sheet, studies predict a 60% increase in precipitation with the proportion falling as rain predicted to increase, affecting the relationship between air temperature and water temperature. Alongside this, air temperatures are predicted to increase, particularly in winter (Stendel et al 2008), and there is predicted to be a 8 – 12 cm increase in active layer thickness (Hollesen et al. 2011; Westermann et al. 2015). The increased nivation processes and permafrost degradation associated with these changes will lead to a rise in sediment entering streams and a decrease in channel stability, affecting water retention time and stream albedo (Han 1997; Richards and Moore 2011; Blaen et al. 2013), whilst increased snowmelt inputs could act as a buffer on water temperature. The large increase in Arctic air temperature expected during the winter months due to the decrease in sea ice (Chapman and Walsh 2007, Walsh et al 2011), is expected to have consequences on summer stream flow dynamics (Dahlke et al. 2012), influencing water temperature during peak productivity. This will be through decreases in river ice cover (Vaughan et al. 2013), changes to snowpack conditions, and increased rain-on-snow events during the winter. Furthermore, an increase in autumn and spring water temperatures will affect stream ice-on and ice-off timing, extending the length of summer stream flow period and highlighting the importance of full year studies on water temperature.

Water temperature dynamics and their importance in high latitudes and alpine environments have been examined in past literature (Vincent & Howard Williams, 1989; Constantz 1998; Brown et al. 2005; Cadbury et al. 2008; Adams et al. 2010; Blaen et al. 2013; MacDonald et al. 2014; Comola et al. 2015; Khamis et al. 2015; Lisi et al. 2015; Madsen et al. 2015; King et al. 2016; Mellor et al. 2016). However, previous studies have often focused on areas with a large glacial influence and there has been no high-resolution research focused on Greenlandic stream temperature dynamics. Furthermore, most existing data from the Arctic focuses on the melt season, and Arctic winter stream water temperature dynamics therefore remain largely unknown.

This paper details Greenlandic stream thermal dynamics for the first time, and builds on past stream water temperature studies conducted in other Arctic areas. It addresses the paucity of information on temperature dynamics in snowmelt streams, particularly during the winter period. To address this research gap, we compiled a high-resolution water temperature data series over 24 months from streams in northeast Greenland. Through this, we aimed to: (1) characterise thermal variability in space and time, (2) infer key controls and processes on stream temperature and (3) consider the implications of the findings in the context of hydroclimatic change in the Arctic.

4.2 Methods

4.2.1 Study area

Field data were collected from around the Zackenberg research station (74º28’ N, 20º34’ W), within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 4.1). The region is not connected to the ice sheet, which is located approximately 60km away. Altitude within the study site varies between sea level and 1450 m a.s.l with a glacial plateau occurring above 1000m a.s.l and wide horizontal valleys caused by glacial erosion below (Mernild et al. 2007). The valley is in a zone of continuous permafrost and active layer thickness varies between 0.4 and 0.8 m (Hollesen et al. 2011; Westermann et al. 2015).

The geology is divided by the Zackenberg river and comprises Caledonian gneiss and granite in the west and cretaceous and tertiary sandstones and basalts in the east at higher altitudes of Palnatoke and Aucella mountains. Loose and sometimes well developed soils (Hasholt & Hagedorn 2000; Mernild et al. 2007) occupy the valley and lower slopes.Vegetation distribution is largely divided by the area's geology (Elberling et al. 2008). In the west, bog bilberry (*Vaccinium uliginosum)* heath is more abundant, among areas with scattered boulders and fens with high species diversity. To the east, lowland vegetation comprises Arctic white heather (*Cassiope tetragona)* heaths, Arctic willow (*Salix arctica)* snow beds, grasslands and fens. At higher altitudes, between 150 and 300 m, mountain avens (*Dryas* sp.) heath dominates (Bay 1998).

The mean annual air temperature is -9.1 ˚C. The warmest month is July with a mean air temperature of 5.8 ˚C and the coldest month is February with a mean air temperature of -22.4 °C. Annual precipitation is 261mm and falls mainly as snow (Hansen et al. 2008).
To date, hydrological research in this region has focused on sediment and solute transport of Zackenberg river and the regions streams (Hasholt & Hagedorn 2000; Rasch et al. 2000, Hasholt et al. 2008; Ladegaard-Pedersen et al. 2016), while stream thermal dynamics are unknown.

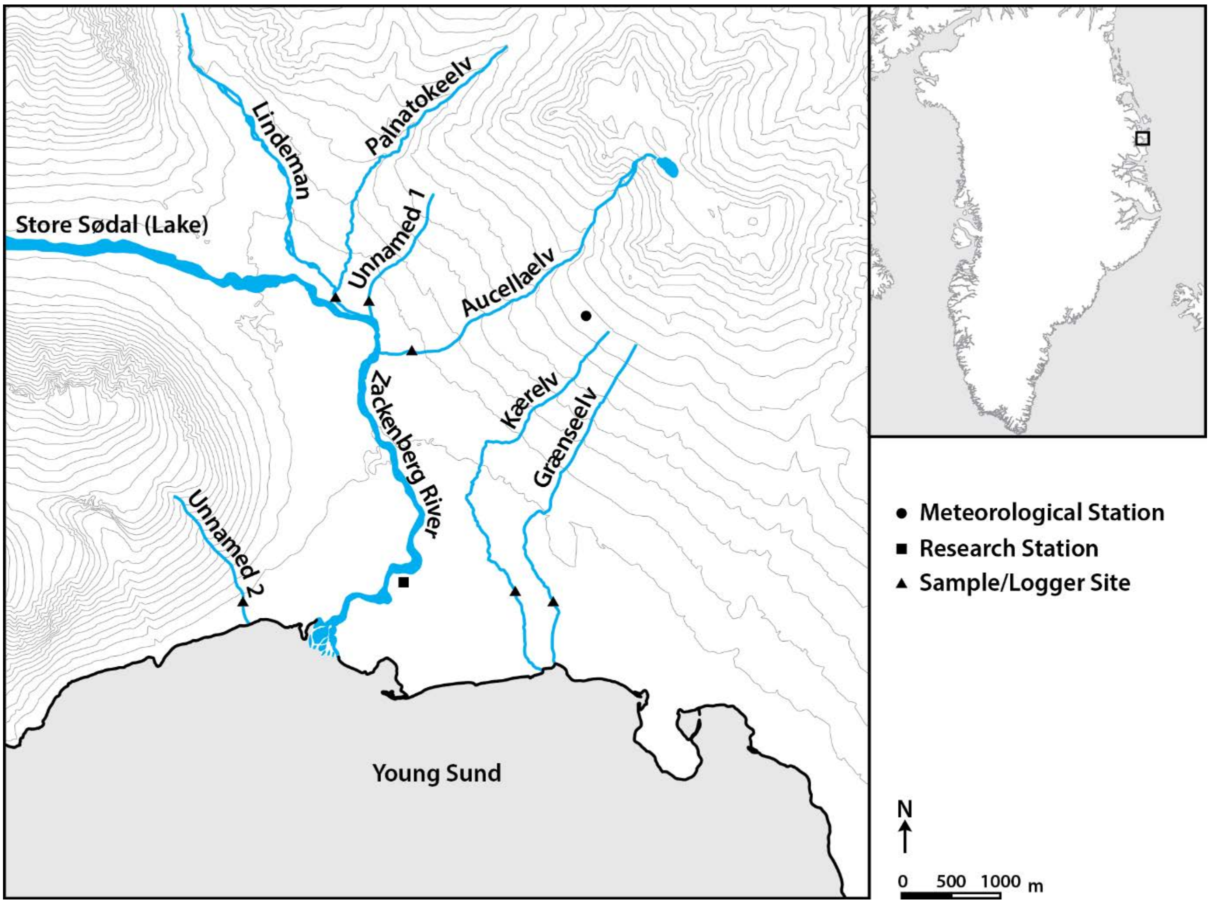

Figure 4.1. Site map and study streams.

4.2.2 Field sites and sampling framework

Six streams were included in the study, of which three (Lindeman, Unnamed1 and Aucellaelv) are located within the Zackenberg valley and are tributaries of the larger Zackenberg river (drainage basin: 512 km^2, 20 % glacier cover (Mernild et al 2008)) that discharges into the Yound Sund (Figure 4.1). The other three (Unnamed2, Kærelv and Grænseelv) are found alongside the fjord coast and discharge directly into Young Sund. Site selection was restricted by the high mobility and high erosion levels of some streams and the borders of locally protected areas. Nonetheless, sites were chosen to represent the valley floor and low altitude areas.

Water temperature was measured at four sites between September 2013 and July 2014 (Kærelv, Grænseelv, Aucellaelv and Unnamed2), and four sites between July 2014- July 2015 (Kærelv, Grænseelv, Aucellaelv and Unnamed1) although equipment failure at Kærelv caused a gap in the data for this stream between October 2014 and July 2015. A high flow event also caused a loss of data at Grænseelv, Aucellaelv and Unnamed1, with observations consequently only available for Kærelv during summer 2015. We used Gemini TinyTag loggers (stated accuracy of ± 0.5 ºC) covered with radiation shields, which collected water temperature continuously during the study period (cf. Garner et al. 2014). The loggers recorded temperature every 30 minutes and were replaced at the start of each field season to ensure long recording.

Stream bed temperature was measured at 3 sites (Kærelv, Grænseelv and Lindeman) using Campbell Scientific 107 temperature probes inserted at depths of 0.05 m, 0.25 m and 0.40 m. The probes were attached to a CR1000 data logger which scanned every 10 seconds and recorded a mean of these values every 15 minutes. All sensors were cross calibrated before deployment and internal clocks were synchronised.

4.2.3 Meteorological observations

Meteorological variables were used to assess atmospheric influences on water temperature. Air temperature and precipitation were obtained from the main climate station located near the research station on the valley floor, close to all streams, other data were obtained from a weather station called M3, that is located on the south-west facing slope of Aucella mountain at 420 m a.s.l. and represents atmospheric conditions close to the stream sources (Figure 4.1). Both weather stations were maintained by the Greenland Ecosystem Monitoring Programme. Pearson correlations were conducted on meteorological data from M3 station and the main climate station on the valley floor to determine differences between sites, however data were found to be significantly similar in the two locations. Data included in this study were: air temperature (˚C), relative humidity (%), snow depth (cm), incoming shortwave radiation (W m^{-2}; SWR) and incoming longwave radiation (W m^{-2}; LWR) and precipitation (mm). Data were recorded to a CR1000 Campbell Scientific data logger every half-hour; precipitation data were recorded hourly. Appendix A1 provides details of instrumentation and their specifications.

4.2.4 Data Analysis

Due to the large quantity of data, the data were analysed at nested temporal scales from larger to shorter. Data are presented from the two winter periods although emphasis is placed on summer 2014 because stream temperatures during this period are the most variable and responsive to climatological variables, and also because this data series was the most complete. From within summer 2014, five six-day periods were chosen to describe diurnal variation and to represent the full range of summer climatological conditions the area experiences. Periods were chosen to highlight periods of low and high air temperature and precipitation events throughout the short summer season. These six-day periods were decided to be a time frame large enough to highlight conditions before and after climatic events.

Descriptive statistics were calculated for water temperature and meteorological variables during all time periods to characterise environmental conditions. Temperature duration curves were established for three time periods (September 2013 – July 2014, July 2014 – July 2015 and 11th July – 15th September 2014) to represent the two years’ data and to allow for comparison of water temperature variability between streams (eg. Blaen et al. 2013; Khamis et al. 2015).

For the summer data, autoregressive integrated moving average (ARIMA) models were fitted to assess the relationship between climatological variables and water temperature and to account for serial autocorrelation within the data. Models were fitted in the 'Forecast' package (Hyndman 2016) for R between daily averages of water temperature data for each stream and meteorological data. Nagelkerke pseudo-R^2 values were calculated to assess model strength and P values are provided to indicate significance of models, not significance of covariate. One-way ANOVAs were used to determine differences in water temperature between streams.

During the short six-day periods, descriptive statistics were calculated to characterise water temperature and meteorological conditions, and one-way ANOVAs were undertaken to analyse differences in water temperatures between streams.

4.3 Results

4.3.1 Interannual and seasonal meteorological context

The winter of 2013-2014 was cooler (mean of -13.4 ˚C) than winter 2014-2015 (mean of -11.6 ˚C) and received heavier snowfall (85 cm vs. 43 cm). In both years, June is the month of peak snow melt which coincides with the first month of the year where mean air temperatures rise above 0˚C (June 2014: 3.4 ˚C, June 2015: 4.1 ˚C). In both years, July was the warmest month (mean temperature 2014: 5.6 ˚C, 2015: 7.4 ˚C) and the lowest temperature recorded was during February 2015 (-29.7 ˚C; Figure 4.2; Table 4.1). Cooler air temperatures towards the end of the summer period were associated with decreased shortwave and longwave radiation and an increase in snow depth. (Figure 4.2; Table 4.1).

There was no observed seasonality in relative humidity throughout the 24-month monitoring period, (Figure 4.2). Precipitation data were not available for January - May 2014, however, for the months when data was available, January 2015 was wettest (112 mm total precipitation) and June 2014 was driest (4 mm total precipitation). Precipitation during the summer monitoring months consisted of short episodic events. A total of 64 mm was measured between 11 July and 15 September 2014, primarily caused by 3 storm events on 14-16 July (31 mm), 23-26 August (28 mm) and 15 September (4 mm). The precipitation event coincided with a period of low air temperatures (see period 1) (Figure 4.3; Table 4.1).

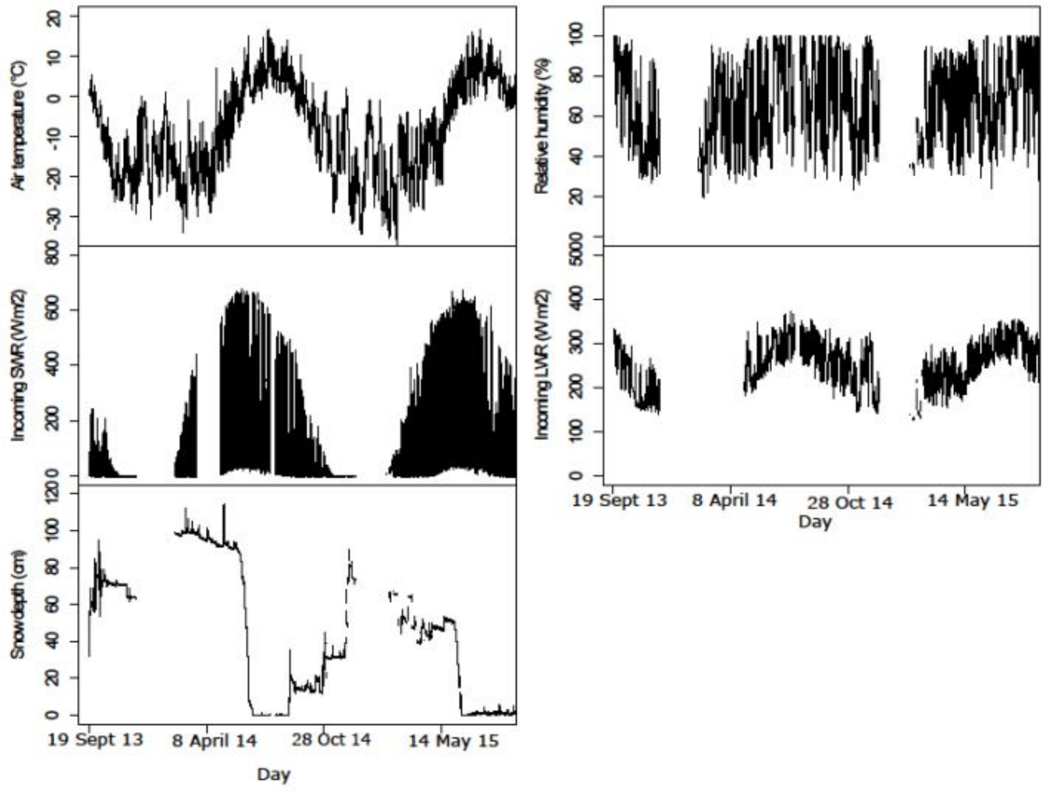

Figure 4.2. Timeseries of air temperature, relative humidity, incoming shortwave (SWR) and longwave (LWR) radiation and snow depth between September 2013 and September 2015.

Table 4.1. Descriptive statistics for air temperature, relative humidity, snow depth, soil moisture at 10cm depth, incoming shortwave and longwave radiation and precipitation during the summer periods.

	Air temperature	Relative humidity	Snow depth	Soil moisture (10cm)	Incoming shortwave radiation	Incoming longwave radiation	Precipitation
	˚C	%	Cm	%	MJ m^{-2} day^{-1}	MJ m^{-2} day^{-1}	mm
Season 11 July - 15 September							
mean	3.7	69.4	6.2	45.6	11.69	25.17	0.0
σ	4.6	18.3	8.0	3.5	6.51	2.73	0.2
max	15.2	100.0	35.5	47.1	28.03	29.90	1.9
min	-5.3	29.3	0.0	34.9	2.30	19.08	0.0
13 - 18 July							
mean	3.5	91.5	0.0	46.9	6.48	28.21	0.2
σ	1.2	10.2	0.0	0.1	1.36	1.63	0.4
max	6.4	100.0	0.0	47.1	8.41	29.31	1.9
min	1.1	55.1	0.0	46.6	5.50	24.62	0.0
19 - 24 July							
mean	11.0	55.8	0.0	46.9	22.49	25.72	0.0
σ	2.0	9.9	0.1	0.1	5.57	2.22	0.0
max	15.2	90.3	0.4	47.1	26.70	29.90	0.0

min	5.2	35.5	0.0	46.7	12.92	23.28	0.0
9 - 14 August							
mean	4.3	67.7	0.1	46.9	14.62	24.99	0.0
σ	3.3	19.1	0.2	0.1	3.33	1.73	0.0
max	9.3	100.0	1.1	47.0	19.39	27.32	0.0
min	-2.2	32.9	0.0	46.7	9.91	22.91	0.0
22 - 27 August							
mean	2.5	82.5	8.0	47.0	6.23	27.12	0.2
σ	3.6	14.3	9.3	0.1	3.49	1.22	0.3
max	11.0	100.0	35.5	47.1	13.16	28.10	1.7
min	-0.7	56.0	0.0	46.7	3.75	24.61	0.0
10 - 15 September							
mean	-1.7	62.5	14.5	35.7	7.31	22.65	0.0
σ	2.4	19.5	0.3	0.7	3.12	2.96	0.2
max	6.6	99.7	15.5	37.8	10.19	27.11	1.3
min	-4.5	32.4	13.2	34.9	2.30	19.22	0.0

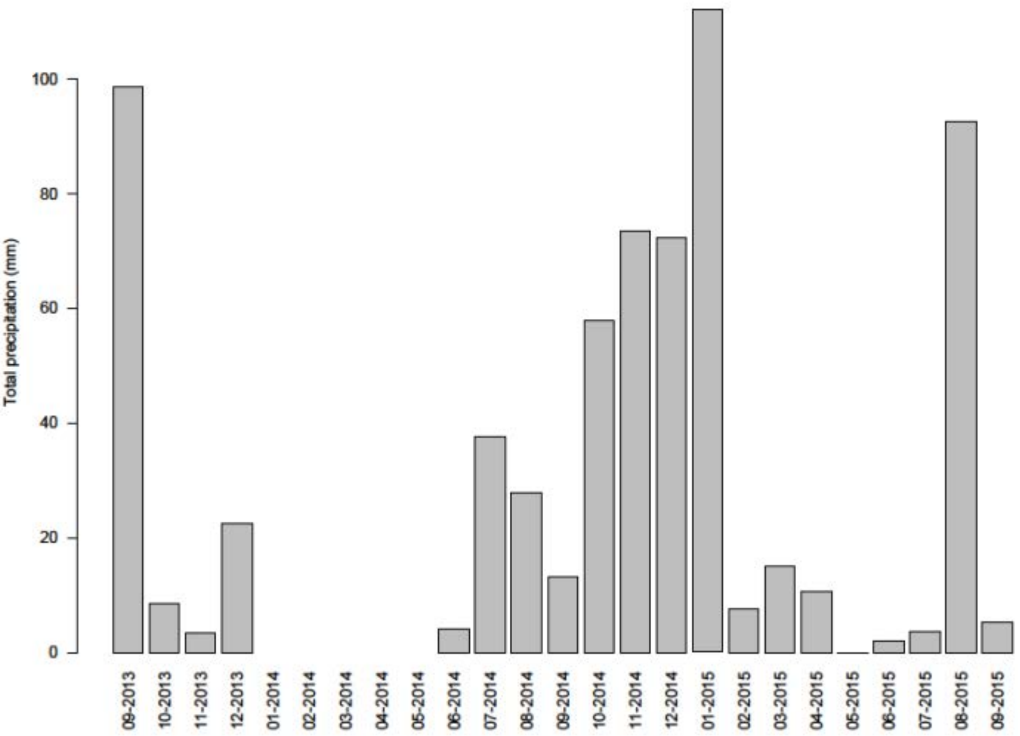

Figure 4.3. Monthly precipitation during the study period.

4.3.2 Habitat conditions

Kærelv and Grænseelv were comprised of stable channels, whilst the other streams were observed to be more dynamic. Aucellaelv was characteristed by its braided, highly mobile stream bed and high suspended sediment load. Site characteristics are presented in Table 1. Stream discharge (measured during the summer field campaigns using the velocity area measurement) varied between sites with the lowest found in Kærelv and Grænseelv during the field campaign in 2014 (151 L/s and 189 L/s respectively). Unnamed1 showed high variability with the lowest measurement of 181 L/s and the highest of 622 L/s during the field campaign in 2014 (Table 1). Discharge was higher at all sites during the field campaign in 2015 compared to 2014. Streambed sediment size (D50, obtained from measuring the b-axis of 100 clasts) ranged from 33 mm in Grænseelv to 95 mm in Aucellaelv (Table 4.2).

Table 4.2. Site characteristics measured during 2014 field campaign.

Site	Approximate distance from source (km)	Altitude (m)	Channel width (m)	Discharge (L/s)	Mean EC (µS cm-1)*	Aspect (facing)	Sediment D_{50} (mm)
Kærelv	4.00	47.00	3.54	151 (n=1)	36	S	51
Grænseelv	2.57	19.00	2.96	189 (n=1)	32	S	33
Unnamed1	3.30	113.00	9.10	335 (n=3, σ: 202.7)	42	SW	90
Aucellaelv	4.30	68.00	6.10	484 (n=2, σ: 96)	88	SW	95
Unnamed2	2.50	52.00	1.50	NA	31	S	35
Lindeman	NA	50.00	10.00	NA	52	S	NA

4.3.3 Interannual and seasonal stream temperature variability

4.3.3.1 Summer period

Streams were found to be highly variable both temporally and between sites in thermal dynamics. During the summer, the warmest mean temperature was recorded in Unnamed1 (5.6 ˚C) and the coldest in Aucellaelv (3.3 ˚C; Table 4.3). Stream temperature variability (defined as the temperature standard deviation) is similar among all streams apart from Unnamed2 which showed the highest variability (σ = 5.0). Temperature duration curves showed similarity between streams in thermal regimes whilst also highlighting some differences (Figure 4.4). The low temperatures experienced by Unnamed2 showed a contrasted thermal regime to other streams in the area, and highlight that water may have continued to flow during winter in this stream. Other differences between streams include in Unnamed1, which was found to remain warmer for longer compared to other streams during the same time-period, and the low water temperatures of Aucellaelv compared to other streams during the summer 2014 (Figure 4.4). Diurnal temperature oscillation cycles were evident for all sites during the summer months but were not evident during the winter (Figure 4.5; Figure 4.6). During this period, water temperatures were frequently found to be higher than air temperature in all four streams.

ARIMA models showed stream water temperature to be significantly correlated with air temperature, relative humidity, incoming shortwave radiation and precipitation for all streams, and incoming longwave radiation in Kærelv and Grænseelv (Table 4.4).

For the whole summer period, all streams were significantly different from one another in relation to water temperature except for Kærelv and Unnamed1 (Table 4.5). There was a strong correlation between water temperature and stream bed temperature at 0.05 m for all three streams monitored (r= between 0.977 and 0.999), which remained significant with increasing depth though with reduced correlation strength. At 0.40 m, Aucellaelv showed the highest correlation (r=0.709), Kærelv showed a correlation of 0.596, whilst Lindeman had the lowest (r=0.393) with bed temperatures of 0.0 ˚C at the start of the monitoring period but that increased to 3˚C by the end (Figure 4.7).

Table 4.3. Descriptive statistics for water column temperature during summer 2014 (°C).

	Kærelv	Grænseelv	Aucellaelv	Unnamed1
Season 11 July - 15 September				
Mean	5.4	4.8	3.3	5.6
σ	3.6	3.1	2.5	3.6
Max	14.0	12.8	10.1	14.9
Min	-0.1	0.0	-1.0	-1.9
Period 1 13 - 18 July				
Mean	5.1	4.0	2.7	5.2
σ	1.6	1.6	1.8	1.9
Max	10.0	8.3	9.0	11.0
Min	2.8	2.2	0.6	2.9
Period 2 19 - 24 July				
Mean	8.9	7.3	4.8	9.8
σ	2.9	2.6	1.6	3.0
Max	13.7	11.6	7.7	14.9
Min	2.9	2.1	1.5	3.0
Period 3 9 - 14 August				
Mean	7.4	6.9	4.7	7.1
σ	2.5	2.5	2.3	0.9
Max	12.5	12.1	9.6	9.7
Min	3.6	3.2	1.8	5.8
Period 4 22 - 27 August				
Mean	4.7	4.5	3.0	4.7
σ	2.5	2.3	2.2	2.8
Max	12.4	12.0	10.1	12.4
Min	2.0	1.9	0.5	0.8
Period 5 10 - 15 September				
Mean	0.2	0.2	0.3	0.3
σ	0.2	0.2	0.9	2.0
Max	1.1	1.2	4.4	10.0
Min	-0.1	0.0	-0.5	-1.9

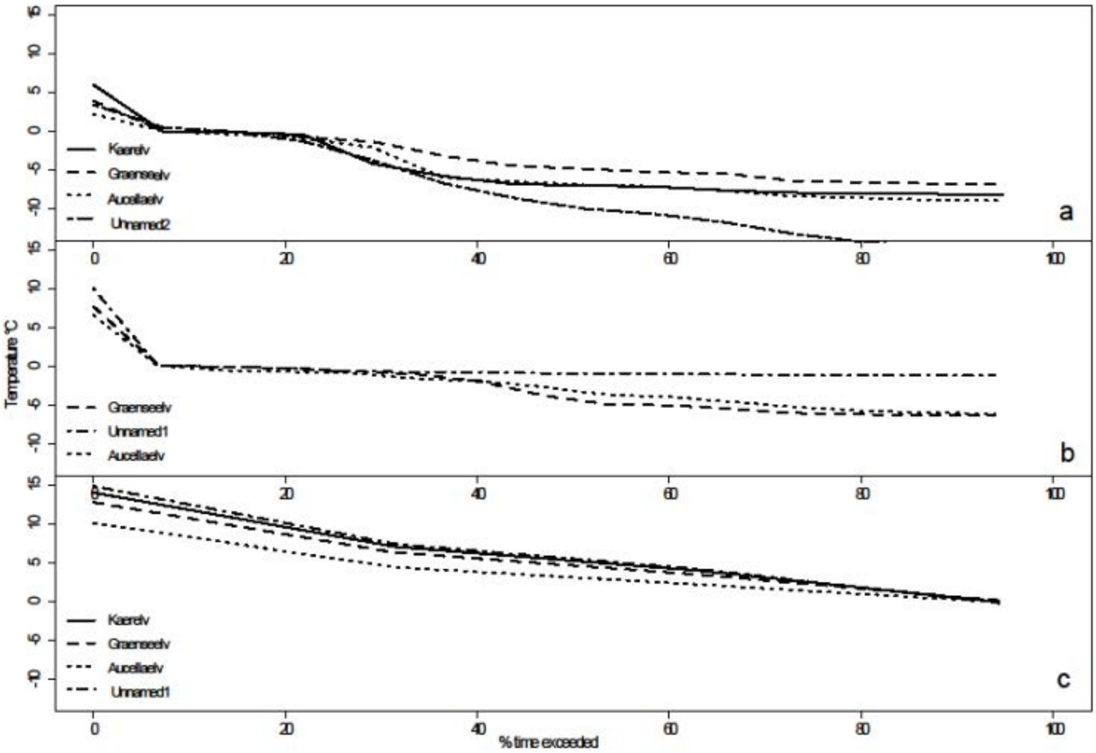

Figure 4.4. Temperature duration curves (a) Sept 2013 - July 2014, (b) July 2014 - July 2015, and (c) 11 July – 15 September 2014.

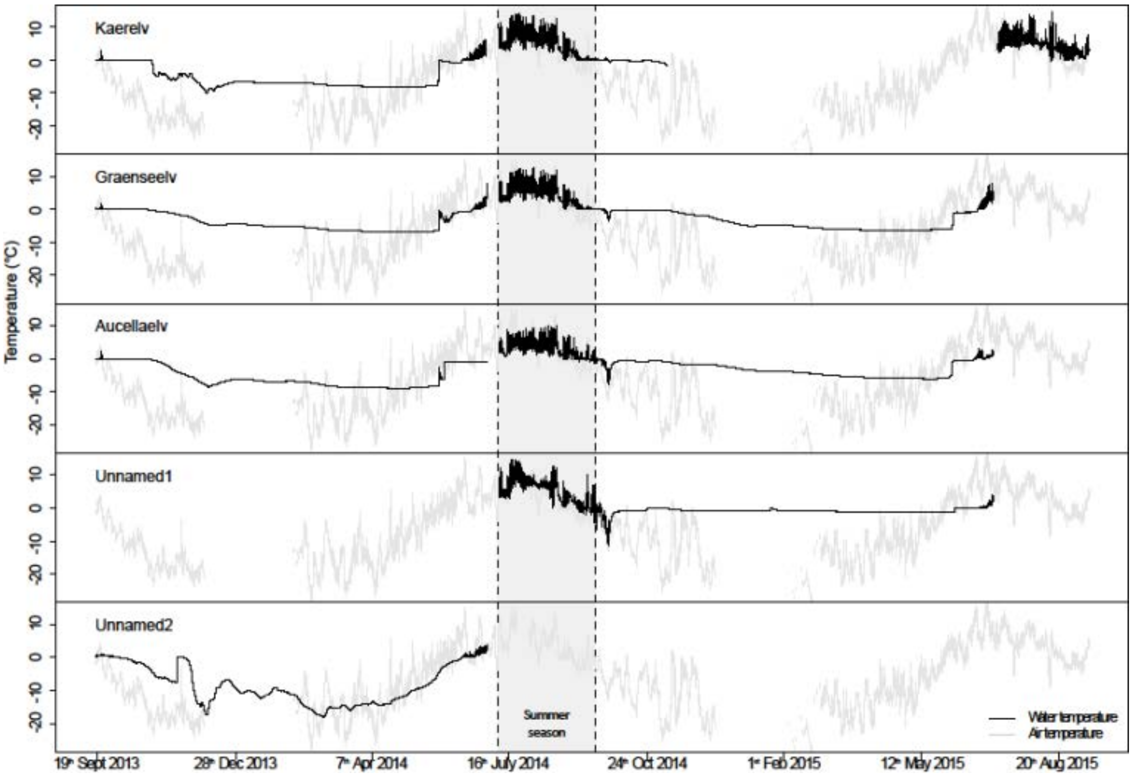

Figure 4.5. Time series of water temperature for all streams during 24-month study period. The study summer season is highlighted

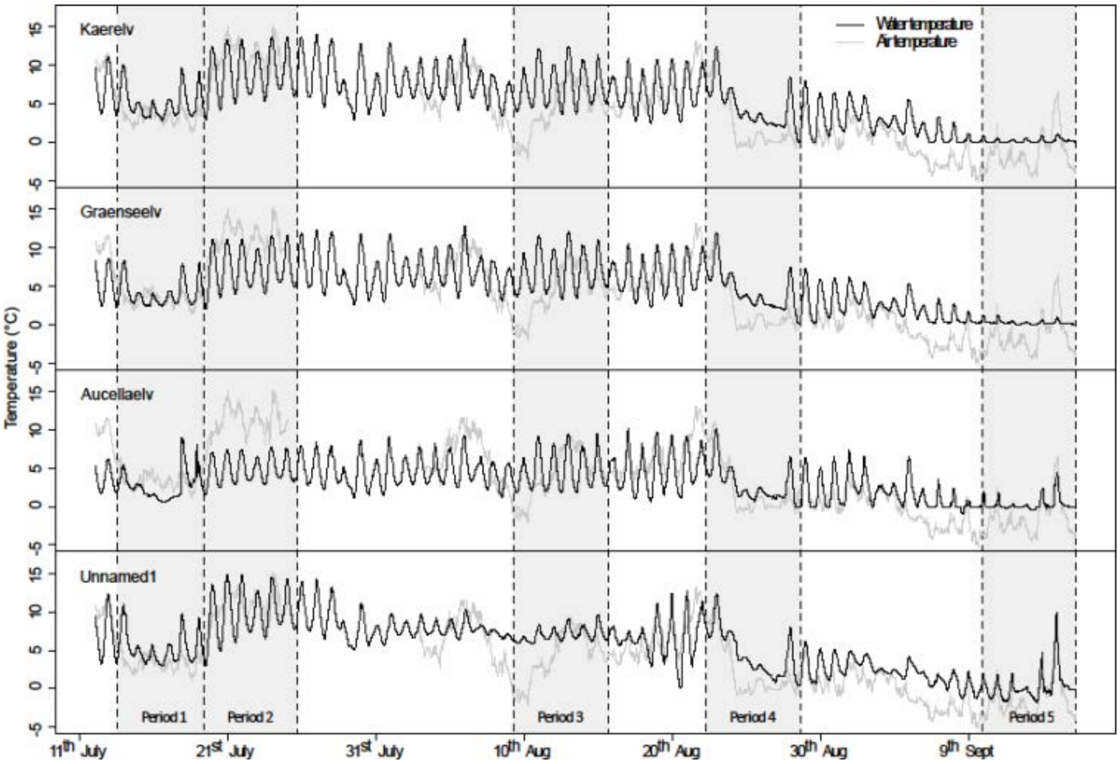

Figure 4.6. Time series for the study summer season 11 July – 15 September 2014 with 6-day periods highlighted. Periods are ordered to place similar conditions together as opposed to chronologically.

Table 4.4. ARIMA models fitted between daily averages of stream water temperature and meteorological variables. Bold values= significant correlations.

Stream		Air temperature	Relative humidity	Snow depth	Incoming shortwave radiation	Incoming longwave radiation	Precipitation
Kærelv	Slope	0.289	-0.023	0.029	0.008	-0.008	-4.867
	Nagelkerke pseudo-R^2	0.343	0.456	0.353	0.549	0.399	0.246
	P value	<0.001	0.004	0.683	<0.001	0.035	<0.001
Grænseelv	Slope	0.254	-0.019	0.006	0.006	-0.007	-4.142
	Nagelkerke pseudo-R^2	0.329	0.454	0.341	0.508	0.382	0.222
	P value	<0.001	0.005	0.924	<0.001	0.049	<0.001

Aucellaelv	Slope	0.232	-0.016	0.000	0.005	-0.004	-3.968
	Nagelkerke pseudo-R^2	0.296	0.342	0.255	0.370	0.272	0.233
	P value	<0.001	0.026	0.996	0.002	0.263	<0.001
Unnamed	Slope	0.311	-0.029	-0.001	0.006	-0.006	-5.846
	Nagelkerke pseudo-R^2	0.344	0.410	0.266	0.373	0.290	0.309
	P value	<0.001	0.001	0.993	0.002	0.171	<0.001

Table 4.5. One way ANOVA results for water temperature differences between streams. DF(1, 6358) for all analyses

	Kærelv		Grænseelv		Aucellaelv		Unnamed1	
	F	P	F	P	F	P	F	P
Season 11 July - 15 September								
Kærelv			**46.08**	**<0.0001**	**743.844**	**<0.0001**	2.31	0.128
Grænseelv					**459.262**	**<0.0001**	**70.57**	**<0.0001**
Aucellaelv							**844.29**	**<0.0001**
Unnamed1								
Period 1 13-18 July								
Kærelv			**53.44**	**<0.0001**	**256.04**	**<0.0001**	1.13	0.287
Grænseelv					**91.41**	**<0.0001**	**68.78**	**<0.0001**
Aucellaelv							**281.98**	**<0.0001**
Unnamed1								
Period 2 19-24 July								
Kærelv			**52.59**	**<0.0001**	**437.37**	**<0.0001**	**12.524**	**<0.001**
Grænseelv					**437.37**	**<0.0001**	**116.78**	**<0.0001**
Aucellaelv							**599.57**	**<0.0001**
Unnamed1								
Period 3 9-14 August								
Kærelv			**3.95**	**0.0473**	**173.28**	**<0.0001**	3.48	0.0625
Grænseelv					**124.99**	**<0.0001**	0.61	0.436
Aucellaelv							**260.41**	**<0.0001**
Unnamed1								
Period 4 22-27 August								
Kærelv			0.68	0.411	**72.56**	**<0.0001**	0.06	0.806
Grænseelv					**63.52**	**<0.0001**	1.04	0.308

Aucellaelv							**66.80**	**<0.0001**
Unnamed1								
Period 5 10-15 September								
Kærelv			**5.73**	**0.0169**	**6.87**	**0.008**	1.80	0.181
Grænseelv					2.99	0.084	0.87	0.350
Aucellaelv							0.02	0.883
Unnamed1								

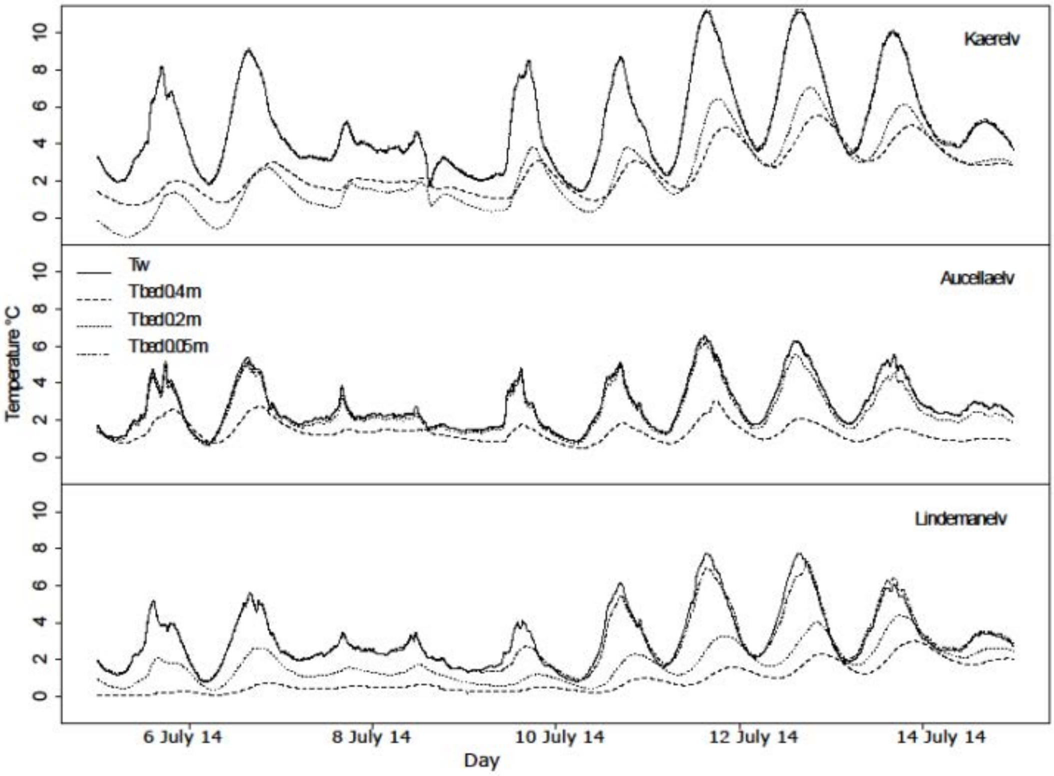

Figure 4.7. Time series of stream water column and bed temperature for Kærelv, Aucellaelv and Lindeman between 5 – 14 July 2014.

4.3.3.2 Winter period

Winter data was available between September 2013 – May 2014 and September 2014 – May 2015. The winter season in 2014 began with a large decrease in water temperature around 27th September, before increasing and stabilising over winter, due to the nature of frozen water being less susceptible to diurnal fluctuations and due to the insulating effect of snow. At the end of the winter season, the time of spring ice-off was eleven days later in 2015 (8 June) compared to 2014 (28th May) but occurred at a similar time in all streams and was represented by a sudden increase in water temperature.

All streams were frozen to the bed apart from Unnamed2, as such, all data presented are ice temperatures, not flowing water. Compared to the summer period, stream temperature during winter showed minimal diurnal variability and did not respond to fluctuations in meteorological variables in Grænseelv, Aucellaelv, Unnamed1, and largely Kærelv (Figure 4.5). However, water temperature fluctuated in Kærelv between 30 October and 27 December 2013, and water temperature in Unnamed2 fluctuated throughout winter 2013 – 2014, where it was significantly more variable than other streams (Max: $F_{(1,2)}$ =46.02 P=0.021; Min: $F_{(1,2)}$ =23.93 P=0.039; σ: $F_{(1,2)}$ = 46.998 P=0.020), recording both higher maximum and lower minimum temperatures. Data is available for two winter periods for Grænseelv and Aucellaelv. While Grænseelv displayed no significant differences between the two years, water temperature at Aucellaelv was significantly cooler during winter 2013 – 2014 compared to winter 2014 - 2015 ($F_{(1,14)}$ =5.484, P= 0.035) (Table 4.6).

Table 4.6. Descriptive statistics of water column temperature for the winter periods October 2013-May 2014 and October 2014 – May 2015 (°C).

	Kaerelv		Graenseelv		Aucellaelv		Unnamed1		Unnamed2	
	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015	2013-2014	2014-2015
Season										
Mean	-6.2	-0.4	-4.4	-4.0	-6.2	-3.6	NA	-0.9	-9.8	NA
SD	2.7	0.3	2.4	2.4	3.0	1.9	NA	0.4	5.0	NA
Max	-0.1	-0.1	-0.1	-0.1	0.0	-0.6	NA	-0.0	0.4	NA
Min	-10.2	-1.6	-6.9	-6.3	-9.0	-6.1	NA	-5.6	-18.1	NA
October										
Mean	-0.2	-0.3	-0.1	-0.2	-0.1	-0.9	NA	-0.9	-1.3	NA
SD	0.5	0.1	0.1	0.1	0.1	0.5	NA	0.7	1.4	NA
Max	-0.1	-0.1	-0.1	-0.1	0.0	-0.6	NA	-0.0	0.4	NA
Min	-3.9	-1.0	-0.4	-1.7	-0.5	-4.4	NA	-5.6	-4.9	NA
November										
Mean	-4.9	-0.8	-1.4	-0.8	-3.3	-1.2	NA	-0.3	-4.7	NA
SD	0.7	0.3	0.7	0.5	1.7	0.4	NA	0.3	3.1	NA
Max	-3.78	-0.3	-0.4	-0.1	-0.5	-0.6	NA	-0.0	0.0	NA
Min	-6.1	-1.6	-3.0	-1.7	-6.1	-1.9	NA	-0.7	-10.9	NA
December										
Mean	-7.9	NA	-4.4	-2.8	-7.2	-2.1	NA	-0.7	-11.0	NA
SD	1.0	NA	0.5	0.8	0.7	0.3	NA	0.0	3.3	NA
Max	-5.9	NA	-3.0	-1.7	-6.1	-1.8	NA	-0.6	-6.6	NA
Min	-10.2	NA	-4.9	-4.3	-8.6	-2.8	NA	-0.8	-17.3	NA
January										
Mean	-6.9	NA	-4.9	-4.9	-6.7	-3.5	NA	-0.8	-10.7	NA
SD	0.2	NA	0.3	0.2	0.4	0.3	NA	0.2	0.8	NA
Max	-6.6	NA	-4.3	-4.3	-6.1	-2.8	NA	-0.1	-9.0	NA
Min	-7.1	NA	-5.3	-5.0	-7.1	-3.8	NA	-1.0	-12.4	NA
February										

Mean	-7.1	NA	-5.4	-5.2	-7.1	-4.2	NA	-0.9	-13.1	NA
SD	0.1	NA	0.2	0.2	0.2	0.2	NA	0.0	2.4	NA
Max	-7.0	NA	-5.3	-4.9	-6.8	-3.8	NA	-0.7	-10.0	NA
Min	-7.3	NA	-5.8	-5.6	-7.7	-4.6	NA	-0.9	-17.3	NA
March										
Mean	-7.8	NA	-6.4	-6.0	-8.4	-5.2	NA	-1.0	-15.6	NA
SD	0.2	NA	0.2	0.1	0.3	0.3	NA	0.1	1.1	NA
Max	-7.3	NA	-5.8	-5.6	-7.7	-4.6	NA	-0.9	-14.4	NA
Min	-8.0	NA	-6.6	-6.2	-8.8	-5.6	NA	-1.1	-18.1	NA
April										
Mean	-8.1	NA	-6.8	-6.3	-8.9	-5.8	NA	-1.1	-13.8	NA
SD	0.0	NA	0.1	0.0	0.0	0.1	NA	0.0	0.7	NA
Max	-8.0	NA	-6.6	-6.2	-8.8	-5.6	NA	-1.1	-12.1	NA
Min	-8.1	NA	-6.9	-6.3	-9.0	-6.0	NA	-1.2	-14.6	NA
May										
Mean	-7.2	NA	-6.3	-6.2	-8.4	-6.0	NA	-1.2	-8.5	NA
SD	2.3	NA	1.5	0.0	1.0	0.0	NA	0.0	2.5	NA
Max	-0.1	NA	-0.5	-6.1	-2.5	-6.0	NA	-1.1	-2.9	NA
Min	-8.2	NA	-6.9	-6.3	-9.0	-6.1	NA	-1.2	-12.1	NA

*Kaerelv season 2014-2015 data only 1 October – 11 November

4.3.4 Subseasonal stream temperature variability

Due to the large data set, five time periods of six days were selected to highlight climatological events experienced across the summer season in order to examine diurnal patterns of water temperature. These represent a combination of warm and dry, cold and wet, and cold and dry climatological conditions representative of the early, mid and late summer season (Figure 4.8).

4.3.4.1 Period 1: Early season low air temperatures with high precipitation (days 194-199, 13th – 18 July 2014)

Relatively low mean incoming SWR (130 W m^{-2}) and the highest mean incoming LWR (326 W m^{-2}) define this snow-free period along with the highest precipitation inputs (total 32 mm) and the highest mean relative humidity (91 %) of all periods. Mean air temperature was low during this period (3.5 ˚C). The mean water column temperature was below the summer average in all streams, especially in Aucellaelv (2.7 ˚C) compared to other streams (between 4.0 ˚C and 5.2 ˚C). The one-way ANOVA results revealed Aucellaelv to have a significantly different thermal regime to all other streams (Table 4.5).

4.3.4.2 Period 2: Early season warm and dry period (days 200-205, 19th – 24th July 2014)

The highest mean incoming SWR (255 W m^{-2}) was observed during this period due to clear skies along with high mean incoming LWR (301 W m^{-2}). There was no recorded precipitation and low mean relative humidity (56 %) persisted. This period had a mean air temperature of 11.0 ˚C, and recorded the highest temperature during summer (15.2 ˚C).

Mean water temperatures were high and above the summer average during this period. The highest summer water temperature, recorded in Unnamed1, was observed during this period (14.9 ˚C). Kærelv and Grænseelv also recorded high temperatures (Max: 13.7 ˚C and 11.6 ˚C respectively). Mean water temperature was lower in Aucellaelv (4.8 ˚C) compared to other streams (between 7.4 ˚C and 9.8 ˚C) as was variability (σ: 1.6 compared to between 2.6 and 3.0). Water temperature was significantly different between all streams (Table 4.5).

4.3.4.3 Period 3: Mid-season mild and dry period (days 200-205, 9th – 14th August 2014)

A mean incoming SWR of (196 W m^{-2}) and a low incoming LWR (289 W m^{-2}) define this period. There were no precipitation inputs during these six days and mean relative humidity was 67%. Mean air temperature for this period (4.3 ˚C) was higher than the summer mean (3.7 ˚C). Mean water temperature was above the summer average during this period. There were highly significant differences between streams Kærelv and Aucellaelv, Grænseelv and Aucellaelv and Unnamed1, and Aucellaelv and weak but significant difference between Kærelv and Grænseelv (Table 5). Aucellaelv had a substantially lower mean water temperature compared to other streams which had similar water temperatures (4.7˚C compared to between 6.9˚C and 7.4˚C).

