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Sediment monitoring of glacial rivers in Iceland: new data on bed load transport

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Abstract Sediment monitoring of glacial rivers in Iceland has been carried out at the Hydrological Service of the National Energy Authority during the past five decades. This paper describes the expansion of the monitoring in recent years, with special emphasis on recent bed load sampling. As an example, the results from an extensive sediment sampling project in the harnessed glacial river Thjórsá, south Iceland, are discussed and compared with results from three other glacial rivers (Skaftá in south Iceland and Jökulsá á Fjöllum and Jökulsá á Dal in north and northeast Iceland) where bed load studies were carried out in 2001. Great changes in "at-a-point" bed load rate measured with a Helley-Smith sampler are seen among the four rivers, and variability within individual channels and sampling campaigns at diverse river discharge is prominent. Mean total bed load discharge for an individual sampling campaign was lowest in Thjórsá (0.03 kg s^{-1} m^{-1}) and highest in a June campaign in Jökulsá á Dal (1.58 kg s^{-1} m^{-1}). The mean total bed load transport rates in this study are higher than many published rates for arctic and alpine environments.

Key words bed load transport; glacial rivers; Iceland; jökulhlaup; suspended sediment load

INTRODUCTION

Nowhere in the world is freshwater of equal profusion per capita as in Iceland (over two thirds of a million m^3 per capita per year); hence, water resources are of special importance to the country. Evaluation of this resource has been an integrated part of environmental monitoring in Iceland, and carried out during the last 55 years at the Hydrological Service of the National Energy Authority (HS). Most of this water, both groundwater and surface water, originates from glaciers, which cover approximately 10% of Iceland's surface. Consequently, most of the largest rivers in Iceland are glacially derived and transport great amounts of sediment within their course from the glaciers towards the ocean.

Many processes effect the sediment load in these rivers, including both human disturbances, such as land use and hydroelectric power construction, and natural instability caused by e.g. weather related flood events, glacier outburst floods (jökulhlaups) and glacier surges. Thorough knowledge of sediment load is thus vital for environmental and engineering evaluation related to hydroelectric development of the rivers, but also gives a basis to study processes such as glacial surging and melting, as well as land erosion.

Sediment sampling in Icelandic rivers has been an integrated part of the river monitoring carried out by the HS in Iceland since its establishment in 1947. Tómasson has introduced the pre-1990 suspended sediment data set collected at HS in several papers (e.g. Tómasson, 1976, 1986a,b, 1991), and used it to evaluate geomorphic processes such as shore development and glacier erosion, as well as the effect of hydropower reservoirs on sediment load in rivers. In the last 15 years the sediment monitoring of Icelandic rivers has extended greatly with increased studies at the HS, including more detailed suspended analysis, and has recently initiated bed load studies. Moreover, several studies have been focused on the variability of suspended sediment load in Icelandic rivers (e.g. Lawler, 1991; Lawler *et al.*, 1994; Old, 2000; Pálsson *et al.*, 1998; Lawler & Wright, 1999). In addition, many studies have concentrated on the sedimentological aspect of jökulhlaups; especially following the great jökulhlaup (peak flow of about 50 000 m^3 s^{-1}) from the Vatnajökull glacier in 1996 (e.g. Russell & Knudsen, 2002; Snorrason *et al.*, 2002).

In this paper we will briefly introduce the suspended sediment monitoring network at HS, which has today produced data sets that are of supreme value for studying both fluvial and glacial processes. However, our main focus will be on the new bed load project, which has greatly extended during the last three years.

THE SEDIMENT SAMPLING PROGRAMME AT HS

Throughout the last five decades samples of suspended sediment have been obtained predominantly from rivers with potential for hydroelectric power generation, or rivers subject to jökulhlaups. From 1963 to 2001 measurements of grain size and total dissolved sediment have been made on over 11 000 suspended sediment samples, in addition to measurements of total suspended sediment concentration that were started in 1949. During the decades, the continuous data set has expanded greatly (Pálsson & Vigfússon, 1996) and today it comprises the basis of all evaluations of sediment transport in Icelandic rivers (see e.g. Tómasson *et al.*, 1996; Pálsson *et al.*, 2000, 2001).

