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An Extreme Sediment Transfer Event in a Canadian High Arctic Stream

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Abstract

Two large suspended sediment concentration (SSC) pulses were recorded in 1998 in a small snowmelt-fed stream on Ellesmere Island in the Canadian High Arctic. The largest pulse occurred from 7 to 8 July, when 32% of the monitored seasonal sediment transport occurred in only four hours. SSC reached 83,760 mg L^{-1}, exceeding all previously recorded values from high arctic glacially-fed and snowmelt-fed rivers by more than one order of magnitude. The event occurred after the majority of snow in the watershed had melted, and was preceded by a long period of relatively high air temperature, and a small rainfall event on 7 July. We consider the most likely cause of the event to be a rapid mass movement.

Introduction

In a simple arctic snowmelt-fed stream regime, annual suspended sediment yield is primarily a function of winter snow accumulation and the intensity and duration of melt (Forbes and Lamoureux, 2005). However, breaching snow dams (Woo and Sauriol, 1981), slush flows (Braun et al., 2002), eolian activity (Lewkowicz and Young, 1991), mass movements (Doran, 1993; Hartshorn, 1995), and large precipitation events (Cogley and McCann, 1976) can rapidly transport large volumes of fine-grained sediment, and these short-lived events can account for much of the total annual sediment flux. Unfortunately, most high arctic fluvial monitoring has not been conducted at a sufficiently high temporal resolution to confidently resolve short-term variability in suspended sediment concentration (SSC; cf. Hardy, 1995), so sediment contributions from large but short-lived events are poorly documented.

In this note, we present a high-resolution hydrometeorological record for most of the 1998 melt season from the main river that drains into snowmelt-fed South Sawtooth Lake (SSL; unofficial name; 79.3°N, 83.9°W; Fig. 1), Fosheim Peninsula, Ellesmere Island. We focus on the second of two unusual SSC pulses, since it contributed a large percentage of the 1998 sediment yield. Hydrometeorological measurements were carried out to provide insight into factors that control sediment flux into the lake, to improve paleoenvironmental interpretation of the varved lake sediments (cf. Francus et al., 2002).

Site Description

The closest Meteorological Service of Canada (MSC) station to SSL is Eureka (84 km NW; 10 m a.s.l.; Fig. 1). From 1947 to 2001, the average Eureka monthly air temperature in June, July, and August was 2.2, 5.5, and 3.1°C, respectively; all other monthly mean air temperatures were below freezing. Average annual rainfall is 25 mm; respective mean June, July, and August rainfall totals are 3.7, 11.2, and 8.8 mm. On average, precipitation occurs on 14% of days from June to August, but the largest single day of rain typically accounts for 33% of the annual rainfall total, and daily rainfall totals of up to 41.7 mm have been recorded.

The area of the SSL stream watershed is 47 km^2. Maximum and minimum elevations are ~915 m (3000 ft) and 280 m (958 ft) a.s.l. (Fig. 1), and the entire watershed is above marine limit (cf. Bell, 1996). The watershed was probably glaciated in the Pleistocene (Ó Cofaigh et al., 2000), but is not currently glacierized. There are several small, possibly perennial snowbanks in the upper reaches of the watershed.

Plants and flowers on the Fosheim Peninsula are among the most diverse and abundant in the High Arctic. Communities are dominated by *Salix arctica* and *Dryas integrifolia* (Edlund and Alt, 1989; Edlund et al., 2000). A partially vegetated paleo–lake bed is present immediately above SSL (Fig. 1). Evidence of gelifluction was observed on slopes slightly above lake level, and shallow debris flow channels are present on steeper slopes in the northeast and southwest portions of the watershed, and on steep north-facing slopes adjacent to SSL. Regional permafrost thicknesses are typically about 500 m (Judge et al., 1981), and thaw depths are usually less than 70 cm during summer (Lewkowicz, 1992).

Two branches of the SSL stream drain the highlands in the northeast and southwest portions of the watershed. The branches coalesce into a single channel about 1.5 km from SSL, which is incised less than 2 m into unconsolidated paleo–lake bed sediments (Fig. 1).