4.3.4.4 Period 4: Late season low air temperatures, high precipitation and high snow cover (days 234 – 239, 22nd – 27th August 2014)

This period received the lowest mean incoming SWR of all the periods (81 W m^{-2}) due to cloud cover and being further from summer solstice, and the second highest incoming LWR (314 W m^{-2}). There were high precipitation inputs (28 mm), high relative humidity (82 %), and a high maximum snow depth compared to other periods (36 cm), marking the end of the summer season. Air temperature during this period was cold, with a mean temperature of 2.5˚C. Mean water temperatures were low during this period (between 3.0˚C and 4.7˚C) and below the summer average, with minimum temperatures between 0.5˚C and 2.0˚C. Aucellaelv and Unnamed1 had significantly lower minimum temperatures compared to Kærelv and Grænseelv (Table 4.5).

4.3.4.5 Period 5: End of season cold period with low precipitation and declining soil moisture (days 253 – 258, 10th – 15th September 2014)

The mean incoming SWR during this period was very low (85 W m^{-2}) and the mean incoming LWR was the lowest of all periods (262 W m^{-2}). Precipitation inputs totalled 4 mm and were combined with low relative humidity (62%) and a maximum snow depth of 16 cm. The coldest mean air temperature of all investigated periods was recorded during this period (-1.3˚C). Water temperature was coldest during this period, with minimum temperatures being close to freezing (between 0.0˚C and -0.5˚C). During this period Kærelv and Grænseelv had significantly lower water temperatures. Compared to other periods there is little difference in water temperature between streams, with the only significant differences being between Kærelv and Grænseelv, and Kærelv and Aucellaelv (Table 4.5).

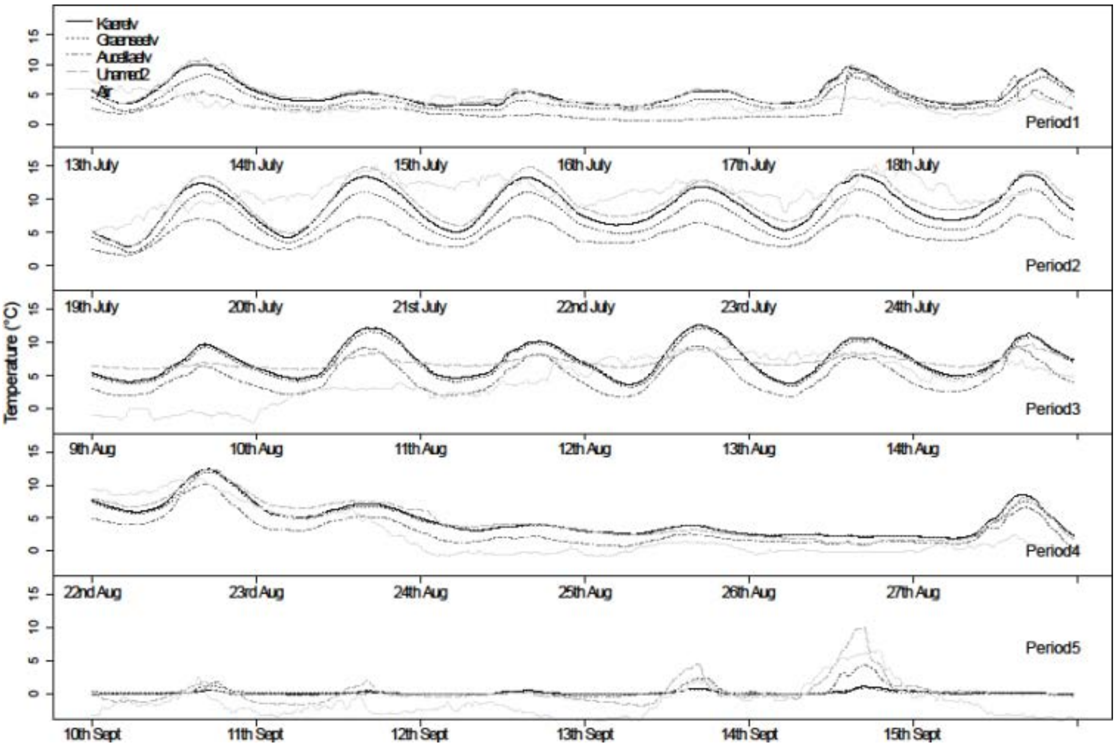

Figure 4.8. Time series of stream temperature during sub-seasonal periods.

4.4 Discussion

4.4.1 Interannual and seasonal patterns and controls on water temperature variability

The streams at Zackenberg demonstrated high variability both temporally and between streams. Water temperature in all streams at Zackenberg demonstrated a high degree of coupling with meteorological variables during the summer months, but not during the winter. However, winter meteorological conditions appeared to influence summer stream thermal habitat. During summer 2013, all streams experienced low flows with channels drying out at some sites after an unusually dry winter with minimal snowfall. This indicates the importance of snow as a water source for the region’s streams and highlights the importance of winter snowfall on summer stream characteristics. High snow depth in spring 2014 led to increased insulation of streams. This, combined with two days of positive air temperatures and high incoming SWR, caused the earlier onset of spring ice-off compared to 2015, where shallower snow depth led to higher air-water temperature coupling, preventing ice-off until later in the season even though air temperature was above 0 °C.

The presence of the 200-300 m deep permafrost layer (Christiansen et al. 2008) prevents surface water interaction with deep groundwater, and during peak snowmelt (June-July) this leads to poor drainage and allows standing water to accumulate in fen areas and local depressions. This could be a possible explanation as to the high water temperatures recorded during the summer months compared to air temperature, as these shallow pools of standing water are heated through incoming solar radiation, before inflow to streams, raising stream temperature. As water temperature was higher than air temperature in all four streams, this data is thought to be true and not due to sensor error.

The high variability and low temperatures exhibited by Unnamed2 could be due to two reasons. First, Unnamed2 lies on crystalline bedrock whilst the other streams flow over sedimentary rock and soils. Crystalline rocks generally have a higher thermal conductivity than sedimentary rocks (Midttomme & Roaldset 1999; Drury 1987) leading to cooler water temperatures. Second, Unnamed2 had a steeper gradient than the other streams, which were located within wide valleys. This steep gradient resulted in shading and a shorter surface residence time of water during the summer months when streams were unfrozen. The steep gradient and resulting shorter residence time maintained water temperatures low, and meant that snow was unable to develop deep cover during winter due to high wind exposure, preventing stream water insolation and making Unnamed2 more sensitive to climatic forcing. The colder water temperatures that characterised Aucellaelv compared to other streams may be due to either the comparatively large upstream snowpack driving larger meltwater inputs compared to other streams, resulting in lower thermal coupling between water and air temperature (Lisi et al 2015) or to the poorly developed unconsolidated soil in the area, leading to shorter residence times and faster meltwater runoff (Blaen 2013). The sensitivity of stream thermal dynamics to snow melt inputs leading to reduced water and air temperature coupling could mean the relationship between air temperature and water temperature is highly variable over seasonal and annual timescales, and alone, not a valuable indicator of future stream thermal dynamics (Arismendi et al. 2014; Lisi et al. 2015). High suspended sediment load, as found in Aucellaelv, has been known to cause increased SWR absorption due to the associated lower albedo compared to other streams, increasing water temperature (Han 1997; Richards & Moore 2011; Blaen 2013; McMahon & Moore 2017). However, Aucellaelv is notably cooler than other streams, indicating other factors to have higher importance than suspended sediment in this system with regards to temperature regime.

4.4.2 Subseasonal stream temperature variability

The subseasonal periods highlighted the impact of meteorological events on water temperature dynamics. Low air temperature and rainfall events resulted in reduced water temperature and diurnal variability, something that has been noted in other alpine and arctic studies (Brown et al. 2005; Brown & Hannah 2007; Blaen et al. 2013; Mellor et al. 2016). Rainfall is thought to reduce water temperature in these systems by melting snow and consequently, increasing meltwater inputs to streams (eg. Smart et al. 2000; Cadbury et al.

2008). In these high latitude regions, this process is thought to impact stream thermal dynamics more than the influence of direct advective heat transfer from rain to streams. Early in the summer season water temperatures were controlled not only by air temperatures, but by the large snow melt inputs (Web & Nobilis 1994; Brown et al. 2006; Blaen et al 2013) where the advective fluxes of cold water inputs outweigh the exchanges in surface energy associated with higher air temperatures (Leach and Moore 2014; Lisi et al. 2015). Coupling of water and air temperatures is known to increase towards the end of summer with the decrease in meltwater inputs (Malard et al. 1999; Blaen et al 2013).

The largest difference in thermal regimes between streams was during the summer months. Stream thermal regimes became increasingly similar towards late summer and into winter (excluding Unnamed2) as found in other studies (Caissie et al. 2005). The air-water temperature coupling is known to break down when air temperatures drop below 0 °C, (Mohseni & Stefan 1999). The 28th August marked the start of a steady decrease in water temperatures, corresponding to reduced incoming SWR. During late summer, the stream bed could play an important role in stream thermal dynamics whereby the residual ground heat accumulated over summer results in a thermal gradient which heats the water column (Alexander et al. 2003) and due to increased importance of groundwater inputs caused by the active layer being at its deepest (Rasch et al. 2000).

4.4.3 Global context and implications of a changing climate

The results from this study in Greenland fit into the growing body of literature on high resolution stream thermal dynamics throughout Arctic and Alpine regions. Zackenberg streams showed high temporal variability in water temperature compared to sites in Svalbard (Blaen et al. 2013), Swedish Lapland (Mellor et al. 2016), the New Zealand Alps (Cadbury et al. 2008) and the European Pyrenees (Brown et al. 2005). They also showed higher mean water temperatures compared to groundwater and snowmelt streams studied at 79 °N in Svalbard (Blaen et al. 2013) and lower mean temperatures compared to all streams at Abisko, Swedish Lapland at 68 ºN except for glacier-fed streams at sites close to the glacier snout (Mellor et al. 2016). In comparison to streams in Alpine regions, streams at Zackenberg showed lower mean temperatures than groundwater and snowmelt streams in the New Zealand Alps and the European Pyrenees (Cadbury et al. 2008; Brown et al. 2005).

The lower latitude of Zackenberg compared to Svalbard means that streams receive higher SWR inputs. However, Zackenberg receives lower SWR inputs when compared to alpine areas. The higher variability in stream temperature at Zackenberg compared to other areas could therefore be due to the reduced importance of groundwater inputs, as seen by the low stream bed temperatures indicating the very shallow active layer in some parts of the valley. Groundwater inputs normally act to stabilise water temperature (Constantz 1998), and their absence or reduced importance could therefore explain the variable stream temperatures observed in this study.

Zackenberg streams are predicted to receive increased snowmelt runoff and groundwater inputs by the end of the century due to increased snow depth and active layer thickness. This could potentially engender a weaker coupling between water temperature and climatic forcing. Stream bed temperature could become an increasingly important factor influencing stream thermal dynamics due to warmer bed temperatures, and increased soil water influxes to stream environments. This, combined with a shift towards lower channel stability, could lead to reduced summer water temperature variability, causing thermal dynamics in Zackenberg streams to be increasingly similar to those in other Arctic and Alpine regions where groundwater inputs regulate temperature dynamics. Conversely, the predicted increase in summer rainfall events could lead to more frequent short term cool spells. During the winter, an increase in air temperature and the number of thaw days could see increased water temperature variability.

Changes in water temperature regimes could have ecosystem - wide implications. Previous studies have found water temperature changes to impact in-stream processes such as nutrient uptake (Blaen et al. 2014) as well as causing changes to biological community structure, abundance and diversity (Vincent & Howard Williams, 1989; Milner et al. 2001; Brown et al. 2007; Adams et al. 2010; Jacobsen et al. 2012; Madsen et al. 2015). Given this, research on Arctic water temperature dynamics and drivers is vital in order to potential understand changes to wider ecosystem processes under a changing climate.

Future studies on water temperature in the Zackenberg region would benefit from frequent discharge measurements, which is lacking in the present study. This data would allow better comparison between streams and of seasonal variability, taking stream size into account when comparing water temperature dynamics.

4.4.4 Conclusion

This paper contributes to the growing body of literature on Arctic stream thermal dynamics by providing insights into Greenlandic streams, particularly snowmelt dominated systems that are currently underrepresented in the literature and by providing a detailed description of thermal dynamics during the winter months for the first time. Spatial and temporal variation in stream thermal dynamics is largely related to a combination of climatological conditions, geology and local geomorphology. With a changing climate, Zackenberg streams will be subjected to increased snowmelt runoff and groundwater inputs due to increased snow depth and active layer thickness, possibly leading to a weaker coupling between water temperature and climatic forcing. Changes in water temperature regimes could impact in-stream processes such as nutrient uptake as well as causing changes to biological community structure, abundance and diversity. Whilst stream temperature was highly coupled with meteorological variables during the summer months, during the winter streams were mainly frozen to the stream bed. Further research into the relationship between snow depth and water temperature in Arctic streams as well as on the meteorological drivers to spring ice-off and autumn ice-on in streams is necessary to fully understand the impact of a changing climate on these sensitive systems.

4.5 References

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CHAPTER 5: NUTRIENT UPTAKE CONTROLS AND LIMITATION DYNAMICS IN NORTHEAST GREENLAND

Abstract

Permafrost thaw induced by climate change will cause increased release of nutrients and organic matter from the active layer to Arctic streams, and with increased water temperature, will potentially enhance algal biomass and nutrient uptake. Overall knowledge of nutrient release on current Arctic in-stream processing is limited, however it is essential for accurately predicting the response of Arctic streams to environmental change. Addressing this research gap, we quantified nutrient uptake of short-term releases of NO_3^-, PO_4^{3-} and NH_4^+ during peak snow-melt season, in five streams of contrasting physiochemical characteristics (from unstable, highly turbid to highly stable, clear-water systems) in northeast Greenland to elucidate the major controls driving nutrient dynamics. Releases were plus or minus acetate to evaluate uptake dynamics with and without a DOC source. To substantiate limiting nutrients to algal biomass, nutrient-diffusing substrates (NDS) were installed in the five streams for 16 days with NH_4^+, PO_4^{3-} or, NH_4^+ + PO_4^{3-} on organic and inorganic substrates. Low uptake rates were observed due to a combination of low nutrient and DOC concentrations, combined with low water temperature and primary producer biomass, and substantial variation occurred between streams. N was found to be the primary limiting nutrient for biofilm, whilst streams displayed widespread PO_4^{3-} limitation. This research has important implications for future changes in nutrient processing and export in Arctic streams, which are predicted to include increased nutrient uptake rates due to increased nutrient availability, warmer water temperatures and increased concentration of labile carbon. These changes could have ecosystem and landscape-wide impacts.

5.1 Introduction

Over the next century, a changing climate in northeast Greenland is predicted to increase winter air temperature by up to 18°C and total precipitation by up to 60%, principally as snow in winter and rain in summer (Stendel et al. 2008). Permafrost is expected to degrade significantly, both through deepening active layer and localised thermokarst processes (Frey & McClelland 2009; Docherty et al 2017) with significant consequences for freshwater systems. Streams will potentially experience higher flow, water temperature, and suspended sediment, and lower channel stability. Permafrost degradation is expected to lead to soil water becoming an increasingly important water source for stream ecosystems, providing nutrients and DOC previously bound within the permafrost (Maden et al. 2007; Frey & McClelland 2009). Increased nutrient fluxes in streams are associated with increased biological activity in the biofilm (Lock et al. 1990; Hershey et al. 1997), increased by warmer water temperatures (Gíslason et al. 2000; Blaen et al. 2014), leading to an increase in nutrient uptake in headwater Arctic streams (Rasmussen et al. 2011) with consequences for the food web. However, high channel mobility and suspended sediment concentration are unfavourable to biofilm growth, and as such, predicted decreases in channel stability could have negative impact on nutrient uptake dynamics through reductions in biofilm biomass (Ryan 1991). Headwater streams play an important role in the ecosystem by transporting nutrients and carbon to downstream rivers and oceans. In addition, due to their high surface to volume ratio, they can have a high nutrient processing capacity, converting them into major controllers of nutrient fluxes in large watersheds (Alexander et al. 2000).

The assimilation of inorganic nutrients in streams is largely undertaken by biofilms, typically comprised of both autotrophic (algae and specialised bacteria) and heterotrophic (bacteria and fungi) components, playing an important role in structuring stream food webs (Hoellein et al. 2010). Autotrophic communities are largely found on inorganic substrate (Johnson et al 2009) typically outcompeting heterotrophs which are more prevalent on organic substrates due to the higher availability of labile carbon (Hoellein et al. 2010). As such, the presence of carbon can increase nutrient uptake in heterotrophic communities (Hoellein et al. 2010). As both nitrogen and phosphorous availability can limit growth of both heterotrophs and autotrophs (Pringle et al. 1986; Tank & Webster 1998), increased concentrations of these nutrients can significantly influence community structure and function (Tank & Dodds 2003; Cross et al. 2006). Understanding nutrient limitations to microorganisms is thus vital in order to understand the future dynamics of nutrient processing in Arctic streams.

During the early summer snowmelt season, high Arctic streams are characterised by high hydrological connectivity with the terrestrial environment through snowmelt inputs. This input results in peak flow and peak nutrient concentration and bioavailability in the headwaters at that time of year (Holmes et al. 2008; Mann et al. 2012) and also the peak time for nutrient export to the ocean (Finlay et al. 2006; Holmes et al. 2008; Mann et al. 2012). Despite the accelerated climate change experienced in high latitude regions the number of studies that have examined nutrient uptake in Arctic headwater streams is limited (but see Wollheim et al. 2001, Blaen et al. 2014, Diemer et al. 2015; Schade et al. 2016).

The aim of this study was thus to determine the key processes involved in nutrient uptake controls and identify nutrient limitations during the peak snowmelt season across a gradient of physicochemical stream habitats associated with varying degrees of channel stability in northeast Greenland. The objectives were to elucidate; 1) reach-scale nutrient uptake rates and limitation to biofilm growth, 2) the main controls on nutrient uptake and limitation, and 3) by comparison with other studies, the wider implications of the findings in the Pan-Arctic region with respect to the effect of a changing climate on nutrient dynamics. We hypothesised that; 1) nutrient uptake would occur in all streams due to low nutrient availability in Arctic tundra ecosystems (Maden et al. 2007; Kelley & Epstein 2009); 2) nutrient uptake would increase in the presence of a carbon source by increasing DOC availability needed for heterotrophic activity (Hoellein et al. 2010); 3) nutrient uptake would be highest in streams with warmer water temperature due to enhanced algal growth (Gíslason et al. 2000; Blaen et al. 2014); and 4) Biofilm biomass would be highest in the most stable stream channels, where channel mobility and suspended sediment concentration were lower and so more favourable to primary producer growth (Ryan 1991).

5.2 Methods

5.2.1 Study site

The study streams were accessible from the Zackenberg research station (74º28’ N, 20º34’ W), within Northeast Greenland National Park in the high Arctic climatic zone (Figure 5.1). Although not connected to the ice sheet approximately 60km away, a number of small, high altitude glaciers are present in the area. The mean annual air temperature is -9.1˚C, the warmest month being July (mean 5.8˚C) and annual precipitation is 261mm falling mainly as snow (Hansen et al. 2008). Altitude varies between 0 and 1450m a.s.l with glacial plateau occurring above 1000m a.s.l and a wide horizontal valley caused by glacial erosion below (Mernild et al. 2007). The valley is in a zone of continuous permafrost with active layer thickness varying between 30 and 65cm (Christiansen et al. 2008).

Five streams were selected in early July 2014. All streams were fed by snowmelt representing a gradient of physicochemical variables, from low channel stability with high turbidity to high channel stablity with low turbidity. Larger snowpacks were evident in the streams Aucellaelv and Palnatokeelv than Kærelv and Grænseelv. A small snowpack was directly upstream of Unnamed, but also received input from proximal larger snowpacks. Palnatokeelv and Aucellaelv in addition received glacial meltwater, but this contribution was minimal during the study period. Kærelv, Grænseelv and Unnamed supported vegetated banks whereas the banks of Aucellaelv and Palnatokeelv were unvegetated and these streams showed high channel mobility and braiding. Water sources for Aucellaelv and Palnatokeelv originated at a higher altitude and mobilized a large amount of sediment. Study reaches were limited to approximatetely 100m in length to ensure all study reaches were single channels with no connecting tributaries. Experiments were undertaken within a 10-hour period between 12th and the 20th July 2014.

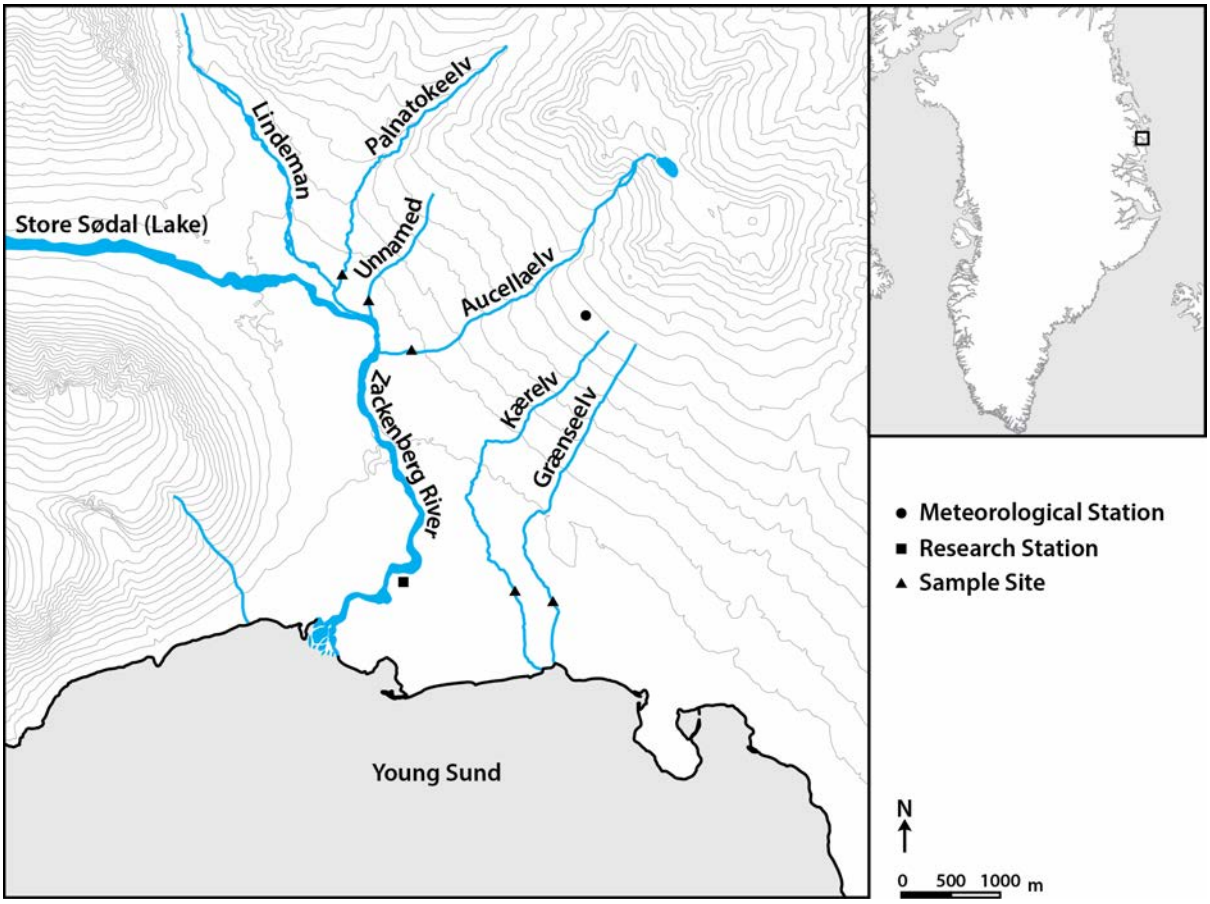

Figure 5.1. Location of the five study streams and associated nutrient uptake experiments

5.2.2 Stream characteristics and environmental variables

Air temperature and precipitation data were obtained from a weather station located within 5km of the study streams maintained by the Greenland Ecosystem Monitoring Programme. All climate data were recorded every 30 min except precipitation which was recorded hourly.

Data loggers (Gemini TinyTag Aquatic 2 TG-4100) recorded water temperature every 30 min at the study streams from 11 July to 15 September and water velocity was measured using a hand-held flow meter (µP-TAD from Höntzsch instruments, Germany). The entire Pfankuch Index (Pfankuch 1975) was calculated at each site as a measure of channel stability. Ambient nutrient concentrations were measured at all sites using a Lachat QuikChem flow injection analyzer (Lachat Instruments, APC Bioscientific Limited, England; APHA 2012).

Suspended sediment was estimated by filtering 1L of stream water through pre-weighed GF/F filter papers, dried at 60°C for 48 h and then re-weighed. Suspended organic carbon (TOC) was measured using a TOC-V CPH analyser (Shimadzu, Japan).

Sediment respiration was measured as a proxy for heterotrophic activity where three samples from areas of fine sediment were collected and placed in a container along with 500ml of filtered stream water with no headspace remaining in the container. DO was measured (ProODO Optical dissolved oxygen meter) in the container, the sample was stored at 5ºC in the dark for 24 h until DO was re-measured. The sediment was dried at 105ºC for 48 hours to give the units µg O_2/g of sediment/hr.

Fine benthic organic matter (FBOM; <1mm in size) was estimated at each site using an open-ended PVC cylinder (16 cm diameter; 201 cm^2 area) inserted into the sediment. The sediments were lightly disturbed by hand down to approximately 2 cm depth. The water in the cylinder was then mixed and a 200ml sample filtered onto a pre-combusted Whatman GF/C filter paper in the laboratory before combustion at 480 °C to obtain ash free dry mass to estimate organic matter content (Wallace et al. 2006).

Chlorophyll *a* (Chl *a*) was measured as a proxy for benthic algae biomass and determined for two substrate types: stone and gravel. Five stone samples (>6cm b-axis) and gravel samples (200cm^2 core to collect upper gravel layer from stream bed) were collected. In the laboratory, a toothbrush removed biofilm onto a Whatman GF/C filter paper and frozen before Chl *a* extraction in 96% ethanol and absorbance measured at 665 and 750nm using a spectrophotometer (UV 1700 Spectrophotometer, Shimadzu, Japan). Chl *a* biomass was calculated as:

$$\frac{Chl\ a = (Abs_{665} - Abs_{750}) * E}{83.4 * A * 10^{-4}}$$

where E is volume of ethanol (ml), 83.4 is the absorption of Chl *a* in ethanol, A is the sample area (cm^2) and 10^{-4} is the conversion factor from cm^2 to m^2. Habitat weighted Chl *a* was calculated as the sum of biomass of Chl *a* on stones and gravel multiplied by the percentage of the two habitats, respectively.

5.2.3 Nutrient uptake experiments

Short-term nutrient experiments were undertaken at five stream sites following the protocol of Tank et al. (2006). A transect along a reach of each stream, free from tributaries, was selected with the point of nutrient injection at the upstream site. Further sites were identified along the transect length to determine change in nutrient concentration. A water sample was collected from each site prior to nutrient addition to determine ambient nutrient concentrations. A prior injection of NaCl was made to ascertain time to asymptote and to obtain a measure of mean travel time. Continuous injections of NH_4^+, NO_3^-, PO_4^{3-} and NH_4^+ with acetate as a carbon source diluted in 8L of stream water were made at each site using a peristaltic pump with a flow rate of 100ml/min. Nutrient concentration levels were increased above ambient by 15µgL^{-1} (NH_4^+), 20µg L^{-1} (NO_3^-), 30µgL^{-1} (PO_4^{3-}) and 100µg L^{-1} for acetate (cf. Blaen et al. 2014). Bromide (Br) was added as a conservative tracer and concentrations measured at each site. Water samples were collected from each of the designated sampling sites at the following distances from the injection site: 10m, 20m, 35m, 50m, 70m, 90, 107m. However, the final sampling site was shorter in some streams to avoid the influence of tributaries; in Unnamed the final site was at 103m from the injection site and in Aucellaelv the final site was at 97m. In Palnatokeelv, due to braiding and tributaries, the sampling transect was shorter and samples were collected every 10m up until 65m distance from the injection site. In all streams, the mean water travelling time was 15-25 min. Water samples were filtered through Whatman GF/F 0.7µm filter papers in the field and frozen within 8 h. Possible downstream dilution was taken into account by dividing the increase in nutrient concentration by the increase in Br^- concentration between ambient and raised levels.

Nutrient uptake length (S_w, m), velocity (V_f, m min^{-1}) and areal uptake rate (U, mg m-^{2} min^{-1}) were determined using standard protocols (Tank et al. 2006) based on the longitudinal decrease in nutrient concentration along the study reaches, discharge, and stream width. Water samples were analysed for NH_4^+, NO_3^-, and PO_4^{3-} using the hypochlorite, cadmium reduction, and ascorbic acid methods, respectively, on a Lachat QuikChem flow injection analyzer. Bromide concentrations were determined using ion-chromatography (Dionex Ionchromatograph system 2500, Thermo Fisher Scientific Inc., USA).

5.2.4 Nutrient Diffusion Substrate (NDS) experiments

To determine nutrient limitation at each stream site to autotrophic growth, Polycon cups were filled with 0.2% agar solution combined with one or more nutrients on either a glass disc (inorganic substrate) or cellulose sponge (organic substrate) to act as different substrate types for biofilm colonisation following Tank et al. (2006). There were four treatments with five replicates; (1) NH_4^+ additions (0.5M NH_4Cl), (2) PO_4^{3-} additions (0.5M KH_2PO_4), (3) combined NH_4^+ + PO_4^{3+} additions (0.5M NH_4Cl + 0.5M KH_2PO_4) and (4) controls with agar only and no added nutrient. The 20 cups per stream were organised into 4 rows in plastic racks and secured in place on the stream bed by rocks. After 16 days, the cups were removed and substrates (glass discs and cellulose sponge) were contained within plastic bags along with the associated stream water and frozen until analysis for Chl *a*. In the laboratory, 4ml of 96% ethanol was added to the bags for 12 hours before measuring absorbance at 665 and 750nm (UV 1700 spectrophotometer, Shimadzu, Japan). Appendix A2 includes images of nutrient uptake and NDS experiments.

5.2.5 Data analysis

A weather graph was derived to show air temperature and precipitation during the field campaign. Differences in water temperature between streams were tested by one-way ANOVA on data collected every 30 minutes between 11 July and 15 September. One-way ANOVAs followed by Tukey post hoc tests on significant results were conducted to ascertain differences in background nutrient concentrations between all streams and Chl *a* biomass on stone and gravel. Spearman’s rank correlation analysis was conducted to test for associations between environmental variables and background nutrients and between different environmental variables. The environmental variables included were: discharge, water temperature, channel stability, FBOM, organic matter content, TOC, Chl *a*, sediment respiration and dissolved oxygen. One-way ANOVAs were conducted to ascertain differences in FBOM, organic matter, sediment respiration and habitat weighted Chl *a* between streams. Other environmental variables were not tested for differences between streams due to a lack of repetitions. The ratio of NH_4^+:NO_3^- was calculated to visualise the relative importance of autotrophic and heterotrophic activity in driving stream metabolism, where a high ratio of NH_4^+:NO_3^- combined with undersaturation of dissolved oxygen suggests heterotrophic activity dominates stream metabolism (Schade et al. 2016). The NH_4^+:NO_3^- results ae intended be taken as a guidance on metabolic conditions, however they should be interpreted with caution due to the possibility of concentrations being transported from other areas upstream.

Spearman’s rank correlation analysis was conducted to test for associations between uptake parameters and the previously-mentioned environmental variables. Two-way ANOVAs were undertaken for the NDS to determine limiting nutrients. There was limitation of a single nutrient if there was a significant result for one of the single nutrient additions compared to the control, and a co-limitation of both N and P if there was a significant result for interaction or for both nutrients added separately compared to the control (Tank & Dodds 2003). For all analyses, results were first analysed for homogeneity of variance using Levene’s test, and if they were found to not be homogeneous, data were log transformed before further analysis. The R environment was used for all statistical analysis and graphical representation of data.

5.3 Results

5.3.1 Stream characteristics and environmental variables

Maximum air temperature during the field campaign was 15°C with a minimum of -4.0°C. Two rainstorm events occurred, on the 8th July with a total of 5mm and between July 14 – 16 with 31.1mm (Figure 5.2). Mean water temperature during summer 2014 (11 July – 15 September) varied between 3.33°C and 5.55°C. Water temperature was significantly different between all streams except for Kærelv and Unnamed (Table 5.1). Palnatokeelv was not included due to a missing data logger. Lower channel stability (Pfankuch Index), higher bed mobility and higher suspended sediment were found in the streams with the largest snowpacks related to larger spring floods and increased nivation processes, such as pronival solifluction and the accumulation of alluvial fans (Table 5.2). For bed substrate, equal amounts of gravel and stone were found at Kærelv whilst Grænseelv was predominantly gravel. Palnatokeelv, Unnamed and Aucellaelv bed substrate was predominantly stone (Table 5.2). Mean suspended sediment was low in Kærelv, Grænseelv and Unnamed (between 0.5 and 7.3mg L^{-1}) but high in Palnatokeelv (96.3mg L^{-1}) and Aucellaelv (1120.3mg L^{-1}). Stream discharge ranged between 151 and 580 L/s (Table 5.2). One-way ANOVA indicated significant differences in background nutrient concentrations between streams. NO_3^- concentrations showed the most variability ($F_{(4,30)}$=405.7, *P*=<0.01) where Aucellaelv and Palnatokeelv were significantly higher than other streams (*P*=<0.01), whilst Kærelv, Grænseelv and Unnamed were not significantly different. NO_3^- varied between < detection limit of 0.056µg/L in Unnamed to 50.66µg/L in Aucellaelv. PO_4^{3-} was highly variable ($F_{(4,30)}$=19.79, *P*=<0.01) with significant difference between all combinations of streams (*P*=>0.05 for Unnamed and Grænseelv, all other combinations *P*=<0.01) except for between Unnamed and Kærelv, and between Aucellaelv and Palnatokeelv, that were not significantly different. Highest concentrations were found in Aucellaelv and Palnatokeelv. NH_4^+ was also variable ($F_{(4,30)}$=32.18, P=<0.01), and was significantly higher in Aucellaelv than the other streams (P=<0.01). Ambient nutrient concentrations were not significantly correlated with any environmental variables. There was no significant correlation between any environmental variables, with the highest correlation found between channel stability and suspended sediment, and Chl *a* with water temperature (Spearman rank: r=0.9, P= 0.083 for both, P=>0.05 for all combinations).

Moss was present in small amounts in the three most stable streams (Kærelv, Grænseelv and Unnamed), making it a minor contributor to primary production in these systems. (Table 5.2). Sediment respiration was significantly different between streams ($F_{(4,10)}$=5.85, P=0.01), being significantly higher in Palnatokeelv than Unnamed and Aucellaelv (P=<0.05). Organic matter also varied significantly between sites ($F_{(4, 19)}$=10.56, P=<0.001) where Unnamed was significantly higher than all streams (P=<0.05 for all sites) and Palnatokeelv was significantly higher than Grænseelv (P=<0.05) (Table 5.2). Benthic algae biomass was highest in Unnamed (habitat weighted: 218.95µg/m^2) and lowest in Grænseelv (habitat weighted: 110.25µg/m^2). In all streams stones were found to have larger benthic algal biomass compared to gravel, and biomass was significantly higher on both stones ($F_{(4,18)}$=4.23, P=0.014), and gravel ($F_{(4,20)}$=3.33, P=0.03) in Kærelv compared to Aucellaelv (Stone: P_{adj}=0.018, gravel: P_{adj}=0.05) and Palnatokeelv (stone: P_{adj}=0.04, gravel: P_{adj}=0.03) (Figure 5.3). NH_4^+:NO_3^- show high ratios in the streams that had highest channel stability according to the Pfankuch index (Kærelv, Grænseelv and Unnamed), with an exceptionally high ratio found for Kærelv (14,530.00), (Table 5.2).

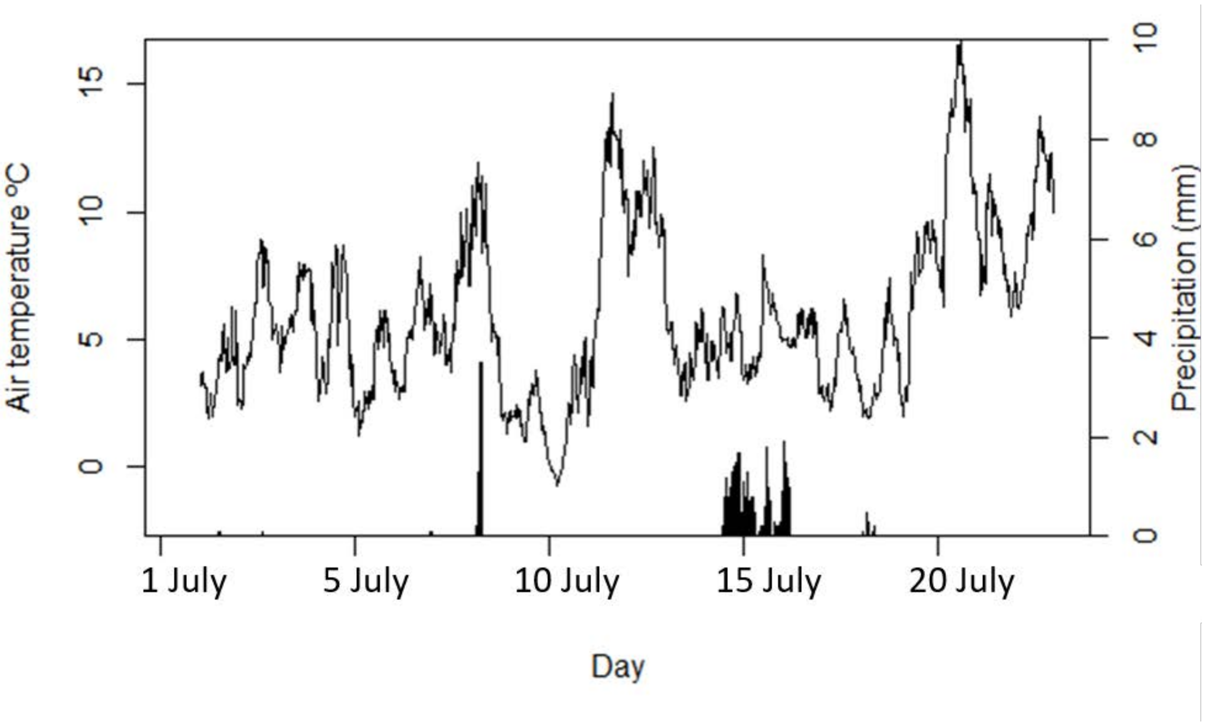

Figure 5.2. Air temperature (line) and precipitation (bars) during the field campaign.

Table 5.1. F values from one-way ANOVAs for water temperature between streams during the period 11 July to 15 September. Df=(1, 6358). * P=<0.0001

	Kærelv	Grænseelv	Aucellaelv	Unnamed
Kærelv		**46.1***	**743.8***	-
Grænseelv			**459.3***	**70.6***
Aucellaelv				**844.3***
Unnamed				

Table 5.2. Environmental characteristics and background nutrient concentrations of the five study streams. DO measurements are all from 2015. All other conditions measured on day of sampling. Abbreviations: Q = discharge; EC = electrical conductivity, DO= dissolved oxygen, FBOM= Fine benthic organic matter, TOC= total organic carbon. *= significant difference between sites.

Environmental variable		Kærelv	Grænseelv	Unnamed	Aucellaelv	Palnatokeelv
Q	L/s	151	189	204	580	247
Channel width	m	3.2	2.6	4	2.8	2.4
EC	(µS cm^{-1})	54	93.1	88.3	192.4	58
*Water temperature	°C	7.2	4^{-}	12.1^{-}	5.8^{-}	7^{-}
DO	%	76.5	78	88	75.1	77.8
Pfankuch Index		74	78	113	116	114
Suspended sediment	mg L^{-1}	5.1	7.3	0.5	1120.3	96.3
Dominant bed sediment types	% stone (>6cm)	31.3	31.6	66.7	79.4	71.6
	% gravel (2-6cm)	29.8	42.4	20.7	15.5	13.8
Moss coverage	%	2.6	1.9	2	-	-
FBOM	g m^{-2}	8.11	21.47	19.67	25.94	19.35
	SD	2.04	2.67	8.14	8.28	4.93
*Organic matter	%	4.01^{a}	2.48^{ab}	9.09^{a}	5.01^{a}	5.84^{ab}
	SD	1.34	0.77	2.37	0.76	1.06

*Sediment respiration	mg O_2 ml^{-1} sediment/day	3.43	2.61	1.86^{b}	1.52^{b}	4.31^{b}
	SD	1.09	0.12	0.33	0.17	0.94
Habitat weighted Chl *a*	µg m^{-2}	163.49	110.25	218.95	131.92	124.8
	SD	73.63	72.27	91.73	187.88	118.87
TOC	mg L^{-1}	2.14	2.79	2.93	7.76	1.11
	SD	0.06	0.1	0.3	1.15	0.04
*PO_4^{3+}	µg L^{-1}	3.98^{+}	1.51^{+}	2.45^{+}	4.18^{+}	4.01^{+}
	SD	0.003	0.004	0.0004	0.002	0.009
*NH_4^+	µg L^{-1}	14.53^{c}	7.47^{c}	6.7^{c}	33.81^{c}	12.48^{c}
	SD	0.006	0.002	0.002	0.007	0.004
*NO_3^-	µg L^{-1}	<0.001^{bc}	0.36^{bc}	0.06^{bc}	50.66^{bc}	11.79^{bc}
	SD	0.001	0.001	0.001	0.012	0.008
NH_4^+:NO_3^-		14,530.00	20.75	111.67	0.67	1.06

$^{+}$All significantly different to one another except for Unnamed with Kærelv, and Aucellaelv with Palnatokeelv. $^{-}$ See Table 1 for significant differences. ^{a}Unnamed significantly higher than all other sites. ^{b}Palnatokeelv higher than Unnamed and Aucellaelv. ^{c}Aucellaelv higher than all other sites

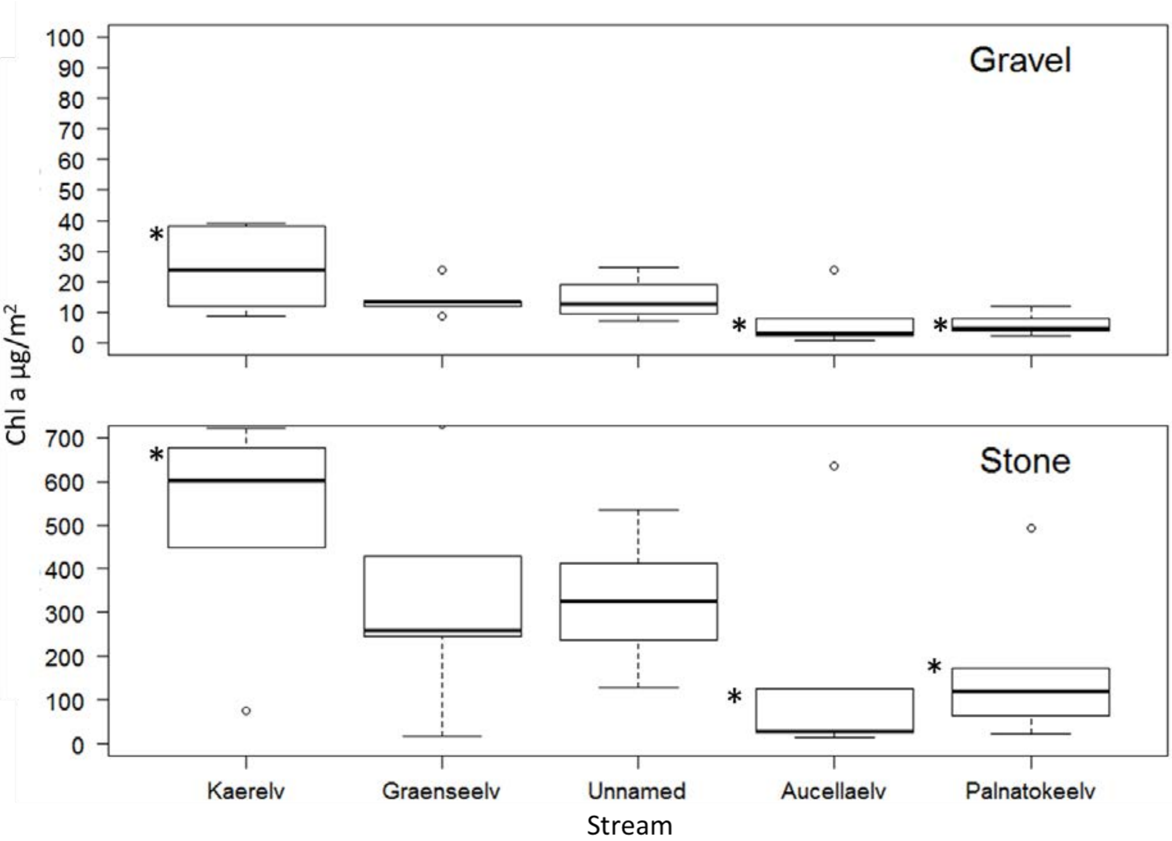

Figure 5.3. Chl *a* biomass on stones and gravel in each study stream. Note different Y axis scale. Asteryx highlights significant differences between streams.

5.3.2 Nutrient uptake experiments

No detectable uptake of any added nutrients was observed in Grænseelv and Aucellaelv (Table 5.3). Detectable uptake of PO_4^{3-} was found in the other three streams. Palnatokeelv was the only stream to exhibit uptake of all injected nutrients whereas there was also detectable NH_4^+ uptake in Kærelv. Upon injecting acetate alongside NH_4^+ in Palnatokeelv, uptake length declined by more than half from 92.79m to 37.87m. The longest uptake lengths and lowest uptake velocity were for PO_4^{3-} in the two streams that recorded uptake of two or more solutes (Palnatokelv and Kærelv). We did not find any significant relationships between uptake parameters (Sw, Vf, U) and the environmental variables listed in the data analysis section.

Table 5.3. Nutrient uptake variables during peak snow-melt period in 2014. S_w in m, V_f in m/hr, U in µg m^{-2} hr^{-1}. - indicates no detectable uptake.

Nutrient addition	Uptake parameter	Stream				
		Kærelv	Grænseelv	Unnamed	Aucellaelv	Palnatokeelv
PO_4^{3-}	S_w	586.34	-	686.16	-	163.25
	V_f	0.29	-	0.27	-	2.27
	U	0.46	-	0.04	-	0.55
NH_4^+	S_w	192.4	-	-	-	92.79
	V_f	0.88	-	-	-	3.99
	U	0.77	-	-	-	2.99
NH_4^+ + Acetate	S_w	-	-	-	-	37.87
	V_f	-	-	-	-	9.78
	U	-	-	-	-	7.33
NO_3^-	S_w	-	-	-	-	52.43
	V_f	-	-	-	-	7.07
	U	-	-	-	-	4.22

5.3.3 Nutrient Diffusion Substrate (NDS)

Heavy storm events during the field campaign removed diffusing cups in Aucellaelv and Palnatokeelv. For the other three streams, control Chl *a* biomass varied between 0.33 and 0.79µg/cm^2 on glass substrate and 0.13 and 0.27µg/cm^2 on sponge. In all three streams, highest biofilm biomass was found on glass substrate. The highest Chl *a* biomass recorded was 1.58 µg/cm^2 after N+P addition on glass substrate in Kærelv and the lowest was 0.13 µg/cm^2 in the control on sponge in Kærelv and P addition in Unnamed (Figure 5.4). In all streams, biofilm biomass was highest when nitrogen and phosphorous were added together, and more notably so for autotrophic biofilms. Two-way ANOVA indicated nutrient limitation in all streams. Nitrogen and phosphorous were co-limiting on both substrate types in Unnamed stream and on glass in Kærelv and sponge in Grænseelv (Table 5.4). However, nitrogen limitation, either alone or combined with phosphorous limitation, was the most frequent significant response. Phosphorous limitation alone was only found in two cases (Table 5.4).

