

Editor Dr. Robert Bingham,

Please see below our reply to reviewers. The text of the review is in italics or response is in plain text.

Reviewer 1

General overview

This is an interesting study looking at the temporal variation in the hydrochemistry of a sizeable glacial catchment in SW Greenland. On the downside, there is relatively little data – only four days of coupled relative discharge and chemical composition data, with no absolute discharge data. To be fair, this is clearly a logistically challenging site to work in, with no fixed points to allow reliable continuous data logger monitoring, and even limited robust time series data from such a large catchment is worthwhile. This paper is building on their recent Geology paper ‘Chemical weathering under the Greenland Ice Sheet’, which examined the bulk chemistry of a series of boreholes waters across the catchment.

We thank the reviewer for their interest in our study. We felt that although the data record presented is relatively short, it is still of interest to the broader community, both in that it presents novel methods for assessing relative discharge and in the unusual features of the record that are observed.

The authors do a commendable job of attempting to maximize the interpretation of the limited data set through the use of time lapse photography. The principal conclusion is that there is a phase shift between relative discharge and solute concentration, perhaps best explained by the expansion of a distributed subglacial hydrologic network into seldom accessed regions during high flow. This conclusion appears intuitively reasonable, although I have some reservations that need to be addressed. My key concern is whether the relative discharge measurements are robust enough given relatively poorly constrained potential variations in water depth and water velocity (see major points below).

Some of the objections in the specific major points section (below) are valid and we have addressed the corresponding uncertainties in the revised version of the manuscript. However, we feel strongly that our photographic record is robust in assessing relative discharge. The reviewer’s main objections focus on the relatively few and imprecise velocity measurements. We agree that it would have been wise to assess velocity more frequently. However, the doubling of the width of the active channel over the course of a day is a more important signal than velocity. A well-established property of braided streams in unconsolidated fluvial sediment is that they expand and contract. Without changes in depth or gradient, changes in velocity are not possible. Furthermore, if there were velocity changes that we failed to observe, we would expect the higher flow periods to have higher velocities. This would accentuate the change in relative discharge that we observed, not diminish it.

Major specific points

Lines 159-162 – you base one of your major conclusions on the assumption that the width of the active channel is proportional to discharge. This is based on the assumptions that a) water velocity doesn’t change, and b) water depth doesn’t change (line 204). I have the following concerns/questions with this approach:

a) You state that your velocity measurements were measured only in the first two days only of the sampling period – from reading the methods, this would appear to be a period when you didn't assess discharge through photography. Since you do not have paired velocity (from surface object movement)-relative discharge measurements (from photography), how can you be sure that your conclusion that velocity does not change during the crucial last 4 day period of study is robust? (line 204; a critical underlying assumption for assuming active channel width is proportional to relative discharge).

Though we did not systematically photograph the stream from a consistent vantage point during the first two days of the study, we did still take plenty of photographs and field notes about the stream's behavior. These qualitative observations support that conclusion that the stream's behavior is consistent between the first two and later four days of the study. I.e. the naled is exposed and covered, and the width of the active channel grows and shrinks similarly over both periods. We have modified both the methods and results to discuss this qualitative similarity between the periods in the text. (Lines 141 and 231)

Particularly as the initial 2 day period was when the naled was completely covered in water hence discharge likely anomalously higher than remainder of study (or bedload sediment depth higher).

The reviewer's impression that the naled was covered for the entire first two days of the study is incorrect. (I do not know what portion of the text gave that impression.)

b) Line 159-162 – you need to give more details of your methods here. How many repeats of surface velocity measurements were made? From results you state 6 total measurements? (this doesn't seem a lot to base your conclusions on over the whole period of study). What were the 'other objects' in the water that you use as velocity indicators? I'd also question the validity of using ice blocks as reliable relative velocity indicators – could they not become snagged by debris in river, or velocity altered by differences in wind direction and speed, position in channel etc? You also need to state that the cross sectional normalized flow rate is likely to be substantially different from the surface velocity, particularly when using non neutrally buoyant objects.

We have now described our method of timing the stream's surface flow in greater detail (line 136).

c) You also state there is no change in depth in the river, although you also state that there is considerable mobility of sediment with collapsing banks, and scouring and deposition of sediment. Surely the assumption of constant river depth (line 204) should be viewed as a guesstimate?

We have rewritten the language to better reflect the uncertainty (line 220)

Line 299-301 – given the large uncertainties in relative discharge measurements (see above), I don't think you can make a quantitative statement that the discharge variation is substantially larger than the variation in concentration of dissolved solutes – though fair to say that the likely width of the active channel roughly doubles.

This statement has been removed.

Other specific/technical points

Line 8 – would be more correct to state that there are 4 days of continuous relative discharge and hydrochemical data

Text has now been added to clarify that only four of those days had measurements based on repeat photography. During the first two days, we attempted to use velocity and a stage pole. This was unsuccessful for reasons discussed on lines 114-115.

Line 11/12 – don't need to state that element and ions were measured in lab in abstract (plus you also measured suspended sed weights in lab, and

All measurements employed in the study now appear on a single list (without discussion of which are lab and which are field).

Line 17/18 – I'd omit this sentence from abstract – it is based on the prior season's discharge from a single supraglacial stream. Worth mentioning in main text, but not strong enough for abstract.

The sentence has been removed.

Line 56 – would be worth referencing Wadham et al Global Biogeochem Cycl 'Size Matters' article here

The Wadham et al. citation is appropriate here and has been added.

Line 93 – need to either reference this subjective number of 500 m³s⁻¹ to something (visually, similar to observed discharge at x, which has a discharge of x) or omit.

We have modified the statement to be more qualitative and added referenced the quantitative measurements made in the Watson River.

Line 110 – what kind of bottle, Nalgene PP?, was it cleaned, rinsed with sample etc? how long was pole?

More detail about the bottle, pole, and sample rinsing is now included (Line 169)

Line 120 – 0.1 um nylon filters seem an odd choice – most studies use 0.2 um or 0.45 um, why were these chosen? What filtration apparatus was used, Nalgene? Were procedural blanks (e.g. using MQ water) carried out, what were these blank values and how did they compare to instrument detection limits?

Our choice to use such fine filters came from concern that colloidal sized particles (from glacial comminution) were able to pass through larger filters. However, we feel that a discussion of this point is beyond the scope of the paper. We now discuss procedural blanks (line 191).

Line 126 – pH is always tough to accurately measure in low conductivity glacial waters. Please give further details – was 2 or 3 point calibration used, how long was pH probe left to stabilize prior to reading? Two decimal points for pH in Table 1 seems v optimistic.

This is now discussed in lines 186.

Line 128 – please state precisions and detection limits here, ditto line 130

Does the reviewer intend for us to list the lower limits of detection for all analyzed elements in the manuscript text? I don't believe this is customary.

Line 130 – what temp were filters dried, and for how long?

This is now in the manuscript (line 192)

Line 176 – typo, should be gauge

Fixed.

Line 176 to 178. What was the comparative weather like during the 6 day main study water sampling? To what depth into ice interior had snow line retreated to during both seasons – the outlet has a large catchment, and snow cover will have a major impact on the timing/magnitude of discharge runoff.

We now discuss the temperature during the study period on lines 166-168. We discuss the comparability of the ablation seasons in lines 150-152. As it turns out, the total progress of ablation was comparable between the two field seasons. The 2012 data are from earlier in the season, but from a year of extraordinary melt.

Line 182 – you start with discharge results. You should ideally be consistent with the order of methods section – perhaps best to start methods with discharge.

We have reordered the methods section to mirror the results section.

Line 200 – you need to put in these calculations, and state assumptions

We added a parenthetical explaining the basic concept (line 216). We feel that the equation sufficiently well known that further elaboration is not necessary.

Line 240 – how were lab TDS calculated: from summing inorganic ions, or by measurement using conductivity/TDS meter?

The text now reads “sum of laboratory measured inorganic ions.”

Line 343 – should put relative discharge, not just discharge – also see major points

The word “relative” has been added.

Line 343 – you only measured relative discharge over 6 days, not four

The reference to six days has been removed from the sentence.

Line 344-347 – given many uncertainties in measuring relative discharge, I think this statement is too strong

We have replaced the word “show” with “suggest” to indicate greater uncertainty.

Table 1 – there are too many decimal points – I would have thought one decimal point is sufficient for most (though need to compare to precision of analyses). Also, need to put charges on anions to be consistent with main text. Plus better to have field alkalinity and calculated alkalinity in adjacent columns to aid comparison.

We have dropped the second decimal on everything but the suspended sediment analysis and made the other requested changes.

Figure 2 – these were too small in my printed copy to see properly. Please make photos larger, they are a key component of the study

We have increased the size of the figure and zoomed in most of the images to enlarge the most relevant details.

Figure 3 – Rather than having smoothed lines for min/max discharge, put on hourly points (or as well)

It seemed inappropriate to actually label figure 3a with hourly points from figure 3b, as the two datasets are from different time periods. The smoothed max-min curves are meant to represent the range suggested by the combination of qualitative and quantitative observations discussed in the text. The figure caption has been modified to reflect this.

Reviewer 2 (Bingham):

This paper provides a relatively high-resolution record of hydrochemistry measurements obtained just in front of the subglacial outlet of a western Greenland glacier over 6 days in July 2013. The record is primarily compared with discharge as assessed with time-lapse photography. The authors use these data to infer properties of the subglacial drainage system upstream from the terminus, and suggest that the lack of an inverse relationship between discharge and solute concentrations could be indicative of subglacial water accessing a linked-cavity system during peak discharge and being effective at drawing solutes from these cavities during the falling limb. The paper presents a useful new dataset on subglacial hydrochemistry which was clearly hard won, albeit covers rather a short period (6 days, albeit with 3 hour increments). The use of time-lapse photography to obtain a measure of relative discharge is a neat concept for overcoming the difficulties of measuring stage in such an active environment. So I think that ultimately the authors present some good material here.

We thank Dr. Bingham for his interest in our data set.

However, in its current form, I did not find the discussion of the data especially insightful or even especially novel. In essence, I feel the authors have to rewrite the discussion for the paper significantly to make a convincing case that the paper is presenting a novel advance. At the moment, because the paper is based on rather limited data, I think that approach has to involve providing a far more comprehensive

grounding of the ideas proposed here against what has, or they might argue has not, been interpreted from elsewhere.

My comments below concern the Discussion section (though some wider referencing and context would also benefit the introduction). I also made some minor comments throughout the paper (not including the Discussion/Conclusions) in the attached supplement.

We have revised the introduction and discussion to better reference the wide range of contexts in which hysteresis between solute flux and discharge is observed, including non-glacial settings. Whereas gradual increases solute flux during waxing flow may been observed in a wide range of contexts, we feel that the observed spikes during waning flow are in fact novel. The only previous study that (to our knowledge) has reported such behavior in a glacial context is the Anderson and others paper cited in the introduction. And in that study, the phenomenon occurred on a multi-day timescale, whereas it occurred on an hourly scale here.

Discussion Given the precariousness of the discharge results (I do have sympathy; I know all about the challenges of getting these data), I'd recommend the discussion explicitly focuses on the hydrochemistry variations, albeit using some of the qualitative discharge observations as context (i.e. I suggest excising Section 5.1). I then think you should partition the discussion into subsections which might broadly be described as (i) synthesise the main finding here, i.e. midsummer lag observed between hydrochemistry and discharge; and propose the conceptual model that water accesses distributed system on falling limb; (ii) compare this model comprehensively with findings/suggested interpretations of subglacial hydrological behaviour from other glacial systems where hydrology and/or hydrochemistry of meltwater have been observed.

