Jökulhlaups and sediment transport in Watson River, Kangerlussuaq, West Greenland

A. B. Mikkelsen, B. Hasholt, N. T. Knudsen and M. H. Nielsen

ABSTRACT

For 3 years, during a 4-year observation period (2007–2010), jökulhlaups were observed from a lake at the northern margin of Russells Gletscher. At a gauging station located on a bedrock sill near the outlet of Watson River into Sdr Strømfjord, discharge and sediment transport was monitored during the jökulhlaups. The stage rose up to 5.3 m and a maximum discharge of 1,430 $m^3 s^{-1}$ was recorded. The jökulhlaups were very different, indicating varying influences of weather and englacial drainage conditions. Although the jökulhlaups caused high discharge and sediment transport rates, their share of the annual discharge and sediment transport were less than 2%.

Key words | discharge, Greenland, jökulhlaups, Kangerlussuaq, sediment transport

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INTRODUCTION

Jökulhlaups have been observed and described at Kangerlussuaq as early as in 1984 by Sugden *et al.* (1985). This is probably the most-observed jökulhlaup location in Greenland, as also described by Russell (1989, 2007, 2009), Russell *et al.* (1990), Mernild *et al.* (2008) and Mernild & Hasholt (2009). The geomorphologic impact of these jökulhlaups on the adjacent sandurs has been studied by Russell (2007, 2009), who demonstrated they have a large impact on the sandurs. However, no investigations into how this affects the sediment transport further downstream Watson River, which drains into a delta front, have been made. From many places it is known that jökulhlaups can have a major impact on the fluvial deposits of sediments in river deltas and adjacent fjords and oceans. Examples of these span the gigantic Lake Missoula that drained 13,000 years BP (Knight 1999) to more recent jökulhlaups on Iceland as well as other glaciated places as described by, for example, Magilligan *et al.* (2002), Björnsson (2003) and Cuffey & Paterson (2010).

It has been clearly demonstrated in the literature that jökulhlaups have occurred over a longer time span at Kangerlussuaq. Russell *et al.* (2011) suggest that a new cycle of jökulhlaups is being experienced and the reason for this is a thinning of the glacier front damming the water in the lake (Knight 1999; Russell *et al.* 2011). It is suggested that the timing of these events at the end of the runoff season can be related to a sudden reduction in subglacial water pressure caused by less meltwater production (Tweed & Russell 1999; Russell *et al.* 2011). The occurrence of the jökulhlaup in 2010 supports the hypothesis of cyclicity in the way that the big event in 2007 created an englacial drainage system that can be used and kept open by a series of minor jökulhlaups, as long as the movement of the Greenland ice sheet (GrIS) keep the ice margin at a position where it closes the bottom drainage of the valley forming the proglacial lake.

Jökulhlaups have also been observed at other locations in Greenland. At the Mittivakkat glacier, at least two jökulhlaups were recorded in 1958 by Valeur (1959). The discharge recorded (maximum 80 $m^3 s^{-1}$) is four to 10 times higher than later recorded annual maxima. No simultaneous observations of sediment transport were available, but later observations of the fluvial system by Hasholt (1976) and Busskamp & Hasholt (1996) indicated that pebble and stone size material could only be transported all

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the way from the glacier to the marine delta during jökulhlaups or by ice rafting. It was also observed that the jökulhlaup eroded in terminal moraine deposits within the valley.

Other documented observations of jökulhlaps are from the research station Zackenberg in northeast Greenland (Hasholt *et al.* 2008). Jökulhlaups have occurred here several times, endangering the work at the field station and causing bed erosion in the river. The amount of sediment transport related to the jökulhlaups was up to 82% of the total annual load. In this case, deposits from jökulhlaups may be used as markers in the sediment column deposited in a lake and on the marine delta, maybe even in the fjord. In a recent survey carried out by Tøttrup *et al.* (2011) near the capital Nuuk, the potential of using satellite observations for the monitoring of ice-dammed lakes and their tapping is demonstrated. In their study they include lakes with volumes up to $1.76 \times 10^9\,\text{m}^3$ that have been observed draining.