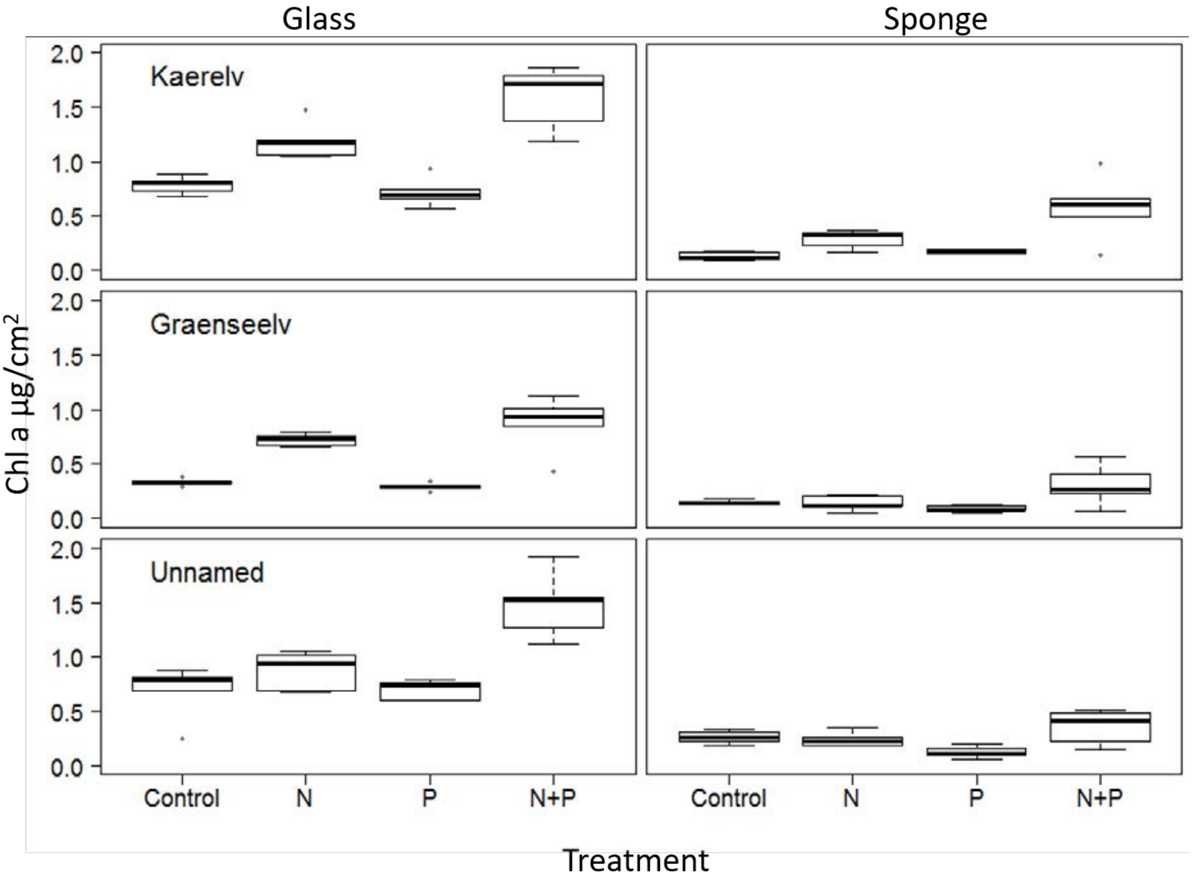

Figure 5.4. Chl *a* content in biofilm following different nutrient additions after 16 days.

Table 5.4. Two- way ANOVA results for NDS investigations to determine limiting or used nutrients in each stream. *n* = 20 for all sites and substrate types. F values presented. Significant P values are in bold. *P=<0.05 **P= <0.001

Stream	Substrate	NH_4^+	PO_4^{3-}	$NH_4^+ * PO_4^{3-}$
Kærelv	Glass	**58.65****	3.86	**7.59***
	Sponge	**22.1****	**4.98***	0.46
Grænseelv	Glass	**95.1****	<0.00	2.07
	Sponge	3.54	0.1	**6.19***
Unnamed	Glass	**23.5****	**9.4****	**8.48***
	Sponge	**5.75***	0.06	**8.52***

5.4 Discussion

5.4.1 Nutrient uptake dynamics

As nutrient uptake was not detected in Grænseelv or Aucellaelv, hypothesis 1, that nutrient uptake would occur in all streams due to low nutrient availability in the Arctic tundra, was not accepted. The lack of detectable uptake in these two streams could possibly be explained by low biofilm biomass or the low water temperature found in these two streams preventing detectable uptake. The large variation in nutrient uptake between the remaining three streams was similar to findings from Siberia (Diemer et al. 2015; Schade et al. 2016) and Svalbard (Blaen et al. 2014). NH_4^+ uptake was lower than observed in Siberia, but comparable to the lower uptake results from Svalbard, whilst PO_4^{3-} and NO_3^- uptake were lower than other studies (Blaen et al. 2014; Diemer et al. 2015; Schade et a. 2016). With low benthic algae biomass, and moss not evident, uptake of all nutrients in Palnatokeelv was unexpected.

However, high sediment respiration rates (> 2 x other streams) and increased NH_4^+ uptake when injected alongside a DOC source suggests uptake was principally by heterotrophic bacteria.

DOC uptake is known to be largely controlled by heterotrophic activity (Martí et al. 2009) in Svalbard freshwater systems (Säwström et al. 2007) whilst autotrophs obtain carbon largely from CO_2 or HCO_3^- (Allen & Spence 1981). The increased uptake alongside a DOC source indicates that biotic processes in streams in this region are potentially limited by DOC availability and highlight the coupled biogeochemical cycles of N and C, as previous studies have found DOC to be a principal driver and strong control on nutrient uptake (Dodds et al. 2004; Johnson et al. 2009; Diemer et al. 2015; Rodríguez-Cardona et al. 2016). However, experimental additions of a carbon source alongside nutrients in Arctic tundra streams have been negligible (but see Blaen et al. 2014). Whilst the influence of DOC addition on nutrient uptake was limited to only one site, the substantial increase in uptake and decrease in uptake length supports our hypothesis that uptake would increase in the presence of a carbon source. The other two streams where uptake was observed –Unnamed and Kærelv – showed different biofilm conditions to Palnatokeelv. Unnamed was the opposite of Palnatokeelv, supporting high benthic algal and moss biomass and low sediment respiration, and so autotrophic activity was largely responsible for nutrient uptake. The dominance of autotrophic activity was confirmed for Unnamed, Kærelv and Grænseelv through the NDS experiments as biomass was highest on the inorganic substrate where heterotrophs were outcompeted. This pattern was also supported by the higher NH_4^+:NO_3^- ratios in Kærelv, Grænseelv and Unnamed whilst Palnatokeelv showed a small ratio. Hence our findings indicate nutrient uptake in high Arctic streams can be driven by heterotrophic or autotrophic processes. The proportion of nutrients sorbed to sediments was not investigated in this study. Nethertheless, the NDS experiments indicate biological uptake within the system, as does the increased uptake of NH_4^+ when injected alongside a carbon source.

In contrast to Arctic Siberia and Svalbard, PO_4^{3-} was a limiting nutrient as three of the five streams showed detectable uptake. However, when NH_4^+ uptake was evident, NH_4^+ was in higher demand compared to availability than PO_4^{3-}, meaning that NH_4^+ was the overall primary limiting nutrient in these systems, as found in Arctic Siberia and Svalbard (Blaen et al. 2014; Schade et al. 2016). In a study from boreal Siberia, both PO_4^{3-} and NH_4^+ were found to be limiting in different streams (Diemer et al. 2015). The NDS experiments also suggested nitrogen to be the primary limiting nutrient in these Greenlandic systems alongside phosphorous (as was also found in Tank & Dodds 2003). Whilst the NDS experiments test nutrient limitation in specific components of the stream ecosystem, i.e. the biofilm colonising inorganic and organic substrate, the uptake experiments measure whole stream uptake (Tank et al. 2006). Thus, N may be only limiting autotrophic biofilm growth whereas heterotrophic uptake in sediment could have driven the whole reach P limitation. However, the lack of P sorption data meant that the overall role of heterotrophic uptake of P is uncertain. More replication of the short-term nutrient uptake experiments in different streams at different times would be required to confirm these findings.

DOC and nutrient concentrations peak in Arctic streams during peak snowmelt as it is flushed into freshwater systems from where soluble organic material has accumulated over winter due to heterotrophic microbial activity underneath snowpacks (Brooks et al. 1999). Because of this, studies conducted in late summer may provide different insights into nutrient uptake in streams as benthic algal communities would have had time to increase surface area cover, water temperature would be higher, nutrient-rich groundwater inputs would be more constant and lower stream flow would increase water-stream bed contact time. These probabilities could also explain the low uptake of nutrients in these streams during early summer. Increasing the study reach length could have resulted in greater uptake but this was not feasible as other meltwater inputs could have caused too large a dilution effect.

5.4.2 Environmental habitat conditions and effects on nutrient uptake rates

The size of snowpacks that streams are sourced from are thought to play an important role on stream physicochemical habitat as different snowmelt proportions entering streams could alter water temperature and solute concentration. Snowpack size is thought to have a large influence on stream water temperature and channel stability due to a combination of effect of spring floods and nivation processes, loosening and weathering sediment, increasing input to streams and increasing channel mobility. However, as neither nutrient uptake nor Chl *a* were significantly correlated with water temperature, hypothesis 3 was not accepted. This lack of correlation may be due to the small sample size of only five streams, and the small range of water temperature. Significant correlations between Chl *a* and water temperature have been found in other studies, indicating warmer water temperature enhances algal growth (Gíslason et al. 2000; Blaen et al. 2014). Chl *a* biomass was markedly lower in this area of Greenland compared to other Arctic locations (e.g. Parker & Huryn 2011; Blaen et al. 2014).

Channel stability was the most significant habitat difference between streams and was a function of source snowpack size. The role of higher channel stability was emphasised by the presence of moss in Kærelv, Grænseelv and Unnamed but not in Aucellaelv and Palnatokeelv. However, the low overall relative abundance of moss in all streams could partly explain the low nutrient uptake. Whilst Kærelv supported significantly higher biofilm biomass than the two low stability streams Aucellaelv and Palnatokeelv, hypothesis 4 was not accepted as biofilm biomass was lowest in Grænseelv. However, the low biomass in Grænseelv could be a function of the stream’s low water temperature as opposed to a function of channel stability preventing biofilm growth. Biofilms were almost exclusively responsible for biological uptake in these systems but the surface area for biofilm uptake is smaller compared to moss (Rasmussen et al. 2011; Blaen et al. 2014). As such, even small biomasses of moss can contribute disproportionately to nutrient uptake. Channel stability differences were also highlighted for Aucellaelv and Palnatokeelv, where bed sediment consisted of a lower proportion of gravel compared to the other streams, and high disturbance events evident at Aucellaelv, which led to increased solute and sediment load in stream water (Docherty et al. 2017), creating different habitat conditions for biofilm colonisation.

Organic matter was similar in quantity between all streams apart from Grænseelv (low percentage) and Unnamed (higher percentage). Organic matter is known to control carbon and nutrient budgets in streams (Webster & Meyer 1997) through heterotrophic microbial activity (Meyer 1994), principally bacteria in fine benthic organic matter (Ellis, Stanford & Ward, 1998). However, in this study, no direct correlation between organic matter biomass and nutrient uptake was found. This could be due to variation in quality of organic matter between streams due to varying hydrology, geomorphology and disturbance regimes, and as such variation in bacterial abundance (Findlay et al. 2002). All streams had higher organic matter than those included in a study in alpine Austria, where FBOM was typically less than 1% during summer (Schütz et al 2001). These sites in northeast Greenland were comparable to open canopy streams from a study in northwest Wyoming where FBOM ranged from 3 – 13% (Johnson & Tank 2009). Streams in Arctic regions overlaying permafrost typically have some of the highest organic matter content compared to streams globally (eg. Dittmar & Kattner

2003; Balcorozyk et al. 2009) although it has been found to be less biodegradable than organic matter in areas of less permafrost (Kawahigashi et al. 2004).

TOC was low in all streams (mean 2.24mg L^{-1}) apart from Aucellaelv (7.76mg L^{-1}) in comparison to streams in other Arctic regions, where an average of between 6.7 and 10.8mg L^{-1} has been reported for streams in the Alaskan tundra (Peterson et al. 1986; Oswood et al. 1989) and between 1.2 and 30mg L^{-1} had been reported for streams in boreal Finland (Kortelainen et al. 2006). Low FBOM, TOC and DOC availability can reduce nutrient uptake rates on a reach-scale due to less heterotrophic uptake associated with organic matter respiration and as such, could have contributed to the low nutrient uptake rates seen in this study. DOC concentration has previously been found to be the main driver of nutrient uptake in streams in more temperate regions (Rodríguez-Cardona et al. 2016) and can be seen to be so in the case of Palnatokeelv in this study. The ratio of C:N of stream organic matter may affect N retention due to linkages in the N and C biogeochemical cycles (Dodds et al. 2004). The implications of DOC concentration on nutrient uptake dynamics highlights the need for future studies in Arctic streams to understand the impact of carbon releases from thawing permafrost on stream nutrient dynamics.

5.4.3 Summary and implications

The streams in this study displayed both N and P limitation, whilst streams in Svalbard and Siberia proved to be primarily N limited (Blaen et al. 2014; Schade et al. 2016). The reach-scale P limitation in Greenland seems to be primarily driven by heterotrophic uptake while the autotrophic biofilm production is mainly N limited. Low nutrient uptake rates in these streams are thought to be due to low water temperature resulting in low moss and algal densities and activities, combined with low nutrient concentration and DOC concentration to facilitate uptake. Although results are limited, DOC additions were shown to substantially increase N uptake. As heterotrophic processes are controlled by a combination of water temperature, dissolved nutrients, organic substrate availability, and both the quality and quantity of organic carbon (Tank & Webster 1998), a combination of environmental variables need to be taken into consideration when considering future nutrient dynamics in Arctic streams in a changing climate.

Increased nutrient and DOC concentration in streams, as predicted with a changing climate, can impact the whole ecosystem, increasing algal growth and bacterial activity, converting the main carbon source from allochthonous to autochthonous and shifting metabolism from heterotrophic to autotrophic (Peterson et al. 1985). However, the negative impact of high suspended sediment concentration on stream biota associated with decreased channel stability leads to large uncertainty as to future stream nutrient cycling in these systems.

This research provides the first insights into stream nutrient dynamics in northeast Greenland streams during peak snowmelt in early summer. Although there is high variation in climatological conditions both throughout the summer season and between years creating spatial and temporal variation on in-stream processes, this study can be used in the growing body of literature on Arctic stream nutrient cycling dynamics (Wollheim et al. 2001; Blaen et al. 2014; Diemer et al. 2015; Schade et al. 2016) to build an understanding that spans the entire Arctic region over a large temporal scale. The findings can be built upon in future in-depth studies into northeast Greenland stream nutrient cycling, as well as to gain insights into how a changing climate could impact these systems.

A warming climate is expected to increase active layer depth, releasing previously unavailable nutrients into streams along with labile DOC (O'Donell et al. 2010). Our results indicate these nutrient inputs, coupled with higher water temperature, could increase biological activity in Arctic streams, enhancing nutrient uptake and retention. This increased activity will influence nutrient processing in the future and alter nutrient export to downstream regions (Blaen et al. 2014; Schade et al. 2016). However, further investigation is needed into the role of physical sorption compared to biological uptake in these streams, and into the predicted increases in suspended sediment concentration and the possible negative consequences this could have on algal communities. As well as this, given the importance of the ratio C:N in organic matter for nutrient retention (Dodds et al. 2004), further studies to determine the importance of DOC for nutrient uptake in the region, as well as the proportions of DOC and nutrient release from thawing permafrost are needed to understand if stoichiometry will be maintained, and how nutrient uptake will be affected in the future.

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CHAPTER 6: LONGITUDINAL DISTRIBUTION OF MACROINVERTEBRATES IN SNOWMELT STREAMS IN NORTEAST GREENLAND: UNDERSTANDING BIOPHYSICAL CONTROLS

Abstract

In a changing climate, Arctic streams are expected to show more influence from snowmelt, rainfall and groundwater, and less domination from glacial meltwater sources. Snowmelt streams are characteristic features of Arctic ecosystems, yet our current understanding of longitudinal patterns in benthic macroinvertebrate assemblages in these systems is limited when compared to glacier-fed systems. This study characterised longitudinal patterns of macroinvertebrate communities in snowmelt streams in northeast Greenland to provide novel insights into Arctic stream communities as dominant water sources shift with climate change. Benthic macroinvertebrates and environmental variables were sampled at three sites along five streams. Taxa diversity, evenness and abundance were expected to increase with distance from the stream source due to enhanced channel stability and warmer water temperature. This expectation for diversity and evenness was found in two streams, but abundance was up to 10 times higher at the upstream sites compared to downstream, where biofilm biomass and ionic load were also highest. Here communities were largely dominated by the genus *Eukiefferiella* (Chironomidae). In the other three streams, no clear pattern in longitudinal macroinvertebrate community composition was evident due to low channel stability along the entire stream length. This study highlights the considerable variation in macroinvertebrate zonal distribution between snowmelt streams in northeast Greenland. A change towards more snowmelt-dominated streams in the Arctic could lead to shifts in the longitudinal organisation of macroinvertebrate community assemblages and the dominant species as a function of channel stability characteristics.

6.1 Introduction

Over the past 100 years, climate change has had a major impact on Arctic regions, with air temperature rise three times higher than the global average (2.9˚C compared to 0.8˚C respectively) (Comiso & Hall 2014, Overland et al. 2015). Winter air temperature is predicted to further increase by 18˚C by the end of the century in northeast Greenland (Stendel et al. 2008) and with predicted increases in snowfall and rainfall, and decreased permafrost extent (Dyurgerov & Meier 2000; White et al. 2007; Foster et al. 2008; Stendel et al. 2008) these changes are expected to significantly influence Arctic freshwater ecosystems. Both hydrology and thermal regimes (van Vliet et al. 2013) will be changed with effects on stream communities (Blaen et al. 2014; Chin et al. 2016). High Arctic streams are typically extreme habitats (Wharton et al. 2002) characterized by low water temperature and high turbidity supporting specialized taxa able to tolerate these conditions, as observed in alpine regions (Snook & Milner 2001). Glaciers are principal water sources for Arctic streams as they are for alpine streams (Brown et al. 2003) but because of the retreat of glaciers across the region due to climate change, Arctic streams are expected to become less characterised by glacial runoff and snow will become the dominant meltwater source, along with increased rainfall and groundwater inputs, as predicted for alpine streams (Hannah et al. 2007). This shift in water source will potentially alter stream physicochemical habitat. Given that macroinvertebrate species have evolved specific adaptations and survival strategies (Danks 1971; Danks and Oliver 1972, Danks 1990; Danks et al. 1994; Danks 2004) to tolerate the harsh environmental conditions found in Arctic streams (including low water temperature, low channel stability, and limited food availability), changes in dominant stream water source are predicted to change macroinvertebrate community assemblages (Prowse et al. 2006; Anisimov et al. 2007; Milner et al. 2009; Blaen et al. 2014).

The Milner & Petts conceptual glacier-fed streams model (Milner & Petts 1994; Milner et al. 2001) was devised to predict longitudinal changes in macroinvertebrate communities downstream of a glacial source as a function of a changing physicochemical environment.

The model states that glacier-fed streams have particularly deterministic physicochemical variables and macroinvertebrate assemblages in their headwaters that change with increasing distance from the glacier snout. This change allows for predictions to be made as to macroinvertebrate community composition given that some macroinvertebrate species are restricted to specific niches determined by certain environmental variables (Milner & Petts 1994; Lencioni and Rossaro 2005; Niedrist & Füreder 2016). The glacier-fed model characterised the primary environmental variables shaping macroinvertebrate communities along the length of a glacial stream to be downstream changes in; (1) maximum water temperature; and (2) channel disturbance regime where water becomes increasingly warm and stream channel becomes increasingly stable with distance from the source (Milner & Petts, 1994, Milner et al. 2001). As macroinvertebrates develop adaptations to specific environmental conditions, stream reaches that undergo high levels of disturbance are expected to have low species richness characterized by a few high disturbance-tolerant species (Townsend, Scarsbrook and Duledéc, 1997; Lods-Crozet et al. 2001). Milner & Petts (1994) state that the Chironomidae subfamily Diamesinae will often be the only taxon located near the glacial snout in the harshest of environmental conditions, and will be found further downstream jointly with Orthocladiinae before being replaced by other taxa, when species diversity increases. Since its publication, the model has been tested extensively in different glacial environments. Whilst deviations have been noted due to unique situations and local biogeography, there have been many similarities found globally in glacial streams that match the predictions of the Milner and Petts model (Gíslason et al. 2001; Maioli & Lencioni 2001; Milner et al. 2001; Lods-Crozet et al. 2001; Hieber et al. 2005; Lods-Crozet et al. 2007; Finn et al. 2010; Jacobsen et al. 2010; Kuhn et al. 2011; Hamerlik & Jacobsen 2012; Jacobsen et al. 2014).

Compared with glacier-fed streams, our understanding of longitudinal macroinvertebrate community changes in snowmelt streams is not extensive and it is uncertain whether models such as the Milner & Petts model (1994) can be applied to these streams dominated by this water source. Snowmelt streams are characterised by having a wider water temperature range and marked diurnal variation, with maximum temperatures reaching 10°C. The typical definition of snowmelt streams is that they generally have low turbidity, apart from during peak snowmelt, and have higher channel stability than glacial melt streams (Milner & Petts 1994; Ward, 1994; Brown et al. 2003). This variability in habitat conditions can make snowmelt streams a challenging environment for macroinvertebrates. Longitudinal patterns in macroinvertebrate communities in glacial streams are deterministic due to the downstream decrease in glacial influence. Snowmelt streams are not so predictable (Ward 1994) because the presence of snowmelt inputs along the length of the stream act as localised modifiers of physicochemical habitat. With the likely increase in snowmelt-fed streams in a warmer Arctic, it is vital we build a greater understanding of longitudinal changes on these systems.

To fill this research gap, we investigated longitudinal patterns in macroinvertebrate community composition in five snowmelt streams in northeast Greenland. Limited research has been conducted on Greenlandic stream ecology (but see Friberg et al. 2001 and González-Bergonzoni et al. 2014 for studies from the west coast), and it is known to have a limited diversity of aquatic insects due to its geographical isolation and short time since deglaciation for establishment (Böcher et al. 2015). Our aim was to understand the longitudinal distribution of macroinvertebrates in snowmelt streams in northeast Greenland and their relation to environmental controls. The objectives of the study were to: (1) explore changes in macroinvertebrate taxa richness, diversity and abundance with increasing distance from snowmelt sources in relation to environmental variables; (2) identify indicator taxa for specific habitats conditions, and; (3) to compare changes with the glacier-fed rivers model to see if there are predictable patterns.

Given the harsh environmental conditions of snowmelt streams, we hypothesize that macroinvertebrate community assemblages in snowmelt streams will follow the general trend of the model for glacial streams (Milner et al. 2001), with higher taxa diversity, abundance, richness and evenness at sites furthest from the snowmelt source, where environmental conditions are more favourable.

6.2 Methods

6.2.1 Study area

The five streams studied were headwater streams in close proximity to the Zackenberg research station (74º28’ N, 20º34’ W) located within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 6.1). The drainage basin is not connected to the Greenland ice sheet, which is at approximately 60km distance. Altitude in the region varies between sea level and 1450m a.s.l. and the low lands are characterised by wide valleys created through glacial erosion (Mernild et al. 2007). The region is characterised by continuous permafrost with active layer depth varying between 0.3 and 0.65m (Christiansen et al. 2008). The underlying geology of the area is sedimentary.

Mean annual air temperature is -9.1˚C with the warmest month being July with a mean air temperature of 5.8˚C. Annual mean precipitation is 261mm falling mainly as snow (Hansen et al. 2008) which is the principal water source for all five streams, however Palnatokeelv and Aucellaelv also receive small glacier meltwater contributions. All streams originate in the mountains Aucellabjerg and Palnatokebjerg from snowpacks of varying sizes. During fieldwork, smaller snowmelt inputs were present along the length of the streams. We sampled three sites (A-C, Figure 6.1) along each of the five study streams, and all fieldwork was undertaken between the 9th and the 14th July 2015. Due to the short field campaign, weather conditions could not be controlled and so some variation was experienced when sampling different sites. Weather conditions were mild and sunny when sampling Kaerelv and Aucellaelv, and cool and cloudy when sampling Graenseelv, Unnamed and Palnatokeelv. In all streams excluding Palnatokeelv, site A was immediately in front of the main snowpack, at the stream source. However due to logistical difficulties it was not possible to reach the source of Palnatokeelv and so site A in this stream was located at a lower longitudinal reach. Images of field sites can be seen in appendix A2

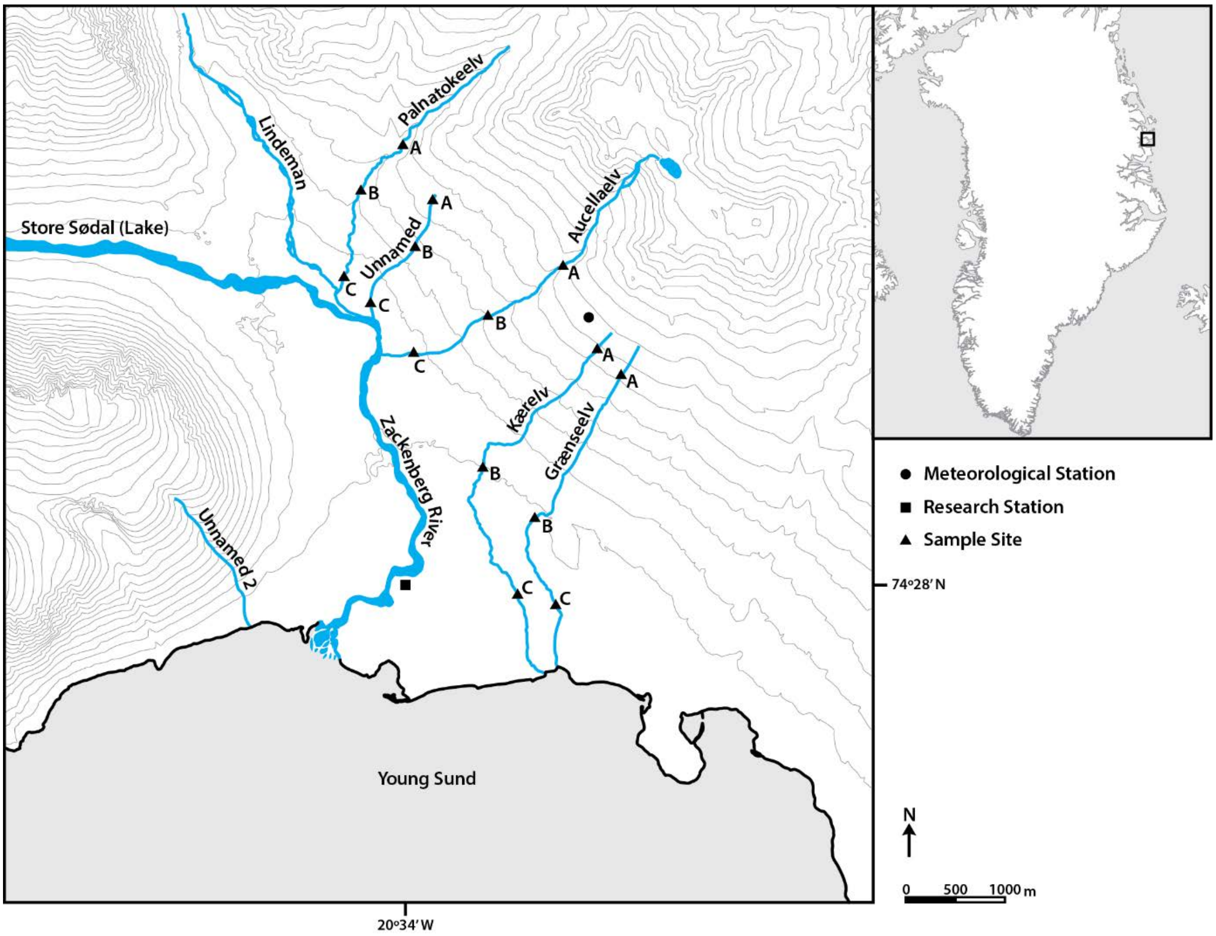


Figure 6.1 Map of the sampled stream systems around the Zackenberg research station with sites A, B and C.

Note: The large snowpack above Aucellaelv covered a large proportion of the upper reaches of the stream during the field campaign, as such, in the map the top sampling site appears far from the stream source, however it was located directly below the main snowpack.

6.2.2 Environmental variables

To characterise hydrological regimes and to verify change in environmental conditions along the stream continuum, physicochemical variables were measured at the same time as macroinvertebrate sampling occurred. Water temperature, conductivity and pH were measured using a waterproof HI-98129 Pocket EC/TDS and pH Tester (Hanna). Dissolved oxygen was measured using a YSI ProODO Optical Dissolved Oxygen meter. Discharge was calculated using the velocity-area method with a flow meter (µP-TAD Höntzsch instruments Germany). Water samples were collected to analyse for major ions and nutrients. NH_4^+, NO_3^-, and PO_4^{3-} were analysed using the hypochlorite, cadmium reduction, and ascorbic acid methods, respectively, on a Lachat QuikChem flow injection analyzer (Lachat Instruments, APC Bioscientific Limited, England; APHA 2012) and major ions were analysed on a ICP-MS (PerkinElmer Instruments, Optima 2000 DV). The Pfankuch Index was calculated for each site to determine channel stability (Pfankuch 1975) using all three components of the index (upper banks, lower banks and stream bed), where higher Pfankuch Index values correspond to lower channel stability. Suspended sediment samples were collected manually only at downstream sites (site C). Samples were filtered onto pre-weighed GF/F filter papers, dried at 60˚C for 48 hours and then re-weighed. In order to measure stream bed sediment size (D_{50}), 100 randomly selected stones or pebbles were measured along their widest section (B axis).

Chlorophyll *a* (Chl *a*) was measured as a proxy for benthic algae biomass. Five stone samples (>6cm) were collected from each site. Biofilm was removed from the stones using a toothbrush and was collected on a Whatman GF/C filter paper and frozen until analysis. The filter papers were then submerged in 96% ethanol and absorbance was measured at 665 and 750nm on a spectrophotometer (UV 1700 Spectrophotometer, Shimadzu, Japan). Chl *a* biomass was calculated as:

$$\frac{Chl\ a = (Abs_{665} - Abs_{750}) * E}{83.4 * A * 10^{-4}}$$

Where E is volume of ethanol (ml), 83.4 is the absorption of Chl *a* in ethanol, A is the sample area (cm^2) and 10^{-4} is the conversion factor from cm^2 to m^2.

6.2.3 Benthic macroinvertebrate sampling

Five replicate macroinvertebrate samples were collected randomly within a reach of approximately 20m using a Surber sampler (0.1 m^2 300-µm mesh size) at each site. Samples were preserved in 90% ethanol in the field and stored in Whirlpak bags until identification. In the laboratory, samples were rinsed through a 200µm sieve and sorted under 10 x magnification. Subsampling was carried out on samples from Kaerelv site A and Graenseelv site A, which supported the highest densities of Chironomidae. Chironomids with dark head capsules were immersed in 10% potassium hydroxide (KOH) solution on a hot plate at 60°C, for 15 minutes to lighten the head capsule and to make characteristic features easier to see. They were then mounted on slides using Dimethyl Hydantoin Formaldehyde (Steedman 1958) (DMFH) mountant. Chironomidae were identified to species-group or type using the following keys; Brooks *et al.* (2007), Cranston (1982), Ferrington & Sæther (2011), Lindegaard (2015) and Wiederholm (1983). Oligochaeta were identified only to subclass, Collembola to order, and other taxa were identified to family or subfamily level using the keys Nilsson (1997) and Dobson (2013). Appendix A3 provides a taxa list and A4 provides a dichotomous key to the identification of chironomids.

6.2.4 Data analysis

In order to visualise similarities and dissimilarities between sites, a non-metric multidimensional scaling (NMDS) analysis was compiled with the Bray Curtis dissimilarity coefficient. Macroinvertebrate data was square root transformed due to the small proportion of large values distorting distribution. Log10 transformed environmental variables were fitted to the ordination after 999 permutations and significant variables were plotted in the ordination space. To describe downstream changes in community composition, Bray-Curtis dissimilarity was calculated on log transformed data. One-way ANOVA was used to determine significant differences in community measurements between the three sites for each stream. Spearman's Rank correlation coefficients were used to determine the correlation between different community measurements and the environmental variables determined significant through the NMDS. Spearman's Rank was used due to the small size of the data set and potential for non-linear relationships (Zar 2010). Cluster analysis was calculated for community similarity between sites in the R environment using the complete method distances of Bray Curtis similarity index and square root transformed data. A two-way cluster analysis between sites and taxa similarity was constructed in the PAST software using paired-group method with Bray Curtis similarity index. Sites were grouped by taxa abundance and taxa were grouped by abundance in different streams. Rare taxa (< 5%) were excluded to avoid large influence on analysis by low abundance taxa (e.g. Niedrist & Füreder 2016). Indicator taxa were determined for specific habitats using the labdsv function in R.

6.3 Results

6.3.1 Environmental conditions

Environmental variables varied spatially along the longitudinal gradient and between streams (Table 6.1). Graenseelv sites B and C were at a lower altitude than sites B and C in other streams, whilst site C of Unnamed was at a higher altitude than site C in other streams. Discharge and water temperature increased downstream except in Aucellaelv. No marked longitudinal patterns in electrical conductivity were evident but was notably higher in Aucellaelv (mean:89.3µS ± 3.40 n=3) compared to all other streams (mean varies between 23.67µS ± 1.7 and 27.33µS ± 4.11 n=3). Channel stability was highest at downstream sites in Kaerelv and Graenseelv with the highest channel stability recorded at Kaerelv B (Pfankuch Index: 70). No defined pattern in channel stability with distance from the source was found in the other three streams. Channel stability was lower in Unnamed, Palnatokeelv and Aucellaelv where all sites scored between 111 and 124 (excluding Unnamed site B which scored 85), and displayed a high degree of channel mobility. Although suspended sediment concentration was only measured at the lower reaches of each stream, marked differences existed between streams, with Kaerelv, Graenseelv and Unnamed having low concentrations (0.5 - 7.3mg L^{-1}) compared to Palnatokeelv (96mg L^{-1}) and Aucellaelv (1120mg L^{-1}).

Stream bed substrate decreased in size with distance from the source in all streams except Unnamed, where lowest size was situated at the middle sampling site. Biofilm biomass was highly variable. Unnamed and Palnatokeelv showed increasing biomass with distance from the source, where as Kaerelv and Graenseelv showed exceptionally high biofilm biomass at upstream sites that gradually decreased with increasing distance downstream (Table 6.1).

Si concentration was highest in Kaerelv and Graenseelv compared to Unnamed, Palnatokeelv and Aucellaelv and tended to be highest at upstream sites, whilst NO_3^- was lowest in Kaerelv, Graenseelv and Unnamed. PO_4^{3-} concentration decreased with increasing distance from the water source but NH_4^+ concentration showed no pattern (Table 6.2).

Table 6.1. Stream physicochemical properties in three sites in five study streams in Zackenberg area in Northeast Greenland.

Stream	Site	Elevation	Approximate distance from site A	Pfankuch Index	pH	Water temperature	Conductivity	DO	Discharge	Suspended sediment	Sediment D_{50}	Chl *a*
		m.a.s.l	m			°C	µs cm^{-1}	%	L s^{-1}	mg L^{-1}	mm	µg m^2
Kaerelv	A	179	0	93	7.0	2.7	26	82.4	190	-	113.8	8241.8
	B	102	1560	70	6.9	6.3	36	92.0	235	-	71.1	3172.7
	C	47	3040	74	7.0	9.4	36	76.5	316	5.1	51.2	392.7
Graenseelv	A	125	0	104	7.4	2.3	32	79.1	177	-	196.5	3096.4
	B	46	1340	83	7.2	3.4	34	81.2	186	-	115.4	1301.6
	C	19	2570	78	7.1	4.4	32	78.0	199	7.3	33.9	198.5
Unnamed	A	193	0	116	7.6	2.8	38	79.4	69	-	87.5	267.8
	B	136	500	85	7.2	2.2	32	79.9	68	-	76.0	266.4
	C	113	1234	113	7.0	2.3	42	88.0	376	0.5	90.3	504.0
	A	137	0	116	7.6	3.1	23	78.7	-	-	246.1	234.2

Palnatokeelv	B	124	707	124	7.3	4.2	22	74.5	-	-	151.6	562.9
	C	56	1429	114	7.2	5.8	26	77.8	788	96.3	100.7	544.6
Aucellaelv	A	185	0	119	7.4	2.6	86	74.1	631	-	193.2	134.4
	B	101	881	111	7.2	4.0	94	73.8	976	-	156.5	341.2
	C	68	1678	116	7.0	5.3	88	75.1	646	1120.3	96.5	289.9

Table 6.2. Water chemistry data in three sites in five study streams in Zackenberg area in Northeast Greenland.

Stream	Site	Si	NH_4^+	NO_3^-	PO_4^{3-}
		MgL^{-1}	$\mu g\ L^{-1}$	$\mu g\ L^{-1}$	$\mu g\ L^{-1}$
Kaerelv	A	1.47	11	19	7
	B	1.17	30	19	7
	C	1.28	15	6	3
Graenseelv	A	1.57	18	18	7
	B	1.35	11	9	3
	C	1.42	55	3	3
Unnamed	A	1.01	43	8	4
	B	0.72	11	5	2
	C	0.95	13	9	3
Palnatokeelv	A	1.14	48	49	9
	B	1.19	21	22	5
	C	0.95	19	43	3
Aucellaev	A	1.02	20	31	11
	B	0.94	15	37	4
	C	0.80	19	27	5

6.3.2 Macroinvertebrate community assemblages

In total, 3,103 individuals were identified (37 taxa) of which 94 % were Chironomidae, encompassing 29 taxa. Eight taxa were found only at sites B and C, whilst only one taxon was found exclusively at the uppermost site A (*Chaetocladius dentiforceps-type*) (see appendix A3 for taxa list).

Both the NMDS and the cluster analysis divided the study sites into three groups (Figure 6.2; Figure 6.3). The first group consisted of all Palnatokeelv and Aucellaelv sites along with Unnamed site C. This group was characterised by low channel stability and high nutrient concentration (Table 6.3), although this was variable within the group with upstream sites having lowest channel stability and highest nutrient concentration. Macroinvertebrate abundance was low in these streams, and Aucellaelv and Palnatokeelv displayed no clear patterns within streams in abundance, evenness, diversity or taxa richness (Figure 6.4). No indicator taxa were identified for this group although the genera *Diamesa* and *Eukiefferiella* were the most common taxa (Figure 6.5). Group 2 consisted of Kaerelv and Graenseelv upstream sites and were characterised by high Chl *a* and high Si concentrations (Figure 6.2 and 6.3). Macroinvertebrate abundance was exceptionally high at these sites but evenness and diversity were low (Figure 6.4). Indicator taxa were the genus *Eukiefferiella* (indicator value: 82%, p= 0.009) and *Orthocladius oliveri*-type (indicator value: 68%, p=0.014) (Figure 6.5 and Table 6.4). *Eukiefferiella* were found in very large numbers at these two sites (3713 m^2 in Kaerelv and 3316 m^2 in Graenseelv) and were found to be highly correlated with Chl *a* density (Spearman rank correlation: $rs = 0.61$, $n = 15$, $p = 0.02$). The third group consisted of sites B and C in Kaerelv and Graneseelv and sites A and B in Unnamed (Figure 6.2 and 6.3). This group was characterised by high channel stability and low Chl *a* concentration. Sites in Kaerelv and Graenseelv in this group had the highest macroinvertebrate evenness, diversity and taxa richness of all the streams (Figure 6.4). One indicator taxa was identified for this group and that was the species group *Metriocnemus eurynotus* (indicator value: 60%, p=0.047).

Longitudinal patterns were visible in Kaerelv, Graenseelv and to a lesser extent Unnamed as can be seen by the NMDS and dendrograms (Figures 6.2; 6.3; 6.5). In Unnamed, abundance was much lower at site A compared to the respective sites in Kaerelv and Graenselv, but decreased gradually between the three sites (Figure 6.4a). In Kaerelv, Graenseelv and

Unnamed, evenness, diversity and richness were lowest at site A compared to sites B and C (Figure 6.4b; 6.4c; 6.4d).

In Kaerelv and Graenseelv, site A was significantly different from sites B and C for density, evenness and diversity. Evenness was significantly different in sites A and B of Unnamed compared to site C (Table 6.5). Kaerelv and Graenseelv showed large differences in terms of the community composition between sites A and B, whilst sites B and C were more similar. This is in contrast to Unnamed, Palnatokeelv and Aucellaelv where sites B-C show the largest variation (Figure 6.6).

Channel stability and Si concentration were found to be the most significant environmental predictors for Kaerelv and Graenseelv macroinvertebrate community composition, where there is a negative relationship with evenness, Shannon diversity and taxa richness (Table 6.6). Due to the method used to measure channel stability, these results signify an increase in stability leading to an increase in evenness, diversity and richness. However, when all streams were tested together, Si concentration was shown to be significantly correlated with density (Spearman rank correlation $rs = 0.80$, $n = 15$, $p = 0.0004$) and taxa richness (Spearman rank correlation $rs = 0.70$, $n = 15$, $p = 0.0037$) and for channel stability to be significantly correlated with taxa richness (Spearman rank correlation $rs = -0.66$, $n = 15$, $p = 0.008$) (Table 6.6).

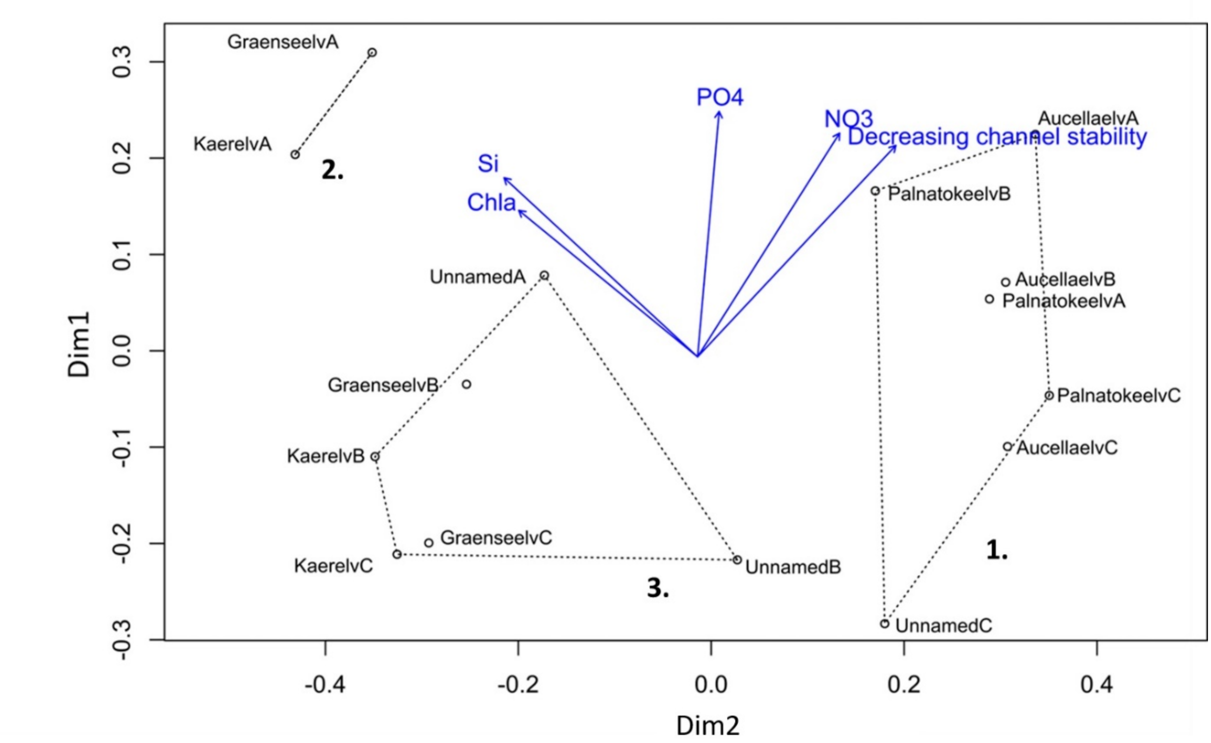


Figure 6.2 NMDS of sites using abundance of macroinvertebrate taxa. Dimensions: 2, stress: 0.113. Group 1-3 are marked and corresponds to groups 1-3 in Figure 3. Sites were always sampled from upstream (site A) to downstream (site C)

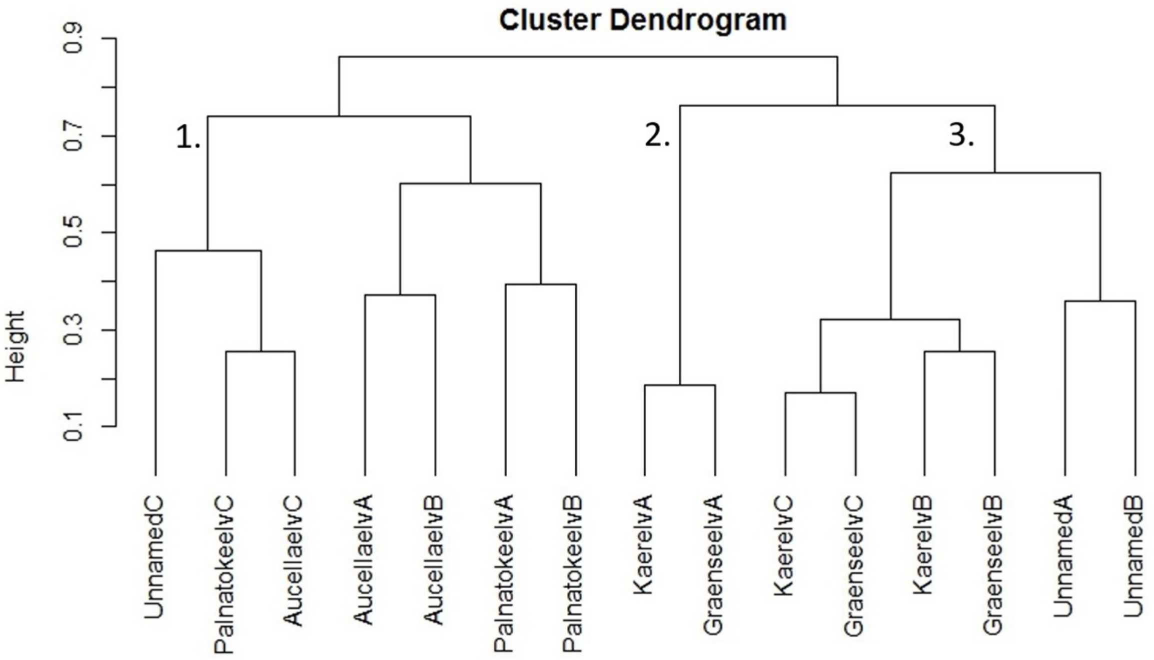


Figure 6.3 Dendrogram based on abundance of macroinvertebrate taxa. Cophenetic correlation: 0.814. Group 1-3 are marked and corresponds to group 1-3 in Figure 2

Table 6.3. Significant correlations for environmental variables in the ordination space.