We have rewritten the first paragraph of section 5.2 to discuss differences and similarities with other hydrological systems. We felt it was necessary to keep section 5.1 most because the Smith and others paper argued against any diurnal changes in discharge at Isunnguata Sermia, and our study refutes that.

I think the single biggest failing of the paper right now is that it doesn't adequately reference many other relevant studies, and therefore much of the context for justifying the discussion here is missing. For example, I'd say it should be well known from a number of studies of the hydrology of Greenland's outlets (e.g. from the Edinburgh and Bristol groups), and even large polythermal glaciers (Skidmore and Sharp, 1999, Annals of Glaciology) that the larger the catchment, the less likely one is to observe an "alpine-style" inverse relationship between solute concentration and discharge. Similarly, the above groups, and others, have acquired datasets that evince significant subglacial drainage system evolution as the melt season progresses many km upstream of outlet portals (e.g. Bartholomew et al., 2010, Nature Geoscience; 2011, EPSL) – and you'll see in Bingham et al. (2006; Earth Surface Proc. Landforms) evidence that by late July an Arctic subglacial system at similar latitude to your study area can be channelized, but discharge still accesses the distributed (your "linked-cavity") system at times of exceptional melt inputs. If you're going to entitle the paper "gives insight into subglacial conditions" then I think the insight only comes by making a much more comprehensive comparison with other relevant studies.

We now include the papers you suggest in our discussion section.

Finally, since one of the setups of the paper is to assess whether solute/discharge follows a positive/inverse/complex relationship, a comprehensive background for this (albeit pre most Greenland

hydrology studies) is given by G.H. Brown (2002) Glacier meltwater hydrochemistry, Applied Geochemistry, 17, 855-883.

The Brown paper is now cited in the introduction.

Please also note the supplement to this comment:

<http://www.the-cryosphere-discuss.net/tc-2016-137/tc-2016-137-RC2-supplement.pdf>

Interactive comment on The Cryosphere Discuss., doi:10.5194/tc-2016-137

Most of the annotations on the PDF have been implemented as requested.

Combined diurnal variations of discharge and hydrochemistry of the Isunnguata Sermia outlet of the Greenland Ice Sheet give insight on subglacial conditions

Joseph Graly, Joel Harrington, Neil Humphrey

University of Wyoming

Abstract

In order to examine daily cycles in meltwater routing and storage in the ~~Isunnguata~~ Isunnguata Sermia outlet of the Greenland Ice Sheet, ~~variation~~ variations in outlet stream discharge and in major element hydrochemistry were assessed over a six day period in July, 2013. ~~Discharge~~ Over four days, discharge was assessed from hourly photography of the outlet from multiple vantages, including where mid-stream naled ice provided a natural gauge. pH, electrical conductivity, suspended sediment, and ~~alkalinity~~ major element and anion chemistry were measured in samples of stream water collected every three hours. ~~Element and ion concentrations were subsequently measured in a laboratory setting.~~

Photography and stream observations reveal that although river width and stage have only slight diurnal variation, there are large diurnal changes in discharge shown ~~in by~~ the ~~portion doubling in width~~ of what we term the ~~width~~ “active channel”, which is characterized by large standing waves and fast flow. ~~Width of this active channel approximately doubles over a diurnal cycle. Together with changes in flow over the naled, these features allow an observationally based relative record of stream discharge in this unconstrained alluvial setting. Peaks in discharge were offset by 3–7 hours from peak melt of the interior ice surface.~~

~~Concentration~~ The concentration of dissolved solutes follows a sinusoidal diurnal cycle, except for large and variable increases in dissolved solutes during the stream’s waning flow. ~~Diurnal changes in solute concentration average 31% of the base value. Diurnal solute concentration~~ Solute concentrations vary by ~30% between diurnal minima and maxima. Discharge maxima and minima lag ~~peak and minimum~~

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Not Bold

~~stream~~temperature and surface melt by 3-7 hours; diurnal solute concentration minima and maxima lag discharge by 3-6 hours.

This phase shift between discharge and solute concentration suggests that during high flow, water is either encountering more rock material or is stored in longer contact with rock material. We suggest that expansion of a distributed subglacial hydrologic network into seldom accessed regions during high flow could account for these phenomena, and for a spike of partial silicate reaction products during waning flow, which itself suggests a pressure threshold-triggered release of stored water.

1. Introduction

Dissolved load in glacial outlet streams has long been employed as a metric for assessing water-rock interactions occurring beneath glaciers and ice sheets. Glacierized basins have comparable dissolved loads to non-glacial rivers, but are enriched in mobile cations and depleted in Si (Anderson et al., 1997). ~~Chemistry~~The chemistry of glacial water typically suggests that observed solute concentrations are reached due to presence of reactive accessory minerals and fresh mineral surfaces in glacial sediments (Drever and Hurcomb, 1986). Dissolved load is therefore linked to physical erosion in subglacial environments (Anderson, 2005). Dissolved load is also indicative of the degree to which atmospheric gases have been sequestered by chemical processes in the subglacial environment (Hodson et al., 2000).

Diurnal variation of solute concentration is a potential indicator of meltwater routing and storage-~~Solute concentration is controlled by total water-rock contact during water residence time in the subglacial environment and by~~ (e.g. Brown, 2002). ~~Solute concentration is controlled by total water-rock contact over the water residence time in the subglacial environment and by the~~ reactivity of minerals contacted by the water. In particular, two end member cases are expected: if dilution produces an inverse relationship between discharge and solute concentration, minimal changes in water-rock interaction over

time are suggested; whereas if increased discharge is coupled to increased solute concentration, diurnal changes in the processes of water-rock interaction or storage are suggested.

~~Studies~~Several studies of small alpine glaciers have ~~typically~~ found solute concentration and discharge to vary inversely, with rising discharges corresponding to falling concentrations of dissolved solutes (~~Collins, 1995; Hindshaw et al., 2011; Tranter et al., 1993~~)(e.g. Collins, 1995; Hindshaw et al., 2011; Tranter et al., 1993; Tranter and Raiswell, 1991). Ions produced by saturation limited reactions, such as calcite dissolution, can show increased load with discharge, but typically with diminished concentration per water volume (Mitchell and Brown, 2007). Elements that are limited by factors such as the rate of sorption/desorption will have constant flux levels and will only be diluted by increased water flow (Mitchell and Brown, 2007). ~~Resultantly~~Consequently, correlations between discharge and dissolved load are typically weak (~~Collins and MacDonald, 2004~~)(Collins and MacDonald, 2004). These dilution relationships have been attributed to the dominance of conduit/channelized flow in alpine environments. In cases where subglacial water is confined to fixed conduits, increased water flow will expand the size of ~~these~~the conduits and increase the speed of through-flow but will have a minimal impact on the area of water-bed contact (Nye, 1976; Röthlisberger, 1972).

~~Studies of larger glacial systems suggest more complex water-rock interactions. In~~Larger glacial systems have more complex water-rock interactions (e.g. Wadham et al., 2010), and have frequently demonstrated more complex hysteresis in the relationship between discharge and solute concentration.
At the outlet of a large glacierized basin in SE Alaska, increases in dissolved load lag spikes in discharge by several days (Anderson et al., 2003). Anderson and others attribute this to storage of water in a distributed system only released during the waning stages of flow. In distributed or linked-cavity flow, increased discharge allows flowing water to spread out across the glacier's bed and thereby increase the area of water-bed contact (Humphrey, 1987; Kamb, 1987). Time series data from the Watson River, near Kangerlussuaq, West Greenland, show out of phase variation in discharge and solute concentration, with

maximum daily solute concentrations occurring ~~as on the rising limb of the~~ discharge ~~is rising and minima~~
~~occurring as discharge is falling~~ hydrograph (Yde et al., 2014). However, on the scale of the melt season as
a whole, Yde and others find a strong inverse correlation between discharge and solute concentration,
which they attribute to conduits carrying a substantially higher portion of the meltwater flow than the
distributed subglacial system. Lags between minimum discharge and peak solute concentrations ~~are have~~
also ~~been~~ observed ~~at in karst dominated systems, such as~~ Tsanfleuron Glacier, Swiss Alps, ~~where flux from~~
~~groundwater is hydrologically important (Zeng et al., 2012)(Zeng et al., 2012)~~. Such lags are also observed
in non-glacial streams and have long been understood to result from the mixing of groundwater, soil
water, and surface runoff –each having a unique response time to rainfall events (e.g. Evans and Davies,
1998). The existence of a range of distributed and channelized flow mechanisms under larger ice bodies
similarly suggests a range of response times to input from surface melt water.

Seven measurements of dissolved solute chemistry taken from samples collected over the course
of 2 days in 2011 at the terminus of Isunnguata Sermia, a major land-terminating west Greenland outlet
glacier, potentially show a direct relationship between solute concentration and discharge (~~Graly et al.,~~
~~2014; Landowski, 2012)(Graly et al., 2014; Landowski, 2012)~~. In this limited time series, solute
concentration appears to peak at midafternoon, while discharge is high, and be minimal in the early
morning hours, with total variation of <20%. To ~~further~~ investigate further whether a direct relationship
~~exists~~ between discharge and solute concentration exists ~~in the Isunnguata Sermia outlet of the western~~
~~Greenland Ice Sheet~~, we returned to the same site for a six day period of the summer of 2013, collecting
8 samples per day for chemical analysis.

2. Field site

Water samples were collected from the terminus of the Isunnguata Sermia, ~~a major land-~~
~~terminating~~ outlet of the ~~western~~ Greenland Ice Sheet (Figure 1). The outlet glacier ~~Isunnguata Sermia~~

95 occupies a deeply cut glacial valley, with surrounding hilltops >400 m above sea level. Deep, glacially-
96 carved trenches continue under the ice sheet for more than 20 km into the interior, ~~with where~~ ice depths
97 ~~of greater than reach~~ >1,000 m (~~Jezek et al., 2013~~)(Jezek et al., 2013). The Isunnguata Sermia outlet has a
98 catchment that encompasses >2,400 km² of the ablation zone, making it one of the largest ~~regional~~
99 subglacial drainage basins in Western Greenland (~~Palmer et al., 2011~~)(Palmer et al., 2011). ~~Regional~~The
100 regional geology consists ~~of~~ primarily of Paleoproterozoic gneisses and granitoids (~~van Gool et al.,~~
101 ~~2002~~)(van Gool et al., 2002). ~~The Isunnguata Sermia outlet is located 25 km from the town of~~
102 ~~Kangerlussuaq. It is the next outlet to the north of the Russell Glacier and feeds a separate glacial river~~
103 ~~system from the Watson River, providing a silicate bedrock substrate for subglacial chemistry.~~

104 Water emerges from a single location on the south side of Isunnguata Sermia's terminus front
105 ~~~30m~~30 m above sea-level (Figure 1) and traverses a broad, >100 km long sandur to the fjord. Discharge
106 of pressurized subglacial water creates a large upwelling capable of expelling water multiple meters into
107 the air and, although no fully quantitative measurement could be made, peak discharge was estimated ~~to~~
108 ~~exceed 500 m³s⁻¹ in the hundreds of m³s⁻¹, as is consistent with typical summer discharge in the nearby~~
109 Watson River (Hasholt et al., 2013). Ice-cored moraines and frozen outwash shape the course of outlet
110 waters. On the sandur, frozen outwash channels the water into a single thread, although the large
111 sediment load creates rapidly changing channel and bed geometry. Near the terminus, the frozen outwash
112 of the sandur is elevated ~2-4 meters above the discharging stream. The main stream is also fed by minor
113 ice surface melt streams. A small stream that runs along the south lateral margin of the glacier joins the
114 main terminal outlet stream just below the primary upwelling site.

