Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **30**, 1441–1460 (2005)
DOI: 10.1002/esp.1216

Discharge and suspended sediment dynamics during two jökulhlaups in the Skaftá river, Iceland

Gareth H. Old,[1]* Damian M. Lawler[2] and Árni Snorrason[3]

[1] *Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, OX10 8BB, UK*
[2] *School of Geography, Earth and Environmental Sciences, The University of Birmingham, Birmingham, B15 2TT, UK*
[3] *Orkustofnun (Icelandic National Energy Authority), Grensasvegur 9, 108 Reykjavik, Iceland*

*Correspondence to:
*G. H. Old, Centre for Ecology and Hydrology, Maclean Building, Crowmarsh Gifford, Wallingford, OX10 8BB, UK.
E-mail: GHO@ceh.ac.uk*

Received 2 December 2002;
Revised 26 November 2004;
Accepted 30 November 2004

Abstract

This paper investigates the dynamics and significance of discharge and suspended sediment transport (SST) during two jökulhlaups (glacier outburst floods) in the Skaftá River, south Iceland. Jökulhlaups occur frequently in many glacial environments and are highly significant in the geomorphological evolution of river basins and coastal environments. However, direct high-resolution monitoring of jökulhlaups has rarely been accomplished and hardly ever at more than one station in a downstream sequence. Here we present detailed data on jökulhlaup discharge and water quality from an intensive monitoring and sampling programme at two sites in summer 1997 when two jökulhlaups occurred. Evidence is discussed that supports the origin of both jökulhlaups being subglacial reservoirs, produced over several months by subglacial geothermal activity. At the downstream site, Ása-Eldvatn, the larger jökulhlaup (1) had a peak discharge of 572 m^3 s^{-1} and a peak suspended sediment flux of 4650 kg s^{-1} (channel-edge value) or 4530 kg s^{-1} (cross-sectional). These values compare to the non-jökulhlaup flow of 120 m^3 s^{-1} and suspended sediment flux of 190 kg s^{-1} (channel-edge) or 301 kg s^{-1} (cross-sectional). Significantly, the jökulhlaups transported 18·8 per cent of the annual runoff and 53 per cent of the annual suspended sediment transport in 6·6 per cent of the year. Furthermore, water chemistry, suspended sediment and seismic data suggest that volcanic activity and geothermal boiling (possibly including steam explosions) may have occurred during Jökulhlaup 1. The research illustrates the value of integrating high-resolution, multi-point field monitoring of meteorological, hydrological, hydrochemical, geomorphological and seismological data for understanding the dynamics, significance and downstream translation of jökulhlaups. Copyright © 2005 John Wiley & Sons, Ltd.

Keywords: Iceland; glacial outburst floods; jökulhlaup; suspended sediment; turbidity; discharge; volcanic activity; steam explosions

Introduction

Jökulhlaups (glacial outburst floods) originate from the sudden release of water stored within a glacier or from marginal ice-dammed lakes (e.g. Björnsson, 1992, 2002; Tweed and Russell, 1999). Knowledge of jökulhlaup dynamics is essential to a full understanding of their triggering mechanisms, their importance in relation to long-term valley/sandur development and sediment recruitment to nearshore zones (e.g. Boulton *et al.*, 1988; Knudsen and Russell, 2002; Lacasse *et al.*, 1998; Magilligan *et al.*, 2002; Maizels, 1989; Russell *et al.*, 2002; Russell and Knudsen, 2002; Tómasson, 1985), and their likely impacts on infrastructure. In Iceland, discharge records (for approximately 50 years) are available for many jökulhlaups (e.g. Rist, 1976, 1981, 1984; Zóphóníasson and Pálsson, 1996). River water samples have been collected during several events for the analysis of their suspended sediment concentration and chemical composition (e.g. Pálsson *et al.*, 2001; Russell, 1989; Steinþórsson and Óskarsson, 1983; Tómasson *et al.*, 1980). Furthermore, Elefsen *et al.* (2002) continuously monitored variations in stage and electrical conductivity of the Skeiðará, Jökulsá á Sólheimasandi and Skaftá rivers during jökulhlaups. However, directly monitored/sampled, high-resolution information on how discharge, sediment and solute concentrations covary dynamically is rarely available.

Many jökulhlaup analyses are restricted to contemporary qualitative descriptions (e.g. Johannasson, 1919 and Sveinsson, 1919, cited in Tómasson, 1996), or post-event reconstructional approaches. The latter are supported by empirical relationships (e.g. Clague and Mathews, 1973), geomorphological evidence (e.g. O'Connor and Baker, 1992), sedimentary deposits (Maizels, 1989; Roberts *et al.*, 2001), observed lake level data (e.g. Russell *et al.*, 1990), aerial photographs and video (Roberts *et al.*, 2000) or ice block obstacle marks (Russell, 1993).

Given limited direct monitoring of jökulhlaup dynamics, many of their features are unexplained (Tweed and Russell, 1999). To help address this research gap this paper aims to: (1) present detailed information on the dynamics of discharge and the transport of suspended sediment and solutes in the Skaftá system, south Iceland, from the direct monitoring of two jökulhlaups, at two stations, in summer 1997; (2) elucidate the processes responsible for the observed dynamics of discharge and sediment transport; and (3) quantify the significance of the jökulhlaups for longer-term flow and sediment transfer in the Skaftá basin. The use of two stations allows downstream translation effects to be considered.

Study Area

Monitoring was based in the partly glacierized Skaftá basin in subarctic southern Iceland, upstream of a road-bridge where Route 1 crosses the Skaftá at 18°26′ W, 63°40′ N (Figure 1). The Skaftá was chosen because: (i) it experiences recurrent jökulhlaups (Björnsson, 1977); (ii) it is reasonably accessible, except at its upstream end; (iii) it incorporates three Orkustofnun (Icelandic National Energy Authority) gauging and water quality sampling stations; (iv) seismic data are available for the region; and (v) there is minimal anthropogenic disturbance in the basin. Additionally, there is an applied aspect to the study as the basin contains infrastructure at risk from jökulhlaups.

The Skaftá was monitored at Sveinstindur, Ása-Eldvatn and Kirkjubæjarklaustur (Figure 1). Sveinstindur, the nearest monitoring station to the Vatnajökull ice cap, is located below Langisjór (a large proglacial lake), *c.* 30 km and *c.* 25 km downstream of the ice fronts of the Tungnaárjökull and Skaftárjökull glaciers, respectively. The Ása-Eldvatn monitoring station, *c.* 81 km and *c.* 76 km downstream of the Tungnaárjökull and Skaftárjökull glaciers, respectively, lies on a representative distributary branch of the Skaftá below Skaftárdalur, and is the principal site for monitoring water quality. The Kirkjubæjarklaustur monitoring station is located *c.* 28 km downstream of Skaftárdalur.

The Skaftá at Ása-Eldvatn (the main monitoring station) drains an area of 1506 km^2 (Figure 1). At Kirkjubæjarklaustur, summer air temperatures are low (mean July temperature *c.* 11 °C) and mean annual precipitation is high at 1645 mm a^{-1} (G. Gísladóttir, pers. comm.), increasing towards the basin summit. The Skaftá basin contains the 464 km^2 Skaftárjökull glacier, an outlet of the Vatnajökull ice cap (8100 km^2; Björnsson, 2002). Skaftárjökull is a long and narrow temperate glacier and ranges in altitude from 700 m above sea level (a.s.l.) to 1660 m a.s.l. (Figure 1) (Björnsson, 1988). Vatnajökull overlies part of the eastern volcanic zone, encompassing the large volcanoes Hamarinn, Bárdarbunga and Grímsvötn (Björnsson and Einarsson, 1990). As part of the Grímsvötn field, the Skaftá basin is geothermally influenced and seismically active (Björnsson, 1977, 1988, 2002; Björnsson *et al.*, 2001; Björnsson and Einarsson, 1990).

Skaftá originates from Tungnaárjökull and Skaftárjökull (Figure 1). Water drains from the glacier fronts at *c.* 700 m a.s.l. and flows in braided channels over an outwash plain that is 15–20 km long and 2–5 km wide (Björnsson, 1977) (Figure 1). However, during heavy precipitation events the river receives significant quantities of direct runoff. Below Skaftárdalur a distributary branch flows eastwards to Kirkjubæjarklaustur (Figure 1). At Ása-Eldvatn channel width is >50 m, and discharges range from $<50\ m^3\ s^{-1}$ to $>750\ m^3\ s^{-1}$. There have been 27 jökulhlaups in this river between 1970 and 1997 (Zóphóníasson and Pálsson, 1996; S. Zóphóníasson, 1998, pers. comm.), and they occur in most years. They originate from below the eastern and western cauldrons on the ice cap (Figure 1). At present jökulhlaups normally exit the Vatnajökull ice cap from below Tungnaárjökull (S. Zóphóníasson, 2003, pers. comm.). Owing to the permeability of the lava in the catchment a significant amount of the overbank floodwater contributes to groundwater.

Methods

Discharge is measured through many jökulhlaups by Orkustofnun, but water quality sampling is usually only logistically feasible after the flood has begun (see Elefsen *et al.*, 2002; Lawler *et al.*, 1992). Therefore, we established an intensive, high-resolution field monitoring operation on the Skaftá over two summer meltwater field seasons (1997 and 1998); this paper concentrates on the 1997 season, spanning from 14 July to 8 September (Julian Day (JD) 195 to 251). All instruments were connected to Grant Instruments Squirrel (SQ1200 and SQ8) dataloggers, scanning at 100 s frequency and recording 5-min averages, unless otherwise stated.