Variable	**R^2**	***p***
Channel stability	0.77	0.001
Chl *a*	0.49	0.019
Si	0.64	0.002
NO_3^-	0.65	0.001
PO_4^{3-}	0.56	0.018

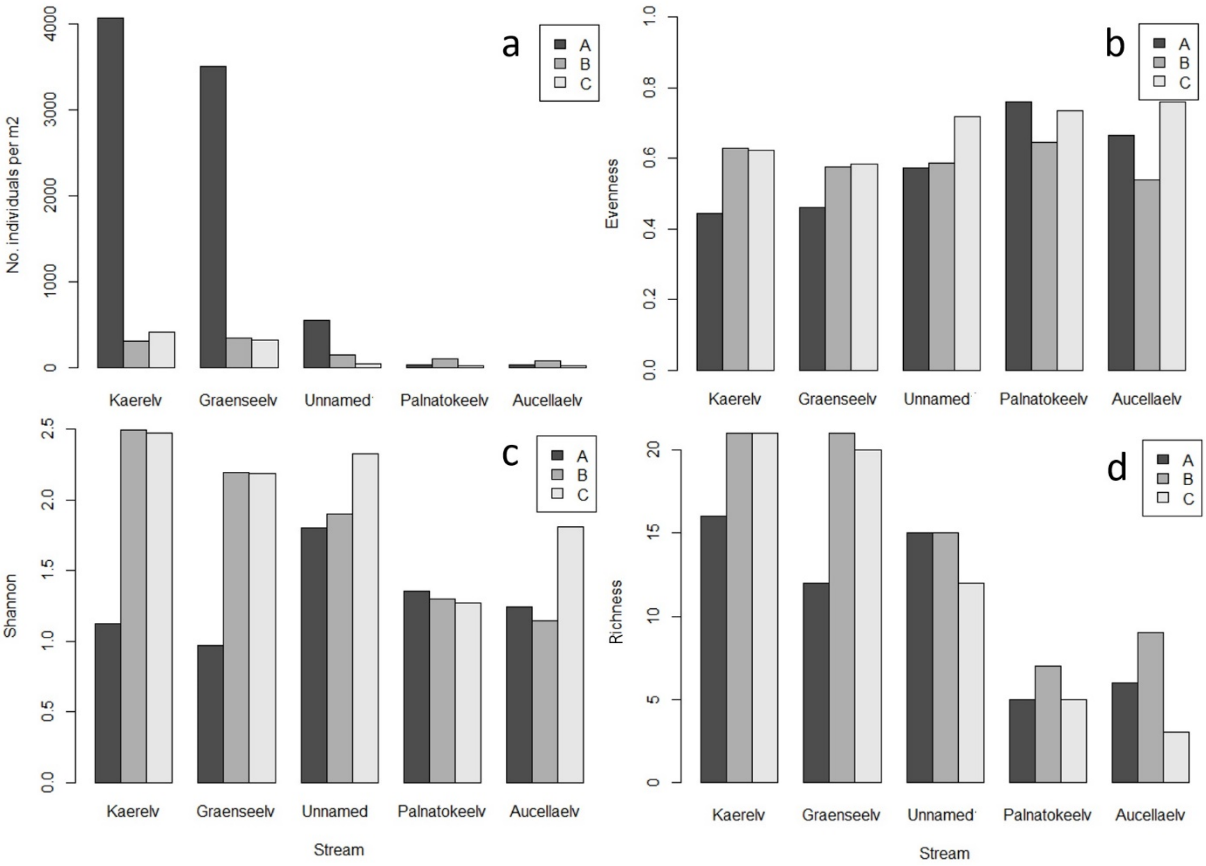
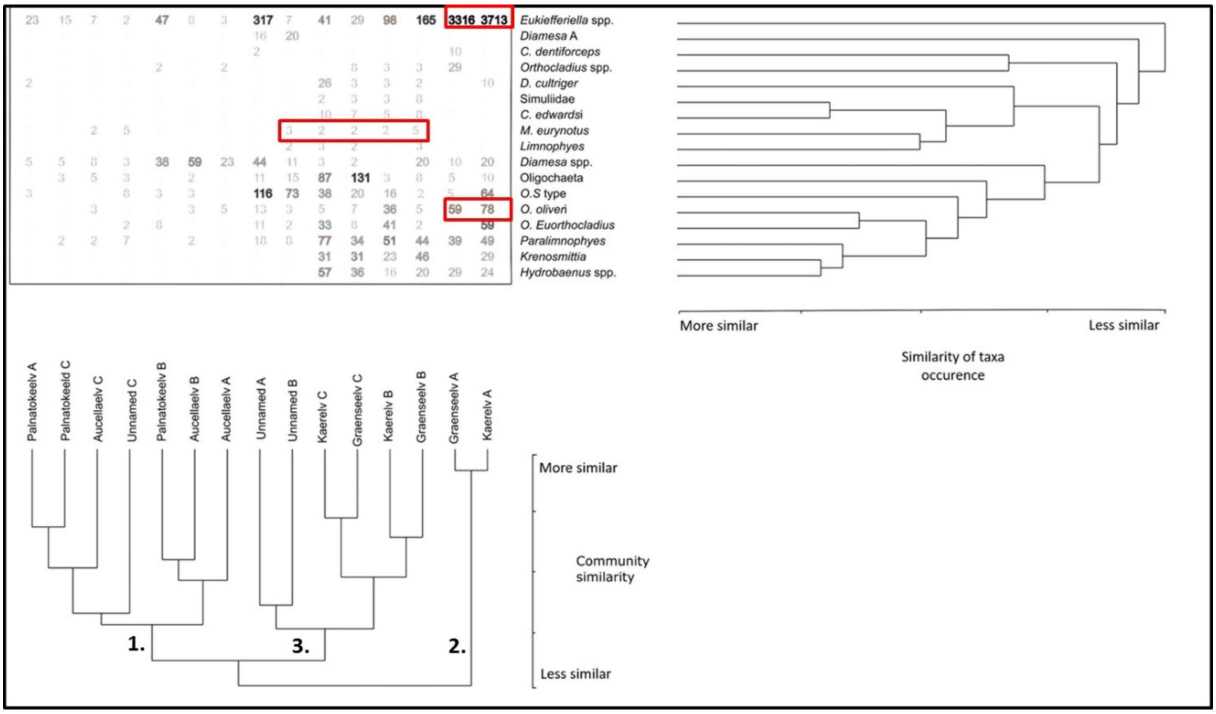


Figure 6.4 Macroinvertebrate community composition measurements at stream sites A, B and C: a) Macroinvertebrate abundance, b) Evenness, c) Shannon’s Diversity, d) Richness



Palnatokeelv A	Palnatokeeld C	Aucellaelv C	Unnamed C	Palnatokeelv B	Aucellaelv B	Aucellaelv A	Unnamed A	Unnamed B	Kaerelv C	Graenseelv C	Kaerelv B	Graenseelv B	Graenseelv A	Kaerelv A	
23	15	7	2	47	8	3	317	7	41	29	98	165	3316	3713	*Eukiefferiella* spp.
							16	20							*Diamesa* A
							2						10		*C. dentiforceps*
				2		2				8	3	3	29		*Orthocladius* spp.
2									26	3	3	2		10	*D. cultriger*
									2	3	3	8			Simuliidae
									10	7	5	8			*C. edwardsi*
		2	5					3	2	2	2	5			*M. eurynotus*
								2	3	2		3			*Limnophyes*
5	5	8	3	38	59	23	44	11	3	2		20	10	20	*Diamesa* spp.
	3	5	3		2		11	15	87	131	3	8	5	10	Oligochaeta
3			8	3	3		116	73	38	20	16	2	5	64	*O.S* type
		3			3	5	13	3	5	7	36	5	59	78	*O. oliveri*
			2	8			11	2	33	8	41	2		59	*O. Euorthocladius*
	2	2	7		2		18	8	77	34	51	44	39	49	*Paralimnophyes*
									31	31	23	46		29	*Krenosmittia*
									57	36	16	20	29	24	*Hydrobaenus* spp.

Figure 6.5 Two-way cluster analysis of most abundant taxa (top right) and the 15 stream sites (bottom). Data matrix gives taxa abundance (individuals m^2) at each site

Table 6.4. Indicator taxa for different habitats

Cluster	Principal streams	Habitat type	Species group	Indicator value (%)	*P* value
2	Kaerelv Graenseelv	Upstream sites. Close proximity to snowpack source. Low channel stability. Low suspended sediment.	*Eukiefferiella*	82	0.009
2			*Orthocladius oliveri*	68	0.014
3	Kaerelv Graenseelv	Downstream sites. Stable channels and warmer water temperatures.	*Metriocnemus eurynotus*	60	0.047

Table 6.5. One-way ANOVA results comparing longitudinal sites. All significant sites, site A is different to sites B and C, however *= significant difference between sites A and B with site C.

Stream	Density	Evenness	Shannon	Richness
Kaerelv	**F(1,2)=1575.9, *p*=0.016**	**F(1,2)=1697.2, *p*=0.015**	**F(1,2)=6144.519, *p*=0.008**	-
Graenseelv	**F(1,2)=41621.95, *p*=0.003**	**F(1,2)= 317.12, *p*=0.036**	**F(1,2)=45226.5, *p*=0.003**	-
Unnamed	-	**F(1,2) =158.4, *p*=0.050***	-	-
Palnatokeelv	-	-	-	-
Aucellaelv	-	-	-	-

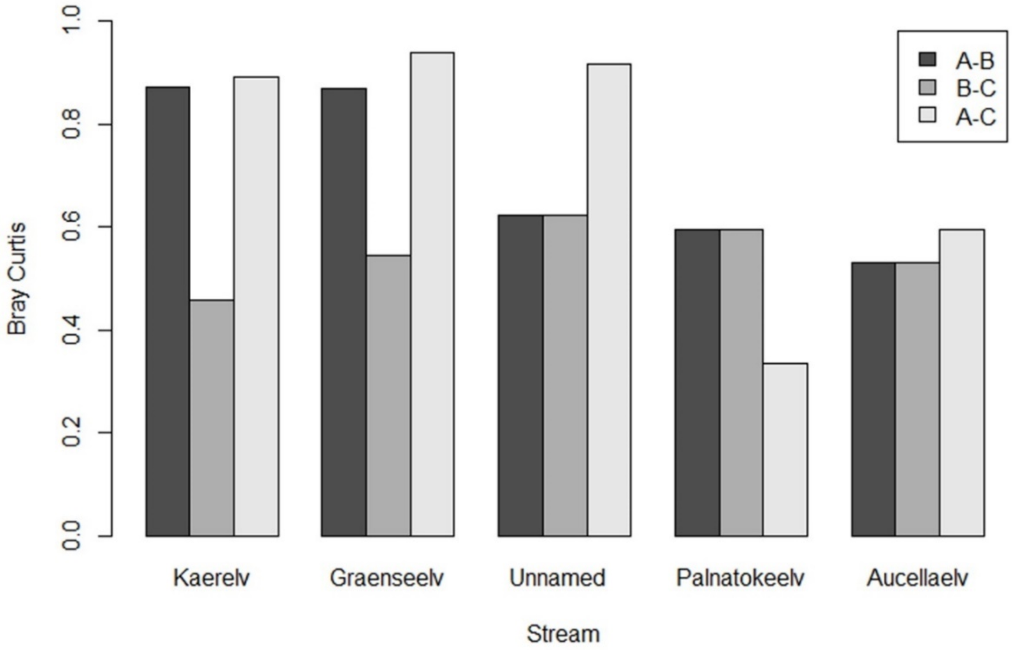


Figure 6.6 Bray Curtis dissimilarity between sites A and B, sites B and C and sites A and C

Table 6.6. Spearman’s rank correlation coefficients for community measurements with significant environmental variables.

	Kaerelv & Graenseelv								All streams							
	Density		Evenness		Shannon		Richness		Density		Evenness		Shannon		Richness	
	rs	*p*	*rs*	*p*	*rs*	*p*	*rs*	*p*	*rs*	*p*	*rs*	*p*	*rs*	*p*	*rs*	*p*
Channel stability	0.77	**0.103**	**-0.93**	**0.008**	**-0.94**	**0.017**	**-0.81**	**0.046**	-0.48	0.073	0.43	0.107	-0.34	**0.220**	**-0.66**	**0.008**
Chl *a*	0.37	0.497	-0.32	0.538	-0.14	0.803	-0.27	0.600	0.39	0.149	-0.33	0.223	0.06	0.822	0.42	0.117
Si	0.71	**0.136**	**-0.93**	**0.008**	**-1**	**0.0028**	**-0.94**	**0.005**	**0.80**	0.0004	-0.48	0.068	0.02	**0.929**	**0.70**	**0.004**
NO_3^-	0.09	0.919	-0.03	0.957	0.09	0.919	-0.09	0.863	0.80	0.723	0.45	0.093	0.09	0.763	0.16	0.578
PO_4^{3-}	0.20	0.714	-0.41	0.425	-0.31	0.564	-0.52	0.294	0.18	0.511	0.09	0.737	0.34	0.221	0.05	0.859

n=15 for all sites. N=6 for Kaerelv and Graenseelv correlations.

6.4 Discussion

This study provides new insights into the macroinvertebrate community composition dynamics in snowmelt streams in northeast Greenland, which is vital as snow becomes an increasingly important water source for streams in the Arctic as glacial influence declines.

6.4.1 Landscape scale patterns in habitat and macroinvertebrate community assemblages

This study found a marked difference in macroinvertebrate community structure between streams, with Kaerelv and Graenseelv supporting high taxa richness and diversity whereas in Palnatokeelv and Aucellaelv these metrics were low, and intermediate in Unnamed. Unlike the typical definition for snowmelt streams, the streams in this study displayed low water temperature variation between sites, whereas channel stability was highly variable. The low temperature variation between sites was found even though weather conditions varied between the days when samples were collected. As such, the different weather conditions are thought to have minimal impact on the results of this study. Palnatokeelv and Aucellaelv were characterised by very high levels of suspended sediment (96.3 and 1120.3mg L^{-1} respectively), and low channel stability with a high degree of channel mobility along the entire stream length (see chapter 3; Docherty et al. 2017). Despite these two streams having small headwater glaciers located within their catchments, glacial inputs were minimal due to the large snowpacks present and the early field campaign before peak glacier melt. This means they fitted the classification of Brown et al. (2003) as nival streams. Here we propose the low channel stability of Palnatokeelv and Aucellaelv was caused by the larger snowpacks at the stream source leading to large spring floods during the initial melt season destabilising floodplain sediments. Increased nivation processes weathering soils underneath snowpacks and in the surrounding areas of summer snowpack retreat (Christiansen 1998), creating stream sediments during melting and altering the habitat from what is typically defined as a snowmelt stream. The high nutrient load in Palnatokeelv and Aucellaelv is likely to be from in-stream weathering of suspended sediment (Chin et al. 2016). These low stability systems typically support low macroinvertebrate abundance as found in previous research on highly disturbed stream environments (Chin et al. 2016) dominated by the chironomids *Diamesa*, a genus typical of harsh glacial streams, and *Eukiefferiella*.

6.4.2 Longitudinal patterns in habitat and macroinvertebrate community assemblages

Palnatokeelv, Aucellaelv and Unnamed did not show any deterministic longitudinal patterns and proved to be largely unpredictable in terms of their patterns in longitudinal macroinvertebrate community assemblages. For Palnatokeelv, this could be due to the location of the upstream site being a relatively large distance downstream of the source snowpack, making environmental conditions at the upstream site different compared to the other sites studied. Kaerelv and Graenseelv followed the predicted longitudinal patterns of higher diversity and richness at sites downstream from the source, similar to glacier-fed rivers, as well as in environmental conditions, with site A being significantly different from the other two sites (Milner & Petts 1994; Milner et al. 2001; Jacobsen et al. 2014). However, the marked decrease in macroinvertebrate abundance downstream from the water source was not expected as previous research on glacial streams shows macroinvertebrate abundance to increase with distance from the source or for there to be no clear pattern (eg. Milner & Petts 1994; Ward 1994; Gíslason et al. 2001; Blaen et al. 2014). The high abundance of macroinvertebrates was significantly correlated with high biofilm biomass at upstream sites of Kaerelv and Graenseelv. Previous work on these streams suggests N is a main limiting nutrient in these systems and that biofilm biomass increases with N additions (cf. chapter 5) and that diatom growth is determined by Si concentrations (Sabater and Roca 1990). In the majority of our study streams, especially Kaerelv and Graenseelv, Si and NO_3^- concentration was highest at the upstream sites. This was due to discharge being lowest at upstream sites, creating more highly concentrated solutes, as well as the weathering action of snowpacks causing increased Si concentrations, and the preferential elution of ions from snowpacks (Johannssen & Henriksen 1978; Tranter et al. 1987; Helliwell et al. 1998; Brown et al. 2003). This causes larger NO_3^- inputs to the stream, compared to further downstream, through snowmelt runoff (Robinson et al. 2001; Hodson et al. 2002; Brown et al 2003). This led to increased biofilm production and an ample food source for chironomids.

Eukiefferiella brehmi- group was the dominant species group at upstream sites in Kaerelv, Graenseelv and Unnamed. Whilst this is usually classified as a collector-gatherer, feeding on deposited sediment, it has also been described as a scraper, shearing food from the surface of rocks (Tavares-Cromar & Dudley Williams 1997; Armitage et al. 1995). In general, many species of chironomids show flexibility in food resource preference, and as such are able to adapt to food resources available within the local environment (Armitage et al. 1995 and references therein) and the genus *Eukieffereilla* has been described as an opportunistic taxon (Herbst & Cooper 2010). *Eukiefferiella* in these systems typically fills a niche that excludes many other taxa, which are restricted to downstream regions. However, upstream sites in Kaerelv and Graenseelv were characterised by low water temperature and channel stability, which are known to limit primary productivity and macroinvertebrate growth, and to affect the ability of algae and invertebrates to attach to substrate (Milner & Petts 1994; Brown et al. 2003). These habitat characteristics are typical of upstream sites in glacier melt streams that are typically dominated by the genus *Diamesa*. However, *Diamesa* may be restricted to low channel stability habitats as they are competitively excluded from more preferable habitat where other taxa are able to colonise (Flory & Milner 2000). The ionic enrichment at upstream sites characteristic of snowmelt appears to create suitable habitat conditions to support high densities of benthic algae to grow, creating a refugia and supporting large macroinvertebrate abundances, namely of the genus *Eukiefferiella*, which then excludes *Diamesa* from the community assemblage. Other studies have found *Eukiefferiella* in European glacier-fed streams but at further distance from the source, inhabiting unstable channels within 200m of glacial snouts alongside *Diamesa* spp. (Brittain et al. 2001; Gíslason et al. 2001; Lods-Crozet et al. 2001). However, in New Zealand glacial streams where *Diamesa* are absent, *Eukiefferiella* are co-dominant with *Maoridiamesa* in close proximity to the glacier snout along with two *Deleatidium* an ephemeropteran species (Cadbury et al. 2011).

With increasing distance from the source in Kaerelv and Graenseelv, biofilm biomass and macroinvertebrate abundance decreased, however the increase in channel stability led to an increase in macroinvertebrate richness, diversity and community evenness, typical of glacier-fed streams (eg. Milner & Petts 1994; Ward 1994; Gíslason et al. 2001; Blaen et al. 2014). The results follow previous studies on glacial streams, showing water temperature to increase downstream (Milner et al. 2001; Jacobsen et al. 2010; Kuhn et al. 2011; Jacobsen et al. 2014), however as temperature was recorded only by spot tests, we could not determine the importance of this in influencing macroinvertebrate communities. The variation in temperature between sites could also be due to variation in the time of day when measurements were taken. Reductions in NO_3^- and Si associated with decreased meltwater inputs and higher discharge diluting ion concentrations resulted in fewer resources available for biofilm colonisation and so, notably reduced biofilm biomass compared to upstream sites.

However, the increase in channel stability provided a suitable habitat for more diverse macroinvertebrate assemblages to form (Milner & Petts 1994).

6.4.3 Insights to indicator taxa

The three indicator taxa identified in this study represent two different habitat types. *M. eurynotus*-type was characteristic of high stability stream reaches and formed part of a macroinvertebrate community characterised by high taxa richness, diversity and evenness. This finding was in contrast to research by Snook & Milner (2001) where *Metriocnemus* was most commonly found in high-stress habitats. It is possible that the individuals were different species of *Metriocnemus* in the two cases, or it could be a result of chironomid flexibility in feeding preferences, where they are able to adjust to different environmental conditions available. The other two indicator taxa were *Eukiefferiella* and *Orthocladius oliveri-type.* These were characteristic of upstream sites in the stable streams that had low channel stability but high nutrient and biofilm biomass. They showed high levels of stress tolerance in accordance with previous research on the taxa (Kownacki & Zosidze 1980; Gíslason et al. 2001; Lods-Crozet et al. 2001; Cadbury et al. 2011).

6.4.4 Implications of global change

A reduction in glacial cover caused by a warming Arctic, combined with increased snowfall in some regions, will result in streams to become more influenced by snowmelt, as well as rainfall and groundwater, as is also being experienced in alpine regions (Hannah et al. 2007; Kattsov et al. 2007; Stendel et al. 2008; Dankers & Middelkoop 2008; Collins et al. 2013). Because of this, it is vital we have a full understanding of snowmelt stream dynamics, incorporating hydrological processes and ecological community composition, in order to make predictions for how Arctic streams will change in the future. Zackenberg provides an interesting base for research on snowmelt streams due to the low water temperature variability but high variation in channel stability - the two factors identified as being most influential to glacial stream community assemblages - providing a diversity of snowmelt streams that are both characteristic and uncharacteristic in their habitat. With reduced glacial extent and increased snowfall predicted in many areas of the Arctic, testing these findings in other Arctic regions is essential to understand patterns in snowmelt stream geomorphology and physicochemical habitat, and in macroinvertebrate community composition. This will allow us to better predict future changes.

A shift away from glacial streams towards more snowmelt-dominated streams could have two different outcomes for macroinvertebrate community composition along the stream length depending on local snowpack size and local geology. 1) In streams that meet the definition of typical snowmelt streams, higher nutrient inputs are to be expected through ionic enrichment with snowmelt, and increased benthic algae biomass at upstream sites. Macroinvertebrate community composition patterns could remain the same for taxa richness, evenness and diversity, but reverse for abundance with highest abundance at upstream sites, as well as see different species types present in macroinvertebrate communities. This includes the possible local extinction of typical glacial coloniser taxa such as *Diamesa*. Or; 2) low stability snowmelt streams characterised by their large snowpacks and unconsolidated soils could lead to a loss of macroinvertebrate zonation along the stream length, with low abundance and diversity typical, but with taxa composition more similar to glacial streams. Although these streams have high ionic loads due to high weathering rates, the low channel stability prevents nutrient uptake.

The findings from the streams in northeast Greenland, combined with previous research highlighting the unpredictability of snowmelt stream habitat and ecological zonation, draws attention to the considerable variation in macroinvertebrate distribution and community composition in snowmelt streams across northeast Greenland and the Arctic. However, despite these variations, patterns in community composition have been observed in these systems and indicator taxa identified for some of the streams. To improve the quality of these findings, research should be conducted over a longer timespan to represent the zonation patterns during the whole summer season and to capture inter-annual variation.

6.4.5 Future research directions

The large differences between Kaerelv and Graenseelv with Unnamed, Palnatokeelv and Aucellaelv highlights the complexity and diversity in snowmelt stream habitat conditions with snowpack size and local geology influencing stream phyiscochemical habitat. This provides new aspects to consider when defining Arctic and alpine stream types and could be used to build on from the work of Brown et al. (2003) to divide the definition of nival stream systems into two new categories.

In relation to the Milner & Petts model (1994) for glacial streams, this study has found clear differences compared to glacial systems as macroinvertebrate community assemblages are not deterministic in all snowmelt streams as was determined by Ward (1994). Streams with large snowpacks, showing low channel stability and high suspended sediment concentration throughout their lengths, leading to low macroinvertebrate abundance, diversity and taxa richness along their entire lengths. However, the streams in this study that best fit the definition of a typical snowmelt stream had certain characteristics which did fit the Milner &

Petts model, such as increased diversity and taxa richness downstream along with increased channel stability.

The differences in length of streams and the distance between sites in the five streams could influence the results given the site furthest from the source in a short stream will be more influenced by source water conditions than the corresponding site in a longer stream. As such, this should be taken into account and incorporated into future studies.

Future directions of research should include increased taxonomic resolution, ideally through DNA barcoding, to be able to compare between sites on a species level. Replicating this study on snowmelt streams in other Arctic regions would be beneficial and would provide a broader understanding of macroinvertebrate communities in snowmelt streams, as would replicating this study in longer stream systems. To understand temporal changes and to infer how a changing climate could affect these systems, it is necessary to conduct long-term studies over the whole summer period linking stream habitat conditions and macroinvertebrate community composition to local weather conditions. Finally, to gain a full understanding of ecosystem scale processes on a longitudinal scale, it would be useful to study longitudinal nutrient spiralling dynamics and primary productivity within snowmelt streams, allowing us to determine the most biogeochemically active reaches of snowmelt streams.

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CHAPTER 7: SPATIO-TERMPORAL DYNAMICS OF MACROINVERTEBRATE COMMUNITIES IN NORTHEAST GREENLANDIC SNOWMELT STREAMS

Abstract

Future climate change throughout the Arctic is expected to increase channel stability in glacially-influenced streams through reduced contributions from glacial meltwater and increases in groundwater. In contrast, predictions for northeast Greenland of increased precipitation for the next 100 years – including winter snowfall, which with warmer air temperature, is expected to increase the size of spring floods in snowmelt streams. Coupled with increased disturbance through frequent summer rainfall events, nivation processes and permafrost degradation will reduce resistance of channel sediments to erosion and thereby decrease channel stability. Decreased channel stability will impact macroinvertebrate abundance and diversity. Five streams sourced by snowpacks of varying extent were studied over three summer seasons (2013 – 2015) to investigate the potential effect of shift in snowmelt regime on macroinvertebrate communities.

Total abundance and taxa richness were significantly higher in streams with small snowpacks, where the chironomid genus *Hydrobaenus* was the most abundant taxon. Streams with large snowpacks were dominated by the chironomid genus *Diamesa.* Multivariate ordination models and correlation indicated macroinvertebrate communities were significantly influenced by channel stability and bed sediment size. Macroinvertebrate abundance was significantly higher in 2013, following low winter snowfall and associated low meltwater inputs to streams, highlighting interannual variability in macroinvertebrate communities.

A shift towards less stable habitats in snowmelt streams will potentially lead to reduced macroinvertebrate abundance and taxa richness, and local extinction of specialised taxa. Thus, snowmelt-fed streams in northeast Greenland may respond very differently to changing climate compared to streams in parts of the Arctic dominated by glacial meltwater.

7.1 Introduction

Climate change is expected to cause large shifts in Arctic ecosystems (Walsh et al. 2005; Anisimov et al. 2007; Prowse et al. 2009a; Prowse et al. 2009b), with some of the most pronounced changes in northeast Greenland (Stendel et al. 2008). Air temperature in the region is predicted to increase and due to the reduction in regional sea ice extent, local surface evaporation will result in increased precipitation by up to 60%, falling as rain in summer and snow in winter (Stendel et al. 2008; Bintanja & Selten 2014). These changes will shift local climatic conditions from a continental high-Arctic climate towards an increasingly maritime low-Arctic climate with a marked influence on freshwater ecosystems in this region.

Glacial meltwater is currently the principal meltwater source for streams in many regions of the high Arctic. Climate change will lead to reduced extent of glaciers, which although for larger glaciers runoff will initially increase in the near term, will in the long term or for smaller glaciers lead to decreased glacial runoff and groundwater becoming a more dominant water source as the active layer deepens (eg. Hannah et al. 2007; Milner et al. 2009; Blaen et al. 2014). These changes are predicted to increase channel stability and water temperature, leading to increased macroinvertebrate density and alpha diversity (Brown et al. 2007; Lods-Crozet et al. 2007; Milner et al. 2009; Blaen et al. 2014). However, in areas of low glacial cover such as coastal northeast Greenland, the predicted increases in snowfall (Kattsov et al. 2007; Collins et al. 2013) means increased snow meltwater contributions to streams, alongside increased summer rainfall events. These snowmelt inputs to streams will have both a more prolonged impact on streams throughout the summer due to the longer time required for snowpack melting, and also increased inputs to streams during days with high air temperature. The absence of predictable summer glacier melt, as evident in glacially dominated systems increases flow stochasticity with high short-term variability in magnitude and duration (Milner et al. 2017). Snow packs can have a large influence on local geomorphology dependent upon their size through a variety of processes, influencing permafrost thaw by insolating ground from cold air temperature (Westermann et al. 2015); causing large spring floods that destabilise stream bank sediment, and; by triggering a range of nivation processes, such as pronival solifluction, backwall failure and accumulation of alluvial fans and basins (Christiansen 1998), with larger snowpacks potentially having the largest impact. These processes can lead to increased sediment fluxes and solute inputs into stream systems (Christiansen 1998; Moiseenko et al. 2001; Buffem et al. 2007; Kokelj et al. 2013; Malone et al. 2013, Kokelji et al. 2015; Chin et al. 2016) and increase stream channel mobility, thereby overall lowering channel stability. As a result, increased snowfall in northeast Greenland could lead to negative consequences for benthic communities with reduced macroinvertebrate abundance and diversity. This outcome contrasts to general predictions of increased channel stability in glacially dominated Arctic streams in a warmer future due to reduced glacial meltwater contributions. Also, interannual variation in snowfall conditions, as currently seen in the region (Pederson et al. 2016), would combine with increased frequency of heavy summer rainfall events and together could lead to variation in macroinvertebrate community structure between years due to an increase in extreme events, varying habitat conditions and disturbance regimes. Stream studies on increased thermokarst activity in Arctic Canada, indicated that high sediment load from increased channel disturbance can cause decreased macroinvertebrate community complexity in streams (Chin et al. 2016) by reducing habitat availability, altering water chemistry and causing negative physiological impacts such as the clogging of feeding and respiratory organs (Lemly 1982; Jones et al. 2012). However, whilst this has been tested for thermokarst activity, this has not been tested in relation to the overall effect of climate change on snowmelt dominated Arctic streams.

Previous river research in northeast Greenland has largely been restricted to hydrological research on sediment and solute transport dynamics (Ladegaard-Pedersen et al. 2016; Søndergaard et al. 2015; Hasholt et al. 2008; Hasholt & Hagedorn 2000; Rasch et al. 2000) whilst ecological studies in freshwater systems have been principally restricted to lakes and ponds (e.g. Christoffersen et al. 2008). River ecology research in Greenland has been limited to the more accessible southwest coast (Friberg et al. 2001; González-Bergonzoni et al. 2014), thus our understanding of stream ecology along the east coast is negligible. The northeast coast of Greenland is more isolated than the west, and is thought to have reduced macroinvertebrate diversity due to its northern latitude, its recent deglaciation and its biogeographical isolation between the Greenland ice sheet and the ocean where harsh environmental conditions and large distances restrict invertebrate dispersal routes (Böcher et al. 2015). Documenting the species present in this region will provide a vital record to monitor change in stream ecosystems over the coming decades.

Here, we investigate the influence of climate change on stream ecosystems in northeast Greenland by undertaking an analogous study of streams sourced by snowpacks of varying extents, representing different snowpack conditions. The aim of this study was to investigate the influence of disturbance regimes associated with different snowpack conditions on macroinvertebrate community composition. To meet the aim, we tested the following hypotheses: (1) streams sourced from larger snowpacks will have reduced channel stability, (2) streams with lower channel stability will have lower macroinvertebrate taxa richness, diversity and abundance, (3) higher interannual variability in macroinvertebrate community will be related to size of the snowpack. From this, indicator taxa for different stream ecosystems will be determined, and results compared to other areas of Greenland and the wider Arctic in order to explore the implications of climate change for Arctic snowmelt streams.

7.2 Methods

7.2.1 Study site

Five streams were selected for study in close proximity to Zackenberg research station (74º28’ N, 20º34’ W) located within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 7.1). Fieldwork was undertaken between 25 June – 17 July 2013, 1 - 22 July 2014 and 6 – 22 July 2015. The field site was located 70km from the Greenland ice sheet, and was not hydrologically connected to it. Mean annual air temperature is -9.1˚C with July the warmest month with a mean air temperature of 5.8˚C. Annual mean precipitation is 261mm and falls predominantly as snow (Hansen et al. 2008).

Altitude in the region varies between sea level and 1450 m a.s.l. and the lowlands are characterised by a wide valley created through glacial erosion (Mernild et al. 2007). AP Olsen ice cap is within the catchment of Zackenberg river, and a few high-altitude glaciers remain within the area. All sample sites were located on the valley floor, which is characterised by continuous permafrost with an active layer depth varying between 0.3 and 0.65 m (Christiansen et al. 2008). All streams were overlying a combination of cretaceous and tertiary sandstones, with upper reaches overlying conglomerates, black shale and basalts. The valley floor and low altitude slopes were characterised by a layer of loose soils that were vulnerable to erosion, even though soils were well developed in areas (Hasholt & Hagedorn 2000; Mernild et al. 2007). Lowland vegetation in this region comprised *Cassiope tetragona* heaths with *Salix arctica*, and grasslands, fens and snowbeds were characteristic of this area (Bay 1998).

Snow was the principal water source for all study streams. Aucellaelv and Palnatokeelv also received small glacier meltwater contributions, but this was minimal during the field period and they would be classed as nival streams as defined by Brown et al. (2003). Streams are sourced from snowpacks of varying sizes. Aucellaelv (N74.49 4062° -20.575144°) and Palnatokeelv (N74.510095° -20.602894°) were characterised by large, perennial snowpacks, the principal snowpack for Unnamed (N74.506048° -20.585924°) was small, however it also received inputs from larger perennial sources, whilst smaller, seasonal snowpacks that typically melted by the end of the summer season were found at Kærlev (N74.471039° -20.519908°) and Grænseelv (N74.468211° -20.497409°).

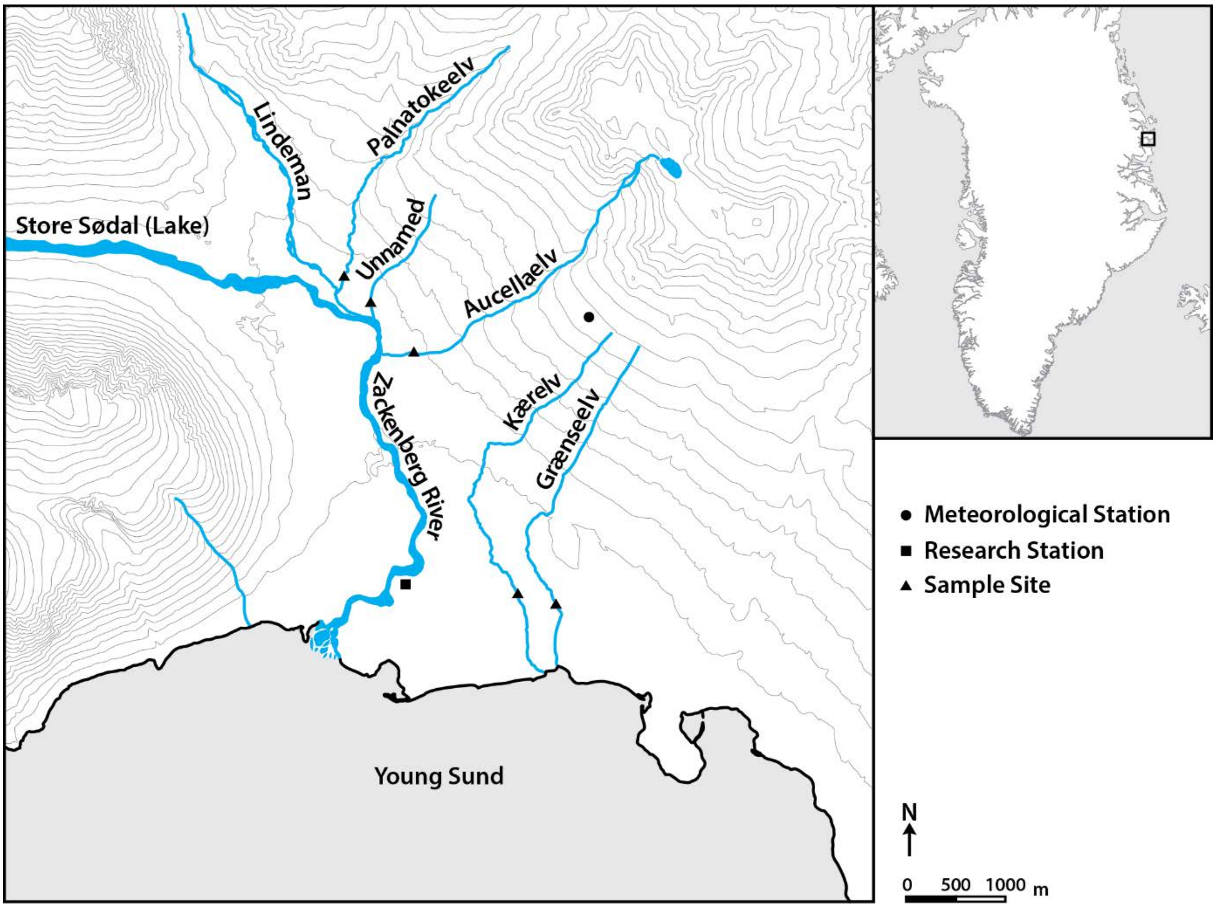

Figure 7.1. Map of study area showing the five study streams and their location in Northeast Greenland.

7.2.2 Environmental habitat conditions

Air temperature, snow depth and precipitation data were obtained from a weather station located within 5km of all sites maintained by the Greenland Ecosystem Monitoring Programme (GEM). Air temperature and snow depth were measured half-hourly whilst precipitation was measured hourly. Habitat condition was monitored and data collected simultaneously to macroinvertebrate collection. The Pfankuch Index was calculated for each site to determine channel stability (Pfankuch 1975) using all three components of the index (upper banks, lower banks and stream bed). Higher Pfankuch Index values correspond to lower channel stability. Water samples were collected to analyse for major ions and nutrients.

Samples were filtered in the field using Whatman GF/F paper and frozen within 6 hours of collection until analysis could take place. NH_4^+, NO_3^-, and PO_4^{3-} were analysed using the hypochlorite, cadmium reduction, and ascorbic acid methods, respectively, on a Lachat QuikChem flow injection analyzer (Lachat Instruments, APC Bioscientific Limited, England; APHA 2012). To determine suspended sediment, 1L water samples were collected from each stream and filtered onto pre-weighed GF/F papers in the laboratory. These were then dried at 60°C for 48 hours, before being reweighed to calculate suspended sediment concentration. Water temperature, conductivity and pH were measured as spot tests using a waterproof HI-98129 Pocket EC/TDS and pH Tester (Hanna meter). Water depth was measured every 0.2 m and average water depth was calculated. To calculate average bed sediment size (D_{50}), 100 randomly selected stones were measured along the B axis. Chlorophyll a (Chl a) was measured as a proxy for benthic algal biomass. Five stone samples with a B axis of over 6cm were selected for benthic algae measurements. Biofilm was removed from substrate using a toothbrush and collected on a Whatman GF/C filter. In the laboratory, filter papers were submerged in 96% ethanol and absorbance was measured at 665 and 750 nm on a spectrophotometer (UV 1700 Spectrophotometer, Shimadzu, Japan). Chl a biomass was calculated as:

$$\frac{Chl\ a\ (\mu g) = (Abs_{665} - Abs_{750}) * E}{83.4 * A * 10^{-4}}$$

Where E is volume of ethanol (ml), 83.4 is the absorption of Chl a in ethanol, A is the sample area (cm^2) and 10^{-4} is the conversion factor (cm^2 to m^2) (Steinman et al.2007) in order to compare on the same scale as macroinvertebrates.

7.2.3 Macroinvertebrate community structure

Macroinvertebrates were collected each year in July 2013, 214 and 2015 using five replicate samples with a Surber sampler (0.093 m^2 and 300 µm mesh size) in the same 20 m reach. Samples were preserved in 90% ethanol in Whirlpak bags. In the laboratory, samples were sieved through a 200 µm sieve and sorted under 10x magnification. Chironomids with dark head capsules were immersed in 10% potassium hydroxide (KOH) solution on a hot plate at 60°C, for 15 minutes to lighten the head capsule and to make characteristic features easier to see. Chironomids and Ceratopogonindae were then mounted on slides using DMFH mountant. Chironomidae were identified to species-type or the lowest taxonomic level possible using the following keys: Cranston (1982), Wiederholm (1983), Brooks *et al.* (2007), Ferrington & Saether (2011) and Lindegaard (2015). Other macroinvertebrates were identified to the lowest level possible using the keys Nilsson (1997) and Dobson (2013). A dichotomous key to the chironomids can be found in appendix A4.

7.2.4 Data analysis

Time series were constructed to show air temperature and precipitation throughout the three field campaigns and snow depth variation over the three years. One-way and two-way ANOVAs were conducted to determine significant differences in environmental variables between sites and years. Significant results were then subjected to Tukey HSD post hoc tests to determine significantly different pairs. All statistically significant pairings were reported. Previous to analysis, normality of data was tested using Levenes test and residual plots. Non-normally distributed data were log10 transformed before analysis.

Replicate macroinvertebrate samples were pooled before being used to determine the community metrics: abundance, Shannon diversity, taxa richness and evenness to quantify how equal the community is numerically. The difference in community metrics between years was calculated to show interannual variation between sites. The ratio of Diamesa to Orthocladiinae was calculated for each site and year.

Differences in macroinvertebrate community metrics between streams and years were investigated by two-way ANOVA and Tukey post hoc tests where abundance data were log10(x+1) transformed following standard procedure and to make comparable to other studies. Similar to the environmental variables, data were first tested for normality using Levenes test and residual plots. To determine the correlation between different environmental variables and community metrics, Spearman’s rank correlation coefficient was conducted. Spearman’s Rank was used due to the small size of the data set and potential for non-linear relationships (Zar, 2010).

The relationship of macroinvertebrate community assemblages to habitat variables was examined using non-metric multidimensional scaling (NMDS) as a 2-dimensional ordination plot. Previous research indicates adding more dimensions only minimally reduces stress (Soininen 2004). The ordination was compiled using Bray Curtis dissimilarities after 999 permutations to avoid the risk of local optima (Soininen 2004) and macroinvertebrate abundance data were log10(x+1) transformed prior to use. Environmental variables were also log10(x+1) transformed and fitted in the ordination using 119 permutations. The environmental variables significantly correlated with the ordination plot were added to the ordination space.

To investigate taxa similarity between study sites, a two-way cluster analysis was constructed in the PAST software using the paired-group method with Bray Curtis similarity index on log10(x+1) transformed data. Taxa were clustered by abundance in different streams and sites were clustered by taxa abundance. Rare species (<5%) were excluded to avoid their large influence on the analysis (Niedrist & Fureder 2016). The labdsv function in the R environment was used to determine indicator species for specific habitats, where the given indicator value is a function of frequency and mean abundance of species in specific classes, and the P value provided indicates the probability of finding higher indicator values under random permutations where low probability gives a significant value ($p<0.05$) (Oksanen 2014). Species with indicator value of 95% or higher are presented.

7.3 Results

7.3.1 Environmental habitat conditions

Weather conditions over the three field campaigns varied markedly with 2014 characterised by two large rain storm events (total precipitation: 37.6 mm). The 2013 field campaign was characterised by small rainfall events (total precipitation: 8.8 mm), whilst the 2015 field campaign was comparatively dry (total precipitation: 0.4 mm). (Figure 7.2). Highest mean air temperatures were during the 2015 field campaign at 7.1°C whilst mean air temperatures were very similar during the 2013 (5.9°C) and 2014 (6.0°C) field campaigns (Figure 7.2). Snow depth was highly variable during the winters previous to sampling. Winter 2012-2013 (September – June) saw very low snow fall (maximum snow depth of 0.16m), compared to winter 2013-2014 (0.91m) and winter 2014-2015 which saw high snow accumulation (1.44m) (Figure 7.3).

Environmental variables showed marked variation between streams and between years. Channel stability was significantly higher in Kærelv and Grænseelv than Unnamed, Aucellaelv and Palnatokeelv ($F_{(1,4)}=417.63$, $P<0.001$) with significantly smaller bed sediment size ($F_{(1,4)}=48.83$, $P<0.01$). Suspended sediment was substantially higher in Aucellaelv and

Palnatokeelv compared to Kærelv, Grænseelv and Unnamed (Table 7.1). Two-way ANOVAs revealed no significant differences in water temperature or Chl *a* between streams or years (Table 7.2) although no Chl *a* data was available for 2013. Conductivity was significantly higher in in 2013 compared to 2014 and 2015 ($P<0.01$). No significant variation was found in NH_4^+ or PO_4^{3-} but NO_3^- varied between sites and years, with higher NO_3^- concentrations in Aucellaelv than Kærelv and Grænseelv, although not significantly different ($P=0.06$, $P=0.055$ respectively). Ca and Mg concentrations showed significant variation between years (see Table 7.2). Ca concentration was significantly higher in Unnamed than Palnatokeelv (P<0.05) and was significantly higher in 2013 compared to 2014 and 2015 (both: P<0.01). Mg concentrations were significantly higher in Aucellaelv compared to Kærelv and Palnatokeelv, and in 2013 compared to 2014 (P<0.05) and 2015 (P<0.01) (Table 7.3).

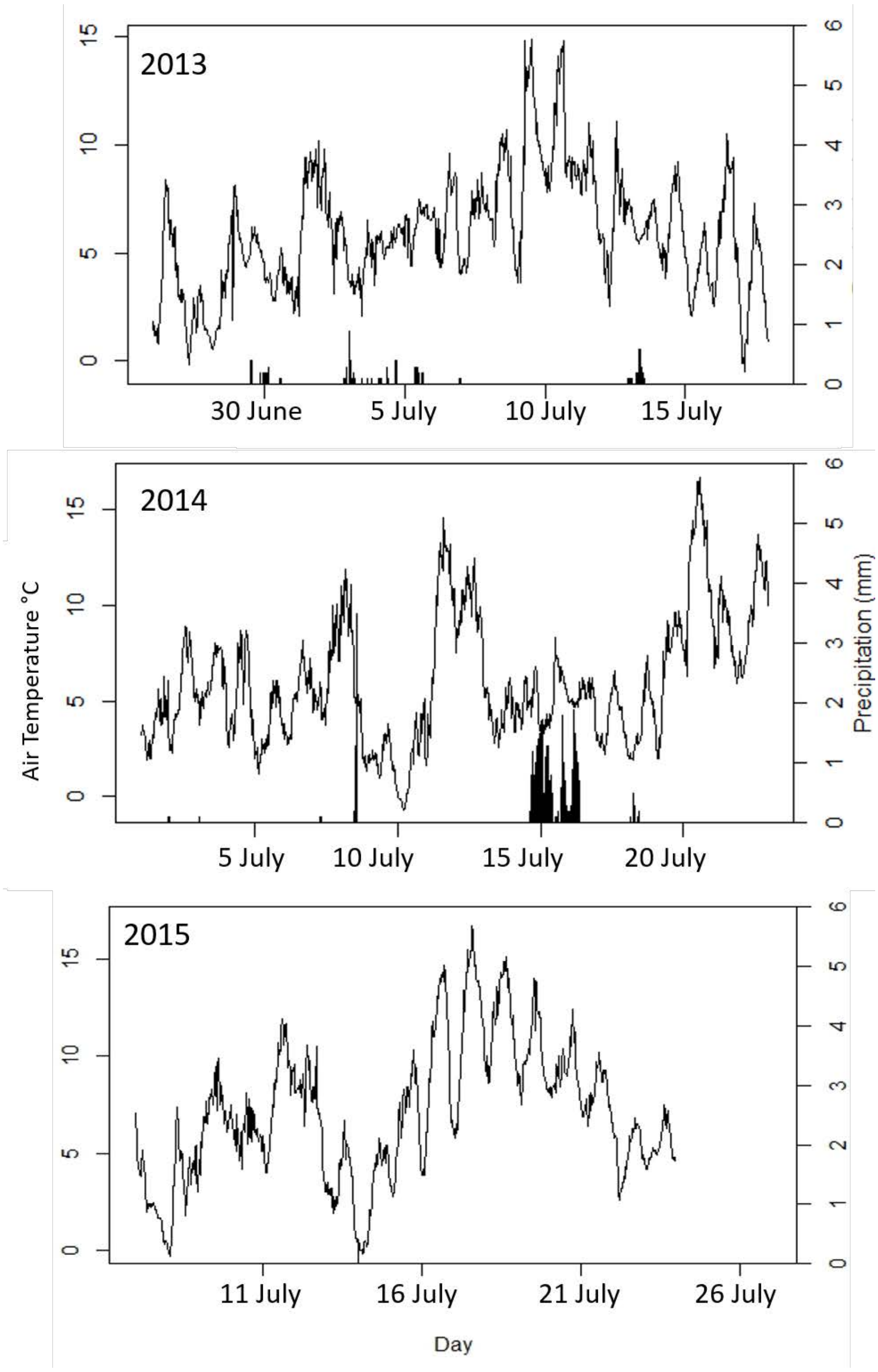

Figure 7.2. Mean air temperature and precipitation for the three field campaigns 2013 to 2015.

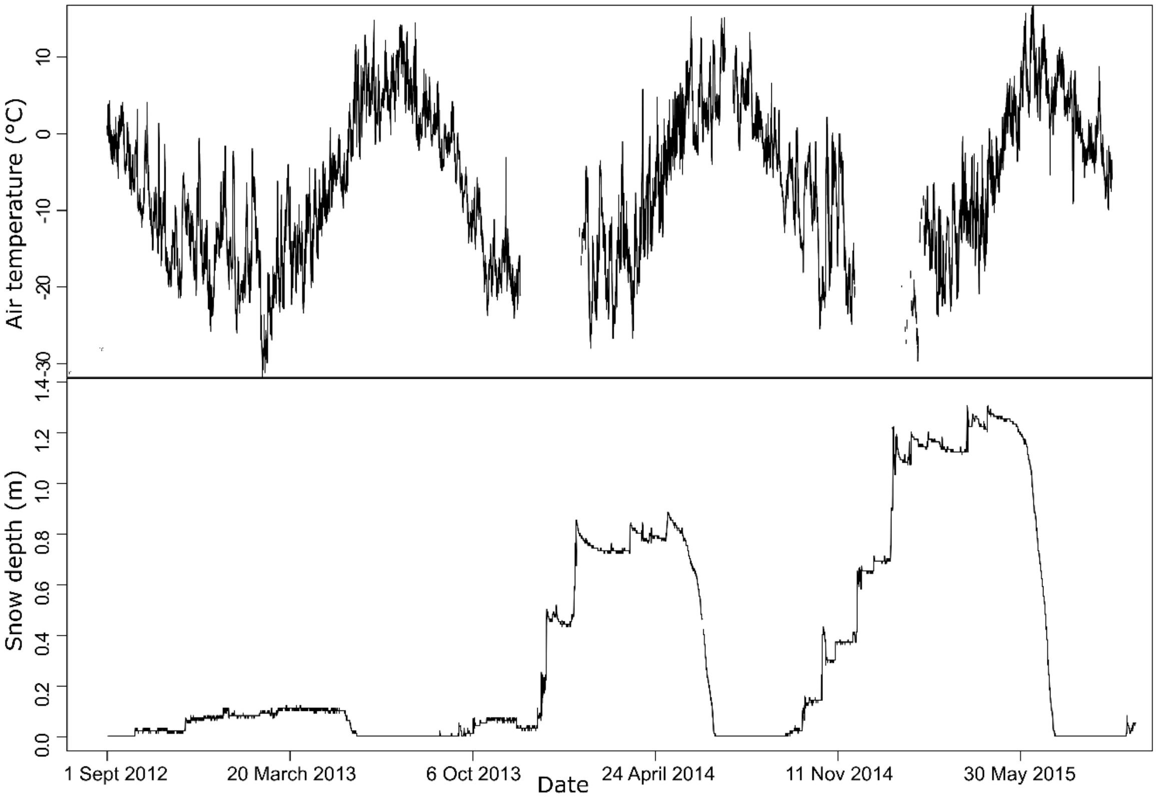

Figure 7.3. Air temperature and snow depth at Zackenberg valley over the three-year study period between September 2012 and September 2015.