Methods

Unless otherwise stated, dates refer to 1998, and regressions use linear fits, with $p < 0.0001$.

METEOROLOGY

A weather station (Fig. 1) recorded from 27 May 1998 to 10 December 2000. Air temperature was measured with a Vaiasala HMP45C sensor protected from solar radiation inside a 12-plate Gill shield. Measurements obtained every minute were stored as hourly averages on a Campbell Scientific Inc. (CSI) model 21x datalogger. An unshielded cylindrical precipitation gauge, precise to 0.254 mm, and graduated to 0.2 mm, was placed on the ground, and read several times daily during the 1998 field period.

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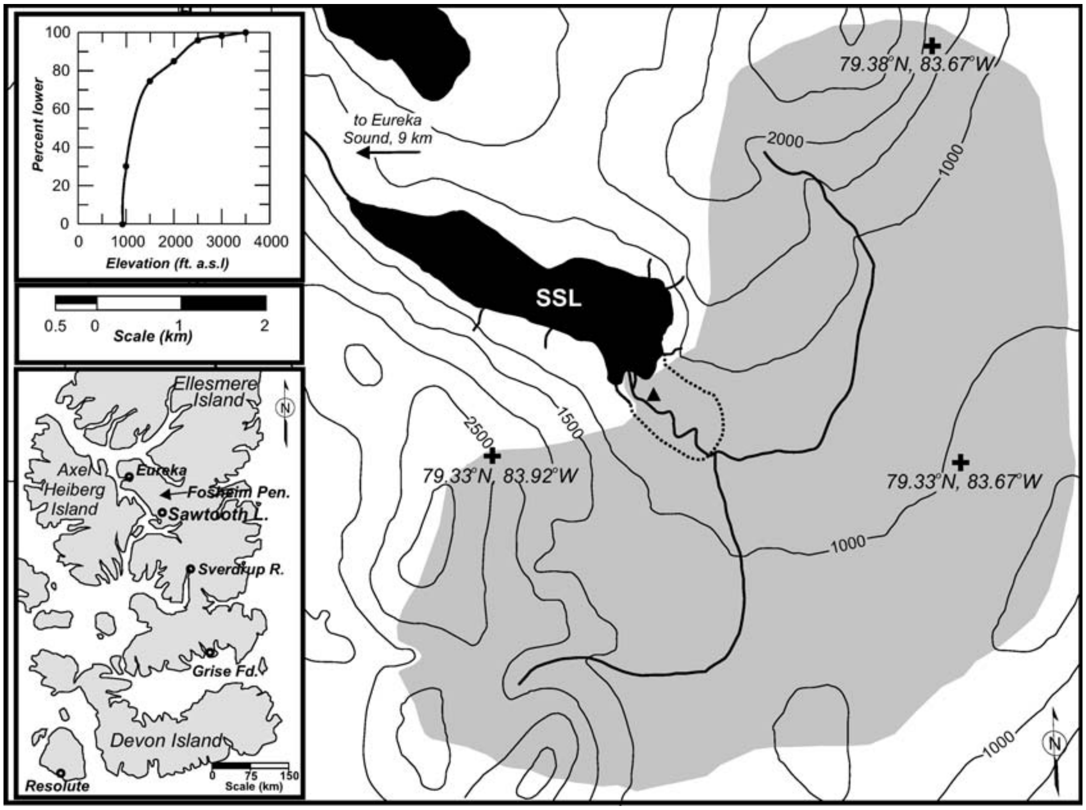

FIGURE 1. Topographic map of the South Sawtooth Lake watershed (shaded), and surroundings (lower inset). Topographic contours are from 1: 250000 NTS maps 49H: Cañon Fiord, and 49G: Slidre Fiord. Contours are feet a.s.l., interval is 500 ft (152 m). SSL, South Sawtooth Lake; Triangle, automated weather station and hydrometeorologic monitoring stations; Dashed line, paleo–lake bed (location estimated visually). Crosses represent arbitrarily chosen latitude/longitude markers. Upper inset, relative area-elevation curve for the South Sawtooth Lake watershed.