In the ongoing project Climate Record in Kangerlussuaq (CRIK) where the main aim is to relate the sediment deposition in the fjord to climatic events and changes, it is important to know if events such as jökulhlaups can contribute sufficient amounts of sediment to create distinct layers in the sediment record found in the river delta and fjord. This investigation was initiated in 2007. The main objectives are to investigate the freshwater and sediment input to the fjord in order to elucidate the hydrodynamics of the fjord and to provide background information for an interpretation of the sediment column deposited there. A description of the discharge and sediment transport during the jökulhlaup in 2007, based on the preliminary stage discharge relationship, was given by Mernild *et al.* (2008). The discharge and sediment transport during the jökulhlaup in 2008 has been described in Mernild & Hasholt (2009). Russell *et al.* (2011) pointed out that the accumulated discharge presented in Mernild *et al.* (2008) and Mernild & Hasholt (2009) is significantly lower than what they find from measurements of volume changes in the drained lake responsible for the jökulhlaup. They also indicate that an inadequate stage discharge relationship may be the cause for this discrepancy. Due to the use of an improved stage discharge relationship, the difference has been diminished as described by Hasholt *et al.* (2012). The investigations continued through 2009 and 2010, where 2010 was characterized by a prolonged and intense runoff period resulting in the highest record of both accumulated discharge and sediment transport during the 4-year period. Furthermore, a new jökulhlaup occurred on 11 September in 2010.

The objectives of this study are to: (1) provide a revised description with a high time resolution of stage and discharge during the three jökulhlaup events; (2) provide a revised description of the sediment concentration and sediment transport during the jökulhlaups to compare with the accumulated annual transport; (3) investigate effects within the fluvial system; and (4) discuss the possible trigger mechanisms in relation to the literature and the weather conditions before and during the jökulhlaups in order to identify possible triggers.

STUDY AREA

The drainage area (9,743 km^2) of Watson River at Kangerlussuaq stretches from the head of Sdr Strømfjord at the west coast of Greenland to the ice divide on the GrIS. The gauging station is close to 67°00′ N ; 50°40′ W and is located 22–35 km downstream from GrIS terminus. The jökulhlaup lake drains into the river 29 km upstream of the gauging station. The river has two main tributaries: the northern Sandflugtsdalen and the southern Ørkendalen. The river drains at least four lobes of the GrIS, of which the Russell Gletscher and Leverett Gletscher drains into Sandflugtsdalen. Sandflugtsdalen is the valley system where the jökulhlaups have been observed. The lake which was emptied during the jökulhlaups is depicted in Figure 1. The drainage area is dominated by GrIS (9,168 km^2). The ice-free area (575 km^2) (Hasholt *et al.* 2012) consists of gently rolling bedrock hills, up to about 500 m a.s.l. with a thin cover of glacial material. River and lake valleys are cut into the landscape by previous glacial erosion. The vegetation is sparse and consists mainly of grass and scrub.

Mean annual temperature, relative humidity and wind speed are –3.3 °C, 67% and 3.7 m s^{-1} respectively and the uncorrected mean annual precipitation is 170 mm for the period 2007–2010, based on data from the local Danish Meteorological Institute (DMI) weather station. According to Born & Böcher (2001), the climate is characterized as Low Arctic. The ice-free area is dry as demonstrated by the presence of saline lakes (Hasholt & Anderson 2003). The

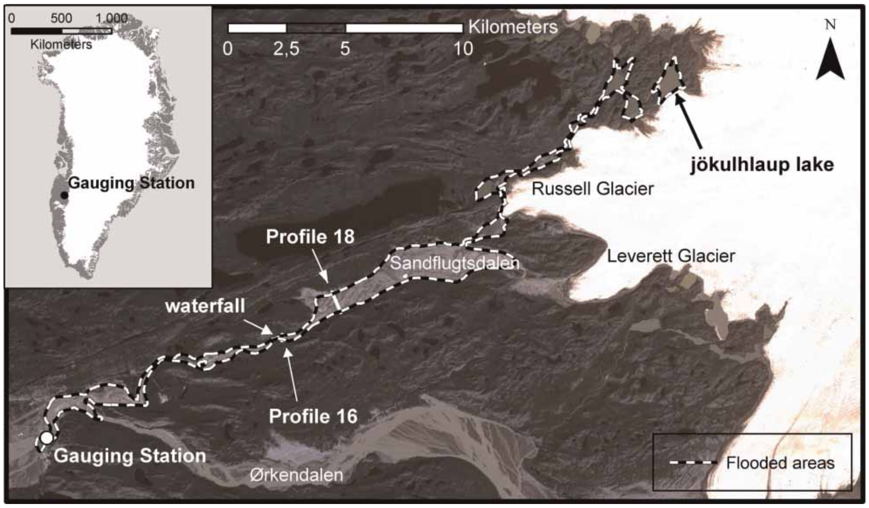

Figure 1 | Landsat 7 image of the area. The dashed lines outline the extent of the flooded areas during the jökulhlaup on 31 August 2007. The study area location is shown in the index map in the upper left corner.

location of the equilibrium line at this part of the GrIS is located at ~1,500 m a.s.l. (van de Wal *et al.* 2005; Broeke *et al.* 2008).

