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RESEARCH ARTICLE

Controls on stream hydrochemistry dynamics in a high Arctic snow-covered watershed

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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 concentrations. Suspended sediment concentration was identified as a key driver of stream solute concentrations, and varying snowpack levels caused high interannual variability in solute concentrations. Winter snowpack size was confirmed 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, alternative methods to fingerprint water sources should be considered in this region.

KEYWORDS

Arctic, landscape processes, nivation processes, permafrost, solute concentration

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, Brown, & Dixon, 1985; Hawkins, Hogue, Decker, & Feminella, 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; Chin, Lento, Culp, Lacelle, & Kokelj, 2016; Kokelj et al., 2013; Thienpont et al., 2013). During spring snowmelt, sheet floods—where water moves in sheets instead of streams—can occur due to the frozen active layer preventing infiltration and causing large sediment deposition. Within a small area, permafrost landscapes can have diverse geomorphology, hydrology, and permafrost conditions (Haeberli, 2013). Both nivation processes and localized permafrost thaws can release large amounts of sediment and solutes to streams (Chin et al., 2016; Christiansen 1998b; Kokelj et al., 2015; Malone, Lacelle, Kokelj, & Clark, 2013; Messenzehl, Hoffmann, & Dikau, 2014) 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 (Bluth & Kump, 1994; Peters, 1984).

Although 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, Christiansen, & Petersen, 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, Elberling, & Jansson, 2011; Westermann et al., 2015). Deeper snowpacks can warm permafrost to a depth of 18 m (Rasmussen 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 region's geomorphology, (Christiansen, 1998a), and through permafrost degradation, thaw slumps, and rain-induced erosion events. Increased snow depth and active layer depth will increase nutrient and carbon run-off contributions to streams. Stream physicochemical processes influence 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; Bilotta & Brazier, 2008; Chin et al., 2016; Milner, Brown, & Hannah, 2009; Prowse et al., 2006),

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 characterized 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 | METHODS

2.1 | Study site

The Zackenberg research station (74°28′ N, 20°34′ W) is located within the Northeast Greenland National Park in the high Arctic climatic zone (Figure 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 261 mm of which approximately 10% falls as rain (Hansen et al., 2008).

The valley floor was deglaciated 8,000 ybp with only a few small high altitude glaciers remaining in the area. Lying in the 1,300 km long East Greenland Caledonian belt (Higgins, Soper, & Leslie, 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, Liston, & Hasholt, 2007).