WATER CONDUCTIVITY

Water conductivity and temperature were measured every 10 s at a hydrometeorological monitoring station (HMS; Fig. 1) using a CSI 247 probe ($< \pm 5\%$ precision at 25°C from 5 to 440 milliSiemens cm^{-1} [mS cm^{-1}]). Conductivity was temperature compensated using synchronously obtained stream water temperatures ($\text{mS cm}^{-1}{}_{\text{cor}}$; Gardiner and Dackombe, 1983; Campbell Scientific, Inc., 1996). Mean 10-min values were recorded with a CSI CR10 datalogger, and were averaged to produce an hourly record during post-processing.

STAGE

The HMS recorded stage between 12 June and 17 July with two Geokon Model 4850 vibrating wire pressure transducers interfaced with the CR10 datalogger. One transducer was inside a 5.1 cm diameter slotted stilling well, and the other measured air pressure changes. Ten-minute mean and standard deviation values were recorded using measurements made every 20 s.

Before the channel was sufficiently ice-free for installation of the HMS, stage was measured manually using an anchored "offset gauge" with five datums on its shaft, and the distance between the water surface and the nearest datum was measured. To assess the precision of the vibrating wire and offset gauges, a manually read staff gauge was anchored in the stream channel from early June to mid-July. Coeval measurements from the three instruments were assessed and determined to be intercomparable. Therefore, the pre–12 June offset gauge, and 12 June to 17 July HMS records were combined to produce a continuous log of stage.

DISCHARGE

Stream velocity was measured with a Swoffer Model 2100 flow meter (precision $\pm 1\%$ from 0.03 to 7.50 m s^{-1}). Discharge measurements were performed manually at 60% of the stream depth using standard measurement techniques (cf. Hardy, 1995). The rating curve uses discharges between 0.03 and 1.50 $\text{m}^3 \text{ s}^{-1}$ (polynomial fit, $r^2 = 0.99$, $n = 14$, standard error of estimate $= 0.06 \text{ m}^3 \text{ s}^{-1}$).

SUSPENDED SEDIMENT CONCENTRATION

Suspended sediment samples were manually obtained near the thalweg using a US DH-48 depth-integrating sampler. Sample frequency varied from 4 to 15 samples per day, and volume ranged from 120 to 435 mL. Samples were vacuum filtered on Whatman Type WCN 0.45 μm papers, and air-dried in the field. Papers were pre- and post-weighed using balances with precision and reproducibility of ± 0.1 mg.

SSC was automatically recorded using a D&A Instruments OBS-3 infrared backscatterance unit interfaced with the CR10 datalogger. Voltages from the OBS-3 were calibrated to directly measured SSC ($r^2 = 0.93$, $n = 178$, slope $= 1.48$). Hourly averages of SSC were obtained from 15 June to 17 July; however, OBS-3 readings were spurious on 15, 16, and 27 June, and 7, 8, and 9 July, when overwhelmed by extremely high SSC, or when organic debris blocked the sensor face. At these times, SSC samples were obtained manually at a sampling frequency sufficient to adequately resolve diurnal SSC cycles, which allowed linear interpolation to an hourly resolution.