METHODS

The monitoring station for discharge and sediment transport is located on a bedrock sill south of the Kangerlussuaq Airport (see Figure 1). Stage is recorded with pressure transducers corrected for barometric pressure and discharge is measured using the float method at all stages, utilizing the fixed cross-section profile provided by the bedrock sill. At very low stages, the discharge has been measured with ordinary current meters and at high stages it was measured with acoustic doppler current profiler (ADCP) in 2010. The sediment concentration is found from daily manual water samples, supplied by automatic pump sampling when manual sampling was not possible. The sediment concentration found in the water samples has been used for calibration of the recording transmissometers and optical backscatter sensors used to describe the sediment concentration at 10 minute intervals. Bedload finer than about 5 mm are assumed to be in suspension at the monitoring site due to violent turbulence, and is therefore included in the measurements of suspended transport. Coarser particles are not measured. For further details about the monitoring program, see Hasholt *et al.* (2012). In 2007, the sediment sensor malfunctioned and the concentration is based on a relationship between the water discharge and sediment concentration found from water bottle samples (a Q/C-relation; see Mernild & Hasholt 2009; Hasholt *et al.* 2012). For the 2008 and 2010 jökulhlaup events, the concentration is obtained from the automatic sensors.

In spring 2008, the Sandflugtsdalen valley system was surveyed in order to identify maximum stages from the jökulhlaup on 31 August 2007 and to identify tracks of related erosion and deposition in the fluvial system. A number of cross-sections were established with a Trimble 4000 GPS and a Topcon theodolite. In 2010, a pressure transducer was installed upstream of a major waterfall (see Figure 1). By comparing with records from the gauging station, it was possible to determine attenuation and travel time of the flood wave during the jökulhlaup in 2010.

RESULTS

2007

From when the stage began to rise on 26 August until late on 31 August, a diurnal variation was clearly visible. The stage rose abruptly on 31 August from 16 m a.s.l. at 04:00 to 20 m a.s.l. at 14:00 (Figure 2(a)). Discharge, sediment transport and weather observations are shown in Figure 2(a)–(c). Data from the three jökulhlaups are listed in Table 1. The

