Temporal variability of suspended sediment flux from a subarctic glacial river, southern Iceland

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ABSTRACT Orkustofnun (Icelandic National Energy Authority) has operated a river sediment sampling programme at around 40 stations in Iceland since 1963. These provide useful data from the relatively-neglected high-latitude regions. This paper discusses the procedures and problems of measuring sediment loads in the Icelandic environment, with particular reference to the Jökulsá á Sólheimasandi glacial river in southern Iceland. The sediment yield (suspended and solute) from this system is estimated at 10269 t km^{-2} a^{-1} (equivalent to an erosion rate of 3.8 mm a^{-1}) - one of the highest values in the world for a glacial river. Measurement problems are caused by channel instability, seasonal stage-discharge hysteresis and temporal variations in sediment fluxes at all timescales. These aspects are explored using (a) high-frequency melt-season data from an automated turbidity monitoring and water sampling programme mounted in the summers of 1988 and 1990 and (b) manually-collected information covering the 1973-1988 period.

INTRODUCTION

Glacierized river basins deliver some of the world's highest sediment loads, but few data are available from high-latitude areas. In this paper, our aims are to (i) outline the Icelandic sediment transport monitoring network and methods, and the very substantial fluxes of material that are possible from Icelandic glacierized river basins; (ii) discuss some of the problems with monitoring sediment fluxes in Icelandic catchments; and (iii) illustrate the temporal variability in sediment flux at a range of timescales for the Jökulsá á Sólheimasandi glacial river in southern Iceland. This paper is part of a series of studies dealing with sediment yields, sources and dynamics (and their meteorological, hydrological and glaciological controls) in the Jökulsá á Sólheimasandi system (e.g. Lawler, 1991).

ORKUSTOFNUN SUSPENDED SEDIMENT MONITORING NETWORK

The present network of around 40 Orkustofnun (Icelandic National Energy Authority Hydrological Survey) suspended sediment sampling stations (Fig.1) was gradually built up from 1963, although a few ad hoc samples and analyses are available from earlier years. The sampling stations are mostly bridges on the main road around Iceland; some inland sites have cableways. Most sampled