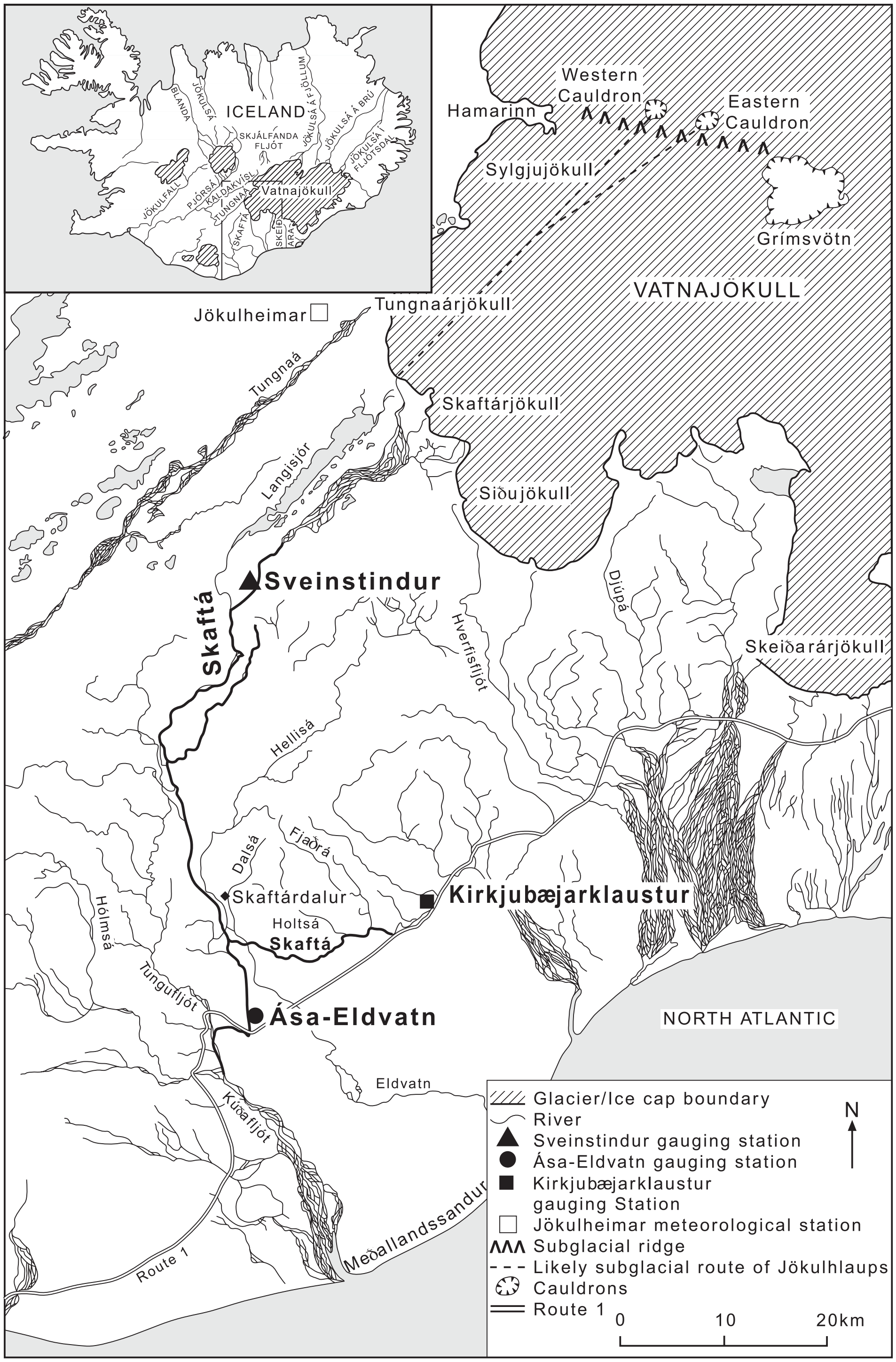

Figure 1. Map of southwest Vatnajökull and the Skaftá basin.

Discharge and meteorological monitoring

Discharge was monitored at Sveinstindur, Ása-Eldvatn and Kirkjubæjarklaustur by Orkustofnun (Figure 1). At all three sites, stage was monitored continuously with a Stevens bubble gauge linked to a chart recorder. Stage records were converted to discharge values using rating equations derived from natural sections. Flow velocity is usually determined with current meters, but during high flows an acoustic doppler velocity meter (ADVM) is used.

Precipitation was recorded as 5-min totals at Ása-Eldvatn (Figure 1) using a simple tipping bucket rain gauge. Hourly precipitation totals are reported here. Hourly air temperature data were provided by the Icelandic Meteorological Office for Jökulheimar, 14 km NW of Skaftárjökull terminus (Figure 1).

Turbidity and suspended sediment concentration monitoring

Turbidity was monitored at Ása-Eldvatn (Figure 1) as a surrogate measure of suspended sediment concentration (SSC) (e.g. Lawler, 1995, 2004), using a Partech infra-red IR15C absorptiometric sensor, chosen because it is suitable for measuring the high SSC values (0–10 000 mg l^{-1}) expected here, as in other southern Icelandic rivers (e.g. Lawler, 1991; Lawler *et al.*, 1992; Lawler and Wright, 1999; Pálsson and Vigfússon, 1996). The turbidity sensor was located in fast-flowing water, 2 m out from the left channel bank and 30 cm above the channel bed.

Automatic water sampling and processing

Water samples were required to determine suspended sediment concentrations for use in calibrating data from the turbidity meter. Samples were taken at Ása-Eldvatn from the left bank (adjacent to the turbidity sensor), using a Northants Engineering MK4b vacuum Automatic Water Sampler (AWS). Duplicate samples of approximately 700 ml were taken at least twice daily, at minimum flow (*c.* 2230 h GMT i.e. Icelandic local time) and maximum flow (*c.* 0900 h). Approximately 250 ml of one of the samples was filtered through a 3·5 μm glass fibre filter circle to determine SSC values in g l^{-1}. This pore size represents a compromise between trapping efficiency and filtration times for these highly turbid waters (Old, 2000).

On seven occasions in the 1997 summer monitoring season and on two occasions in summer 1998, Orkustofnun took width- and depth-integrated suspended sediment samples across the entire Skaftá cross-section at the bridge at Ása-Eldvatn, *c.* 200 m downstream of the AWS site using a US S 49 suspended sediment sampler on a winch. Water samples were taken to the Orkustofnun laboratory for SSC determinations using a sedimentation column, and particle size distributions using a Sartorius sedimentation balance. SSC values derived from this laboratory analysis are termed SSC_{xs} (cross-section suspended sediment concentration) values. At Sveinstindur (Figure 1), Orkustofnun also took channel-edge depth-integrated suspended sediment samples using a USGS DH 48 sampler.

SSC and turbidity data processing

The 5-minute turbidity record at Ása-Eldvatn was calibrated against SSC values from 230 coincident AWS samples (e.g. Lawler, 1995; Wass *et al.*, 1997; Gippel, 1995). Figure 2 illustrates that the SSC–turbidity relationship for the Skaftá at Ása-Eldvatn (1997–98) is strong, though curvilinear:

$$SSC_{cet} = 3{\cdot}4465\ Tu - 1{\cdot}4794\ Tu^2 + 0{\cdot}2866\ Tu^3 - 0{\cdot}0161\ Tu^4 \qquad (1)$$
$$(r^2 = 0{\cdot}94;\ r = 0{\cdot}97;\ n = 230;\ p = <0{\cdot}001)$$

where Tu is turbidity meter reading (volts), and SSC_{cet} is suspended sediment concentration values (g l^{-1}) estimated from the channel-edge turbidity record. Equation 1 has been applied to the turbidity data to produce SSC_{cet} values for the entire summer of 1997. However, in large rivers suspended sediment may not be evenly mixed throughout the section (Horowitz *et al.*, 1990; Wass and Leeks, 1999; Wass *et al.*, 1997). Therefore, it was desirable to determine estimated cross-sectional $ESSC_{xs}$ values by calibrating channel-edge SSC_{cet} values against the few measured cross-sectional SSC_{xs} values (g l^{-1}) from Orkustofnun, thus (Figure 3):

$$ESSC_{xs} = 0{\cdot}8383(SSC_{cet}) + 1{\cdot}1445 \qquad (2)$$
$$(r^2 = 0{\cdot}89;\ n = 9;\ p < 0{\cdot}001)$$

Equation 2 (solid line in Figure 3) is convergent with the 1:1 line at high SSCs (Figure 3); this tentatively suggests that, at the times of higher discharges and turbulence, channel-edge suspended sediment concentrations are reasonably representative of mean cross-sectional values. However, there is a tendency at low SSC levels for SSC_{cet} values to underestimate SSC_{xs}, sometimes by 50 per cent (Figures 3 and 4B). In this paper, we recognize the uncertainties and present both SSC_{cet} and $ESSC_{xs}$ values, the latter in parentheses.

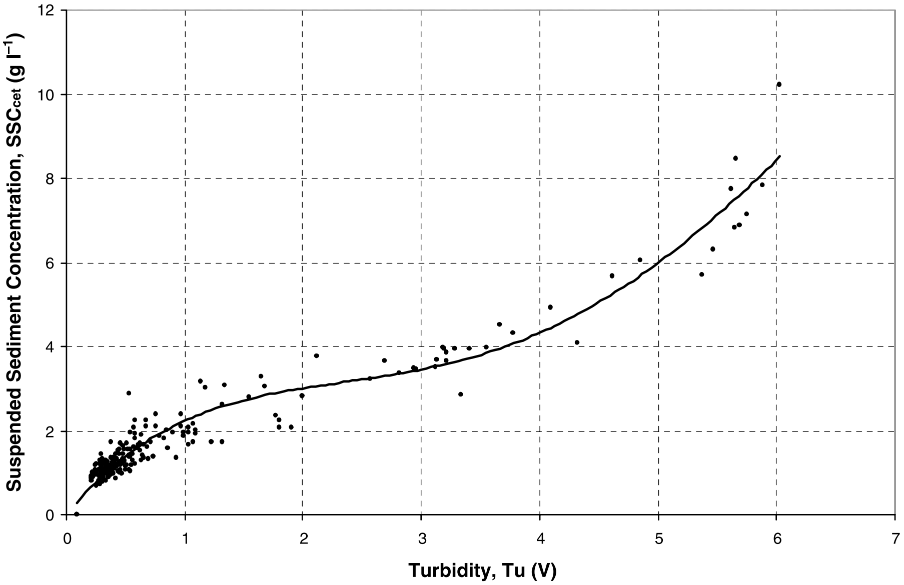

Figure 2. Relationship between turbidity and sampled channel-edge SSC_{cet} at Ása-Eldvatn during summers 1997 and 1998. The fourth-order polynomial that best fits the relationship is forced through the origin.

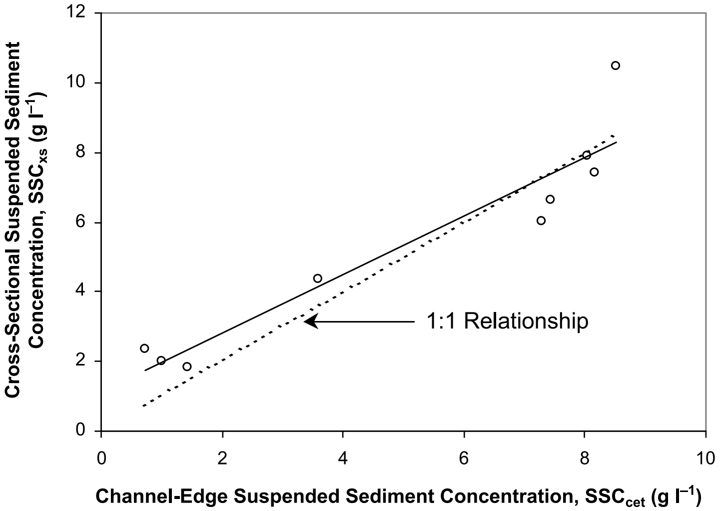

Figure 3. Relationship between sampled cross-sectional SSC_{xs} ($n = 9$) and SSC derived from the channel-edge calibration of the turbidity record SSC_{cet} at Ása-Eldvatn (1997 to 1998). Equation of the solid line is: $ESSC_{xs} = 0{\cdot}8383(SSC_{cet}) + 1{\cdot}1445$ where $ESSC_{xs}$ is estimated cross-sectional SSC_{xs}; $r^2 = 0{\cdot}89$, $n = 9$ and $p < 0{\cdot}001$.

Hydrochemistry

At Ása-Eldvatn, continuous monitoring of electrical conductivity (EC) was undertaken to help identify pulses of solute-rich water associated with subglacial geothermal/volcanic activity, as Lawler *et al.* (1996) found for the Jökulsá á Sólheimasandi system in southern Iceland (see also Elefsen *et al.*, 2002; Kristmannsdóttir *et al.*, 1999; Tómasson *et al.*, 1980). EC was monitored with a cell fixed on the left bank and connected to a Walden Precision Apparatus CM35 conductivity meter. Water temperature was monitored with a thermistor at the same point, to allow temperature compensation of EC values. EC data here were adjusted to 0 °C using Smart's (1992) modification of the Calles and Calles (1990) formula, to facilitate comparison with other glacial meltwater quality studies.