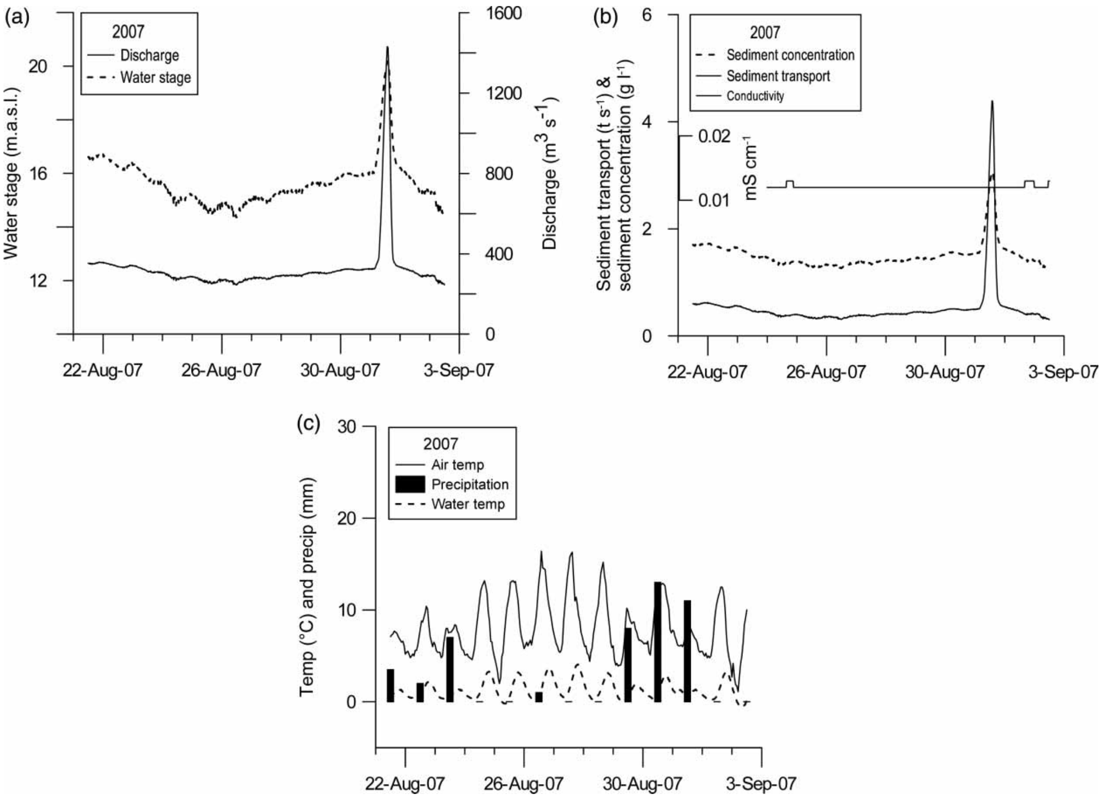

Figure 2 | (a) The gauged water stage above the reference datum (mean sea level) and discharge during the 2007 jökulhlaup. (b) Sediment transport (solid line with a distinct peak), sediment concentration (dashed line) and conductivity. (c) Air temperature, precipitation (DMI) and water temperature at the gauging station.

Table 1 | Selected values in relation to the observed jökulhlaups. The water stage is defined as above the datum where zero flow is occurring (H_0)

	2007	2008	2010
Start (date and time)	31–08–07; 04:00	31–08–08; 04:40	11–09–10; 13:20
End (date and time)	01–09–07; 01:20	01–09–08; 01:00	12–09–10; 09:20
Duration (hours)	21.3	20.3	20
Maximum stage (m above H_0)	10.4	5.3	8.1
Increase from start (m)	4.1	3.3	5.3
Maximum discharge including baseflow (m^3 s^{-1})	1,430	276	523
Maximum jökulhlaup discharge (m^3 s^{-1})	1,103	156	373
Total volume caused by jökulhlaup ($\times 10^6$ m^3)	25.5	3.6	8.4
Drainage volume from Russell *et al.* (2011) ($\times 10^6$ m^3)	39.1	12.9	–
Discharge share of total for the year (%)	0.69	0.13	0.15
Maximum transport (t s^{-1})	4.4	0.7	1.3
Maximum concentration (g L^{-1})	3.06	2.59	2.55
Total transport caused by jökulhlaup ($\times 10^3$ t)	82.8	14.4	22.4
Transport share of total for the year (%)	1.16	0.29	0.19

total volume of water originating from the jökulhlaup was $25.5 \times 10^6\,m^3$ which is about 0.7% of the annual runoff. The sediment transport caused by the jökulhlaup was 83×10^3 t or 1.2% of the annual transport, indicating increased concentration of sediment related to the jökulhlaup (see Table 1). However, the 2007 hysteresis curve is based on a Q/C-relation from water samples, and some uncertainty is therefore related to sediment transport determined for this event.

The conductivity of the water does not change significantly during the jökulhlaup, indicating that all water is meltwater from the GrIS. The diurnal temperature variation of the water was dampened to a maximum of 1 °C as seen in Figure 2(c), indicating a large input of relatively cold water. The rise in stage is congruent with a period with rising temperatures; temperatures on all days are above the freezing point and daily maxima of above 15 °C were recorded.

The jökulhlaup originated in the lake described earlier by Sugden *et al.* (1985), Russell (1989, 2007, 2009), Russell *et al.* (1990) and Russell *et al.* (2011). The lake drained through a tunnel within the ice near the southwest end of the lake. The water level dropped by 49.2 m and the released volume of water was determined as $39.1 \pm 0.8 \times 10^6\,m^3$, as found by Russell *et al.* (2011). The tapping of the lake caused severe flooding in Sandflugtsdalen (see Figure 1). Large ice blocks were deposited on the only road in the area and vegetation was torn apart and removed to leave bare rock at narrow cross-sections close to the ice margin. In flat areas, the inundation was indicated by debris of vegetation and by larger particles deposited on the vegetation. Bank erosion was observed in narrow sections cut through glacial deposits. Several meters were eroded into an old river terrace 10 km upstream of the gauging station. The maximum stage during the jökulhlaup is shown on two cross-sections in Figure 3.