115 This work was performed ~~in the context as part of several other~~ a wider program of coordinated
116 studies of the Isunnguata Sermia terminus region. Hot water boreholes along a transect from the outlet
117 to 40 km ~~in the interior~~upstream have provided data regarding water pressure (Meierbachtol et al., 2013),
118 ice temperature (Harrington et al., 2015), subglacial water chemistry (Graly et al., 2014), and mass balance

between subglacial sediment and rock (Graly et al., 2016). More limited datasets from Isunnguata Sermia's terminal and lateral outlets were reported for the 2010, 2011, and 2012 seasons (Graly et al., 2014). The work reported here is based on samples and data collected over a 6 day period from July 16th to July 21st, 2013.

3. Methods

3.1 Water Sampling

~~Water sampling began at 8:00 hours local time on July 16th, 2013 and continued in 3 hour increments through 20:00 hours on July 21st, 2013. Samples were collected by lowering a liter bottle attached to a pole into discharging waters within 400 m of the subglacial upwelling. During July 16th and July 17th, samples were collected from the south bank of the outlet stream from the banks at the beginning of the outwash plain (Figure 1). During July 17th, the main course of the river shifted so that location had diminished flow and an emerging bank channeled waters from the lateral side stream to the location. Commencing at 14:00 hours on July 18th, sampling was relocated above the lateral side stream on the banks of the terminal moraine (Figure 1). The sampling location was not subsequently changed. Excepting periods where the emerging bank channeled lateral stream water to the first location, both locations sampled water from the main subglacial outlet and should produce comparable results.~~

~~Upon collection, 125 ml of water sample were pumped through 0.1 μ m nylon filters, with filtered water and filter papers saved for laboratory analyses. A colorimetric alkalinity test, a conductivity measurement, and a pH measurement were performed on the remaining unfiltered sample. Alkalinity tests were performed with a Hach Model AL AP alkalinity test kit. Results of field alkalinity tests were only accurate to 25 μ M. Alkalinity was therefore also calculated by charge balance from the other measured ions. pH measurements and conductivity measurements were performed with Beckman Coulter Φ 460 multi-parameter meter. pH was measured using a low ionic strength probe.~~

Subsequent water analyses were performed in the University of Wyoming Aqueous Geochemistry Lab. Concentrations of Si, Ca, Mg, Na, and K were measured on a Perkin Elmer Elan 6000 inductively coupled plasma-quadrupole mass spectrometer (ICP-MS). Concentrations of SO_4^{2-} , Cl^- , NO_3^- , and F^- were measured on a Dionex ICS-500 ion chromatograph. The filter papers were dried and weighed to assess suspended load.

3.2 Discharge

Discharge measurements of the outlet were difficult to obtain. There is no exposed bedrock near the stream to act either as an elevation reference or to stabilize the river bed. Obtaining accurate cross profiles of the stream was prohibitively dangerous, with high flows, collapsing banks, and a considerable flux of mobile ice blocks. Attempts to install a stage pole were frustrated by considerable stage variation over time associated with cutting and filling of the riverstream bed ~~and banks~~. Once the stream opens out from its restriction by remnant glacier ice near the upwelling, stage is poorly correlated with discharge. The stream instead scours sediment during the rising limb and deposits it on the trailing limb of the daily hydrograph. It was decided to assess only relative discharge. This was aided by repeat photography from two fixed locations.

Hourly stream photography began at 10:00 hours on July 18th and continuing through 20:00 hours on July 21st. From one vantage point, the central upwelling of subglacial water was photographed from the south, as it poured out from around the moraine. This vantage captured a ~1-meter-high, mid-channel naled formed from freezing of outlet waters during winter months. The naled was variably covered or exposed as discharge varied and acted as a stream gauge in this respect. This portion of the stream is restricted by frozen sediment and stream height is controlled by discharge.

A second vantage, from a rise above the south bank, captured a ~200m long stretch of the outlet stream. In this portion of the stream, increased discharge caused scour and expansion of the stream's

active channel. Photography allowed assessment of relative active channel width. Large waves and faster velocities are confined to this active channel, ~~allowing fairly unambiguous, though qualitative, determination of which portions of an overhead photograph comprise the active channel.~~ The distance between the upstream end of a persistent, mid-stream point bar and a distinct feature on the south shore was measured on each photograph (Figure 1). The length of the portion of this transect characterized by large waves and flow features was also measured, allowing for the calculation of the ~~percentage~~fraction of the stream width contained by the active channel. On most of the photographs, the break between the large standing waves and the surrounding quiescent flow was unambiguous. The second vantage also allowed assessment of flow state and Froude number from the presence of features such as standing waves.

During the first two days of the sampling period, stream surface velocity was measured by ~~repeated timing the motion of floating ice and other stream surface features down a 100 m section of the stream, repeatedly running in pace with the movement of the stream surface along a 100 m stretch of the sandur. This was accomplished by observing visually consistent mobile features of the stream, such as lineations within wave forms and small pieces of floating ice.~~ Measurements were taken during morning, afternoon, and evening stages to assess variation in velocity associated with high and low flow. During this earlier period, changes in the width of the active channel and volume of the water pouring over the ~~naled were also observed (though without systematic photography from a consistent vantage).~~

3.3.2 Interior Surface Melt

In order to compare variation in terminus discharge to melt in the surface interior, we ~~are~~ also ~~including~~consider discharge measurements from an interior ice sheet surface stream. The stream was gauged during ~~the summer~~June of 2012, so the data are not directly comparable to the measurements collected in 2013. However inasmuch as interior melt is primarily controlled by insolation, the stream's

variation likely represents a typical pattern for the timing and scaling of diurnal summer surface melt fluctuations. Coincidentally, the progression of the Greenland Ice Sheet melt season was fairly comparable between June 2012 and July 2013, with ablation rates of 6-10 Gt per day during both periods (Langen et al., 2013). The supraglacial stream was gauged during a period in which bare ice was melting, so water retention in snow did not affect its hydrology.

The surface stream was located at 67.2°N and 49.8°E, ~25 km from the terminal outlet. Stream height was gauged with a calibrated pole drilled into ice. Surface velocity was measured by timing floating ice along a course of known distance. Cross-sectional area was directly measured in the region where the gauge was emplaced and calibrated to gauge height. Transect slope was measured by pole and automatic level. Six measurements of surface velocity used to calculate an average Manning coefficient from the measured slope and hydraulic radius of the stream. Discharge was then calculated from change in gagegauge height. Stage height was measured every half hour or hour for a period from 11:30 ~~6/June~~ 18/12 2012 to 20:00 ~~6/June 21/12 2012~~. During June ~~18th, 19th~~ 18, 19, and ~~20th~~ 20, sunny weather predominated; June ~~21st~~ 21 had rainy, cooler weather.

3.3 Water Sampling

Water sampling of Isunnguata Sermia's terminal outlet began at 8:00 hours local time on July 16, 2013 and continued in 3 hour increments through 20:00 hours on July 21, 2013. Temperatures in the interior ablation zone measured at PROMICE KAN M weather station stayed at ~0.5 positive degrees per day over July 16-18 and steadily rose to 1.3 positive degrees per day over July 19-21. Samples were collected by lowering a liter Nalgene polypropylene bottle attached to an adjustable-length pole into discharging waters within 400 m of the subglacial upwelling. The bottle was dipped and rinsed in flowing stream water prior to final sample collection. Samples were initially collected from the south bank of the outlet stream, from the banks at the beginning of the outwash plain (Figure 1; Site 1). During July 17, the

215 main course of the river shifted so that location had diminished flow and an emerging bank channeled
216 waters from the lateral side stream to the location. Commencing at 14:00 hours on July 18, sampling was
217 relocated above the lateral side stream on the banks of the terminal moraine (Figure 1; Site 2). The
218 sampling location was not subsequently changed. Excepting periods where the emerging bank channeled
219 lateral stream water to the first location, both locations sampled water from the main subglacial outlet
220 and should produce comparable results.

221 Upon collection, 125 ml of each water sample were pumped through 0.1 μm nylon filters, with
222 filtered water and filter papers saved for laboratory analyses. A colorimetric alkalinity test, a conductivity
223 measurement, and a pH measurement were performed on the remaining unfiltered sample. Alkalinity
224 tests were performed with a Hach Model AL-AP alkalinity test kit. Results of field alkalinity tests were only
225 accurate to 25 μM . Alkalinity was therefore also calculated by charge balance from the other measured
226 ions. pH measurements and conductivity measurements were performed with Beckman-Coulter Φ 460
227 multi-parameter meter. pH was measured using a low ionic strength probe, with a three-point calibration
228 employed daily.

229 Subsequent water analyses were performed in the University of Wyoming Aqueous Geochemistry
230 Lab. Concentrations of Si, Ca, Mg, Na, and K were measured on a Perkin Elmer Elan 6000 inductively
231 coupled plasma quadrupole mass spectrometer (ICP-MS). Concentrations of SO_4^{2-} , Cl^- , NO_3^- , and F^- were
232 measured on a Dionex ICS 500 ion chromatograph. Element and ion analyses were measured together
233 with procedural blanks, which were consistently measured below the lower limits of detection. The filter
234 papers were dried overnight at 85° C and weighed to assess suspended load.

236 4. Results

237 4.1 Discharge

238 Over the four days during which repeat photographic observations were made, photographs of
239 the naled show consistent minima at 8:00 hours, with the naled is mostly exposed, and a small volume of
240 water overtopping a portion of the ice body (Figure 2). ~~During the first two days of observation~~On July 18
241 ~~and 19~~, the naled was completely covered by flowing water from 19:00 to 0:00 hours. On ~~the third day~~July
242 ~~20~~, it was covered from 16:00 hours, and remained covered for the remainder of the study period.

243 Maximum discharge is harder to determine from observations of the naled alone. Once the naled
244 is completely covered in water, visual interpretation of maximum flow is ambiguous. Some discrimination
245 can be made based on ~~the~~ height of the covered naled feature compared to the surrounding waves and
246 ~~the~~ angle at which the water pours over the naled (greater flows overtop the naled at a lower angle). From
247 these features, maximum stream flow ~~appears~~appeared to occur at 21:00 hours on July ~~18th~~18 and ~~19th~~19,
248 and 20:00 hours on July ~~20th~~20.

Formatted: Superscript

249 Standing waves are observed at all flows (Figure 2), although substantial differences in wave and
250 surface morphology were noted during waxing and waning phases, with rougher water in waning flow
251 and smoother water in waxing flow. The roughness change may represent a change in the sediment load
252 of the river between the erosive waxing stage and the depositional waning stage. The persistence of
253 standing waves implies near critical flow conditions, or a Froude number approximately 1, for the entire
254 study period. Measurements of stream velocity showed surface speeds of 2.86 ± 0.12 m/s (2σ , $n=6$).
255 Variation in velocity between morning and evening stages was within measurement error. ~~Based on~~
256 ~~calculations from a Froude number of 1, stream depths of 0.5–0.9 m are suggested; these depth estimates~~
257 ~~were supported by observing ice blocks rolling or bouncing down the flow. The lack of~~The lack of
258 relationship between stage and discharge and velocity has been noted before in sediment laden glacial
259 rivers (Humphrey and Raymond, 1994).