The area is a zone of continuous permafrost, with depth modelled to be 200–300 m in the main valley and 300–500 m in the mountains (Christiansen, Sisgaard, Humlum, Rasch, & Hansen, 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 1,450 m a. s.l with the glacial plateaux occurring above 1,000 m with wide horizontal valleys caused by glacial erosion below (Mernild, Liston et al., 2007). 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, whereas the easten sedimentary side is characterized 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 run-off 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 1), which were all located in the sedimentary catchment and were sourced predominantly from snowmelt; however, Aucellaelv and Palnatokeelv had small high-
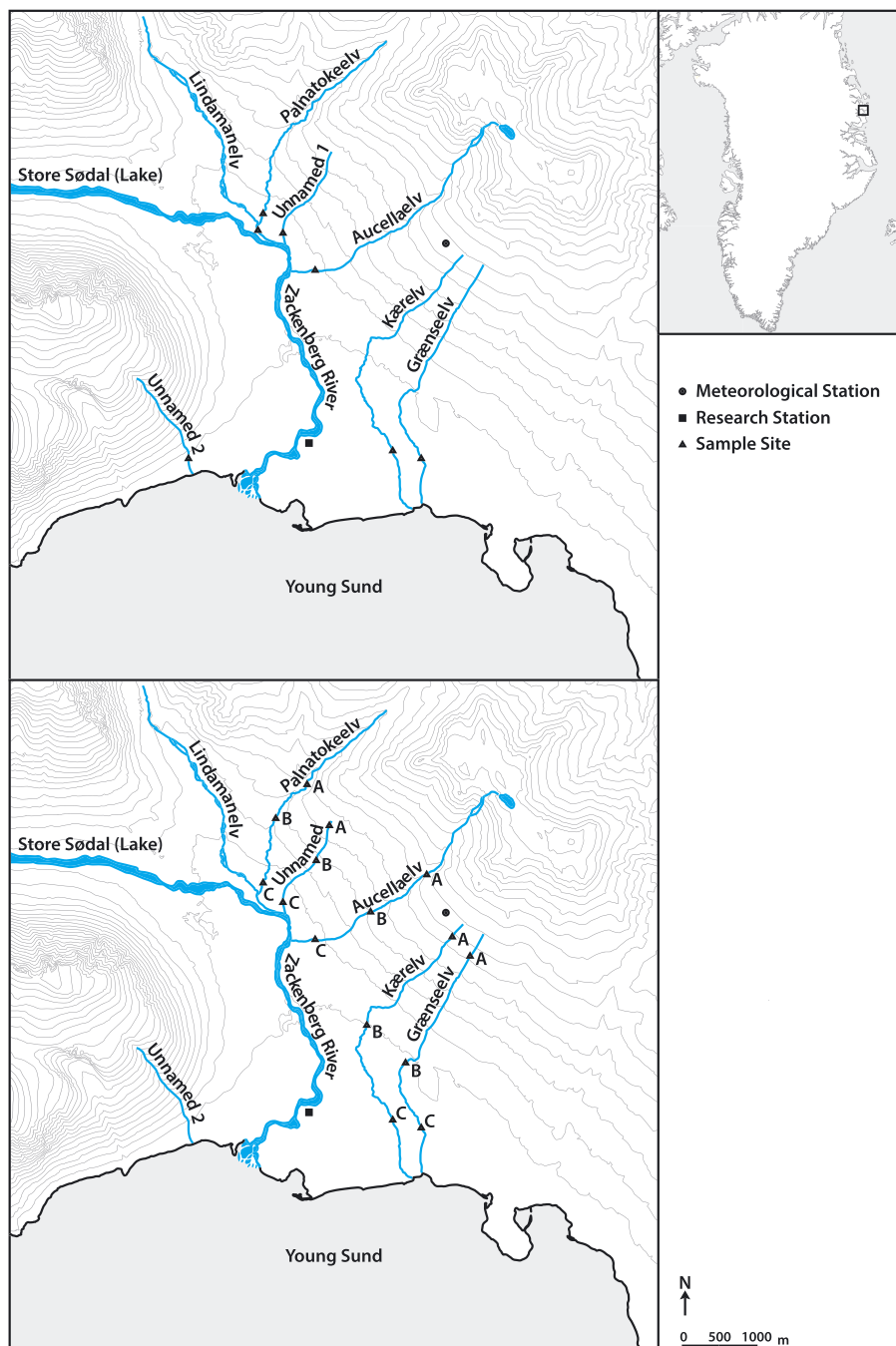
FIGURE 1 (Top) Sampling sites in 2013–2015; (bottom) longitudinal sampling in 2015

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 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 1 shows site characteristics.

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 5 km of all sites. Air temperature and snow depth were recorded every 30 min whereas precipitation was recorded hourly.

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

TABLE 1 Site characteristics and physicochemical measurements during the July 2015 field campaign

	Altitude (m)	Aspect (facing)	Conductivity (µS cm⁻¹)*	pH*	DO (%)*	Water temperature (°C)*	Depth (cm)*	Width (m)*	Mean Velocity (m s⁻¹)*	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

*Spot measurements.

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 1). For longitudinal sampling, samples were collected from the upstream (Site A) first starting at around 9 a.m., with a space of no more than ~90 min between sites. Samples were collected where water was assumed to be completely mixed.

Channel stability was calculated using the whole Pfankuch Index in 2015 (Pfankuch, 1975). Although this method is not quantitative, it is a reliable assessment of stream channel stability when the same observers undertake similtaneous assessments at streams targeted for comparison (Peckarsky et al., 2014), as was the case in this study. Stream discharge was calculated using the velocity-area method using a flow metre (µP-TAD from Höntzsch instruments, Germany) wetted width and average depth 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 where water was well mixed and were collected in 1-L containers before being passed through a preweighed Whatman Glass Fibre Filter paper. Filter papers with sediment were dried at 60°C for 48 hr 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 min.