2008

The stage rose abruptly by 3.3 m on 31 August, as depicted by Figure 4(a). The exact stage before the onset of the jökulhlaup is not known because the stage was below the pressure sensor. The estimated total volume of water originating from the jökulhlaup was $3.6 \times 10^6\,m^3$ or 0.1% of the annual runoff (see Table 1). The sediment transport was 14×10^3 t or 0.3% of the annual total. The concentration rose steeply to a concentration of $2.6\,g\,L^{-1}$ (see Figure 4(b)), indicating an uptake of sediment within the fluvial system. The hysteresis curve (Figure 5(b)) has an anticlockwise pattern, which is opposite to the clockwise pattern during the 2010 jökulhlaup. The conductivity when the sensor was under water is seen in Figure 4(b). The water temperature was again low during the jökulhlaup. The air temperature began to rise on 30 August with a diurnal amplitude of up to 15 °C,

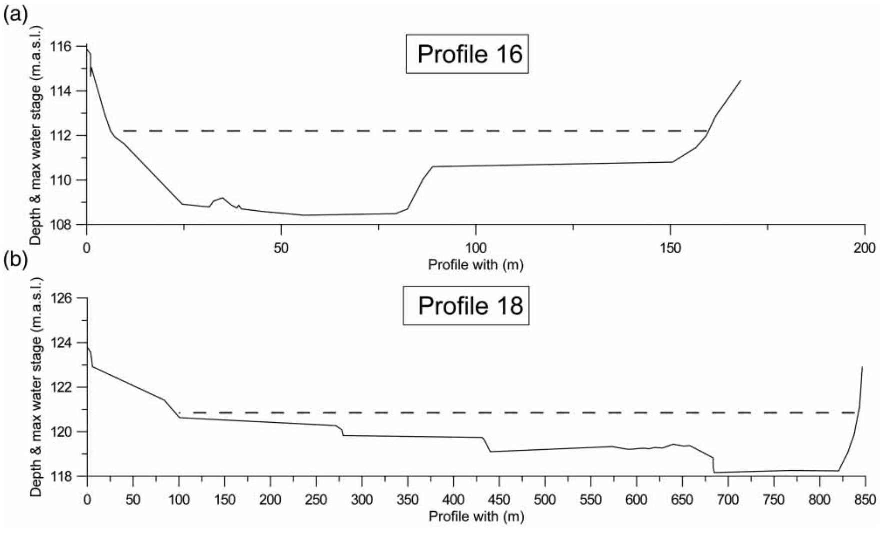

Figure 3 | Maximum water stage in two cross-sections of the river.