Field Code Changed

260 ~~Since neither stream velocity nor depth change with discharge, variations in discharge are~~
261 ~~accommodated by changes in the width of the active channel.~~Based on calculations from a Froude number

of 1 (i.e. stream velocity squared is equal to stream depth times acceleration from gravity) and assuming a total velocity within 20% of surface velocity, stream depths of 0.5 - 0.9 m are suggested. These depth estimates were supported by observing ice blocks rolling or bouncing down the flow. The active channel's approximately constant stream velocity and persistent standing waves suggest a fairly constant stream depth. Wide areas of shallow slow water remained present during low flows and the total surface area of the stream remained approximately constant. Pole probing of these shallow areas suggests 10 to 20 cm depths. Because the active channel has an order of magnitude greater discharge per transect meter than the stream's marginal areas ~~and changes in active channel water velocity were not observed,~~ we infer that the cross-sectional area of the active channel is the primary control on discharge. Rising discharge is accommodated by scouring on the margins of the active channel; falling discharge is accommodated by deposition.

Assessment of the active channel width from repeated photography shows substantial differences between morning hours (~5:00-10:00), where 20-30% of the stream is comprised of active channel characteristics, and late afternoon / evening hours (~18:00-0:00) where >40% of the stream is comprised of active channel characteristics. These observations are generally consistent with assessments of the height of water pouring over the naled (Figure 3). Though repeated photography from a consistent vantage was not performed during the first two days of the study, field observations and photographs from that period show similar changes in the active channel width and naled overflow.

4.2 Interior Surface Stream

The calculated Manning coefficient for the interior stream was 0.0117 ± 0.0018 (2σ). ~~Discharge measured in the interior ice surface stream~~ its discharge varied by as much as an order of magnitude during the course of diurnal cycles, with low values as small as $0.3 \text{ m}^3\text{s}^{-1}$ and high values greater than $3.5 \text{ m}^3\text{s}^{-1}$ (Figure 3). Minimum stage heights consistently occurred around 4:00 hours. Maximum stage heights

consistently occurred at 14:00 or 15:00 hours. These data contrast with our observations of water pouring over the naled. The naled minimum occurred approximately 4 hours later than minimum of surface melt. The naled maximum occurred approximately 6 hours later than maximum surface melt. This delay is representative of the integration of the travel time delays from the entire glacier catchment.

4.3 Water Analyses

~~Sampled~~The sampled waters ~~are~~were generally chemically dilute, with 292 ± 50 micromoles per liter dissolved solutes (Table 1). Ca ~~is~~was the dominant cation, followed by Na, K, and Mg (Figure 4). Mg abundances ~~are~~were an order of magnitude lower than the other major cations. Dissolved Si ~~occurs~~occurred at comparable abundance to Na. Standard deviations of the mass spectrometer measurements were $<1\%$ of the measured value. Bicarbonate (measured as alkalinity) ~~is~~was the dominant anion. SO_4^{2-} and Cl^- are detected in all samples, but occur at an order of magnitude lower concentration. Trace amounts of NO_3^- and F^- were detected in some samples, at values an order of magnitude below SO_4^{2-} and Cl^- concentrations (Figure 4). On average, field alkalinity measurements ~~exceed~~exceeded the alkalinity estimates from charge balance by $25 \pm 14 \mu\text{M}$ (2σ). Some over-measurement in the field titration is expected, as the value is recorded at the level where the color tracer disappears (and therefore is a maximum compared to previous drop). Charge imbalance may also result from absorption of H^+ particles to suspended sediment in unfiltered water. Field electrical conductivity measurements ~~show~~showed similar results to the sum of laboratory analyses measured inorganic ions ($p < 0.0001$) (Figure 4). Suspended sediment concentration ~~does~~did not show a consistent correlation or anti-correlation with dissolved load (Figure 4).

~~Relative~~The relative abundances of cation species ~~is~~are comparable to measurements taken at the Isunnguata Sermia terminus in the summer of 2011 (~~Graly et al., 2014~~)(Graly et al., 2014). The SO_4^{2-} /alkalinity ratios are diminished compared to those measured in 2011, but are comparable to those found

310 in samples collected in 2010 and 2012. The concentrations of suspended sediment are similar to those
311 observed at nearby Leverett Glacier during the summer of 2010 (Cowton et al., 2012).

Field Code Changed

312 When normalized to average concentration, the magnitude and timing of cation and silica
313 concentration variation ~~iswere~~ highly consistent between species over time (Figure 5). Covariation of all
314 cation and Si species is statistically significant with $p < 0.05$. Covariations of K-Mg, K-Si, and Na-Si have p -
315 values ranging from 0.01 to 0.05; all others are < 0.0001 . All cations and silica concentrations
316 ~~follow~~followed a diurnal pattern, with higher concentrations present during morning and early afternoon
317 hours and significantly lower concentrations present during later afternoon and evening hours. In several
318 of the studied cycles, large changes in total concentration ~~arewere~~ limited to the 20:00 and 23:00 hours
319 samples, which are substantially lower than the other samples collected throughout the day.

320 ~~There are two major deviations from the diurnal pattern.~~ The 11:00, 14:00, 17:00, and 20:00
321 samples from July 17th ~~have~~had substantially lower solute concentrations than would be otherwise
322 suggested by diurnal fluctuations observed elsewhere in the record. This corresponds with the period
323 during which an emerging bank partially separated site 1 from the main channel allowing a surface-fed
324 side stream to substantially dilute the water.

325 At 2:00 on July 20th 20, there ~~iswas~~ a $> 60\%$ spike in total concentration of all cations. Similar, but
326 smaller magnitude spikes ~~arewere~~ also present ~~induring~~ the ~~2:00 samples~~other four measured periods of
327 ~~July 19th and 21st and the July 16th 23:00 sample~~waning flow. The ~~most clearly expressed~~largest of these
328 spikes ~~(July 20th and 21st)~~ are substantially more expressed in Na and K concentrations than in Ca, Mg, or
329 Si. (Figure 5). During the ~~July 21st final measured overnight~~ spike, ~~the spike in~~elevated concentrations of
330 Mg and Si ~~appears to proceed the spike in~~preceded those of Ca, Na, and K ~~in that it appears during the~~
331 ~~previous sampling by a 3-hour measuring~~ period. ~~Large~~The large variability in the magnitude of these spikes
332 suggests that the 3-hour sampling schedule was insufficiently frequent to characterize them entirely.

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Formatted: Font: Tahoma, 10 pt, Font color: Black

Anions generally follow similar patterns, but with greater variability (Figure 4). In particular, Cl^- does not co-vary with other ions toward the end of the record. ~~The; the 2:00~~ spike on July ~~18th~~ coincides with a drop in SO_4 concentration; ~~the spike on the 20th~~ ²⁰ coincides with a drop in Cl^- concentration. SO_4 SO_4^{2-} concentrations ~~generally only increased very~~ minimally ~~increase~~ during the waning flow spikes, and in one case declined. During the final spike, SO_4^{2-} rises during the 11:00 period, together with Mg and Si.

Formatted: Superscript

Excluding ~~these anomalies~~ the spikes that occur during waning flow, the highest concentration of dissolved solids occurs at 11:00 on July ~~16th, 19th, 20th~~ ^{16, 19, 20}, and ~~21st~~ ²¹ (Figure 5). On July ~~17th~~ ¹⁷ and ~~18th~~ ¹⁸, the 11:00 sample was likely diluted by the side stream (which was a significant component of flow to site 1 during that period). Concentration minima are reached at 23:00 hours on July ~~17th~~ ¹⁷ through ~~20th~~ ²⁰. On July ~~16th~~ ¹⁶, the ~~minimum~~ minimum occurs in the 20:00 sample. The ~~size of the diurnal variation~~ varies from maximum solute concentration ranged between 22% to 49% ~~of larger than~~ the ~~lowest~~ minimum concentration, with an average daily ~~range~~ value of $31 \pm 9\%$.

Formatted: Superscript

5. Discussion

5.1 Discharge and Outlet Stream Observations

Observations from oblique photography suggest large diurnal changes in discharge. ~~Width~~ The width of the active channel, with deeper faster water, approximately doubles in the course of the day (Figure 3b). An approximate doubling of discharge is also suggested by observations of the midstream naled. The naled is of comparable scale to the depth of the stream (both order of 1 meter). Its exposure during low flow and burial during high flow suggests a change in stage comparable to its height. At the naled site, increased width of active channel flow is restricted by ice. Increases in flow height at the naled location are therefore approximately equivalent to increases in active channel width downstream.

356 During high flows, diurnal increases in discharge of up to 50% of base value are observed in the
357 Watson River at Kangerlussuaq, where a bridge over a narrow gorge has allowed for the construction of
358 a reliable gauge (Hasholt et al., 2013)(Hasholt et al., 2013). As the Watson River is 20–30 km from its glacial
359 outlet sources and integrates several independent glacial outlet streams, these diurnal cycles are likely
360 muted compared to their expression at the ice margin. Larger diurnal changes are therefore expected
361 directly at glacier outlet termini. Contrastingly, Smith and others_. Contrastingly, Smith and others
362 (2015)(2015) found minimal diurnal variation in discharge at Isunnguata Sermia terminus. However, as
363 Smith and others estimated discharge based solely on the surface area of the outlet stream water, their
364 analysis missed the variation in the width of the active channel and height of its flow over static features
365 that we present. Based on our limited observational record, it appears that changes in discharge at the
366 Isunnguata Sermia terminus are similar or larger in magnitude to those recorded at the Watson River.

367

368 5.2 Diurnal Changes in Solute Flux

369 The critical observation is that variability in the dissolved solute concentrations cannot be
370 explained by dilution alone. First, the scale of discharge variation is substantially larger than variation in
371 concentration of dissolved solutes. Approximate width of the main channel doubles during diurnal cycles,
372 while concentrations of dissolved solutes only change by an average of 21–40% (Figure 5). Secondly,
373 maximum and minimum solute concentrations are offset from minimum and maximum discharge. Such
374 lags imply periods where solute concentration is increasing even as discharge rises and periods where
375 solute concentration is falling even as discharge falls.

376 Periods of in-phase changes between discharge and solute concentration suggest that increased
377 water flow is either stimulating increased water-rock interaction or allowing for release of stored water
378 (that has developed higher solute concentrations over longer residence times). While the single upwelling
379 structure of the terminus of Isunnguata Sermia implies local channelized flow, observations of water

pressures at interior sites (Meierbachtol et al., 2013) and hydrologic theory for low ice surface slopes (Werder et al., 2013) both suggest that much of the catchment interior has a linked cavity flow system. Linked cavity systems would allow for expansion of the basal hydrological system and flushing of long water residence time regions under high flow conditions.

~~Sudden~~The lag between relative discharge minima and maximum solute concentrations is similar to other glacial and non-glacial systems where waters of differing response times are merged into a single stream. Similar lags are observed when groundwater, soil water, and surface flow mix into a stream after a rainfall event (Evans and Davies, 1998). Substantial lags between discharge and solute flux are also observed where glacial melt mixes with groundwater in a karstic system (Zeng et al., 2012) and in the mixing of marginal melt streams with a subglacial pool in a polythermic setting (Skidmore and Sharp, 1999). Even in a small alpine system, observable chemical differences between the leading and lagging limbs of the discharge hydrograph have been attributed to mixing of englacial and subglacial waters (Tranter and Raiswell, 1991).

In the context of the Greenland Ice Sheet, periods of in-phase change between discharge and solute concentration are best explained by the flushing of a linked-cavity or other distributed hydrological system as hydraulic pressure rises. Seasonal changes in ice velocity in this sector of the Greenland ice sheet have been linked to a combination of distributed and channelized subglacial flow (Bartholomew et al., 2011). Dye-tracing of the hydrological connections between moulins and glacial outlets has also indicated a mixture of subglacial flow regimes (Chandler et al., 2013). Though the single upwelling structure of the terminus of Isunnguata Sermia implies locally channelized flow, observations of water pressures at interior sites (Meierbachtol et al., 2013) and hydrologic theory for low ice surface slopes (Werder et al., 2013) both suggest that much of the catchment interior has a distributed flow system.