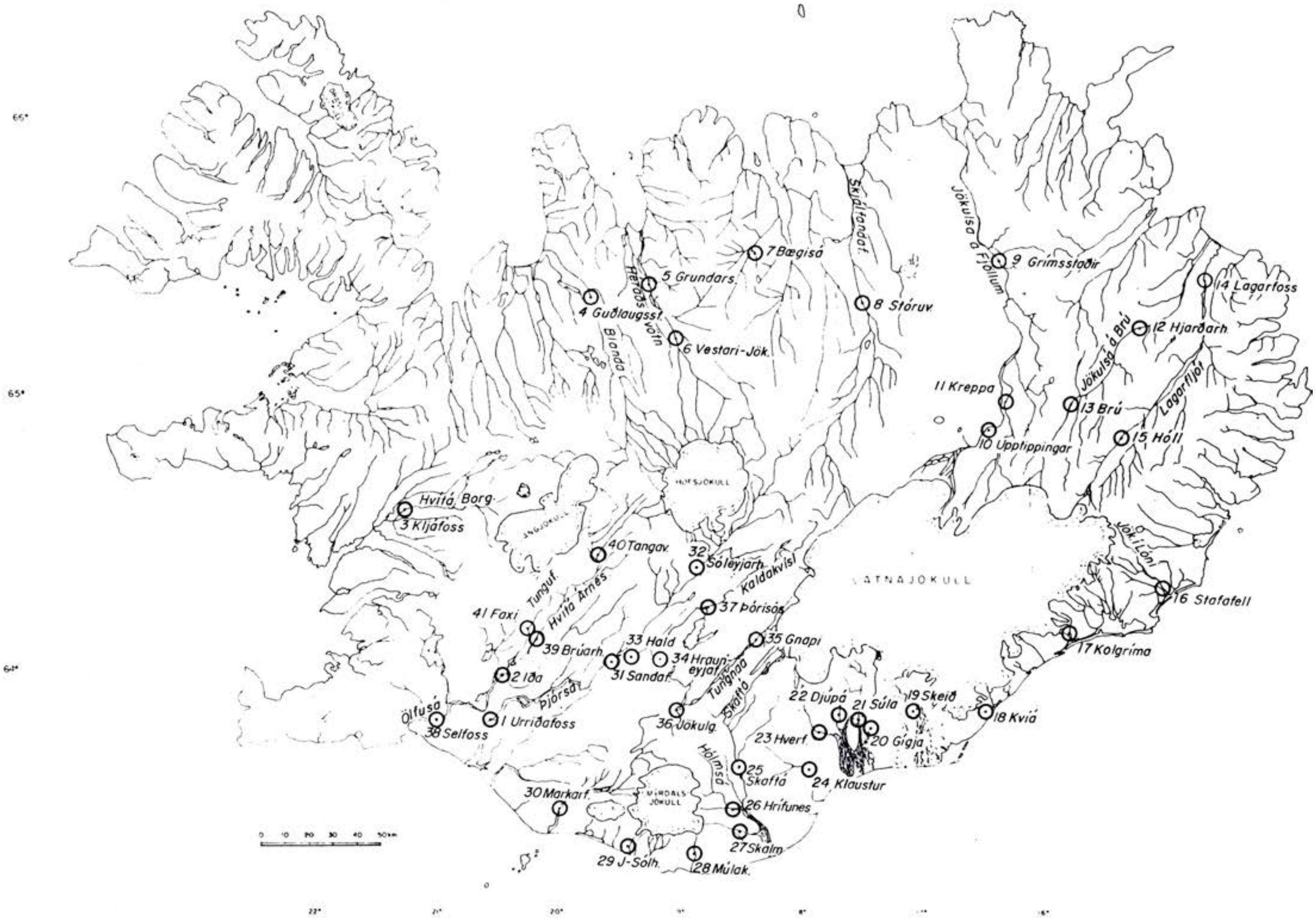

FIG. 1 Orkustofnun (Icelandic National Energy Authority) suspended sediment sampling stations.

rivers on the regular network are glacier-fed. The non-glacial rivers carry little sediment load except in floods. No routine automatic monitoring is carried out in Iceland. Instead, most sites are manually sampled approximately once a month, less frequently in winter and for the more remote locations. The applications of sediment-load data in Iceland are related to hydro-electric power generation and the associated problems of reservoir siltation, changes in river courses due to degradation downstream of reservoirs, and erosion of the sandy coasts due to diminishing sediment supply from the rivers (e.g. Tómasson, 1986). This network is important in the global context because all lie in the relatively-neglected subarctic zone, between 63.5 and 66° N.

Orkustofnun sampling methods

Orkustofnun uses the US D-49 depth-integrating sediment sampler (Guy & Norman, 1970). The sampling is done in a number of verticals, depending on river width, often using a winch in the sampling vehicle (see Lawler, 1991, his Fig. 2). In some rivers depth-integrated sampling is done by hand using the US DH-48 sampler, but the number of verticals can be lower depending on site constraints. The nozzle used is most commonly 6 mm but can go down to 2 mm in deep rivers. Discharge measurements are made at natural sections with Ott current meters or float gauging techniques using bridges or cableways where appropriate. The channel geometry and area of cross section of the water prism is obtained at the same time as water samples by using the suspended sediment sampler as a sounding weight. Not all sediment sampling stations are equipped with automated stage-measuring devices: a number rely instead on instantaneous discharge measurements at the time of site visits.

Orkustofnun laboratory techniques

The aim of the laboratory processing of water samples is to yield values of suspended sediment concentration, total dissolved solids concentration and the particle size distribution of suspended sediment. The samples from the different verticals are bulked prior to analysis: mean-section results for all determinands are thus obtained. The bulked sample is allowed to stand in measuring cylinders until all sediment coarser than approximately 0.0015 mm has settled out according to Stoke's law. Fine clay may still be in suspension. A 200 ml subsample of the water (sample A) containing fine clay and dissolved solids is oven dried. Another 200 ml subsample (sample B) is centrifuged for 1 hour at 3000 r.p.m. to isolate the fine clay, and the supernatant (containing solutes only) is oven dried. The content of fine clay is then found by subtracting the dry weight of sample B supernatant from sample A residue. The sediment from the cylinders is boiled with hydrogen peroxide to dissolve organic material. The grain size distribution of material >0.062 mm is measured by sieving. The grain size distribution 0.062 to approximately 0.0015 mm is determined by an automatically-reading Sartorius sedimentation balance.