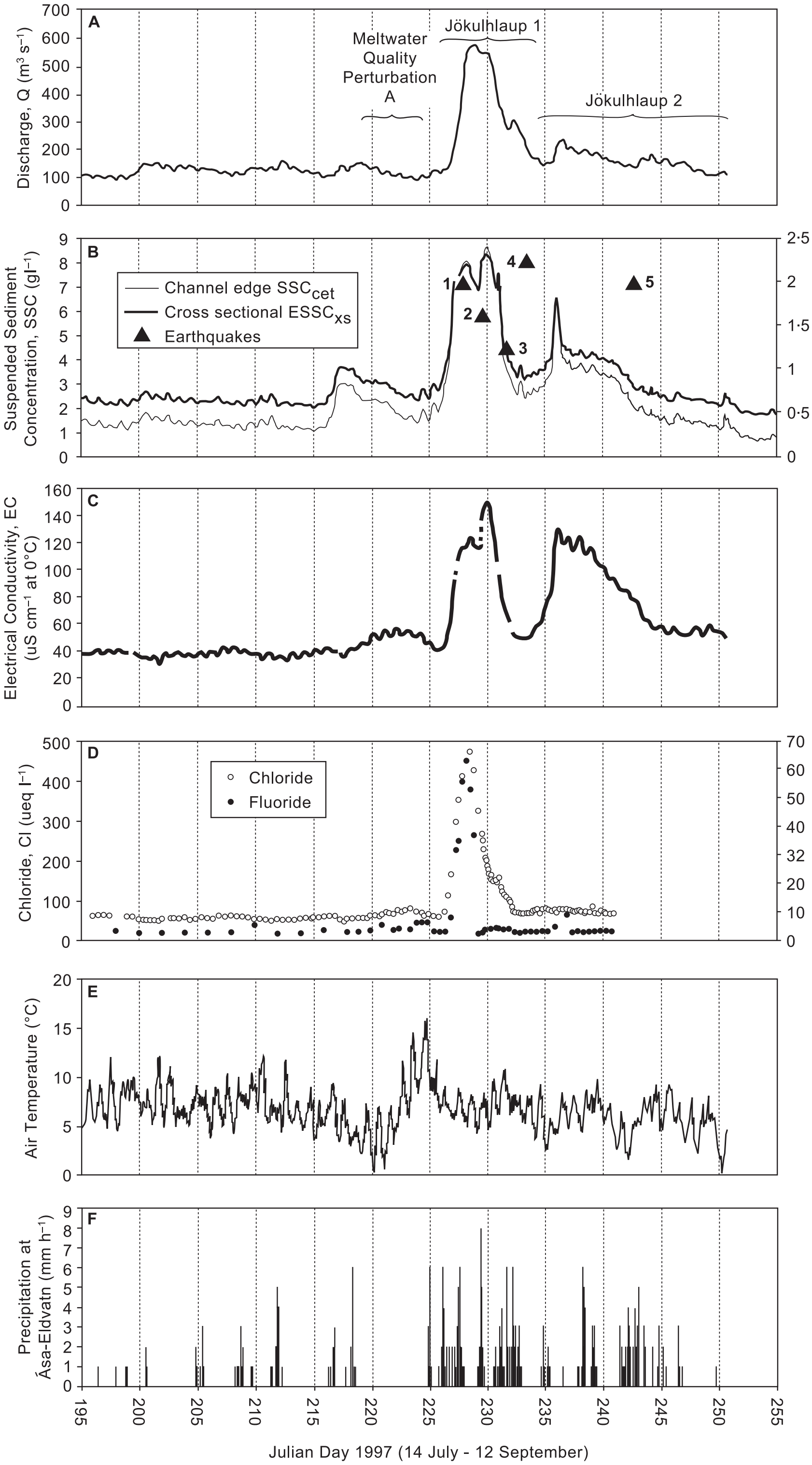

Figure 4. Time series data for the Skaftá river during the 1997 monitoring period (14 July 1997 to 8 September 1997; JD 195 to 251) at Ása-Eldvatn. (A) Discharge; (B) SSC and earthquakes; (C) electrical conductivity; (D) chloride and fluoride concentrations (E) air temperature; (F) precipitation. Julian Days are presented as decimal Julian Days (e.g. 12·00 hours on January 1st is represented as Julian Day 0·5).

Detailed hydrochemical analyses were conducted on 246 samples (the duplicate AWS sample) covering the summer 1997 period, but sampling intensified during significant events. Only data on chloride and fluoride concentrations (246 and 56 samples respectively) are presented here, however, because they are likely to reflect magma–water interaction, signifying upstream volcanic disturbance. HCl and HF gases often degas from magma (Sigurdsson *et al.*, 1985) and may condense into overlying meteoric water (Ármannsson *et al.*, 1989; Nicholson, 1993). The duplicate samples were filtered through 0·45 μm cellulose nitrate filter circles to minimize post-sampling sediment dissolution (Brown *et al.*, 1994) and stored untreated in plastic bottles according to guidelines on water quality analysis (e.g. American Public Health Association, 1992). Chloride was analysed at Orkustofnun in Reykjavik using a Dionex 2010I; fluoride was determined at Keele University using a Dionex DX500. Precision of chloride analyses was high as the concentrations were well above the detection limit of *c.* 0·7 μeq l^{-1}. Over 90 per cent of chloride analyses had replicate measurements that differed by less than 2 per cent of their mean. However, the precision of fluoride analyses was low, because the concentrations were close to the detection limit of *c.* 1·5 μeq l^{-1}.

Earthquake activity

The locations, depths and magnitudes of local earthquakes were recorded by the South Iceland Lowlands (SIL) digital seismic station network (Geophysical Department, Icelandic Meteorological Office (http://www.vedur.is/ja)). Locations of earthquakes are defined with a horizontal accuracy of ± 3 km, while depths are known to, at best, ± 1 km (Bransdóttir, 1984; M. Roberts, 2003, pers. comm.). Earthquake magnitudes are recorded as a local magnitude index, M_L. However, not all earthquakes in this region are recorded.

Results

Jökulhlaup characteristics

Figure 4 shows the meteorological, hydrological, water quality and earthquake time series for the 1997 summer monitoring period at Ása-Eldvatn on the Skaftá. The 1997 summer was generally cool and wet in the Skaftá basin, with significantly more rainfall in the second half, after JD 225 (Figure 4E and F). The first and last parts of the summer were characterized by classic diurnal discharge fluctuations characteristic of glacial rivers (e.g. Collins, 1979; Lawler *et al.*, 1992), even though the Ása-Eldvatn monitoring station is ≥76 km downstream of the glaciers (Figure 1). These cycles are driven largely by diurnal variations in melt energy (indexed here simply by air temperature in Figure 4E). Discharge cycles lag behind air temperature variations owing to the travel time of river flow from the glacier to the monitoring station. Broadly in phase with these discharge variations are similarly small daily fluctuations in suspended sediment concentration (amplitude *c.* 100–300 mg l^{-1}; Figure 4B). Electrical conductivity, however, is generally inversely related to discharge under these early season background conditions (Figure 4C) (e.g. Collins, 1977, 1979, 1995; Gurnell *et al.*, 1994).

However, superimposed on these minor fluctuations, the discharge record in Figure 4A shows that, beginning in mid-August 1997, two jökulhlaups occurred. The first, main jökulhlaup (Jökulhlaup 1) took place between 15 and 22 August (JD 227–234), and was followed by a second, extended event with a modest peak (Jökulhlaup 2) between 22 August and 8 September (JD 234–251) (Figure 4A). From Figure 4F it can be seen that heavy rainfall occurred during Jökulhlaup 1. Details of discharge characteristics and hydrograph measures for both jökulhlaups are given in Table I.

The hydrographs of both jökulhlaups at all three monitoring station (Sveinstindur, Ása-Eldvatn and Kirkjubæjarklaustur) are presented in Figure 5. Figures 4A, 5 and Table I illustrate that at Ása-Eldvatn during Jökulhlaup 1, discharge rose rapidly from 120 $m^3 s^{-1}$ to a peak of 572 $m^3 s^{-1}$ in 53·5 hours (a rate of 8·45 $m^3 s^{-1} h^{-1}$). During Jökulhlaup 2, discharge rose rapidly from 120 $m^3 s^{-1}$ to a peak of 228 $m^3 s^{-1}$, but the whole event lasted some 17 days (Figure 4A). For both jökulhlaups, rising limbs were either quasi-linear or convex at Ása-Eldvatn and Sveinstindur (Figures 4A and 5). Hydrographs of both jökulhlaups had steeper rising limbs than recessions (Figure 4A). To index this asymmetry, we used a very simple hydrograph symmetry ratio (*HSR*):

$$HSR = T_R/T_F \tag{3}$$

where T_R is time duration of rising limb (days) and T_F is time duration of falling limb (days). *HSR* values of unity imply symmetrical hydrographs; $HSR < 1$ means steeper rising limbs; $HSR > 1$ implies gentler rising limbs. Table I demonstrates that both jökulhlaups produce *HSR* values significantly less than 1, especially the later event (Jökulhlaup 1: 0·47; Jökulhlaup 2: 0·22).

Table I. Flow characteristics of Jökulhlaups 1 (JD 227–234) and 2 (JD 234–251) at Sveinstindur, Ása-Eldvatn and Kirkjubæjarklaustur in 1997

Characteristic of Jökulhlaup Flow	Jökulhlaup 1 Sveinstindur	Jökulhlaup 1 Ása-Eldvatn	Jökulhlaup 1 Kirkjubæjar-klaustur	Jökulhlaup 2 Sveinstindur	Jökulhlaup 2 Ása-Eldvatn	Jökulhlaup 2 Kirkjubæjar-klaustur
Initial flow ($m^3 s^{-1}$)	172	120	82	172	120	82
Peak discharge ($m^3 s^{-1}$)	852	572	213	333	228	121
Time of peak discharge, GMT (decimal Julian Day)	228·459	228·72	N/A	235·697	236·59	N/A
Duration of rising limb, T_R (days)	2	2·23	N/A	1	3·13	N/A
Duration of falling limb, T_F (days)	6·25	4·75	N/A	5·83	14·05	N/A
Hydrograph symmetry ratio, *HSR* (T_R/T_F)	0·32	0·47	N/A	0·17	0·22	N/A
Total volume* (km^3)	0·290	0·228	0·091	N/A	0·229	0·156
Peak ($m^3 s^{-1}$) to total volume* (m^3) ratio, *PV*	$2·94 \times 10^{-6}$	$2·51 \times 10^{-6}$	$2·34 \times 10^{-6}$	N/A	$0·994 \times 10^{-6}$	$0·775 \times 10^{-6}$

*Total volume including baseflow and jökulhlaup water.

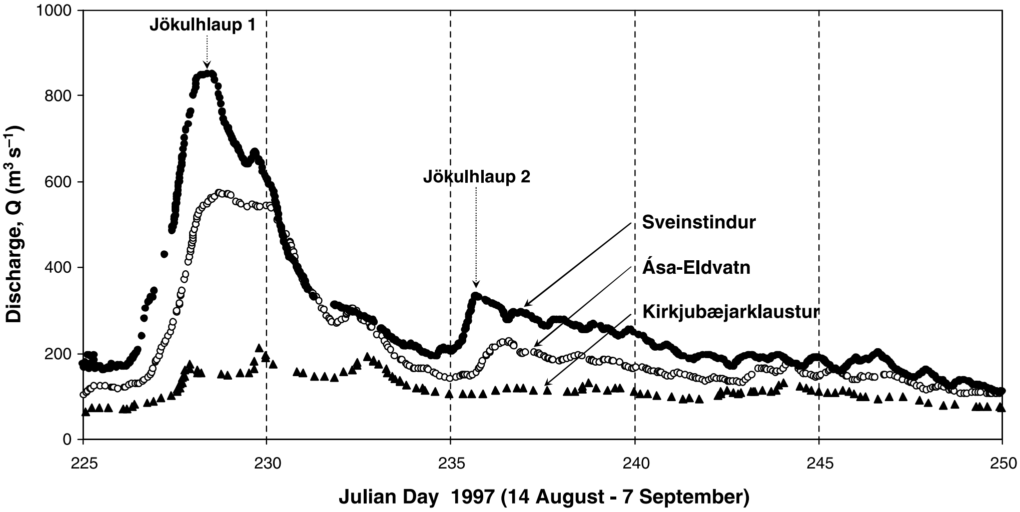

Figure 5. Downstream translation of the flood waves of Jökulhlaups 1 and 2, from Sveinstindur (upstream) to Ása-Eldvatn and Kirkjubæjarklaustur (downstream), in the Skaftá during summer 1997. Julian Days are presented as decimal Julian Days (e.g. 12·00 hours on January 1st is represented as Julian Day 0·5).