Figure 1 shows the sampling locations of the suspended sediment programme in operation during 2001. During that year, over 500 suspended samples were obtained from 41 locations. The number of samples at each station (1–95) and quality of the samples ranged greatly among the stations, as in some instances they were a part of a detailed integrated sediment study, but in other cases a part of an annual sediment monitoring programme integrated with the hydrometric network (operation). Most samples are made of cumulative sub-samples taken from three or more locations across the river channel. However, where conditions are unfavourable, sub-samples from only two or even one location make up the suspended sample. The suspended sediment samples are analysed for grain size, total suspended sediment concentration, and TDS before a rating curve is constructed, which is used for correlation between water discharge and sediment load. For pure glacier-fed rivers, the correlation coefficient is usually good ($r = 0.7$–0.95), but differs greatly, depending on the number of used samples and characteristics of the rivers.

Bed load sampling has, on the contrary, been a negligible part of the sediment monitoring of Icelandic rivers (Pálsson, 2000). A major step forward was taken in 2000 when a pilot bed load sampling programme was initiated in Jökulsá á Dal, a river in northeast Iceland studied for possible hydroelectric development (Fig. 1) (VST & Orkustofnun, 2003). Bed load sampling had not been employed in any detail at the Hydrological Service before, as the great current speed in the Icelandic glacial rivers

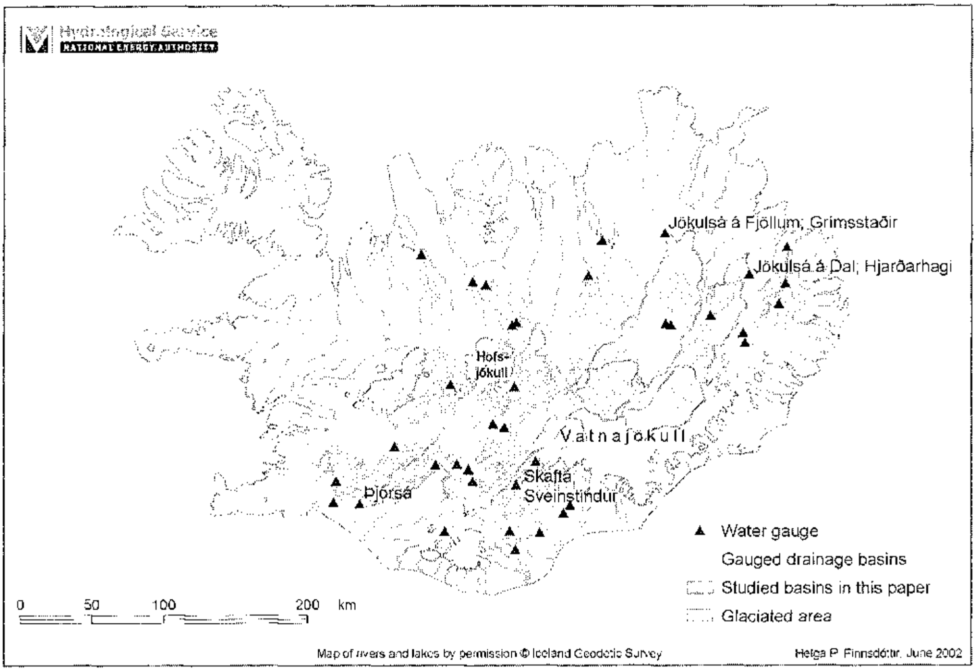

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Fig. 1 Suspended sediment sampling sites in 2001. Shaded area represents the gauged drainage basins at these sites.

Table 1 Characteristics of rivers subjected to bed load studies in 2001. Q_{mean} is the long-term discharge average, Q_{min} and Q_{max} are the lowest and highest mean monthly discharge values.

River, sampling site	No. of trips in 2001	Basin total (km^2)*	Basin glacier (km^2)	Q_{mean} (m^3 s^{-1})	Q_{max} (m^3 s^{-1})	Q_{min} (m^3 s^{-1})
Thjórsá, Krókur**	7	7379	1014	352	1459	44.1
Jökulsá á Fjöllum, Grímsstadir	2	5178	448	170	2757	43.9
Jökulsá á Dal, Hjardarhagi	3	3322	1421	145	1180	7.6
Skaftá, Sveinstindur	2	714	494	42.8	1363	14.5

* basin area at water gauge.