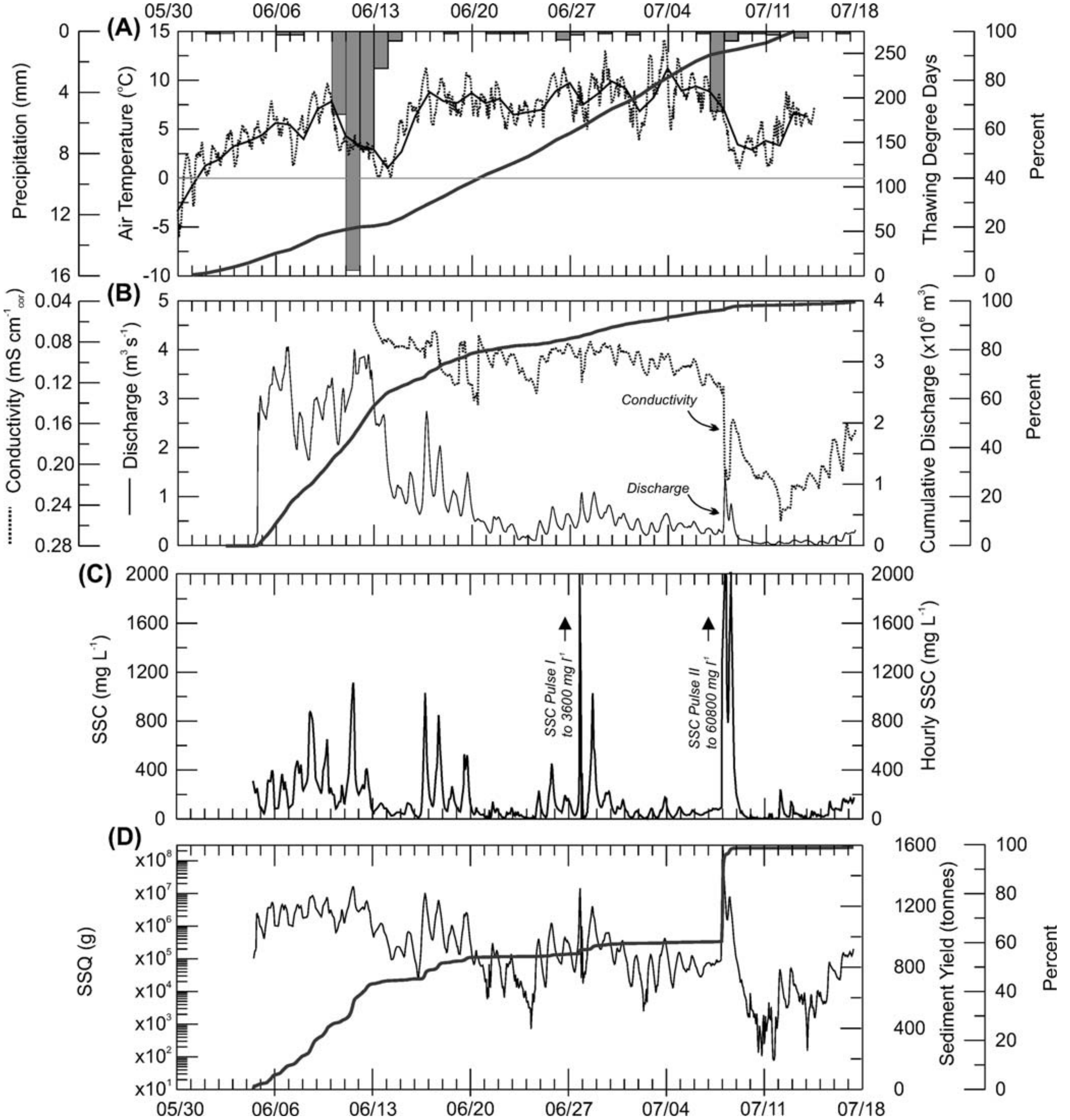

FIGURE 2. Monitored 1998 hydrometeorological conditions near lake level at South Sawtooth Lake. (A) Hourly and mean daily air temperature, thawing degree-days, and daily precipitation (inverted Y-axis); (B) hourly discharge, cumulative discharge, and hourly conductivity (inverted Y-axis); (C) hourly suspended sediment concentration (SSC); (D) hourly suspended sediment discharge (SSQ, $\log_{10}$ scale), and sediment yield (cumulative SSQ).

Results

Mean daily summer air temperature at SSL was highly correlated with temperature at Eureka ($r^2 = 0.85$), but mean daily air temperature was on average 0.9°C warmer at SSL than at Eureka. Periods of spring and summer precipitation at Eureka and SSL generally coincided in timing, but not magnitude: 52% less rain fell at Eureka than at SSL from 4 June to 14 July.

Snowmelt at lower watershed elevations began on 29 May and daily air temperature rose above freezing on 1 June. Minimal channelized streamflow began on snow and ice on 2 June (Fig. 2B). Between 4 and 14 June, 65% of the seasonal discharge, and 45% of the seasonal sediment transfer occurred (Fig. 2B, D). Not including the second SSC pulse, the highest sustained rates of sediment transfer occurred between 10 and 13 June during a multi-day period of nearly continuous precipitation, when 77% of the recorded rain fell (Fig. 2A). Discharge dropped sharply on 13 and 14 June, after air temperature at lake level had been decreasing since 9 June, and approached freezing on 13 June and early on 14 June. However, air temperature increased following the morning of 14 June, and discharge somewhat recovered for about six days.