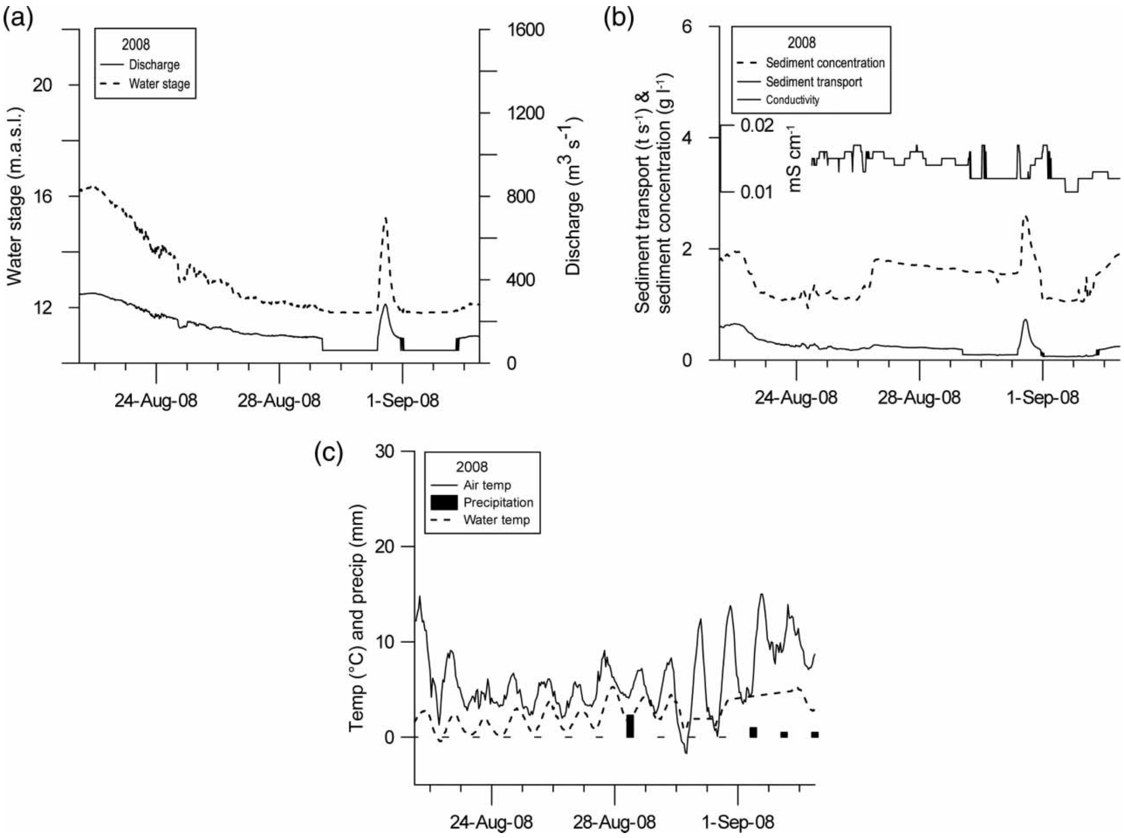

Figure 4 | (a) The gauged water stage above the reference datum (mean sea level) and discharge during the 2008 jökulhlaup. (b) Sediment transport (solid line with a distinct peak), sediment concentration (dashed line) and conductivity. (c) Air temperature, precipitation (DMI) and water temperature at the gauging station.

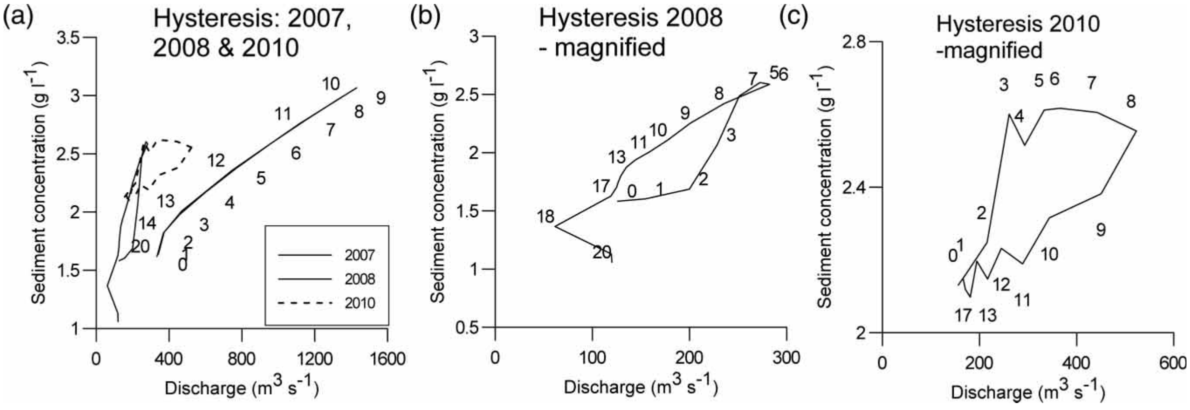

Figure 5 | Hysteresis curves for the jökulhlaup events: (a) 2007 event; numbers correspond to the time from start (hours); 2008 and 2010 jökulhlaups are also plotted; (b) 2008 and 2010 events, magnified and plotted with time labels (hours); note the anticlockwise sequence; (c) as (b) except for the clockwise sequence.

indicating a clear sky and thereby increased melting because of shortwave radiation. The precipitation prior to the jökulhlaup was only 2 mm, and is assumed not to have influenced the triggering. Parts of the englacial drainage system from the 2007 event were probably intact; when the water reached a certain level in the lake, the water entered and expanded the older drainage system. There was no significant erosion or deposition in the fluvial system because the stage was below the previous high stages from 2007.

2010

The year 2010 was characterized by a very high discharge throughout the summer resulting in a record high annual discharge. After a recession period of about 10 days, the water stage rose abruptly from about 13:20 on 11 September until it peaked at 21:20 (see Figure 6(a)). The volume of water related to the jökulhlaup was about $8.4 \times 10^6\ \mathrm{m}^3$ or 0.2% of the annual discharge. The amount of sediment was 22×10^3 t, equal to 0.2% of the annual transport (Table 1). The sediment concentration is seen in Figure 6(b); it rose steeply to a value of $2.6\ \mathrm{g\ L}^{-1}$ and dropped to the same level as before the jökulhlaup when the stage was low again. The hysteresis curve (Figure 5(c)) shows a clockwise rotation because the concentration is lower during the falling stage than during the rising stage at the same discharge. This indicates that the sediment supply is limited, probably because the sediment deposits have been flushed out of the river system during the abnormal high discharges in 2010. The conductivity shows a clear drop during the jökulhlaup, indicating a contribution of water with low conductivity from the proglacial lake into the fluvial system in recession.