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, within 10 m of stream bed 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 2012/2013, only two snow samples could be collected, namely, (a) 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 (b) near Young Sund. Soil water samples were collected in 2015 and 2016. Samples were collected 3 to 5 m from the stream bed at downstream sampling sites. Shallow active layer depth in July 2015 meant only one soil water sample was collected at ~20 cm depth. In August 2016, deeper active layer depth allowed for soil water sample collection at 80–90 cm depth. Limited sampling of soil water means that samples are not intended to be representative of the wider area nor the whole summer season but to provide insight into inputs to the nearby stream channel during the time period during which the sample was collected. All samples were collected by hand and passed through a Whatman glass fibre filter paper in the field. Logistical constraints and short field seasons limited the frequency of sampling from each site. Samples were frozen within 6 hr 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.

2.3 | 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 analyser (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 (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 (e.g., Cooper, Wadham, Tranter, Hodgkins, & Peters, 2002), and low Ca^{2+} : Mg^{2+} ratios signify high dolomite weathering, as is typical in nonglacierized basins (Blaen, Hannah, Brown, & Milner, 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, and K^+: 0.02) as opposed to the snowpack (Holland, 1978).

2.4 | Data analysis

Normality of data was tested using Levene's test and residual plots. Nonnormally distributed data were natural log transformed before analysis. One-way analyses of variance (ANOVAs) were undertaken for air temperature, precipitation, and snow depth variables to characterize 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.

3 | RESULTS

3.1 | Hydroclimatological variables during the three field campaigns

Snow depth varied markedly between years (Table 2). Winter 2012/2013 was a record dry year with maximum snow depth of 7.7 cm whereas the following two winters received relatively high snowfall (111.3 and 90.2 cm, respectively; November to May all years). Air temperature in 2013 and 2014 was significantly cooler compared with 2015 with a mean temperature of 5.9°C and 6.0°C in 2013 and 2014, respectively, compared with 7.1°C in 2015 (Table 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. During the longitudinal study conducted in 2015, weather conditions varied on sampling days between sunny conditions for Kærelv, Aucellaelv, and Palnatokeelv and cloudy for Grænseelv and Unnamed1.

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 0.01 km^2 or under; Aucellaelv was sourced from a snowpack of 0.06 km^2 and Palnatokeelv from a snowpack of 0.08 km^2.

Discharge at streams Kærelv, Grænseelv, and Unnamed1 increased downstream in 2015 (Table 3) but not at Aucellaelv. However, the pattern seen in discharge at Aucellaelv may be unreliable due to the highly braided nature of the stream at the downstream site making measurement difficult. Discharge for Palnatokeelv was not measured at its upstream and intermediate site due to high water velocities and depth; however, measurements for velocity are

TABLE 2 Descriptive statistics for air temperature and precipitation during each field season and snow depth for the winter months November to May previous to each field season

Variable	Statistic	Year		
		2013	2014	2015
Temperature (°C)	Mean ± SD (min–max) ANOVA	5.9 ± 2.71 (−0.5, 14.9) 2013–2014: $F(1, 2,110) = 0.14$, $P = 0.71$ 2013–2015: $F(1, 1,870) = 69.67$, $P < 0.0001$ 2014–2015: $F(1, 1,870) = 53.73$, $P < 0.0001$	6.0 ± 3.26 (−0.7, 16.7)	7.1 ± 3.51 (−0.3, 16.7)
Precipitation (mm)	Mean ± SD (min–max) ANOVA	0.02 ± 0.07 (0.0, 0.9) 2013–2014: $F(1, 1,054) = 16.65$, $P = <0.0001$ 2013–2015: $F(1, 1,054) = 24.2$, $P = <0.0001$ 2014–2015: $F(1, 1,054) = 28.6$, $P = <0.0001$	0.07 ± 0.3 (0.0, 3.5)	<0.01 ± 0.14 (0.0, 0.4)
Snow depth (cm)	Mean ± SD (min–max) ANOVA	3.45 ± 2.66 (0–7.7) 2013–2014: $F(1, 8,627) = 82,040$, $P = <0.001$ 2013–2015: $F(1, 7,731) = 20,437.66$, $P = <0.001$ 2014–2015: $F(1, 12,754) = 30,283.75$, $P = <0.001$	88.4 ± 12.52 (61.3–111.3)	48.56 ± 13.32 (30.2–90.2)

Note. ANOVA: analysis of variance; SD: standard deviation.