Table 7.1. Environmental variables and Diamesa:Orthocladiinae ratio during the three field campaigns (2013 to 2015). EC= electrical conductivity.

Site	Year	Mean water temperature (n= 336 unless different below)		Channel stability (Pfankuch Index)	Suspended sediment		Bed sediment d_{50} (n=100)		Water depth (n=5 unless different below)		EC	pH	Chl *a* (n=5)		Diamesa: Orthocladiinae
		°C	SD (n)		Mg L^{-1}	SD (n)	mm	SD	cm	SD (n)	µS cm^{-1}		µg/m^2	SD	
Kærelv	2013	6.1	3.1	-	-	-	-	-	10	- (1)	192.2	-	-	-	0
	2014	5.7	2.5	-	5.1	0.0 (7)	-	-	20	3.9	55.1	-	504.49	233.7	0
	2015	6.1	2.7 (3)	74	-	-	51.2	6.6	21	7.9	36	7.0	392.69	125.8	1
Grænseelv	2013	7.3	2.5	-	-	-	-	-	3	- (1)	208	-	-	-	0
	2014	4.5	2.2	-	7.3	- (1)	-	-	16.8	2.3	54	-	336.16	236.3	0
	2015	3.7	1.8	78	-	-	33.9	2.7	14.4	9.4	32	7.1	198.52	90.8	0.8

Unnamed	2013	10	3	-	0.6	- (1)	-	-	2	- (1)	340	-	-	-	40
	2014	5.9	2.7	-	0.5	- (1)	-	-	20	2.4	-	-	327.29	140.2	0
	2015	1.4	1.0	113	-	-	90.3	4.9	7.6	4.5	42	7.0	503.97	301.9	8.7
Palnatokeelv	2013	10.1	- (1)	-	557.3	- (1)	-	-	5	- (1)	339	-	-	-	424.1
	2014	7.0	- (1)	-	96.3	- (1)	-	-	19	3.0	58.2	-	174.63	166.9	0
	2015	4.4	1.1 (3)	114	-	-	101.4	6.6	10.6	5.3	26	7.2	544.61	342.6	30
Aucellaelv	2013	6.4	2.7	-	463.1	- (1)	-	-	-	-	313	-	-	-	153.9
	2014	3.0	4.9	-	1120.3	0.6 (4)	-	-	16	4.2	127	-	165.53	238.4	100
	2015	0.8	0.6	116	-	-	96.5	5.7	12.8	4.9	88	7.0	289.94	149.7	62.5

Table 7.2. Two-way ANOVA results for environmental variables with site and year.

Variable	Site	Year	Site*Year
Water temperature	-	-	-
Chl *a*	-	-	-
EC	-	$F_{(1,4)}$=28.54, P=<0.01	-
NH_4	-	-	-
NO_3	$F_{(1,4)}$=22.50, P=<0.05	F(1,4)=11.03, P=<0.05	-
PO_3	-	-	-
Si	-		-
Ca	F(1,4)=7.33, P=<0.05	$F_{(1,4)}$=58.54, P=<0.01	-
Mg	F(1,2)=6.83, P=<0.05	$F_{(1,4)}$=56.57, P=<0.01	-

Table 7.3. Water chemistry data for stream sites over the three field campaigns. M= mean, SD= standard deviation, n= number of samples.

		Mg^{2+}		Na^{+}		K^{+}		Ca^{2+}		Si		NH_4^{+}		NO_3^{-}		PO_4^{3-}	
		(μEq L^{-1})								mg/L		(μEq L^{-1})					
Site	n	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Kærelv 2013	1	122.6	NA	143.4	NA	24.15	NA	641.3	NA	2.2	NA	NA	NA	NA	NA	NA	NA
Kærelv 2014	6	64.6	16.9	143.9	171.5	14.7	7.2	195.0	50.1	1.1	NA	1.1	0.8	0.0	0.1	0.3	0.4
Kærelv 2015	3	50.1	4.5	64.4	8.2	13.0	3.5	144.2	20.3	1.3	0.11	0.8	0.2	0.1	0.1	0.1	0.01
Grænseelv 2013	1	266.7	NA	321.6	NA	48.2	NA	728.7	NA	2.0	NA	NA	NA	NA	NA	NA	NA
Grænseelv 2014	4	54.3	13.4	41.4	11.9	9.6	2.7	143.3	37.7	1.1	NA	0.4	0.1	0.01	0.01	0.1	0.01
Grænseelv 2015	3	38.4	20.9	36.8	14.9	10.3	4.5	102.9	41.6	1.3	0.2	3.1	3.1	0.04	0.02	0.1	0.02
Unnamed 2013	1	291.7	NA	130.0	NA	29.7	NA	1504.8	NA	1.75	NA	NA	NA	NA	NA	NA	NA
Unnamed 2014	3	138.1	44.4	42.0	16.2	13.2	3.8	586.5	292.7	1.2	NA	0.4	0.1	0.0	0.01	0.1	0.01
Unnamed 2015	3	38.0	6.0	39.1	5.2	10.7	1.5	157.1	16.6	1.0	0.1	0.7	0.1	0.1	0.6	0.1	0.00
Aucellaelv 2013	1	345.8	NA	592.6	NA	42.8	NA	933.3	NA	2.0	NA	2.4	0.4	1.80	0.2	0.1	0.04
Aucellaelv 2014	3	211.0	62.8	305.8	62.9	26.1	3.4	460.2	118.6	2.2	NA	1.9	0.4	0.8	0.2	0.1	0.05

Aucellaelv 2015	3	88.6	18.4	148.8	23.6	5.3	0.6	227.8	30.0	0.8	0.1	1.1	0.1	0.4	0.2	0.1	0.02
Palnatokeelv 2013	0	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Palnatokeelv 2014	2	71.46	2.29	66.96	4.35	10.38	0.38	164.25	15.5	1.23	NA	0.69	0.23	0.19	0.12	0.13	0.03
Palnatokeelv 2015	3	38.60	10.05	19.52	16.51	4.16	3.51	102.46	13.4	0.95	0.11	1.06	0.27	0.69	0.26	0.10	0.03

7.3.2 Macroinvertebrate community structure

Over the three years, 39 taxa were identified, of which 71.7% of the individuals were Chironomidae (29 taxa) and 26.5% Oligochaetae. The remaining 1.8% comprised Ceratopogonidae, Simuliidae, Limoniidae, Musciidae, Sciaridae, Acari, Araneae and Collembola (as can be seen in appendix A3). Abundance varied between streams and year with the highest abundance found in Kærelv 2013 (4335 /m^2) and the lowest in Aucellaelv in 2014 (8 /m^2). Taxa richness varied between 4 and 25 taxa per site (Figure 7.4). Interannual variability in evenness and Shannon diversity was greatest in Unnamed, Aucellaelv and Palnatokeelv (Figure 7.5).

No significant difference was found for evenness or diversity between sites or years. Taxa richness was found to be significantly different between sites (F(5,7)=20.8, P<0.001) where a Tukey post hoc test found richness to be significantly higher in Kærelv and Grænseelv compared to Aucellaelv (P<0.01), Palnatokeelv (P <0.01) and Unnamed (P<0.05). Taxa richness between Aucellaelv, Palnatokeelv and Unnamed was not significant. However, macroinvertebrate abundance was significantly different between sites (F(5,7)=11.9, P<0.01) and years (F(2,7)=8.2, P<0.05). Kærelv and Grænseelv supported significantly higher abundance than Aucellaelv (P<0.01), and Kærelv than Palnatokeelv and Unnamed (P<0.05). Abundance was significantly higher in 2013 compared to 2015 (P<0.05).

The ratio of Diamesa:Orthocladiinae was low and showed negligible variation in Kærelv and Grænseelv over the 3 years (mean:0.3%, SD: 0.4) whilst in Unnamed, Palnatokeelv and Aucellaelv, the ratio was high and also highly variable between sites and between years (mean: 91.0%, SD: 127.1) (Table 7.1).

Oligochaeta were found in all sites in all years, however abundance varied. Highest abundance was found in all sites during the 2013 field campaign, excluding Grænseelv when the highest abundance was found in 2014. Kærelv supported the highest abundance of all sites with 849 /m^2 in 2013. Lowest abundance was found in 2015 for all sites apart from Aucellaelv (2014).

NMDS indicated the distinct grouping of the two most stable streams, closely distributed within the ordination space with negligible variation between them over the three years. In contrast variation was large in the three unstable streams both interannually and between the sites (Figure 7.6). The NMDS reported a stress of 0.09. Only channel stability (R^2= 0.67, P<0.01) and bed sediment size (R^2= 0.62, P<0.01) were significantly correlated within the ordination. Channel stability increased and bed sediment size decreased towards the two more stable streams with highest taxa diversity.

Along with channel stability and bed sediment size, community metrics were significantly correlated with other environmental variables (Table 7.4). Evenness was significantly correlated with climate variables (winter snow depth and summer air temperature both r= 0.605, P<0.05). Shannon diversity was significantly correlated with conductivity and Mg concentration (r= -0.57 P<0.05 and r= -0.6 P<0.05 respectively) and taxa richness was significantly correlated with NO_3^- concentration (r= -0.79 P<0.01).

Four indicator taxa were identified with values over 95%. These were Podonominae (Indicator value (Iv)=100% P=0.014), *Corynoneura* (Iv=99%, P=0.003), *Hydrobaenus* (Iv=98%, P=0.002) and *Orthocladius* species types (Iv=97%, P=0.002) including *O.*

oliveri type and *O.* G1 type. All indicator taxa were representative of high channel stability areas with small bed sediment size, and high macroinvertebrate abundance, diversity and taxa richness. No indicator species were identified for low stability streams as taxa at these sites were also present in some stable streams even though *Diamesa* were found in high numbers in Aucellaelv and Palnatokeelv in 2013.

The two-way cluster analysis also highlighted high macroinvertebrate abundance in stable streams, particularly in 2013 and the distance between *Diamesa* spp. and *D. aberrata* compared to all other taxa, emphasizing the different environmental conditions in which they are found (Figure 7.7). Abundance of *Diamesa* increased in streams with lower channel stability and increased bed sediment size.

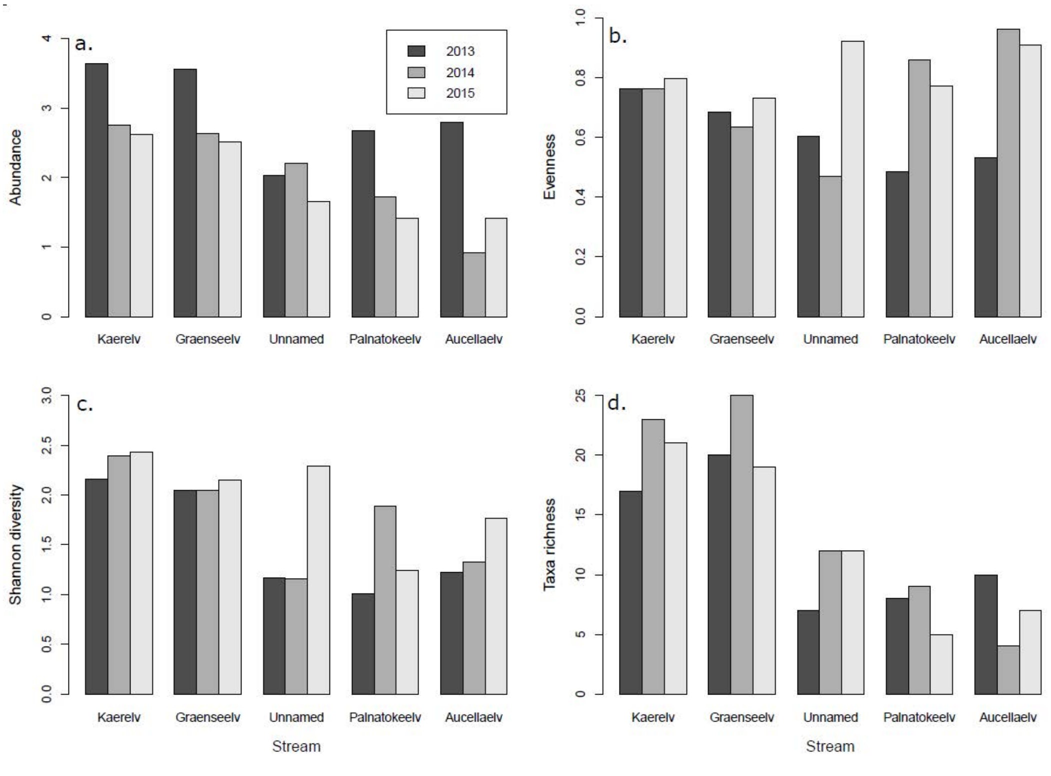

Figure 7.4. Bar charts showing a) Abundance (individuals/m^2 log10(x+1) transformed), b) Evenness, c) Shannon Diversity Index and d) Taxa richness.

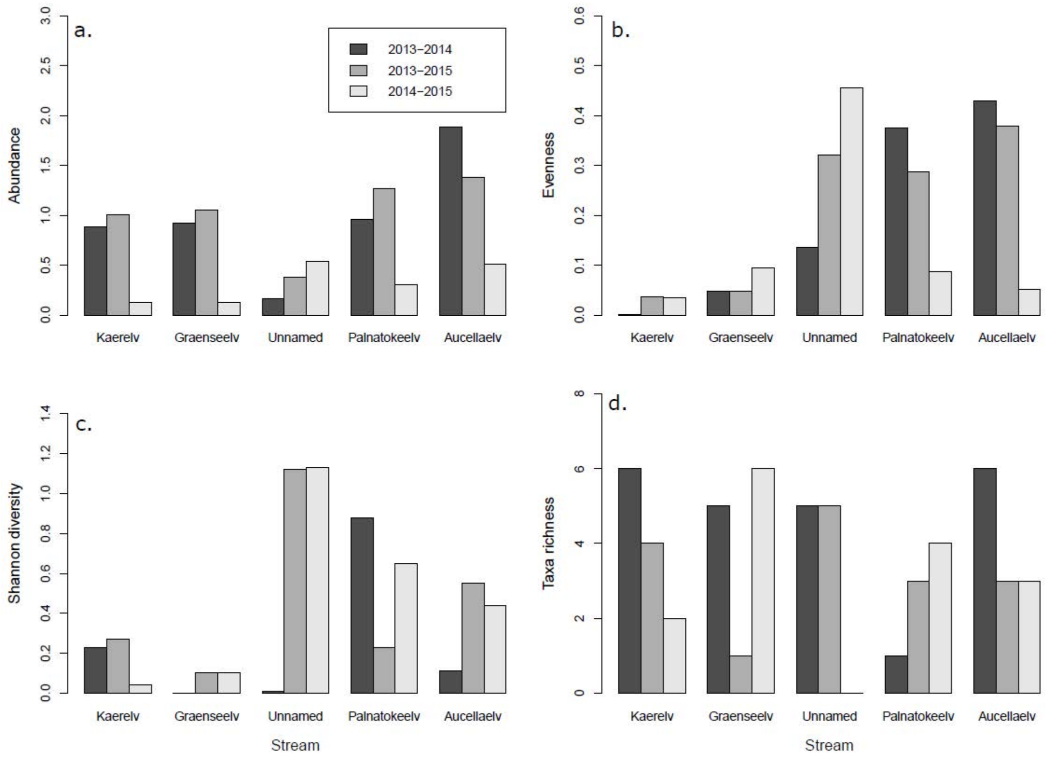

Figure 7.5. The difference between years in community metrics per site. Note largest difference in Evenness and Shannon diversity in the streams Unnamed, Palnatokeelv and Aucellaelv.

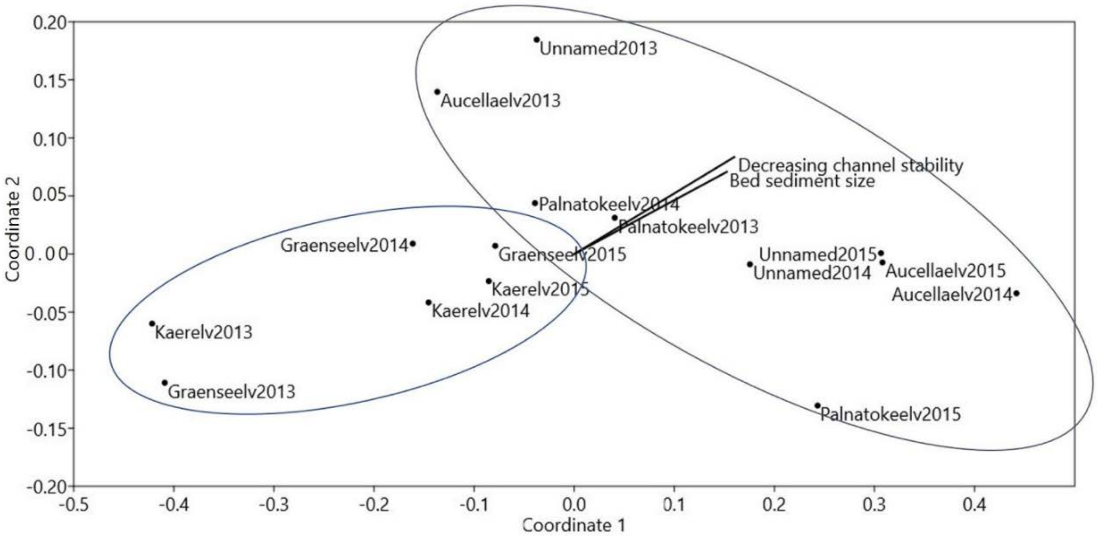

Figure 7.6. NMDS of sites with significant environmental variables plotted. Circles show streams sourced from small seasonal snowpacks (Kærelv and Grænseelv) and from large perennial snowpacks (Unnamed, Aucellaelv and Palnatokeelv).

Table 7.4. Spearmans rank correlation coefficients for community metrics from all streams and years with environmental variables. *P<0.05 **P<0.01

	Abundance	Evenness	Shannon diversity index	Taxa richness
	r	r	r	r
Channel stability	**-0.57***	-	**-0.7****	**-0.83****
Temperature	-	-	-	-
Chl a	-	-	-	-
EC	-	-	**-0.57***	-
Suspended sediment	-	-	-	-
pH	-	-	-	-
Water depth	-	-	-	-
Bed sediment size	**-0.51***	-	**-0.61***	**-0.83****
Mean winter snow depth	**-0.62***	**0.605***	**-**	**-**
Mean air temperature	**-0.624***	**0.605***	**-**	**-**
NH_4	-	-	-	-
NO_3	-	-	-	**-0.79****
PO_3	-	-	-	-
Si	-	-	-	-
Ca	-	-	-	-
Mg	-	-	**-0.6***	-

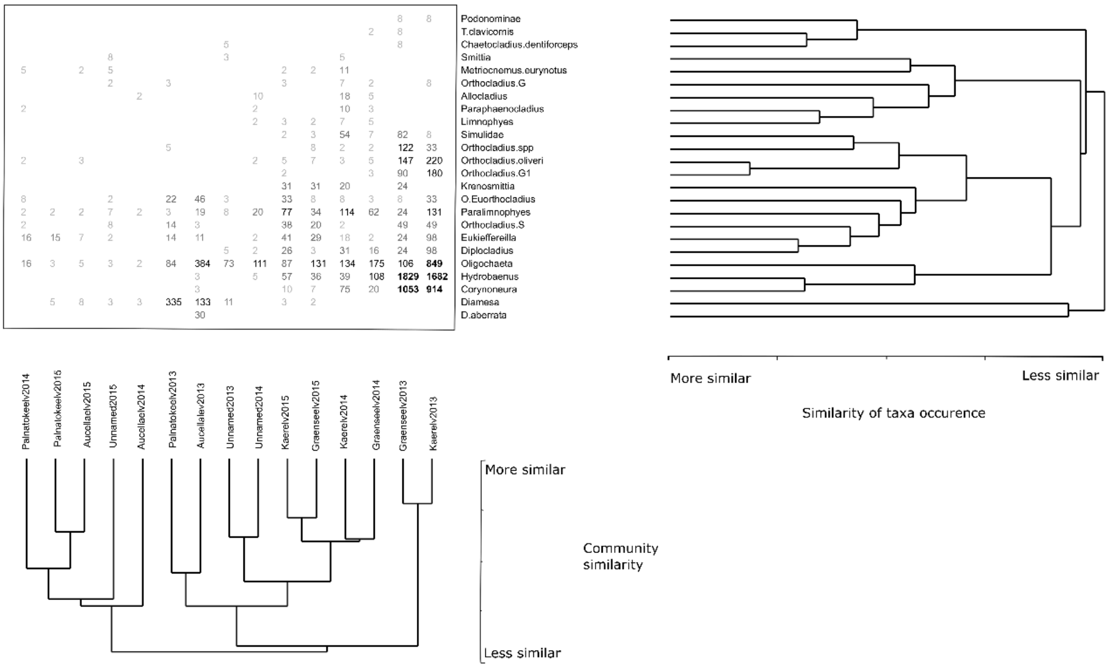

Figure 7.7. Two-way cluster analysis showing similarity between streams and taxa. Kærelv and Grænseelv, which have highest macroinvertebrate abundance, are shown to be least similar to Aucellaelv and Palnatokeelv, which have lowest macroinvertebrate abundance.

7.4 Discussion

Macroinvertebrate community structure was significantly different between streams with small snowpacks compared to streams with large snowpacks, and between the 3 years. Channel stability and bed sediment size were the best predictors for macroinvertebrate community dynamics as indicated by ordination and Spearman's rank correlation.

7.4.1 Variation in environmental habitat conditions

The influence of water source on stream physicochemical habitat has been well documented (eg. Ward 1994; Brown, Hannah & Milner 2003; Parker & Huryn 2011; Blaen et al 2014).

However, past research has typically focused on the comparative influence of different water source types (glacier, snow, groundwater) and less so on variation in influence within one water source type. Streams in the Zackenberg region sourced from large, perennial snowpacks (Aucellaelv, Palnatokeelv, and to a lesser extent Unnamed) were characterised by low channel stability and high suspended sediment concentration compared to streams from smaller, seasonal snowpacks (Kaerelv, Graenseelv). These findings support hypothesis 1 that streams sourced from larger snowpacks would have reduced channel stability and increased disturbance.

The traditional model for snowmelt dominated streams states that they are characterised by low turbidity due to transporting low levels of sediments, although turbidity can be elevated during high flow (Milner & Petts 1994; Brown et al. 2003), and that their hydrochemistry is determined by the release of ions from melting snowpacks (Malard 1999; Brown et al. 2003). Kærelv and Grænseelv, the two streams with seasonal snowpacks, and also Unnamed, the stream fed by both seasonal and perennial snowpacks, met the definition in this model, however Aucellaelv and Palnatokeelv did not. Aucellaelv and Palnatokeelv demonstrated hydrochemistry related to soil erosion more than ionic release from snowpacks. High turbidity and channel mobility was standard in these two streams, where Aucellaelv moved by 1 m during a heavy precipitation event in 2014 (personal observation) and formed a large thermo-erosional tunnel in 2015 (Docherty et al. 2017). The high variability in conductivity and solute load between sites is representative of the different levels of fluvial erosion and nivation processes taking place at each site (Hasholt & Hagedorn 2000) leading to high suspended sediment concentrations in streams, which are then weathered in-stream by turbulent flow, releasing ions and nutrients (Chin et al. 2016).

In the Zackenberg region, the largest snowpacks generally accumulate on south facing lee slopes following northerly winds blowing snow and sediment into ridges and fluvial terraces (Christiansen 1998). Whilst under future scenarios of increased snowfall, all areas would receive more snow. However, these larger snowpacks could be expected to cause more extreme spring flood events at the onset of snow melt (Dankers & Middelkoop 2008), destabilising stream bed and the nearby floodplain sediment, increasing channel mobility and uprooting vegetation. The variation in snow accumulation throughout the landscape leads to large spatial variation in ground thermal regime by snow cover acting as an insulator between ground and air (Westermann et al. 2015), leading to different permafrost degradation and active layer depth locally, and subjecting streams in close proximity to one another to different pressures based on local geomorphology. As well as snowfall, streams could see increased disturbance due to increased summer rain events. In summer, rain events in the Arctic are known to have large influences on streams by increasing sediment load, inundating floodplains and causing rapid mass movements (Cogley & McCann 1976; Lewis et al. 2005; Lamb & Toniolo 2016).

Environmental conditions in streams were markedly different in 2013 compared to 2014 and 2015 due to the unusually low snow depth during the previous winter, reducing snow melt inputs to all streams. Low water levels caused higher solute concentrations due to solutes constituting a larger fraction of the water body, and some stream reaches of Kærelv and Grænseelv constituted mainly of pools with limited surface water connectivity. Even though ionic load and suspended sediment concentration was found to be highly variable between sites and years¸ this was not found to have a significant impact on Chl *a* concentration. However, Chl *a* data were not available from 2013, when habitat conditions were most contrasting, and as biofilms form an important food source for macroinvertebrates, this could have provided interesting insights into macroinvertebrate abundance variability. The different time periods each year could have been a factor influencing variation between years due to variation in air temperature and timing of onset of snowpack melting, as air temperature was notably colder in the 2013 field campaign (June) compared to that in 2015 (July). However, the large variation in snow depth throughout the three winter seasons is believed to have a much larger influence than the two-week difference in field campaign onset timing.

7.4.2 The relationship between benthic macroinvertebrate communities and environmental habitat variables

Macroinvertebrate abundance and taxa richness varied between streams, with the most stable streams Kærelv and Grænseelv supporting higher densities and richness than Unnamed, Aucellaelv or Palnatokeelv. Spatial variation in abundance and taxa richness was found to be correlated with channel stability and bed sediment size, supporting hypothesis 2, that lower channel stability will lead to reduced macroinvertebrate taxa richness and abundance, but not supporting the hypothesis that it will also lead to reduced diversity. Several taxa, found in low numbers, were only found in the most stable streams including *Thienmaniella clavicornis*, *Orthocladius* G1 and *Krenosmittia*, highlighting the importance of these streams for local diversity. Four indicator taxa characteristic of stable snowmelt streams in this region were identified which were Podonominae, *Corynoneura*, *Hydrobaenus* and *Orthocladius*. The streams sourced from seasonal snowpacks demonstrated low channel mobility, relatively stable water levels (field observations), low suspended sediment concentration and small bed sediment size, creating a stable environment for macroinvertebrate communities. In contrast, streams with perennial snowpack sources had high channel mobility, large bed sediment size and, apart from Unnamed, had high suspended sediment concentration. High suspended sediment concentration is known to have a large negative impact on macroinvertebrate communities for a number of reasons, including; increasing invertebrate drift through substrate instability; affecting respiration through silt accumulation on respiratory organs and through reducing water oxygen concentration; and by reducing food availability by reducing biofilm growth (Eriksen 1966; Lemly 1982; Peckarsky 1984; Wood & Armitage 1997).

Bed sediment provides refuge from disturbances and predation, for feeding and for egg deposition for macroinvertebrates (Brusven & Rose 1981; Dole-Olivier et al. 1997; Palmer et al. 1992; Gayraud et al. 2000; Gayraud & Philippe 2003). Large heterogeneity in bed sediment size, for example, a combination of large cobbles and silt, causes interstitial spaces to become blocked (Gayraud & Philippe 2003), reducing macroinvertebrate habitat and making them unsuitable for certain taxa (Erman & Ligon 1988; Richards & Bacon 1994). In this study, streams with large bed sediment supported reduced macroinvertebrate abundance, diversity and taxa richness, and two of the three streams with large sediment size also showed the largest suspended sediment concentrations, leading to increased sediment size heterogeneity and reduced interstitial spaces for invertebrates.

Water temperature in this study was not significantly different between sites or years. Warmer water temperature causes higher metabolic demands of both individuals and ecosystem as a whole (Brown et al. 2004), and water temperature and channel stability are considered the best predictor of macroinvertebrate community composition in glacially influenced rivers (Milner & Petts 1994; Milner et al. 2001). Along with channel stability, water temperature has been found to be the habitat variable that best explains macroinvertebrate community composition (Friberg et al. 2013) and taxa richness (Castella et al. 2001; Friberg et al. 2001) and in alpine regions, increased water temperature has been found to cause decreases in beta diversity (Finn et al. 2013). Whilst other studies in Arctic and alpine regions find significant variation in water temperature between streams and sites due to variations in water source contributions (eg. Cadbury al. 2008; Blaen et al. 2013; Mellor et al. 2016), the similarity between the streams in this study in terms of their water source limits variation in water temperature, where variation maybe more due to stream size and consequently, the time needed to warm up.

Macroinvertebrate abundance and evenness was found to be significantly correlated with winter snow depth, supporting hypothesis 3, that streams sourced from larger snowpacks will see higher interannual variability in community structure between years of different snowfall amount. Given this correlation, the interannual variation in snow depth and associated variation in stream habitat is likely the principal contributing factor causing interannual variation in macroinvertebrate community structure.

Low water levels typically result in decreased abundance, but higher overall abundances can also be found where water levels are reduced, both due to changes in habitat suitability and food resources (Gore, 1977; Wright & Bernie, 1987; Wright & Symes, 1999; Dawson et al. 2003; Dewson et al. 2007, Epele et al. 2012). Of the four indicator taxa identified for high stability streams, Podonominae was found only in stable streams in 2013, when water level was at its lowest, *Corynoneura*, *Hydrobaenus* and *Orthocladius* spp., the other three indicator taxa, also had the greatest densities in 2013, when *Hydrobaenus* was dominant followed by *Corynoneura,* This genera have been found previously to peak in abundance during low flow periods in Patagonian streams (Epele et al. 2012).

Whilst some chironomids are thought to have a long larval stage in cold regions before emergence, the large interannual variation in abundance is not expected to be explained through this mechanism. Orthocladinae and Diamesiinae, the principal Chironomidae subfamilies present, are known to be adapted to cold environments (Milner & Petts 1994; Lindegaard 1995) and to have a degree of flexibility in their developmental rate dependent upon habitat conditions (Ferrington & Mastellar 2015). Water temperature regimes have been found to be important to developmental rate, where developmental period of *Diamesa mendotae* have been shown to be shortest at low temperatures, being 63 days at 4 – 6°C, but 93 days at 8-10°C (Bouchard & Ferrington 2009; Ferrington & Mastellar 2015). *D. mendotae*, *D. incallida* and *D. cheimatophila* are all thought to produce more than one generation during a season (Ferrington & Mastellar 2015). The low variation in water temperature between years and sites and the adaptive nature of Arctic macroinvertebrates to cold environments, implies that habitat conditions in this study should not be restricting factors for larval development.

7.4.3 Zackenberg in a global context

Mean macroinvertebrate abundance was low at Zackenberg (747 /m^2) when compared to west Greenland, where mean abundance was 1113 individuals/m^2 in streams with weak glacial influence (Friberg et al. 2001) However, taxa richness was found to be higher at Zackenberg (13.3) compared to on the west coast (10.5 in streams with weak glacial influence) (Friberg et al. 2001). When compared to streams of all water sources on the west coast, higher taxa diversity was found in west Greenland streams compared to Zackenberg. At Zackenberg, taxa were restricted to the order Diptera and Oligochaeta, whilst on the west coast in streams either sourced from groundwater or downstream of lakes, taxa also included Ephemeroptera, Trichoptera and the snail *Lymnaea* sp. (González-Bergonzoni et al. 2014; Friberg et al. 2001). Despite these differences, *Hydrobaenus* was found to be one of the most abundant genera (Friberg et al. 2001) similar to this study from northeast Greenland. The more southern location in the low Arctic climate zone and the proximity to mainland Canada may explain the higher diversity present in West Greenland, as diversity is known to decrease with increasing latitude for all aquatic taxa apart from Chironomidae (Bocher et al. 2015). Coastal Greenland has been ice free since the Pleistocene glaciation 10,000 years BP (Bennike 1999; Böcher et al. 2015). Due to the small time frame invertebrates have had to colonise the region, combined with the isolation of the east coast of Greenland, where dispersal routes are either from Canada, crossing the harsh climatic conditions of north Greenland or across oceans (Böcher et al. 2015), taxa diversity is low in this region. However, there is evidence that ice-free areas may have existed along the east coast during the last glaciation even though average air temperatures were 23°C lower than present, which may have acted as refugia for some invertebrate species (Funder 1978; Funder 1979; Dahl-Jensen et al. 1998; Böcher et al. 2015). Streams at Zackenberg had restricted diversity compared to streams in eastern Canada, where 92 species types of Chironomidae were found in rivers of different water sources (nival, glacial and lake fed) between 58 and 82°N (Namayandeh et al. 2016), and compared to a glacial stream in Iceland, where macroinvertebrate communities included Chironominae, Plecoptera and Trichoptera as well as other Diptera (Gíslason et al. 2001). However, macroinvertebrate abundance at Zackenberg was found to be much more variable between streams compared to those in Svalbard, where abundance varied between 446 individuals/m^2 and 1558 individuals/m^2 in streams of varying water sources (glacial melt, snow melt, groundwater) (Blaen et al. 2014).

7.4.4 Implications of climate change on Arctic stream ecosystems

Most research on the impact of climate change on Arctic streams has been focused on a shift from glacial (unstable) to groundwater or snowmelt (stable) streams. This paper presents the opposite scenario where streams decrease in channel stability through increased snowmelt water inputs, and so provides novel insights into future ecosystem dynamics in Arctic streams. Under this proposed scenario, streams are suggested to support lower macroinvertebrate abundance and diversity, and for there to be higher variability both between streams and interannually dependent on the size of the snowpack. This could provide favourable conditions for taxa adapted to unstable environments, such as *Diamesa*, but could potentially result in the local extinction of rare species types that are only able to inhabit stable streams *(eg. Trichotanypus)*, and reductions in numbers of many present common taxa such as *Hydrobaenus* and *Corynoneura*.

This research shows the large variation in climate change pressures upon streams within a small area, and highlights the need for increased research efforts on snowmelt streams to understand the different dynamics. The interannual variation in habitat variables and community metrics highlights the importance of long-term studies for a full understanding of stream dynamics.

The different environmental and climatic conditions in this region compared to other Arctic locations mean that the response of stream ecosystems to a changing climate in ice-free northeast Greenland, is expected to be different to that of other Arctic regions. However, previous research has predicted increased snowfall in parts of north Russia and associated peaks in stream discharge during spring floods (Dankers & Middelkoop 2008), which could see similar patterns on stream habitat and macroinvertebrate communities to those predicted in this paper for northeast Greenland. Further research is required to see if this model is applicable to other Arctic regions.

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CHAPTER 8: SYNTHESIS, IMPLICATIONS AND FUTURE DIRECTIONS

8.1 Introduction

The principal aim of the research was to elucidate **the key variables determining patterns and processes of northeast Greenland stream systems and the likely response in a changing climate.** This will provide recommendations for Arctic stream monitoring programmes, and to place the results in a pan-Arctic context, adding to past research in snow and ice dominated systems in other Arctic locations. Interdisciplinary, hydroecological field-based research has been undertaken over three summer field campaigns (2013 to 2015) to Zackenberg Research Station in northeast Greenland to address this aim. This thesis has the following structure: an introduction to the topic of Arctic stream research, climate change in the Arctic and study site, to provide context for the research (chapter 1); the relationship between local geomorphology and hydrochemistry (chapters 2 and 3); water temperature dynamics over a continuous period of 24 months in streams with different hydrochemistry (chapter 4); nutrient uptake and limitation dynamics (chapter 5); spatial and temporal patterns in stream macroinvertebrate community composition in the context of the hydrological variables determined in the previous chapters (chapters 6 and 7).

This chapter provides a summary and synthesis of the principal findings of the research. Limitations and future directions will be overviewed.

8.2 Synthesis

8.2.1 Principal findings

The originality of the project focuses on the hydroecology of snowmelt stream systems in the high Arctic, and on the impact of a changing climate upon them, which has not previously been studied.

Climate change effects on stream systems have principally focused on decreased melt inputs (glacial) due to the reduction of glacial cover (eg. Brown et al. 2007; Milner et al. 2009; Jacobsen et al. 2012; Finn et al. 2013). However, increased melt inputs are expected in some regions due to increased snowfall in the long term (Kattsov et al. 2007; Stendel et al. 2008; Dankers & Middelkoop 2008; Collins et al. 2013). Previous to this project, research on the effect of increased snowfall on stream hydroecology had been negligible. This study addresses this gap and provides predicted patterns of change in snowmelt streams in regions expecting increased snowfall in the coming decades.

Previous stream ecology research in Greenland has been restricted to southwest Greenland (Friberg et al. 2001; González-Bergonzoni et al. 2014) and stream hydrological studies in Zackenberg have been limited to sediment and solute dynamics (Hasholt & Hagedorn 2000). The findings in this study provide novel information, including on taxa distribution and interannual variation in physicochemical habitat and benthic community assemblages for this region of Greenland. Streams in the region can be divided into two separate categories based on the size of their snowpack source. Streams with large, perennial snowpacks typically have low channel stability with high bed mobility, suspended sediment and ionic load resulting in low macroinvertebrate density and diversity. Streams sourced from small, seasonal snowpacks created channels with higher stability, limited bed mobility, low sediment and ionic load and support comparatively high macroinvertebrate density and diversity. Through this work, it is proposed that the definition for nival streams, as given by Brown et al. (2003) be subdivided further into two new categories, based on size of snowpack source and taking into consideration underlying bedrock and its vulnerability to erosion.

The principal findings of this project are highlighted below:

- Streams with a similar water source type (snow) and overlying similar bedrock (sedimentary) can vary largely in stream habitat. Snowpack size can influence the duration and quantity of spring floods and the degree of nivation processes, influencing channel stability and channel mobility and altering stream physicochemical habitat (Chapter 2; Chapter 3). Future increases in snowpack size may result in decreased channel stability and increased ionic and nutrient load.
- Variability of water temperature can be high during the summer months in response to climatic events, and is correlated principally to air temperature, incoming shortwave radiation and snow depth. The long polar night during the winter months means incoming shortwave radiation does not influence water temperature during these months. Winter water temperature shows no diurnal variation and low variability in all streams. These findings suggest two possible outcomes; that with a changing climate, winter water temperatures may become increasingly higher and variable as air temperatures increase and have a larger influence on water, or, that the deeper winter snowfall further insolates streams, limiting the influence of climate. A likely scenario is a combination of both, where winter warm events cause short-term melting of snow, increasing stream water vulnerability to climate variables (Chapter 4).
- As seen in other studies on Arctic stream nutrient dynamics, NH_4^+ was found to be the main limiting nutrient in the region (Chapter 5). Increased active layer depth in the future will cause increased nutrient and ionic leaching into stream systems, reducing nutrient limitation.
- Longitudinal patterns in macroinvertebrate communities varied between streams. Low-stability streams showed no clear longitudinal pattern. Streams with higher

channel stability showed clear longitudinal patterns, with highest Chl *a* and macroinvertebrate densities at upstream sites, closest to the snow water source. These streams differed to the characteristic patterns from glacier dominated streams, and nutrient and ionic leaching from melting snow is thought to be the reason for this. A future shift towards low stability streams may lead to reduced patterns in longitudinal community composition (Chapter 6).

- Macroinvertebrate communities exhibited large spatial variation in abundance and taxa richness between streams, and temporal variation between years in macroinvertebrate density. Streams with the highest channel stability supported highest abundance and taxa richness. Low channel stability streams showed higher interannual variation in diversity and evenness (Chapter 7) which implies that under future scenarios, streams in the region can be expected to have reduced macroinvertebrate density and taxa richness and increased interannual variation.
- The *Paralimnophyes* (Chironomidae) morphotype was reported for the first time in modern day Greenland, increasing our knowledge of taxa distribution throughout Greenland and the Arctic region (Dichotomous key in the appendix).

A dichotomous key to the Chironomidae of the region has been produced (Appendix A4) to assist future research efforts in the area.

8.2.2 Climate change in the Arctic

The Arctic is experiencing climate change three times faster than the rest of the world, where air temperature has risen by 2.9°C in the last century (Comiso & Hall 2014; Overland et al. 2015). Air temperatures are predicted to continue to increase and to cause large alterations to Arctic ecosystems, including decreasing the extent of glaciers (Walsh et al. 2005; Anisimov et al. 2007; Prowse et al. 2009a; Prowse et al. 2009b). Precipitation is expected to increase due to the retreat of sea ice intensifying local surface evaporation (Bintanja & Selten 2014) and active layer depth is expected to increase with melting permafrost.

The decrease in sea ice extent along east Greenland is predicted to alter the climate from continental to maritime. In northeast Greenland, precipitation is predicted to increase by up to 60% by the end of the 21st century, falling as snowfall in winter and rainfall in summer (Stendel et al. 2008). Air temperature is predicted to increase by up to 18˚C in winter and the number of thaw days in northeast Greenland is expected to increase from 80 to 248 per year (Stendel et al. 2008). The Zackenberg region has minimal glacial cover, as such predicted increases in snowfall are expected to cause increased meltwater contributions to stream ecosystems, unlike other parts of the world with a large glacial coverage.

8.2.3 Implications of a changing climate

The increase in snowpack size is expected to have a large impact on freshwater ecosystems. Larger spring floods destabilise stream bed and nearby sediments, increasing sediment inputs and channel mobility (Christiansen 1998a). Increased nivation processes such as backwall failure, pronival solifluction and the accumulation of alluvial fans further impact on stream sediment load and channel stability (Christiansen 1998b). Figure 8.1 highlights the impacts caused by small and large snowpacks on the landscape and stream ecosystems. Alongside this, the increased frequency of rain events and degradation of permafrost expected in the region have also been found to cause increased sediment flux and channel mobility. Streams are expected to receive increased runoff contributions from both meltwater and groundwater from increased snow depth and active layer depth.

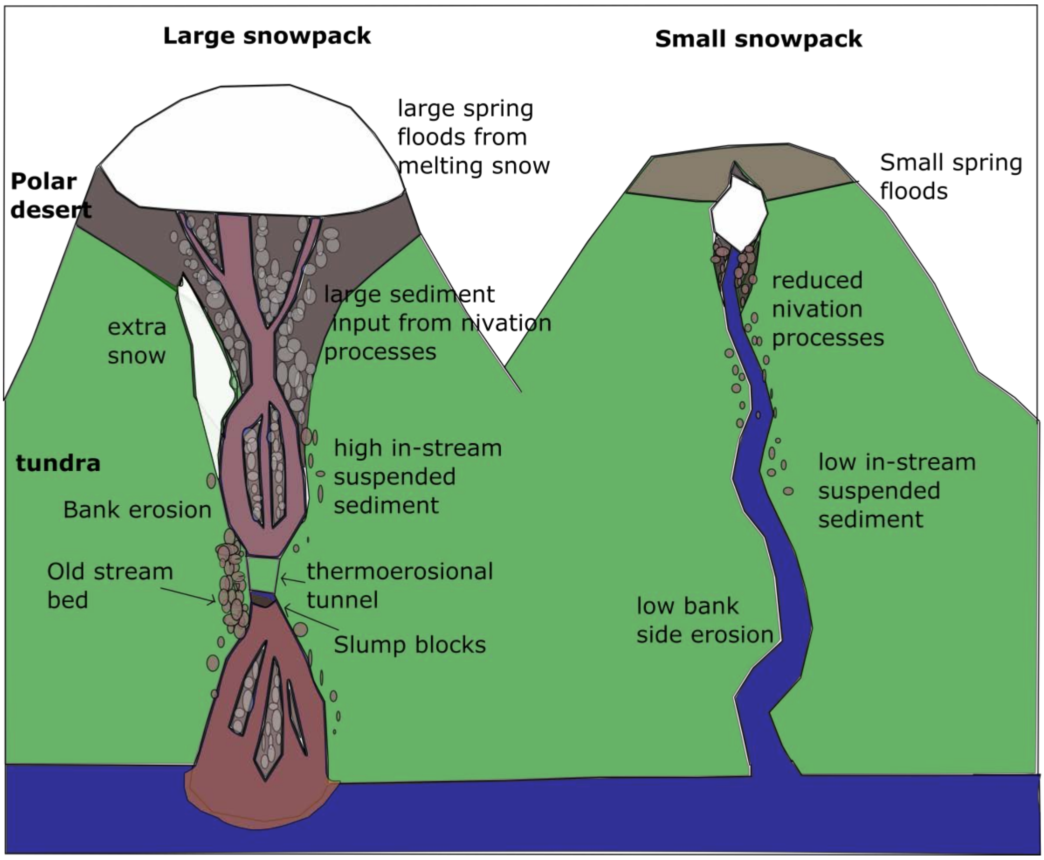

Figure 8.1. The impact of snowpack size on stream ecosystems. Left) large snowpacks lead to large spring floods and large nivation processes, increasing stream mobility and suspended sediment concentration, causing streams to have low channel stability. Right) small snowpacks lead to smaller spring floods and smaller nivation processes, causing streams to have higher channel stability.

The predicted climatic changes expected in the Zackenberg region by the end of the century could have a large impact on stream ecosystems, each chapter of this thesis has focused on different components of the cascading process that causes these impacts, where changes to climate impact water, sediment and solute inputs to streams, altering physicochemical habitat conditions and in turn, ecological communities. Figure 8.2 shows how these different components studied throughout this research, fit together through a conceptual flow diagram, and show how the predicted climatic changes will impact on stream ecosystems through this cascade.

The large variation in hydrological and ecological dynamics between the three consecutive years highlights the vulnerability of these systems to climatological forcing, illustrating the importance of long term records to fully understand stream dynamics. Whilst Zackenberg research station currently has a very well developed long term monitoring programme, the region’s streams are currently not a part of it. The variability in hydrological and ecological components of these stream ecosystems and their dependence upon climatic conditions highlights the importance of including them, even more so when considering the wider implications of shifts in macroinvertebrate community structure due to their role in the regions food web as a food source for Arctic char in the case of lakes (Svenning et al. 2007), and newly hatched bird chicks (Schekkerman et al. 2003; Tulp & Schekkerman 2008).

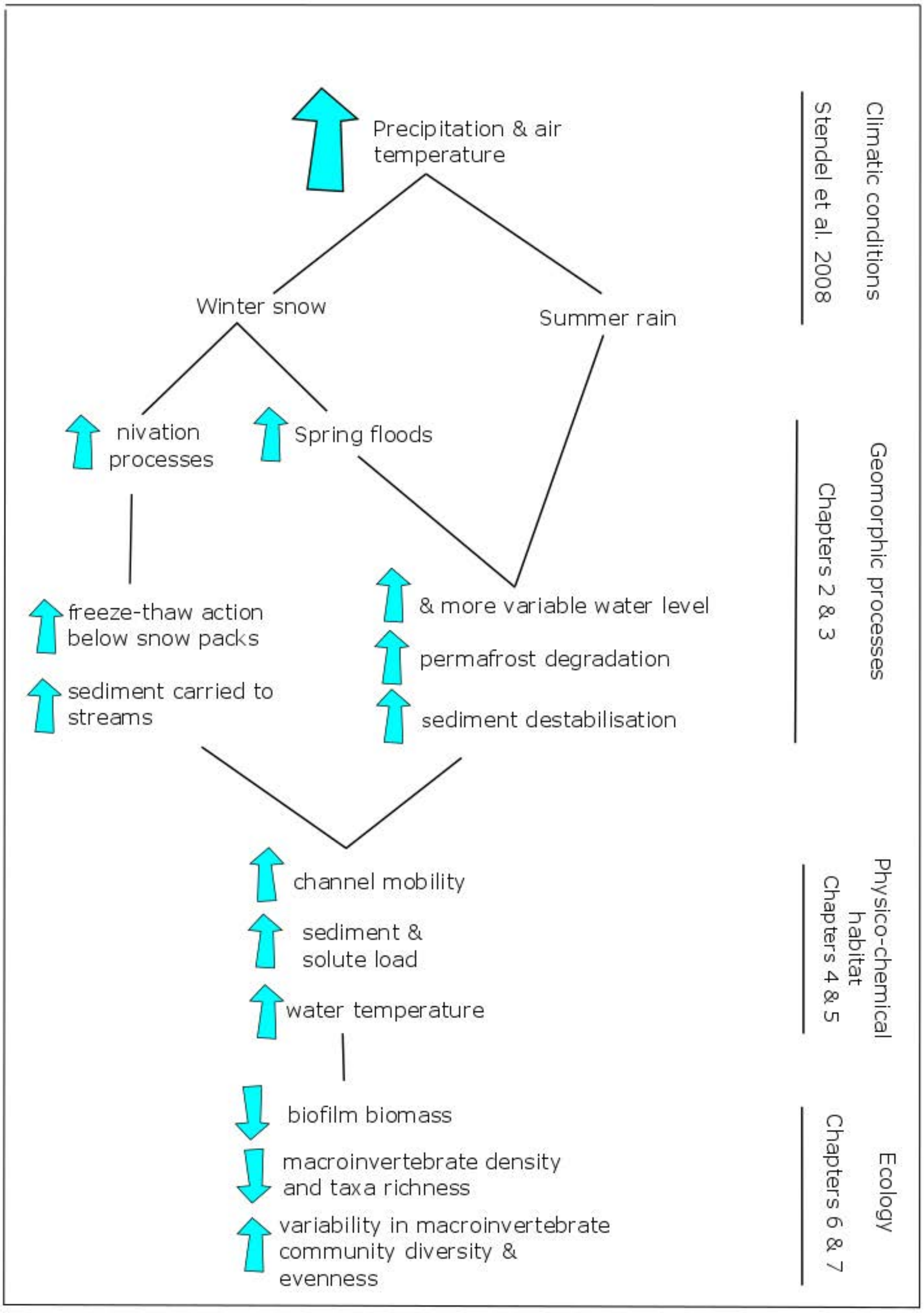

Figure 8.2. Conceptual model showing the impact of climate change on landscape and stream ecosystems. Blue arrows signify increase or decrease.