The sudden increases in solute concentration during waning flow suggest that discharge from subglacial regions with a high concentration of dissolved solutes is triggered when a

threshold is reached. ~~Multiple triggering~~ To our knowledge, the release of stored water during waning flow has only been previously documented on a multiday scale (Anderson et al., 2003), whereas here it occurred as part of the diurnal melt cycle. For slow-moving, distributed subglacial water to be both flushed by rising hydraulic pressures and released from storage by falling hydraulic pressures, multiple subglacial flow paths or mechanisms ~~are plausible~~ must be operating simultaneously.

The contrast in solute chemistry between the long-wavelength increases in solute concentration (in which, all major chemical constituents respond comparably) and the waning flow spikes (in which Na, K, and alkalinity dominate) suggests differing subglacial environments and mechanisms. Na- and K-dominated waters likely form in settings where water-rock interactions occur only over a limited time, such that cation exchange occurs on fresh feldspar and mica surfaces, but complete silicate dissolution and clay precipitation does not occur (Blum and Stillings, 1995; Graly et al., 2014). The lack of constituents derived reactive accessory minerals such as pyrite (i.e. SO_4^{2-}) implies the waters were reacting with sediment that has been depleted of accessory minerals. Such accessory mineral depletion can occur if sediment residence time in the subglacial system is sufficiently long (Graly et al., 2014). Sampling of sediment beneath ice boreholes has shown the greatest chemical depletion in portions of the ice sheet most influenced by distributed flow (Graly et al., 2016).

This variation in water chemistry suggests that the spike of chemical solutes comes from water that has temporarily entered regions of distributed flow as a part of a diurnal cycle. Modeling of subglacial water pressures suggests that near the ice sheet margin, water flows from conduits to the distributed cavity system at high conduit water pressures and back to conduits at low pressures (Meierbachtol et al., 2013). The spikes in solute concentration ~~spikes~~ result from the crossing of a pressure threshold ~~allowing that allows~~ water stored during high flow to suddenly enter the glacial outlet system.

Solute concentration spikes might also be explained by creep closure of linked cavities that opened during high flow and expulsion of remaining solute-concentrated water. Anderson and others (2003) proposed a similar creep closure mechanism to explain increases in solute concentration during waning flow that occurred on a multiday scale in a mountain glacier setting. Following the Glenn-Nye relation, the rate of creep closure of ice scales to approximately the third power of effective pressure (Cuffey and Paterson, 2010). Differences in timing of these effects between ice sheets and mountain glaciers can therefore be explained by differences in ice thickness.

~~Relative dominance of Na and K in these spikes is consistent with water-rock interactions occurring only over a limited time, such that cation exchange occurred on fresh feldspar and mica surfaces but complete silicate dissolution and clay precipitation did not (Blum and Stillings, 1995; Graly et al., 2014). Contrastingly, constituents associated with weathering of reactive accessory minerals such as pyrite and calcite (especially SO₄) are minimally expressed. This implies that the spikes' composition reflects waters that have rapidly passed through reactive sediment that is depleted of accessory minerals. Such accessory mineral depletion can occur if sediment residence time in the subglacial system is sufficiently long (Graly et al., 2014). Sampling of sediment beneath ice boreholes has shown the greatest chemical depletion in portions of the ice sheet most likely to be influenced by distributed flow (Graly et al., 2016). This suggests that the spike of chemical solutes comes from water that has temporarily entered regions of distributed flow as a part of a diurnal cycle.~~

6. Conclusions

A semi-quantitative relative discharge record can be constructed through hourly photographic monitoring of the static and dynamic features of a large, sediment laden glacial outlet stream. These assessments ~~showsuggest~~ large diurnal changes in discharge over the ~~six-day~~ study period at the Isunnguata Sermia outlet of the Greenland Ice Sheet (c.f. Smith et al., 2015). Simultaneously collected

chemical measurements show substantially smaller fluctuation in dissolved load; thus this Greenland outlet glacier does not show the discharge-driven dilution of solute concentration that is common in smaller ice masses. Periods where dissolved solute ~~concentration~~concentrations increase and decrease along with discharge, and abrupt and variable increases in solute concentration during waning flow imply that significant contributions to the solute load is made by changes to the routing and storage of meltwater in the subglacial system over the course of the day. In particular, these results indicate considerable diurnal exchange of water ~~diurnally~~ between the conduit and linked cavity drainage systems, as well as implying threshold pressure conditions for these exchanges.

Acknowledgements. This work would not have been possible without funding from the Greenland Analogue Project (SKB, Posiva, NWMO) and NSF grant ARC-0909122. Janet Dewey assisted with laboratory analyses. Data from the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) were provided by the Geological Survey of Denmark and Greenland (GEUS) at <http://www.promice.dk>. Thoughtful reviews by editor Rob Bingham and an anonymous referee greatly improved the manuscript.

Cited References

- Anderson, S.P., 2005. Glaciers show direct linkage between erosion rate and chemical weathering fluxes. *Geomorphology* 67, 147-157.
- Anderson, S.P., Drever, J.I., Humphrey, N.F., 1997. Chemical weathering in glacial environments. *Geology* 25, 399-402.
- Anderson, S.P., Longacre, S.A., Kraal, E.R., 2003. Patterns of water chemistry and discharge in the glacier-fed Kennicott River, Alaska: Evidence of subglacial water storage cycles. *Chemical Geology* 202, 297-312.
- Blum, A.E., Stillings, L.L., 1995. Feldspar dissolution kinetics, in: White, A.F., Brantley, S.L. (Eds.), *Chemical Weathering Rates of Silicate Minerals*. Mineralogical Soc Amer, Chantilly, pp. 291-351.
- Bartholomew, I.D., Nienow, P., Sole, A., Mair, D., Cowton, T., King, M.A., Palmer, S., 2011. Seasonal variations in Greenland Ice Sheet motion: Inland extent and behaviour at higher elevations. *Earth and Planetary Science Letters* 307, 271-278.
- Brown, G.H., 2002. Glacier meltwater hydrochemistry. *Applied Geochemistry* 17, 855-883.

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Chandler, D.M., Wadham, J.L., Lis, G.P., Cowton, T., Sole, A., Bartholomew, I., Telling, J., Nienow, P., Bagshaw, E.B., Mair, D., Vinen, S., Hubbard, A., 2013. Evolution of the subglacial drainage system beneath the Greenland Ice Sheet revealed by tracers. *Nature Geoscience* 6, 195-198.

Collins, D., 1995. Dissolution kinetics, transit times through subglacial hydrological pathways and diurnal variations of solute content of meltwaters draining from an alpine glacier. *Hydrological Processes* 9, 897-910.

Collins, D.N., MacDonald, O.G., 2004. Year-to-year variability of solute flux in meltwaters draining from a highly-glacierised basin. *Nordic Hydrology* 35, 359-367.

Cowton, T., Nienow, P., Bartholomew, I., Sole, A., Mair, D., 2012. Rapid erosion beneath the Greenland ice sheet. *Geology* 40, 343-346.

Cuffey, K.M., Paterson, W.S.B., 2010. *The Physics of Glaciers*, 4th ed.

Drever, J.I., Hurcomb, D.R., 1986. Neutralization of atmospheric acidity by chemical weathering in an alpine drainage basin in the North Cascade Mountains. *Geology* 14, 221-224.

Evans, C., Davies, T.D., 1998. Causes of concentration/discharge hysteresis and its potential as a tool for analysis of episode hydrochemistry. *Water Resources Research* 34, 129-137.

Graly, J.A., Humphrey, N.F., Harper, J.T., 2016. Chemical depletion of sediment under the Greenland Ice Sheet. *Earth Surface Processes and Landforms* *In Press* 41, 1922-1936.

Graly, J.A., Humphrey, N.F., Landowski, C.M., Harper, J.T., 2014. Chemical weathering under the Greenland Ice Sheet. *Geology* 42, 551-554.

Harrington, J., Humphrey, N.F., Harper, J.T., 2015. Temperature distribution and thermal anomalies along a flowline of the Greenland Ice Sheet. *Annals of Glaciology* 56(70), 98-104.

Hasholt, B., Mikkelsen, A.B., Nielsen, M.H., Larsen, M.A.D., 2013. Observations of runoff and sediment and dissolved loads from the Greenland Ice Sheet at Kangerlussuaq, West Greenland, 2007 to 2010. *Zeitschrift für Geomorphologie* 57, sup. 2, 3-27.

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

Hodson, A., Tranter, M., Vatne, G., 2000. Contemporary rate of chemical denudation and atmospheric CO₂ sequestration in glacier basins: An arctic perspective. *Earth Surface Processes and Landforms* 25, 1447-1471.

Humphrey, N.F., 1987. Coupling between water pressure and basal sliding in a linked-cavity hydraulic system, *The Physical Basis of Ice Sheet Modelling*. IAHS Publ. No. 170, pp. 105-118.

Humphrey, N.F., Raymond, C.F., 1994. Hydrology, erosion and sediment production in a surging glacier: Variegated Glacier, Alaska, 1982-83. *Journal of Glaciology* 40, 539-552.

Jezek, K., Wu, X., Paden, J., Leuschen, C., 2013. Radar mapping of Isunnguata Sermia, Greenland. *Journal of Glaciology* 59, 1135-1147.

Kamb, B., 1987. Glacier surge mechanism based on linked cavity configuration of the basal water conduit system. *Journal of Geophysical Research* 92, 9083-9100.

Landowski, C., 2012. *Geochemistry and subglacial hydrology of the West Greenland Ice Sheet*, MS Thesis, Geology and Geophysics. University of Wyoming.

Langen, P.L., Ahlstrøm, A.P., Andersen, K.K., Andersen, S.B., Barletta, V., Box, J.E., M, C., Colgan, W., Dybkjær, G., Fausto, R.S., Forsberg, R., Hansen, B., Hanson, S., Høyer, J.L., Sørensen, L.S., Tonboe, R.T., 2013. *Polar Portal Season Report 2013*. Available at: <http://polarportal.dk/en/nyheder/arkiv/2013-season-report/>.

Meierbachtol, T., Harper, J., Humphrey, N., 2013. Basal drainage system response to increasing surface melt on the Greenland Ice Sheet. *Science* 341, 777-779.

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

526 Mitchell, A.C., Brown, G.H., 2007. Diurnal hydrological - physicochemical controls and sampling methods
 527 for minor and trace elements in an Alpine glacial hydrological system. *Journal of Hydrology* 332,
 528 123-143.

529 Nye, J.F., 1976. Water flow in glaciers: Jokulhlaups, tunnels, and veins. *Journal of Glaciology* 17, 181-207.

530 Palmer, S., Shepherd, A., Nienow, P., Joughin, I., 2011. Seasonal speedup of the Greenland Ice Sheet linked
 531 to routing of surface water. *Earth and Planetary Science Letters* 302, 423-428.

532 Röthlisberger, H., 1972. Water Pressure in Intra- and Subglacial Channels. *Journal of Glaciology* 11, 177-
 533 203.

534 Skidmore, M.L., Sharp, M.J., 1999. Drainage system behaviour of a High-Arctic polythermal glacier. *Annals*
 535 *of Glaciology* 28, 209-215.

536 Smith, L.C., Chu, V.W., Yang, K., Gleason, C.J., Pitcher, L.H., Rennermalm, A.K., Legleiter, C.J., Behar, A.E.,
 537 Overstreet, B.T., Moustafa, S.E., Tedesco, M., Forster, R.R., LeWinter, A.L., Finnegan, D.C., Sheng,
 538 Y., Balog, J., 2015. Efficient meltwater drainage through supraglacial streams and rivers on the
 539 southwest Greenland ice sheet. *Proceedings of the National Academy of Sciences of the United*
 540 *States of America* 112, 1001-1006.