THE JÖKULSA A SOLHEIMASANDI STUDY

Study area

The Jökulsá á Sólheimasandi basin is one of the most southerly stations in Iceland (Fig. 1, number 29), at latitude 63° 30' N and longitude 19° 25' W. The basin consists of three very distinct parts, namely (a) the glacier Sólheimajökull which issues from the Myrdalsjökull ice-cap; (b) the extra-glacial mountains; and (c) the sandur plains downvalley of the snout (see Lawler, 1991, his Fig. 1). The drainage area at the bridge gauging station is 110 km^2, of which 78 km^2 (71%) is glacierized. These figures are approximate, as little is known about subglacial topography and drainage routes here. Sólheimajökull has advanced at a mean rate over the 1970-1990 period of 23.6 m a^{-1}, although it has slowed in recent years (Lawler, in review).

The gauging site is about 4 km from the snout of Sólheimajökull (Fig. 1). The basin was chosen for a detailed study of sediment loads, sources and dynamics (Lawler, 1991, in review, in prep; Lawler & Brown, 1992) because (a) it is the closest to a glacier snout of any of the Orkustofnun stations (and one aim of the research was to examine the relationship between glacier behaviour and sediment-flux response); (b) it exports very high sediment loads (Tómasson, 1986; Lawler, 1991); and (c) it is relatively accessible. These advantages outweighed the drawbacks imposed by an absence of long-term, continuous, flow data for this river. Peak runoff usually occurs in July, although some exceptional events have occurred later in the year.

Much of the basin lies on the flanks of the ice-covered volcano Katla which has been very active during the last millenium. Periodic eruptions of Katla cause catastrophic outburst floods, some of which have flowed down the Jökulsá valley and created the Sólheimasandur sandur plain which consists mostly of sand and gravel (see Thorarinsson, 1957; Maizels, 1989; 1991). The Katla and other volcanic systems have also regularly ejected tephra into the basin, which currently plasters many glacial surfaces. Hydroclastic and acid volcanic rocks dominate the solid geology of the basin (Carswell, 1983). The mountain part of the basin is made up of erodible palagonite tuffs and volcanic breccias. Soils are generally very thin on the terrace surfaces and hillslopes. The land is sparsely vegetated largely with grass. Human impact is not especially pronounced.

Waters draining subglacially and englacially, and supraglacially in the terminal region, have large stores of sediment at their disposal. A proportion of this, however, may well have been produced outside the basin. This begs the question: how long must introduced debris (e.g. loessic or, as in this case, tephra material) be resident in a basin before it is considered 'indigenous', and allowed to enter into erosion-rate calculations based on sediment yield measurements?

Field measurement techniques

Orkustofnun has made instantaneous sampling and discharge measurements in the Jökulsá á Sólheimasandi on a fairly regular, approximately monthly, basis since 1973 (see Lawler (1991) for details). In the summer melt seasons of 1986 and 1988-1991, DML and MD, as part of wider investigations into glaciofluvial solute- and sediment-dynamics here (e.g. Dolan, 1991; Lawler, 1989, 1991), monitored with dataloggers the meteorological variables controlling glacial runoff (inputs) and river stage, discharge, suspended sediment concentration, turbidity, river temperature and conductivity (outputs) at the minute and hourly timescales. Custom-built, as well as Partech IR15C, turbidity sensors have been used, although only data from the former (Lawler & Brown, 1992) are discussed here. An automatic water sampler operated at a 1 - 8 hour sampling frequency to provide calibrations for the turbidity meters. A pressure transducer supplied river-level data. The high-frequency water quality data are drawn from one point in the gauging section near the right bank.

