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Recent changes in rates of suspended sediment transport in the Jökulsá á Sólheimasandi glacial river, southern Iceland

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Abstract This paper examines change over the 1973-1992 period in suspended sediment concentrations and loads for the Jökulsá á Sólheimasandi glacial river in southern Iceland. The main data set used is derived from all-year-round depth-integrated suspended sediment samples taken by the Icelandic National Energy Authority (Orkustofnun) from a bridge site 4 km downstream from the glacier snout. The Jökulsá á Sólheimasandi system delivers very high suspended sediment yields (mean annual value, 1973-1988, is 8990 t km^{-2} $year^{-1}$). Between 1973 and 1992, however, the trend shows that average sediment loads have decreased by 48%, from 14.6 kg s^{-1} to 7.6 kg s^{-1}, and average suspended sediment concentrations have dropped by 33% from 725 mg l^{-1} to 487 mg l^{-1}. Although *annual* runoff appears relatively stable, *melt-season* flows have become more dominant while spring and autumn runoff has declined, as have spring and autumn suspended sediment concentrations and loads. This growing flow seasonality appears to be driven by a significant warming in summer air temperatures in southern Iceland (at 0.27°C per decade) over the last twenty years. Sediment load decreases may also relate to fine-sediment exhaustion effects, possibly associated with a depletion of proglacial sediment supplies in response to substantial readvance of the basin glacier, Sólheimajökull.

INTRODUCTION

Studies of glaciofluvial sediment transport are receiving renewed attention recently, largely because of its importance in: (a) shedding light on glacial, geomorphological and hydrological processes upstream; (b) estimating sediment yields and erosion rates in inhospitable terrains; (c) influencing the quality of turbidity-sensitive aquatic habitats; (d) sediment-associated contaminant transfer; (e) water potability issues; (f) hydroelectric turbine operation; and (g) downstream siltation impacts, including delivery of sediment to nearshore zones which is often vital to the stability of coastlines. However, few data exist from subarctic environments. Recent work by the Icelandic National Energy Authority (Orkustofnun) and the author has shown that many of the glacierized basins in southern Iceland deliver very high sediment yields by world standards (in the order of 10 000 t km^{-2} $year^{-1}$) (Tómasson, 1991; Lawler *et al.*, 1992). Little is known, however, of the longer-term stability of sediment concentrations and yields in response to environmental and climatic changes at different timescales. The aim of this paper, therefore, is to make a preliminary examination of changes in suspended sediment fluxes from the Jökulsá á Sólheimasandi basin over the 1973-1992 period, in relation to climatic, hydrological and glaciological fluctuations. As far as the author is aware, this is the first all-year-round study of longer-term sediment transport trends in relation to climatic and glaciological change within a glacierized basin. Results of complementary studies of melt-season sediment transport dynamics will be published elsewhere.

RESEARCH AREA

All field measurements reported here were carried out at a natural-section gauging station below a road bridge over the Jökulsá á Sólheimasandi glacial river, the meltwater outlet of the valley glacier Sólheimajökull in southern Iceland (19°25'W; 63°30'N). The station is 4 km from the glacier snout – the first point at which all braided meltwater rivers are collected together in a single-thread reach. The sampling site is the nearest to a glacier snout of any of those operated by Orkustofnun. Drainage area at the bridge is around 110 km^2, of which approximately 71% is ice-covered, and bankfull discharge is estimated to be 100 m^3 s^{-1} (Lawler, 1991; Lawler *et al.*, 1992). Annual precipitation (1931-1960) is estimated to rise from at least 1600 mm at the bridge gauging site (altitude 50 m) to over 4 000 mm near the highest boundary of the catchment (1493 m) (Eythorsson & Sigtryggsson, 1971 (cited in Björnsson, 1979)). Hydroclastic and acid volcanic rocks dominate the basin, and palagonite tuffs and breccias are common (Carswell, 1983). Anthropogenic impact in the uninhabited and undeveloped Jökulsá á Sólheimasandi basin is minimal. There is no evidence that basin land use has changed during the study period. This makes it ideal for the study of the impact of natural environmental forcing on sediment transport. A full description of the study area can be found in Lawler (1991).