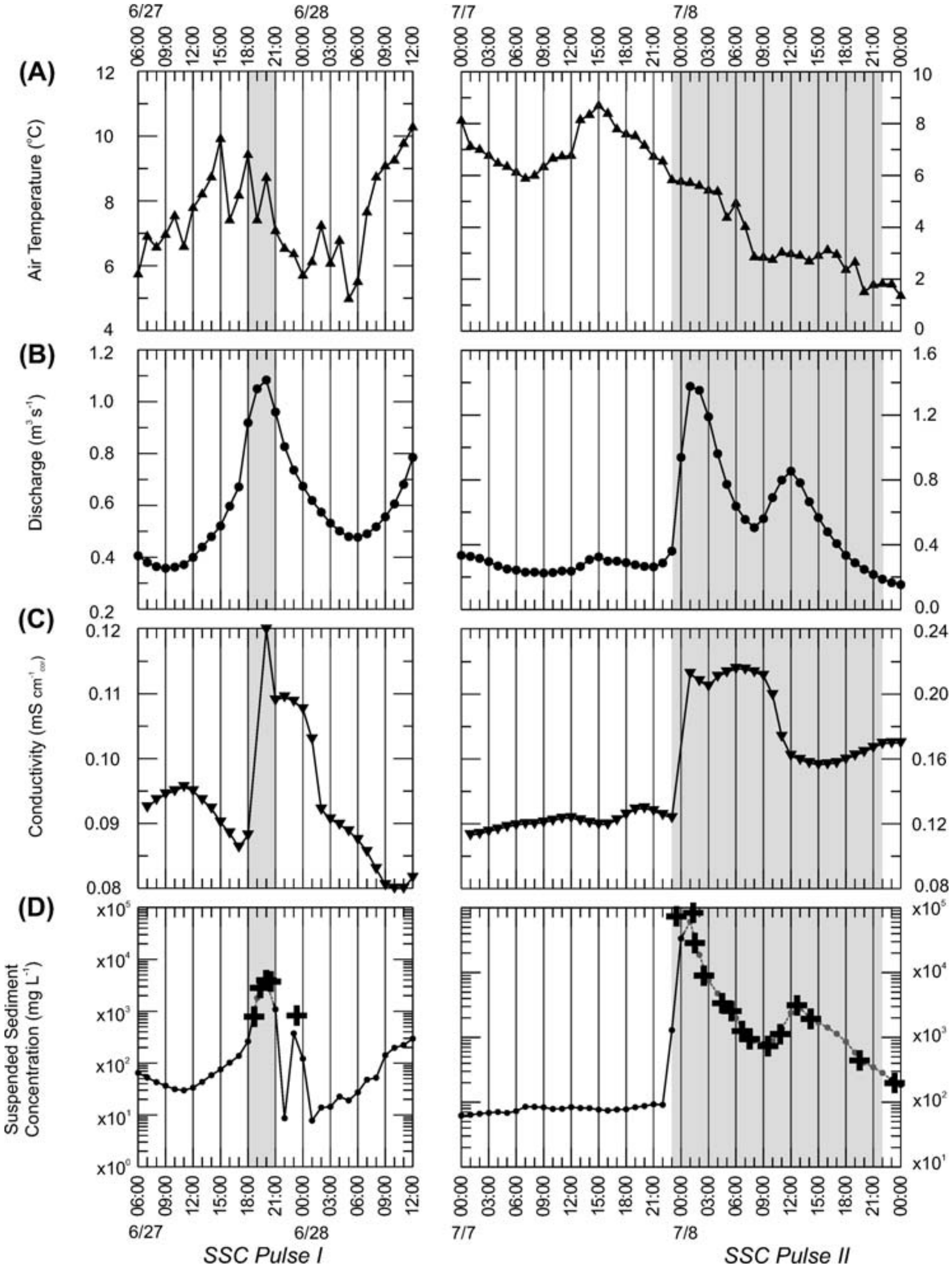

FIGURE 3. Detail of monitored hydrometeorological conditions around suspended sediment concentration (SSC) Pulses I (left series of graphs) and II (right series). Note the difference in y-axis scales between left and right series of graphs. Gray shading represents the timing of the two SSC pulses. (A) Air temperature, (B) discharge, (C) conductivity, (D) SSC ($\log_{10}$ scale). Cross symbols represent SSC obtained with the DH-48; other symbols represent hourly averages; dashed lines represent times when the OBS-3 measurement was outside our measurement range, and hourly SSC was determined from manually obtained water samples.

SSC Pulse I occurred between 18:00 and 21:00 on 27 June (Fig. 3). Unusually high SSC was recorded (peak hourly SSC = 3600 mg L^{-1}), but the event was short-lived and occurred without exceptional discharge, so it was not responsible for large volumes of sediment transfer (Fig. 2D). Daily discharge decreased after SSC Pulse I, and distinct diurnal discharge fluctuations occurred until about 4 July (Fig. 2B).

SSC PULSE II

SSC Pulse II occurred from 23:00 on 7 July to 22:00 on 8 July. The event had extremely high SSC, and a rapid and large sediment yield. It occurred late in the melt season: 90% of the monitored thawing degree-days had been recorded (Fig. 2A). On the afternoon of 7 July, air temperature decreased from a high of 8.7°C to a minimum of 1.8°C on 8 July (Fig. 3A).

On the late evening of 7 July, rain fell relatively intensely at lake level, and sleet fell at higher watershed elevations. At lake level, 5.2 mm fell, the fourth daily largest rainfall recorded in 1998. At Eureka, a 5.2 mm rainfall event has a 1.2 year recurrence interval. At Eureka, 4.2 mm of rain and 12 mm of snow fell on 7 and 8 July, respectively.

Assuming the rainfall amount recorded at lake level was consistent across the watershed and was not appreciably stored, about 20% more discharge occurred during SSC Pulse II than would be expected from rainfall runoff alone. Discharge increased abruptly on the late evening of 7 July and early morning of 8 July. A secondary discharge peak occurred at 12:00 on 8 July (Fig. 3B); this was the only time after the period of peak snowmelt (early to mid-June) when two distinct discharge peaks occurred in one day. During SSC Pulse II, 1.4% of the recorded discharge for the season entered the lake.