Seasonal stage-discharge hysteresis

One of the main problems in such environments is the changeable nature of the stage-discharge relationship caused by channel instability. Fig. 2 illustrates distinct anti-clockwise hysteresis in the stage-discharge plot during 1988. The highest discharges for a given stage occur in the mid- and late-summer period, with lower discharges for a given stage early in the melt season but especially in the latter half of the year (Fig. 2). The excursions from the early-season rating relationship start in early July and continue till 10 August; this coincided with a large flood event which peaked on 9 August (see Lawler, 1991, his Fig. 11). This was followed by a distinctly lower discharge at the time of the 18 August measurement, despite a higher stage (Fig. 2). These hysteretic effects relate directly to channel geometry and cross-sectional area changes detected by the Orkustofnun repeat surveys. Fig. 3 shows clearly how the 30 June 1988 profile was deeply scoured and widened by 10 August - giving artificially low stages for high flow-rates (Fig. 2) - only to be infilled substantially over the following month (resulting in high stages for only moderate discharges). The 1988 situation was perhaps an extreme example, but it serves to illustrate the potential scale of the problems faced here. The 'mid-summer' rating equation (Lawler, 1991) has been used for all 1988 discharge data presented below.

TEMPORAL VARIABILITY IN SUSPENDED SEDIMENT FLUXES

Sediment yields

Sediment transport studies in Icelandic rivers have not received great attention in the international literature (e.g. they are absent from summaries in Ferguson (1984), Gurnell (1987), Walling & Webb (1983)). Nevertheless, data show that Icelandic rivers transport extremely high suspended sediment loads, even in non-glacierized basins, and can reach exceptional proportions during jökulhlaups (e.g. Tómasson, 1974, 1986, 1991, Tómasson et al., 1980; Lawler, 1991; Lawler & Brown, 1992). It was estimated by Tómasson (1986), for example, that the Jökulsá á Sólheimasandi system exports around 10000 t km^{-2} a^{-1} of sediment. This early value has been confirmed using the 'Method 2' calculating procedure of Walling & Webb (1981) on the complete 1973-1988 dataset which gives a sediment yield (suspended and dissolved) of 1.13 Mt a^{-1} (Lawler, 1991). This converts to 9776 t km^{-2} a^{-1} for suspended sediment alone and 10269 t km^{-2} a^{-1} for suspended sediment and solutes together, which is amongst the highest in the world for a glacial river (see Gurnell, 1987). The latter is equivalent to a mean basin erosion rate of 3.8 mm a^{-1}. Note that these figures are based on an accepted drainage area of 110 km^2 and are downgraded revisions of the preliminary values given in Lawler (1991). Work proceeds to refine these estimates further. They are based on depth- and width-integrated suspended sediment samples withdrawn by a recognized sampler, not single-point turbidity measurements, and water discharges which are <u>measured</u>, not estimated from rating curves. Nevertheless, they suffer from a lack of quasicontinuous data on streamflow and suspended sediment concentration, and are probably underestimates, given that many peaks will be missed by the infrequent manual sampling (see below). It should be possible now to update maps of global sediment yield to include these and other data now emerging from Iceland - a country which is usually shown as an environment of low sediment export (e.g. $<$ 50 t km^{-2} a^{-1} for basins $>$ 1000 km^2 (Walling & Webb, 1983)) or ignored altogether (e.g. Strakhov, 1967; Fournier, 1960 (cited in Walling & Webb, 1983)). These time-averaged figures cited above, of course, mask pronounced