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

543 Tranter, M., Raiswell, R., 1991. The composition of the englacial and subglacial component in bulk
 544 meltwaters draining the Gornergletscher, Switzerland. *Journal of Glaciology* 37, 59-66.

545 van Gool, J.A.M., Connelly, J.N., Marker, M., Mengel, F.C., 2002. The Nagssugtoqidian Orogen of West
 546 Greenland: Tectonic evolution and regional correlations from a West Greenland perspective.
 547 *Canadian Journal of Earth Science* 39, 665-686.

548 Wadham, J.L., Tranter, M., Skidmore, M., Hodson, A.J., Prisco, J., Lyons, W.B., Sharp, M., Wynn, P., Jackson,
 549 M., 2010. Biogeochemical weathering under ice: Size matters. *Global Biogeochemical Cycles* 24,
 550 GB3025.

551 Werder, M.A., Hewit, I.J., Schoof, C.G., Flowers, G.E., 2013. Modeling channelized and distributed
 552 subglacial drainage in two dimensions. *Journal of Geophysical Research: Earth Surface* 118, 1-19.

553 Yde, J.C., Knudsen, N.T., Hasholt, B., Mikkelsen, A.B., 2014. Meltwater chemistry and solute export from
 554 a Greenland Ice Sheet catchment, Watson River, West Greenland. *Journal of Hydrology* 519, 2165-
 555 2179.

556 Zeng, C., Gremaud, V., Zeng, H., Liu, Z., Goldscheider, N., 2012. Temperature-driven meltwater production
 557 and hydrochemical variations at a glaciated alpine karst aquifer: implication for the atmospheric
 558 CO₂ sink under global warming. *Environmental Earth Science* 65, 2285-2297.

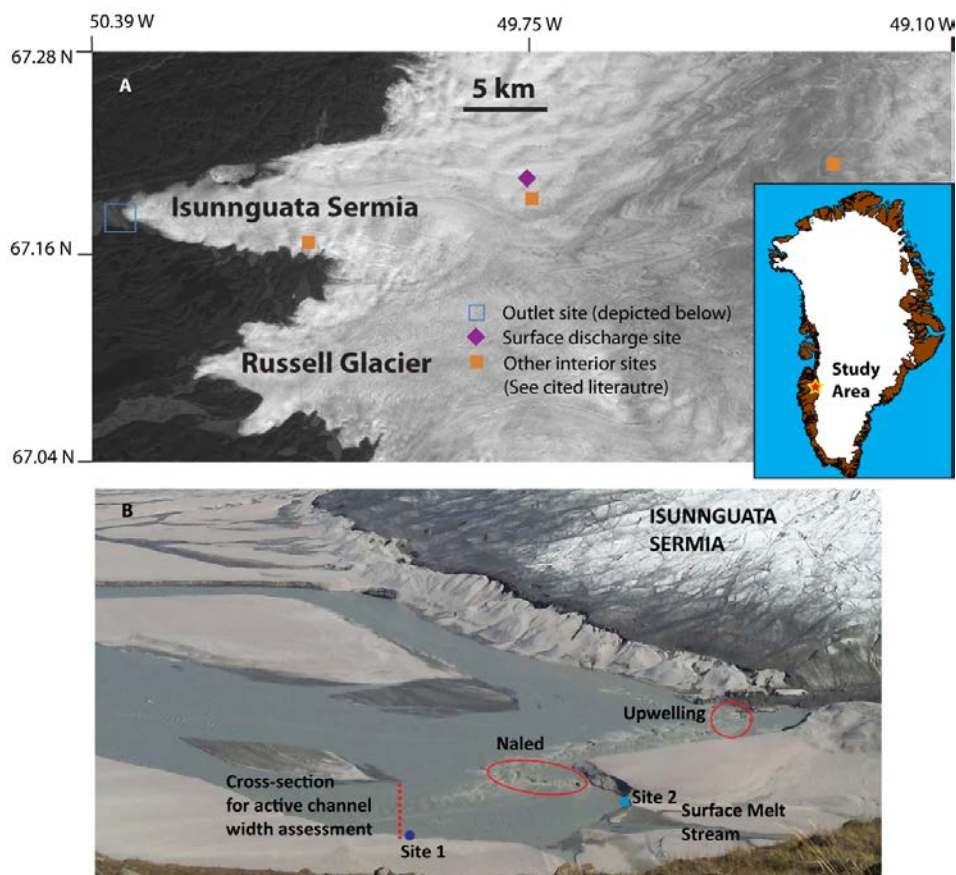
Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Formatted: Indent: Left: 0", Hanging: 0.5", Line spacing: single

Formatted: Indent: Left: 0", Hanging: 0.5"

561 **Figures:**



562
 563 **Figure 1.** A) Location of the study area- on satellite imagery provided by polar geospatial datacenter. B)
 564 Overhead photograph of the study area (taken 7/22/13) with important July 2013 on an overlooking ridge,
 565 400 m above and 900 m away from the stream. Important sampling and observational features are
 566 labeled. Samples were collected at site 1 from 10:00 hrs on 7/16/13 through 11:00 hours on 7/18/13.
 567 Samples were collected at site 2 from 14:00 hrs on 7/18/13 through 20:00 hrs on 7/22/13. Beginning at
 568 10:00 hrs on 7/18/13, hourly photographs on the labeled naled and ~100 m cross-section were taken.

A



B



C



D



E



F



570

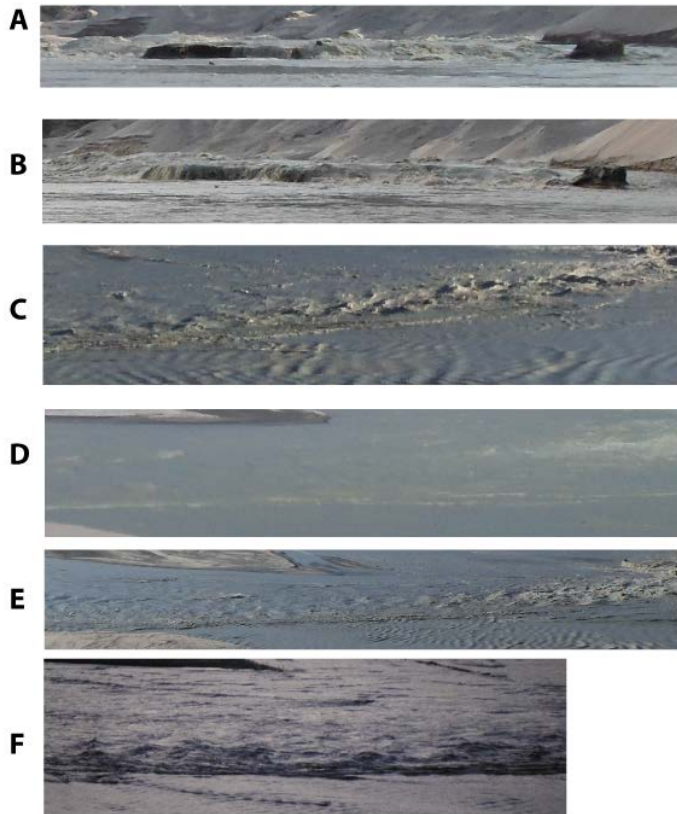
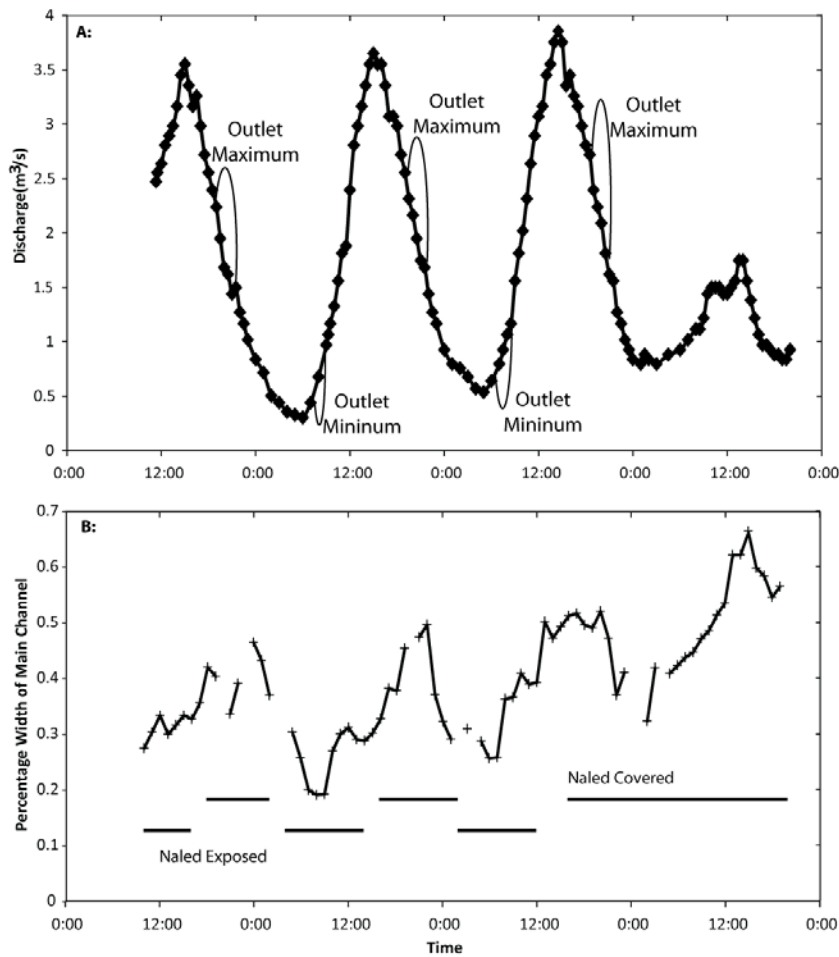
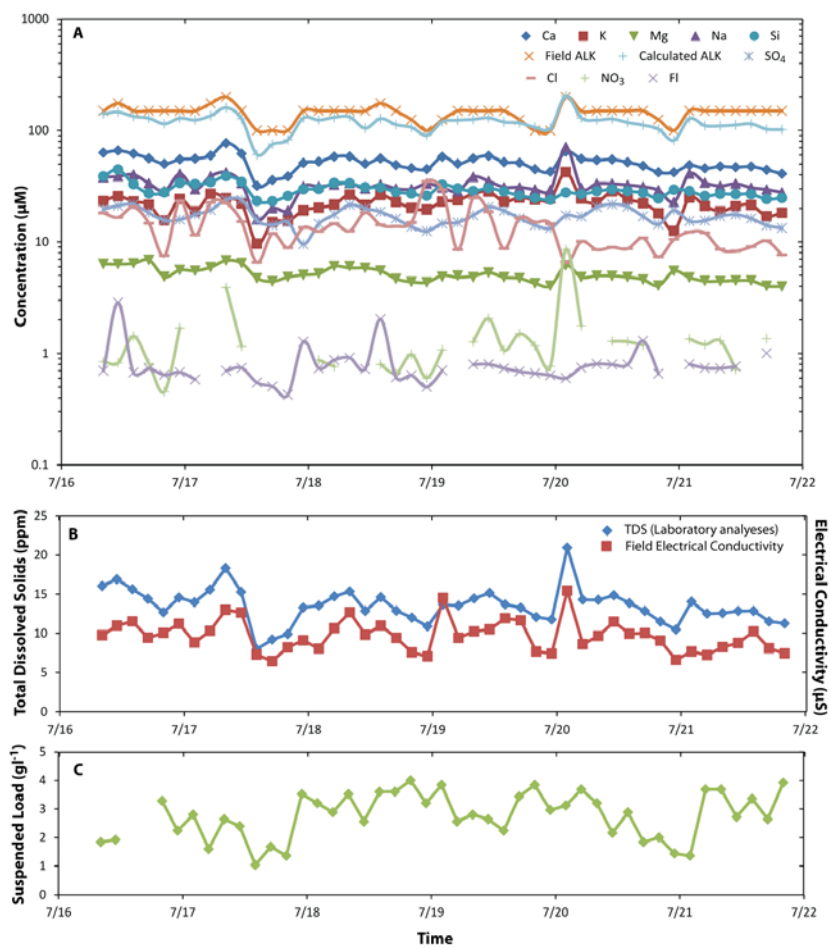


Figure 2. Photographs of typical flow patterns in the Isunnguata Sermia outlet. A) Midstream naled exposed at during low flow (8:00). B) Midstream naled covered during high flow (21:00). C-F show [images of flow captures from the overhead vantage](#) during low (8:00), waxing (14:00), high (21:00) and waning (0:00) stages. Waxing and waning stages show different wave morphology but maintain standing wave features.