Mean annual suspended sediment yield (1973-1988) is 8990 t km^{-2} year^{-1} (standard error = 1285 t km^{-2} year^{-1} or 14.3%). Likely suspended sediment sources include: supraglacial material in the ablation zone of the glacier tongue (Lawler, 1994, his Fig. 1); voluminous bands of englacial debris, including tephra; subglacial sediments; proglacial moraines, terraces, channel and sandur deposits; and extra-glacial hillslopes which are deeply gullied and sparsely vegetated.

DATA SOURCES

Continuous flow and sediment records are rarely available for the more remote high-latitude regions of the world. The main Orkustofnun data set used in this paper comprises, for the 1973-1992 period, the 226 values for mean instantaneous suspended sediment concentration (bulked from around 1200 individual samples), for which discharge measurements were available. Field sampling techniques and laboratory methods are discussed by Lawler (1991) and Lawler *et al.* (1992).

The main strengths of the Orkustofnun dataset are: use of recognized samplers (e.g. US D-49)); full depth- and width-integrated sampling; *measurement* of discharge at the time of sampling (not simple *estimation* from rating curves subject to substantial error associated with rapidly-changing channel geometries (Lawler *et al.*, 1992); a reasonably long data series, beginning in 1963 (1973 for the Jökulsá á Sólheimasandi); all-year-round sampling; and representation of a range of subarctic environments, which are relatively under-researched in global terms. Disadvantages, however, include a low sampling frequency (approximately monthly) which is not designed to detect transient and diurnal sediment pulses (e.g. Lawler & Brown, 1992; Lawler *et al.*, 1992), and lack of continuous river flow data at a number of sampling stations, including the Jökulsá á Sólheimasandi.

CHANGES IN SUSPENDED SEDIMENT LOAD

Figure 1 confirms the very high sediment loads (calculated as the products of the instantaneous suspended sediment concentration and discharge values) characteristic of this system (Tómasson, 1991; Lawler *et al.*, 1992). Although much of the scatter in Fig. 1 is seasonal variation normally associated with the regularities of melt seasons in glaciofluvial systems, such variability can hinder the identification of trend in the data. Nevertheless, the trend in Fig. 1 shows a statistically significant decline in average sediment loads of 48% between 1973 and 1992, from 14.6 kg s^{-1} to 7.6 kg s^{-1}. Note also how the annual minima decline at a faster rate than the maxima (Fig. 1): the system today, then, is still apparently able to generate high loads, but instances of low sediment flux are now much more common. Many possible causes of sediment flux decline can be hypothesized, related to changes in sediment production mechanisms, source locations, supply volumes, access processes, delivery pathways, transport rates and storage opportunities, and these will be addressed elsewhere. Space permits here simply a brief exploration of covariance in some relevant hydrological and glaciological variables, which possibly point to shifts in the sediment supply and transport regimes.

There is no evidence from these "snapshot" discharge measurements to suggest that *annual* runoff has declined during the study period, as has been found by Snorrason (1990) elsewhere in Iceland. Instead, it seems that significant suspended sediment

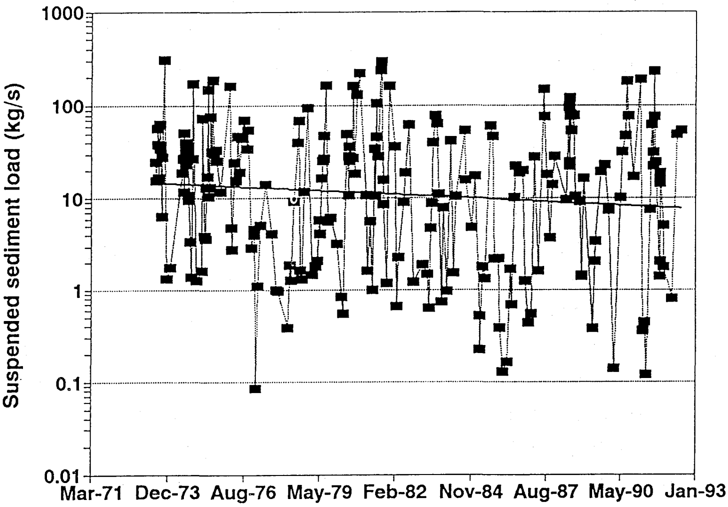

Fig. 1 Changes in suspended sediment load (SSL; kg s^{-1}) for the Jökulsá á Sólheimasandi, 1973-1992. The fitted linear regression, significant at $p < 0.05$, is: log SSL = 2.243893 − 0.0000403 D, where D is number of days from 1 January 1900.