TABLE 3 Pfankuch Index channel stability scores (Pfankuch, 1975), discharge, and suspended sediment concentration for each stream and longitudinal site (A–C)

| Stream | Longitudinal site | Channel stability | | | | Discharge (l s^{-1}) | | Suspended sediment (mg L^{-1}) |
| | | Excellent | Good | Fair | Poor | | | |
		(<38)	(39–76)	(77–114)	(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)

Note. For channel stability, "excellent" represents highly stable channels and "poor" represents highly unstable channels. Significant differences for channel stability are shown; significant differences in suspended sediment are shown.

*$P < 0.05$ and ***$P < 0.0001$ significant difference with Unnamed1, Aucellaelv, and Palnatokeelv.

**$P < 0.05$ significant difference with Aucellaelv and Palnatokeelv.

***$P < 0.0001$ and **$P < 0.01$ significant difference with Aucellaelv, Palnatokeelv, and Lindemanelv.

recorded in Table 1. Given that the upstream site at Palnatokeelv was not located near the source such as 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 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 3) with significantly higher levels in Aucellaelv, Lindemanelv, and Palnatokeelv compared with 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, Hannah, Riis, Rosenhøj Leth, & Milner, 2017), and the channel shifted by 1 m after a heavy rain event (personal observation). Palnatokeelv was also characterized 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 because it is falling into both categories.

3.3 | Spatial variation in stream hydrochemistry dynamics

Conductivity varied markedly between streams but not within streams (Table 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 Unnamed2 draining the crystalline catchment (31 μS cm^{-1}). Variation in conductivity between streams was characterized by the marked difference in the low stability stream Aucellaelv compared with 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 the rain storm event on July 8 (Figure 2). No diurnal variability was observed in Lindemanelv despite glacial melt additions, possibly due to the larger stream size. The summer 2014 time series data show that conductivity was significantly correlated with precipitation in Kærelv ($r = 0.199$, $P = <0.01$)

TABLE 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
Unnamed2		31	-	-
Lindemanelv		-	45	-

and Aucellaelv ($r = 0.268$, $P = <0.0001$) but not in Lindemanelv and with suspended sediment at all sites ($r = 0.999$, $P = <0.001$).

Marked differences were found between streams in hydrochemistry dynamics (Table 5). There was no significant correlation between channel stability and hydrochemistry, Na^+, K^+, Si, NO_3^-, and NH_4^+ were all significantly positively correlated with suspended sediment concentration (Table S1).

Results indicated low solute concentrations in the stream draining the crystalline catchment, Unnamed2, compared with other sites in the