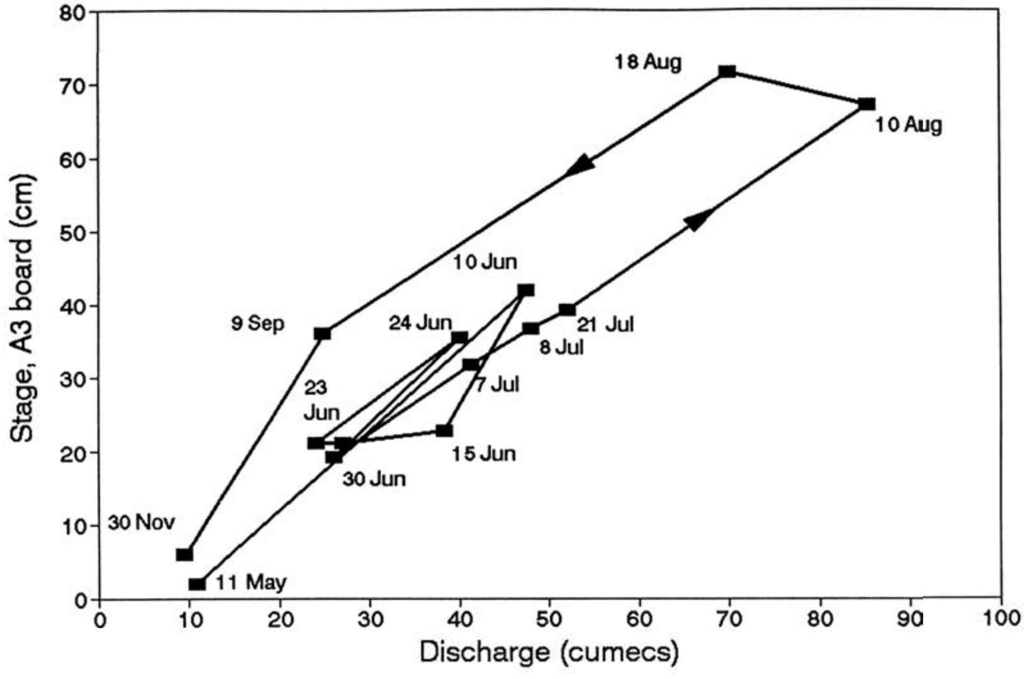

FIG. 2 Seasonal hysteresis in the stage-discharge relationship for the Jökulsá á Sólheimasandi in 1988.

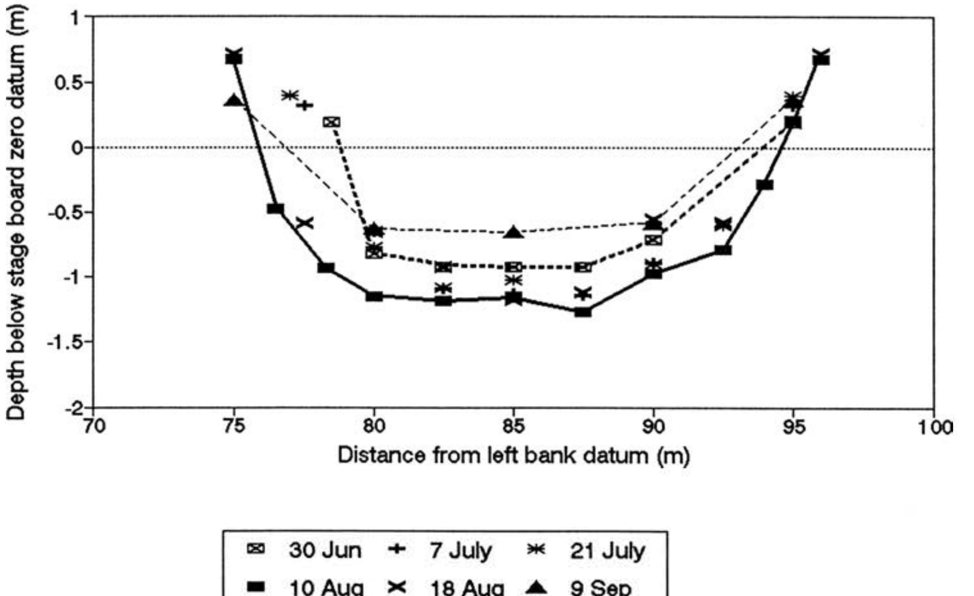

FIG. 3 Scour and fill of the Jökulsá á Sólheimasandi cross section during summer 1988.

temporal variability at many timescales, to which the discussion now briefly turns. Interpretation of the variations will be discussed elsewhere.

Hourly and sub-hourly timescales

Fig. 4 shows an example of typical high-flow sediment pulsing phenomena (recorded by turbidity meter), despite a fairly stable river flow. Even though the two events last little more than 2 hours each, because suspended sediment concentrations almost double from already-high levels, and with discharge averaging around 85 - 90 $m^3 s^{-1}$, very substantial amounts of sediment are exported (up to 325 kg s^{-1}). To place this in perspective, the first, three-hour, event of Fig. 4, for example, increases sediment yield by about 675 tonnes over background levels - more than the total sediment export from Storbregrova, Norway, over a complete 11-day study period (see Richards, 1984). Such pulsing has often been noted in glacial rivers (e.g. Bogen, 1980; Gurnell, 1987), being attributed, amongst other causes, to subglacial channel-switching (Fenn, 1987), which is particularly common with rising and/or high stages, when water is forced into new conduits where liberal sediment supplies are located.