578
 579 **Figure 3.** A) Measured discharge in an interior surface stream over a 4 day period in 2012 compared to
 580 time ranges of maximum and minimum discharge as suggested by qualitative observation of flow volumes
 581 over midstream naled ice in the outlet of Isunnguata Sermia during the study period. B) Assessment of
 582 percentage of distance between a point bar and the shore that is characterized by large waves suggestive
 583 of deep, fast flow. Periods of time where the midstream naled is exposed and covered are included for
 584 comparison.

585



586

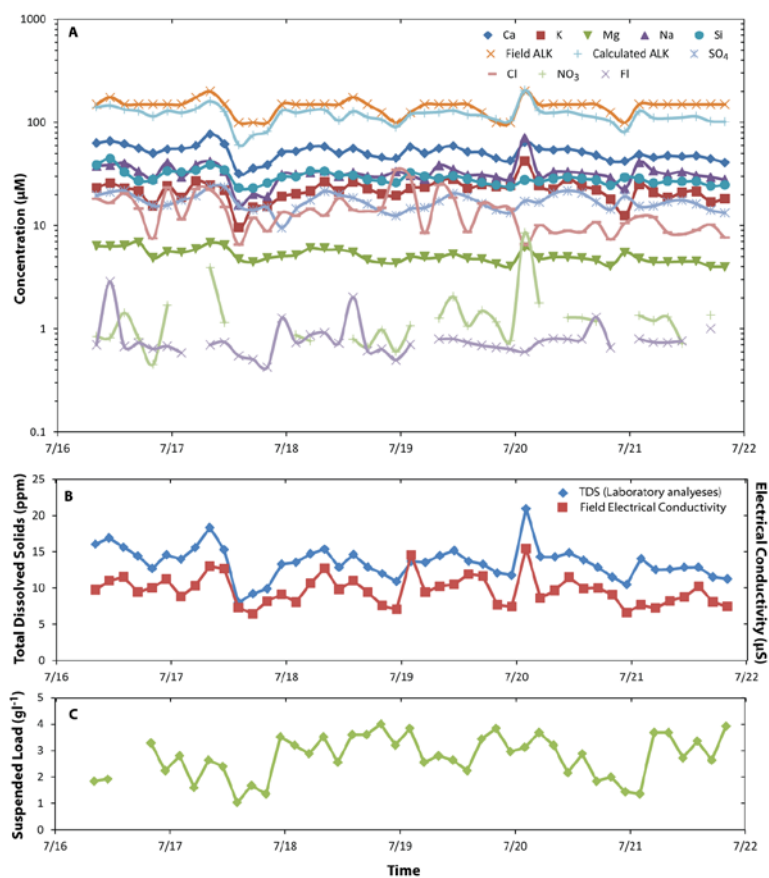


Figure 4. A) Concentration of dissolved constituents in sampled waters over time, including laboratory measurements of cations and Si by ICP-MS, anions by ion chromatography, and field measurements of alkalinity (ALK). Alkalinity as calculated by charge balance is also depicted. B) Total dissolved solids from the sum of the laboratory measurements and charge balance alkalinity (HCO₃) compared to field conductivity measurements. Co-variation is statistically significant ($p < 0.0001$). C) Dry weight of suspended sediment on filters.

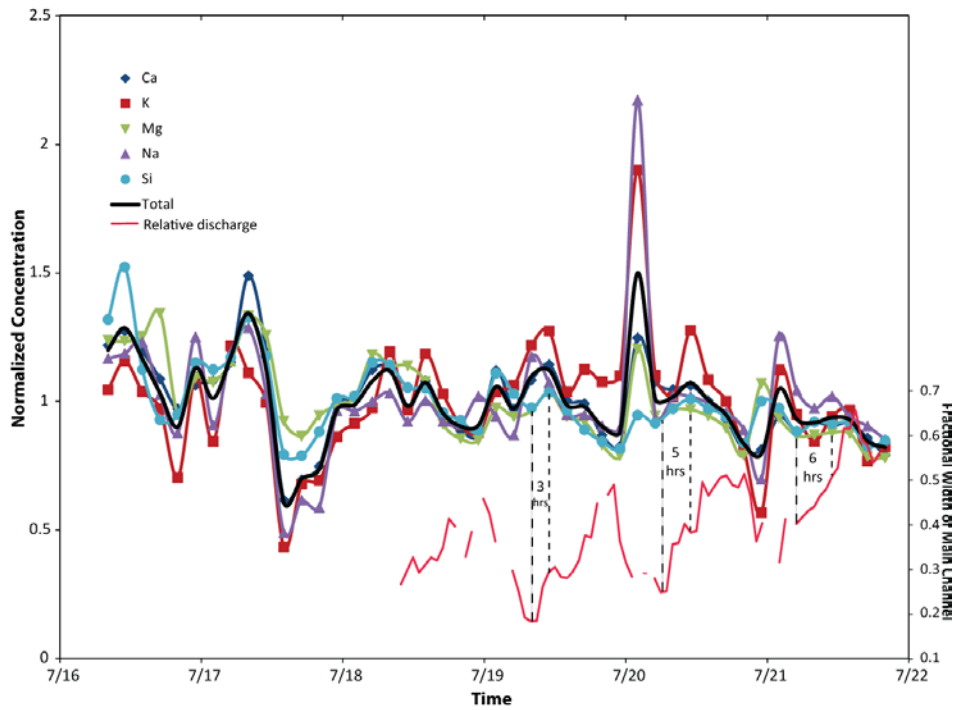


Figure 5. Concentration of dissolved cations and Si normalized to average concentration. Discharge from relative active channel width is shown for comparison. Lags between active channel width channel minima and solute concentration maxima are illustrated with dashed lines.

599 **Tables:**

600

601 Table 1. Field and laboratory measurements (results in micro-molarity unless otherwise noted)

Sample	Time	pH	Electrical Conductivity (µS)	Suspended Sediment (g l ⁻¹)	Field Alkalinity (µM)	Ca	K	Mg	Na	Si	Fl	Cl	NO ₃	SO ₄	Calculated Alkalinity
GL13-1	7/16/2013 8:10	8.59	9.74	1.84	150	63.11	23.24	6.36	38.12	38.67	0.70	18.24	0.85	19.67	141.17
GL13-2	7/16/2013 11:00	8.82	10.98	1.92	175	65.99	25.72	6.33	38.77	44.68	2.86	16.65	0.82	21.16	146.46
GL13-3	7/16/2013 14:00	8.70	11.54	NA	150	61.88	23.10	6.43	40.20	32.96	0.67	20.58	1.43	21.68	133.87
GL13-4	7/16/2013 17:00	8.70	9.44	NA	150	56.32	21.61	6.89	33.53	27.25	0.73	14.71	0.81	18.27	128.76
GL13-5	7/16/2013 20:00	8.65	10.04	3.28	150	50.31	15.65	4.87	28.65	27.84	0.64	7.53	0.45	15.63	114.79
GL13-6	7/16/2013 23:00	8.75	11.22	2.24	150	55.07	24.32	5.60	40.89	33.75	0.68	23.38	1.69	15.88	129.06
GL13-7	7/17/2013 2:00	8.73	8.82	2.80	150	55.96	18.77	5.52	29.67	32.96	0.58	11.53	<0.45	17.62	124.03
GL13-8	7/17/2013 5:00	8.84	10.32	1.60	175	59.65	27.05	5.94	38.90	34.34	<0.43	22.57	<0.45	19.35	135.86
GL13-9	7/17/2013 8:00	8.90	13	2.64	200	77.11	24.73	6.83	42.06	38.95	0.70	22.27	3.91	23.84	160.13
GL13-10	7/17/2013 11:00	8.51	12.66	2.40	150	61.76	22.14	6.46	33.64	34.54	0.74	15.23	1.16	23.85	127.40
GL13-11	7/17/2013 14:00	8.01	7.28	1.04	100	31.93	9.62	4.74	15.96	23.29	0.55	6.56	<0.45	15.56	60.69
GL13-13	7/17/2013 17:00	8.32	6.46	1.68	100	35.97	15.07	4.44	20.12	23.15	0.51	11.90	<0.45	14.14	75.32
GL13-14	7/17/2013 20:00	8.62	8.2	1.36	100	38.71	15.41	4.85	19.19	25.86	0.43	8.85	<0.45	14.99	82.45
GL13-15	7/17/2013 23:00	8.80	9.1	3.52	150	51.23	19.17	5.06	31.51	29.70	1.27	13.49	<0.45	9.54	129.42
GL13-16	7/18/2013 2:00	8.71	8.04	3.20	150	52.52	20.33	5.21	31.44	29.94	0.74	12.48	0.87	14.55	124.02
GL13-17	7/18/2013 5:00	8.53	10.66	2.88	150	58.17	21.66	6.06	32.69	33.77	0.87	14.59	0.76	17.66	131.26
GL13-18	7/18/2013 8:00	8.90	12.7	3.52	150	58.34	26.52	5.85	33.74	33.52	0.92	12.56	<0.45	21.50	132.18
GL13-19	7/18/2013 11:00	8.48	9.82	2.56	150	50.27	21.52	5.84	30.12	30.90	0.73	18.38	<0.45	19.98	104.80
GL13-20	7/18/2013 14:00	8.53	10.98	3.60	175	56.00	26.34	5.53	32.80	30.84	2.03	14.21	0.80	18.63	127.88
GL13-21	7/18/2013 17:00	8.66	9.42	3.60	150	48.92	22.88	4.68	30.15	28.08	0.61	13.82	0.66	16.16	112.80
GL13-22	7/18/2013 20:00	8.61	7.56	4.00	125	45.92	20.21	4.39	29.79	27.19	0.64	14.99	0.98	13.68	106.64
GL13-23	7/18/2013 23:00	8.60	7.06	3.20	100	44.93	19.53	4.35	33.33	26.04	0.50	34.89	0.60	12.51	90.43
GL13-24	7/19/2013 2:00	8.68	14.54	3.84	125	58.06	23.07	5.00	30.77	32.56	0.71	29.45	1.08	14.63	119.46
GL13-25	7/19/2013 5:00	8.27	9.42	2.56	150	50.26	23.64	4.83	28.40	30.22	<0.43	8.51	<0.45	14.96	123.76
GL13-26	7/19/2013 8:00	8.58	10.24	2.80	150	56.08	27.09	4.95	38.39	28.60	0.79	24.85	1.27	17.39	125.83
GL13-27	7/19/2013 11:00	8.70	10.5	2.64	150	59.22	28.32	5.32	35.07	30.39	0.80	18.63	2.05	20.54	129.90
GL13-28	7/19/2013 14:00	8.46	11.92	2.24	150	52.04	23.07	4.82	30.99	28.33	0.74	8.69	1.07	19.07	119.13
GL13-29	7/19/2013 17:00	8.35	11.66	3.44	125	51.33	25.01	4.73	30.98	26.10	0.69	16.41	1.50	16.31	116.88
GL13-30	7/19/2013 20:00	8.58	7.68	3.84	100	44.99	23.94	4.26	29.57	24.76	0.66	15.06	1.17	14.15	106.81
GL13-31	7/19/2013 23:00	8.58	7.42	2.96	100	42.73	24.46	4.05	29.26	23.92	0.64	14.57	0.77	13.32	104.67
GL13-32	7/20/2013 2:00	8.53	15.46	3.12	200	64.60	42.27	6.17	70.99	27.76	0.60	6.56	8.54	17.23	204.64
GL13-33	7/20/2013 5:00	8.03	8.62	3.68	150	55.74	24.52	4.85	30.50	26.84	0.75	10.08	1.78	16.88	129.83
GL13-34	7/20/2013 8:00	8.37	9.66	3.20	150	54.24	22.61	4.97	33.37	28.51	0.81	8.52	<0.45	20.50	124.06
GL13-35	7/20/2013 11:00	8.30	11.48	2.16	150	54.99	28.39	4.97	33.30	29.61	0.79	8.94	1.29	21.77	127.04
GL13-36	7/20/2013 14:00	8.39	9.94	2.88	150	51.93	24.12	4.84	32.49	28.51	0.79	8.71	1.28	20.74	117.89
GL13-37	7/20/2013 17:00	8.48	10.02	1.84	150	48.16	22.25	4.60	31.28	27.60	1.29	10.85	1.19	16.96	111.80
GL13-38	7/20/2013 20:00	8.69	9.06	2.00	125	42.10	18.12	4.06	29.09	24.59	0.66	7.35	<0.45	14.37	102.76
GL13-39	7/20/2013 23:00	8.12	6.62	1.44	100	42.13	12.60	5.49	22.80	29.38	<0.43	10.54	<0.45	19.25	81.60
GL13-40	7/21/2013 2:00	8.80	7.68	1.36	150	48.73	24.96	4.80	40.99	28.59	0.80	12.31	1.35	15.40	127.78
GL13-41	7/21/2013 5:00	8.20	7.22	3.68	150	45.80	21.11	4.45	34.07	25.88	0.74	12.08	1.20	15.56	110.55
GL13-42	7/21/2013 8:00	8.70	8.24	3.68	150	47.55	18.79	4.46	31.80	26.99	0.74	8.58	1.30	17.01	109.97
GL13-43	7/21/2013 11:00	8.42	8.76	2.72	150	46.89	20.93	4.51	33.33	26.81	0.76	8.28	0.72	17.63	112.03
GL13-44	7/21/2013 14:00	8.12	10.24	3.36	150	47.52	21.48	4.49	30.72	26.82	<0.43	9.04	<0.45	16.26	114.65
GL13-45	7/21/2013 17:00	8.32	8.08	2.64	150	44.42	17.05	4.03	29.55	24.22	1.01	10.22	1.36	14.10	102.73
GL13-46	7/21/2013 20:00	8.62	7.44	3.92	150	40.93	18.31	4.00	27.84	24.85	<0.43	7.66	<0.45	13.31	101.73