Stream water conductivity increased sharply at the beginning the event, staying around 0.22 mS cm^{-1}_{cor} for 9 h on the morning of 8 July (Fig. 3C). Conductivity dropped after the morning of 8 July; however, for the remainder of the monitoring period, conductivity was on average about double the pre–SSC Pulse II mean (Fig. 2C).

Hourly SSC increased from 90 mg L^{-1} to ~60,800 mg L^{-1} from 22:00 on 7 July to 01:00 on 8 July (Fig. 3). The highest individually measured SSC was ~83,760 mg L^{-1}, sampled at 01:20 on 8 July. Of the recorded sediment yield for the entire field campaign, 39% occurred during SSC Pulse II, representing 610 tonnes (Fig. 2D), or 13 tonnes km^{-2} averaged across the watershed. Of the whole season sediment yield, 32% occurred in only 4 h. Sediment transfer reached a maximum of 28 standard deviations from the seasonal mean at 01:00 on 8 July. Discharge and conductivity rises were roughly synchronous at the beginning of the event; however, discharge increased an hour after SSC (Fig. 3).

Discussion

Hourly and individually recorded SSC during Pulses I and II greatly exceed all previously published high arctic values from both glacial and nival streams (cf. Hardy, 1995). The highest previously recorded SSC, from the large and highly glacierized Sverdrup River, Ellesmere Island (Fig. 1), during an exceptional 54.6 mm precipitation event in 1973 (Cogley and McCann, 1976), is more than an order of magnitude less than the maximum recorded SSC during SSC Pulse II.

One definition of an extreme hydrologic event is when the measured property is greater or less than two standard deviations from the mean (Desloges and Gilbert, 1994). Much of SSC Pulse II greatly exceeds this criterion for sediment transfer, while SSC Pulse I does not, so the following is a brief assessment of possible triggering events for SSC Pulse II.