Fig. 5 shows suspended sediment concentration change, also measured by turbidity meter, in response to a 'heartbeat' effect in the flow series (Lawler, 1989). These were quite common events in summer 1988 and comprise a rapid discharge decrease, followed by a sharp rebound to higher stages, before previous flow levels are re-established. The whole event is usually over within one hour (Fig. 5). These have tentatively been ascribed elsewhere to temporary blockage of glacial conduits or ice-marginal channels, probably by ice-collapse (e.g. Ballantyne & McCann, 1980), although work is continuing on the problem here (Lawler, in prep.). The important point here is that although there is only a marginal change in total runoff during this event - with the flow-retardation phase almost balancing the subsequent flow increase - there is a pronounced net gain in suspended sediment export because suspended sediment concentrations only seem to respond to the discharge 'rebound' (Fig. 5).

Diurnal and sub-seasonal signals

Although a clear diurnal variation in river discharge exists here in summer, as is common for glacial rivers, and at seasonal timescales a reasonably strong relationship is present between discharge and suspended sediment concentration, the diurnal signal in sediment concentration is rather subdued, and the magnitude of variations is not very high (Lawler, 1991). Precipitation events generate very high flows and the highest sediment loads here. Fig. 6 displays preliminary results from Dolan (in prep.) recorded during a prolonged wet spell in summer 1990. The high-magnitude, highly-erratic, variations in sediment concentration (estimated from turbidity-meter records) are immediately striking. Heavy rainfall between 12 and 27 July led to steadily increasing flows culminating in a very substantial, 24-hour long, suspended sediment purge in which concentrations quadrupled (Fig. 6). Even the recessional limb was punctuated with pulsing of a high order (Fig. 6).

Seasonal fluctuations

It is at seasonal timescales, however, that suspended sediment concentration variability is at its greatest. Aggregating the results from the low-frequency,

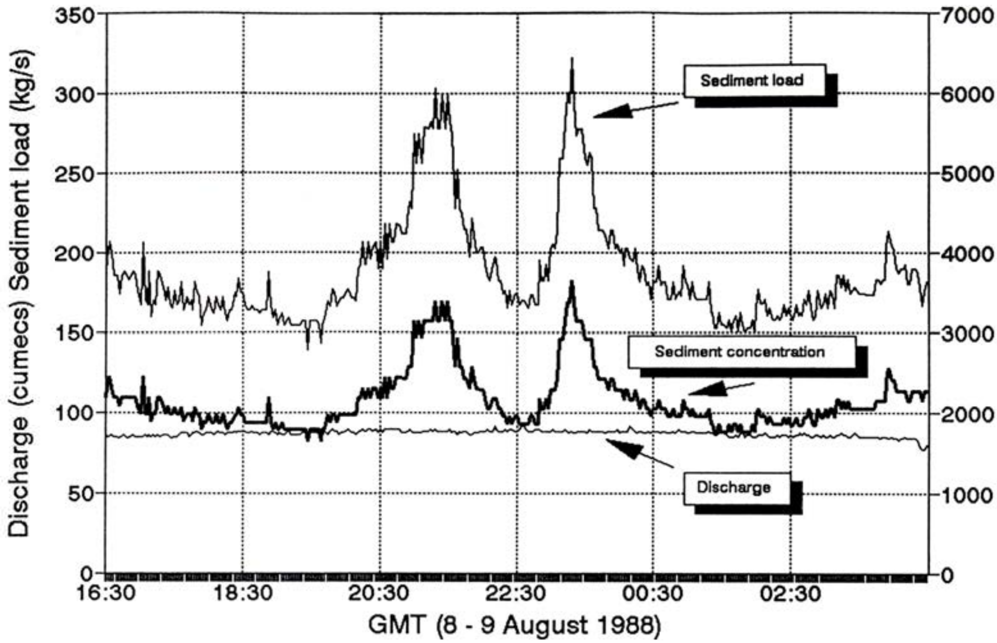

FIG. 4 Compound suspended sediment pulsing event during a period of relatively stable discharges on the Jökulsá á Sólheimasandi system, August 1988 (data at 2-minute intervals).