8.3 Recommendations for future research

As is common when conducting fieldwork in remote locations, this study has a number of limitations due to difficulties and trade-offs made in the field. Through these trade-offs and through the findings made in this thesis, the following recommendations for future research are made.

For this research project, field campaigns were short due to the economic cost involved in conducting research in remote locations. This limited the amount of data that could be collected (eg. repeated macroinvertebrate samples throughout the season; discharge measurements; suspended sediment samples), meant special attention could not be given to extreme events eg. heavy rain events, monitoring the development of the thermoerosional tunnel, and limited findings to a narrow window of time – during early summer peak melt season. As such, future research would benefit from longer field campaigns, ideally over the full summer season, or two field campaigns, one in early summer and one in late summer, to capture different conditions and to better represent conditions during the full summer season. This could also prove useful for macroinvertebrate identification. As Simuliidae (Diptera) collected in these field campaigns were too small to identify past family level, samples collected from later in the summer season may have been larger enough to successful identify, providing additional taxonomic information.

For the most part, all streams in this study were overlying sedimentary rock. The susceptibility of sedimentary rock to erosive processes means that the forces undergoing streams in this study may not be transferable to streams overlying less erosive material. Studies on streams overlying different rock types would provide additional information on snowmelt dynamics which combined with this study, would provide valuable information transferable to other Arctic stream systems.

The nutrient uptake experiments revealed interesting insights into nutrient limitations in Zackenberg streams, however results were limited due to the lack of replications. Future studies would benefit from including more streams in the experiment and conducting repeated uptake experiments throughout the summer season. This would provide information on the timing of peak nutrient uptake in streams in relation to peak snowmelt and groundwater inputs, and as such, provide information on how this peak may change temporally with changing water source contributions.

In order to understand if macroinvertebrate taxa variation between years is partly due to differences in adaptation between taxa in the length of time spent in the larval stage, it would be valuable to collect samples of frozen bed sediment throughout the winter months in order to ascertain which, if any, species are able to overwinter and as such, determine time spent in larval stage. Also, to better account for this variability in community composition, I would recommend sampling both hydrological and ecological variables on a regular basis throughout the whole summer season, from spring ice-off to autumn ice-on in order to ascertain seasonal variation in physicochemical habitat and macroinvertebrate communities throughout the productive, summer period.

This research has highlighted considerable variation in both physicochemical properties and ecology within streams sourced by snowmelt. As the hydroecology of snowmelt streams have received negligible attention compared to glacial streams, yet snowmelt is expected to become the dominant meltwater source in many areas, further research within these systems is recommended in order to understand the full implications of a changing climate.

The variation in macroinvertebrate density over the three years depending on snowfall conditions, highlights how unpredictable these systems are. The inclusion of stream hydrological and ecological properties in the current Zackenberg long term monitoring programme would be beneficial to trace ecological changes and the indirect influence of meteorological variables. Given the large time commitment required for macroinvertebrate identification, and based on the results of this thesis, as a trade-off, I would recommend focusing monitoring efforts on two of the streams used in this study, Kaerelv, as a representative for stable streams sourced from temporary snowpacks, and Aucellaelv, representative of low stability streams with perennial snowpacks.

8.4 Final summary

The aim of this thesis was to understand the patterns and processes determining how climate drives hydroecological patterns and processes in Arctic snowmelt streams, thus increasing our understanding of the vulnerability of Greenlandic stream systems to a changing climate. Large differences in physicochemical habitat and ecological dynamics have been found between streams with large perennial snowpacks and streams with small seasonal snowpacks, and large interannual variation has been found dependent upon meteorological variables. This thesis has significantly increased our understanding of hydroecological patterns and processes in snowmelt streams in the high Arctic and has broadened our knowledge of Arctic stream patterns and processing by increasing the span of sites studied within the Arctic. Our knowledge of the taxa inhabiting isolated northeast Greenland streams has increased, and an identification key to aid future research in the area has been produced. It is thought that with a changing climate in northeast Greenland towards increased air temperatures and increased precipitation, larger snowpacks will cause larger spring floods and increased nivation processes, reducing channel stability and increasing channel mobility, and warmer air temperatures will lead to permafrost degradation. These processes will cause increased sediment and solute inputs to streams, summer water temperatures could initially remain low due to high meltwater inputs, but into later summer could increase in line with warmer air temperatures. Due to these habitat changes, it is predicted that macroinvertebrate communities under future conditions will have reduced density and taxa richness.

With Arctic stream literature focusing largely on the impact of climate change on glacial systems, it is hoped that the information provided in this thesis will compel increased research efforts onto snowmelt streams and the impact of climate change in parts of the Arctic where meltwater contributions are predicted to increase, instead of decrease.

8.5 References

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APPENDICES

A1. INSTRUMENTATION

In this section, details on instrumentation used for data collection will be given.

A1.1 Meteorological variables

Data were collected from the M3 meteorological station, maintained by Geobasis, Zackenberg. The station was located on a gently sloping, southwest facing slope, halfway up the mountain Aucellabjerg at 420m above sea level, and approximately 5km in distance from the five principal study streams. All data were stored on CR1000 Campbell Scientific data loggers.

Table A1.1. Meteorological instrumentation

Variable	Unit	Resolution	Model	Manufacturer	Accuracy
Air temperature	˚C	30 minutes	MP103A Temperature and relative humidity probe	Campbell Scientific	±0.5˚C
Relative Humidity	%	30 minutes	MP103A Temperature and relative humidity probe	Campbell Scientific	±1%
Snow depth	cm	30 minutes	SR50A Sonic ranger	Campbell Scientific	±1cm
Soil moisture	$M^3. M^{-3}$ or % vol.	30 minutes	Theta ML2X Soil moisture probe	Delta T, Cambridge UK	$0.05M^3. M^{-3}$
Precipitation	mm	60 minutes	Belfort 5915 x Ott Pluvio	Belfort Ott Pluvio	±0.05% F.S. Amount ±0.05 mm
Incoming shortwave radiation	W/m^2	30 minutes	Four component net radiometer CNR1	Kipp & Zonen	10% accuracy for daily totals
Incoming longwave radiation	W/m^2	30 minutes	Four component net radiometer CNR1	Kipp & Zonen	10% accuracy for daily totals

A1.2 Hydrological variables

Continuous readings of water temperature, stream bed temperature and water level were stored on Campbell Scientific CR1000 data loggers which scanned every 10s and recorded every 15 minutes.

Table A1.2. Hydrological instrumentation

Variable	Unit	Resolution	Model	Manufacturer	Accuracy
Water temperature	˚C ˚C	30 minutes 15 minutes	TinyTag Aquatic 2 TG-4100 107 temperature probe	Gemini Campbell Scientific	±0.01˚C ±0.01˚C
Stream bed temperature	˚C	15 minutes	107 temperature probe	Campbell Scientific	±0.01˚C
Conductivity	mS µs/cm	15 minutes -	CS547A Water conductivity and temperature probe HI-98129 Pocket EC/TDS and pH Tester	Campbell Scientific Hannah Instruments	±5% ±2% F.S.
pH		-	HI-98129 Pocket EC/TDS and pH Tester	Hanna Instruments	±0.05Ph
Water level	m	15 minutes	1830 Druck High Performance Level Pressure Sensor	Druck	±0.10%
Water velocity	m/s	-	µP-TAD	Höntzsch instruments, Germany	
Dissolved oxygen	%	-	YSI ProODO optical dissolved oxygen meter	YSI	±1%

A1.3 Hydrochemistry analysis

Major cations and nutrients were analysed on a Lachat QuickChem flow injection analyser (Lachat Instruments, APC Bioscientific Limited, England; APHA 2012). Accuracy: 0.5%.

A2. IMAGES

Additional images of sites and methods are included in this section. All images copyright to Catherine Docherty unless otherwise mentioned.

Figure A2.1 Unnamed2 stream from chapters 2 and 4. Sampled in 2013 only. Downstream view.

Figure A2.2 Unnamed2 upstream view

Figure A2.3 Photo taken from plane in July 2014 showing Zackenberg station and locations of streams.

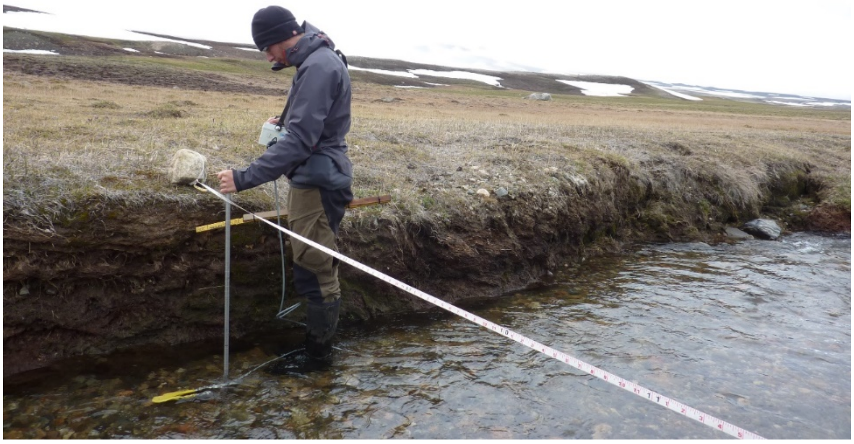

Figure A2.4 Water velocity measurements being taken to calculated discharge.

Figure A2.5 Nutrient uptake experiment in Aucellaelv (cross reference to chapter 5)

Figure A2.6 Nutrient diffusing substrate. Photo: Simon Rosenhøj Leth (cross reference to chapter 5)

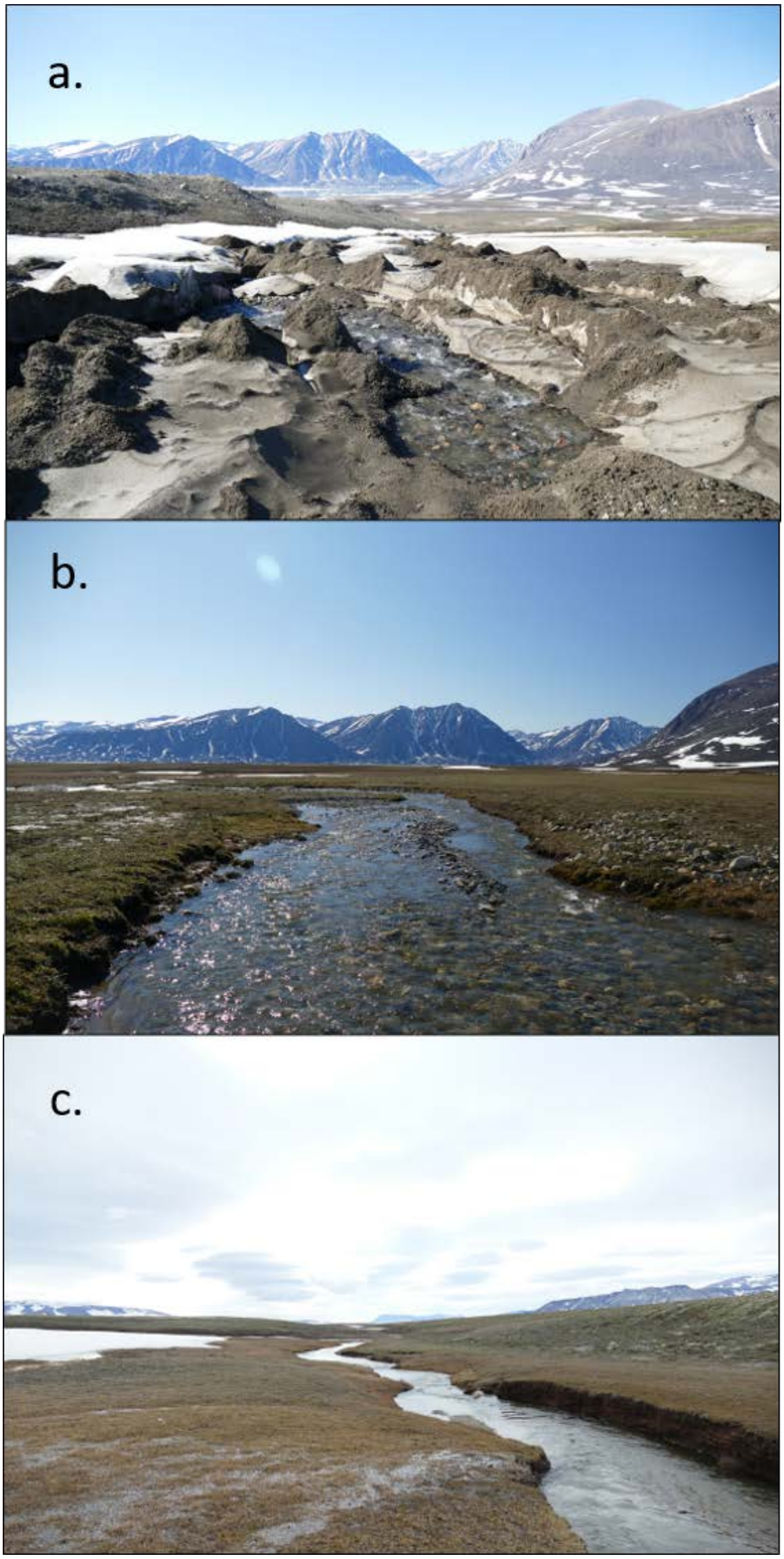

Figure A2.7 Longitudinal sites A, B, C in Kaerelv (cross reference to chapter 6)

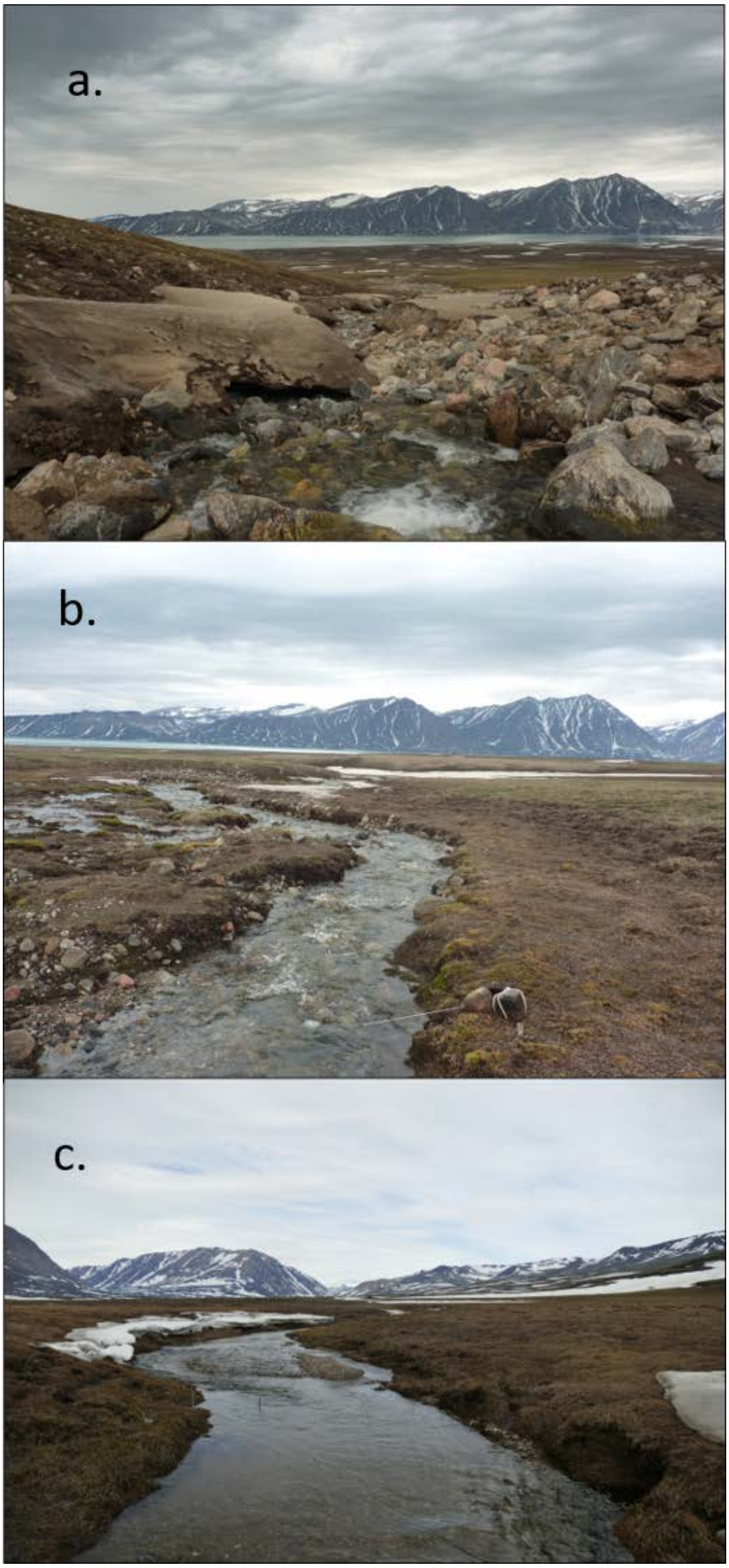

Figure A2.8 Longitudinal sites A, B, C in Graenseelv (cross reference to chapter 6)

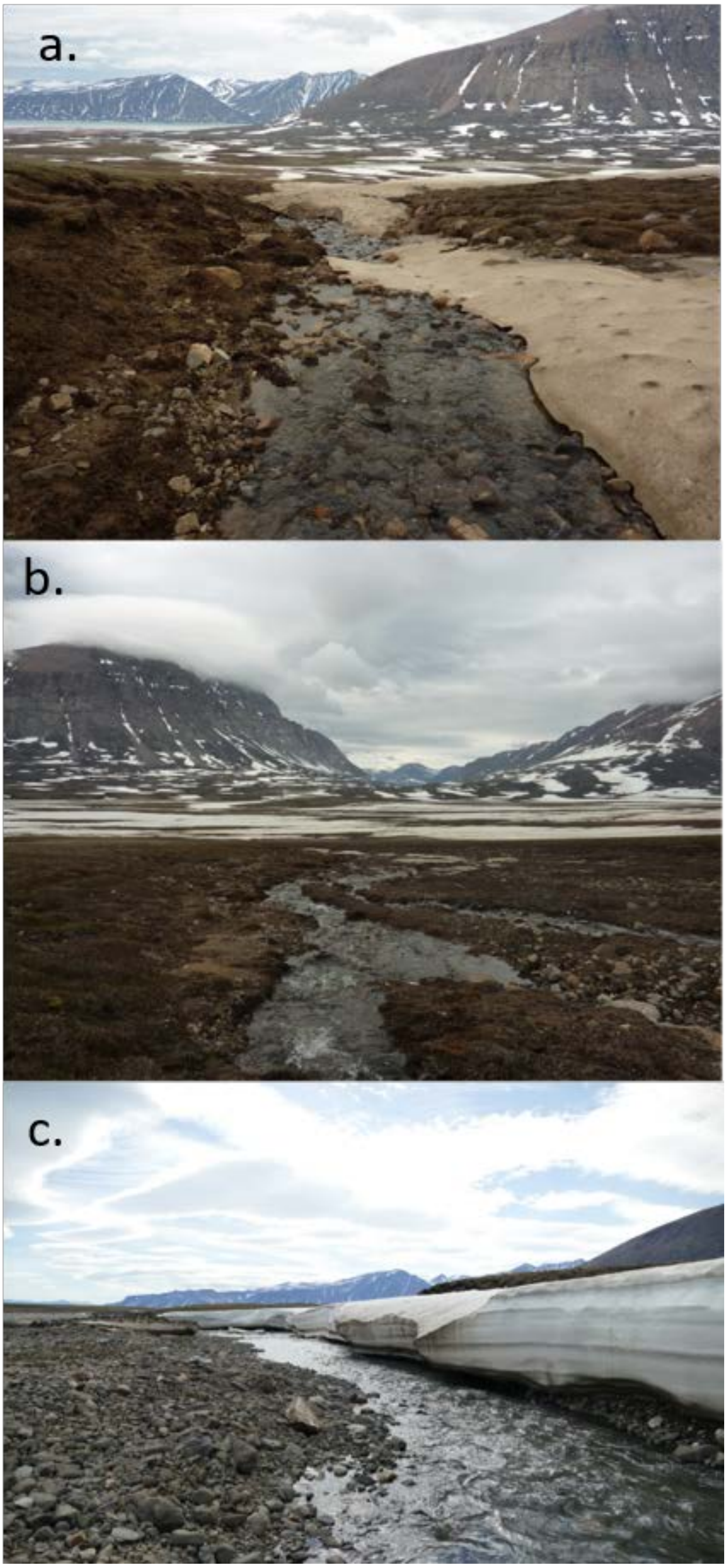

Figure A2.9 Longitudinal sites A, B, C in Unnamed (cross reference to chapter 6)

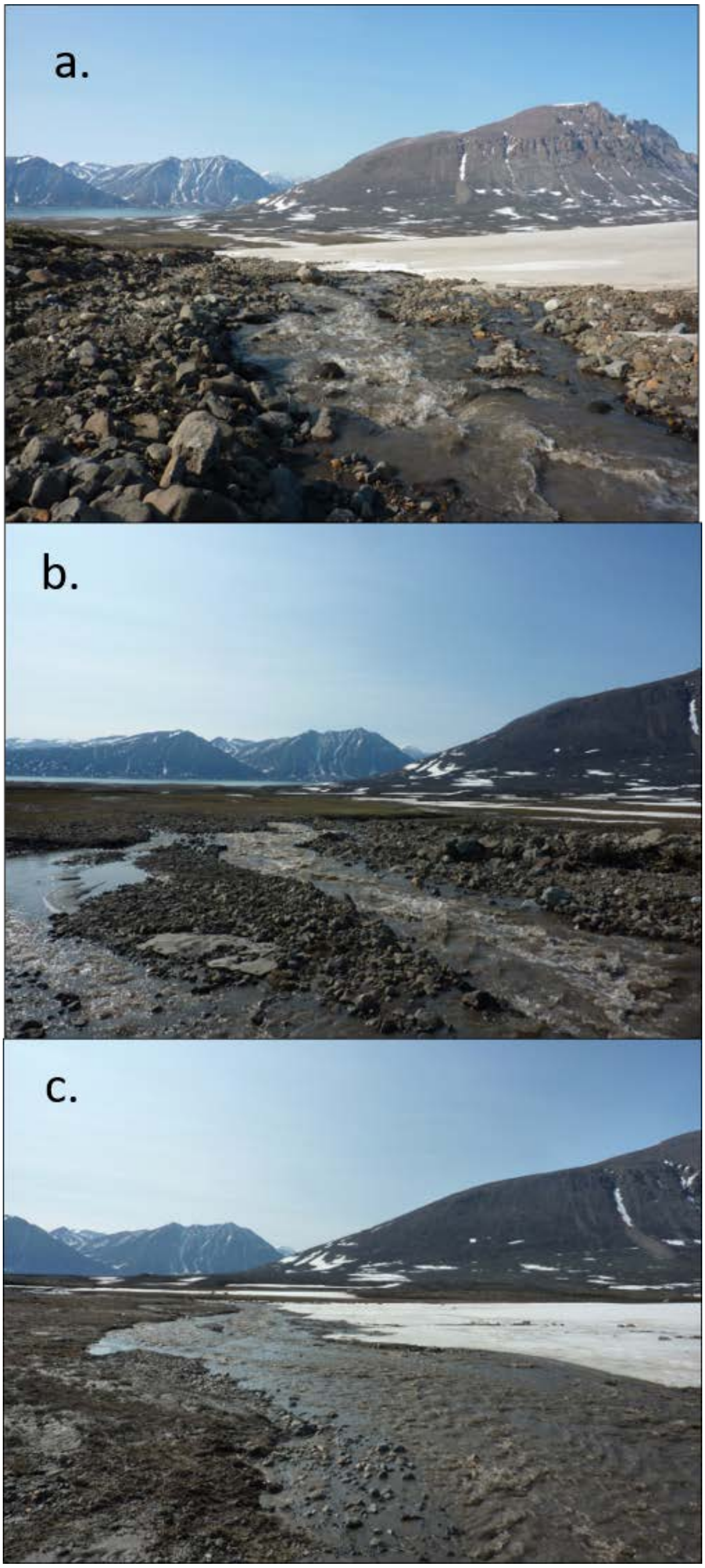

Figure A2.10 Longitudinal sites A, B, C in Aucellaelv (cross reference to chapter 6)

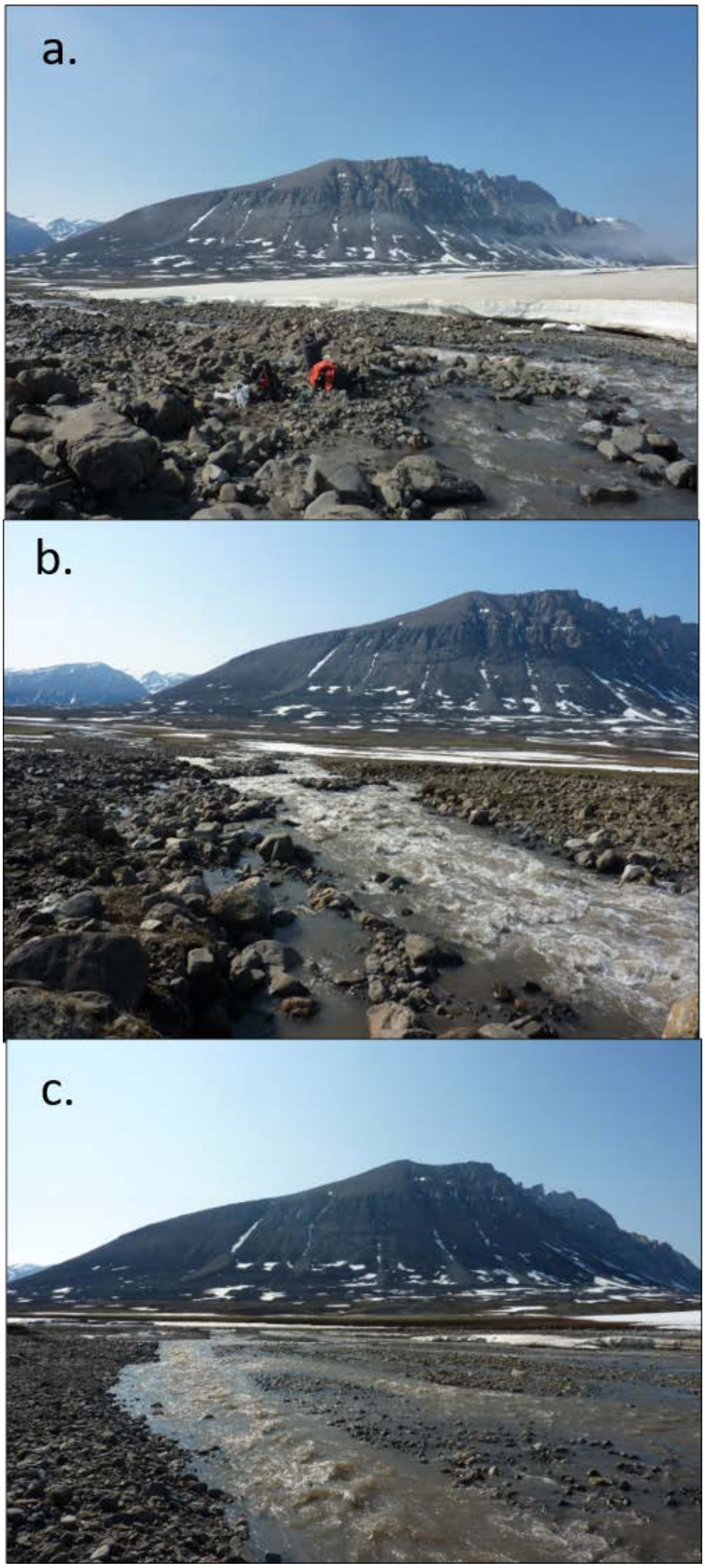

Figure A2.11 Longitudinal sites A, B, C in Palnatokeelv (cross reference to chapter 6)

A3. TAXA LISTS

Table A3.1 List of identified taxa from longitudinal sites in 2015

Taxa	**Identification literature**	**Number of specimens per site and stream***
Chironomidae		
Diamesinae		
Diamesa	Brooks 2007; Wiederholm 1983	4,0,2; 2,12,1; 27,7,2; 14,36,5; 3,23,3
Diamesa A.		0,0,0; 0,0,0; 10,12,0; 0,0,0; 0,0,0
Orthocladinae		
Chaetocladius dentiforceps-type	Brooks et al. 2007	0,0,0; 2,0,0; 1,0,0; 0,0,0; 0,0,1
Chaetocladius piger- type	Brooks et al. 2007	2,0,1; 0,0,0; 0,0,0; 1,0,0; 0,1,0;
Corynoneura edwardsi- type	Lindegaard 2015; Wiederholm 1983	0,3,6; 0,5,4; 0,0,0; 0,0,0; 0,0,0
Cricotopus type P	Brooks et al. 2007	0,0,0; 0,0,1; 0,0,0; 1,0,0; 0,0,0
Diplocladius cultriger	Lindegaard 2015; Brooks et al. 2007	2,2,16; 0,0,2; 0,0,0; 0,0,0; 1,0,0
Eukiefferiella	Wiederholm 1983	423,33,15; 324,38,11; 127,1,0; 0,4,3; 4,2,0
Eukiefferiella brehmi group	Wiederholm 1983	335,27,10; 353,63,7; 67,3,0; 2,1,1; 10,27,9
Eukiefferiella gracei group	Wiederholm 1983	0,0,0; 0,1,0; 0,0,0; 0,0,0; 0,0,0
Hydrobaenus conformis type	Brooks et al. 2007; Sæther 1976	1,0,1; 0,0,1; 0,0,0; 0,0,0; 0,0,0
Hydrobaenus lugubris type	Brooks et al. 2007; Sæther 1976	3,5,25; 5,10,15; 0,0,0; 0,0,0; 0,0,0
Krenosmittia	Lindegaard 2015; Brooks et al. 2007; Wiederholm 1983	6,14,19; 0,28,19; 0,0,0; 0,0,0; 0,0,0
Limnophyes	Wiederholm 1983	0,0,2; 0,2,1; 0,1,0; 0,0,0; 0,0,0
Metriocnemus eurynotus (=hygropetricus)- type	Wiederholm 1983	0,3,1; 0,0,1; 0,2,3; 0,0,1; 0,0,0
Orthocladius Euorthocladius	Cranston 1982	12,25,20; 0,1,5; 7,0,1; 0,0,0; 0,5,0
Orthocladius oliveri type	Brooks et al. 2007	16,22,3; 12,3,4; 8,2,0; 3,2,1; 0,0,0
Orthocladius S type	Brooks et al. 2007; Oliver & Roussel 1983	13,10,23; 1,1,12; 71,45,5; 0,2,1; 2,2,0

Paralimnophyes	Wiederholm 1983	10,31,47; 8,27,21; 11,5,4; 0,1,1; 2,2,0
Paraphaenocladius	Wiederholm 1983	2,2,0; 0,0,0; 0,0,0; 0,0,0; 0,0,0
Pseudosmittia	Ferrington & Saether 2011	0,0,0; 0,1,0; 1,1,2; 0,1,0; 0,0,0
Smittia	Wiederholm 1983	0,0,0; 0,1,0; 0,1,5; 0,0,0; 0,0,0
Other taxa		
Oligochaeta	-	2,2,54; 1,8,80; 7,9,2; 0,1,3; 0,0,2
Simuliidae	-	0,2,2; 0,5,2; 0,0,0; 0,0,0; 0,0,0
Collembola	-	0,0,0; 0,0,0; 3,1,0; 0,0,0; 0,0,1
Aranea	-	0,0,0; 0,0,0; 0,0,1; 0,0,0; 0,0,0
Ceratopogonidae		0,1,1; 0,0,0; 0,0,0; 1,0,0; 0,0,0
Clinohelea	Dobson, 2013; Nilsson, A. 1996	0,1,0; 0,0,0; 0,0,0; 0,0,0; 0,0,0
Culicoides	Dobson 2013; Nilsson, A. 1996	0,0,1; 0,0,0; 0,0,0; 1,0,0; 0,0,0
Limoniidae		
Chioneinae	Dobson, 2013; Nilsson, A. 1996	0,0,0; 1,1,0; 0,1,0; 0,0,0; 0,0,0

*Number of specimens per stream in order sites A,B,C for streams Kaerelv, Graenseelv, Unnamed, Aucellaelv, Palnatokeelv, respectively.

Table A3.2 List of identified taxa and number of individuals collected in 2013, 2014 and 2015.

Taxa	Kærelv			Grænseelv			Palnatokeelv			Unnamed			Aucellaelv		
	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015	2013	2014	2015
Chironomidae															
Allocladius	0	11	0	0	3	0	0	0	0	0	6	0	0	1	0
Chaetocladius dentiforceps- type	0	0	0	1	0	0	0	0	0	2	0	0	0	0	0
Chaetocladius piger - type	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0
Corynoneura edwardsi - type	112	46	6	129	12	4	0	0	0	0	0	0	1	0	0
Cricotopus type P	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
Diplocladius cultriger	12	19	16	3	10	2	0	0	0	2	1	0	0	0	0
Eukiefferiella	2	5	15	2	1	11	5	5	0	0	0	1	3	0	3
Eukiefferiella brehmi group	10	6	10	1	0	7	0	5	9	0	1	0	0	0	1
Eukiefferiella cynea group	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Hydrobaenus	95	2	9	63	14	6	0	0	0	0	0	0	0	0	0

Hydrobaenus conformis type	43	5	1	88	8	1	0	0	0	0	0	0	0	0	0
Hydrobaenus lugubris type	68	17	25	73	44	15	0	0	0	0	3	0	1	0	0
Hydrosmittia	0	3	0	0	1	0	0	0	0	0	0	0	0	0	0
Krenosmittia	0	12	19	3	0	19	0	0	0	0	0	0	0	0	0
Limnophyes	0	4	2	0	3	1	0	0	0	0	1	0	0	0	0
Metriocnemus eurynotus (=hygropetricus) type	0	7	1	0	0	1	0	3	0	0	0	3	0	0	1
O. Euorthocladius I	4	5	20	1	2	5	8	5	0	1	0	1	17	0	0
Orthocladius G1	22	0	1	11	2	0	0	0	0	0	0	0	0	0	0
Orthocladius oliveri type	27	2	3	18	3	4	0	1	0	0	1	0	0	0	2
Orthocladius S type	6	1	23	6	0	12	5	1	0	0	0	5	1	0	0
Orthocladius	4	1	0	15	1	5	2	0	0	0	0	0	0	0	0
Paralimnophyes	16	70	47	3	38	21	1	1	1	3	12	4	7	1	1
Paraphaenocladius	0	6	0	0	2	0	0	1	0	0	1	0	0	0	0
Pseudosmittia	0	1	0	0	2	0	0	0	0	0	0	2	0	0	0
Smittia	0	3	0	0	0	0	0	0	0	1	0	5	0	0	0

Thienmaniella clavicornis	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0
Podonominae	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Diamesa aberrata	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0
Diamesa	0	0	2	0	0	1	123	0	3	4	0	2	49	2	5
Collembola	0	0	0	0	1	0	0	0	1	0	0	0	0	0	0
Oligochaeta	104	82	53	13	107	80	31	10	2	27	68	2	141	1	3
Ceratopogonidae															
Clinohelea	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Culicoides	0	0	1	0	1	0	0	0	0	0	1	0	0	0	0
Simulidae	1	33	1	10	4	2	0	0	0	0	0	0	0	0	0
Limonidae															
Chioneinae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Muscidae															
Spilogona	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
Sciaridae	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Acari	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Araneae	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0

A4: IDENTIFICATION KEY TO THE CHIRONOMIDAE (INSECTA: DIPTERA) LARVAE OF ZACKENBERG STREAM SYSTEMS, NORTHEAST GREENLAND

Abstract

Chironomidae are notoriously difficult to identify beyond family level, however they can provide us with copious information on habitat conditions and can be used as a method of monitoring environmental change. Arctic streams are expected to be largely affected by a changing climate due to changes in glacial and permafrost extent and precipitation, altering stream water source proportions. For the first time, larval Chironomidae are documented from streams in northeast Greenland, specifically around Zackenberg research station. Collected over four consecutive field campaigns (2013 to 2015), 7,053 individual larvae were mounted and identified distinguishing 33 morphological types in the subfamilies Orthocladiinae, Diamesinae, Podonominae and Tanypodinae. *Paralimnophyes* (Orthocladiinae) was recorded for the first time in modern day Greenlandic records. Two new Orthocladiinae morphotypes and Diamesinae morphotypes are also described. This key provides an identification tool for future freshwater research on stream ecosystems in the Zackenberg valley thereby increasing our knowledge of Greenlandic and Arctic Chironomidae larvae.

A4.1 Introduction

The family Chironomidae (Diptera), commonly referred to as non-biting midges, are found on every continent and in all ecosystems where water can be found, from the tropical rainforests of South America, Africa and Asia, to the high Arctic at 81° N in Ellesmere Island, Canada, and mainland Antarctica to 68° S (Oliver & Corbet 1966; Usher & Edwards 1984). Globally they are abundant and diverse. Larvae have colonised environments that are characterised by extremes of water temperature, current velocity, pH, depth, and salinity (eg Armitage *et al.* 1995). Given that Chironomidae species have different and wide ecological requirements, they are an effective group for monitoring water quality and a changing climate. However, limitations and contradictions in taxonomy and the perception that larval Chironomidae are difficult to identify typically means that most ecological studies only identify chironomids to family level, leaving a significant gap in an accurate understanding of freshwater biodiversity and their role in ecosystem functioning.

A4.1.1 Chironomids in Greenland

Greenland spans subarctic, low arctic and high arctic climate zones, and 80% of its land area is covered by the ice sheet, making it a harsh environment for many species. Greenland is known to have a low diversity of aquatic invertebrates (Böcher *et al*. 2015), however, compared to other aquatic insect taxa, Chironomidae are well represented in Greenland becoming more dominant with increasing latitude (Böcher *et al.* 2015).

Northeast Greenland is an area experiencing change. Currently dominated by the ice sheet, and glaciers, ice recession is causing more land to be exposed, a process expected to increase in the coming years. Climate change also has a direct impact on Greenlandic stream systems by influencing stream water sources. With reduced glacier mass balance and a decrease in the extent of permafrost, streams are shifting from being predominantly meltwater sourced to being sourced by snowfall, rainfall, wetlands and groundwater, thereby altering stream physico-chemical habitat (Brown *et al*. 2007). These changes will influence the area's ecology.

The in-depth identification key to the Insecta and Arachnida of Greenland recently published (Böcher *et al.* 2015), including a chapter where chironomid larvae are identified to genus level (Lindegaard 2015), is a tremendous resource in Greenlandic and Arctic taxonomy, especially given the lack of stream ecology research conducted in Greenland (but see Friberg et al. 2001; González-Bergonzoni et al. 2014; Docherty et al. 2017). However, as this present study will show, the coverage is not exhaustive. Due to the large size of Greenland incorporating different climate zones, wide spread, in-depth studies are needed to build a thorough compilation of Greenlandic Chironomidae, as well as to monitor change over the coming decades.

The aim of the project was to undertake the first in-depth study of Chironomidae, the dominant macroinvertebrate group in streams within the Zackenberg valley, and identify larvae beyond family level. The identification key produced as a result of this project has three principal objectives: (1) to provide a mechanism to identify Chironomidae larvae of northeast Greenland to morphotype, (2) to build on the knowledge base provided by Lindegaard (2015) on the distribution of Greenlandic Chironomidae; and (3) to serve as a tool for future researchers in the Zackenberg valley and surrounding area to enhance both taxonomic and biogeographic data both for Greenland and as a contribution to the wider Arctic area.

A4.2 Methods

A4.2.1 Study site

The Zackenberg Research Station was set up in 1995 to undertake long term ecosystem monitoring and research in the Arctic. It was the first of its kind in high-Arctic Greenland (Meltofte *et al.* 2008) and, although previous studies have included terrestrial invertebrates and pond ecosystems, this was the first study of stream communities at Zackenberg.

Zackenberg (74º28’ N, 20º34’ W) is located in the northeast Greenland National Park (Figure 1) approximately 60km from the Greenland ice sheet in the high Arctic climatic zone. Altitude varies between 0 and 1450m a.s.l with glacial plateaux occurring above 1000m a.s.l and wide valleys caused by glacial erosion below (Mernild *et al.* 2007). It has low glacial coverage, with only a number of small glaciers remaining at high altitude. It is a zone of continuous permafrost with active layer thickness between 30 and 65cm (Christiansen et al. 2008) within the valley. The main sampling sites as shown in Figure 1 are all located on the valley floor, however in 2015 sampling also took place further upstream on hillslopes. With the recession of the main ice sheet, the total ice-free area of Greenland is expected to increase, and hence the Zackenberg valley provides a future indication of an increasingly common ecosystem in northeast Greenland. Samples were collected from the nine streams shown in Figure 1. Kaerelv, Graenseelv and Vestelv are relatively high stability streams with low turbidity. Aucellaelv and Palnatokeelv are low stability, high turbidity, systems where the streams are known to change course frequently. Other streams represent a range of intermediate stabilities. All streams are known to freeze to the stream bed between late September and early June, and mean water temperature during the summer months of mid-July to mid-September is between 3.3°C and 5.6°C.

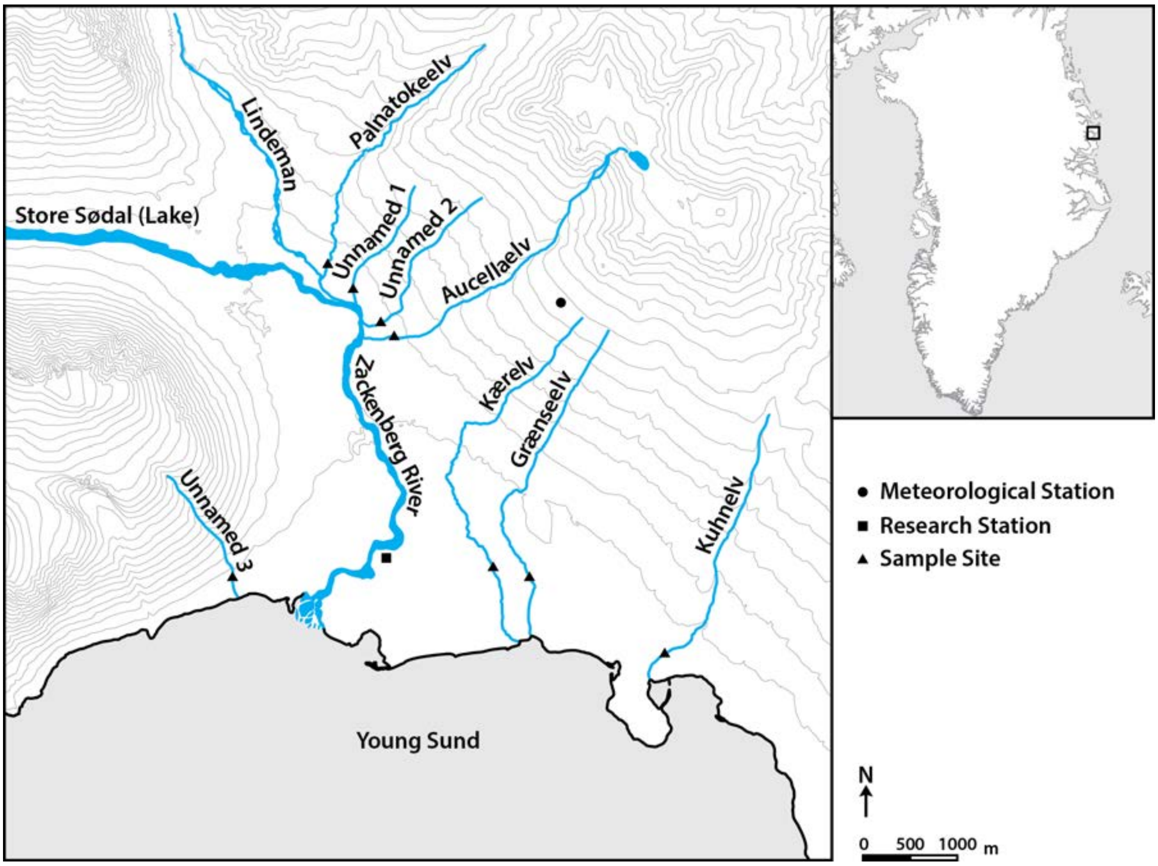

Figure A4.1. Study site and its location within Greenland.

A4.2.2 Specimen collection and Identification

Macroinvertebrate samples were collected by Surber sampler in riffle areas, collecting five replicates at each site over three years (2013 to 2015), from a total of nine streams, in late June and July each year and again in September 2014. Samples were stored in 90% ethanol in plastic Whirlpak bags. In the laboratory, samples were hand sorted and mounted onto microscope slides using DMFH mountant. Before mounting, specimens with dark-coloured head capsules were immersed in 10% potassium hydroxide (KOH) solution on a hot plate at 60°C, for 15 minutes to lighten the head capsule in order to make characteristic features easier to see. Specimens were identified to the lowest possible taxonomic level using the following keys; Brooks *et al.* (2007), Cranston (1982), Ferrington & Saether (2011), Lindegaard (2015) and Wiederholm (1983). Antennal ratios were calculated as the length of basal segment: length of remaining segments.

A4.3 Results and Taxonomy

A total of 7,053 individual Chironomidae larvae were identified between 2013 and 2016. Of the eleven subfamilies of Chironomidae, only four were collected in the Zackenberg area in comparision to the six subfamilies found by Lindegaard (2015) for Greenland as a whole. The most abundant was Orthocladiinae (28 species-morphotypes), followed by Diamesinae and then Podonominae and Tanypodinae. A total of 33 morphotypes were identified. *Paralimnophyes* Brundin 1956 (Orthocladiinae) appears to be a new record of this genus for Greenland. Two new morphotypes of Orthocladiinae: *Orthocladius G* type, and *Orthocladius G1* type, and two Diamesinae: *Diamesa "A"*and *Diamesa "B"* are described in this key that cannot be identified further using current keys.

This key adds additional data to Lindegaard (2015), including the high abundance of *Paralimnophyes*, the discovery of *Hydrosmittia* Ferrington and Saether 2011 and *Allocladius* Kieffer 1913 (although adult *Allocladius* is documented in Zackenberg by Wirta et al. 2015), and the morphological variation found for *Orthocladius (Euorthocladius)* Thienemann 1935. These findings add to our current knowledge of species distribution within Greenland as documented in Lindegaard (2015). For example, *Diplocladius cultriger* Kieffer 1908, is currently documented only in the southwest; and *Krenosmittia* Thienemann and Krüger 1939 currently documented only in the south and southwest of the country. This key identifies their presence in Northeast Greenland.

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A4.3.1 Morphology

The key characteristics used for identification are given in Figures 2 and 3 below.