same year. The low stability stream, Aucellaelv, was characterzsed by high solute concentrations compared with other sites, where in 2013, all solutes, except Si, were significantly higher ($P = <0.01$; Table 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 6) 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 with all other streams and Palnatokeelv compared with 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 with all other streams (ANOVA, $F(5, 23) = 7.25$, $P = <0.001$, Tukey, P values 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 3). For K^+ : Si ratios, whilst there was no significant difference between streams, an increase in K^+ : Si was confirmed downstream from the source in the three most stable streams (Kærelv,
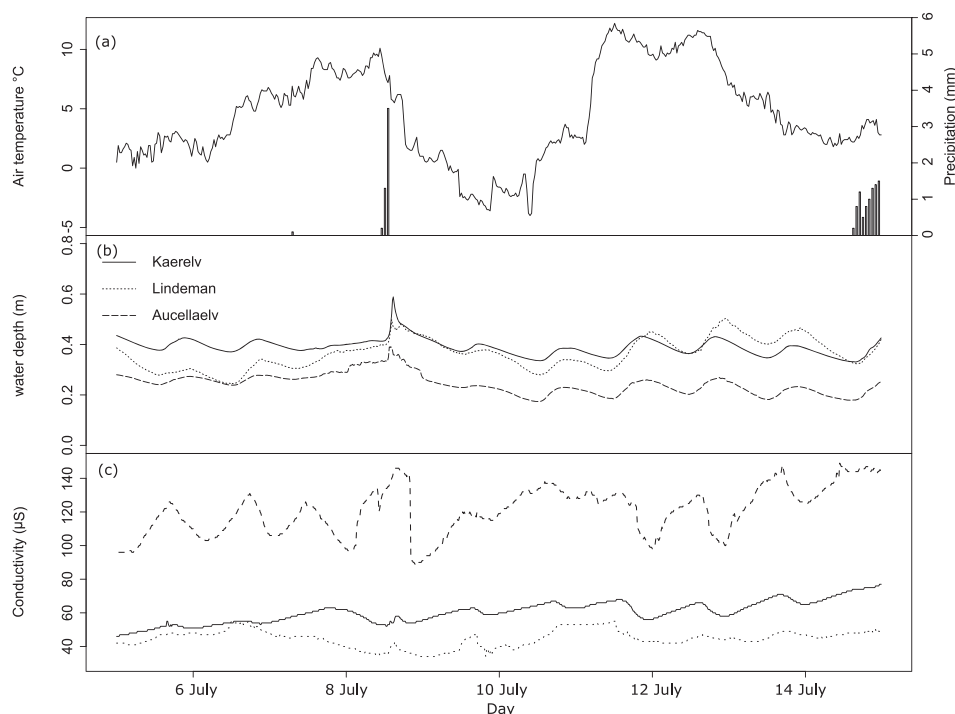

FIGURE 2 (a) Air temperature and precipitation, (b) water level, and (c) conductivity timeseries for Kærelv, Aucellaelv, and Lindemanelv between July 5 and 14, 2014

TABLE 5 Descriptive statistics for major ions for stream water, soil water, and snow in the 2013, 2014, 2015, and 2016 melt seasons

Site	n	Mg²⁺ (µEq L⁻¹)		Na⁺		K⁺		Ca²⁺		Si (mg L⁻¹)		NH₄⁺ (µEq L⁻¹)		NO₃⁻		PO₄³⁻	
		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

Note. N = number of samples, M = mean, σ = standard deviation.

TABLE 6 Descriptive statistics for major ions from streams longitudinal for 2015 melt season

| | | Mg^{2+} | | Na^+ | | K^+ | | Ca^{2+} | | Si | |
| | | $\mu Eq\ L^{-1}$ | | $\mu Eq\ L^{-1}$ | | $\mu Eq\ L^{-1}$ | | $\mu Eq\ L^{-1}$ | | $mg\ L^{-1}$ | |
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
Palnatokeelv A	3	39.47	3.09	68.19	3.41	5.29	0.71	86.78	3.70	1.14	0.03
Palnatokeelv B	2	44.01	1.15	69.25	2.98	4.65	0.09	94.67	2.75	1.19	0.00
Palnatokeelv C	3	38.60	10.05	64.19	16.30	4.84	1.14	102.46	13.41	0.95	0.11