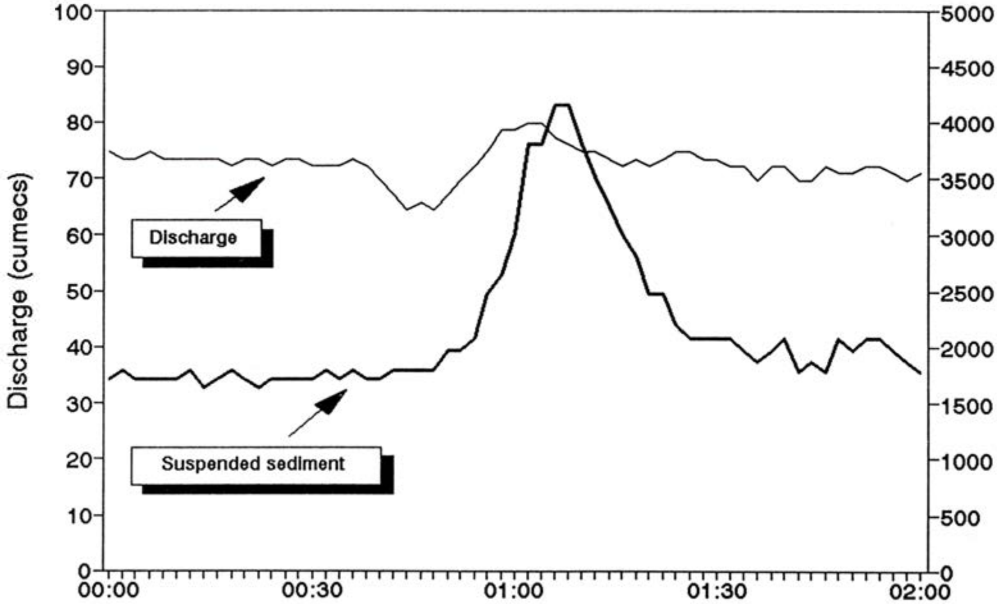

FIG. 5 Suspended sediment pulsing during a flow perturbation of the Jökulsá á Sólheimasandi, August 1988 (data at 2-minute intervals).

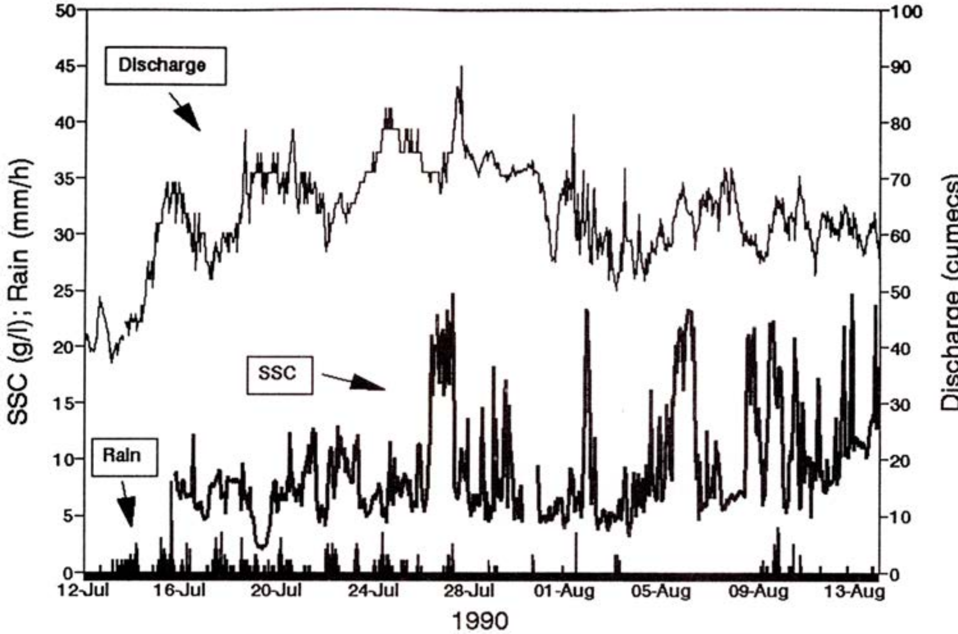

FIG. 6 Repeated pulsing of suspended sediment concentration (SSC) in the Jökulsá á Sólheimasandi river during a prolonged storm sequence in summer 1990 (data are hourly averages derived from 10-min scans (Dolan, in prep.)).