** extensive hydroelectric development on the river.

was thought to prevent such measurements. Results from the pilot study in the River Jökulsá á Dal proved satisfying and subsequently extensive total sediment programmes were established in three additional glacial rivers. Those are the River Jökulsá á Fjöllum in north Iceland, and the rivers Thjórsá and Skaftá in south Iceland (Fig. 1) (Hardardóttir & Þorláksdóttir, 2002a, 2002b; Hardardóttir & Gunnarsson, 2002), which are all presently being studied as future or possible hydroelectric projects. The characteristics of these rivers at the sampling sites differ greatly, e.g. in discharge variables and size of their water basins (Table 1). Thjórsá is the only harnessed river with several upstream reservoirs, whereas major jökulhlaups affect Skaftá on average every year due to geothermal activity beneath the glacier it originates from. At the sampling site Grímsstadir, Jökulsá á Fjöllum includes a significant groundwater component in addition to the glacial water. Occasional glacier surges have been monitored in the outlet glaciers of Vatnajökull and Hofsjökull glaciers (Fig. 1), from which, the four rivers are derived.

METHODS OF BED LOAD SEDIMENT SAMPLING AND ANALYSES

The bed load samples have been collected with a Helley-Smith cable-suspended sampler at 5–10 locations on each river transect. The number of sediment campaigns carried out at each river in 2001 ranged from two in Skaftá and Jökulsá á Fjöllum, to three in Jökulsá á Dal and nine in Thjórsá (Table 1). Most of the samples were collected with a 47.7-kg Helley-Smith sampler with a 0.0762 × 0.0762 m opening and a 3.22 expansion ratio, but a heavier 75.8 kg sampler with a 0.152 × 0.152 m opening but the same expansion ratio was used in one sediment campaign for comparison.

All the bed load samples were weighed on location, but selected samples from each river were dry-sieved to establish grain-size distribution of the bed load material. After collecting 10 or more samples at each location on the river transect during each trip, the total mean bed load transport was calculated in several steps. First the bed load transport of each sample at each station was calculated by dividing the weight of each sample (in grams) by the time interval the sampler sat on the river bed. The mean transport at each station (*j*) was then calculated by:

$$q_{b\,j} = \frac{1}{n_j}\sum_{i=1}^{n_j}\frac{M_i}{t_i d}$$

where q_{bj} is in g s^{-1} m^{-1}, M_i is the mass of sample *i* (in grams), t_i is the sampling time (in seconds) for sample *i*, *d* represents the width of sampler opening (0.0762 m), and n_j is the total number of samples at station *j*. Total transport through cross section Q_b:

$$Q_b = \frac{q_{b1}}{2}x_1 + \frac{q_{b1}+q_{b2}}{2}x_2 + \ldots + \frac{q_{bn-1}+q_{bn}}{2}x_n + \frac{q_{bn}}{2}x_{n+1}$$

where Q_b is in g s^{-1} and *x* represents the distance between sampling points, between a marginal point and the edge of the water surface, or that of the moving strip of stream bed (World Meteorological Organization, 1994). If the discharge varied greatly over the sampling period, the procedure above was carried out in steps for each discharge interval.

For comparison of mean total bed load transport between rivers the values were normalized by the active width of the channel.

CASE STUDY—THJÓRSÁ RIVER, SOUTHERN ICELAND

The most extensive study was done at Krókur on Thjórsá River, southern Iceland (Fig. 1), where bed load samples were taken at variable discharge values during nine sediment campaigns in 2001, and during a 10-year flood event in January 2002 (Table 2). Close to 800 bed load samples were collected with the Helley-Smith 47.7-kg cable-suspended sampler at 7–10 stations during each campaign.

Table 2 Results from bed load sampling at Thjórsá in 2001 and the January flood in 2002.