At this time of the year, the shallow groundwater from the floodplains seeps into the river after having been in contact with the sediment for a longer period, thus extracting solutes from the sediment. The jökulhlaup water with lower conductivity therefore dilutes this water. The jökulhlaup occurred during a period with relatively low but positive temperatures (Figure 6(c)). There was a small

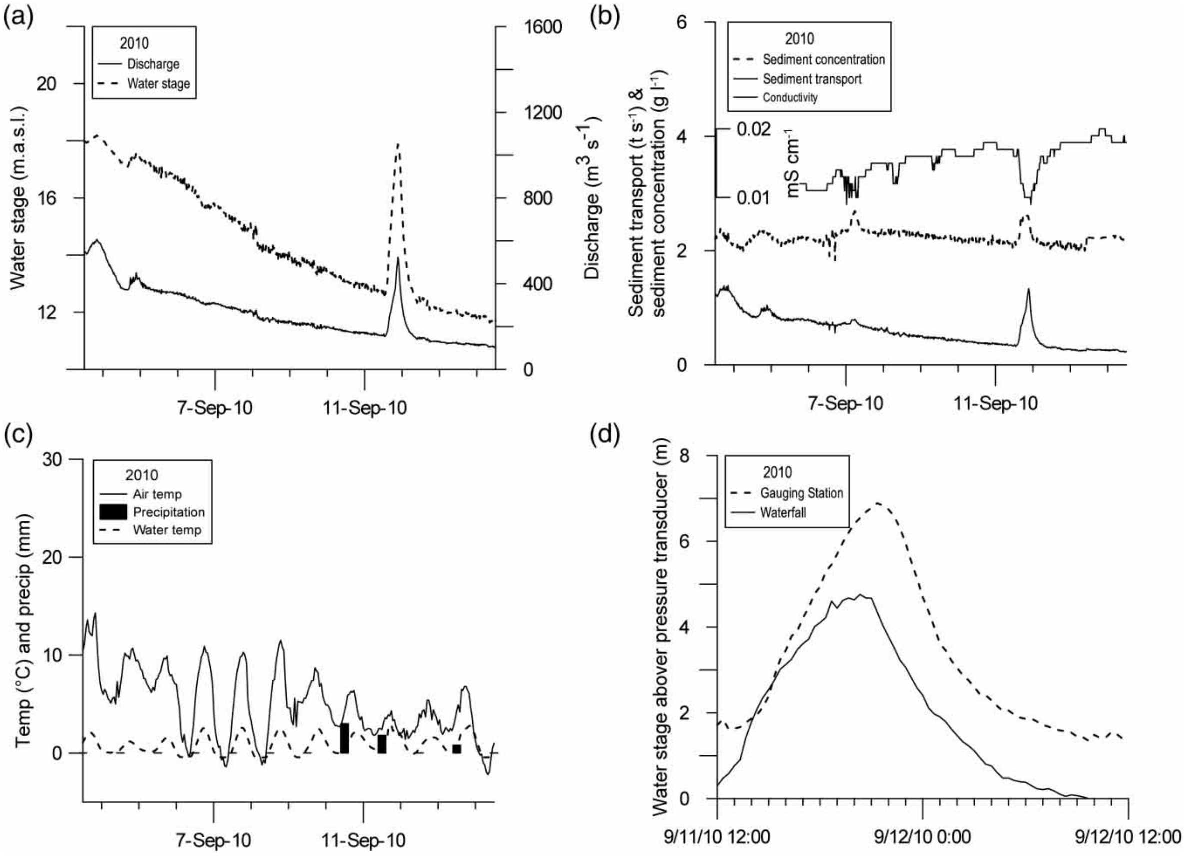

Figure 6 | (a) The gauged water stage above the reference datum (mean sea level) and discharge during the 2010 jökulhlaup. (b) Sediment transport (solid line with a distinct peak), sediment concentration (dashed line) and conductivity. (c) Air temperature, precipitation (DMI) and water temperature at the gauging station. (d) The delay of the flood wave from the waterfall to the gauging station.

amount of precipitation prior to the jökulhlaup (2–3 mm), but this is not likely to have had any influence on the jökulhlaup event. As there was no tapping from the lake in 2009, the englacial drainage system has probably partly deteriorated close to the bottom, preventing the water from escaping.