Table I also illustrates that very significant *total* volumes of water (baseflow and jökulhlaup water) flowed in Skaftá during Jökulhlaups 1 and 2 which, at 0·228 and 0·229 km^3 respectively, were virtually identical, despite peak discharge for the first event being more than double that of the second. Jökulhlaup flow was not separated from baseflow because the high coincident rainfall would have introduced large uncertainties.

A simple peak-to-volume ratio (*PV*) for each hydrograph was calculated (Equation 4) to further facilitate comparisons of jökulhlaups between sites:

$$PV = P/V \tag{4}$$

where P is peak jökulhlaup discharge ($m^3 s^{-1}$) and V is total volume (m^3). *PV* for Jökulhlaup 1 was 2·5 times that of Jökulhlaup 2 (Table I) at Ása-Eldvatn. Baseflow is included in this calculation.

Table II. Suspended sediment transport characteristics of Jökulhlaups 1 (JD 227–234) and 2 (JD 234–251) at Ása-Eldvatn in 1997 (values based on estimated cross-sectional suspended sediment concentration data ($ESSC_{xs}$) in parentheses)

Characteristic of jökulhlaup suspended sediment transport	Jökulhlaup 1	Jökulhlaup 2
Non-jökulhlaup SSC (g l^{-1})	1·53 (2·42)	1·53 (2·42)
Peak SSC (g l^{-1})	8·54 (8·31)	6·38 (6·49)
Non-jökulhlaup SST (JD194·78 to 219·23) (kg s^{-1})	190 (301)	190 (301)
Peak SST (kg s^{-1})	4650 (4530)	1270 (1300)
Total SST* (Mt)	1·48 (1·51)	0·61 (0·77)

*Total SST includes baseflow contribution.

Downstream translation of hydrographs

The downstream translations of the hydrographs of both jökulhlaups at Sveinstindur, Ása-Eldvatn and Kirkjubæjarklaustur are shown in Figure 5. The peak discharges of Jökulhlaups 1 and 2 occurred *c.* 6 h and *c.* 21·5 h, respectively, later at Ása-Eldvatn than at Sveinstindur. It was not possible to accurately calculate the celerity of the flood wave as the downstream hydrographs were significantly modified by heavy rainfall. However, during summer 1997 minimum daily discharge occurred at a mean time of 14:27 hours at Sveinstindur and 22:33 hours at Ása-Eldvatn giving a travel time of *c.* 8 h (Old, 2000). Therefore, high jökulhlaup discharges would be conveyed significantly quicker with a <8 h travel time. At Ása-Eldvatn, Jökulhlaup 1 had a peak-to-volume ratio (PV; Equation 4) that was *c.* 15 per cent lower than at Sveinstindur, illustrating that the flood wave had been significantly modified during downstream translation (Table I).

Suspended sediment concentration (SSC)

SSC_{cet} at Ása-Eldvatn, determined from the calibrated turbidity record (Figures 2 and 3), increased rapidly from high non-jökulhlaup levels of 1·53 g l^{-1} ($ESSC_{xs}$ = 2·42 g l^{-1}) to very high peaks of 8·54 g l^{-1} (8·31 g l^{-1}) and 6·38 g l^{-1} (6·49 g l^{-1}) for Jökulhlaups 1 and 2, respectively (Figure 4B; Table II). There was a significant downstream decrease in SSC: the maximum sampled channel-edge depth-integrated SSC at Sveinstindur during Jökulhlaup 1 was *c.* 75 per cent higher, at 14·51 g l^{-1}, than the peak $ESSC_{xs}$ monitored at Ása-Eldvatn, *c.* 51 km downstream.

Width- and depth-integrated suspended sediment samples taken at Ása-Eldvatn by Orkustofnun revealed an increase in the proportion of fines being transported during Jökulhlaup 1, and other jökulhlaups (1964 to 1998), relative to non-jökulhlaup levels (Figure 6). During non-jökulhlaup conditions the proportion of particles in the fine silt size range (0·002–0·02 mm) is typically <40 per cent (Figure 6). However, during Jökulhlaup 1, at 21:20 hours on 18 August (JD 230), 61 per cent or more of the suspended sediment particles lay in this size range.

Suspended sediment transport

Products of 15-min instantaneous discharge and SSC data (SSC_{cet} and $ESSC_{xs}$) were used to estimate instantaneous suspended sediment transport (Equation 5):

$$SST = Q_i C_i \tag{5}$$

where SST is instantaneous suspended sediment transport (kg s^{-1}), Q_i is instantaneous water discharge ($m^3 s^{-1}$) and C_i is instantaneous SSC_{cet} or $ESSC_{xs}$ (g l^{-1}).

At Ása-Eldvatn, mean, non-jökulhlaup instantaneous suspended sediment transport (JD 194·78 to 219·23) was 190 kg s^{-1} (301 kg s^{-1}). This increased to 4650 kg s^{-1} (4530 kg s^{-1}) during Jökulhlaup 1 and 1270 kg s^{-1} (1300 kg s^{-1}) during Jökulhlaup 2 (Table II). Annual suspended sediment transport (t a^{-1}) (14 February 1997 to 14 February 1998) was tentatively estimated through the summation of instantaneous sediment transport data (Equation 5). For this, continuous records of discharge and SSC were needed. Continuous discharge data were provided by Orkustofnun. Turbidity-derived SSC data were available only from 14 July 1997 to 8 September 1997. For periods when

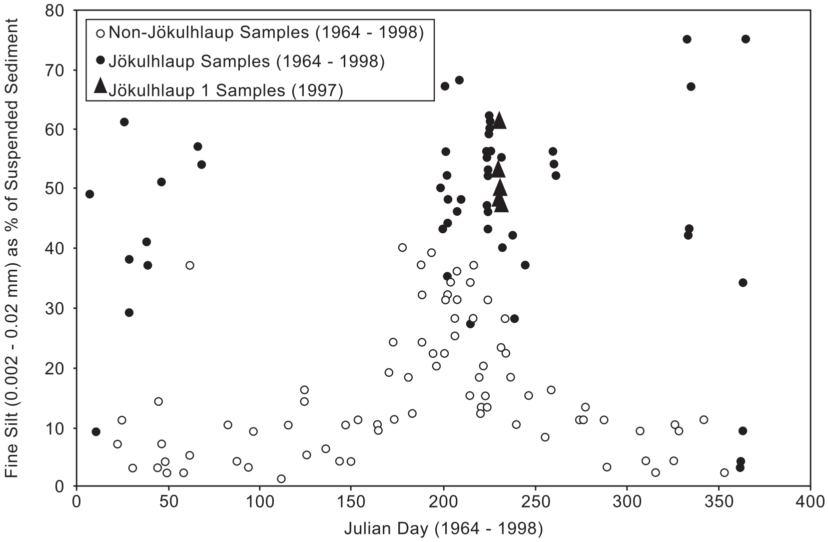

Figure 6. Particle size distribution of suspended sediment in the Skaftá at Ása-Eldvatn (1964–1998). (data source: Pálsson and Vigfússon, 1996; S. Pálsson, pers. comm.)

turbidity-derived SSC data were not available, the discharge-suspended sediment transport rating equations, defined by Pálsson *et al.* (2001) for Ása-Eldvatn, were used. Owing to the seasonal changes in the hydrological functioning of a partly glacierized catchment, summer and winter rating equations were developed. In accordance with Tómasson (1985), power functions described both relationships. The winter and summer rating relationships are described by Equations 6 and 7, respectively.

$$SST_{win} = 0{\cdot}0172Q_i^{1{\cdot}91} \quad (n = 21 \text{ and } r^2 = 0{\cdot}34) \tag{6}$$

where SST_{win} is instantaneous *winter* suspended sediment transport (kg s^{-1}) and Q_i is instantaneous water discharge ($m^3 s^{-1}$).

$$SST_{sum} = 3{\cdot}04Q_i^{0{\cdot}86} \quad (n = 16 \text{ and } r^2 = 0{\cdot}48) \tag{7}$$

where SST_{sum} is instantaneous *summer* suspended sediment transport (kg s^{-1}) and Q_i is instantaneous water discharge ($m^3 s^{-1}$).

The total suspended sediment transport (SST) for the year (14 February 1997 to 14 February 1998) was estimated as 3·8 Mt (4·3 Mt). During the jökulhlaups, the combination of high SSC and high discharge resulted in very high total SST rates (jökulhlaup plus baseflow sediment transport). Estimated total SST of Jökulhlaup 1 was 1·48 Mt (1·51 Mt) and the estimated total SST for Jökulhlaup 2 was 0·61 Mt (0·77 Mt) (Table II).

Hydrochemistry

Background EC levels fluctuated around a mean of 37 μS cm^{-1} (SD = 2·24 μS cm^{-1}) in summer 1997 at Ása-Eldvatn (Figure 4C). Prior to Jökulhlaup 1, however, there was an anomalous period of moderately high EC (EC maximum = 55 μS cm^{-1}) (Perturbation A in Figure 4). This may have been related to geothermal activity below Skaftárjökull prior to Jökulhlaup 1 (see Björnsson *et al.*, 2001). Then, during Jökulhlaups 1 and 2, EC rose to high peak values of 148 μS cm^{-1} and 128 μS cm^{-1} respectively (Figure 4C).

The background concentrations of fluoride and chloride at Ása-Eldvatn, from 17 July to 4 August (JD 198 to 216), were relatively constant (Figure 4D) with mean values of *c.* 3 μeq l^{-1} and 59 μeq l^{-1}, respectively. During Jökulhlaup 1, both fluoride and chloride rose to maxima of 63 μeq l^{-1} and 471 μeq l^{-1}, respectively (Figure 4D). During Jökulhlaup 2, however, only a small peak in fluoride (to 11 μeq l^{-1}) was observed (Figure 4D).

Table III. Magnitudes and depths of earthquakes (1–5) that occurred within a 10 km radius of the eastern and western Skaftá ice cauldrons (Figure 1) during August 1997

Earthquake	Julian Day	Day Date	Time (GMT)	Lat. (°N)	Long. (°W)	Depth (km)	Magnitude (M_L)
1	228	16	21:06	64·49	17·55	0·066	1·97
2	230	18	16:20	64·54	17·70	0·065	1·62
3	232	20	18:38	64·54	17·72	0·144	1·23
4	234	22	10:18	64·50	17·80	1·589	2·24
5	243	31	14:57	64·54	17·55	20·601	1·98
Mean magnitude*							2·04 (SD = 0·69)
Mean depth*						2·80 (SD = 4·12)	

*Mean depths and magnitudes of earthquakes in the locality of the Skaftá cauldrons (64·4 to 64·6° N and 17·4 to 17·9° W) from 1991 to 2000 (*n* = 461).