Campaign date	Mean discharge ($m^3 s^{-1}$)	Total integrated bed load transport ($kg\ s^{-1}$)
11–14 July 2001	351	4.7
23–25 July 2001	320	5.0
31–1 August 2001	326	8.7
8–9 August 2001	327	9.5
13–14 August 2001	326	9.3
23–24 August 2001	442	13.1
29–30 August 2001	342	9.8
18–19 September 2001	352	8.7
19–20 December 2001	352	5.6
10 January 2002	1326	134.3
11 January 2002	1066	37.0

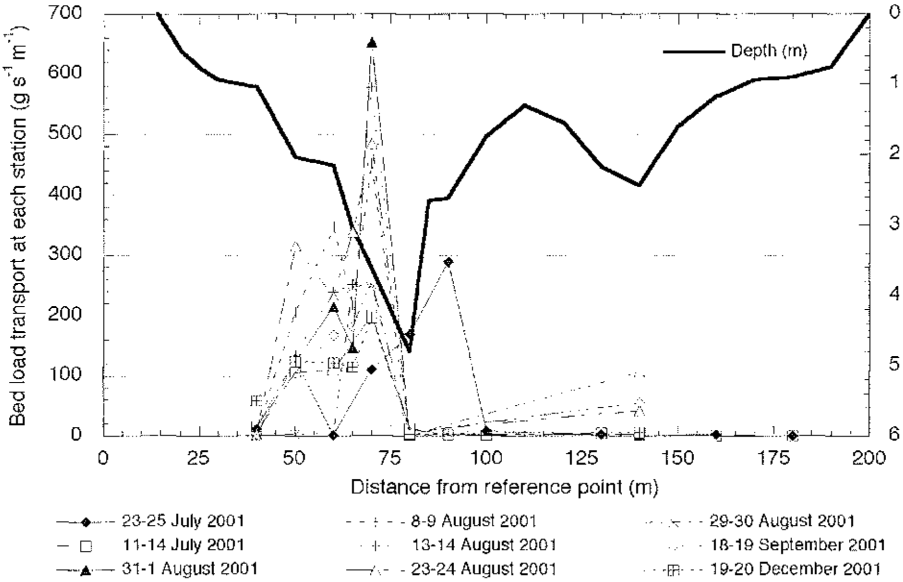

Fig. 2 Mean bed load transport at each station in Thjórsá during sediment campaigns in 2001. Also shown is a depth profile across the river channel from 2002. In this depth survey the left bank was located at 14 m and the right bank at 200 m.

Great differences are seen in bed load transport among the stations within the river channel (Fig. 2). Most of the bed load is transported in a narrow gully in the channel between 50 and 70 m distance from the reference, about 18 m inland from the left river bank. In contrast, only a minor fraction of the bed load is transported at other stations closer to the river banks. Furthermore, grain size measurements of the bed load samples show that the coarsest sediment is transported at the same locations (50–70 m stations). Total bed load transport ranges from *c.* 4.7 to 13 kg s^{-1} during sediment campaigns in 2001, but is greater than 134 kg s^{-1} during the peak of a 10-year-flood event in January 2002 (Table 2, Fig. 3). The flood was triggered by a winter rainstorm with heavy precipitation melting fresh snow on frozen ground.

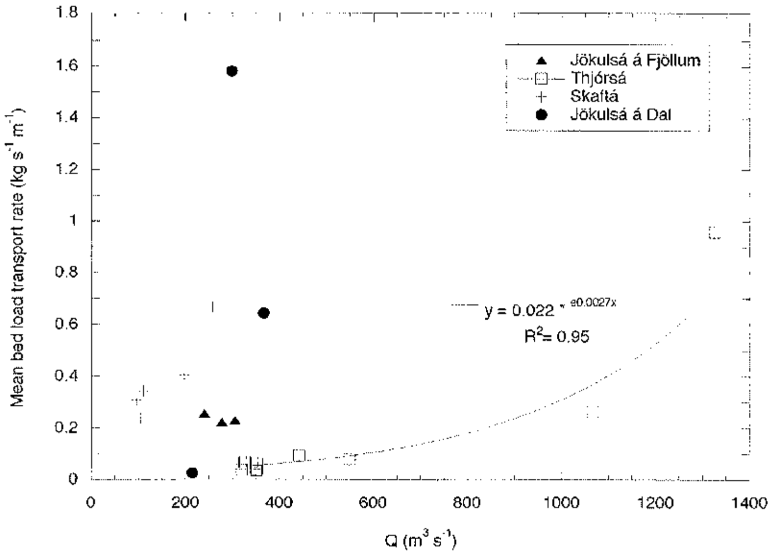

Fig. 3 Mean total bed load rate for individual bed load campaigns on rivers Thjórsá, Jökulsá á Fjöllum, Jökulsá á Dal and Skaftá in 2001 and January flood in 2002. A exponential curve is fitted to the Thjórsá data; however, additional samples have to be taken before a reliable rating curve can be established.