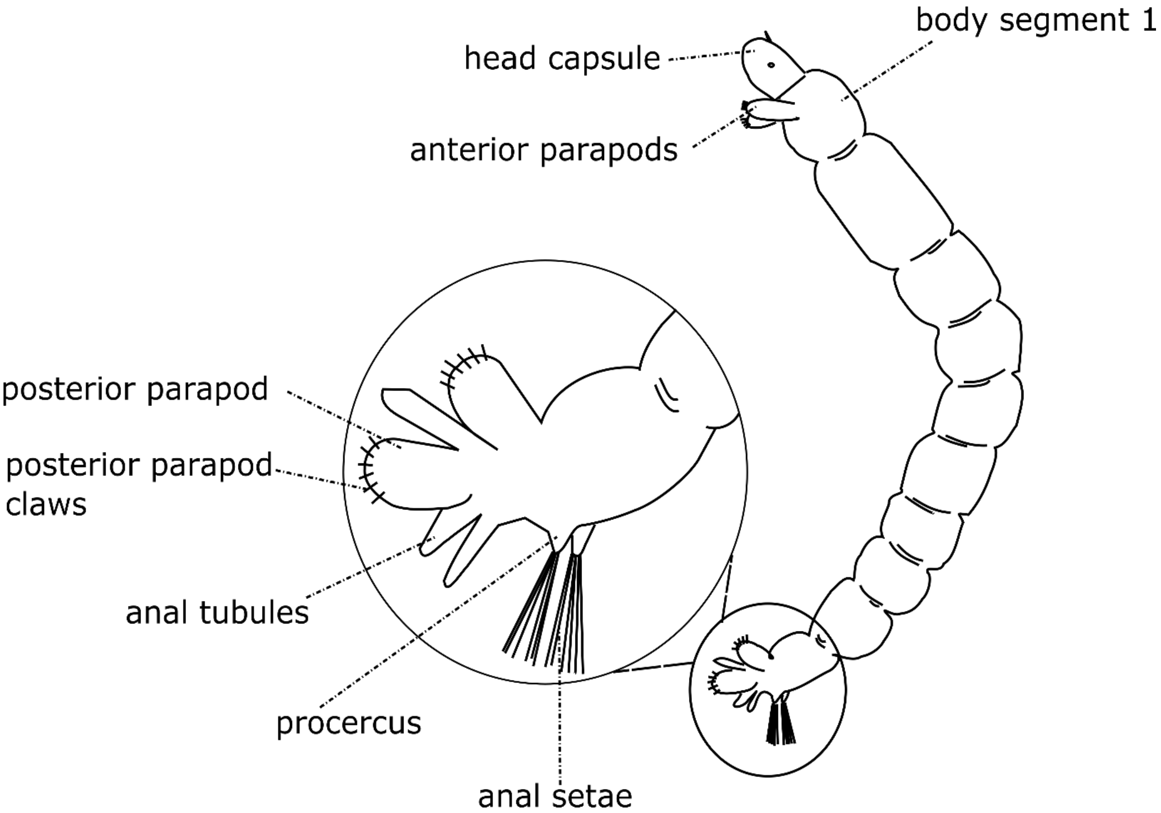


Figure A4.2. lateral view of Chironomidae larvae (modified from Wiederholm, 1983)

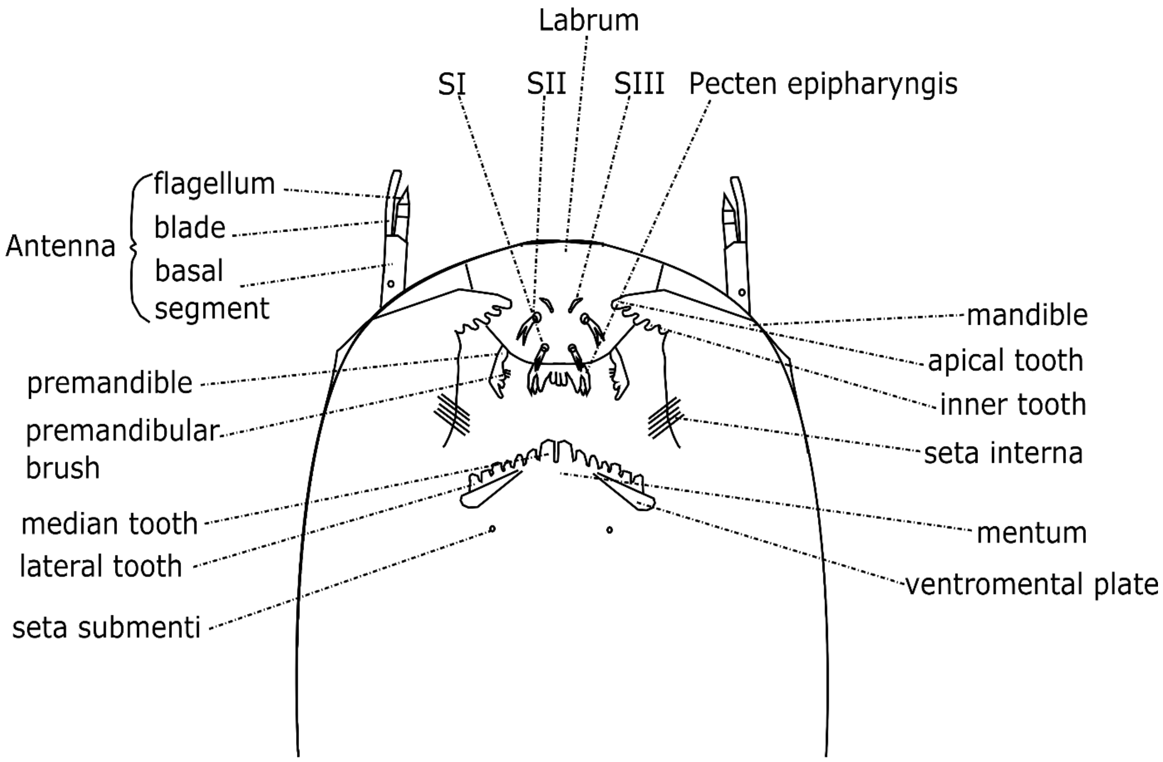


Figure A4.3. Ventral view of Chironomidae larval head capsule (modified from Wiederholm 1983)

A4.3.2 Challenges identifying chironomid larvae

Problems in identification arise when identifying specimens in poor condition due to (i) poor mounting, (ii) natural variation or (iii) 'wear and tear' of specimens. A specimen could be missing an antennal blade, have worn down mandible and mentum teeth, or occasionally have an extra lateral tooth on one side. Figure 4 (a) illustrates a *Paralimnophyes* specimen in good condition, and so relatively easy to identify, and (b) in a worn condition, highlighting the challenges of Chironomidae identification. A reference collection at hand with which to compare difficult specimens is valuable.

Another challenge is related to the identification literature available. Many keys are in need of updating and lack accurate ecological information, however, research efforts on Chironomidae identification are increasing and there are numerous tools available aiding identification (eg. Ashe & Cranston 1990; Oliver *et al.* 1990; Ferrington & Saether 2011; Andersen *et al.* 2013, and Lindegaard 2015).

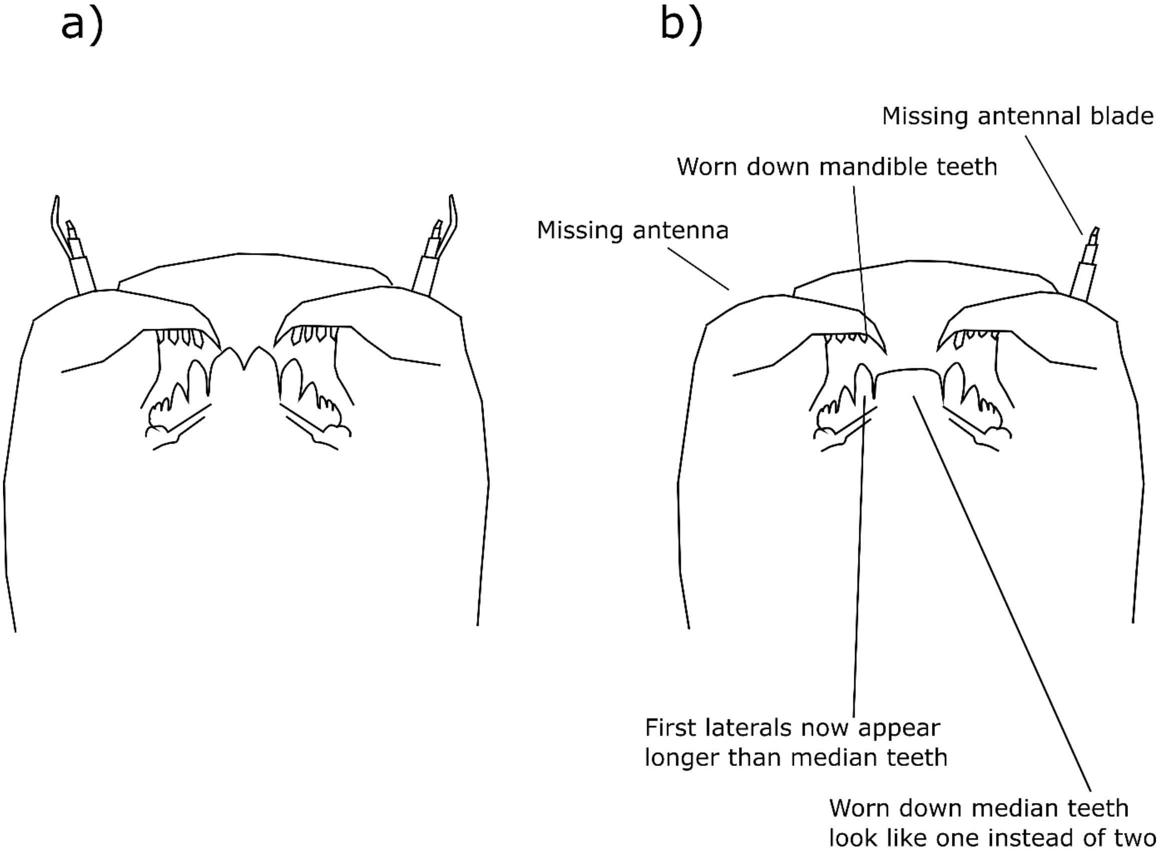


Figure A4.4. Chironomidae larvae recorded from streams in the Zackenberg valley

A4.4 Taxa list

Below is the complete list of larval taxa found throughout this study. For a full list of species from the Zackenberg valley, identified to species level from adult DNA see Table S1 in the supplementary material for Wirta *et al.* (2016)

Diamesinae

Diamesa Meigen 1835

- *Diamesa aberrata* Lundbeck

- *Diamesa A* (first description herein)

- *Diamesa B* (first description herein)

Orthocladiinae

Allocladius Kieffer 1913

Camptocladius V.d. Wulp 1874

Chaetocladius Kieffer 1911

- *Chaetocladius dentiforceps* -group = *connectens* group, Thienemann 1936

- *Chaetocladius piger* -group Goetghebuer

Corynoneura Winnertz 1846

- *Corynoneura edwardsi*-type Brundin

Cricotopus V. d. Wulp 1874

- *Cricotopus* type P Brooks et al. 2007

Diplocladius Kieffer 1908

- *Diplocladius cultriger* Kieffer

Eukiefferiella Thienemann 1926

- *Eukiefferiella brehmi* Gouin-type
- *Eukiefferiella cynea* Thienemann-type
- *Eukiefferiella gracei* Edwards-type
- *Tokunagaia* Saether; Halvorsen & Saether (Previously *Eukiefferiella rectangularis* Thienemann-type)

Hydrobaenus Fries 1830

- *Hydrobaenus lugubris* Fries-group

Hydrosmittia Ferrington & Saether 2011

Krenosmittia Thienemann & Krüger 1939

Limnophyes Eaton 1875

Metriocnemus V. d. Wulp 1874

- *Metriocnemus eurynotus (Holmgren)*
  - =*hygropetricus*-type Kieffer

Orthocladius (Euorthocladius) Thienemann 1935

Orthocladius (Orthocladius) V. d. Wulp 1874

- *Orthocladius oliveri* -type Cranston et al.
- *Orthocladius S* type (resembles Fig. 346 of Oliver & Roussel, 1983 as cited in Brooks et al. 2007)

Orthocladius G type (first description herein)

Orthocladius G1 type (first description herein)

Parakiefferiella bathophila Kieffer

Paralimnophyes Brundin 1956

Paraphaenocladius Thienemann 1924

Pseudosmittia Edwards 1932

Rheocricotopus Brundin 1956

Rheocricotopus effusus -type Walker

Smittia Holmgren 1869

Thienemaniella Kieffer 1911

Thienemaniella clavicornis Kieffer

Podonominae

Trichotanypus Kieffer 1906

Tanypodinae

Procladius Skuse 1889

A4.5 Key to Chironomidae

1 Prementum with distinctive ligula. Antenna retractile. … Tanypodinae: *Procladius*

- Prementum with no distinctive ligula… 2

2 Striated third antennal segment; strongly branched seta interna, more than six lateral teeth on mentum; premandible absent or with three to seven teeth… 32

- Third antennal segment not striated; maximum of seven lateral teeth on mentum; one to two teeth on the premandible; … **Orthocladiinae:** 3

3 One median tooth on mentum, may be notched… 4 NOTE: beware worn teeth. Two may wear down to look like a single broad tooth (see Fig. 4). If unsure, key out both ways.

- More than one median tooth on mentum… 22

4 First pair of lateral teeth fused to a single, broad median tooth. Median and first lateral teeth weakly pigmented…*Parakiefferiella banophila*

- Median and first lateral teeth not as above… 5

5 Median tooth at least twice as broad as first lateral tooth on mentum… 6

- Narrow median tooth less than twice as broad as first lateral tooth on mentum… 17

6 Four lateral teeth on mentum... 7

- More than four lateral teeth on mentum…10

7 Posterior parapods, anal claws and anal setae absent… *Camptocladius*

- Posteriod parapods, anal claws and anal setae present… 8

8 Posterior parapods with zero to five claws, mandible with three inner teeth… *Pseudosmittia*

- Posterior parapods with seven or more claws, mandible with three or four inner teeth… 9

9 Seta submenti bifid…*Allocladius I*

- Seta submenti simple… *Hydrosmittia*

10 Five lateral teeth on mentum… 11

- Six lateral teeth in mentum… 16

11 Median tooth notched in centre; fifth lateral teeth on mentum very reduced; bulbus ventromental plates… *Chaetocladius dentiforceps*-type

- Median tooth not notched in centre; fifth lateral teeth on mentum not reduced; narrow ventromental plates… 12

12 Lateral teeth on mentum narrow; pale and black stripes present below mentum; Short spines present on inner margin of mandible… *Eukiefferiella cynea* type

- Lateral teeth on mentum not narrow; stripes absent below mentum; Spines absent from inner margin of mandible… 13

13 Second antennal segment as long as or longer than basal segment… *Smittia*

- Second antennal segment shorter than basal segment or antennae too small to see… 14

14 Long ventromental plates below outer three lateral teeth and extending beyond outer lateral teeth… *Paraphaenocladius*

-Ventromental plates narrow and do not extend beyond outer lateral teeth… 15

15 seta submenti bifid… *Allocladius* II

- seta submenti simple… *Hydrosmittia*

16 Median tooth flat or rounded, subequal in height to or slightly taller than first lateral teeth on mentum; lateral teeth point inwards towards median tooth; anal setae not long…*Orthocladius* G1

- Median tooth pointed, twice the height of first lateral on mentum; narrow lateral teeth on mentum; long apical tooth on mandible; very long anal setae extending half the length of the body…*Krenosmittia*

17 Five pairs of narrow lateral teeth on mentum; pale and dark stripes present below mentum; short spines present on inner margin of mandible… *Eukiefferiella gracei* type

- More than five pairs of lateral teeth on mentum; pale and dark strips absent below mentum; short spines absent from inner margin of mandible… 18

18 Six pairs of lateral teeth on mentum… 19

- Seven pairs of lateral teeth on mentum… *Orthocladius* (*Euorthocladius)*

19 Second pair of lateral teeth on mentum reduced … *Orthocladius oliveri*

- Second pair of lateral teeth on mentum not reduced… 20

20 Three inner teeth on mandible… 21

- Four inner teeth on mandible; narrow gap between median tooth and first laterals on mentum; first laterals angled strongly towards median tooth… *Cricotopus* P type

21 All mandible teeth gradually decreasing in size… *Orthocladius* S type

- Two inner-most mandible teeth substantially shorter than apical and first inner tooth, forming two distinct groups… *Orthocladius* G type

22 Three median teeth on mentum… 23

- Two median teeth on mentum… 24

23 Middle median tooth of mentum very reduced; antennae subequal to or longer than head capsule… *Corynoneura*

- Median teeth on mentum subequal; antenna half the length of head capsule… *Thienemaniella clavicornis*

24 Beard present on ventromental plates… 25

- Beard absent from ventromental plates… 26

25 Well-developed beard on ventromental plates; two narrow median teeth and first two pairs of lateral teeth form distinct group from other lateral teeth on mentum; six lateral teeth on mentum… *Diplocladius cultriger*

- Beard present on ventromental plates but not as well developed as above; two median teeth approximately twice the width of first laterals on mentum; median teeth form a distinctly separate group from lateral teeth on mentum; five lateral teeth on mentum … *Rheocricotopus effusus* type

26 Five lateral teeth on mentum…27

-Six lateral teeth on mentum… *Hydrobaenus lugubris* group

27 Dark tubercle present at base of mentum… 28

-No dark tubercle present at base of mentum… 29

28 Four inner teeth present on mandible; very long antennal blade reaching well beyond apex of flagellum… *Paralimnophyes*

- Three inner teeth present on mandible; antennal blade reaching to at most apex of flagellum but not extending beyond… *Limnophyes*

29 Pale and black stripes present below mentum… 30

-Pale and dark stripes absent below mentum…31

30 Antennal blade subequal in length to second antennal segment… *Tokunagaia*

-Antennal blade reaching beyond segment two of antennae; usually reaching apex of segment four… *Eukiefferiella brehmi* type

31 Two pointed median teeth narrower and shorter than first pair of laterals on mentum; first pair of lateral teeth distinctly broader than medium teeth and extending beyond apex of median teeth on mentum; second to fifth pairs of mentum lateral teeth gradually reducing in size, although sometimes second pair of lateral teeth is subequal to first; ventromental plates weak… *Metriocnemus eurynotus* type

- Two wide median teeth each with central peak and taller than first laterals on mentum; gap separating first pair of lateral teeth from the remaining four pairs, creating a distinct group on mentum; expanding bulbous ventromental plates… *Chaetocladius piger* type

32 Premandible present… **Diamesinae**: 33

-Premandible absent… **Podonominae**: *Trichotanypus*

33 Nine median teeth and eight pairs of lateral teeth on mentum; mandible teeth rake-like; antennal ratio of approximately three, short anal setae… *Diamesa aberrata* type

- Less than nine median teeth and variable number of lateral teeth on mentum; mandible teeth not rake-like, variable antennal ratio but less than three; long anal setae… 34

34 One median tooth and seven or eight lateral teeth on mentum; first two pairs of lateral teeth form a distinct group with median tooth, separate from remaining five or six pairs of laterals; if eight lateral tooth are present, the last is very reduced… *Diamesa A*

- Variable number of median and lateral teeth on mentum; no separation between mentum lateral teeth… *Diamesa B*

A4.6 Descriptions

Below, brief descriptions for each species group are given. More detailed information can be found in the keys to Chironomidae listed in the references section.

Diamesinae

Characterised by having a premandible with one to 16 teeth though usually between four and six, an annulated third antennal segment and more than six pairs of lateral teeth on the mentum. Mandible with one apical tooth, four or five inner teeth, and a fan-shaped seta interna. They generally exhibit dark-coloured head capsules.

All Diamesinae belonged to the genus *Diamesa*.

Diamesa aberrata: Nine or ten median teeth and eight pairs of lateral teeth on mentum.

Mandible exhibits rake-like shape. Antenna ratio of 3, short anal setae approx. 78µm Weakly developed procercus.

Diamesa A type*:* One median tooth and first two pairs of lateral teeth on mentum separated to form distinct group from the remaining five or six pairs of laterals. If total of 8 lateral teeth on mentum, the outermost tooth is reduced. Antenal ratio of 1.88, very long anal setae approx. 253µm. Well developed procercus.

Diamesa B type: Variable number of mentum and mandible teeth. Antenal ratio of 1.46. Long anal setae approx. 170µm. Both antennal ratio and anal setae length show variation (SD antennal ratio: 0.53, SD anal setae: 0.53). Procercus weakly developed.

Ecology: Diamesinae are found in cold water and low stability systems. In 2013 and 2014 Diamesa were found in streams exhibiting both high and low channel stability, turbidity and water level, but the highest abundance was in low stability streams. In 2015 *Diamesa* were found in all streams in low numbers, with the largest abundance in Aucellaelv.

Orthocladiinae

Allocladius

Mentum with one large median tooth, with or without apical point, and 4 or 5 pairs of lateral teeth. Small antennae, sometimes not visible, antennal blade about as long as flagellum. 7-12 Posterior parapod claws. Seta interna absent. Seta submenti bifid.

Allocladius I: Four lateral teeth, three inner teeth on mandible

Allocladius II: Five lateral teeth, four inner teeth on mandible.

Head capsule features similar to *Pseudosmittia, Hydrosmittia* and *Camptocladius.* Identify using seta submenti and number of posterior parapod claws. Separated from Smittia by antennal length. Antenna is largely reduced in Allocladius.

Ecology: Predominantly found in high stability, low turbidity streams.

Camptocladius

Two specimens were found in 2014 only. The head capsule resembles those of *Allocladius, Pseudosmittia* and *Hydrosmittia*, only in *Camptocladius* the posterior parapods, anal claws and anal setae are absent.

Ecology: Found in both a high turbidity and a low turbidity stream.

Chaetocladius dentiforceps type

Mentum with one wide median tooth with notch in the middle, may resemble two separate teeth. Five pairs of lateral teeth on mentum. Ventromental plates long and expanding at apex to be bulbous.

Ecology: Found in low turbidity, high stability streams.

***Chaetocladius piger* type**

Mentum with five pairs of lateral teeth and two median teeth. Median teeth approximately twice the width of first lateral teeth and forming a point at the end. Fifth lateral teeth reduced. Distinctively wide and bulbous ventromental plates. Mandible with a long, pointed apical tooth.

Ecology: Found in low turbidity, high stability streams.

***Corynoneura edwardsi*-type**

Elongated head shape with antennae subequal to or longer than head. Mentum with five pairs of lateral teeth and three median teeth. The central median tooth being substantially reduced in size. No head capsule reticulations present.

Similar to Thienemanniella but differs through longer antennae and reduced median teeth on mentum.

Ecology: Found in low turbidity, high stability streams. Found in larger numbers in Kaerelv and Graenseelv in 2013 when water levels were low.

***Cricotopus P* type**

Two specimens were found in 2015 only. Mentum with one narrow median tooth and six pairs of lateral teeth, first pair of lateral teeth strongly angled towards median tooth. Narrow gap between first lateral teeth and median tooth. Mandible hook-shaped and with four inner teeth.

Ecology: Specimens found in both high stability and low stability streams.

Diplocladius cultriger

Long sausage shaped ventromental plates, extending far beyond mentum. Thick beard present on ventromental plates. Six pairs of lateral teeth and two median teeth on mentum. First two lateral teeth form distinct group with median teeth.

Ecology: Found in low turbidity, high stability streams.

Eukiefferiella

Mentum with five lateral teeth and one or two median teeth. Mentum with five lateral pairs of teeth. Stripes present below mentum. Small spine often present on lower mandible. SI simple.

Eukiefferiella brehmi: two median teeth on mentum. Antennae with five segments and antennal blade reaching between segment two and segment four.

Eukiefferiella cynea: One median tooth wider than first two pairs of lateral teeth. Antennae with five segments and antennal blade reaching to segment two.

Tokunagaia: Mentum with two median teeth. Antennae with five segments and blade subqual in length to segment two.

Eukiefferiella gracei: One broad median tooth on mentum, approximately as wide as two lateral teeth or more. Antennae with five segments and antennal blade reaching between segment two and segment four.

Ecology: *Eukiefferiella* were found in all streams however they had their highest abundance immediately below the water source in the headwaters of two high stability, low turbidity streams: Kaerelv and Graenseelv.

Hydrobaenus lugubris

Two median teeth and six laterals on mentum. Bulbous ventromental plates.

Ecology: *Hydrobaenus* were found in low turbidity, high stability streams. They were found mainly in Kaerelv and Graenseelv and had the highest abundance in 2013 when the water level was low. One of the most common morphotypes.

Hydrosmittia

One wide median tooth on mentum, with or without apical point and four or five pairs of lateral teeth. Three or four inner teeth on mandible. 7 – 11 posterior parapod claws. Seta interna sometimes present. Seta submenti simple. Can be separated further by the number on inner teeth on mandible:

Hydrosmittia I: Three inner teeth on mandible

Hydrosmittia II: Four inner teeth on mandible.

Can be separated from *Smittia* by length of antennae which is long in *Smittia*- approximately same length as mandible, but reduced in Hydrosmittia.

Ecology: Found in low numbers in low turbidity, high stability streams.

Krenosmittia

Small body length, approximately 3 – 4mm. Mentum with six pairs of lateral teeth and one large, pointed median tooth. Long anal seta, approximately half the length of the body. Apical tooth of mandible long and narrow.

Ecology: Found only in Kaerelv and Graenseelv, high stability streams.

Limnophyes

Two median teeth and five pairs of lateral teeth. Teeth often dark brown Median teeth taller than lateral teeth. Laterals 1 to 3 decreasing in size and 4 and 5 smaller, forming distinct group. Dark lobe below last lateral teeth. Mentum with pale and dark stripes (Cf *Eukiefferiella*). Three inner teeth on mandible. Antennal blade no longer than apex of antennae.

Note: not to be confused with *Paralimnophyes*, which has four inner teeth on mandible and antennal blade which extends beyond apex of antennae.

Ecology: Found in low numbers in high stability, low turbidity streams.

***Metriocnemus eurynotus* type**

Mentum with two median teeth and five pairs of lateral teeth. Median teeth reduced in size compared to first lateral teeth. Lateral teeth gradually reduce in size.

Ecology: Found in low numbers in most streams, including both high and low stability streams.

Orthocladius

Morphotypes:

Orthocladius (Euorthocladius) type: One median tooth and seven pairs of lateral teeth on mentum. Mentum and mandibles usually darker in colour than remaining head capsule. Long apical tooth on mandible.

Orthocladius G type: Similar to *Orthocladius S* type with three inner teeth on the mandible and one apical tooth but in *O. G* type the two inner-most teeth of mandible are reduced. Six lateral teeth on mentum. Median tooth of mentum as narrow as lateral teeth.

Orthocladius G1 type: One median tooth as wide as two lateral teeth, and six pairs of lateral teeth.

Orthocladius oliveri type: One median tooth and six pairs of lateral teeth on mentum. Second pair of lateral teeth slightly reduced compared to first laterals.

Orthocladius S type: One median tooth and six pairs of lateral teeth. All lateral teeth reducing in size. One apical tooth and three pairs of inner teeth on the mandible, all of them being subequal and gradually reducing in size.

Ecology: Found in all streams but they were found in the highest abundance in high stability, low turbidity streams.

Parakiefferiella bathophila

One broad median tooth and six pairs of lateral teeth. The first pair of lateral teeth is fused to the median tooth and weakly pigmented. Antennae with 6 segments, segment 6 vestigial. Antennal segments 3 – 6 substantially smaller than segments 1 and 2.

Ecology: Found in the high stability stream Vestelv during late summer (September 2014).

Paralimnophyes

Two median teeth and five pairs of lateral teeth. Teeth often dark brown colour. Median teeth taller than lateral teeth. The first three pairs of lateral teeth gradually decrease in size and the outer two pairs of lateral teeth are smaller, forming distinct group. Dark lobe below last lateral teeth. Mentum striated (Cf *Eukiefferiella*) Mandible with four inner teeth. Antennal blade which extends greatly beyond apex of antennae. Simple SI and premandibular brush is present.

Note: not to be confused with *Limnophyes*, which has three inner teeth on mandible and the antennal blade reaches to the apex of the antennae.

Ecology: Found in all streams but largest abundance in Kaerelv and Graenseelv. One of most common morphotypes.

Paraphaenocladius

Horizontal mentum with no arch shape with one wide median tooth and five pairs of lateral teeth. Long ventromental plates below outer three lateral teeth and extending beyond outer lateral teeth; apical tooth of mandible short.

Ecology: Found in low numbers in most streams. Highest abundance in Kaerelv and Graenseelv but numbers still low in comparison to other morphotypes.

Pseudosmittia

One median tooth on mentum twice as wide as first lateral teeth, Four lateral teeth. Three inner teeth on mandible. SI and SII on labrum are bifid. Very short antennae with antennal blade extending beyond antennae apex.

Similar to *Allocladius, Camptocladius* and *Hydrosmittia* but distinguished by having zero to five posterior parapod claws.

Ecology: Found in various streams in low numbers including Kaerelv, Graenseelv and Aucellaelv.

Rheocricotopus effusus

Only two specimens found. Mentum with two median teeth and five pairs of lateral teeth on mentum. Median teeth taller than first lateral teeth and up to twice the width of first lateral teeth. Long ventromental plate with a well developed beard, though weaker than *Diplocladius* by comparison.

Ecology: Both specimens found in intermediate-high stability streams in 2013, when water levels were low.

Smittia

One wide median tooth and five pairs of lateral teeth. Antennae approximately subequal in length to the mandible. Four segmented with segment two subequal in length to first.

Ecology: Found in low numbers in high stability, low turbidity streams.

Thienemaniella clavicornis

Only two specimens found. Three median teeth and five pairs of lateral teeth. Mendian teeth are not reduced as in Corynoneura. Antennae approximately half the length of head capsule (cf Corynoneura in which the antenna is twice the length of the head). Dark brown head (cf *Corynoneura* in which the head capsule is pale brown).

Ecology: Both specimens found in Graenseelv, a high stability, low turbidity stream.

Podonominae

Only *Trichotanypus* has been found. *Trichotanypus* is identified by the distinctive shape of its mentum where the median tooth and first lateral teeth are located on a lower level compared to the other 12 pairs of laterals. The seta submenti are located approximately one third of the distance between the mentum and the occipitale. The mandible has 6 teeth, divided into two subapical, two apical and two inner teeth and has a broad seta interna. Podonominae have distinctive labrum features, they have no premandible, and the SI and SII being long and narrow, situated on high, narrow tubercles are easily visible. The third antennal segment is annulated (cf Diamesinae).

Ecology: Specimens were found in Kaerelv, Graenseelv and Vestelv, low turbidity, stable streams during low water levels.

Tanypodinae

Procladius

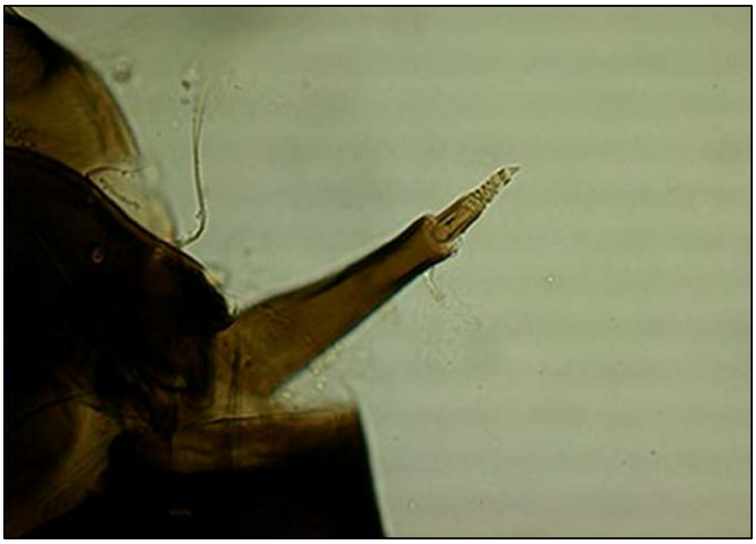
Only one specimen of Tanypodinae was found throughout the field campaigns. Tanypodinae is identified by possessing retractile antennae and the presence of a defined ligula. *Procladius* is characterised by five ligula teeth of dark pigmentation, and paraligula, which is half the length of the ligula, with teeth on both sides. The antennal blade does not extend beyond the apex of flagellum.

Ecology: Found in the highly stable stream Vestelv in late summer (September 2014).

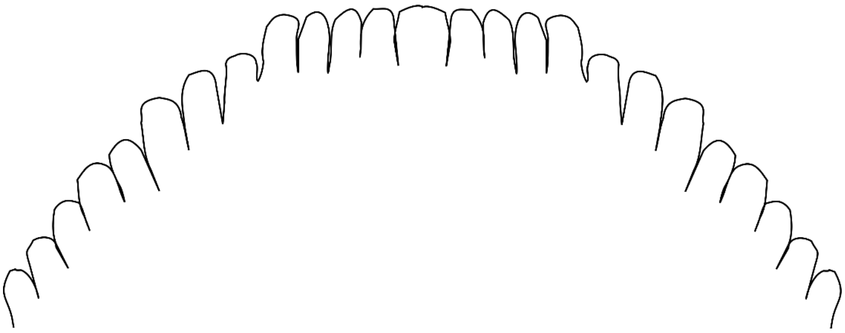
A4.7 Images of head capsules and characteristic features for each species type

Diamesinae

Diamesa aberrata

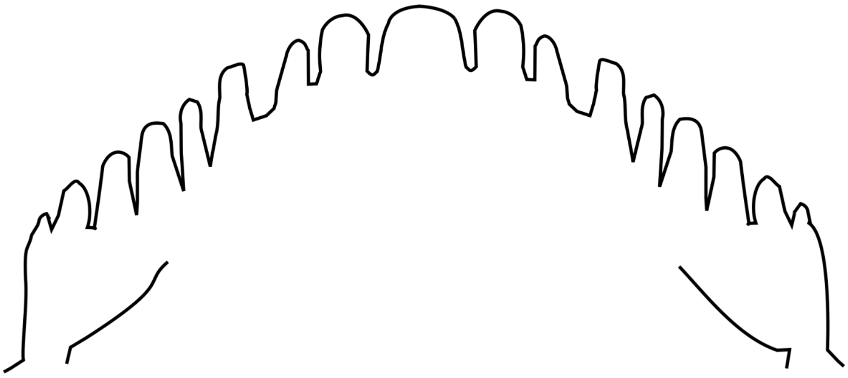


Diamesa aberrata antennae

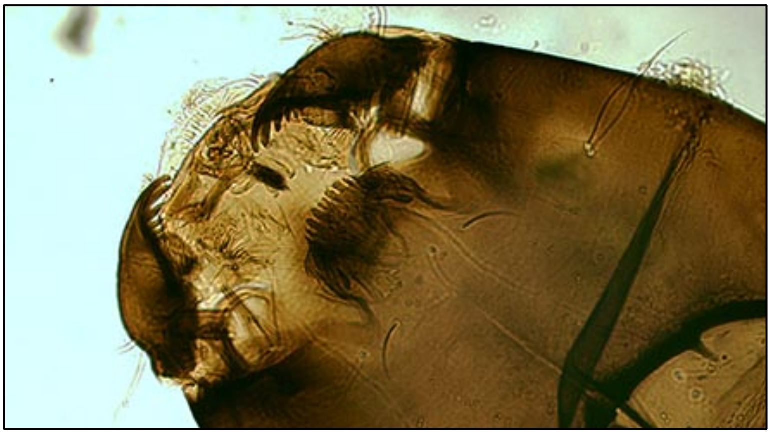


Diamesa aberrata mentum

Diamesa A

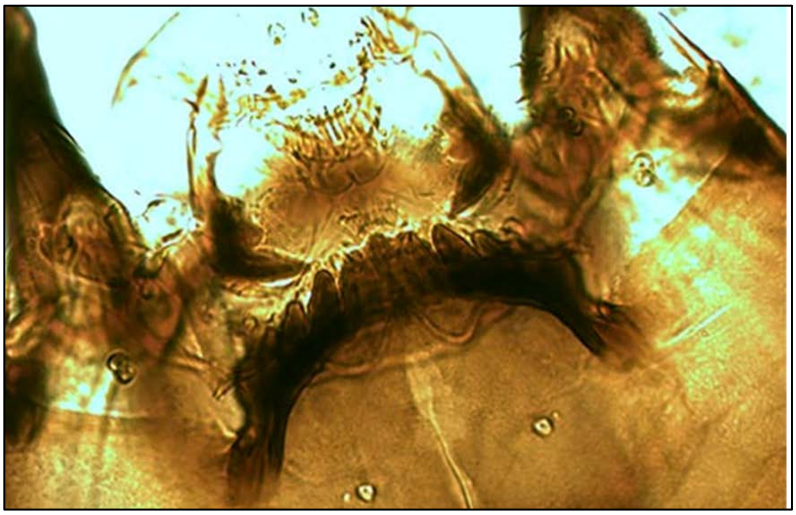


Diamesa A mentum

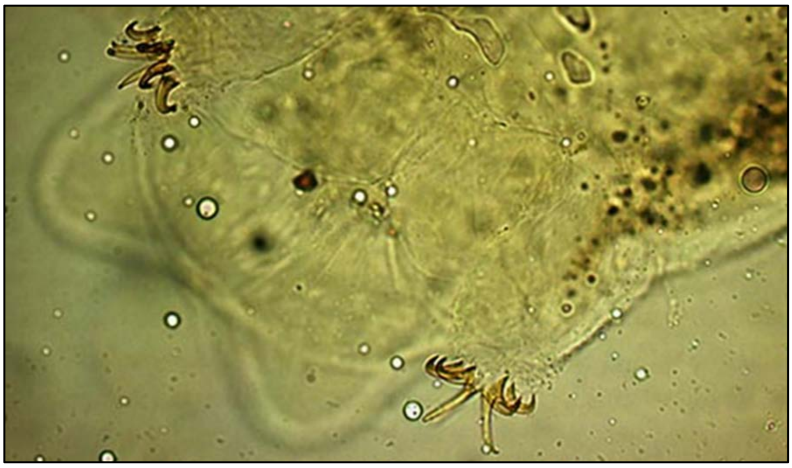


Diamesa B

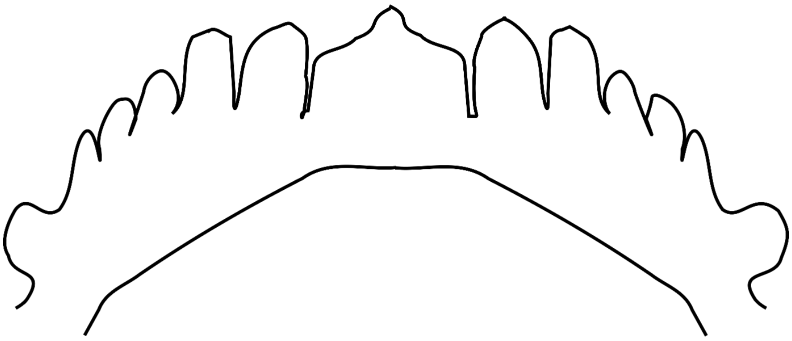
Orthocladiinae



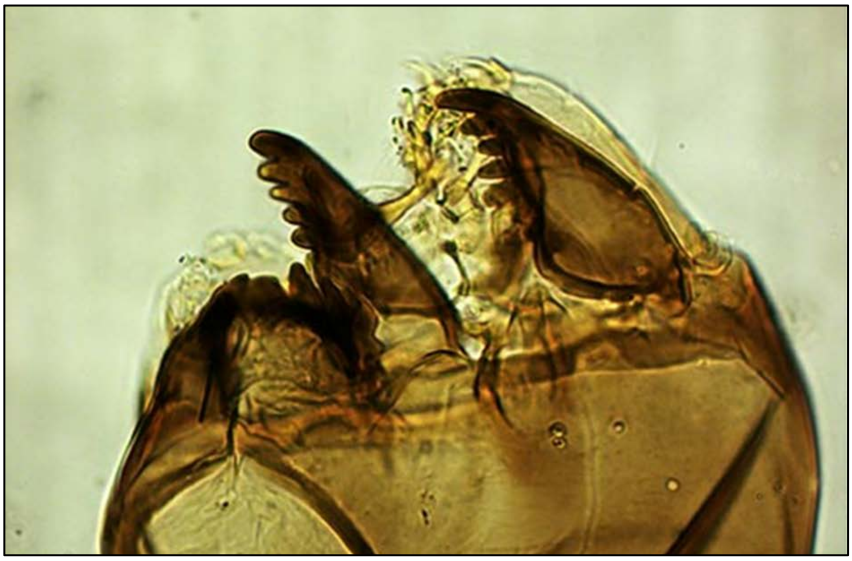
Allocladius



Allocladius posterior parapod claws

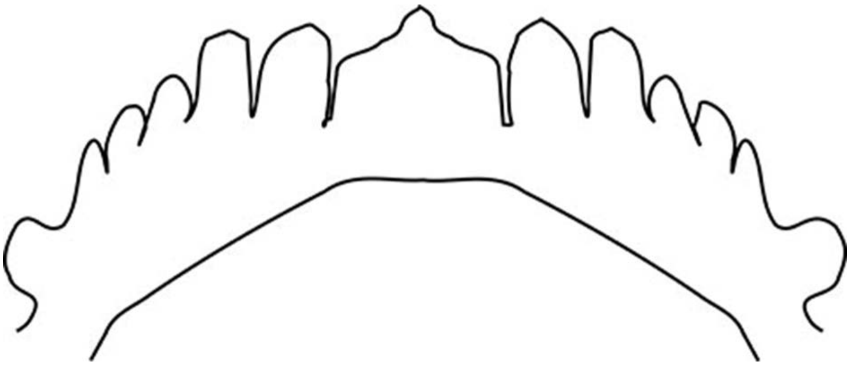


Allocladius mentum

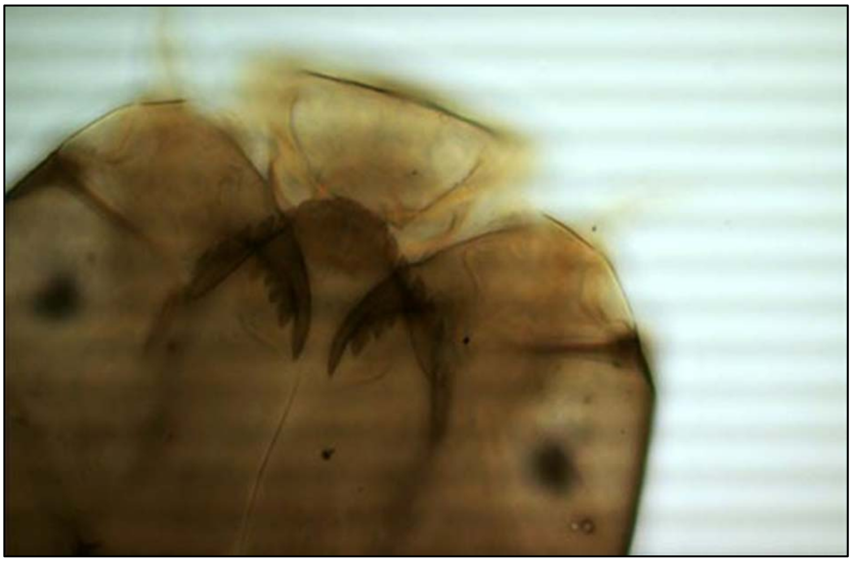


Camptocladius

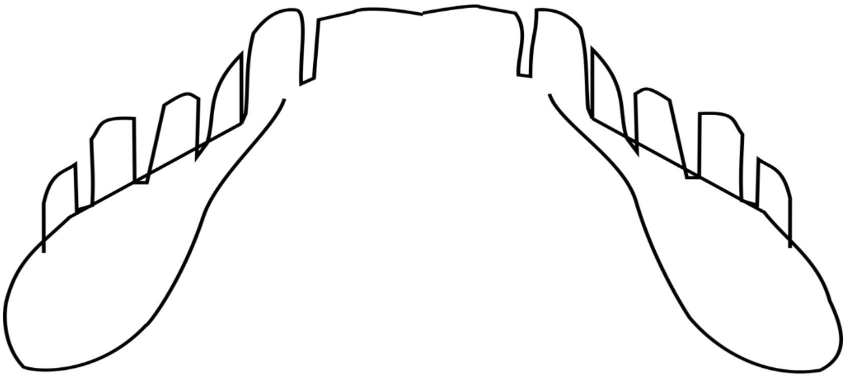
Camptocladius: lack of posterior parapods, claws and anal setae,