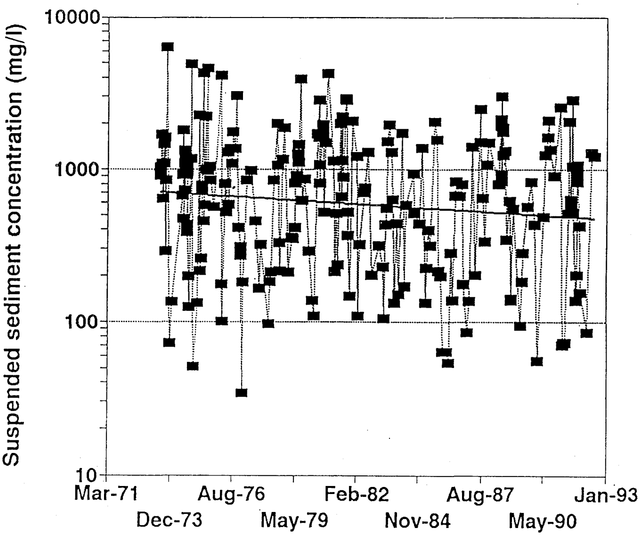

Fig. 2 Changes in suspended sediment concentration (SSC; mg l^{-1}) for the Jökulsá á Sólheimasandi, 1973-1992. The fitted linear regression, significant at $p < 0.05$, is: $\log SSC = 3.522651 - 0.0000247\,D$, where D is number of days from 1 January 1900.

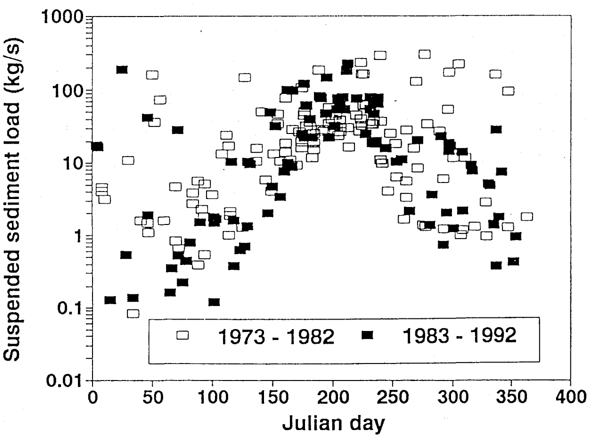

Fig. 3 Seasonal variation in suspended sediment load for each decade of record, 1973-1982 and 1983-1992. Note the greater number of lower values in the spring and autumn seasons of the more recent period, but a preserved peak around day 210.

concentration decreases are important here, the regression trend suggesting a drop of 33% from 725 mg l^{-1} in 1973 to 487 mg l^{-1} in 1992 (Fig. 2). Furthermore, although the *summer* peak in sediment loads has been sustained in the later decade, in *spring* (Julian day 60-150) lower values are now more common and, in *autumn* (day 250-330), the higher values are lacking (Fig. 3). This pattern is mirrored by the suspended sediment concentration and discharge values which are positively correlated (e.g. Lawler, 1991). Sampled spring and autumn river flows (and presumably transportational energy) tend now to be lower, while summer flows have been significantly enhanced ($p < 0.05$; Lawler, in preparation) (Fig. 4). This shift in flow seasonality may also have increased