The correlation between mean total bed load rate and the river discharge for the sampling campaigns at Krókur in 2001 is poor as we have a large distribution of total transport at the same discharge interval (Fig. 3). The poor correlation is probably to some extent related to the narrow distribution of discharge values during the year 2001, as well as intermittent reservoir operation upstream, and shows that we especially lack data from low and high discharge periods. Hence, the three values obtained in the January flood 2002 extended the curve considerably and suggest a semi-exponential correlation between the discharge values and bed load transport. An example of such an exponential curve is shown on Fig. 3; however, more transport values at high and low discharges have to be determined before the correlation between these parameters can be evaluated with greater certainty.

COMPARISON WITH OTHER BED LOAD STUDIES

The box plots in Fig. 4 compare the individual "at-a-point" bed load transport rate in four rivers in Iceland; i.e. Thjórsá, Jökulsá á Fjöllum at Grímsstadir, Jökulsá á Dal and Skaftá at Sveinstindur (Fig. 2; Table 1). The data include all measurements made in each river in 2001 as well as data collected in Thjórsá during the January flood in 2002. As the data are independent of discharge, location on the river, as well as timing of the sampling campaigns, a great scatter is observed in the data sets. Hence, the values are here shown as $\log_{10}$ values to allow comparable representation. Figure 4 shows that although the bed load transport of "at-a-point" samples is on average lowest in Thjórsá, it is also most variable in that river, which is understandable due to the

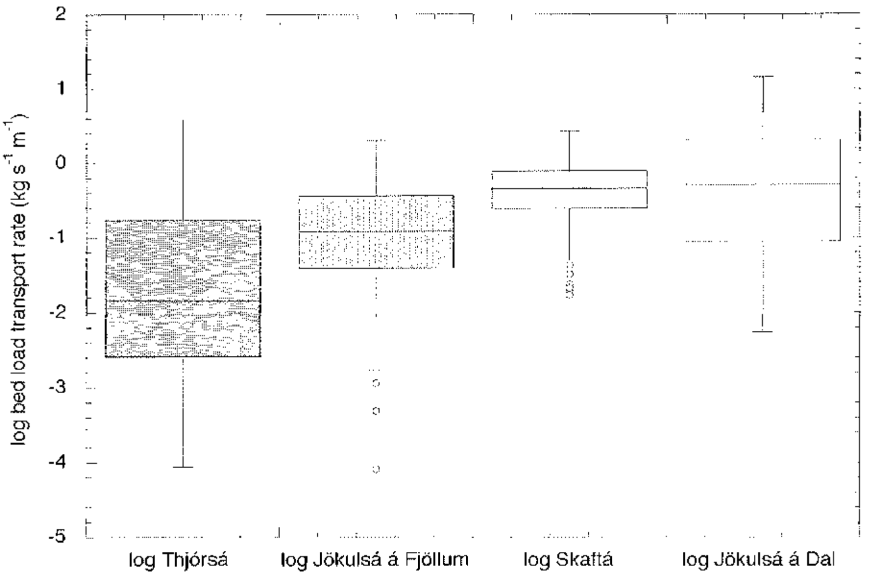

Fig. 4 Box plot showing the range of $\log_{10}$ "at-a-point" bed load transport rates as $\log_{10}$ in the rivers Thjórsá, Jökulsá á Fjöllum, Jökulsá á Dal, and Skaftá during sediment campaigns in 2001 and January flood in 2002. The line within each box shows the median value and the outer limits of the box contain 50% of the data. Circles represent outliers.

great discharge difference during the campaigns and the great variability across the river channel (Fig. 2). In contrast, the highest values are obtained in Jökulsá á Dal (Fig. 1), although a certain scatter is observed in the data (Fig. 4) due to very variable conditions during the three sediment campaigns. The wide distribution of bed load transport values shows the stochastic nature of bed load transport well, as has been recognized in numerous studies (e.g. Iseya & Ikeda, 1987; Pitlick 1988; Gomez *et al.*, 1989; Gomez, 1991; Hoey, 1992; Nicholas *et al.*, 1995). Consequently, one of the best ways to minimize errors in bed load calculations is to sample frequently and calculate the average transport. For this we need to collect numerous samples over a broad discharge spectrum.