Earthquake data courtesy of the Geophysical Department, Icelandic Meteorological Office (see http://www.vedur.is/ja)

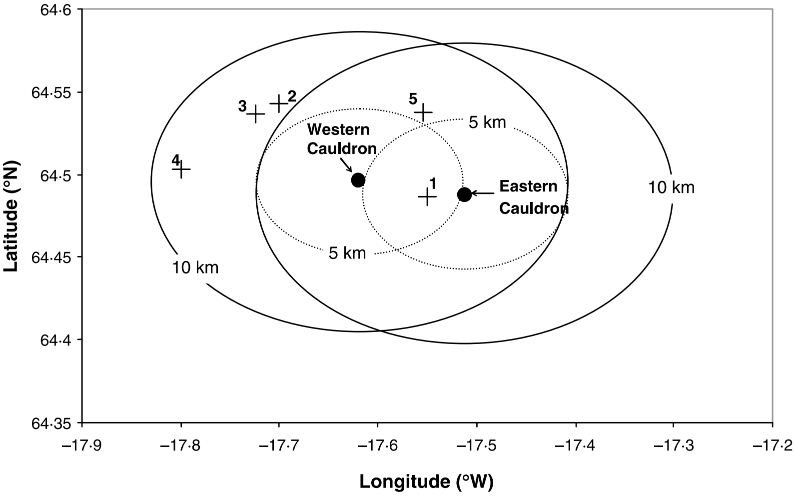

Figure 7. Locations of earthquakes within a 10 km radius of the eastern and western ice cauldrons, on the surface of Skaftárjökull, during the summer of 1997. Earthquakes are numbered 1 to 5. (for details of events see Table II) (data source: Geophysical Department, Icelandic Meteorological Office: http://www.vedur.is/ja)

Earthquakes

Five earthquakes were recorded within a 10 km radius of the Skaftá ice cauldrons (Figure 1) in summer 1997, and they are plotted on Figure 4B. Details of their locations, magnitudes and depths are presented in Table III and Figure 7. Magnitudes ranged from 1·2 to 2·2 M_L, while depths ranged from <1 km to *c.* 20 km. Mean magnitudes and depths (1991–2000) are presented in Table III to provide a context for the 1997 events.

Discussion

Origin of jökulhlaups and discharge dynamics

Jökulhlaups in the Skaftá are believed to be the result of the sudden drainage of water cupolas (dome-shaped subglacial water reservoirs) produced over a period of months in response to subglacial geothermal activity (Björnsson, 1977, 1988). Evidence supporting the existence of subglacial water cupolas is presented in Björnsson (1977) and Old

(2000). In particular, the significant weathering contribution of solutes to both 1997 jökulhlaups (see Old, (2000) and Figure 4C) suggests that subglacial water and sediment had been in contact for some time in a subglacial cupola rather than meltwater being generated instantaneously. In addition, during August 1997, M. Guðmundsson (pers. comm.) flew over Vatnajökull several times and observed subsidence of the ice cauldrons associated with both jökulhlaups. Björnsson *et al.* (2001) also report subsidence of both cauldrons in 1997 during the jökulhlaups. Both 1997 jökulhlaups exited the Vatnajökull ice cap from Tungnaárjökull glacier (S. Zóphóníasson, 2003, pers. comm.).

Jökulhlaup hydrographs often have a gentle rising limb and a steep recession limb (e.g. Björnsson, 1992; Clarke and Mathews, 1981; Rist, 1981; Russell, 1989; Thorarinsson, 1939). Björnsson (1992) successfully modelled the increasing discharge of jökulhlaups from Grímsvötn with this hydrograph shape, using Clarke's (1982) modification of Nye's (1976) hydraulic–thermodynamic model of jökulhlaup discharge. The gentle rising limb is usually produced by the *gradual* enlargement of drainage tunnels in the glacier by ice-melt as the flood progresses. Following the flood peak, discharge normally decreases *rapidly* as the water supply diminishes or cryostatic pressure closes the drainage tunnels. However, during both 1997 Skaftá jökulhlaups at Sveinstindur, discharge rose rapidly in 2 days to peaks of 572 $m^3 s^{-1}$ and 228 $m^3 s^{-1}$ before receding at a slower rate (Figure 5). Hydrograph symmetry ratio (*HSR*) was <1 for both events (Table I). This is the typical form of a jökulhlaup hydrograph in Skaftá (Rist, 1976; 1981; Zóphóníasson and Pálsson, 1996). Both hydrographs are consistent with Bjornsson's (2002) description of the form of Skaftá jökulhlaups originating from the eastern cauldron. Björnsson (1992) and Jóhannesson (2002a,b) state that the increasing discharges of these Skaftá hydrographs are difficult to explain by the classical theory of jökulhlaups (Nye, 1976; Clarke, 1982) draining through a cylindrical ice tunnel. Björnsson (2002) suggests that crevasses observed on the glacier surface after jökulhlaups, across the ice dam of the eastern cauldron, suggests that flotation of the glacier occurred during drainage. In combination with the slow recession of the jökulhlaups, this suggests that the flood waters spread out below the glacier in a sheet flood before collecting at the glacier outlet (Björnsson *et al.*, 2001; Björnsson, 2002). However, as the monitoring stations in this study are located some distance downstream of the glacier portal, the slow recession of the jökulhlaup discharge may also reflect subaerial overbank flood water and groundwater re-entering the river channel. Jóhannesson (2002a,b) proposed that the propagation of a subglacial water pressure wave may account for the rapid increase in jökulhlaup discharge. In this theory a subglacial pressure wave would travel to the terminus and form a subglacial pathway along the bed of the glacier. The formation of a subglacial pathway in response to a pressure wave would be significantly quicker than by ice-melt as assumed in traditional theories. Subglacial water pressure and ice surface topographic data, collected during jökulhlaups, may in future help to elucidate the subglacial drainage mechanism.

The flood wave of Jökulhlaup 1 was modified through the fluvial part of the system. It was attenuated as it travelled from Sveinstindur to Ása-Eldvatn and Kirkjubæjarklaustur (Figure 5), though attenuation was masked to a certain extent by heavy rainfall. The PV ratio of Jökulhlaup 1 decreased by *c.* 15 per cent as it travelled from Sveinstindur to Ása-Eldvatn (Table I). Furthermore, it is likely that the jökulhlaup was attenuated upstream of Sveinstindur. Significant attenuation of jökulhlaups has also been reported by Desloges *et al.* (1989) and Hewitt (1982). Knowledge of downstream changes in the hydraulic characteristics of jökulhlaups is important when assessing flood risks to downstream communities and the potential for flood warnings from an upstream detection system.

Suspended sediment concentration (SSC) dynamics during the jökulhlaups

Figure 8A illustrates that a positive relationship exists between the non-jökulhlaup SSC_{cet} and discharge at Ása-Eldvatn for the summers of 1997 and 1998. As found by many other researchers (e.g. Collins 1979; Clifford *et al.*, 1995; Hasnain, 1996), a power function closely describes the relationship. In this case it is:

$$SSC_{cet} = 0{\cdot}0735 Q_i^{0{\cdot}5887} \quad (n = 5738;\ r^2 = 0{\cdot}57;\ p < 0{\cdot}001) \tag{8}$$

Some scatter about the regression line is produced by hysteresis in the relationship between SSC_{cet} and discharge, as has been observed in many other glacial rivers (e.g. Collins, 1979; Lawler, 1991; Richards, 1984). Jökulhlaups 1 and 2 represent significant departures from this relationship (Figure 8A). During jökulhlaup events 1 and 2, SSC rose rapidly from a background (non-jökulhlaup) value of 1·53 $g\ l^{-1}$ (2·42 $g\ l^{-1}$) to peaks of 8·54 $g\ l^{-1}$ (8·31 $g\ l^{-1}$) and 6·38 $g\ l^{-1}$ (6·49 $g\ l^{-1}$), respectively (Figure 4B). These are high SSC values when compared to many other proglacial rivers (e.g. Collins 1979; Gurnell, 1987; Lawler, 1991), and confirm access to large amounts of fine sediment. However, these SSC values are lower than can be observed in other Icelandic rivers (Lawler *et al.*, 1992). Sediment is likely to have been accessed through the melting of debris-laden basal ice and water flow over the glacier bed (Collins, 1979).

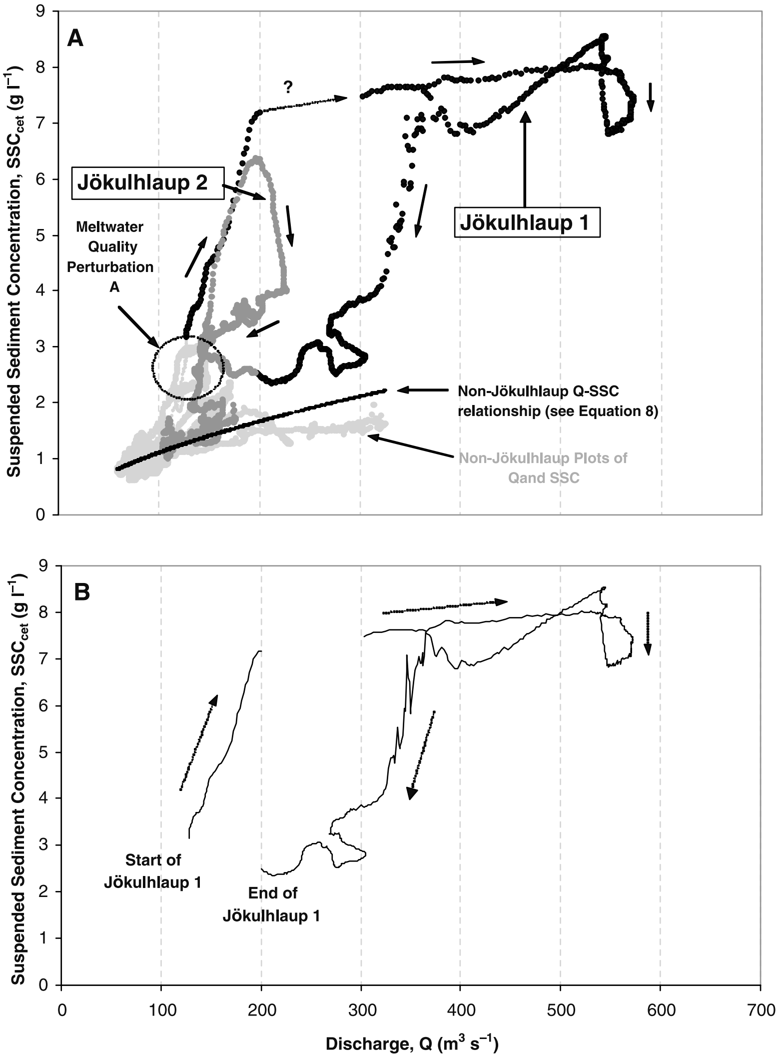

Figure 8. Relationship between discharge (*Q*) and channel-edge SCC(SSC_{cet}) at Ása-Eldvatn (1997–1998). (A) Departure of Jökulhlaup 1 and 2 from the non-jökulhlaup SSC–*Q* relationship. (B) Disturbed clockwise hysteretic loop in the SSC–*Q* relationship during Jökulhlaup 1.

During Jökulhlaup 1, SSC reached a double peak (Figures 4B and 9) resulting in a convoluted clockwise hysteretic loop in the relationship between discharge and SSC (Figure 8B). Figure 9 illustrates clearly that the first SSC peak occurred during the rising stage when draining water would have had access to largely untapped sources of fine sediment. However, the heavy rainfall that coincided with the rising stage of Jökulhlaup 1 may have also contributed to this first sediment peak through wash-off of proglacial sediment sources.