Note. N = number of samples, M = mean, σ = standard deviation.
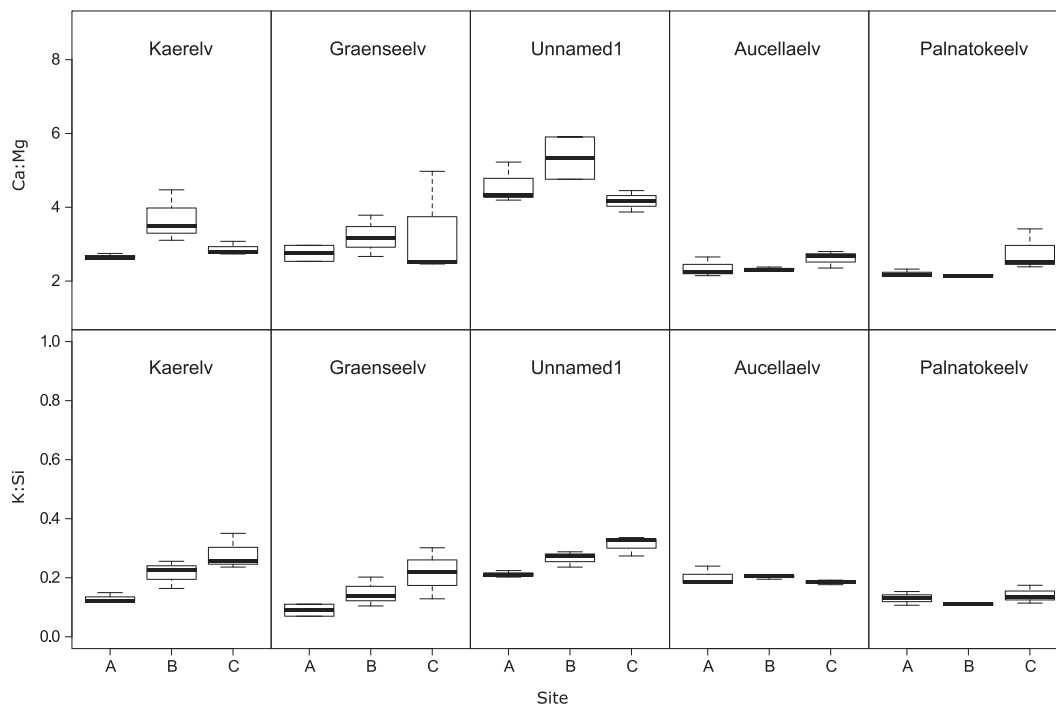
FIGURE 3 Longitudinal variation in stream $Ca^{2+} : Mg^{2+}$ (top pane) and $K^+ : Si$ (bottom pane) ratios

Grænseelv, and Unnamed1) (Figure 3), paralleling an increase in downstream discharge.

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}; Tables 4 and 5).

There were significant differences in stream hydrochemistry between the 2013, 2014, and 2015 for all solutes apart from Si (Table 5; Tables S2 and S3). Ca^{2+} enrichment was highest in 2013 when concentrations were highest in Unnamed1 (1,504 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 (3,152.8 µEq L^{-1}) were recorded in Aucellaelv.

Significant differences were found in nutrient concentrations between years (Table S2). 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 5). $Ca^{2+} : Mg^{2+}$ 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), whereas $K^+ : Si$ was significantly higher in 2013 than 2015 (ANOVA, $F(2, 23) = 5.257$, $P = 0.01$, Tukey for 2013–2015, $P = <0.05$; Figure 4).

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^{-1}; Table 5). Soil water collected in 2016 had very high solute concentrations including highest Si concentrations measured (between 2.61 and 4.55 mg L^{-1}; Table 5). This is thought to be due to the later sampling date compared with previous years, means water will have had a longer soil residence time before entering the stream.

4 | DISCUSSION

Winter snowfall, rainfall, suspended sediment concentration, and underlying geology have been identified as the principal drivers of hydrochemistry dynamics in streams in the Zackenberg valley. Soil water is shown to have little influence on stream hydrochemistry during early summer; however, limited results show that soil water may have more influence towards the end of the summer season, when active layer is thickest.