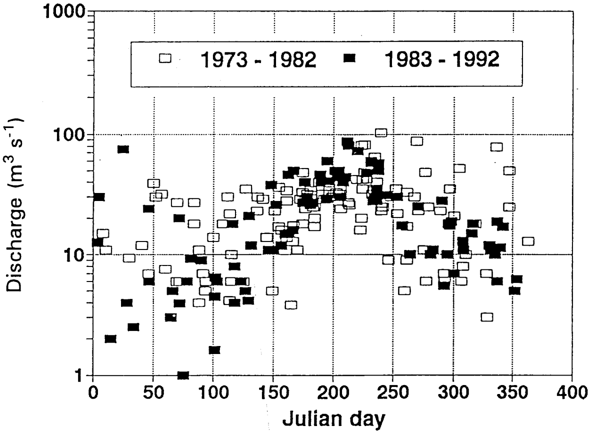

Fig. 4 Seasonal variation in discharge for each decade of record, 1973-1982 and 1983-1992. Note the greater number of lower values in the spring and autumn seasons of the more recent period, compensated for by a significant rise in summer flows.

the stability of the subglacial drainage network, with a corresponding reduction in the frequency with which new subglacial sediment source areas are "swept" before and after the main melt season.

This apparent increase in the dominance of summer flows may in turn be responding to strongly significant summer warming here since 1973 (Fig. 5). The rate of temperature increase here (0.27 °C per decade) is mirrored in other arctic and subarctic environments (e.g. Farmer, 1989 (cited in Kullman, 1992); Nordli, 1991; Alexandersson & Dahlström, 1992; Jónsson, 1992) and is not inconsistent with temperature rises forecast by GCMs for similar latitudes (e.g. Carter *et al.*, 1991). The causes and projected continuity of such warming are separate issues of course.

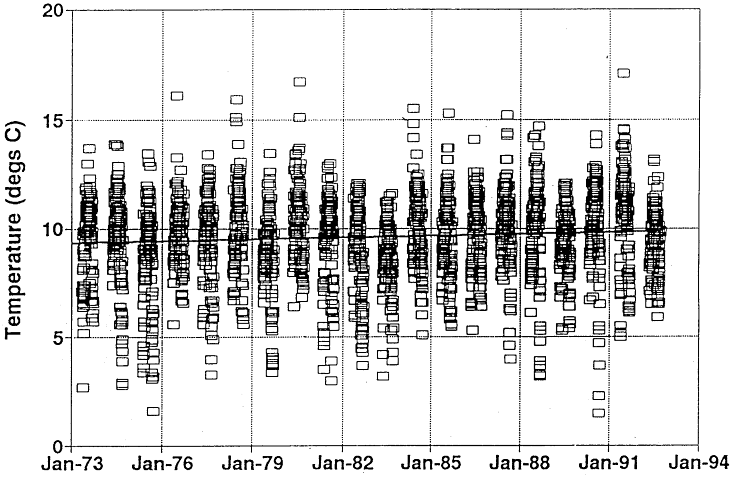

Fig. 5 Changes in mean daily summer (June-September inclusive) air temperature (T_s; °C) at Vík, on the southern coast of Iceland (21 km southeast of the gauging site), showing a distinct warming trend. The fitted linear regression, significant at $p < 0.0001$, is: $T_s = 7.35 + 0.000075D$, where D is number of days from 1 January 1900. Temperature rise is 0.27 °C/decade. The scatter is mainly seasonal variation.

Sediment supply limitations may also be important. Scrutiny of the residuals from the discharge-suspended sediment concentration rating curve indicates that, *for a given flow*, less sediment tends to be transported today than in the 1970s (Lawler, in preparation). These lower sediment fluxes, perhaps paradoxically, coincide with an extremely active phase of glacial advance (Figs 1, 6). There may, of course, be time lags in the system whereby the smaller sediment loads of the 1980s are merely responding to earlier, relatively quiescent, glaciological phases (cf. Harbor & Warburton, 1993): if so, yields may rise again over the coming years in response to the vigorous glacial advance of the mid-1980s. Alternatively, it could be argued that higher sediment loads in the 1970s relate to peak exposure of proglacial sediment stores at that time – shortly after maximum deglaciation was achieved (Fig. 6). These stores are known to be important in some glaciofluvial contexts (e.g. Hasholt & Walling, 1992). Such sediment supplies could have been progressively depleted by rainwash and overbank flow events (if not continually renewed at comparable rates (cf. Richards, 1984)), allowing partial exhaustion phenomena to emerge in the data of later years.