The second peak in suspended sediment concentration, on JD 230 (Figure 9), closely corresponds, to within 2 h, with peaks in EC and surrogate solute flux (Table IV and Figure 9), suggesting that it may have been generated by the maximum discharge from the subglacial reservoir. Surrogate solute flux was estimated by multiplying electrical conductivity (μS cm^{-1}) by discharge (m^3 s^{-1}).

It is likely that subglacial volcanic activity and/or boiling in the geothermal system contributed sediment to Jökulhlaup 1. Peaks in chloride and fluoride were observed early in Jökulhlaup 1 that broadly coincided with the first peak in SSC. Both these anions may be derived from the volcanic gases HCl and HF (e.g. Ármannsson *et al.*, 1989; Nicholson, 1993; Sigurdsson *et al.*, 1985). Furthermore, an earthquake also occurred below or close to the eastern cauldron (<2 km) from where Jökulhlaup 1 is believed to have originated (Table III and Figure 7). This event occurred prior to

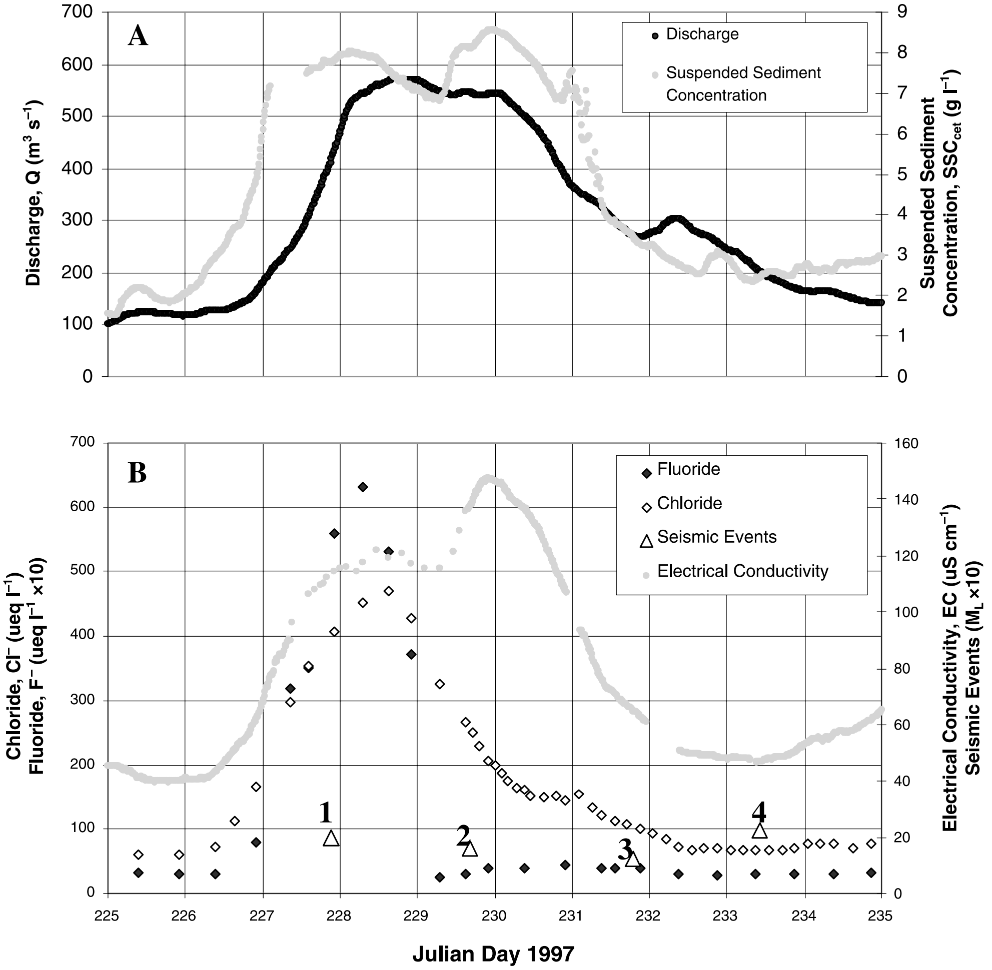

Figure 9. Dynamics of (A) discharge (*Q*) and channel-edge SSC (SSC_{cet}), and (B) electrical conductivity (EC), fluoride, chloride and earthquakes during Jökulhlaup 1 at Ása-Eldvatn (1997). Julian Days are presented as decimal Julian Days (e.g. 12·00 hours on January 1st is represented as Julian Day 0·5).

Table IV. Times of peaks in suspended sediment, chloride, fluoride, electrical conductivity and surrogate solute flux during Jökulhlaup 1 (1997) at Ása-Eldvatn. Lags behind Earthquake 1 are also given

Peak	Unit	Time of 1st peak during Jökulhlaup 1 (JD)	Time of 2nd peak during Jökulhlaup 1 (JD)	Lag of 1st peak after Earthquake 1 (h)
SSC	g l^{-1}	228·140	229·969	6·2
SST	kg s^{-1}	228·464	230·005	14·0
Chloride concentration	μeq l^{-1}	228·628	N/A	18·0
Chloride flux	μeq s^{-1}	228·628	N/A	18·0
Fluoride concentration	μeq l^{-1}	228·292	N/A	9·9
Fluoride flux	μeq s^{-1}	228·292	N/A	9·9
Electrical conductivity	μS cm^{-1}	–	229·922	–
Surrogate solute flux (EC × discharge)	N/A	–	229·974	–

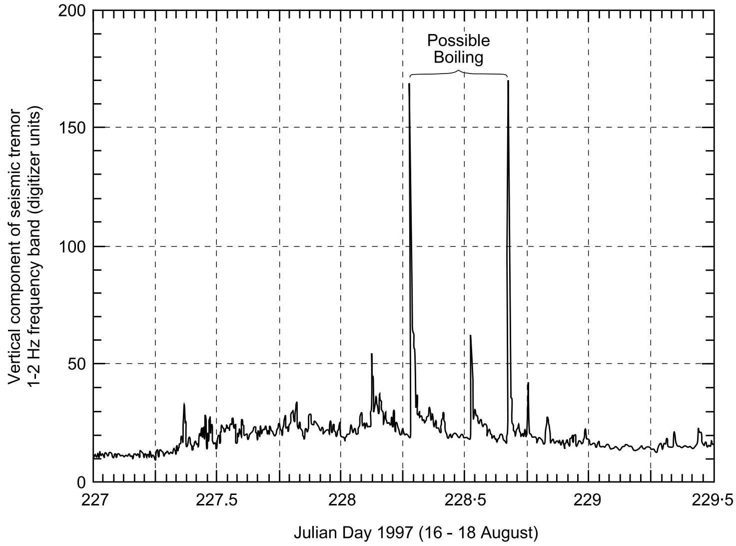

Figure 10. Seismic tremor recorded during Jökulhlaup 1 at the Strokkalda SIL station (*c.* 45 km southwest of the eastern subglacial cauldron: origin of Jökulhlaup 1) (modified from Kjartansson, 1997. Data source: Geophysical Department, Icelandic Meteorological Office: http://www.vedur.is/ja). Julian Days are presented as decimal Julian Days (e.g. 12·00 hours on January 1st is represented as Julian Day 0·5).

observed peaks in suspended sediment, chloride and fluoride in river water at Ása-Eldvatn (Figure 9 and Table IV). Linkages between these observations and further understanding of the timing of degassing of chlorine and fluorine during volcanic activity and transit times of flood waters from the cauldrons to the monitoring site at Ása-Eldvatn are currently being explored and results will be published. Tómasson (1974) also suggested that a peak in SSC during the 1972 jökulhlaup from Grímsvötn may have been produced by a volcanic disturbance.

Kjartansson (1997) suggests that the seismic tremor bursts, detected by most seismometers during the latter part of Jökulhlaup 1 (e.g. Figure 10), were probably caused by boiling within the geothermal system which is likely to have resulted from the sudden drop in pressure as water drained from the cauldron. If boiling occurred then rising steam may have disturbed sediments at the bottom of the subglacial reservoir and contributed to the second peak in suspended sediment. However, Þorbjarnardóttir *et al.* (1997) have interpreted seismic tremor during jökulhlaups in Skaftá to indicate volcanic activity below the cauldrons.

Particle size of suspended sediment transported during both jökulhlaups

Particle size distributions of jökulhlaup suspended sediment samples are finer than non-jökulhlaup samples. The percentage of fines (0·002–0·02 mm) was higher during Jökulhlaup 1, and during other jökulhlaups (1964 to 1998), than under non-jökulhlaup flow conditions (Figure 6). This is probably related to increased contact between flood waters and fresh supplies of fine sediment over wide areas of the glacier bed during jökulhlaups. It may also indicate that the subglacial reservoir itself is a source of fine sediment, generated by vigorous weathering conditions and the accumulation of volcanic ash. It is possible that, during boiling, steam (provided it can be produced subglacially) rising from the geothermal system below disturbs sediment lying on the reservoir bed and results in the preferential mobilization of fine particles.

Suspended sediment transport (SST) through the fluvial part of the system during jökulhlaups

SSC dynamics also reflect processes occurring within the fluvial part of the system. During Jökulhlaup 1, maximum sampled channel-edge SSC at Sveinstindur was *c.* 75 per cent higher than the peak $ESSC_{xs}$ at Ása-Eldvatn downstream. There are two factors that are likely to explain this. First, the sediment-rich flood wave was attenuated and diluted by rainfall as it travelled downstream. Secondly, significant sediment deposition may have occurred along the river course; this is supported by the observations of extensive deposits of sediment on the river banks and on the floodplain once the flood had receded (see also Jónsson, 1982; Tómasson, 1974, 1996).

Table V. Significance of Jökulhlaup 1 and 2 for longer term water and sediment discharge at Ása-Eldvatn, south Iceland. Values in parentheses include cross-sectional adjustment of monitored SSC_{cet}

Period	Time		Water discharge (km^3)	Suspended sediment transport (Mt)	Water discharge (% of year)	Suspended sediment transport (% of year)
	Days	% of year				
Year (14/02/97 to 14/02/98)	365	100	2·44	3·8 (4·3)	100	100
Jökulhlaup 1 (15/08/97 to 22/08/97)	7·0	1·9	0·228	1·48 (1·51)	9·4	38·9 (35·1)
Jökulhlaup 2 (22/08/97 to 08/09/97)	17·2	4·7	0·229	0·61 (0·77)	9·4	16·1 (17·9)
Jökulhlaup 1 and 2 (22/08/97 to 08/09/97)	24·2	6·6	0·457	2·09 (2·28)	18·8	55·0 (53·0)

Jökulhlaup flow and sediment transport includes the baseflow contribution.

Significance of jökulhlaups in Skaftá for longer-term flow and suspended sediment transport (SST)

Discharge. At Ása-Eldvatn, the peak discharge of Jökulhlaup 1 was approximately double the maximum discharge recorded in the river during the year (14 February 1997 to 14 February 1998), which illustrates the often exceptional magnitude of jökulhlaup discharges (Figure 4A). Both jökulhlaups also resulted in large volumes of water being delivered from the basin (Table V). Jökulhlaup 1 transported 9·4 per cent (0·228 km^3) of the annual runoff (14 February 1997 to 14 February 1998) in 1·9 per cent (7 days) of the time. In combination, both jökulhlaups transported *c.* 18·8 per cent of the annual runoff (14 February 1997 to 14 February 1998) in 6·6 per cent (24·2 days) of the time. These figures are broadly in line with the observations of Maizels (1997) that jökulhlaups may contribute 10–15 per cent of the annual meltwater runoff in glacierized basins. Peak discharges and volumes of both 1997 jökulhlaups were below average but within the range of past events (Zóphóníasson and Pálsson, 1996).