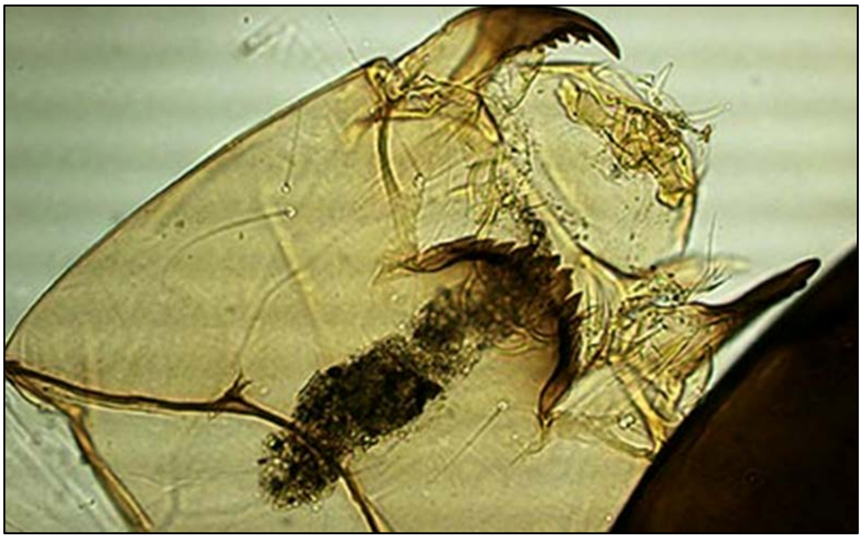
Camptocladius mentum



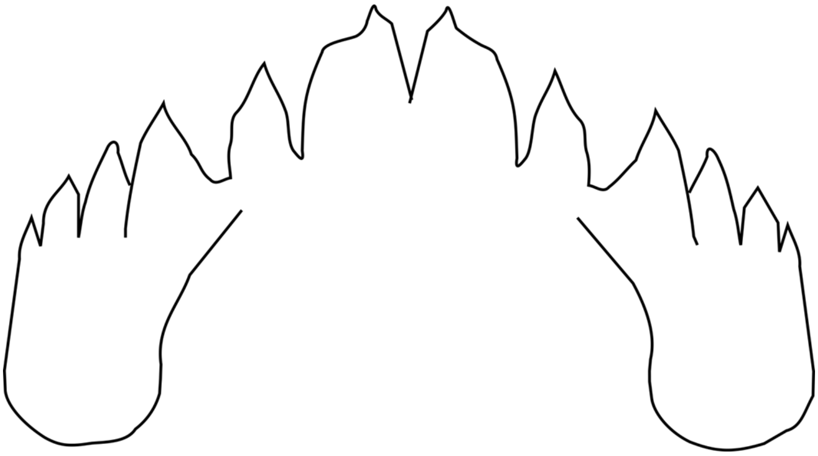
Chaetocladius dentiforceps



Chaetocladius dentiforceps mentum

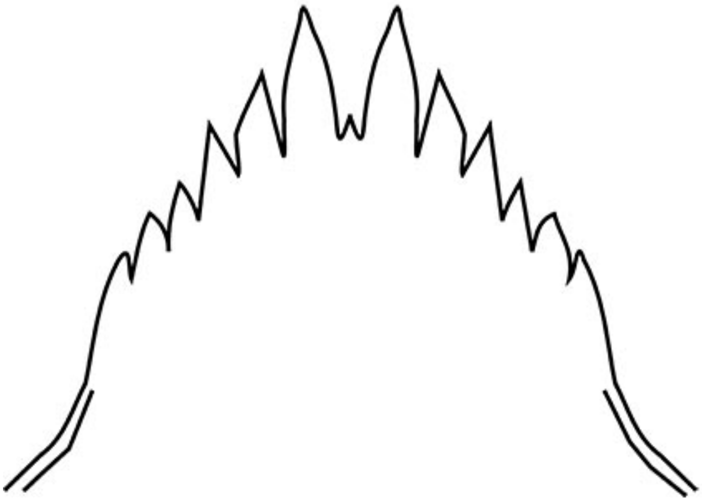


Chaetocladius piger

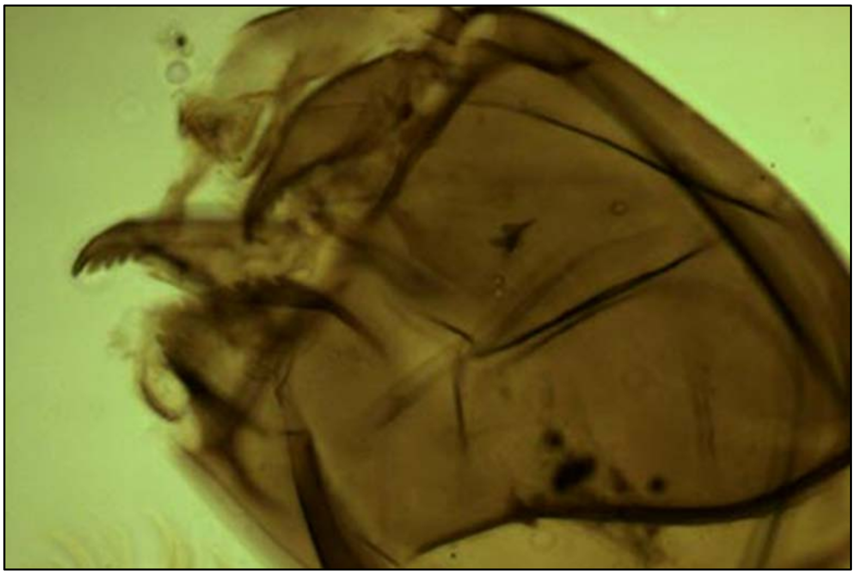


Chaetocladius piger mentum

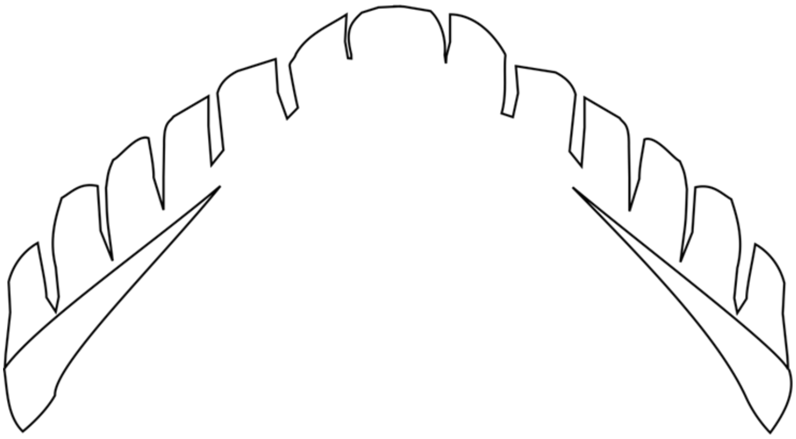
Corynoneura edwardsi-type



Corynoneura edwardsi-type mentum

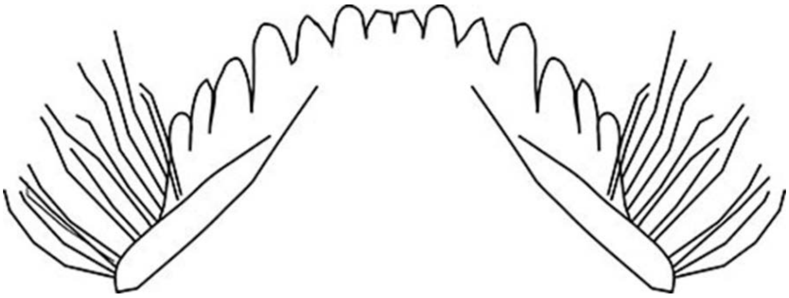


Cricotopus type *P*

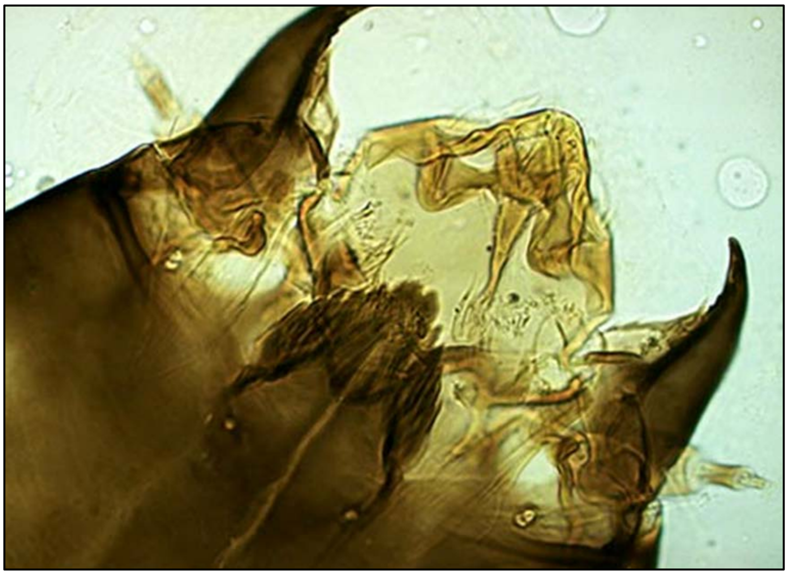


Cricotopus type *P* mentum

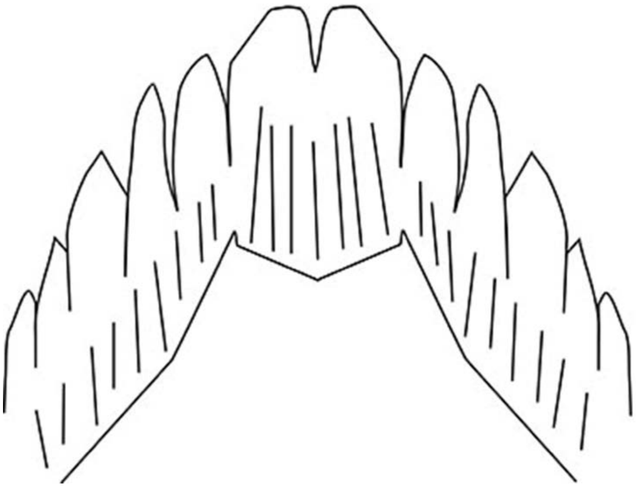
Diplocladius cultriger



Diplocladius cultriger mentum

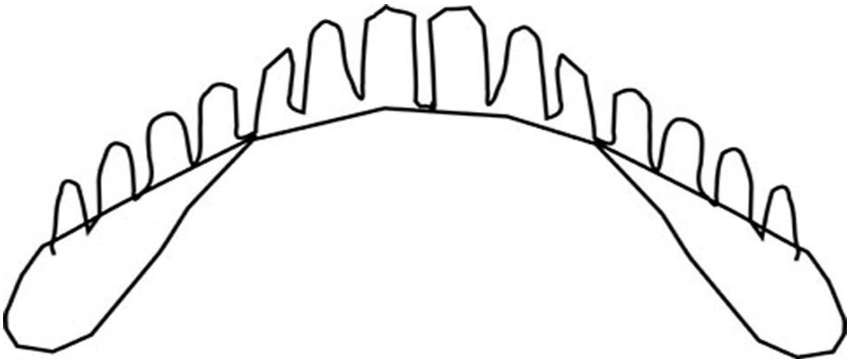


Eukiefferiella

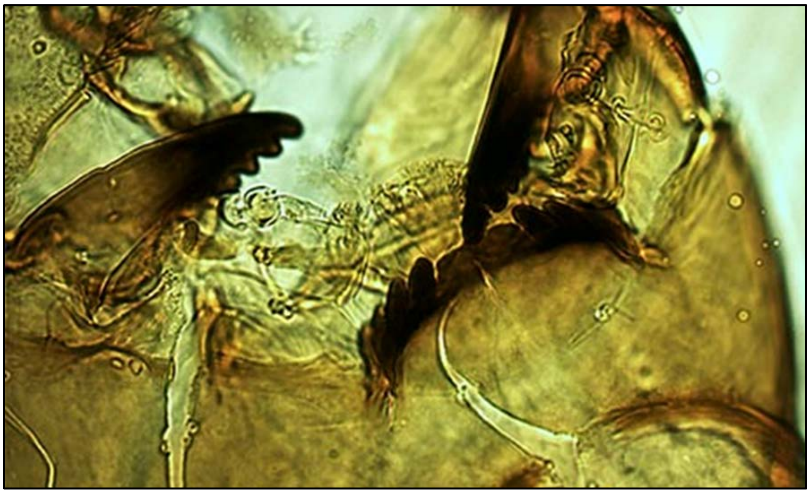


Eukiefferiella mentum

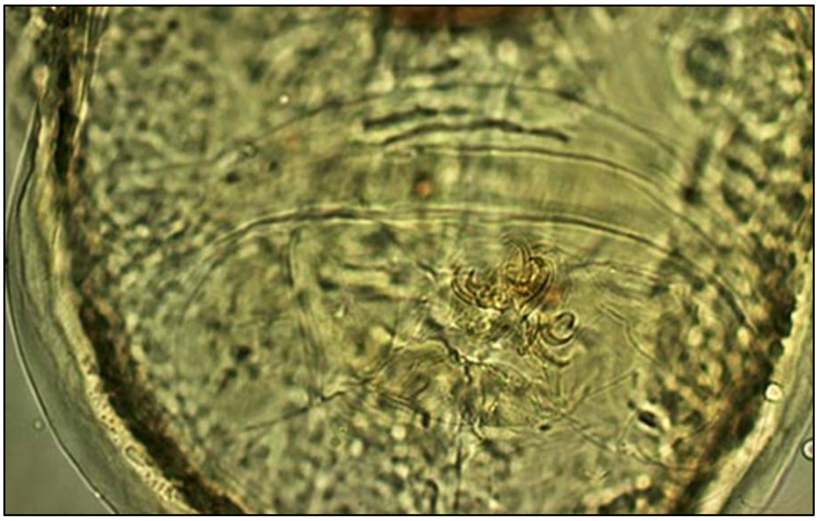
Hydrobaenus lugubris type



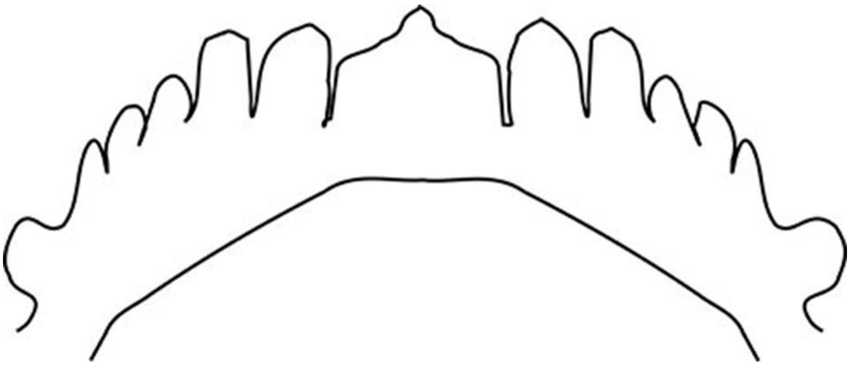
Hydrobaenus lugubris type mentum



Hydrosmittia



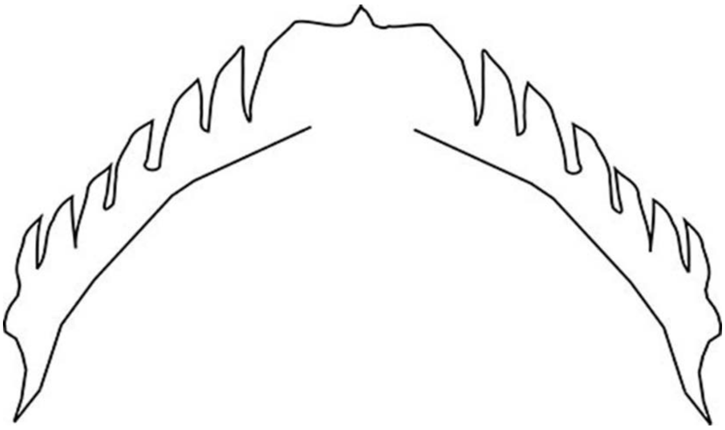
Hydrosmittia posterior parapod claws



Hydrosmittia mentum

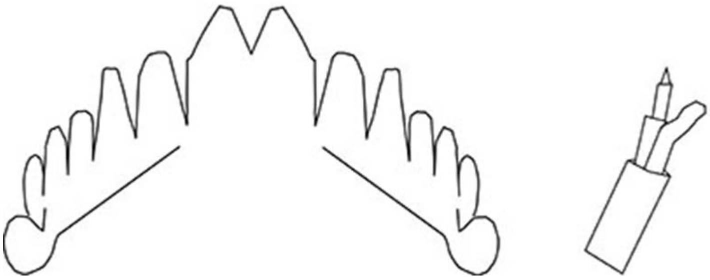
Krenosmittia

Krenosmittia anal seta



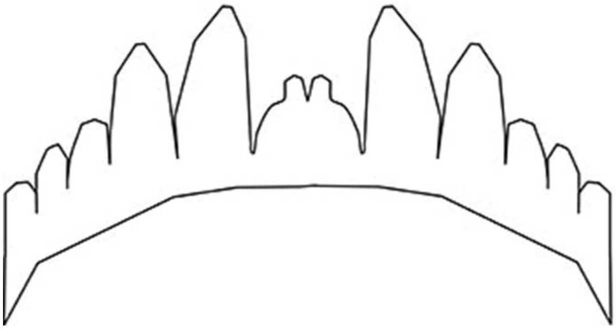
Krenosmittia mentum

Limnophyes

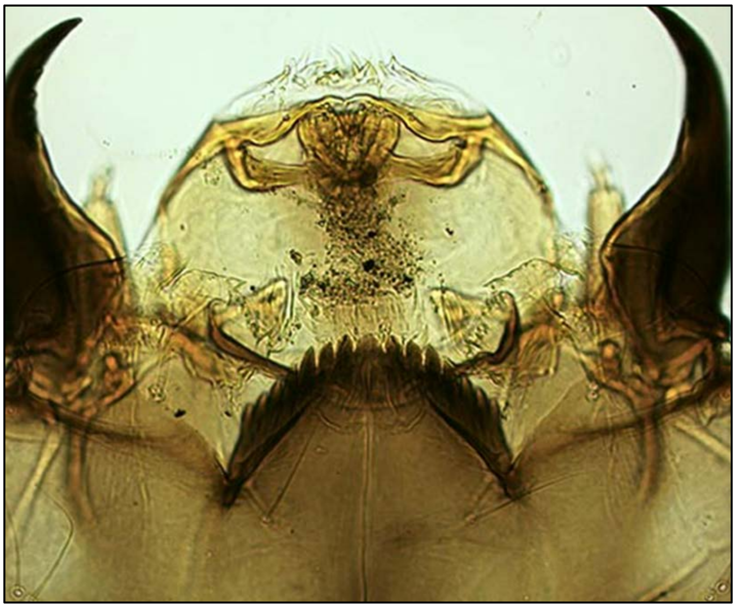


Limnophyes mentum and antenna

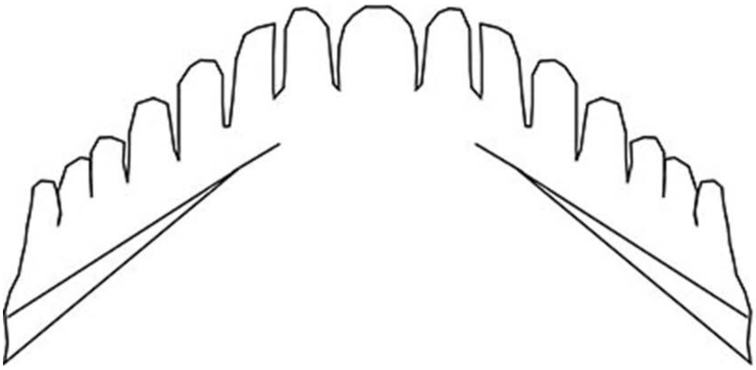
Metriocnemus eurynotus



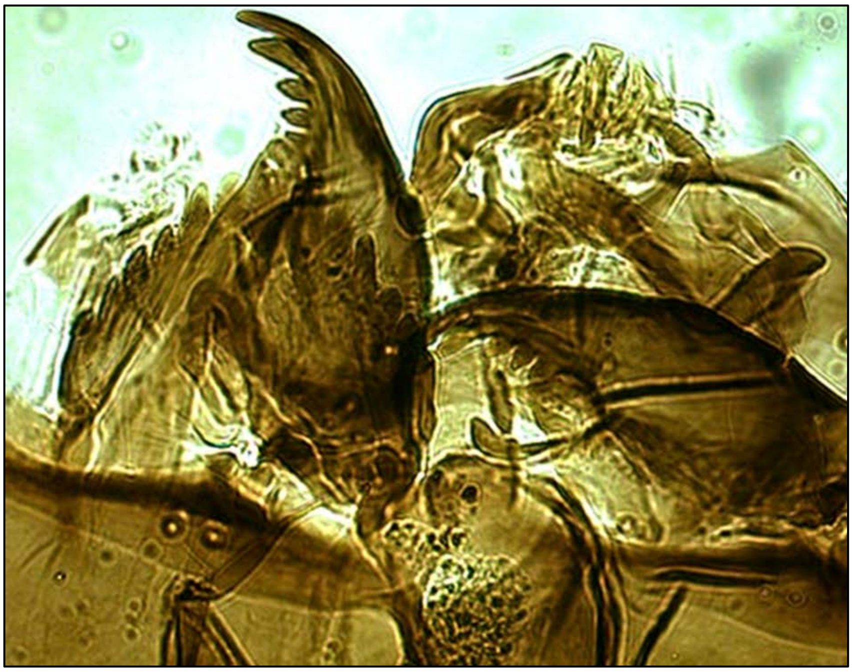
Metriocnemus eurynotus mentum



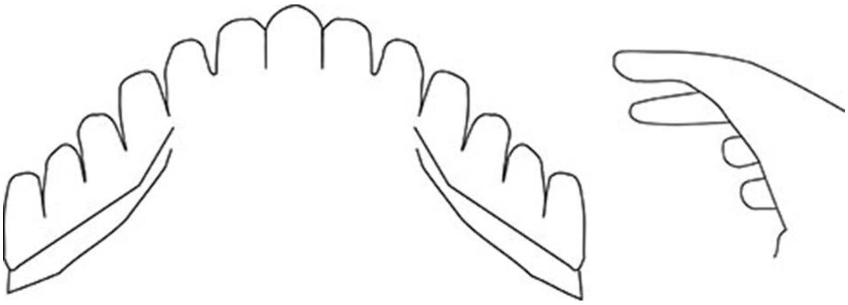
Orthocladius (Euorthocladius)



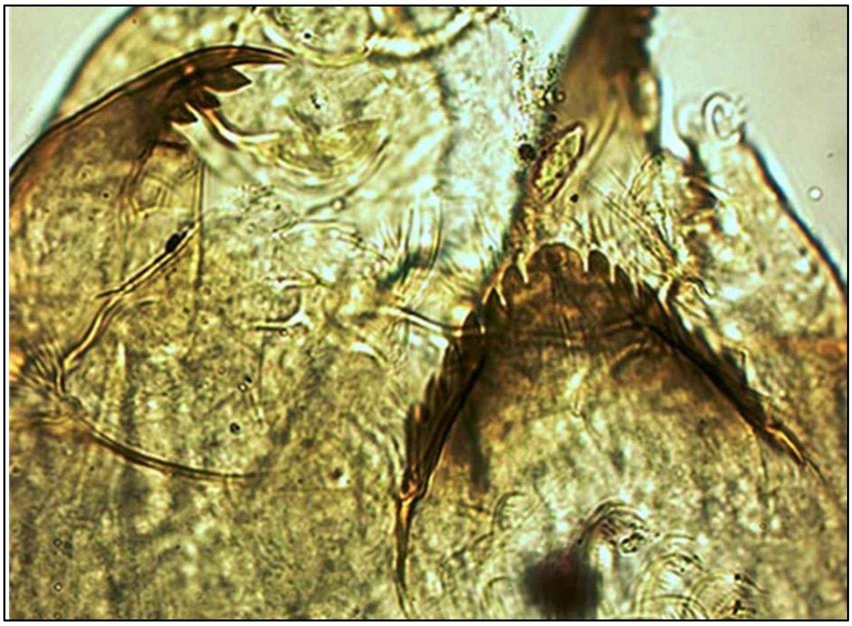
Orthocladius (Euorthocladius) mentum



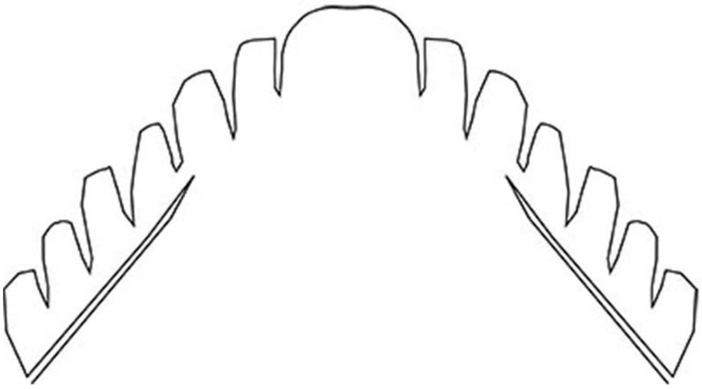
Orthocladius G type



Orthocladius G type mentum and mandible

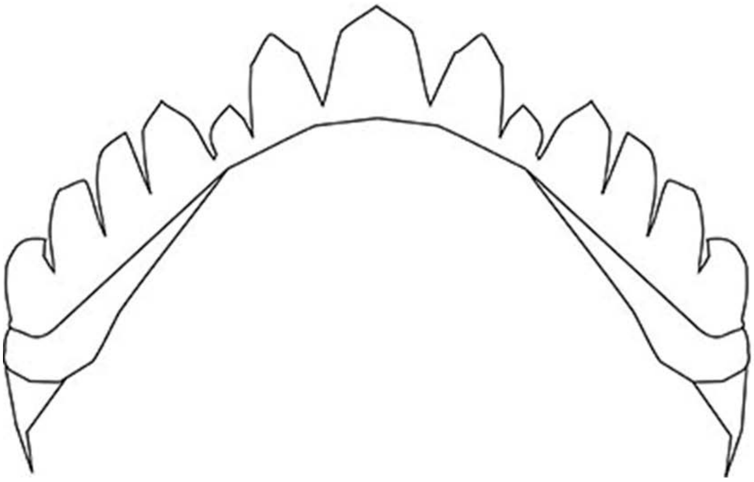


Orthocladius G1 type

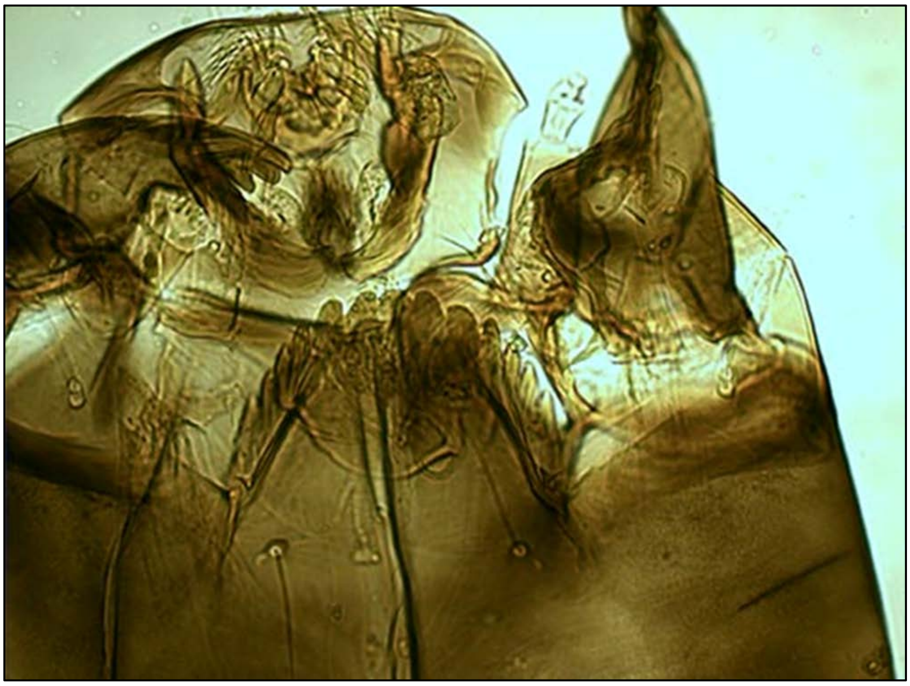


Orthocladius G1 type mentum

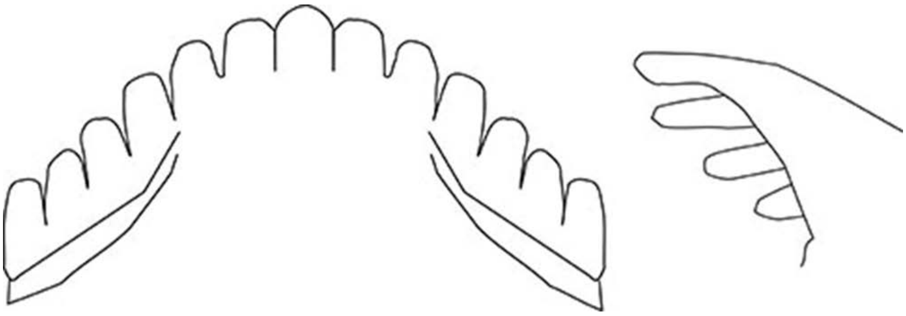
Orthocladius oliveri



Orthocladius oliveri mentum

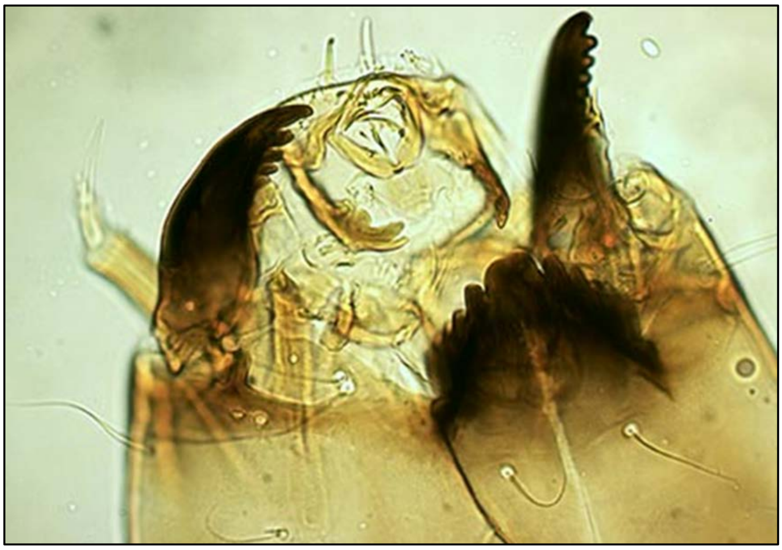


Orthocladius S type

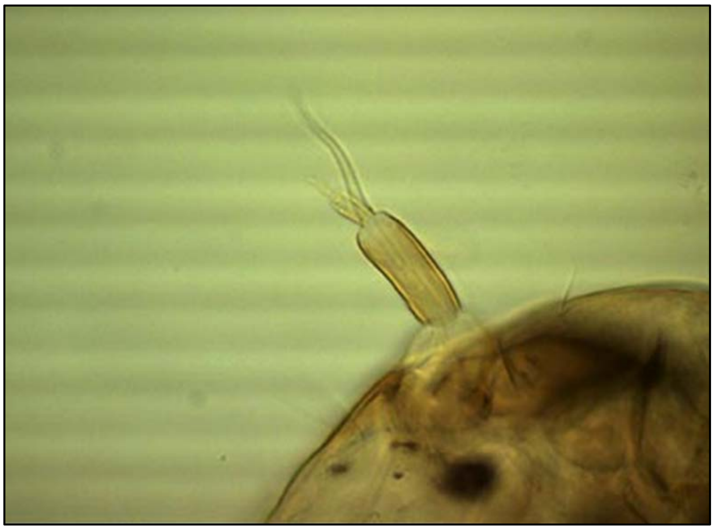


Orthocladius S type mentum and mandible

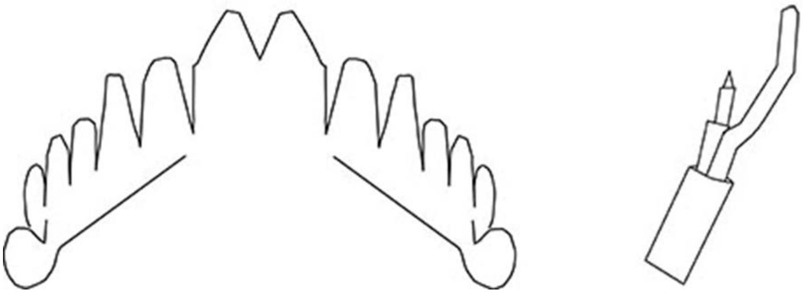
Parakiefferiella bathophilia



Paralimnophyes

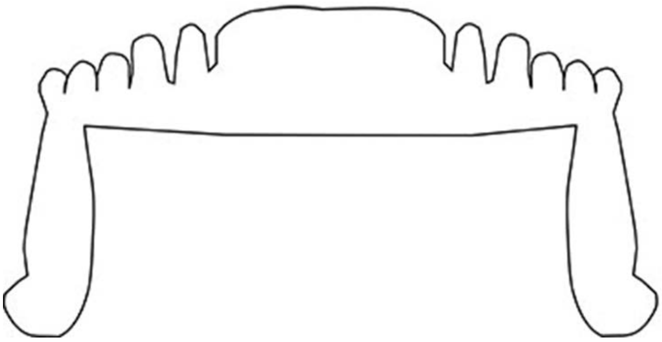


Paralimnophyes antennae



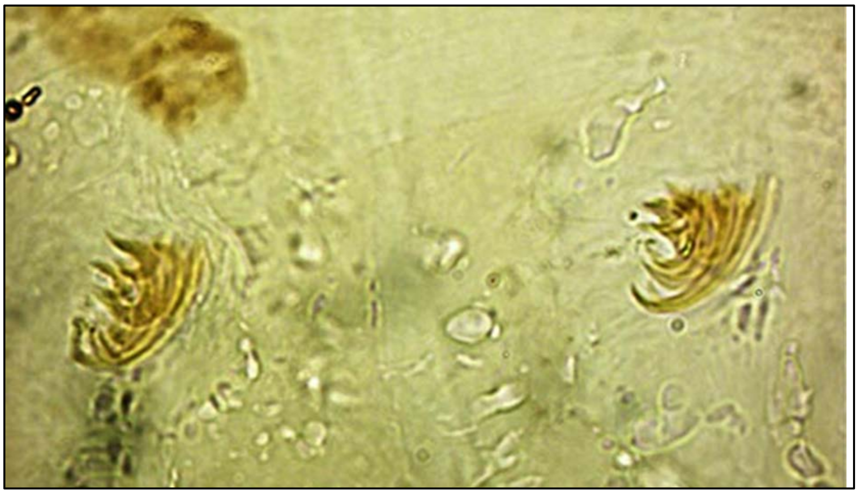
Paralimnophyes mentum and antennae

Paraphaenocladius

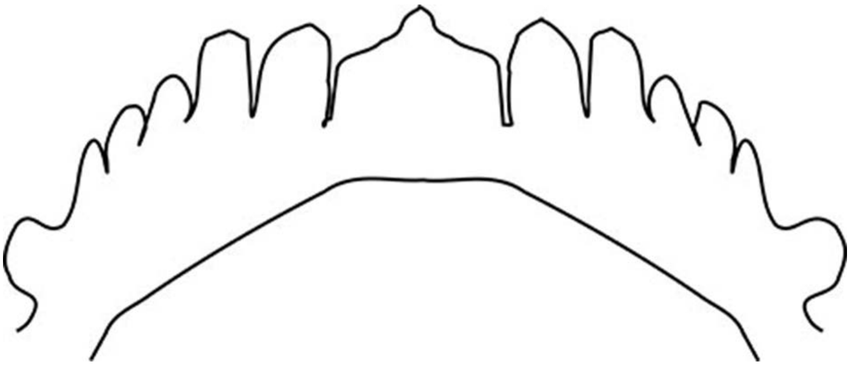


Paraphaenocladius mentum

Pseudosmittia

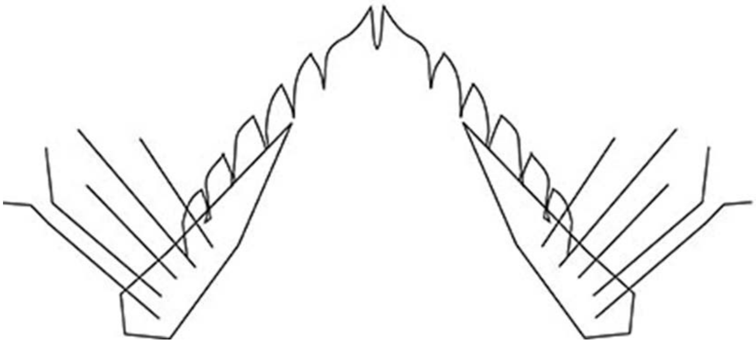


Pseudosmittia posterior parapod claws



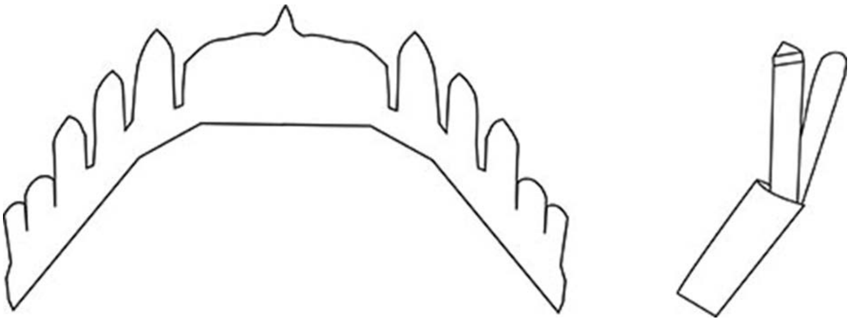
Pseudosmittia mentum

Rheocricotopus effuses type

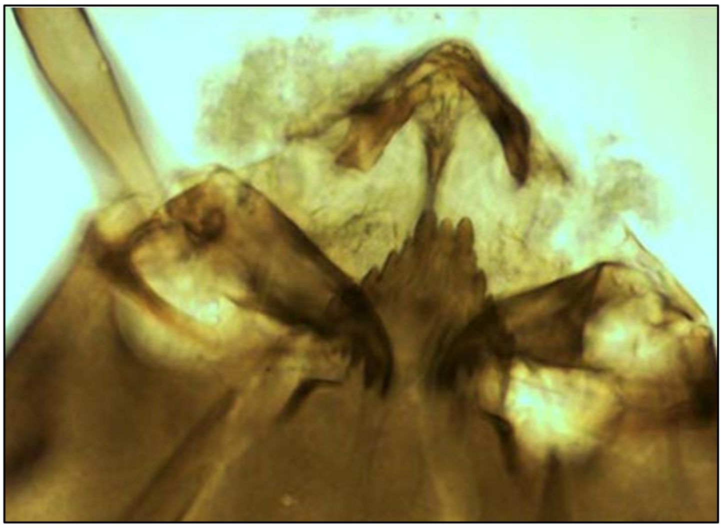


Rheocricotopus effuse type mentum

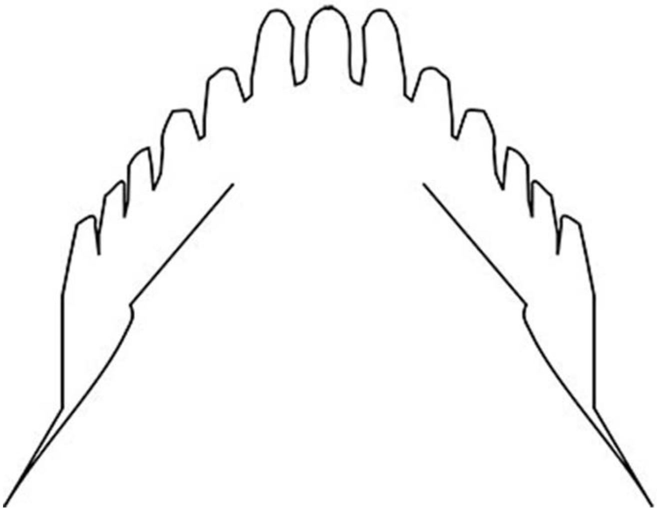
Smittia



Smittia mentum and antenna



Thienemaniella clavicornis

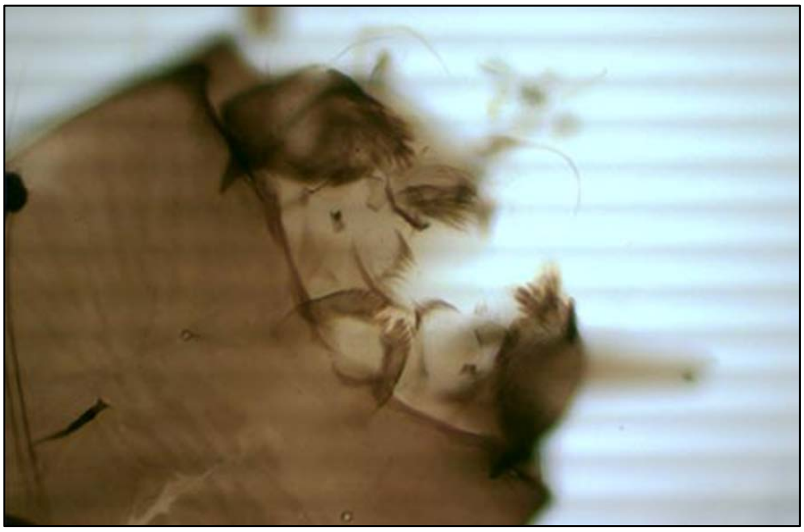


Thienemaniella clavicornis mentum

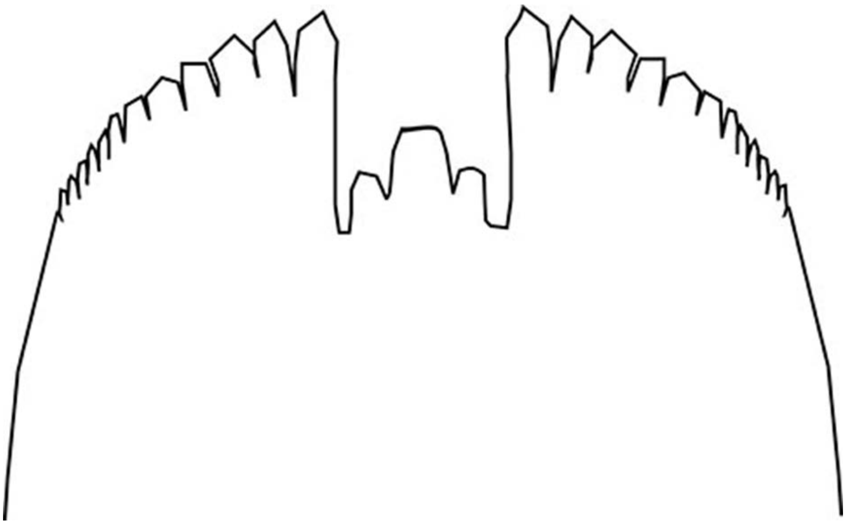
Tanypodinae

Procladius

Podonominae



Trichotanypus



Trochotanypus mentum

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A5: PEER-REVIEWED ARTICLES ACCEPTED FOR PUBLICATION

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Large thermo-erosional tunnel for a river in northeast Greenland

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[b] Department of Atmospheric Environment and Aquatic Ecosystem, Institute of Mountain Science, Shinshu University, Japan
[c] Department of Bioscience, Aarhus University, Aarhus, Denmark
[d] Institute of Arctic Biology, University of Alaska, Fairbanks, AK, USA

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Arctic

ABSTRACT

Thermo-erosional river bank undercutting is caused by the combined action of thermal and mechanical erosion of the permafrost by Arctic rivers whilst the overlying sediment withstands collapse temporarily. Here, we report the discovery of a large thermo-erosional tunnel that formed in the banks of a meltwater-fed stream in northeast Greenland in summer 2015. The tunnel was observed over eight days (14–22 July), during which period the tunnel remained open but bank-side slumping increased. Stream solute load increased immediately downstream and remained high 800 m from the tunnel. Whilst this field observation was opportunistic and information somewhat limited, our study provides a rare insight into an extreme event impacting permafrost, local geomorphology and stream habitat. With accelerated climate change in Arctic regions, increased permafrost degradation and warmer stream water temperature are predicted thereby enhancing potential for thermo-erosional niche development and associated stream bank slumping. This change could have significant implications for stream physicochemical habitat and, in turn, stream benthic communities, through changes in aquatic habitat conditions.

1. Introduction

Thermo-erosional niches are river bank undercutting resulting from the combined action of thermal and mechanical erosion (Walker et al., 1987): running water infiltrates cavities in the frozen active layer, forming underground tunnels, from where fast water current and warmer water temperatures, relative to the frozen ground, simultaneously thaw and erode the permafrost (Walker and Arnborg, 1966; Perreault et al., 2016). Whilst water temperature has been identified as the principal factor influencing thermo-erosional niche development, ice, sand and silt content in the permafrost are also important considerations (Dupeyrat et al., 2011). Thermal erosion is most prevalent in the High Arctic landscape due to (1) higher river flows during summer peak snowmelt and (2) the presence of permafrost which strengthens the river banks but permits larger amounts of bank undercutting, and large slump blocks when the banks finally collapse (Scott, 1978). Whilst the most common type of thermo-erosional niche occurs along stream banks or coastal areas where the above sediment collapses eventually, they can also be created without the sediment above the niche collapsing, forming tunnels. However, due to their tendency to occur in these remote environments, large tunnel forming thermo-erosional niches have rarely been reported. Most reports of large-scale thermo-erosional niches have been from Alaska and Canada and have been formed through ice wedge thaw (eg. Fortier et al., 2007; Godin and Fortier, 2012; Veillete et al., 2015 Kanevskiy et al., 2016). Limited information is available from other areas of the Arctic. To increase our knowledge on this phenomenon and create a pan-Arctic record, here we report and describe a large thermo-erosional tunnel over a stream in northeast Greenland.

2. Methods and data

2.1. Site description

The snowmelt-fed stream Aucellaelv is in close proximity to the Zackenberg research station at 74°28′ N, 20°34′ W in the Northeast Greenland National Park (Fig. 1). The mean annual air temperature is −9.1 °C and the warmest month is July with a mean temperature of 5.8 °C. The mean precipitation is 261 mm and falls mainly as

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ECOLOGY OF TUNDRA ARTHROPODS

Longitudinal distribution of macroinvertebrates in snowmelt streams in northeast Greenland: understanding biophysical controls

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Abstract In a changing climate, Arctic streams are expected to show more influence from snowmelt, rainfall and groundwater, and less domination from glacial meltwater sources. Snowmelt streams are characteristic features of Arctic ecosystems, yet our current understanding of longitudinal patterns in benthic macroinvertebrate assemblages in these systems is limited when compared to glacier-fed systems. This study characterised longitudinal patterns of macroinvertebrate communities in snowmelt streams in northeast Greenland to provide novel insights into Arctic stream communities as dominant water sources shift with climate change. Benthic macroinvertebrates and environmental variables were sampled at three sites along five streams. Taxa diversity, evenness and abundance were expected to increase with distance from the stream source due to enhanced channel stability and warmer water temperature. This expectation for diversity and evenness was found in two streams, but abundance was up to ten times higher at the upstream sites compared to downstream, where biofilm biomass and ionic load were also highest. Here communities were largely dominated by the genus *Eukiefferiella* (Chironomidae). In the other three streams, no clear pattern in longitudinal macroinvertebrate community composition was evident due to low channel stability along the entire stream length. This study highlights the considerable variation in macroinvertebrate zonal distribution between snowmelt streams in northeast Greenland. A change towards more snowmelt-dominated streams in the Arctic could lead to shifts in the longitudinal organisation of macroinvertebrate community assemblages and the dominant species as a function of channel stability characteristics.

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Keywords Chironomidae · Macroinvertebrates · Rivers · Zackenberg · Arctic

Introduction

Over the past 100 years, climate change has had a major impact on Arctic regions, with air temperature rise three times higher than the global average (2.9 °C compared to 0.8 °C, respectively) (Comiso and Hall 2014; Overland et al. 2015). Winter air temperature is predicted to further increase by 18 °C by the end of the century in northeast Greenland (Stendel et al. 2008) and with predicted increases in snowfall and rainfall, and decreased permafrost extent (Dyergerov and Meier 2000; White et al. 2007; Foster et al. 2008; Stendel et al. 2008) these changes are expected to significantly influence Arctic freshwater ecosystems. Both hydrology and thermal regimes (van Vliet et al. 2013) will be changed with

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RESEARCH ARTICLE

Nutrient uptake controls and limitation dynamics in north-east Greenland streams

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ABSTRACT

Permafrost thaw induced by climate change will cause increased release of nutrients and organic matter from the active layer to Arctic streams and, with increased water temperature, will potentially enhance algal biomass and nutrient uptake. Although essential for accurately predicting the response of Arctic streams to environmental change, knowledge of nutrient release on current Arctic in-stream processing is limited. Addressing this research gap, we quantified nutrient uptake of short-term releases of NO_3^-, PO_4^{3-} and NH_4^+ during peak snowmelt season in five streams of contrasting physiochemical characteristics (from unstable, highly turbid to highly stable, clear-water systems) in north-east Greenland to elucidate the major controls driving nutrient dynamics. Releases were plus or minus acetate to evaluate uptake dynamics with and without a dissolved organic carbon source. To substantiate limiting nutrients to algal biomass, nutrient-diffusing substrates were installed in the five streams for 16 days with NH_4^+, PO_4^{3-} or $NH_4^+ + PO_4^{3-}$ on organic and inorganic substrates. Observed low uptake rates were due to a combination of low nutrient and DOC concentrations, combined with low water temperature and primary producer biomass, and substantial variation occurred between streams. N was found to be the primary limiting nutrient for biofilm, whilst streams displayed widespread PO_4^{3-} limitation. This research has important implications for future changes in nutrient processing and export in Arctic streams, which are predicted to include increased nutrient uptake rates due to increased nutrient availability, warmer water temperatures and increased concentration of labile carbon. These changes could have ecosystem and landscape-wide impacts.

KEYWORDS
Arctic; river; biofilm; biogeochemistry; climate change; freshwater

ABBREVIATIONS
ANOVA: analysis of variance; chl *a*: chlorophyll *a*; DO: dissolved oxygen; DOC: dissolved organic carbon; FBOM: fine benthic organic matter; NDS: nutrient-diffusing substrates; TOC: total organic carbon

Introduction

Over the next century, a changing climate in north-east Greenland is predicted to increase winter air temperature by up to 18°C and total precipitation by up to 60%, principally as snow in winter and rain in summer (Stendel et al. 2008). Permafrost is expected to degrade significantly, both through deepening active layer and localized thermokarst processes (Frey & McClelland 2009; Docherty et al. 2017), with significant consequences for freshwater systems. Streams will potentially experience higher flow and water temperature, more suspended sediment and lower channel stability. Permafrost degradation is expected to lead to soil water becoming an increasingly important water source for stream ecosystems, providing nutrients and DOC previously bound within the permafrost (Madan et al. 2007; Frey & McClelland 2009). Increased nutrient fluxes in streams are associated with increased biological activity in the biofilm (Lock et al. 1990; Hershey et al. 1997), increased by warmer water temperatures (Gíslason et al. 2000; Blaen et al. 2014), leading to an increase in nutrient uptake in headwater Arctic streams (Rasmussen et al. 2011) with consequences for the food web. However, high channel mobility and suspended sediment concentration are unfavourable to biofilm growth, and, as such, predicted decreases in channel stability could have negative impact on nutrient uptake dynamics through reductions in biofilm biomass (Ryan 1991). Headwater streams play an important role in the ecosystem by transporting nutrients and carbon to downstream rivers and oceans. In addition, because of their high surface to volume ratio, they can have a high nutrient processing capacity, converting them into major controllers of nutrient fluxes in large watersheds (Alexander et al. 2000).

The assimilation of inorganic nutrients in streams is largely undertaken by biofilms, typically comprised of both autotrophic (algae and specialized bacteria) and heterotrophic (bacteria and fungi) components, playing an important role in structuring stream food webs (Hoellein et al. 2010). Autotrophic communities are largely found on inorganic substrate (Johnson,

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RESEARCH ARTICLE

WILEY

Spatio-temporal dynamics of macroinvertebrate communities in northeast Greenlandic snowmelt streams

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Abstract

Future climate change throughout the Arctic is expected to increase channel stability in glacially influenced streams through reduced contributions from glacial meltwater and increases in groundwater. In contrast, predictions for northeast Greenland of increased precipitation for the next 100 years—including winter snowfall—which with warmer air temperature, is expected to increase the size of spring floods in snowmelt streams. Coupled with increased disturbance through frequent summer rainfall events, nivation processes and permafrost degradation will reduce resistance of channel sediments to erosion and thereby decrease channel stability. Decreased channel stability will impact macroinvertebrate abundance and diversity. Five streams sourced by snowpacks of varying extent were studied over 3 summer seasons (2013–2015) to investigate the potential effect of shift in snowmelt regime on macroinvertebrate communities.

Total abundance and taxa richness were significantly higher in streams with small snowpacks, where the chironomid genus *Hydrobaenus* was the most abundant taxon. Streams with large snowpacks were dominated by the chironomid genus *Diamesa*. Multivariate ordination models and correlation indicated that macroinvertebrate communities were significantly influenced by channel stability and bed sediment size. Macroinvertebrate abundance was significantly higher in 2013, following low winter snowfall and associated low meltwater inputs to streams, highlighting interannual variability in macroinvertebrate communities.

A shift towards less stable habitats in snowmelt streams will potentially lead to reduced macroinvertebrate abundance and taxa richness, and local extinction of specialized taxa. Thus, snowmelt-fed streams in northeast Greenland may respond very differently to changing climate compared with streams in parts of the Arctic dominated by glacial meltwater.

KEYWORDS

Arctic, channel stability, Chironomidae, climate change, freshwater, hydroecology, meltwater, snow