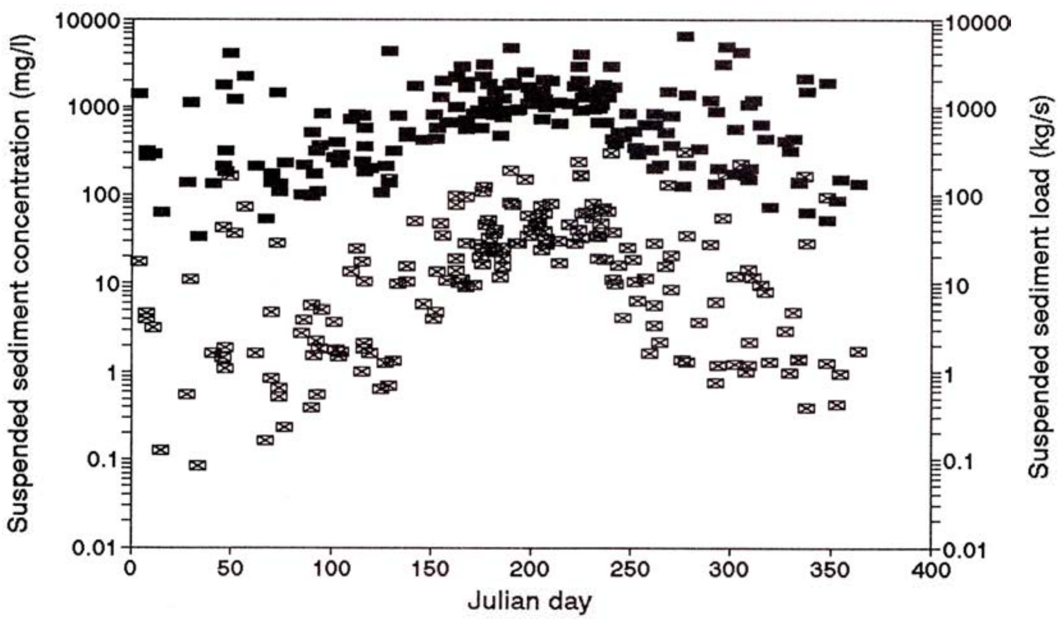

FIG. 7 Seasonal changes in suspended sediment concentration (filled rectangles) and load (crossed rectangles) for the Jökulsá á Sólheimasandi revealed by aggregating results for the 1973-1988 period (n = 189).

instantaneous, sampling since 1973 can reveal something of the magnitude of seasonal changes (Fig. 7). As expected, the low flows of winter are associated with low suspended sediment concentrations. Peak sediment transport tends to occur between day 190 and 210 (mid-end July), although extreme events have occurred at almost any time of the year (Fig. 7). In the 1973-1988 period, the minimum values recorded for suspended sediment concentration and load were 34 mg l^{-1} and 0.09 kg s^{-1} respectively: the maximum values were 6358 mg l^{-1} and 305.2 kg s^{-1} (Lawler, 1991). Thus variations of well over two orders of magnitude exist for sediment concentration, with three orders of magnitude apparent for load (Fig. 7). This is probably an underestimate, given that the low-frequency sampling programme will inevitably miss a number of significant low-flows and flood events.

CONCLUSIONS

The Orkustofnun sediment sampling network has demonstrated that Icelandic glacial rivers can transport exceptionally high sediment loads. A hitherto undocumented and substantial temporal variability is characteristic of the sediment fluxes, however, which makes reliable estimates of sediment yield difficult to obtain. The utility of repeated checking of channel-geometry changes and discharge measurements has been demonstrated. Further work aims to model the controls of temporal variations in sediment transport and to extend analyses to other rivers of Iceland, where even higher sediment loads are likely to exist.

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