Suspended sediment transport (SST). Both jökulhlaups monitored in this study resulted in high SST at Ása-Eldvatn (Table V). Jökulhlaup 1 transported 1·48 Mt (1·51 Mt) of suspended sediment while Jökulhlaup 2 transported 0·61 Mt (0·77 Mt) of suspended sediment. The combined total SST of both events was 2·09 Mt (2·28 Mt). The total SST for the year (14 Febraury 1997 to 14 February 1998) was estimated as 3·8 Mt (4·3 Mt). The two jökulhlaups in 1997 therefore transported 55 per cent (53 per cent) of the annual SST in 6·6 per cent of the time (24·2 days). In addition, the two 1997 jökulhlaups transported more suspended sediment than that estimated to have been transported at Ása-Eldvatn in either of the complete years of 1998 and 1999 (Pálsson *et al.*, 2001). These observations clearly illustrate the importance of low-frequency (approximately annual), high-magnitude extreme events for SST in this basin. This is in accordance with the magnitude–frequency theory of Wolman and Miller (1960) which states that most geomorphic work is done by relatively low-frequency events. Furthermore, it is clear that the jökulhlaups accounted for a greater proportion of the annual sediment transport than the annual water discharge. If bedload transport were included in these calculations, then it is probable that the events would have emerged as even more significant in sediment evacuation from the Skaftá basin. Although these suspended sediment yields are high, significantly higher yields have been recorded during jökulhlaups in other glacierized basins (Tómasson *et al.*, 1980). Beecroft (1983), Church (1972) and Gurnell (1987) have all found jökulhlaups to be significant contributors to the annual sediment yield of glacierized basins. Church (1972) estimated that jökulhlaups transported up to 90 per cent of the total annual suspended sediment transport from a Baffin Island catchment, whereas two events transported *c.* 50 per cent of the 3-month 1981 ablation season sediment yield of an alpine catchment (Beecroft, 1983; Gurnell, 1987).

Representativeness of fixed-point channel-edge calibrated turbidity data

Although in small upland river systems SSC may be relatively homogeneous throughout the cross-section (e.g. Bathurst *et al.*, 1985), in larger and less turbulent rivers SSC may be poorly mixed. In this study, a limited number ($n = 9$) of cross-sectional SSC measurements indicated that channel-edge SSC underestimated cross-sectional SSC by 36·8 per cent when discharge and SSC were low (124 m^3 s^{-1} and 2·42 g l^{-1}, respectively). This is probably because of limited turbulence and poor lateral and vertical suspended sediment mixing. However, during high discharge and SSC conditions (544 m^3 s^{-1} and 8·31 g l^{-1}, respectively), channel-edge SSC is broadly comparable (only 2·8 per cent higher) to cross-sectional SSC (Figures 3 and 4B). This may also relate to the fixed position of the turbidity sensor and AWS intake being proportionally closer to the channel bed during high discharge conditions, where turbulence and sediment concentrations are higher.

These observations are important because they suggest that fixed-point channel-edge SSC monitoring of large rivers may significantly underestimate SST during low flow conditions but be broadly comparable with peak jökulhlaup SST. Channel-edge SSC monitoring underestimated the total SST of Jökulhlaups 1 and 2 by 2 per cent and 21 per cent, respectively. Similarly, the estimated annual cross-sectional suspended sediment flux (14 February 1997 to 14 February 1998) was underestimated by *c.* 12 per cent when SSC_{cet} was included for 14 July 1997 to 8 September 1997.

Conclusions

The adoption of an integrated approach involving direct seismological, meteorological, hydrological, sedimentological and hydrochemical monitoring, much of the data from two sites, permitted the identification of the nature and dynamics of two jökulhlaup events in a large, subarctic glacierized basin and some initial exploration of their controls. Both jökulhlaups are likely to have originated from the water cupolas below ice cauldrons visible on the surface of Vatnajökull.

The hydrographs of both 1997 jökulhlaups are consistent with those previously observed in Skaftá, which are characterized by steep rising limbs and gentle recessions. At Ása-Eldvatn discharge and SSC rose extremely quickly during both jökulhlaups (Figure 4A and B). Discharge rose to peaks of 572 $m^3 s^{-1}$ and 228 $m^3 s^{-1}$ during the period of Jökulhlaups 1 and 2, respectively. Likewise, SSC rose to peaks of 8·54 g l^{-1} (8·31 g l^{-1}), and 6·38 g l^{-1} (6·49 g l^{-1}), during the period of Jökulhlaups 1 and 2, respectively. These events resulted in 18·8 per cent of the annual water discharge and 53 per cent of the annual fine sediment transport occurring in just 6·6 per cent of the year. This suggests that along the subglacial flood tract, floodwater had access to large amounts of fine sediment. Furthermore, it illustrates the necessity of high resolution monitoring of instantaneous sediment transport for the reliable estimation of long-term sediment transport in the Skaftá. Earthquake data and floodwater hydrochemistry support the possibility that volcanic activity may be an important factor influencing SSC increases during Skaftá jökulhlaups. Seismic tremor bursts were also recorded during the latter stages of Jökulhlaup 1 and they suggest that boiling may have occurred in the subglacial geothermal reservoir in response to the drop in pressure as the flood water drained (Kjartansson, 1997). Rising steam may have mobilized and contributed fine sediment to the flood water. This is consistent with the particle size of suspended sediment being significantly smaller during jökulhlaups than during non-jökulhlaup flow conditions. Channel-edge SSC_{cet} values appeared to underestimate SSC_{xs} values, by *c.* 37 per cent, during low flow conditions, but were broadly comparable during high discharge conditions. The dynamics of discharge and water quality quantified during both 1997 Skaftá jökulhlaups are likely to contribute to a longer term understanding of jökulhlaup triggering mechanisms. A novel focus of future research will be the description and interpretation of high resolution hydrochemical data collected at Ása-Eldvatn throughout both 1997 Skaftá jökulhlaup events to provide an insight into subglacial solute acquisition, geothermal processes and volcanic activity. A useful development would also be a programme of concurrent subglacial and supraglacial, glaciological and hydrological observations during jökulhlaups to use as a basis for the testing of jökulhlaup generation, transmission, and flow and sediment transport models.

Acknowledgements

We thank the Icelandic Council of Science for granting research permits, Orkustofnun (Icelandic National Energy Authority) for the invaluable help they gave with logistics, background data and financial support, and the Icelandic Meteorological Office for seismic and meteorological data. The support given by the UK Natural Environmental Research Council (through NERC award no: GT4/96/18/F) is greatly appreciated. The use of analytical laboratories at Keele University (School of Earth Sciences and Geography) is also appreciated. Advice, guidance and review comments were very gratefully received from Professor Ian Fairchild (PhD supervisor, Keele University), Hrefna Kristmannsdóttir, Sverrir Elefsen, Snorri Zóphóníasson, Jórunn Harðardóttir, Einar Kjartansson, Svanur Pálsson (Orkustofnun) and Magnús Guðmundsson (Science Institute, University of Iceland). Constructive comments were also received from two anonymous reviewers. Kevin Burkhill and Anne Ankcorn are thanked for preparing some of the figures. G.H.O. is also very grateful for field assistance given by his sister Bethan and other volunteers.

References

American Public Health Association. 1992. *Standard Methods for the Examination of Water and Wastewater* (18th edn). American Water Works Association and Water Environment Federation, American Public Health Association: Washington.

Ármannsson H, Benjamínsson J, Jeffrey WA. 1989. Gas changes in the Krafla geothermal system, Iceland. *Chemical Geology* **76**: 175–196.

Bathurst JC, Leeks GJL, Newson MD. 1985. Field measurements for hydraulic and geomorphological studies of sediment transport – The special problems of mountain streams. *Proceedings of the International Symposium on Measuring Techniques in Hydraulic Research/IAHR Section on Hydraulics Instrumentation*, Delft, 22–24 April 1985: 137–151.

Beecroft I. 1983. Sediment transport during an outburst from Glacier de Tsidjiore Nouve, Switzerland, 16–19 June 1981. *Journal of Glaciology* **29**: 185–190.

Björnsson H. 1977. The Cause of Jökulhlaups in the Skaftá River, Vatnajökull. *Jökull* **27**: 71–77.

Björnsson H. 1988. Hydrology of ice caps in volcanic regions. *Societas Scientiarum Islandica*, Rit **45**: 1–139.

Björnsson H. 1992. Jökulhlaups in Iceland: prediction, characteristics and simulation. *Annals of Glaciology* **16**: 95–106.

Björnsson H. 2002. Subglacial lakes and jökulhlaups in Iceland. *Global and Planetary Change* **35**: 255–271.

Björnsson H, Einarsson P. 1990. Volcanoes beneath Vatnajökull, Iceland: Evidence from radio echo-sounding, earthquakes and jökulhlaups. *Jökull* **40**: 147–167.

Björnsson H, Rott H, Gudmundsson S, Fischer A, Siegel A, Gudmundsson MT. 2001. Glacier-volcano interactions deduced by SAR interferometry. *Journal of Glaciology* **47**(156): 58–70.

Boulton GS, Thors K, Jarvis J. 1988. Dispersal of glacially derived sediment over part of the continental shelf of south Iceland and the geometry of the resultant sediment bodies. *Marine Geology* **83**: 193–223.

Brandsdóttir B. 1984. Seismic Activity in Vatnajökull in 1900–1982 with Special Reference to Skeiðarárhlaups, Skaftárhlaups and Vatnajökull Eruptions. *Jökull* **34**: 141–149.

Brown GH, Sharp MJ, Tranter MJ, Gurnell AM, Nienow PW. 1994. Impact of post-mixing chemical reactions on the major ion chemistry of bulk meltwaters draining the Haut Glacier d'Arolla, Valais, Switzerland. *Hydrological Processes* **8**: 465–480.

Calles B, Calles UM. 1990. Temperature correction of electrical conductivity values. *Earth Surface Processes and Landforms* **15**: 673–678.

Church M. 1972. Baffin Island sandurs: a study of arctic fluvial processes. *Geological Society of Canada Bulletin* **216**: 1–208.

Clague JJ, Mathews WH. 1973. The magnitude of Jökulhlaups. *Journal of Glaciology* **12**: 501–504.

Clarke GKC. 1982. Glacier outburst floods from Hazard Lake, Yukon Territory, and the problem of flood magnitude prediction. *Journal of Glaciology* **28**: 3–21.

Clarke GKC, Mathews WH. 1981. Estimates of the magnitude of glacier outburst floods from Lake Donjek, Yukon Territory, Canada. *Canadian Journal of Earth Sciences* **18**: 1452–1463.

Clifford NJ, Richards KS, Brown RA, Lane SN. 1995. Scales of variation of suspended sediment concentration and turbidity in a glacial meltwater stream. *Geografiska Annaler* **77A**: 45–65.

Collins DN. 1977. Hydrology of an alpine glacier as indicated by the chemical composition of meltwater. *Zeitschrift Gletscherkunde und Glazialgeologie* **13**: 219–238.

Collins DN. 1979. Sediment concentration in melt waters as an indicator of erosion processes beneath an alpine glacier. *Journal of Glaciology* **23**: 247–257.

Collins DN. 1995. Daily patterns of discharge, solute content and solute flux in meltwaters draining from two alpine glaciers. *International Association of Hydrological Sciences Publication* **228**: 371–378.

Desloges JR, Jones DP, Ricker KE. 1989. Estimates of peak discharge from the drainage of ice-dammed Ape Lake, British Columbia, Canada. *Journal of Glaciology* **35**: 349–354.