RAINFALL RUNOFF

Rainfall runoff probably contributed to SSC Pulse II. However, the timing of the event within the melt season was unusual; active layer storage capacity and evaporation are typically high later in the melt season, so sediment supply and runoff ratios tend to be relatively low (Woo and Young, 1997; Woo, 2000).

While the rain on 7 July fell relatively intensely, the rainfall amount was clearly not exceptional; three larger events were recorded at SSL in 1998. While the Eureka record predicts a 1.2-yr recurrence interval for a 5.2 mm rainfall event, orographic and continental effects in the Sawtooth Mountains enhance precipitation amounts there (Lewkowicz and Hartshorn, 1998; Wolfe, 2000; this study), lowering local recurrence intervals for given precipitation amounts. Also, high arctic MSC stations under-record true precipitation amounts (Woo et al., 1983).

SNOW DAM COLLAPSE AND SLUSH FLOWS

Meltwater and rainfall runoff could have been dammed behind a perennial snowbank, and its breach could have initiated SSC Pulse II. Indeed, it appears that more water ran off during SSC Pulse II than was contributed through precipitation alone. However, slush flows and snow dam collapses usually occur early in the melt season (Woo and Sauriol, 1981; Xia and Woo, 1992; Hardy, 1995; Braun et al., 2000). Based on observations of the watershed, the long time that the stream flowed prior to 8 July, and the relatively high air temperatures recorded in late June and early July (up to ~14°C; Fig. 2A), it is considered unlikely that a snow dam collapse, either within or outside the stream channel, caused SSC Pulse II. Melting permafrost and residual snowpack could have contributed the discharge not derived from rainfall runoff.

RAPID MASS MOVEMENT

The series of small late June to early July precipitation events, combined with consistently high air temperatures (Fig. 2A), likely resulted in increased active layer thickness, pore water content, and slope instability—ideal conditions for active layer detachments and blockfalls.

The sharp and sustained increase in stream conductivity that occurred at the beginning of SSC Pulse II (Fig. 3C), and continued to the end of the monitoring period (Fig. 2B), is consistent with runoff contacting freshly eroded sediment (cf. Kokelj and Lewkowicz, 1999). No active debris flows, detachment slides, slumps, or mudflows were observed; however, a fresh blockfall adjacent to the stream channel might not have been apparent on the incised stream channel walls, where thermoerosional niching occurs throughout the melt season.

Rapid mass movements typically occur on the Fosheim Peninsula in mid- to late summer when the active layer is thick, and thaw rates and soil pore water pressures are high (Hartshorn, 1995; Lewkowicz, 1988; Lewkowicz, 1992; Lewkowicz and Hartshorn, 1998; Lewkowicz and Kokelj, 2002). At three locations on the Fosheim Peninsula monitored from 1988 to 2000, active layer detachment slides in 1998 were the second most numerous on record (Brown and Alt, unpublished document).

Concluding Remarks

This study and analysis of varved sediment cores (Francus et al., 2002) find that most discharge and sediment transfer into SSL occur as a result of snowmelt runoff. However, SSC pulses may confound simple and direct calibrations between hydrometeorological variables and varve parameters, since the pulses are likely quasi-random, interannually variable, and may cause inter- and intraannual disruptions in sediment supply.

If an active layer mass movement or rainfall-induced runoff triggered either of the SSC pulses, an increase in their frequency can be expected as summer arctic air temperatures continue to rise. Active layer thickness is anticipated to increase by 25 to >50% in the Canadian Arctic Archipelago by 2050 (Anisimov et al., 1997), and sediment flux to arctic rivers is projected to increase by an average of 22% for every 2°C increase in regional temperature (Syvitski, 2002).

Finally, we note that SSC Pulses I and II could easily have been missed if SSC was less frequently monitored, or if the monitoring campaign had stopped when discharge and diurnal discharge fluctuations decreased from late June to early July. If SSC Pulse II had been missed, the seasonal sediment yield would have been underestimated by more than one-third. This underscores the need for high SSC sampling frequencies over entire melt seasons.

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