DISCUSSION

Given that the gauging station is located about 29 km downstream from where the lake drains into the river, it can be discussed from exactly where the sediment pulse observed at the gauging station originates. The water in the ice-dammed lake has a low concentration of sediment due to the settling of this. When the lake drains rapidly through the confined channel beneath the ice, as described by, for example, Russell *et al.* (2011), the available sediment near the bottom will be flushed out. Because the bottom area affected by the lake drainage during the jökulhlaup is small, we assume the available amount of sediment is relatively limited. When the pulse of water leaves the GrIS it will cause local erosion of the banks. Sedimentation of coarser particles will take place on the sandurs due to the lower stream velocities. In channels within the sandur and in confined reaches of the river, resuspension of finer bed material (sand and silt) will occur if this is available. Strong local erosion has been observed near the outlet of water from the lake through GrIS, where a morainic ridge has disappeared. Along the river further downstream, major bank erosion has only been observed in a few places.

The most severe bank erosion was observed on a 500-m-long stretch 5 km upstream of the gauging station. Here it was estimated that approximately 2 m of a 10-m-high terrace, corresponding to ~0.4% of the annual transport, was eroded due to the 2007 jökulhlaup. Both the eroded moraine and the terrace contain larger particles that will be deposited in the sandur reaches, so that the weight indicated above is larger than the weight that actually reaches the gauging station. It is therefore argued that the changes in sediment concentration at the gauging station during a jökulhlaup are mainly caused by erosion and resuspension from the proglacial fluvial system. The transport during the jökulhlaups will probably be more coarse-grained than the 'normal' transport; the layers related to these events could theoretically be identified in the fjord sediment deposits. However, since they make up less than 2% of the annual transport, the thickness of these layers will be very small and therefore difficult to distinguish at this location. Regardless of the source of the observed sediment pulse – subglacial or from the river bank or bed – it is still caused by the higher discharges.

The calculations of flow and sediment transport made here are based on separating the flow caused by the jökulhlaup from the baseflow. However, since the cut-off was made at the beginning and end of the steep and very distinct peaks, there is a chance that the values are underestimated if there was any outflow from the lake before and after the dates we have identified. This could partly explain the fact that our total jökulhlaup volume does not sum up to that given by Russell *et al.* (2011) (see Table 1). Another part of the explanation could be that the stage–discharge relationship used here is still underestimating the observed discharge as explained in Hasholt *et al.* (2012).

The morphological effects of the jökulhlaup were inundation of large areas resulting in deposition of ice-rafted sediment and debris in the vegetation far from the normal flood plain. However, the main effect was erosion in the bed and banks, increased sediment transport and later deposition in areas with low slope (sandurs and the coastal delta). An indication of such deposition is observed at the gauging station at the bridges near the mouth of the Watson River. The bottom of the river was raised 1.5–2 m after the occurrence of the jökulhlaup in September 2010. As the concentration of sediment in the water from the proglacial lake is quite low (estimated as <0.1 g L^{-1}), the high concentrations above the base level must be a result of erosion in the bed and the banks of the river. The maximum concentrations related to the jökulhlaups are clearly lower than the maxima related to subglacial outlets or summer floods. This is partly because the observed jökulhlaups have occurred late in the runoff season, when the fluvial system may be more or less flushed out depending on the magnitude of the summer flood.

The amount of sediment transported by the jökulhlaups is less than 2% of the annual transport, and it is therefore assumed that it will be very difficult to identify layers related to jökulhlaups in the deposits on the bottom of the fjord.

Layers with an increased amount of coarse grains are probably more related to drifting of ice from the bed and banks during the freeze-up during autumn and ice break-up during spring. Except for increased erosion at selected locations, the morphological effects of jökulhlaups near Kangerlussuaq are limited.

CONCLUSION

Although the jökulhlaups can be spectacular as a phenomenon, their impact on the geomorphology and sedimentary strata in the Watson River delta is limited since they contribute less than 2% of the sediment transported annually. As opposed to other places such as Zackenberg and Iceland, jökulhlaups do not play a major geomorphologic role in the delta formation in Kangerlussuaq. We therefore conclude that it is difficult to find distinct sediment layers in the delta and adjacent fjord from jökulhlaups in this area. Indications are that the sediment observed in connection to the jökulhlaups is mainly caused by resuspension of bed material in the proglacial area and, to some extent, bank erosion. The subglacial erosion is assumed to contribute less than the above-mentioned sources of sediment.

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