Sample	Time	pH	Electrical Conductivity (μS)	Suspended Sediment (g l^{-1})	Field Alkalinity	Calculated Alkalinity	Ca	K	Mg	Na	Si	F ⁻	Cl ⁻	NO ₃ ²⁻	SO ₄ ²⁻
GL13-1	7/16/2013 8:10	8.6	9.7	1.84	150	141.2	63.1	23.2	6.4	38.1	38.7	0.7	18.2	0.8	19.7
GL13-2	7/16/2013 11:00	8.8	11.0	1.92	175	146.5	66.0	25.7	6.3	38.8	44.7	2.9	16.6	0.8	21.2
GL13-3	7/16/2013 14:00	8.7	11.5	NA	150	133.9	61.9	23.1	6.4	40.2	33.0	0.7	20.6	1.4	21.7
GL13-4	7/16/2013 17:00	8.7	9.4	NA	150	128.8	56.3	21.6	6.9	33.5	27.2	0.7	14.7	0.8	18.3
GL13-5	7/16/2013 20:00	8.7	10.0	3.28	150	114.8	50.3	15.6	4.9	28.6	27.8	0.6	7.5	0.5	15.6
GL13-6	7/16/2013 23:00	8.7	11.2	2.24	150	129.1	55.1	24.3	5.6	40.9	33.8	0.7	23.4	1.7	15.9
GL13-7	7/17/2013 2:00	8.7	8.8	2.80	150	124.0	56.0	18.8	5.5	29.7	33.0	0.6	11.5	<0.5	17.6
GL13-8	7/17/2013 5:00	8.8	10.3	1.60	175	135.9	59.7	27.1	6.0	38.9	34.3	<0.4	22.6	<0.5	19.6
GL13-9	7/17/2013 8:00	8.9	13.0	2.64	200	160.1	77.1	24.7	6.8	42.1	39.0	0.7	22.3	3.9	23.8
GL13-10	7/17/2013 11:00	8.5	12.7	2.40	150	127.4	61.8	22.1	6.5	33.6	34.5	0.7	15.2	1.2	23.9
GL13-11	7/17/2013 14:00	8.0	7.3	1.04	100	60.7	31.9	9.6	4.7	16.0	23.3	0.6	6.6	<0.5	15.6
GL13-13	7/17/2013 17:00	8.3	6.4	1.68	100	75.3	36.0	15.1	4.4	20.1	23.2	0.5	11.9	<0.5	14.1
GL13-14	7/17/2013 20:00	8.6	8.2	1.36	100	82.5	38.7	15.4	4.8	19.2	25.9	0.4	8.9	<0.5	15.0
GL13-15	7/17/2013 23:00	8.8	9.1	3.52	150	129.4	51.2	19.2	5.1	31.5	29.7	1.3	13.5	<0.5	9.5
GL13-16	7/18/2013 2:00	8.7	8.0	3.20	150	124.0	52.5	20.3	5.2	31.4	29.9	0.7	12.5	0.9	14.6
GL13-17	7/18/2013 5:00	8.5	10.7	2.88	150	131.3	58.2	21.7	6.1	32.7	33.8	0.9	14.6	0.8	17.7
GL13-18	7/18/2013 8:00	8.9	12.7	3.52	150	132.9	58.3	26.5	5.8	33.7	33.5	0.9	12.6	<0.5	21.5
GL13-19	7/18/2013 11:00	8.5	9.8	2.56	150	104.8	50.3	21.5	5.8	30.1	30.9	0.7	18.4	<0.5	20.0
GL13-20	7/18/2013 14:00	8.5	11.0	3.60	175	127.9	56.0	26.3	5.5	32.8	30.8	2.0	14.2	0.8	18.6
GL13-21	7/18/2013 17:00	8.7	9.4	3.60	150	112.8	48.9	22.9	4.7	30.1	28.1	0.6	13.8	0.7	16.2
GL13-22	7/18/2013 20:00	8.6	7.6	4.00	125	106.6	45.9	20.2	4.4	29.8	27.2	0.6	15.0	1.0	13.7
GL13-23	7/18/2013 23:00	8.6	7.1	3.20	100	90.4	44.9	19.5	4.4	33.3	26.0	0.5	34.9	0.6	12.5
GL13-24	7/19/2013 2:00	8.7	14.5	3.84	125	119.5	58.1	23.1	5.0	30.8	32.6	0.7	29.5	1.1	14.6
GL13-25	7/19/2013 5:00	8.3	9.4	2.56	150	123.8	50.3	23.6	4.8	28.4	30.2	<0.4	8.5	<0.5	15.0
GL13-26	7/19/2013 8:00	8.6	10.2	2.80	150	125.8	56.1	27.1	4.9	38.4	28.6	0.8	24.9	1.3	17.4
GL13-27	7/19/2013 11:00	8.7	10.5	2.64	150	129.9	59.2	28.3	5.3	35.1	30.4	0.8	18.6	2.1	20.5
GL13-28	7/19/2013 14:00	8.5	11.9	2.24	150	119.1	52.0	23.1	4.8	31.0	28.3	0.7	8.7	1.1	19.1
GL13-29	7/19/2013 17:00	8.4	11.7	3.44	125	116.9	51.3	25.0	4.7	31.0	26.1	0.7	16.4	1.5	16.3
GL13-30	7/19/2013 20:00	8.6	7.6	3.84	100	106.8	45.0	23.9	4.3	29.6	24.8	0.7	15.1	1.2	14.2
GL13-31	7/19/2013 23:00	8.6	7.4	2.96	100	104.7	42.7	24.5	4.1	29.3	23.9	0.6	14.6	0.8	13.3
GL13-32	7/20/2013 2:00	8.5	15.5	3.12	200	204.6	64.6	42.3	6.2	71.0	27.8	0.6	6.6	8.5	17.2
GL13-33	7/20/2013 5:00	8.0	8.6	3.68	150	129.8	55.7	24.5	4.9	30.5	26.8	0.7	10.1	1.8	16.9
GL13-34	7/20/2013 8:00	8.4	9.7	3.20	150	124.1	54.2	22.6	5.0	33.4	28.5	0.8	8.5	<0.5	20.5
GL13-35	7/20/2013 11:00	8.3	11.5	2.16	150	127.0	55.0	28.4	5.0	33.3	29.6	0.8	8.9	1.3	21.8
GL13-36	7/20/2013 14:00	8.4	9.9	2.88	150	117.9	51.9	24.1	4.8	32.5	28.5	0.8	8.7	1.3	20.7
GL13-37	7/20/2013 17:00	8.5	10.0	1.84	150	111.8	48.2	22.3	4.6	31.3	27.6	1.3	10.8	1.2	17.0
GL13-38	7/20/2013 20:00	8.7	9.1	2.00	125	102.8	42.1	18.1	4.1	29.1	24.6	0.7	7.4	<0.5	14.4
GL13-39	7/20/2013 23:00	8.1	6.6	1.44	100	81.6	42.1	12.6	5.5	22.8	29.4	<0.4	10.5	<0.5	19.6
GL13-40	7/21/2013 2:00	8.8	7.7	1.36	150	127.8	48.7	25.0	4.8	41.0	28.6	0.8	12.3	1.4	15.4
GL13-41	7/21/2013 5:00	8.2	7.2	3.68	150	110.6	45.8	21.1	4.5	34.1	25.9	0.7	12.1	1.2	15.6
GL13-42	7/21/2013 8:00	8.7	8.2	3.68	150	110.0	47.5	18.8	4.5	31.8	27.0	0.7	8.6	1.3	17.0
GL13-43	7/21/2013 11:00	8.4	8.8	2.72	150	112.0	46.9	20.9	4.5	33.3	26.8	0.8	8.3	0.7	17.6
GL13-44	7/21/2013 14:00	8.1	10.2	3.36	150	114.6	47.5	21.5	4.5	30.7	26.8	<0.4	9.0	<0.5	16.2
GL13-45	7/21/2013 17:00	8.3	8.1	2.64	150	102.7	44.4	17.1	4.0	29.6	24.2	1.0	10.2	1.4	14.1
GL13-46	7/21/2013 20:00	8.6	7.4	3.92	150	101.7	40.9	18.3	4.0	27.8	24.9	<0.4	7.7	<0.5	13.3