Elefsen SÓ, Snorrason Á, Haraldsson H, Gíslason SR, Kristmannsdóttir H. 2002. Real-time monitoring of glacial rivers in Iceland. In *The Extremes of the Extremes: Extraordinary Floods, Proceedings of Reykjavik Symposium, July 2000*, Snorrason Á, Finnsdóttir HP, Moss M (eds). IAHS Publication No. 271: 199–204.

Gippel CJ. 1995. Potential of turbidity monitoring for measuring the transport of suspended solids in streams. *Hydrological Processes* **9**: 83–97.

Gurnell AM. 1987. Suspended sediment. In: *Glacio-fluvial Sediment Transfer: An Alpine Perspective*, Gurnell AM, Clark MJ (eds). Wiley: Chichester; 305–354.

Gurnell AM, Brown GH, Tranter M. 1994. Sampling strategy to describe the temporal hydrochemical characteristics of an alpine proglacial stream. *Hydrological Processes* **8**: 1–25.

Hasnain SI. 1996. Factors controlling suspended sediment transport in Himalayan glacier meltwaters. *Journal of Hydrology* **181**: 49–62.

Hewitt K. 1982. Natural dams and outburst floods of the Karakoram Himalaya. *International Association of Hydrological Sciences.* **138**: 259–269.

Horowitz AJ, Rinella FA, Lamothe P, Miller TL, Edwards TK, Roche RL, Rickert DA. 1990. Variations in suspended sediment and associated trace element concentrations in selected riverine cross sections. *Environmental Science and Technology* **24**: 1313–1320.

Jóhannesson T. 2002a. The initiation of the 1996 jökulhlaup from Lake Grímsvötn, Vatnajökull, Iceland. In *The Extremes of the Extremes: Extraordinary Floods, Proceedings of Reykjavik Symposium, July 2000*. Snorrason Á, Finnsdóttir HP, Moss M (eds). International Association of Hydrological Sciences Publication 271: 57–64.

Jóhannesson T. 2002b. Propagation of a subglacial flood wave during the initiation of a jökulhlaup. *Hydrological Sciences Journal* **47**(3): 417–434.

Jónsson J. 1982. Notes on the Katla volcanoglacial debris flows. *Jökull* **32**: 61–68.

Kjartansson E. 1997. *Monitoring of volcanic tremor in Iceland*. AGU Fall Meeting, San Francisco, California, 8–12 December.

Knudsen Ó, Russell AJ. 2002. Jökulhlaup deposits at the Ásbyrgi Canyon, northern Iceland: sedimentology and implications for flow type. In *The Extremes of the Extremes: Extraordinary Floods, Proceedings of Reykjavik Symposium, July 2000*. Snorrason Á, Finnsdóttir HP, Moss M (eds). International Association of Hydrological Sciences Publication 271: 107–112.

Kristmannsdóttir H, Björnsson A, Pálsson S, Sveinbjörnsdóttir AE. 1999. The impact of the 1996 subglacial volcanic eruption in Vatnajökull on the river Jökulsá á Fjöllum, North Iceland. *Journal of Volcanology and Geothermal Research* **92**: 359–372.

Lacasse C, Carey S, Sigurdsson H. 1998. Volcanogenic sedimentation in the Iceland Basin: influence of subaerial and subglacial eruptions. *Journal of Volcanology and Geothermal Research* **83**: 47–73.

Lawler DM. 1991. Sediment and solute yield from the Jökulsá á Sólheimasandi Glacierised River Basin, Southern Iceland. In *Environmental Change in Iceland: Past and Present*, Maizels JK, Caseldine C (eds). Kluwer Academic Publishers: Dordrecht: 303–332.

Lawler DM. 1995. Turbidimetry and nephelometry. *Encyclopedia of Analytical Science* Acaduwo Press, London vol. 9: 5289–5297.

Lawler DM. 2004. Spectrophotometry: Turbidity and Nephelometry in Worlsfold D, Townshend A, Poole C (eds). *Encyclopedia of Analytical Science* 2nd edition. Elsevier, Oxford. 343–351.

Lawler DM, Wright LJ. 1999. The impact of recent climate change on river flow and glaciofluvial suspended sediment loads in South Iceland. In *Fluvial Processes and Environmental Change*, Brown AG, Quine T (eds). John Wiley: Chichester; 385–407.

Lawler DM, Dolan M, Tómasson H, Zóphóníasson S. 1992. Temporal variability in suspended sediment flux from a sub-arctic glacial river, southern Iceland. In Bogen J, Walling DE, Day TJ (eds). *Erosion and Sediment Transport Monitoring Programmes in River Basis, Proceedings of Oslo Symposium*. International Association of Hydrological Sciences Publication 210: 233–243.

Lawler DM, Björnsson H, Dolan M. 1996. Impact of subglacial geothermal activity on meltwater quality in the Jökulsá Á Sólheimasandi system, Southern Iceland. *Hydrological Processes* **10**: 557–578.

Magilligan FJ, Gomez B, Mertes LAK, Smith LC, Smith ND, Finnegan D, Garvin JB. 2002. Geomorphic effectiveness, sandur development, and the pattern of landscape response during jökulhlaups: Skeiðarásandur, southeastern Iceland. *Geomorphology* **44**(1–2): 95–113.

Maizels J. 1989. Sedimentology, paleoflow dynamics and flood history of jökulhlaup deposits: Paleohydrology of Holocene sediment sequences in southern Iceland sandur deposits. *Journal of Sedimentary Petrology* **59**: 204–223.

Maizels J. 1997. Jökulhlaup deposits in proglacial areas. *Quaternary Science Reviews* **16**: 793–819.

Nicholson K. 1993. *Geothermal Fluids: Chemistry and Exploration Techniques*. Springer Verlag: New York.

Nye JF. 1976. Water flow in glaciers: Jökulhlaups, tunnels and veins. *Journal of Glaciology* **17**: 181–204.

O'Connor JE, Baker VR. 1992. Magnitudes and implications of peak discharges from glacial Lake Missoula. *Geological Society of America Bulletin* **104**: 267–279.

Old GH. 2000. *The impact of subglacial geothermal and volcanic activity on meltwater quality in the Skaftá river, southern Iceland*. PhD Thesis, University of Birmingham.

Pálsson S, Vigfússon GH. 1996. *Gagnasfn aurburðarmælinga 1963–1995*. Report OS-96032/VOD-05 B. Orkustofnun: Reykjavík.

Pálsson S, Vigfússon GH, Harðardóttir, J. 2001. *Framburður svifaurs í Skaftá*. Report OS-2001/068. Orkustofnun: Reykjavík.

þorbjarnardóttir BS, Bjarnason, Iþ, Einarsson P. 1997. *Seismic tremor in the Vatnajökull region in 1955–1996*. Report RH-03-97. Science Institute, University of Iceland: Reykjavík.

Richards KS. 1984. Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. *Earth Surface Processes and Landforms* **9**: 101–112.

Rist S. 1976. Jökulhlaupaannáll 1974, 1975 og 1976. *Jökull* **26**: 75–79.

Rist S. 1981. Jökulhlaupaannáll 1977, 1978, 1979 og 1980. *Jökull* **31**: 31–35.

Rist S. 1984. Jökulhlaupaannáll 1981, 1982 og 1983. *Jökull* **34**: 165–173.

Roberts MJ, Russell AJ, Tweed FS, Knudsen O. 2000. Ice fracturing during jökulhlaups: Implications for englacial floodwater routing and outlet development. *Earth Surface Processes and Landforms* **25**: 1429–1446.

Roberts MJ, Russell AJ, Tweed FS, Knudsen O. 2001. Controls on englacial sediment deposition during the November 1996 jökulhlaup, Skeiðarárjökull, Iceland. *Earth Surface Processes and Landforms* **26**: 935–952.

Russell AJ. 1989. A Comparison of two recent jökulhlaups from an ice-dammed lake, Søndre Strømfjord, West Greenland. *Journal of Glaciology* **35**: 157–162.

Russell AJ. 1993. Obstacle marks produced by flow around stranded ice blocks during a glacier outburst flood (jökulhlaup) in west Greenland. *Sedimentology* **40**: 1091–1111.

Russell AJ, Knudsen Ó. 2002. The influence of channel flood history on the impact of the November 1996 jökulhlaup, Skeiðarársandur, Iceland. In *The Extremes of the Extremes: Extraordinary Floods, Proceedings of Reykjavik Symposium, July 2000*, Snorrason Á, Finnsdóttir HP, Moss M (eds). International Association of Hydrological Sciences Publication 271: 243–247.

Russell AJ, Aitken JF, Jong DE. 1990. Observations on the drainage of an ice-dammed lake in West Greenland. *Journal of Glaciology* **36**: 72–74.

Russell AJ, Tweed FS, Knudsen Ó, Roberts MJ, Harris TD, Marren PM. 2002. Impact of the July 1999 jökulhlaup on the proximal River Jökulsá á Sólheimasandi, Mýrdalsjökull Glacier, southern Iceland. In *The Extremes of the Extremes: Extraordinary Floods, Proceedings of the Reykjavik Symposium, July 2000*, Snorrason Á, Finnsdóttir HP, Moss M (eds). International Association of Hydrological Sciences Publication 271: 249–254.

Sigurdsson H, Devine JD, Davis AN. 1985. The petrologic estimation of volcanic degassing. *Jökull* **35**: 1–8.

Smart CC. 1992. Temperature compensation of electrical conductivity in glacial meltwaters. *Journal of Glaciology* **38**: 9–12.

Steinþórsson S, Óskarsson N. 1983. Chemical Monitoring of Jökulhlaup Water in Skeiðará and the geothermal system in Grímsvötn, Iceland. *Jökull* **33**: 73–86.

Thórarinsson, S. 1939. The ice dammed lakes of Iceland with particular reference to their values as indicators of glacier oscillations. *Geografiska Annaler* **21**: 3–4, 216–242.

Tómasson H. 1974. Grímsvatnahlaup 1972, Mechanism and Sediment Discharge. *Jökull* **24**: 27–39.

Tómasson H. 1985. Glacial and volcanic shore interaction Part 1: On Land. In *Iceland Coastal and River Symposium, Reykjavik, Iceland 2–4 September 1985,* Sigbjarnason G (ed.) National Energy Authority, Reykjavik 7-16.

Tómasson H. 1996. The Jökulhlaup from Katla in 1918. A*nnals of Glaciology* **22**: 249–254.

Tómasson H, Pálsson S, Ingólfsson P. 1980. Comparison of sediment load transport in the Skeiðará Jökulhlaup in 1972 and 1976. *Jökull* **30**: 21–32.

Tweed FS, Russell AJ. 1999. Controls on the formation and sudden drainage of glacier-impounded lakes: implications for jökulhlaup characteristics. *Progress in Physical Geography* **23**: 79–110.

Wass PD, Leeks GJL. 1999. Suspended sediment fluxes in the Humber catchment, UK. *Hydrological Processes* **13**: 935–953.

Wass PD, Marks SD, Finch JW, Leeks GJL, Ingram JK. 1997. Monitoring and preliminary interpretation of in-river turbidity and remote sensed imagery for suspended sediment transport studies in the Humber catchment. *Science of the Total Environment* **194/195**: 263–283.

Wolman MG, Miller WP. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* **68**: 54–74.

Zóphóníasson S, Pálsson S. 1996. *Rennsli í Skaftárhlaupum og aur- og efnastyrkur í hlaupum 1994, 1995 og 1996*. Report OS-96066/VOD-07 (in Icelandic). Orkustofnun: Reykjavík.