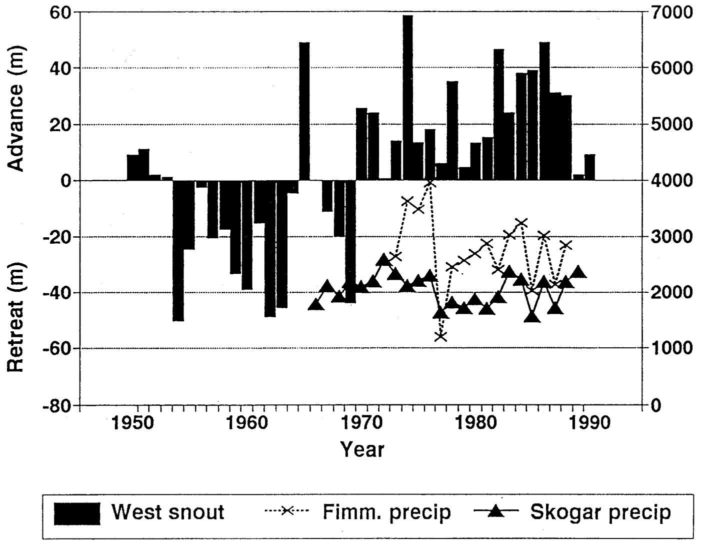

Fig. 6 Changes in the annual position of the west snout of the basin glacier, Sólheimajökull, 1950-1990 (data from *Jökull*, and Oddur Sigurdsson, personal communication). A period of uninterrupted readvance began in 1970. Precipitation at Skógar (6 km west of the gauging station) and Fimmvörduháls (Fimm.), ~2 km from the western edge of the basin at 630 m, is added for comparison in the latter part of the period.

Similar impacts at longer timescales were hypothesized within the "paraglaciation" concept of Church & Ryder (1972). Such complex responses, with so many possible reinforcing, cancelling and inertial effects associated with glacier motion and snout advance/retreat cycles, underline the need for extreme caution in making overly-simple extrapolations about the likely impact of longer-term glaciation on sediment yields and erosion rates (see recent debates involving Hicks *et al.*, 1990; Molnar & England, 1990; Summerfield & Kirkbride, 1992; Harbor & Warburton, 1993).

CONCLUSIONS

The following preliminary conclusions can be drawn:

(a) The trend suggests that average suspended sediment loads in the Jökulsá á Sólheimasandi system have almost halved over the 1973-1992 period.

(b) Average suspended sediment concentrations have also decreased by 33% over the same period.

(c) These statistically significant declines in suspended sediment fluxes are more noticeable in spring and autumn, and the relative stability of summer sediment transport patterns underscores the need for all-year-round and seasonally-sensitive investigations (rather than melt-season studies only) when trying to monitor the impact of environmental change in glacierized basins characterized by significant runoff in all seasons.

(d) Although no trend is identifiable in *annual* runoff, summer river discharges, as sampled, appear to have become more dominant – at the expense of spring and autumn flows. This loss of runoff volume and transportational capacity either side of the main melt season may partly explain the seasonal pattern of suspended sediment declines.

(e) Significant summer warming over the last 20 years in southern Iceland (Vík) may be driving the recent increases in flow seasonality which are helping to sustain melt-season suspended sediment export rates.

(f) Lower rates of suspended sediment transport in the 1980s are synchronous with a phase of especially active glacier snout advance: declines may be lagging behind earlier, less dynamic, glacial phases or relate to a progressive exhaustion of (proglacial) sediment supplies.

Such statistically significant changes (and year-to-year variability) in sediment load reinforce the need to base mean sediment yield estimates on a sufficiently long period of record. The magnitude of change identified here also serves to remind that, when making spatial comparisons of sediment yield between basins, allowances should be made if different periods of record are used relative to local, regional or global gradients of environmental change. Further research is in progress to define all facets of sediment transport change, including seasonal signatures; to model the relationship of change to the driving climatic, hydrological and glaciological processes and to the dynamics of melt-season suspended sediment fluxes; and to determine the spatial coherence of identified patterns across other Icelandic and subarctic systems.

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