The different characteristics of the rivers Thjórsá, Jökulsá á Dal, Jökulsá á Fjöllum, and Skaftá is readily seen on Fig. 3, which compares the mean total bed load transport rate in the Thjórsá campaigns with equivalent data for the other three rivers. It is obvious that the rate is much less in Thjórsá than in the other three rivers at similar discharge (0.03–0.07 kg s^{-1} m^{-1}) (Fig. 4), which is understandable because of the upstream reservoirs in Thjórsá, where most of the coarse sediment accumulates. Only during the January 2002 flood did the mean transport discharge reach values close to those in the other rivers (0.08–0.96 kg s^{-1} m^{-1}).

The extreme difference of mean bed load transport discharge in Jökulsá á Dal during the three sampling campaigns in 2001 (0.03–1.58 kg s^{-1} m^{-1}) shows the seasonal variability of bed load transport well; with highly elevated transport in early summer when glacial melting initiates and flushes out sediment in the channel, and minor bed load transport in October when stream discharge had greatly decreased. The channel of

Jökulsá á Dal from the glacier snout to the sampling site is steep, which in addition to high discharge during the summer melting season (up to 1000 $m^3 s^{-1}$) hinders any major deposition of sediment within the channel and causes the high and coarse bed load transport compared to the other rivers.

The relatively low and comparable mean total bed load transport rate (0.22–0.25 $kg\ s^{-1}\ m^{-1}$) in the sampling campaigns in Jökulsá á Fjöllum at Grímsstadir (Figs 1 and 3) is probably related to the great distance from the glacier to the sampling site, which delimits bed load as it is deposited in sediment traps along the river course, as well as the large component of sediment-deprived groundwater in the river, which moderates the bed load transport at increasing discharge. On the contrary, the relatively high mean total bed load transport rates in Skaftá at Sveinstindur (0.24–0.67 $kg\ s^{-1}\ m^{-1}$) reflects the shortest distance from glacier to sampling station, as well as the recurrent jökulhlaups in the upstream glacier. During the jökulhlaups a great quantity of sediment is transported downstream, which is being incorporated into the river channel for months subsequent to the event.

It is also of major interest to compare the bed load transport in these Icelandic rivers to bed load studies carried out in other parts of the world. It is, however, essential to realize that a direct comparison may not always be practical as values for bed load transport have been achieved using a variety of methods such as transport formulae, morphological research, various indirect methods (e.g. tracer pebbles, magnetic clasts, pebble transmitters, ultra sounding), as well as the direct measurement of bed load with samplers or diverse trapping devices (see Gomez, 1991, for brief summary). Most of these methods have limitations of some sort and do not always produce data with the same spatial and temporal resolution which limits comparison.

Stott (2000) compared six alpine and six arctic/subarctic bed load studies and suggested that bed load transport rate in alpine environments was significantly higher (0.03–4 $kg\ s^{-1}\ m^{-1}$) than in the arctic/subarctic locations of northern Norway, Greenland, Svalbard, Iceland, and Antarctica (0.0002–3.5 $kg\ s^{-1}\ m^{-1}$). When data from this study is compared with the summary by Stott it is seen that all the mean total transport rates greater than 0.03 $kg\ s^{-1}\ m^{-1}$ are higher than other arctic/subarctic bed load transport rates, excluding extreme rain values in Lyngdalselva, Norway (3.5 $kg\ s^{-1}\ m^{-1}$) and transport rates in the Onyx River, Antarctica (0.38–2.16 $kg\ s^{-1}\ m^{-1}$). This includes results from the glacial river Virkisá in southeast Iceland (Nicholas & Sambrook Smith, 1998).

This comparison indicates that the Icelandic total bed load transport rates are more comparable with the alpine sites of White River, Washington, USA (Fergusson *et al.*, 1989), Sunwapta River in Canada (Goff & Ashmore, 1994), and Bas Glacier d'Arolla, Switzerland (Warburton, 1992). Given the much higher discharge in the Icelandic rivers than most of the other rivers, as well as the highly effective glacial erosion the high values are not surprising.

The conclusions shown here are based on the initial results from bed load studies of these four Icelandic rivers. The same rivers were sampled in 2002 and two more locations were added for 2003. Although we are well aware of the limitations and possible errors involved in such studies, we anticipate that these results show the great range of bed load transport in Icelandic rivers and some of the possible causes for the variability.

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