4.1 | Stream channel stability and suspended sediment characterization

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 emphasized 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 (Cable, Christiansen, Westergaard-Nielsen, Kroon, & Elberling, 2017; Christiansen, 1998a). 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 colonize and through this process, 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.
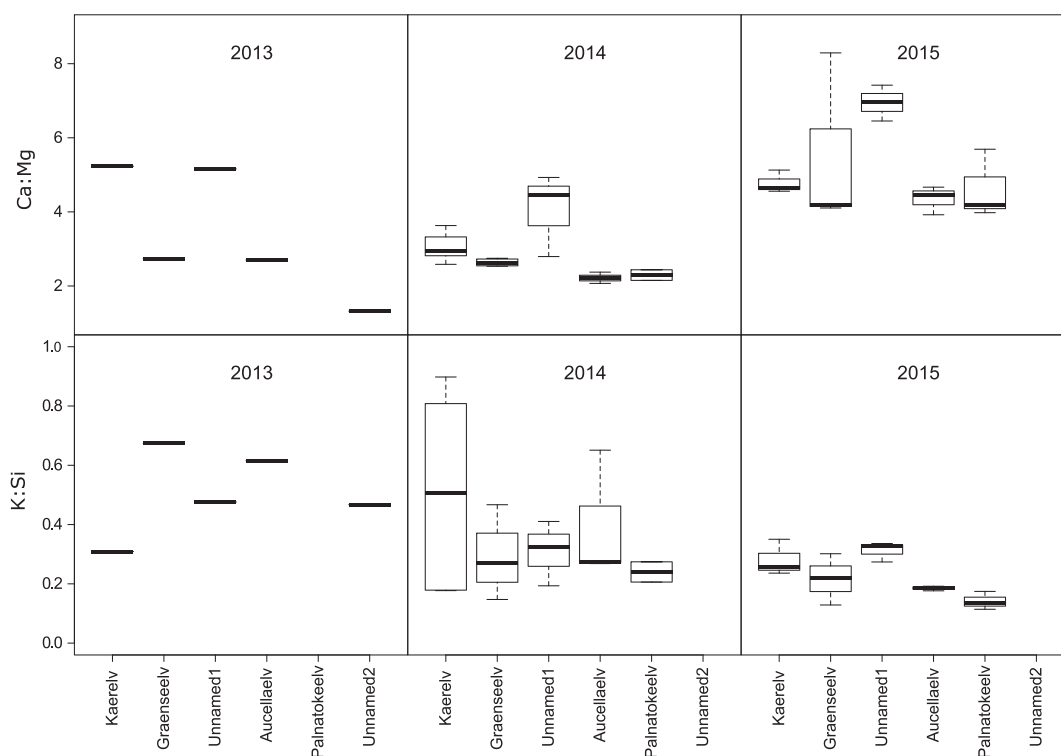

FIGURE 4 Interannual variation in $Ca^{2+} : Mg^{2+}$ (top pane) and $K^+ : Si$ (bottom pane) ratios for streams between 2013 and 2015

Alongside spring floods as a source of sediment, the dirty snow on Aucella mountain in 2013 indicates aeolian sediment transport into snowpacks during winter (Cable et al., 2017), and although infrequent, rainstorm events are known to influence sediment flux by driving increased erosion in sparsely vegetated areas in the sedimentary region (Rasch, Elberling, Kakobsen, & Hasholt, 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 with 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 with 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), with average annual suspended sediment fluxes between 43,000–61,000 ty^{-1} (Ladegaard-Pedersen et al., 2017). 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 characterizing geology into studies of Arctic streams and the important influence of nivation processes and permafrost degradation for sediment transport.

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 with 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 with 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 with 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 and 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 nonglacierized 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, Drever, Frost, & Holden, 2000; Blaen et al., 2013; Fortner, Tranter, Fountain, Lyons, & Welch, 2005).

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 and 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 with the following 2 years. The low water level in 2013 resulted in highly concentrated solute loads, as also found in late summer 2016. The low solute concentrations 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.

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 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, Sigsgaard et al., 2007). 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, Hannah, and Milner (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 localized 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 (Blaen et al., 2013; Rasch et al., 2000). 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, its 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.

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, Riis, Hannah, Rosenhøj Leth, & Milner, 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; Quinn, Davies-Colley, Hickey, Vickers, & Ryan, 1992; Shaw & Richardson, 2001; Wagener & LaPerriere, 1985) and an increase in invertebrate drift (Bilotta & Brazier, 2008; Doeg & Milledge, 1991; Rosenberg & Wiens, 1978). Suspended sediment can cause gills and guts to become clogged (Alabaster & Lloyd, 1982; Bilotta & 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 (Chin et al., 2016; Gray & Ward, 1982). 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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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.